AN ABSTRACT OF THE THESIS OF

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Title: The Effects of Voluntary Step-Training on Slip Recovery

Abstract approved:

Michael J. Pavol

Falls caused by slips are a major health risk to older adults and place a large financial strain on the health care system. Previous research has found that individuals can learn to recover their balance after being exposed to a series of simulated slips. However, training large numbers of older adults through repeated slip exposure is logistically improbable. An easier and less expensive method of training people not to fall is needed. The purpose of this study was to determine whether training the voluntary stepping response would improve the recovery response to an unexpected slip to a similar extent as seen with repeated slip training.

A sliding platform was used to cause 34 healthy young adults to lose their balance while rising from a simulated lifting task. Seventeen subjects in the slip-training group were exposed to slipping perturbations in varying, unpredictable directions for 26 trials. Seventeen subjects in the step-training group performed a corresponding sequence of cued voluntary stepping for 25 trials, followed by a single unexpected slip. Subjects were removed from data analysis if they fell or took a fundamentally different recovery step. Nineteen variables quantifying the proactive

and reactive qualities of the recovery response were derived from motion capture data and compared between the first and last slips of the slip-training and the slip following the step-training, all of which were forward-directed.

Both step- and slip-training resulted in a longer recovery step. The slip-training improved the response time and center of mass position at step lift-off when compared with the step-training. Slip-training also increased the distance between the stepping foot and center of mass and decreased the hip downward velocity at step touchdown, improving both stability and weight support. The slip-training appeared to prepare the reflexive initiation of the recovery step as well as the conscious control of step length, whereas the step-training only affected the step length.

Both training protocols showed that learning does occur from reflexively or voluntarily practicing recovery steps. People often fall from a balance loss because they do not take a sufficiently long recovery step. In these instances, step-training may improve the likelihood of balance recovery. This finding can be used to develop new training protocols for populations at risk for falls.

The Effects of Voluntary Step-Training on Slip Recovery

by
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APPROVED:

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Dean of the Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

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Josh R. Baxter, Author

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

The Effects of Voluntary Step-Training on Slip Recovery

Introduction

Falls pose serious health risks to the general population; however, falls in the workplace and in older populations present the greatest threat to health (Berg et al. 1997; Hausdorff et al. 2001). Many complications arise from fall-related injuries and, while the majority of falls do not produce injury, injuries can be quite severe. Older adults are affected most by falls. Each year, an estimated one-third of older Americans will experience a fall. While many falls are benign, 20-30% of older adults who fall suffer complications including bruising, head trauma, bone fractures, and death (Hornbrook et al. 1994; Hausdorff et al. 2001; Centers for Disease Control and Prevention 2008). Each year, billions of dollars worth of health care and other services are dedicated to fall victims (Stevens et al. 2006).

Falls are often caused by a slip followed by an inadequate step response (Berg et al. 1997; Pai 1999). During a slip, foot traction is lost and the body’s center of mass can move outside the base of support A common response to a slipping stimulus is to take steps in hope of regaining balance (Pavol et al. 2004b). Falls from slips occur when the stepping foot takes delayed or short steps or when the supporting limb does not generate large enough knee and hip extensor moments to support the entire body weight while the other limb is stepping (Pavol et al. 2004b; Pai et al. 2006).

Humans possess preprogrammed postural responses that can be manipulated to respond appropriately to external stimuli (Horak and Nashner 1986; Horak et al.

1989). When a perturbation drastically shifts the center of mass of an individual, recovery steps are taken to avert a fall. However, if a large perturbation has not been previously experienced by the individual, an inappropriate balance response is likely to be performed, often resulting in a fall (Pai et al. 2003; Pavol et al. 2004a; Pai and Bhatt 2007). Training interventions that expose individuals to repeated slips have been shown to effectively match appropriate stepping responses to these external stimuli after several perturbations (Pai et al. 2003; Pai and Bhatt 2007).

While it is well documented that postural balance can be improved through repeated perturbations (Horak and Nashner 1986; Woollacott et al. 1986; Horak et al. 1989; Stelmach et al. 1989; McIlroy and Maki 1995; Pai et al. 2003; Pai and Bhatt 2007), studies examining the effects of voluntary stepping on slip recovery are scarce. A stepping response to an unfamiliar perturbation is a common reflex; however, prior to this study, it was not known whether an appropriate stepping response could be preset through repeated stepping before experiencing a perturbation.

Specific Aim and Hypotheses

The aim of this study was to determine the extent to which training the voluntary stepping response would affect the recovery response to an unexpected slip in comparison to no training and repeated exposure to slipping among young adults. A step-training group performed voluntary stepping in different directions in response to a visual cue and then experienced an unexpected slip during a simulated lifting task. A second, slip-training group was repeatedly exposed to slipping in different, unpredictable directions during the same task.

The following hypotheses were investigated in the study.

Hypothesis 1: Subjects who underwent the step-training would exhibit differences in response timing, pre-slip postural adjustments, center of mass kinematics, hip height kinematics, and step kinematics compared to the first, unexpected slip of the slip-training group. These differences would be consistent with improved balance recovery in the step-trained group.

Hypothesis 2: Subjects who underwent the step-training would exhibit similar response timing, center of mass kinematics, hip height kinematics, and step kinematics as in the final (i.e. end of training) slip of the slip-training group.

Assumptions

In this study, the following assumptions were made.

1. Subjects represented the healthy young adult population.
2. Subjects were not under the influence of drugs, alcohol, or other substances that may have affected balance or reflexes.
3. The initial exposure to a novel slipping perturbation during a simulated squat-lifting task represented a realistic, unexpected slip that is commonly experienced during everyday activities.
4. Subjects responded to the slipping perturbations in a natural manner.

Delimitations

The following were the delimitations of the study.

1. The study investigated the effects step-training and slip-training had on slip recovery in healthy young adults.

2. The study investigated the effects step-training and slip-training had on a backwards loss of balance from an unexpected slip produced artificially in a laboratory setting.
3. The subjects of the study were aware that a slipping perturbation would be delivered; because of this anticipation, subjects were given no indication of when or in what direction the slipping perturbation would be delivered.

Limitations

1. The findings of this study are only applicable to healthy young adults.
2. The study investigated slip recovery success immediately following step-training and slip-training; therefore, the extent to which benefits from step-training and slip-training are retained over time cannot be determined.
3. The study investigated recovery from slips resulting in backward balance loss, so the results can only be generalized to forward slips.

Significance of the Study

The effectiveness of repeated perturbation exposures on balance improvement has been well documented (Horak and Nashner 1986; Woollacott et al. 1986; Horak et al. 1989; Stelmach et al. 1989; McIlroy and Maki 1995; Pai et al. 2003; Pai and Bhatt 2007). These studies suggest that postural responses are preprogrammed and that the appropriate responses are quickly identified after exposure to one or more perturbations. However, the literature does not indicate whether the appropriate stepping response to a perturbation can be preset through the training of voluntary stepping responses. If voluntary step training can increase the likelihood of recovering from a slip, inexpensive and safe methods may become available to help prevent falls in older populations. This study addressed, and began to answer, the question of whether voluntary stepping might preset an appropriate stepping response to a novel, unexpected perturbation in a manner comparable to repeated slip exposures (Welsh 2006). The rationale was that, if the results of this study were to show that voluntary step-training improves the recovery response to a slip in young adults, further studies could be developed to identify the specific mechanisms that cause this presorting of postural responses, as well as the extent to which the findings apply to older adults and other high-risk populations.

Review of Literature

The consequences of falls in the United States are severe. The cost to treat and care for fall victims, along with the emotional hardships endured because of serious injuries and diminished quality of life, warrant thorough investigation into possible interventions that can help curb the prevalence of falls in all populations. Over the past several decades, resources have been dedicated to successfully understand many aspects of balance and the associated postural reflexes. Still lacking, however, is a deep understanding of how certain reflexes may be modulated to better protect individuals against the hazards of balance loss.

This literature review will cover many classic studies that investigated why responses to balance perturbations work and how they can be modulated. This chapter will first discuss the negative impact falls have on our society, especially older fall victims and the medical sector. Postural control and reflex modulation will be discussed. This will lead into the different balance recovery strategies common among humans and how these responses can be used to prevent falls. The aforementioned topics will be supported by the collective findings of nearly thirty years of research.

Epidemiology of Falls

Falls and resulting injuries inflict substantial health and economic woes, particularly in older adults. Each year, nearly one-in-three adults over the age of 65 fall and half of older adults in institutionalized care facilities fall at least once per year (Tinetti et al. 1988; Hornbrook et al. 1994; Hausdorff et al. 2001; Centers for Disease

Control and Prevention 2008). Falling in older adults often becomes a chronic problem. Older adults with a history of falling have a two-thirds probability of experiencing a fall in the following year (Nevitt et al. 1989).

Falls by older adults can have severe consequences. Approximately one-quarter of older adults who fall sustain moderate to severe injuries, ranging from bruising to bone fractures and even severe head trauma (Alexander et al. 1992; Sterling et al. 2001; Stevens et al. 2006). Traumatic brain injuries resulting from falls are responsible for nearly one-half of fall-related deaths among older adults (Stevens et al. 2006). Bone fractures can also be particularly damaging to the health of the victim. Fractures of the spine, hip, forearm, pelvis, and hands are some of the common fractures that result from falling (Scott 1990). Hip fractures caused by falls in older adults have an 18-33% mortality rate within the first year after the fall (Magaziner et al. 2000). Hip fractures often force individuals to stay in the hospital or an assisted living facility for an extended period of time (Magaziner et al. 2000; Leibson et al. 2002).

Physical trauma caused by falls reduces the mobility of older adults. Nearly a third of older adults who fall develop a fear of falling (Vellas et al. 1997). This fear often causes the individual to alter daily activity. This reduction in mobility can lead to a decrease in physical fitness and ambulatory capacity, which may increase the risk of falling again (Vellas et al. 1997; Cumming et al. 2000).

Falls among the elderly affect all of society. While the health consequences of falls are the most severe, the financial costs of treating fall-related injuries are also very large. In 1996, the average health care cost to treat a fall injury was around $20,000 (Rizzo et al. 1998). In the year 2000, the cost of services dedicated to fall injury treatment in older adults was more than $19 billion (Stevens et al. 2006). Only $179 million was spent on treating fatal falls; the overwhelming amount spent was dedicated to nonfatal-fall treatment (Stevens et al. 2006). It has been estimated that the annual costs of fall-related injuries in the United States will reach $44 billion by 2020 (Englander et al. 1996). There is clearly a need to prevent falls.

Preventing slip-related falls is of particular importance. Nearly 60% of falls by older adults are caused by slipping or tripping (Berg et al. 1997). One-third to one-half of falls suffered by community-dwelling ambulatory older adults are thought to be a result of environmental hazards (Masud and Morris 2001). These hazards include poor lighting, uneven or slippery walking surfaces, a lack of railings, and inappropriate footwear (Masud and Morris 2001). While minimizing slipping hazards is an important aspect of fall prevention, understanding the mechanics of slip recovery and applying this knowledge to falls prevention is essential to improving quality of life among older adults.

Postural Control and Adjustment

Reflexive responses to small postural perturbations have been researched in depth (Berger et al. 1984; Dietz et al. 1986; Horak and Nashner 1986; Woollacott et al. 1986; Horak et al. 1989; Stelmach et al. 1989). Postural reflexes are categorized in the literature into three discrete groups: M1, mono-synaptic stretch reflexes; M2, poly-synaptic automatic postural responses; and M3, integrative responses that utilize several redundant senses (Diener et al. 1982; Berger et al. 1984; Woollacott et al. 1986; Horak et al. 1989). Mono-synaptic reflexes have a latency of 40-50 ms in the distal leg and are unlikely to play any meaningful role in balance recovery. The literature shows strong evidence that stretch reflexes are not utilized to any great extent during balance perturbation (Berger et al. 1984; Woollacott et al. 1986; Horak et al. 1989; Stelmach et al. 1989) and may actually be suppressed during gait (Berger et al. 1984).

Long-loop automatic postural responses, M2, are poly-synaptic responses initiated by somatosensory stimulation. These M2 responses occur at the spinal cord and brain, producing responses to a stimulus based on the current task (Berger et al. 1984; Lewis et al. 2006). Several unique responses to a stimulus may be available to select from. The selection of the response may be influenced by previous exposures to a similar stimulus and real-time changes to the response can also occur during the response to the stimulus (Horak and Nashner 1986). In a study by Berger et al. (1984), the same stimulation was presented at different ankle angles during stance and phases of gait, each time eliciting a different response. While these M2 responses are involuntary, the triggering of the appropriate response can be trained by repeated exposure to a familiar or expected perturbation (Horak et al. 1989). These reflexes initiate the recovery strategies during a balance perturbation.

The integrative response system, M3, coordinates sensory information collected by the visual, vestibular, and somatic sensory systems. These multiple sensory systems create a redundant postural control mechanism that retains functionality when one or more of the inputs are lost, either acutely or chronically (Woollacott et al. 1986). M3 reflexes are critical in balance during quiet stance (Woollacott et al. 1986). Slow changes in body position are perceived by the aforementioned senses and the appropriate responses are made (Woollacott et al. 1986). Dysfunctions of these sensory systems, along with aging, impact their functionality (Woollacott et al. 1986; Stelmach et al. 1989).

It appears that M2 responses play the most important role in immediate responses made to a balance perturbation (Horak and Nashner 1986; Horak et al. 1989). The central nervous system also seems to use previous experiences to stimulations to prepare the M2 responses to similar perturbations in the future (Horak and Nashner 1986). The concept of M2 responses being altered by exposure to a perturbation will be applied to voluntary stepping.

Modulation of Central Set

Automatic postural responses, M2, appear to be programmed to a perturbation before the perturbation is presented. This pre-programmed state is referred to as ‘central set’ (Horak et al. 1989). Central set responses are modulated by higher neural functioning, such that different responses are elicited by the same stimulus as the conditions change (Berger et al. 1984; Pavol et al. 2001). In an early study, subjects received the same perturbation or stimulus in trials of varying gait and stance conditions (Berger et al. 1984). These different conditions were followed by varying M2 responses, suggesting that long-loop responses elicited were dependent on both the stimulus and the gait or stance condition. Long-loop responses can be modulated through repeated exposure to the stimulus and based on expectations from previous experience. Muscle activation patterns become more efficient if the expectations of a perturbation are met and after repeated exposures to the perturbation (Horak et al. 1989). These M2 responses initiate the recovery strategies used to maintain upright posture.

Balance Recovery Strategies

After exposure to a balance perturbation, the center of mass is displaced. Three balance recovery strategies are employed to maintain upright posture. When exposed to a small, slow perturbation, the ankle strategy is used to keep the center of mass within the base of support (Horak and Nashner 1986). The distal leg muscles are recruited first to produce either a dorsiflexion or plantarflexion moment, whichever is appropriate, to maintain balance. Muscle activation continues proximally on the same dorsal or ventral side of the body. During perturbations that are larger or have a small base of support relative to the length of the feet, the hip strategy is used to maintain postural equilibrium (Horak and Nashner 1986). The hip strategy begins with the musculature across the hip being recruited first. This is followed by distal musculature on the same dorsal or ventral side of the body being recruited. The hip strategy results in a static ankle joint and noticeable sway at the hips to maintain upright posture. These two strategies do not result in a changed base of support and are often used when environmental constraints require leaving the feet on the ground.

The stepping strategy is the third recovery strategy available. Steps are taken as a recovery strategy when the perturbation becomes large, when no spatial constraints are present, or to quickly reduce sway following perturbation recovery (McIlroy and Maki 1995; Maki et al. 1996; Pavol et al. 2004b; Mille et al. 2005). Base of support perturbations cause the center of mass to shift in the opposite direction in relation to the perturbation. Stepping responses are often employed well before the center of mass reaches the limits of stability (McIlroy and Maki 1995). Successful recovery step responses typically restore balance by performing an ankle-like strategy followed by quickly placing the foot underneath the moving center of mass (McIlroy and Maki 1995). Anticipatory adjustments are normally lacking after exposure to a novel perturbation (McIlroy and Maki 1995). For sagittal-plane perturbations, in the case of no anticipatory adjustment, the step is taken with the center of mass positioned evenly between the two feet. As a recovery step is taken, the weight of the body shifts towards the stepping leg and causes the hips to lower in height (McIlroy and Maki 1995; McIlroy and Maki 1996).

These compensatory steps show distinct differences from stepping observed during typical gait (Berger et al. 1984). Anticipatory postural adjustments are typically found during voluntary stepping and in gait preceding every swing phase. These anticipatory adjustments load the stance leg with body weight. This shifts the center of gravity towards the stance foot and, as swing occurs, the center of mass moves back to the midline of the body as the swing leg strikes the ground (McIlroy and Maki 1995; McIlroy and Maki 1996). In a study by McIlroy and Maki (1995), responses to a novel perturbation during stance elicited no anticipatory adjustment prior to the step. However, after repeated exposures, anticipatory adjustments were made prior to stepping, indicating that the central nervous system adapts its stepping response with repeated exposure to a perturbation.

Adaptations to Repeated Perturbation Exposure

As stated, compensatory steps are often taken following an exposure to a novel perturbation. When exposed to the same perturbation repeatedly, several changes in response are present. These adjustments to perturbation exposure are both proactive and reactive in nature.

After being repeatedly exposed to a perturbation, anticipatory adjustments are made before the perturbation may present itself. These proactive adjustments align the center of mass in a position that increases the chance of balance recovery if and when a perturbation is presented (Pai et al. 2003; Pavol et al. 2004b). Anticipatory adjustments in reactive stepping can also appear with repeated perturbation exposure. These anticipatory adjustments shift the body weight towards the support leg prior to the step occurring. This causes the center of mass to begin more contralateral to the stepping leg and results in a central location of the center of gravity after the step is taken (McIlroy and Maki 1995; McIlroy and Maki 1996).

Other adaptations in the reactive response are observed with repeated perturbation exposure. Fewer steps are executed, recovery steps are sometimes not initiated at all, steps are initiated more rapidly, stability at touchdown of the recovery step is increased, the extent of hip descent is decreased, and falls caused by the perturbation are drastically reduced following one or more exposures (McIlroy and Maki 1995; Maki et al. 1996; Pavol et al. 2004b; Pai and Bhatt 2007).

Predicting and Preventing Falls

Falls from a perturbation often occur when the center of mass leaves the limit of stability and no recovery strategy successfully returns the center of mass within the limit of stability. A recent study by Welsh (2006) exposed subjects to repeated and random perturbations. The perturbations had five distinct directions and the speed of the perturbation was enough to require a recovery step if subjects were to prevent a fall. Welsh (2006) found that individuals who fell upon the first, unexpected forward slip took shorter backward recovery steps, leading to lesser stability at step touchdown than those who recovered. Fallers also experienced greater hip descent prior to step touchdown.

Pavol et al. (2001) introduced a tripping hazard during the gait cycle and identified factors that increased the likelihood of a fall following a trip. If the trip occurred early in the gait cycle, the step was lengthened in an attempt to restore balance by moving the base of support in front of the center of mass. These fallers walked faster, had lower hip heights, and had twice the amount of lumbar flexion. When the trip occurred later in the gait cycle, the tripped foot was quickly placed on the ground and the contralateral foot was used to clear the tripping hazard. Fallers who fell during the first recovery step took a shorter recovery step, walked faster, and loaded the support leg slower than those who recovered. When the fall occurred after a series of stumbling steps, the cause was likely due to increased flexion at the waist and buckling in the support leg. The results of these studies suggest that falls are a multifaceted problem resulting from combinations of abnormal properties of the recovery strategy.

With repeated exposure to a perturbation, the incidence of falls decreases (Pavol et al. 2002; Welsh 2006; Pai and Bhatt 2007). This learning has been associated with proactive adaptations, such as changes in the center of mass position and velocity prior to the perturbation, along with changes in the reactive stepping response. Fallers learn to reduce their extent of balance loss and their hip descent prior to step lift-off, to place their stepping foot farther behind their center of mass, and increase their hip height at step touchdown (Pavol et al. 2004b; Welsh 2006)

It is well established that repeated exposure to a perturbation will improve the efficiency of the elicited response and reduce the incidence of falls. These responses are trained through repeated involuntary balance recovery responses. The literature is unclear as to whether these responses can be trained through a voluntary pathway.

Preparation and Voluntary Stepping

Balance recovery strategies are known to be dependent on many factors: previous experience, environmental constraints, perturbation qualities, body position, body velocity, available sensory information, and age (McIlroy and Maki 1996). Previous studies have investigated involuntary balance recovery responses due to a perturbation of the base of support. No research has focused on the effects of voluntarily performing similar balance recovery strategies. Repeated exposure to a perturbation has been shown to improve recovery outcome (Pavol et al. 2004b; Welsh 2006), but no studies have focused on the effects of voluntary step-training.

In healthy young adults, voluntary and involuntary steps taken in response to similar initial stimuli have similar time characteristics (Luchies et al. 1999). During these involuntary steps, the steps were significantly longer and higher. During a voluntary step, choice complexity increases the reaction and step times (Luchies et al. 2002). However, another study suggests that preparatory level during voluntary stepping affects the reaction time but not the time it takes to shift weight or step (Brauer and Burns 2002). Similarly, in a study in which subjects were presented with visual cues informing them about the impending perturbation, the step properties were not altered when pre-cued with the perturbation (Maki et al. 1996). The subjects did reduce the number of recovery steps used when pre-cued information was available. This suggests that many kinematic properties of an individual's stepping response do not depend on volition or preparation. If voluntary and involuntary steps share similar properties, they may share similar neural pathways. Practicing the desired step might then improve the stepping response to a novel stimulus.

Rationale

Falls often result from perturbations because insufficient responses are initiated by long-loop mechanisms. The three balance recovery strategies are scaled and combined to produce a single response for any possible stimulus in any situation. The literature shows that these responses can be correctly modulated in as few as one exposure to the stimulus (McIlroy and Maki 1995). Unfortunately, for many older adults, a single fall often causes traumatic consequences, sometimes proving fatal.

The studies in this chapter have investigated the modulation of automatic responses through involuntary responses to a perturbation. It is widely accepted that long-loop response latencies cannot be improved. Therefore, the focus of our research will be to investigate a new mechanism through which these responses can potentially be modulated. No current literature investigates the possibility of modulating automatic responses through the repeated voluntary execution of the desired response. If stepping responses could be preprogrammed to a slip without ever exposing the individual to a slip, a new balance training paradigm would emerge.

Methodology

The purpose of this study was to determine the extent to which training the voluntary stepping response affects the recovery response to an unexpected slip in comparison to no training and repeated exposure to slipping among young adults. This was attempted by having a group of participants complete a series of cued steps that were considered adequate for recovering from slips in different directions, followed by their experiencing an actual slipping perturbation. Another group was exposed to repeated slips in randomly varying directions. The effectiveness of this slip-training has been shown (Welsh 2006) and the step-trained and slip-trained responses were compared to determine the effectiveness of step-training. This chapter will describe the subject selection, instrumentation, data collection procedures, and statistical analysis used to test the hypotheses.

Subjects

Thirty-four healthy young adults participated in this study. Each subject was randomly assigned to either a *slip-training* group or a *step-training* group. Each group consisted of 17 subjects (Table 1). Subjects had to be between 18-40 years of age and less than 86 kg in mass. They completed a health history questionnaire that screened for medical conditions that would place them at elevated risk of injury or that would pose a threat to the validity of the study. Individuals were also excluded from participating if they were experiencing any physical or mental impairment from drugs or medications. This study was approved by the Oregon State University Institutional Review Board and subjects signed informed consent forms before participating.

Instruments and Apparatus

A moving platform was used to produce a perturbation that represented a slip while the subject was standing on it (Welsh 2006). The platform was round, with a 40cm diameter, and was attached to a pair of rails and a pneumatic cylinder. The rails and pneumatic cylinder were attached, in turn, to a turntable that was mounted to a force plate (Bertec, Columbus, OH) and could be rotated in the transverse plane to orient the platform in different directions. The pneumatic cylinder was driven by compressed air at 483 kPa. When triggered to, the pneumatic cylinder quickly slid the platform along the rails in the anterior, posterior, left, or right direction, as specified, with respect to the subject. The platform was positioned on top of a stationary cover plate that blocked the orientation of the rails and pneumatic cylinder from the subject's vision. A large false floor (2.4 m x 2.4 m) was placed around the cover plate to provide a surface for stepping and to reduce any feeling of spatial constraint (Figure 1).

During forward or backward slips, the platform translated 30 cm over a period of approximately 0.35 seconds and, during left or right slips, the platform translated 17 cm in approximately 0.25 seconds. Similar platform translation characteristics were used in a previous study (Welsh 2006). The translation of the platform caused a loss of balance in the opposite direction by the subject.

For the step-training, a display on a computer monitor, located approximately 4 m in front of the subjects, indicated to subjects when and in which direction to step. The display consisted of four large arrows, pointing up (corresponding to forward), down (backward), left, and right. The background of each arrow was able to switch from gray (off) to bright green (on) to indicate that a step should be taken in the direction of the arrow (Figure 2).

A force plate (Bertec, Columbus, OH) was used to measure the ground reaction forces between the feet and the moving platform. These force data were sampled at 600 Hz and were analyzed to identify step lift-off and touch-down during the initial recovery step for each slip. These force data were also used to initiate platform movement and the display of the arrows indicating step direction.

A LabView program (National Instruments, Austin, TX) was used to trigger the slips and the display of the arrows on the computer monitor. In each trial, subjects performed a simulated lifting task in which they squatted down and then stood back up while holding a foam rod (Figure 1). The program sampled the compressive force measured by the force plate and the tensile force measured by the load cell of the fall-arrest system (see below) in real time at a sampling rate of 120 Hz. To determine the height of the subject's center of mass during the squat movement, the vertical acceleration of the subject was computed from the force data and integrated twice. During step-training trials, if the center of mass traveled downward at least 8 cm, the arrow display was automatically activated when the center of mass traveled upward 25% of the distance it had traveled downward during the squat. During trials in which a slip was induced, if the center of mass traveled downward at least 8 cm, the slip was automatically triggered once the center of mass had traveled upward 2% of the distance it had traveled downward during the squat. This earlier activation of the moving platform was to compensate for the slight delay in the pneumatic cylinder activation and cause both training groups to receive the perturbation or visual cue at approximately the same position during the lifting task. As a safety precaution, the program computed the center of pressure in real time and the slip only triggered if the center of pressure was within 6 cm of the center of the platform. This was to protect against any possible foot injuries that might have resulted from the subject's foot stepping into the path of the moving platform.

A nine-camera motion capture system (Vicon, Lake Forest, CA) was used to record the position of 35 passive-reflective markers during each trial. The markers were taped to bony landmarks and tight fitting clothing at the feet, ankles, legs, knees, thighs, pelvis, back, chest, shoulders, elbows, wrists, and head. Each body segment had at least two markers per segment. During each trial, a digital video camera (Sony, New York, NY) recorded ordinary video to help in identifying the properties of the recovery step taken.

A fall-arrest system was used in every trial to prevent any injury upon an unsuccessful slip recovery (Figure 1). Subjects were secured into a full-body safety harness. This harness was attached from both shoulders and the mid-back to an overhead trolley with three dynamic, shock absorbing ropes. The trolley sat securely in a rail system that was mounted to a support beam in the ceiling. The ropes were adjusted for each subject so that, in the event of a fall, the person would be safely stopped before the knees, hips, or any part of the upper body came in contact with the ground. The fall-arrest system had a load cell (Sensotec, Columbus, OH) in series with the ropes to measure the weight supported by the ropes. These data were sampled at 600 Hz for the purpose of determining the recovery outcomes of the slips.

Experimental Protocol

The Biomechanics Laboratory of the Department of Nutrition and Exercise Sciences at Oregon State University was the testing location for all subjects. Each subject provided informed consent and completed the health history questionnaire forms before any data were collected. Body weight was also measured to confirm that subjects met the weight requirements.

Next, subjects completed a simple reaction time test. For the test, a LabView program displayed a yellow light and a green light on a computer monitor. In each trial, the yellow "ready" light came on first for 2 seconds, indicating that the green light was to turn on next. Once the yellow light turned off, the green light turned on after a randomly-varying period of 2-5 seconds. As soon as the green light turned on, subjects were to press a key as quickly as possible. If a key was pressed before the green light came on, then the trial was repeated. Subjects received three practice trials followed by 10 trials in which the elapsed reaction time from when the green light came on to when the key was pressed was recorded. In 2 of the 10 trials, the green light never turned on. Simple reaction time was quantified by the median value of the reaction times measured in the other 8 trials.

Subjects then had their height measured and changed into the appropriate clothing. All subjects wore tight fitting shorts and tops with athletic shoes for this study. Subjects next completed a brief warm-up of five minutes of stationary cycling followed by stretches. These stretches were performed on the plantar flexors, knee flexors, knee extensors, hip flexors, hip extensors, hip abductors, and hip adductors. After the warm-up, subjects put on the full-body safety harness. After the harness was fastened, the reflective markers were placed on the body landmarks described earlier. Subjects performed another warm-up of 10 step-ups onto a 15 cm-high platform in three directions: forward, left, and right. The safety harness was then attached to the fall-arrest system and the ropes adjusted to ensure that, in the event of a fall, subjects would be safely stopped by the harness before striking the ground. Once secured to the fall-arrest system, subjects stood quietly on the platform in a reference body position while a static trial of motion capture data was collected.

Next, subjects were given both visual and verbal instructions on how to properly complete the simulated squat-lifting task. For this task, subjects stood on the movable platform with the lateral edges of the feet 23 cm apart. The squat task was done with a foam rod of negligible weight held in front of the body in both hands with a shoulder-width grasp. A line of tape was placed one-third of thigh-length above the knee on both legs. Subjects were instructed to squat down, touch the foam rod to the lines of tape, and then stand back up. During this squat, the back and elbows were to be kept straight and the shoulders kept rolled back. The downward and upward phases of the squat task were to be completed in about 0.86 seconds each. A computer-generated tone was used to indicate the desired timing while the subject practiced the task. After the subject was comfortable performing the movement and the investigator was satisfied that the movement was being performed correctly, the training activities began.

Slip-training Group

Subjects were told they would first perform trials of the lifting task and that, later, we would try to make them lose their balance. After two no-slip trials, the moving platform translated forward on the third trial, causing a backward balance loss. This slip occurred without demonstration, practice, or explicit warning. Subjects were then told that a similar slip may or may not occur in any direction during subsequent lifts and that they should try not to fall, without letting go of the foam rod. Subjects performed another 25 trials of the lifting task in which the slip direction varied in the same, unpredictable sequence across trials for everyone (Table 2). The number of slips in each direction (forward, backward, right, left, or no slip) was approximately equal, with a forward slip at the end. If a slip failed to trigger, typically because the subject performed the task incorrectly, the trial was repeated. Subjects were unaware of each upcoming slip direction.

Step-training Group

After performing two “normal” trials of the lifting task, subjects were told that they would undergo a training exercise and that, after the training was complete, we would try to make them lose their balance. For the training exercise, subjects stood on the perturbation platform and performed the lifting task while they watched the arrows displayed on the monitor in front of them (Figures 1 & 2). They were instructed that, if an arrow came on, they were to step as quickly as possible in the indicated direction to the associated position marked on the floor. Marked positions corresponded to the average foot placements during successful recoveries in the study of Welsh (2006). These distances were 25% of body height for backward steps, 28% of body height for lateral steps, and 34% of body height for forward steps. Subjects briefly practiced stepping to each of the marked locations from a standing position. Each subject then performed 25 trials of the step-training task. The step directions followed the same, unpredictable sequence as in the slip-training group (Table 3), with trials being repeated if the arrow did not come on because the lifting task was performed incorrectly. Finally, on the 26^{th} training trial, instead of an arrow coming on, the perturbation platform was triggered to move forward, causing an unexpected backward balance loss. This slip occurred without demonstration, practice, or explicit warning.

After the final slip of each group, additional anthropometric data were taken. These included weight and other measurements needed to predict the locations of joint centers and the body center of mass.

Data Analysis

Three trials were of interest in the analysis: the first slip of the slip-training group, the last slip of the slip-training group, and the single slip of the step-training group, all of which were slips in the forward direction. These trials will henceforth be referred to as the untrained condition, the slip-trained condition, and step-trained condition, respectively.

The outcome of each trial was classified as either a recovery or a fall based on the force measured by the load cell in the fall-arrest system. As in a previous study (Welsh 2006), falls were defined to have occurred if there existed a one-second period of time after the perturbation onset in which the average force applied to the load cell was greater than 10% of body weight. When this criterion was not met, the trial was considered a recovery.

For each of the trials of interest, Workstation software (Vicon, Lake Forest, CA) was used to reconstruct the 3-dimensional paths of the reflective markers from what was observed by the nine cameras. After reconstruction, the data were filtered with a low-pass, fourth-order, no-lag, Butterworth filter at 13 Hz. A residual analysis was used to determine the cutoff frequency for the filter (Winter 2005). A custom BodyBuilder program (Vicon, Lake Forest, CA) used the data from the static trial and anthropometric data to build a kinematic model of each subject to accurately determine the positions of joint centers and the center of mass. Sex-dependent body segment inertial properties were used (de Leva 1996). Each dynamic trial was processed with the kinematic model of the corresponding subject to provide kinematic information of each body segment and of the body center of mass. A custom MATLAB program (Mathworks, Natick, MA) computed the center of mass position and velocity relative to the base of support, hip height, hip vertical velocity, step length, step velocity, perturbation duration and peak velocity, response time, and step time.

Three unique events served as time points at which to analyze dependent variables: slip onset, step lift-off, and step touchdown. Slip onset was defined as 3 frames before the movement of both heel markers in the anterior direction between frames exceeded 1.5 mm. Step lift-off was defined by the end of a large center of pressure shift laterally towards the stance limb and step touchdown was identified by the start of a large center of pressure shift laterally towards the stepping limb. Digital video and marker data were used to confirm these events, as well as to identify step touchdowns that occured off the force plate.

Variables of the recovery response were assigned to four categories: slip onset, step lift-off, the step, and step touchdown. At slip onset and step lift-off, the center of mass (COM) position was defined by its anterior position relative to the posterior heel and, at step touchdown, the COM position was defined by its anterior position relative to the heel of the stepping foot. The COM measures were normalized to foot length. COM anteroposterior velocity was computed relative to the velocity of the base of support, with velocities computed using the central difference method. The COM relative velocity was normalized to a Froude number through division by $\sqrt{g \cdot bh}$, where g is the acceleration due to gravity and bh is body height. The hip height for the three time events was computed as the average height of the two hip joint centers (Seidel et al. 1995) and was normalized to body height. The hip vertical velocity was determined from the hip height using the central difference method. The hip vertical velocity was normalized to body heights per second.

The response time was defined as the elapsed time between the slip onset and the step lift-off. The step time was the elapsed time between the step lift-off and step touchdown and the total time of the balance loss was defined as the time from the slip onset to the step touchdown. Step length was the anteroposterior distance between the fifth metatarsal head of the stepping foot and the fifth metatarsal head of the non-stepping foot at step touchdown and was normalized to body height. The step velocity was the average anteroposterior velocity of the stepping foot and was the quotient of the step length divided by the step time.

The slip characteristics analyzed were the duration and peak velocity. The duration was the time difference between perturbation onset and the time at which the non-stepping foot stopped moving forward (heel anterior displacement <1.25 mm between frames). To find the peak perturbation velocity, a finite difference method was used and the largest velocity was taken.

Statistical Analysis

To investigate the effects of step-training in comparison to no training and slip-training, each of the 17 dependent variables describing the recovery response and 2 dependent variables describing the slip characteristics were compared between the untrained, step-trained, and slip-trained conditions. Because of the small number of falls that occurred, only recoveries were included in the statistical analyses.

After excluding the falls, a hierarchical cluster analysis was conducted on the pooled data from the three trials of interest to identify trials in which the recovery responses were outliers relative to the others. The variables included in the cluster analysis were the COM position, COM velocity, hip height, and hip velocity at step lift-off and touchdown, as well as the response time, step length, step time, and step velocity. The centroid clustering method was used with the interval between clusters measured using the squared Eucledian distance. Several trials branched off immediately from the other trials in the dendogram and were excluded from further data analysis.

Independent t-tests were used to compare each of the dependent variables between the step-trained and untrained conditions. Data for the step-trained and slip-trained conditions were also compared using independent t-tests. Finally, paired t-tests were used to compare the dependent variables between the slip-trained and untrained conditions. One-tailed t-tests were used for comparisons for which a directional effect was expected based on the results of Welsh (2006). These consisted of the comparisons to the untrained condition for response time, step length, COM position at step lift-off and touchdown, and hip height and velocity at step touchdown. It was expected that response time would be smaller and the other variables listed would be greater (or less negative) in the trained conditions. The remaining comparisons were analyzed using two-tailed t-tests. Effects were considered significant at $p < 0.05$. All statistical analyzes were performed using SPSS version 17.0 (SPSS, Chicago, IL).

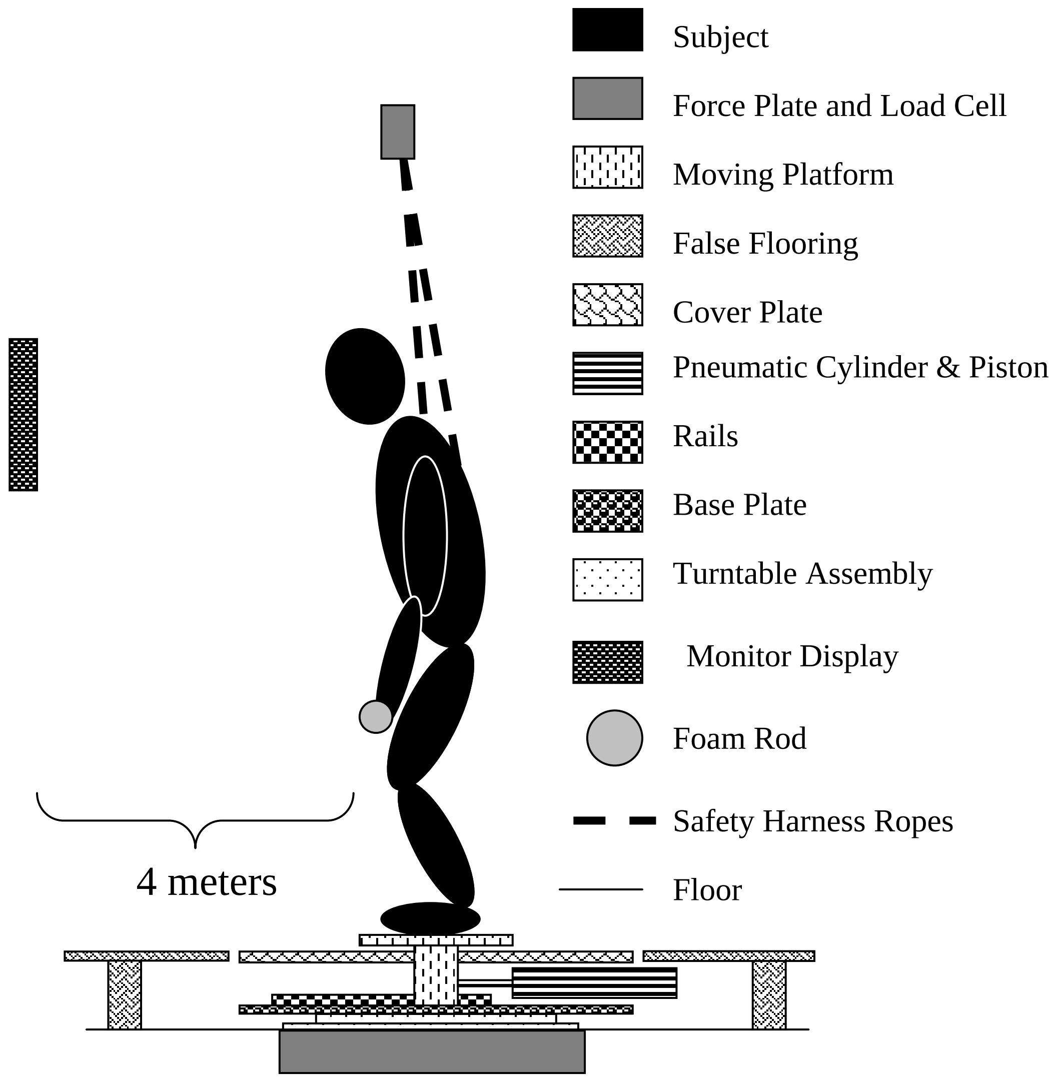

Figure 1: Perturbation platform and apparatus. The subjects stood on a round moving platform and performed a simulated squat-lifting task while grasping a foam rod. During step-training trials, as the subject rose upward from the bottom of the squat, an arrow on the computer monitor in front of the subject indicated the direction in which to step. During slip trials, the platform moved instead. A pneumatic cylinder was used to drive the platform along a pair of rails running parallel to the floor. A cover plate was attached above the rails and cylinder to obstruct the direction of travel from the subject's view and provide a surface to step on. A turntable assembly attached the platform to a force plate, allowing the platform to be oriented in any of four directions. False flooring (2.4 m x 2.4 m) was placed around the cover plate for subjects to step on during the recovery. A fall-arrest system, attached through a load cell to the ceiling, prevented the subject from impacting the ground.

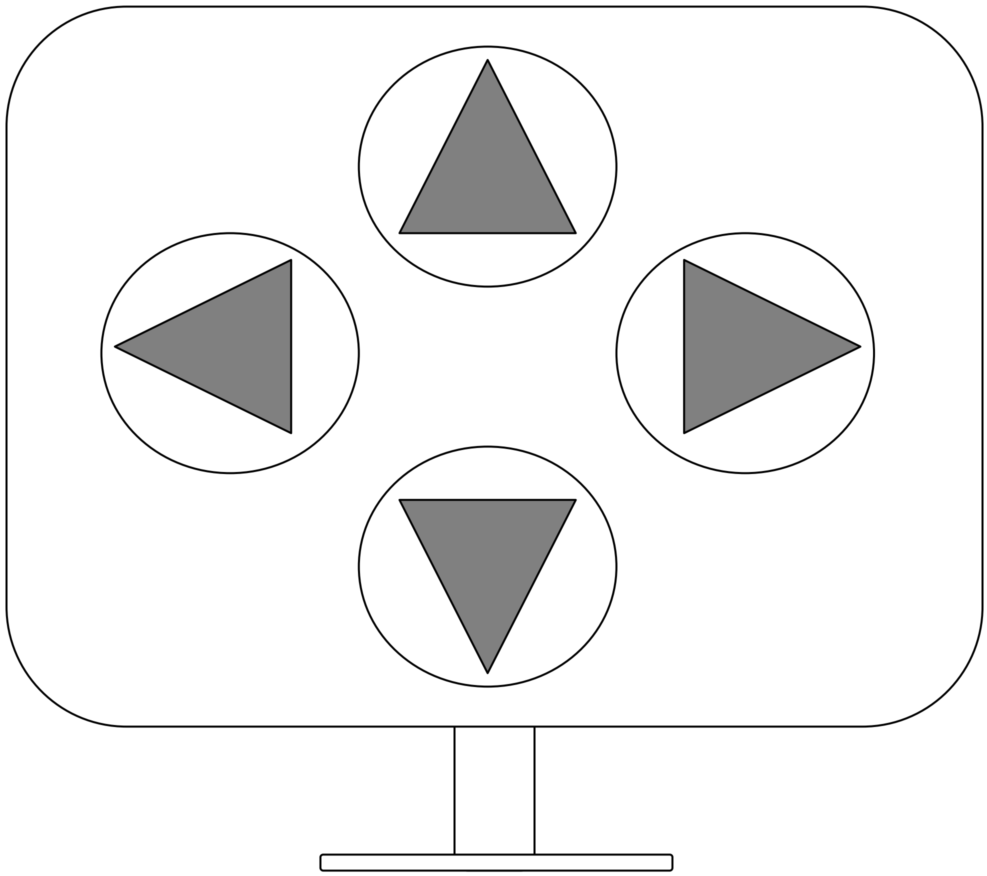

Figure 2: Monitor with step directions. Subjects in the step-training group looked at the monitor while performing the simulated lifting task. During the rising phase of the movement, the circular background behind one of the arrows would turn to green to indicate which direction the subjects were to step. The upward and downward arrows corresponded to forward and backward steps, respectively. Colored masking tape was placed on the floor in each of the four directions at the specific distance subjects were instructed to step.

Table 1. Mean (SD) values of the age, sex, mass, height, and simple reaction time of the two groups of participants.

Variable	*Step-training (n=17)*	*Slip-training (n=17)*
Age (yrs)	24.2 (3.5)	22.0 (3.9)
Sex (# of males)	*n* = 11	*n* = 10
Mass (kg)	67.3 (8.6)	73.7 (6.8)*
Height (cm)	174 (8)	179 (9)
Simple Reaction Time (ms)	332 (42)	313 (30)

* $p < 0.05$ vs. Step-training group using independent t-test.

Table 2. Platform slip direction order for the slip-training.

Trial Number	Platform Direction
1	None
2	None
3	Forward*
4	Left
5	Right
6	Forward
7	None
8	Backward
9	Left
10	Forward
11	Backward
12	None
13	Left
14	Right
15	None
16	Backward
17	Forward
18	Right
19	Right
20	Left
21	Backward
22	None
23	Right
24	Forward
25	Left
26	Backward
27	None
28	Forward†

* Untrained condition
† Slip-trained condition

Table 3. Step direction order for the step-training.

Trial Number	Step Direction
1	None
2	None
3	Backward
4	Right
5	Left
6	Backward
7	None
8	Forward
9	Right
10	Backward
11	Forward
12	None
13	Right
14	Left
15	None
16	Forward
17	Backward
18	Left
19	Left
20	Right
21	Forward
22	None
23	Left
24	Backward
25	Right
26	Forward
27	None
28	Forward slip*

* Trial comprised a forward slip = Step-trained condition

Results

The step-training and slip-training groups did not differ in age, height, and simple reaction time ($p > 0.05$; Table 1). However, the subjects in the slip-training group were 6.4 kg heavier, on average, than the step-trained subjects ($p < 0.05$).

Two falls occurred, one in the untrained condition (in the slip-training group) and one in the step-trained condition. No falls occurred in the slip-trained condition. Among the successful recoveries, the cluster analysis revealed four cases in which subjects displayed fundamentally different responses than the others. Three of these cases were for the step-trained condition and one was for the untrained condition. These subjects all took shorter, slower, and more delayed steps; the hips were moving downward faster at step lift-off; and the stepping foot touched down with the heel nearly directly below the center of mass, instead of behind it. These four cases, considered to show fundamentally different responses than the norm, were excluded from further analysis.

At the onset of the slip, the center of mass anteroposterior position, hip height, and hip vertical velocity did not differ between conditions (Table 4). However, the center of mass velocity was slightly faster posteriorly in the untrained condition compared to the slip-trained condition. There were no other differences between conditions at slip onset.

The characteristics of the slip differed slightly in the slip-trained condition (Table 5). Although the duration of the slip did not differ between the untrained and step-trained conditions, slip duration was approximately 15 ms shorter in the slip-trained condition than in the others. However, there were no differences in peak slip velocity between the three conditions.

The slip-trained subjects exhibited a faster response time to step lift-off and, at step lift-off, a center of mass that was less posterior to their base of support than in both the step-trained and untrained conditions (Table 6). Neither variable differed between the step-trained and untrained condition. The three training conditions did not differ in center of mass anteroposterior velocity, hip height, or hip vertical velocity at step lift-off.

In both of the trained conditions, subjects took longer initial recovery steps than in the untrained condition, and these step lengths did not differ between the step-trained and slip-trained conditions (Table 7). Step time was greater in the slip-trained condition than in the other two conditions. However, because the response time to step lift-off was also quicker in the slip-trained condition, there was no difference in total time from slip onset to step touchdown between the three conditions. Stepping velocity also did not differ between conditions.

At step touchdown, the stepping foot was placed farther behind the center of mass in the slip-trained than in the untrained condition, whereas foot placement in the step-trained condition did not differ significantly from either the untrained or the slip-trained condition (Table 8). Similarly, the hip downward velocity at step touchdown was slower in the slip-trained condition than in the untrained condition, whereas no difference was seen between the step-trained condition and either of the other two conditions. No differences in hip height or center of mass anteroposterior velocity at step touchdown were present between conditions.

Table 4. Mean (SD) variables representing the state of the body at the time of slip onset, as a function of condition.

Variable	*Slip-training Group* Untrained *(n=15)*	Slip-trained *(n=16)*	Step-trained *(n=13)*
COMx (fl)	0.53 (0.07)	0.52 (0.06)	0.49 (0.09)
COMxVel (F)	-0.01 (0.01)	0.00 (0.01) *	0.00 (0.01)
Hip Height (bh)	0.47 (0.03)	0.47 (0.03)	0.47 (0.02)
Hip Z Vel (bh/s)	0.19 (0.07)	0.23 (0.08)	0.23 (0.05)

* $p < 0.01$ vs. Untrained

COMx = anterior position of the body center of mass with respect to the posterior heel; Vel = velocity; Hip Height = average height of two hip joint centers above the platform; Hip Z Vel = velocity of hip height; fl = foot lengths, bh = body height; F = Froude number (normalized to $\sqrt{g \cdot bh}$, g = acceleration due to gravity).

Table 5. Mean (SD) characteristics of the slips as a function of condition.

Variable	*Slip-training Group* Untrained *(n=15)*	Slip-trained *(n=16)*	Step-trained *(n=13)*
Duration (ms)	347 (21)	334 (12) *	351 (28) †
Peak Velocity (m/s)	1.22 (0.11)	1.29 (0.07)	1.22 (0.14)

* $p < 0.05$ vs. Untrained
† $p < 0.05$ vs. Slip-trained

Table 6. Mean (SD) variables representing the state of the body at the time of step lift-off, as a function of condition.

	Slip-training Group		
Variable	Untrained *(n=15)*	Slip-trained *(n=16)*	Step-trained *(n=13)*
RespTime (ms)	304 (51)	240 (33) *	292 (33) †
COMx (fl)	-.31 (0.15)	-0.08 (0.15) *	-0.32 (0.14) ‡
COMxVel (F)	-0.20 (0.10)	-0.29 (0.08)	-0.22 (0.08)
Hip Height (bh)	0.52 (0.02)	0.53 (0.02)	0.52 (0.02)
Hip Z Vel (bh/s)	0.03 (0.11)	0.08 (0.12)	0.01 (0.20)

* $p < 0.01$ vs. Untrained
† $p < 0.05$ vs. Slip-trained
‡ $p < 0.01$ vs. Slip-trained

RespTime = response time from slip onset to step lift-off. All other abbreviations are as defined in Table 2.

Table 7. Mean (SD) variables representing the qualities of the recovery step, as a function of condition.

Variable		*Slip-training Group*		
		Untrained *(n=15)*	Slip-trained *(n=16)*	Step-trained *(n=13)*
Step Time	(ms)	182 (48)	250 (54) †	244 (125)
Step Length	(bh)	0.22 (0.06)	0.29 (0.07) *	0.27 (0.09) *
Step Velocity	(bh/s)	1.22 (0.17)	1.18 (0.19)	1.22 (0.36)
Total Time	(ms)	487 (73)	490 (83)	537 (114)

* $p < 0.05$ vs. Untrained
† $p < 0.01$ vs. Untrained

Total Time = time from slip onset to step touchdown; bh = body height.

Table 8. Mean (SD) variables representing the state of the body at recovery step touchdown, as a function of condition.

	Slip-training Group		
Variable	Untrained *(n=15)*	Slip-trained *(n=16)*	Step-trained *(n=13)*
COMx (fl)	0.78 (0.23)	1.13 (0.30) †	0.96 (0.48)
COMxVel (F)	-0.09 (0.03)	-0.10 (0.05)	-0.10 (0.05)
Hip Height (bh)	0.54 (0.02)	0.53 (0.03)	0.53 (0.02)
Hip Z Vel (bh/s)	-0.13 (0.11)	-0.07 (0.08) *	-0.10 (0.11)

* $p < 0.05$ vs. Untrained
† $p < 0.01$ vs. Untrained

All abbreviations are as defined in Table 2.

Discussion

Falls pose a major health risk to older adults and place a significant financial burden on the healthcare system. Each year, approximately one-third of older adults suffer a fall (Masud and Morris 2001; Centers for Disease Control and Prevention 2008). In the year 2000, almost 10,300 fatal falls were reported and an estimated $19 billion was spent on the direct costs of fall-related injuries (Stevens et al. 2006). It is well documented that fallers often take late, short steps and do not maintain a high hip position during the recovery attempt (Pavol et al. 2001; Pai et al. 2006; Welsh 2006). In a recent study, fallers selected the appropriate recovery step following a single exposure to a slip and subjects took recovery steps that placed their foot further behind their center of mass following a series of unpredictable balance perturbations (Welsh 2006). Other studies have shown proactive and reactive changes to recovery movements after exposure to a series of balance perturbations (Marigold and Patla 2002; Pavol et al. 2004b). While repeated-slip training shows great promise, it may not be a practical intervention due to the equipment needed, its expense, and the difficulty of use.

As a possible alternative to slip-training, half of the subjects in the present study trained by voluntarily practicing steps that were associated with successful recovery from balance loss in a previous study (Welsh 2006). These step-trained subjects were then exposed to a novel and unexpected forward slip. Their recovery responses were compared to those of the other half of subjects who underwent a slip-training protocol. The present slips were intentionally designed to elicit a recovery step but not be so large that a fall would be likely. Only a single person in each group failed to recover their balance upon initial exposure to the slip, and none of the slip-trained individuals fell. Among those who successfully recovered, the results suggest that both types of training had an effect on the recovery response. With a few exceptions, subjects who were step-trained took a longer recovery step in response to a backwards balance loss than in the untrained condition. By comparison, slip-trained subjects also showed improvements in the reactive response over the period before step lift-off. While slip-training has been shown to improve the recovery response to a slip, step-training also shows potential to be a fall-prevention intervention that could be widely adopted by healthcare providers and at-home exercise programs.

Step training

The main aim of this study was to investigate whether voluntarily practicing a certain response will translate to a more effective recovery response when exposed to an unexpected perturbation. The analysis concentrated on the period from slip onset though touchdown of the initial recovery step. After the step-training was completed and the unexpected balance perturbation was delivered, there were no differences in center of mass or hip kinematics at slip onset compared to the untrained condition. This was not surprising. Proactive adjustments occur when exposed to expected balance perturbations (McIlroy and Maki 1995; Pavol et al. 2004b) but these adjustments are less present when exposed to unexpected perturbations (Welsh 2006). It does not appear that the step-trained subjects were attempting to predict the direction or timing of the balance perturbation that they were told about before the step-training began.

At the time of step lift-off, the response time from slip onset and the center of mass and hip positions and velocities for the step-trained responses did not differ from those of the untrained perturbation responses. It appears that the step-training did not have an effect on the subjects' initial reactions to the slip. Early responses to balance perturbations appear to be mostly reflexive behaviors and can be altered by repeated exposures to perturbations that elicit reflexive responses (Horak et al. 1989; Pavol et al. 2004b; Welsh 2006). In a study by Welsh (2006), where perturbations similar to those in this study were delivered, falls during the first slip were associated with a more posterior center of mass and greater hip downward velocity at step lift-off, and significant improvements in both of these variables were seen by the second slip. In contrast to these effects of repeated perturbation exposure, the findings from the present study suggest that the responses from the time of slip onset to the time of step lift-off, which are mainly reflexive in nature, cannot be affected by voluntary training.

The recovery steps of the step-trained subjects were 23% longer than those in the untrained condition. Subjects in the step-training group practiced taking backward steps of approximately 25% of their body height and, when unexpectedly perturbed, took a backward step of 27% of their body height. The training appears to have prepared the subjects to take a longer step after being slipped. This is consistent with a more effective recovery response in the step-trained condition, as a greater recovery step length has been shown to improve the chances of a successful recovery after a slip

(Pai and Bhatt 2007). The fact that the length of the recovery step was greater in the step-trained than the untrained condition suggests that the length of the recovery step is partly under voluntary control and may be altered by voluntarily practicing steps of the desired length.

Horak et al. (1989) showed that the early responses (within 75 ms) to a stimulus were completely reflexive and the responses were scaled appropriately only when the amplitude of the perturbation could be predicted beforehand. But later responses (150-500 ms after the stimulus) were scaled appropriately to the perturbation, regardless of whether the amplitude was predictable or not, suggesting a possible supraspinal influence on these later responses. Also supporting the idea that the length of the recovery step is partly under voluntary control, the voluntary, simple reaction times of the present subjects were approximately 330 ms, whereas step lift-off and touchdown occurred, on average, 240 and 490 ms after slip onset, respectively. Overall, the present findings suggest that the reflexive component of the recovery response may not be trained with step-training, but the voluntary component of the stepping response may be altered by voluntarily practicing steps of the desired lengths.

It is difficult to determine what aspect of the step-training improved the recovery step. It is unlikely that the practice of reacting as quickly as possible to the light was an important factor, since there was no difference in response time between the untrained and step-trained conditions. The overall quality of the backwards steps practiced, including the speed of response to the light, the velocity of the step, and how closely the step length matched that specified, appeared to vary greatly between subjects and even within each subject. Because the step length in response to the slip was affected despite this variability, it is possible that practicing any step could improve the quality of the recovery step. However, because the length of the recovery step taken by the step-trained subjects was so close to the length of that practiced, we feel that the length of the step practiced is crucial in preparing participants to take a recovery step of appropriate length in the event of a balance perturbation.

It should be noted that the step-training was not equally effective across all the subjects. One of the step-trained subjects fell when slipped and three of the step-trained subjects were removed from the analysis because they took very late and short steps, although they still successfully recovered from the slip. Despite the step-training not improving the recovery response for all the subjects, it still improved the vast majority of step-trained subjects' responses to the slip. Thus, on the whole, it appears that the step-training affected the response to an unexpected balance perturbation for the better. It is possible that a more extensive training program might improve other factors, such as the center of mass position and hip vertical velocity at step touchdown, as well. Even if this is not the case, the results of this study suggests that step-training might be an effective and practical means of helping to prepare older adults to successfully recover their balance after a slip.

Slip training

Slip-trained participants showed improvements in many aspects of the slip recovery compared to their untrained condition. Response time and step length were improved, the center of mass was less posterior to the base of support at step lift-off and more anterior relative to the base of support at touchdown, and the hips were not descending as quickly at touchdown. These findings generally agree with previous research that investigated the effects of repeated exposures to balance perturbations, both expected and unexpected (Pavol et al. 2004b; Welsh 2006; Pai and Bhatt 2007). These previous studies also discovered that these changes that occurred with repeated perturbation exposure were accompanied by a reduction in the incidence of falls. In most individuals, falls never occurred after their first exposure to the perturbation, regardless of that initial outcome.

The current study was designed so subjects could not plan for the upcoming trial. The directions of the perturbations varied in an unpredictable order and, consistent with this, no meaningful proactive changes to the state of the body at slip onset were made between the untrained and slip-trained conditions. However, step lift-off occurred 64ms faster in the slip-trained condition than the untrained condition and the center of mass was much less posterior to the base of support. This center of mass was in a better position at lift-off partly due to the quicker response. Yet, qualitatively, the slip-trained subjects also appeared to move their hips upward to greater extent and backward to lesser extent after the onset of the slip compared to the untrained subjects. It is likely that some reflexive strategy, like the hip strategy (Horak and Nashner 1986), was used to greater effect before the step was taken in the slip-trained condition. Activation of the erector spinae and hamstring muscles likely occurred during the first 200ms of the final slip by the slip-training group and improved their center of mass position at step lift-off. Slip-trained participants also took much longer steps than in their untrained condition and this, coupled with the better center of mass position at step lift-off, provided a center of mass position that was more stable at touchdown. Taken together, the changes in recovery response that resulted from the slip-training suggest that this training was effective in improving both the initial, reflexive component and the later, voluntary component of the recovery response to a slip.

Step vs. Slip training

The secondary hypothesis of this study was that reactive responses to a slip would not differ between the step- and slip-trained conditions. Both types of training did elicit a markedly greater step length than in the untrained condition, and this step length did not differ between the two training types. However, in comparison to the slip-trained participants, step-trained participants exhibited a slower response time to step lift-off and a center of mass that was more posterior to the base of support at step lift-off. There were also variables for which the slip-trained and untrained conditions differed and for which intermediate values, differing from neither the slip-trained nor the untrained conditions, were exhibited in the step-trained condition. These included the center of mass anteroposterior position relative to the stepping foot and the hip vertical velocity at step touchdown. These results suggest that the present step-training protocol was less effective than the slip-training protocol in improving the reactive response to a slip.

The observed differences at step lift-off may be explained by several theories. One theory is that slip-training more efficiently trains the recovery response to a slip and the number of step-training trials was not sufficient to provide benefits equivalent to the slip-training. Another theory, as mentioned earlier, is that step-training does not train the reflexive portion of the recovery response. A third theory is that the slip-trained subjects became more familiar with the perturbations and, as a result, could respond more appropriately. It is likely that all three explanations impact the differences seen following the two types of training.

The learning from the slip-training likely provided a better training effect for recovering from likewise perturbations than did the transfer of learning from the step-training (Schmidt and Craig 2008). It is possible that preparation for the recovery step might be improved with a longer step-training protocol. Because of the exploratory nature of this study, the training protocols were developed to be as similar as possible. In future studies, the use of multiple step-training protocols, each consisting of different numbers of practice steps, should be considered to identify whether a longer step-training protocol can provide benefits similar to slip-training and, if so, how much practice is necessary.

Another explanation of why the step-training did not improve early response variables is that the current step-training may only train the step length. This could be an inherent limitation of the step-training or the result of the means used to cue the steps. In the present study, participants undergoing the step-training reacted voluntarily to a visual cue, whereas an actual slip provides earlier somatosensory cues. Of note, in a study by Luchies et al. (1999), young adults showed no difference in response time between reflexive and voluntary responses to a small postural perturbation. It may thus be possible to train the reflexive response by exposing the subject to a small perturbation instead of a visual cue to trigger the voluntary stepping response. This approach might yield improvements in the response time and center of mass position at lift-off, in addition to the improvements in step length, similar to the effects of slip-training.

A third factor that may have affected the relative effects of the two types of training is differences in expectation and familiarity. To the step-trained group, the slip experienced at the end of the step-training was unexpected and novel, whereas the slip-trained subjects had been repeatedly exposed to the same slip perturbation during training. With repeated exposure, the novelty of a balance perturbation wears off and individuals adapt their responses to the characteristics of the perturbation (Horak et al. 1989; McIlroy and Maki 1995; Welsh 2006). This familiarity with the perturbation allows for the correct response to be ready to be used when the perturbation is experienced and improves the recovery properties (Pavol et al. 2002; Pai and Bhatt 2007). However, the response to the slip in the step-trained condition may have been more like that in the slip-trained condition if the step-trained subjects had been aware that the platform would slide rapidly in the next trial, and at what point in the lifting task it would occur. Due to the small size of this study, it was not possible to have such a group control for the expectation of the slip. With additional control groups, we could determine whether the improvement in the response was a function of the training or the knowledge and expectation of the slip.

While the step-training did not seem to improve the position of the center of mass with respect to the stepping foot or the vertical velocity of the hips at touchdown, the results for the step-trained condition appear to be between those for the untrained and slip-trained conditions (Table 8). This study was limited to a small sample size, and we believe that, with more participants, the hip vertical velocity and the distance between the stepping foot and center of mass in the step-trained condition would differ from those in the untrained condition. If this were the case, these would represent additional benefits of the step-training.

Assumptions and Limitations

It was assumed in this study that the first slip experienced by the subjects was unexpected, novel, and realistic. Subjects were aware before the perturbation was delivered that we would attempt to make them lose their balance. However, they were not explicitly told when the perturbation would occur, only that it would occur “later” or “after the training.” The perturbation platform was also constructed in such a way that subjects had no way of knowing the direction, distance, or velocity the platform would travel. Although the perturbations were produced by a platform, previous studies have used similar perturbation platforms to induce balance loss (McIlroy and Maki 1995; McIlroy and Maki 1996; Pavol et al. 2004a; Welsh 2006). Therefore, we believe that the first slip was indeed unexpected, novel, and realistic to the extent feasible.

During the training protocols, subjects likely became accustomed to the point of the movement at which the stimulus was delivered. To minimize the effects of expectation and proactive muscular co-contraction that would cause an unnatural response, the subjects performed a simulated lifting task and the direction of the slip or step was varied unpredictably from trial to trial. The absence of any meaningful differences between conditions in the state of the body at slip onset suggests that any effects of expectation were negligible.

Due to this study's aim of investigating the effects of step-training on the response to a novel and unexpected slip, it was not possible to obtain pre-training slip recovery data on the subjects in the step-training group. It is a possibility that the step-training and slip-training groups were fundamentally different in their ability to recover from a slip. However, we assumed that, through random assignment, both training groups would be similar in balance recovery capacities. No differences in age, height, or simple reaction time were found between groups, supporting the idea that the groups were not fundamentally different from each other before any training.

Previous studies have shown that a single exposure to a slip is sufficient to provide positive training results (McIlroy and Maki 1995; Marigold and Patla 2002; Pavol et al. 2002; Pavol et al. 2004b; Welsh 2006). While the step-trained subjects took a longer recovery step than in the untrained condition, step-training may provide additional benefits that were not demonstrated because the step-training was given in too small of a dose. In addition, the small sample size of this study limits our findings to large differences between the conditions. This compounds the previous limitation of a dosing problem. However, the results show some positive results and an expanded step-training study should be pursued.

There are some additional limitations to this study. The current study investigated how step-training influenced the recovery response to an unpredictable balance perturbation among young adults, whereas falls by older adults are of greater concern. However, a previous study found that both young and older adults respond similarly to repeated exposures to a slip (Pavol et al. 2002; Pavol et al. 2004b) and this suggests young and older adults would respond similarly to step-training as well. Due to the increased injury risk older adults would be exposed to in a falls study, young adults were recruited for this study to determine if an expanded study should be done with older adults.

While the present study found that step-training was effective in improving the recovery step after a perturbation, this study only looked into the recovery response to a backwards balance loss during a squat-lifting task. Furthermore, the perturbation was large enough to require a recovery step to avoid falling but not so large that the subjects were at a high risk of falling; only two falls occurred in the present study. It is unknown to what extent the step-training would affect the recovery responses to perturbations in other directions, of different magnitude, in other real-world settings, or during other movement tasks, such as walking. Nor do we know how long the effects of the training lasted. However, a recent study showed that learning acquired through repeated slips on a moving platform transferred to improved recovery responses from a slip on a slippery surface (Bhatt and Pai 2009). Another study showed that the retention of some of the benefits of slip-training can last up to at least 4 months from the initial training session (Bhatt et al. 2006). It seems plausible that the same would be true of the transfer and retention of the effects of the step-training. Finally, while there is no direct evidence that step-training would reduce the incidence of falls, the effects observed are consistent with an improved ability to prevent a fall, providing a motivation for additional study of the effects of step-training.

While slip-training improves the stepping response to a slip, it is logistically improbable to incorporate into the clinical or home setting. Step-training, however, showed significant effects on the length of the recovery step, consistent with an increased ability to recover from a slip. Step-training could also easily be designed into a regular exercise routine for at-risk populations and is very practical. Inexpensive equipment for the home or clinical setting could be developed to replicate the current step-training protocol. It is likely older adults would be more willing to participate in step-training than in slip-training because of a fear of falling common in this population (Vellas et al. 1997). Given these potential benefits, the findings from this small study suggest step-training should be further studied and is a possible training intervention to help reduce the number of falls among older adults.

Conclusion

Falls among older adults are common and result in severe health and economic effects such as increased fear of falling, increased likelihood of additional falls, a more sedentary lifestyle, broken bones, head trauma, long-term health care, billions of dollars in direct medical treatment, and death (Nevitt et al. 1989; Alexander et al. 1992; Magaziner et al. 2000; Hausdorff et al. 2001; Sterling et al. 2001; Leibson et al. 2002; Stevens et al. 2006; Centers for Disease Control and Prevention 2008). Studies have shown differences in the responses to balance loss between those who fall and those who recover after exposure to a slip (Pavol et al. 2004b)Repeated exposure to unpredictable balance perturbations has been shown to drastically improve balance recovery responses in subsequent trials (Welsh 2006). However, this approach to falls prevention may be clinically impractical. The purpose of the current study was therefore to determine the extent to which training the voluntary stepping response affects the recovery response to an unexpected slip in comparison to no training and repeated exposure to slipping among young adults. A sliding platform was used to cause healthy young adults to lose their balance during a simulated lifting task. Subjects in the slip-training group were exposed to slipping perturbations in varying, unpredictable directions, whereas those in the step-training group performed a corresponding sequence of cued voluntary stepping, followed by a single unexpected slip. Variables quantifying the recovery response to a forward-directed slip were compared between the untrained, slip-trained, and step-trained conditions.

This study has two important conclusions. First, step-trained subjects took a longer recovery step than subjects in the untrained condition. Other differences in the recovery might also have been observed with a larger sample size and more practice steps. Second, although the step-trained subjects took a recovery step equal in length to that taken by the slip-trained subjects, the presently-used step-training protocol was not as effective as the slip-training in improving the initial part of the recovery response. Slip trained subjects exhibited a faster response time to step lift-off and a less posterior center of mass at step lift-off than the step-trained subjects.

In this study, the voluntary step-training appeared to improve the length of the recovery step. This would represent a beneficial effect of the training, as a longer recovery step has been associated with a greater ability to recover from a perturbation (Pavol et al. 2001; Pavol et al. 2004b; Welsh 2006). Response time and the state of the body at step lift-off, on the other hand, were not significantly different between the untrained and step-trained conditions, suggesting that step-training may have no effect on the initial, reflexive component of the recovery response. However, it is possible that, with an expanded step-training protocol, the results might be different. The study was designed with both step- and slip-training having the same amount of training and, while it is not practical to expose older adults to hundreds of balance perturbations, it is not unreasonable to have these adults practice several hundred steps.

The step-trained and slip-trained subjects took similar recovery steps. However, the step-trained subjects took longer to respond to the slip and did not maintain their center of mass over their base of support at step lift-off as well as the slip-trained subjects. As suggested earlier, it may be that step-training affects only the later, voluntary component of the recovery response, whereas slip-training also affects the initial, reflexive component of the response. However, it is also possible that slip-training more efficiently trains the recovery response to a slip and the number of step-training trials was not sufficient to provide benefits equivalent to the slip-training. Greater expectation of and greater familiarity with the perturbation as a result of the slip-training may also have played a role in the differing effects of the two types of training.

While the present findings suggest that step-training could be effective in preventing falls, questions remain. During the step-training, subjects took steps in response to a visual stimulus and, while they were instructed to step as quickly as possible to marks on the floor, there was no way to completely control the speed and distance, or quality, of the step taken. Comparing the properties of the voluntary steps to the properties of the recovery step may yield important information on what aspects of these practice steps are most critical to improving the recovery response to an unexpected slip.

Future research should aim to determine how many steps must be practiced, how quickly they must be taken, and how long these steps need to be to provide enough training to sufficiently prepare individuals to recover from a balance loss. The use of somatosensory cues, such as small perturbations, instead of visual cues to trigger the voluntary stepping responses should also be investigated, as these might potentially train both the reflexive and voluntary components of the recovery response. It is also important to understand how long the step-training effects remain. This will help clinicians decide if such a training program is appropriate for their populations. Similar research should also be conducted with older adults who are at an elevated risk of suffering a fall. Long term studies could follow the participants to determine if the step-training transfers to slips experienced outside of the laboratory setting and reduces the amount of falls.

The current study compliments other fall-related research aimed at finding ways to reduce the number of falls in older adults through improved understanding of why falls occur and how clinicians can prepare these individuals to recover from balance losses better. Reducing the number of falls in older adults would help improve the life-span and quality of life, as well as relieve the financial burden of billions of dollars spent annually on fall-related health care expenses (Stevens et al. 2006). Further study is needed to determine to what extent step-training can improve the recovery response to a perturbation. However, the findings from this small study suggest that step-training is a possible training intervention to help reduce the number of falls among older adults.

Bibliography

Alexander, B. H., F. P. Rivara, et al. (1992). "The cost and frequency of hospitalization for fall-related injuries in older adults." Am J Public Health **82**(7): 1020-3.

Berg, W. P., H. M. Alessio, et al. (1997). "Circumstances and consequences of falls in independent community-dwelling older adults." Age Ageing **26**(4): 261-8.

Berger, W., V. Dietz, et al. (1984). "Corrective reactions to stumbling in man: neuronal co-ordination of bilateral leg muscle activity during gait." J Physiol **357**: 109-25.

Bhatt, T. and Y. C. Pai (2009). "Generalization of gait adaptation for fall prevention: from moveable platform to slippery floor." J Neurophysiol **101**(2): 948-57.

Bhatt, T., E. Wang, et al. (2006). "Retention of adaptive control over varying intervals: prevention of slip- induced backward balance loss during gait." J Neurophysiol **95**(5): 2913-22.

Brauer, S. G. and Y. R. Burns (2002). "The influence of preparedness on rapid stepping in young and older adults." Clin Rehabil **16**(7): 741-8.

Centers for Disease Control and Prevention (2008). Self-Reported Falls and Fall-Related Injuries Among Persons Aged 65 Years and Older. MMWR 57(9) 225-9.

Cumming, R. G., G. Salkeld, et al. (2000). "Prospective study of the impact of fear of falling on activities of daily living, SF-36 scores, and nursing home admission." J Gerontol A Biol Sci Med Sci **55**(5): M299-305.

de Leva, P. (1996). "Adjustments to Zatsiorsky-Seluyanov's segment inertia parameters." J Biomech **29**: 1223-1230.

Diener, H. C., J. Dichgans, et al. (1982). "Stabilization of human posture during induced oscillations of the body." Exp Brain Res **45**(1-2): 126-32.

Dietz, V., J. Quintern, et al. (1986). "Stumbling reactions in man: release of a ballistic movement pattern." Brain Res **362**(2): 355-7.

Englander, F., T. J. Hodson, et al. (1996). "Economic dimensions of slip and fall injuries." J Forensic Sci **41**(5): 733-46.

Hausdorff, J. M., D. A. Rios, et al. (2001). "Gait variability and fall risk in community-living older adults: a 1-year prospective study." Arch Phys Med Rehabil **82**(8): 1050-6.

Horak, F. B., H. C. Diener, et al. (1989). "Influence of central set on human postural responses." J Neurophysiol **62**(4): 841-53.

Horak, F. B. and L. M. Nashner (1986). "Central programming of postural movements: adaptation to altered support-surface configurations." J Neurophysiol **55**(6): 1369-81.

Hornbrook, M. C., V. J. Stevens, et al. (1994). "Preventing falls among community-dwelling older persons: results from a randomized trial." Gerontologist **34**(1): 16-23.

Leibson, C. L., A. Toteson, et al. (2002). "Mortality, disability, and nursing home use for persons with and without hip fracture: a population-based study." J Am Geriatr Soc **50**: 1644-60.

Lewis, G. N., C. D. MacKinnon, et al. (2006). "The effect of task instruction on the excitability of spinal and supraspinal reflex pathways projecting to the biceps muscle." Exp Brain Res **174**(3): 413-25.

Luchies, C. W., J. Schiffman, et al. (2002). "Effects of age, step direction, and reaction condition on the ability to step quickly." J Gerontol A Biol Sci Med Sci **57**(4): M246-9.

Luchies, C. W., D. Wallace, et al. (1999). "Effects of age on balance assessment using voluntary and involuntary step tasks." J Gerontol A Biol Sci Med Sci **54**(3): M140-4.

Magaziner, J., W. Hawkes, et al. (2000). "Recovery from hip fracture in eight areas of function." J Gerontol A Biol Sci Med Sci **55**(9): M498-507.

Maki, B. E., W. E. McIlroy, et al. (1996). "Influence of lateral destabilization on compensatory stepping responses." J Biomech **29**(3): 343-53.

Marigold, D. S. and A. E. Patla (2002). "Strategies for dynamic stability during locomotion on a slippery surface: effects of prior experience and knowledge." J Neurophysiol **88**(1): 339-53.

Masud, T. and R. O. Morris (2001). "Epidemiology of falls." Age Ageing **30 Suppl 4**: 3-7.

McIlroy, W. E. and B. E. Maki (1995). "Adaptive changes to compensatory stepping responses." Gait Posture **3**: 43-50.

McIlroy, W. E. and B. E. Maki (1996). "Age-related changes in compensatory stepping in response to unpredictable perturbations." J Gerontol A Biol Sci Med Sci **51**(6): M289-96.

Mille, M. L., M. E. Johnson, et al. (2005). "Age-dependent differences in lateral balance recovery through protective stepping." Clin Biomech (Bristol, Avon) **20**(6): 607-16.

Nevitt, M. C., S. R. Cummings, et al. (1989). "Risk factors for recurrent nonsyncopal falls. A prospective study." JAMA **261**(18): 2663-8.

Pai, Y. C. (1999). "Induced limb collapse in a sudden slip during termination of sit-to-stand." J Biomech **32**(12): 1377-82.

Pai, Y. C. and T. S. Bhatt (2007). "Repeated-slip training: an emerging paradigm for prevention of slip-related falls among older adults." Phys Ther **87**(11): 1478-91.

Pai, Y. C., J. D. Wening, et al. (2003). "Role of feedforward control of movement stability in reducing slip-related balance loss and falls among older adults." J Neurophysiol **90**(2): 755-62.

Pai, Y. C., F. Yang, et al. (2006). "Mechanisms of limb collapse following a slip among young and older adults." J Biomech **39**(12): 2194-204.

Pavol, M. J., T. M. Owings, et al. (2001). "Mechanisms leading to a fall from an induced trip in healthy older adults." J Gerontol A Biol Sci Med Sci **56**(7): M428-37.

Pavol, M. J., E. F. Runtz, et al. (2002). "Age influences the outcome of a slipping perturbation during initial but not repeated exposures." J Gerontol A Biol Sci Med Sci **57**(8): M496-503.

Pavol, M. J., E. F. Runtz, et al. (2004a). "Diminished stepping responses lead to a fall following a novel slip induced during a sit-to-stand." Gait Posture **20**(2): 154-62.

Pavol, M. J., E. F. Runtz, et al. (2004b). "Young and older adults exhibit proactive and reactive adaptations to repeated slip exposure." J Gerontol A Biol Sci Med Sci **59**(5): 494-502.

Rizzo, J. A., R. Friedkin, et al. (1998). "Health care utilization and costs in a Medicare population by fall status." Med Care **36**(8): 1174-88.

Schmidt, R. and W. Craig (2008). Motor Learning and Performance: a situational-based learning approach. Champaign, IL, Human Kinetics.

Scott, J. C. (1990). "Osteoporosis and hip fractures." Rheum Dis Clin of North Am **16**(3): 717-30.

Seidel, G. K., D. M. Marchinda, et al. (1995). "Hip joint center location from palpable bony landmarks--a cadaver study." J Biomech **28**(8): 995-8.

Stelmach, G. E., N. Teasdale, et al. (1989). "Age related decline in postural control mechanisms." Int J Aging Hum Dev **29**(3): 205-23.

Sterling, D. A., J. A. O'Connor, et al. (2001). "Geriatric falls: injury severity is high and disproportionate to mechanism." J Trauma **7**(2): 134-40.

Stevens, J. A., P. S. Corso, et al. (2006). "The costs of fatal and non-fatal falls among older adults." Inj Prev **12**(5): 290-5.

Tinetti, M. E., M. Speechley, et al. (1988). "Risk factors for falls among elderly persons living in the community." N Engl J Med **319**(26): 1701-7.

Vellas, B. J., S. J. Wayne, et al. (1997). "Fear of falling and restriction of mobility in elderly fallers." Age Ageing **26**(3): 189-93.

Welsh, L. R. (2006). Preventing falls from unpredictable balance disturbances. Exercise and Sport Science. Corvallis, Oregon State University. **Master of Science:** 101.

Winter, D. A. (2005). Biomechanics and Motor Control of Human Movement. Hoboken, NJ, John Wiley & Sons, Inc.

Woollacott, M. H., A. Shumway-Cook, et al. (1986). "Aging and posture control: changes in sensory organization and muscular coordination." Int J Aging Hum Dev **23**(2): 97-114.