



## AN ABSTRACT OF THE THESIS OF

Lisa R. Welsh for the degree of Master of Science in Exercise and Sport Science presented on September 21, 2006.

Title: Preventing Falls from Unpredictable Balance Disturbances

Abstract approved:

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Falls, particularly those due to slips, constitute a major health risk for older adults. Past research has found that individuals can learn not to fall through repeated exposure to a slipping perturbation. Slips can be unpredictable, however. The goal of this study was to determine whether similar adaptations would occur for repeated slips in unpredictable directions.

A sliding platform was used to cause 30 apparently healthy young adults to lose their balance while rising from a semi-squatted position during a lifting task. A series of 27 perturbations were administered in unpredictable directions, forcing participants to either fall or step to recover. Participants were grouped based on whether they fell or successfully recovered in response to the first perturbation. Twenty-two variables quantifying proactive and reactive behavior were derived from motion capture data and compared between groups and across the first, second, and fifth perturbations that caused a backward balance loss, as well as a final “predictable” perturbation.

Eight participants fell upon first exposure to the perturbation. Fallers had a more rearward center of mass at recovery step liftoff and lower hip height at step

touchdown than those who recovered. The fallers' hips were also dropping much faster at step liftoff and touchdown than those who recovered. Hip height at step touchdown was able to predict 100% of falls upon the first perturbation exposure in a stepwise, logistic regression model.

All of the fallers adapted their reactive responses, despite the unpredictability of the perturbation direction, leading to successful recoveries in all trials after the first. By the second backward balance loss, the fallers made improvements to each variable associated with falling to become similar to those who recovered on the first exposure. Over the course of the perturbations, the fallers also increased their hip height at step liftoff and maximum hip height during the initial recovery step. Those who recovered on the first perturbation also made adjustments across perturbations. Both groups decreased their response time to step liftoff, placed their stepping foot further behind the center of mass, and increased the lateral component of their initial recovery step. The "predictable" case differed primarily by the presence of proactive adjustments.

Repeated exposures to this unpredictable perturbation produced evidence of learning and adaptation of the reflexive response for both those who fell and those who recovered as a result of their first exposure. The fact that learning does occur, even in unpredictable situations, may have application to the design of fall prevention programs.

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Preventing Falls from Unpredictable Balance Disturbances

by  
Lisa R. Welsh

A THESIS

submitted to

Oregon State University

in partial fulfillment of  
the requirements for the  
degree of

Master of Science

Presented September 21, 2006  
Commencement June 2007

Master of Science thesis of Lisa R. Welsh presented on September 21, 2006.

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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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Lisa R. Welsh, Author

## ACKNOWLEDGEMENTS

The author would like to thank the following people for their help with this project: Mike Pavol, PhD (advisor) for his countless hours, guidance, advice and constructive criticism. Kathy Gunter, PhD, Mark Hoffman, PhD, and Frank Bernieri, PhD (committee members) for their willingness to serve on this committee and their positive and constructive feedback. Brian Higginson for his late nights in the lab constructing many of the pieces needed to make data collection possible. Kristof Kipp for his help with data collection and participant recruitment. Ken Lindsay (my dad) for building the wooden platform and Lynne Lindsay (my mom) for helping with printing, binding and running errands. Daniel Welsh (my husband) for encouraging me to go back to school, for his service to our country overseas, for enduring an additional year apart so I could finish school and for his love and support throughout the entire process. Without these people this project would not have been possible. Thank you!

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## Preventing Falls from Unpredictable Balance Disturbances

### **Introduction**

Falls constitute a major health risk for the general population, but more importantly, affect up to half of the older adult population each year (Berg et al., 1997; Luukinen et al., 2000; Rubenstein & Josephson, 2002). Adverse effects of falls include both minor and serious injuries. Serious injuries, including spine and hip fractures, occur in only a small fraction of falls, but are still fairly common and can result in hospitalization, institutionalization, altered lifestyle, disability and even death (Tinetti et al., 1988; Kiel et al., 1991; Keene et al., 1993; Rubenstein & Josephson, 2002; National Safety Council [NSC], 2005). In addition to immediate hazards to the faller, falls also affect the rest of society due to the billions of dollars spent annually on institutionalization and medical care as a result of falls (Cummings et al., 1990; Sernbo & Johnell, 1993).

Slips are a common cause of falls, particularly backward falls (Gabelle et al., 1985). Balance is most easily lost in the backward direction, and backward balance losses put the faller at an increased risk of hip fracture due to the resulting impact with the ground near the hip (Hsiao & Robinovitch, 1998). Therefore, the prevention of backward falls due to slips is of great importance.

Successful recovery from a large balance perturbation, like a slip, typically requires a stepping response. Factors involving both the stepping limb and the

support limb are important in initiating and executing a successful stepping response to a balance perturbation (Pavol et al., 2001, 2004a). The stepping limb functions to expand the base of support in the direction of the balance loss so that stability can be reestablished, whereas the support limb functions to minimize the descent of the hips during the step. Deficiencies in either of these functions can lead to a fall. As such, the roles of both limbs in protective stepping need to be considered in relation to preventing slip-related falls.

Evidence indicates that the initial responses to balance perturbations, including stepping responses, are reflexive in nature (Nashner, 1977; Dietz et al., 1986; Horak & Nashner, 1986; Maki et al., 1996). Reflex responses to balance perturbations appear to be preprogrammed, but vary on a continuum based on the “postural set” of the nervous system (Berger et al., 1984; Deitz et al., 1986; Horak & Nashner, 1986; Maki et al., 1996). As a result, the responses to a given perturbation are adaptable and can be modified with experience and expectation (Maki et al., 1996; Owings et al., 2001; Pavol & Pai, 2002; Pavol et al., 2004b).

Older adults have a higher incidence of falls, but they are also able to modify their movement patterns and responses in similar ways, and in as few trials, as younger adults upon repeated exposure to a perturbation (McIlroy & Maki, 1996; Maki et al., 2000; Owings et al., 2001; Brauer & Burns, 2002; Pavol et al., 2004b). Notably, studies have found that both young and older adults who fall can quickly learn how not to fall upon repeated exposures to the same perturbation (Pavol & Pai, 2002; Pavol et al., 2004b). Fallers were able to adjust their proactive and reactive

behavior, often following the first perturbation exposure, to become similar to those who initially recovered (Pavol & Pai, 2002; Pavol et al., 2004b).

Little is known however, about reactive responses to perturbations in unpredictable directions. When the perturbation is unpredictable, participants are able to adapt their proactive behavior based on information from recent perturbations (Scheidt et al., 2001; Pavol & Pai, 2002). It remains unclear whether reactive recovery response adaptations can be made in unpredictable situations when a balance perturbation, of a large enough magnitude to potentially cause a fall, is experienced. This study attempted to answer that question by repeatedly exposing young participants to a relatively large platform perturbation in varied and unpredictable directions. Proactive and reactive responses and adaptations were compared between fallers and non-fallers, and as a function of the number of exposures. Differences in adaptation between predictable and unpredictable situations were also compared. Such knowledge of the differences in proactive and reactive behaviors between those who fell and those who recovered, as well as the adjustments made with increased exposure to the balance perturbation, may potentially be applied to fall prevention programs to help reduce future falls and fall-related injuries.

## **Review of Literature**

### *Epidemiology of falls & related injuries*

Falls are a major health hazard for all ages, but especially for the elderly. Approximately one-third of community-dwelling older adults and approximately 43% of institutionalized older adults experience a fall each year, with half of those experiencing multiple falls (Tinetti et al., 1988; Berg et al., 1997; Luukinen et al., 2000; Rubenstein & Josephson, 2002). Fall incidence increases with advancing age (Rubenstein & Josephson, 2002). Incidence of falls is highest among the very young (birth to 4 years old) and among those 75 and older, with older females being at much greater risk than older males (Fife et al., 1984; Mosenthal et al., 1995; Luukinen et al., 2000). Additional risk factors for falling include use of sedatives, cognitive impairment, lower extremity disability, balance and gait abnormalities, heart disease, and a history of falls (Tinetti et al., 1988; Mosenthal et al., 1995). A 1985 study found uneven ground conditions and less-than-ideal footwear at the time of the fall, or a history of high heel usage, to be involved in more than half the recorded falls (Gabell et al., 1985). The presence of multiple risk factors increases the chances of falling multiplicatively (Tinetti et al., 1988).

Five to 24% of falls among community-dwelling older adults result in serious injury requiring medical attention, with 5-6% resulting in fractures (Tinetti et al., 1988; Berg et al., 1997; Rubenstein & Josephson, 2002). Across all ages, falls are the leading cause of injuries treated by hospital emergency rooms, with nearly seven

million visits in a given year (Fife et al., 1984; NSC, 2005). In older adults, these injuries often result in long-term morbidity and decreased ability to perform activities of daily living (Kiel et al., 1991). In 1990, it was estimated that 1.66 million hip fractures occurred throughout the world, with 72% of those occurring in women (Cooper et al., 1992). This number is expected to rise to over 6.2 million by the year 2050 (Cooper et al., 1992). Ninety-eight percent of hip fractures result from a fall (Parkkari et al., 1999). Of the more than 230,000 older adults who suffer a fall-related hip fracture each year within the United States, 25-75% never recover to pre-fracture functional activity levels (Cummings et al., 1990; Keene et al., 1993; Rubenstein & Josephson, 2002). More than half of patients over the age of 60 require additional walking aids one year post fracture and less than half of those over 80 are able to return to their homes following a hip fracture (Sernbo & Johnell, 1993). For many, a hip fracture will affect their daily living for the remainder of their lives.

Repeated falls are a common reason for admission into long-term care facilities (Kiel et al., 1991; Keene et al., 1993; Rubenstein & Josephson, 2002). Falls also lead to a fear of falling in 30-73% of fallers (Rubenstein & Josephson, 2002). This fear of falling is often associated with reductions in activity levels, social interactions, and self-confidence (Rubenstein & Josephson, 2002). This decreased activity level leads to further dysfunction, which can increase the individual's risk of future falls.

According to the National Safety Council (2005), falls were the second greatest cause of unintentional injury deaths for all ages in the United States in 2003,

with 16,200 occurrences. Older adults account for the majority of deaths as a result of a fall (Mosenthal et al., 1995; NSC, 2005). In 2003, 12,000 falls resulted in deaths of those 65 and older (NSC, 2005). As indicated, 98% of hip fractures are the result of a fall (Parkkari et al., 1999) and 20 to 30% of fallers who experience a hip fracture die within one year of the accident, most of those within the first six months (Keene et al., 1993; Sernbo & Johnell, 1993; Rubenstein & Josephson, 2002). Increasing age also decreases the chances of surviving a hip fracture (Mosenthal et al., 1995). Only 3% of those under the age of 60 died as a result of a hip fracture, compared to 51% of those over 90 years of age (Keene et al., 1993).

Due to the high costs of medical care and institutionalization, falls are a costly risk factor in the older adult population that affects the rest of the population as well. The total cost per patient for the first year following a hip fracture has been estimated as \$26,000, adding up to over \$7 billion annually in the United States alone (Cummings et al., 1990; Sernbo & Johnell, 1993). This figure is expected to climb to \$16 billion annually by the year 2040, with over 500,000-600,000 hip fractures occurring each year in the United States (Cummings et al., 1990; Cooper et al., 1992).

Approximately half of all falls in community dwelling older adults are caused by slips or trips (Gabell et al., 1985; Berg et al., 1997). Slips are also one of the leading causes of falls that result in fractures (Luukinen et al., 2000). Research examining the biomechanical factors associated with slips and trips aims to contribute to new methods for preventing falls and associated injuries or death in the older adult population (e.g. Tang & Woollacott, 1998; Gilles et al., 1999; Pavol et al., 2001;

Marigold & Patla, 2002). A reduction of fall incidence would reduce fall-related injuries, deaths, and societal costs.

#### *Postural Reflexes and Recovery from Balance Loss*

Studies in the late 1970's and 1980's examined reflex responses to postural perturbations, laying the groundwork for future research (Nashner, 1977; Berger et al., 1984; Deitz et al., 1986; Horak & Nashner, 1986; Horak et al., 1989; Stelmach et al., 1989). The responses to postural perturbations appear to utilize medium- to long-latency reflexes (Nashner, 1977; Berger et al., 1984). The timing of muscle onset latencies indicates that these responses are too slow to be monosynaptic reflexes but too fast to be cognitive responses (Berger et al., 1984). Nashner (1977), Dietz et al. (1986), and Horak and Nashner (1986) reported that the initial response to balance perturbations appears to be preprogrammed. In one study, Nashner (1977) perturbed participants by either translating or rotating the platform they were standing on, and changed the perturbation type without warning after a series of 3-4 repeated similar perturbations. In another study, Dietz et al. (1986) administered a variety of perturbations during treadmill walking, including treadmill acceleration, treadmill deceleration, and tibial nerve stimulation, with a second stimulus administered unexpectedly right after the first. In both studies, the different-than-expected or second, opposing perturbation required an opposite recovery response, rendering the expected or first response ineffective, yet participants continued to respond to the expected or initial perturbation. For a given response strategy, muscle reactions occur in a stereotypical sequence each time the same perturbation is given (Nashner, 1977;

Horak & Nashner, 1986). This suggests that responses are not decisions made each time a perturbation is given, but are preprogrammed responses that are ready to engage before the perturbation even arrives.

Even though perturbation responses seem to be prepared ahead of time, there is a great deal of evidence that reactions vary from situation to situation (Berger et al., 1984; Horak & Nashner, 1986; Maki et al., 1996). Berger et al. (1984) and Deitz et al. (1986) observed that responses to perturbations varied depending on what part of the gait cycle they were administered. Responses to perturbations during walking are also different from those responses to perturbations during standing (Berger et al., 1984).

Horak et al. (1986, 1989) found that reactions to postural perturbations during standing differed according to the perturbation magnitude, support situation (i.e. standing surface width), and previous experience. The magnitude of torque and EMG responses to postural perturbations varied based on the size of perturbation expected (Horak et al., 1989). When a large perturbation was given, but a small one expected, the response was inadequate. Conversely, an excessive response was observed when a large perturbation was expected but only a small one was given (Horak et al., 1989). As participants were exposed to repeated postural perturbations, their EMG and torque responses declined in magnitude, indicating increased efficiency or increased adaptation in anticipation of subsequent perturbations (Horak et al., 1989). Maki et al. (1996) similarly reported that participants adapt and recover more easily when exposed to repeated postural perturbations in a predictable direction.

These findings all indicate that, while responses to slips and trips may be preprogrammed and somewhat automated, there is more than one possible response to the same perturbation. This preprogrammed response is likely constantly updated by the brain, changing the excitability of the different possible spinal reflex responses. This affects the sensitivity of reflex responses to potential perturbations and influences whether or not a reflex is triggered and the strength of the response based on the situation at that moment. When a slip or trip happens, the response is triggered automatically but varies based on the magnitude of the perturbation, current posture, which part of the gait cycle it occurs in, environmental constraints, and previous exposure to a similar slip or trip (Berger et al., 1984; Horak & Nashner, 1986; Maki et al, 1996). None of the studies referenced to this point, however, looked at actual falls. In all cases participants were able to recover their balance.

#### *Balance Recovery Strategies*

There are three main strategies for recovery attempts from a balance perturbation. The ankle strategy is used primarily in response to small, slow balance perturbations and involves restoring balance by rotating the body about the ankle joint (Nashner, 1977; Horak & Nashner, 1986). The hip strategy is used to recover from larger perturbations or when the support surface is shorter than the length of the foot, rendering the ankle strategy ineffective (Horak & Nashner, 1986). In this strategy, balance is restored primarily through rotations about the hip joint. Muscles are activated in a distal to proximal order in the ankle strategy, and a proximal to distal order in the hip strategy (Horak & Nashner, 1986). Specific muscles are activated

depending on the direction or type of perturbation given (Nashner, 1977; Woollacott et al., 1986). Perturbations with participants standing on an intermediate-length support surface produced responses incorporating portions of both the hip and ankle strategies, indicating that a continuum of responses exist based on the environmental constraints and perturbation magnitude (Horak & Nashner, 1986).

The third main strategy is the stepping strategy. This strategy is employed in response to larger perturbations, when individuals are not constrained to not step or when individuals are perturbed while distracted or multi-tasking. The stepping strategy is an attempt to move the base of support underneath the center of mass, rather than moving the center of mass back over the base of support, as in the ankle and hip strategies. A variant of the stepping strategy is the grasping strategy, which may be used if handrails, tables, countertops, or other stable objects are available. This research project will focus on the stepping strategy. Arguably, stepping represents the last line of defense, and thus plays a critical role in preventing a fall.

The stepping strategy differs depending on perturbation direction, magnitude, current activity, and previous experience (Maki et al., 1996; Hsiao & Robinovitch, 1999; Bhatt et al., 2005). As would be expected, lateral balance perturbations produce different responses than those initiated in the sagittal plane. The stepping responses to lateral perturbations are influenced a great deal by lateral weight shift. The most common response to lateral perturbations is to step across the body with the unloaded leg (Maki et al., 1996). Due to the unloading of the leg during the perturbation, the time to foot liftoff is typically much quicker for lateral perturbations

than for forward or backward ones (Maki et al., 1996). If the loaded leg is used to execute the lateral step instead, the step duration is typically shorter and the step length is longer (Maki et al., 1996). For lateral recoveries requiring multiple steps, the first step is usually initiated late and is insufficient in length (Maki et al., 1996).

Larger perturbations led to greater step lengths and shorter step times than smaller balance perturbations in tether release trials where participants began in a forward leaning position at various angles (Hsiao & Robinovitch, 1999). Coupling was found to exist between step length (associated with flexibility), step time (associated with reaction time), and strength factors (i.e. muscle forces) (Hsiao & Robinovitch, 1999).

Walking speed also affects the stepping response (Bhatt et al., 2005). When a forward slip was induced shortly after heel contact, faster walkers took larger forward steps with their contralateral leg than slower walkers, thereby decreasing their base of support (Bhatt et al., 2005). The faster walkers' center of mass was moving forward faster, however, so they were still able to maintain their balance as well or better than the slower walkers who took shorter steps (Bhatt et al., 2005).

Knowing perturbation direction ahead of time did not affect swing duration, step length, step direction, or step velocity, but it did increase participants' ability to recover balance without stepping (Maki et al., 1996). Since the stepping response seems to vary based on direction, experience, and expectation or knowledge of the upcoming perturbation, it is important to look at falls and successful recoveries under various conditions of each of these factors. In all the studies mentioned to this point,

the perturbations were large enough to elicit a stepping response, but did not result in any falls.

#### *Aging-Related Changes in Recovery from Balance Loss*

In response to a balance loss, older adults exhibit both similarities and differences when compared to younger adults (Woollacott et al., 1986; Stelmach et al., 1989; McIlroy & Maki, 1996; Tang & Woollacott, 1998; Maki et al., 2000; Brauer & Burns, 2002; Mille et al., 2005). Recent research has shown that older adults' initial reflexes to postural perturbations are not significantly slower than those of young adults (Stelmach et al., 1989, McIlroy & Maki, 1996; Brauer & Burns, 2002). Responses to a variety of postural and walking perturbations revealed that reaction time is similar in older and younger adults (McIlroy & Maki, 1996; Brauer & Burns, 2002; Mille et al., 2005). Older adults also exhibit similar muscle activation patterns and recovery strategies as young adults, but with more variability (Woollacott et al., 1986; Tang & Woollacott, 1998). When comparing stable and functionally unstable older adults, as determined through balance tests, to young adults, stable older adults rarely differed significantly from the young adults (Lin et al., 2004). The functionally unstable older adults, however, differed from the young adults on most variables tested, indicating that declines in functional ability and not age alone may be responsible for balance problems (Lin et al., 2004). Stelmach, et al. (1989) examined the responses of young and older adults to postural perturbations and found that, when given a large/fast perturbation, the reflex responses were similar in both groups. However, when subjected to slow/small perturbations, where there

was time to activate higher-level integrative responses, the older adults showed more sway as a result of the perturbations (Woollacott et al., 1986; Stelmach et al., 1989). This indicates that while reflexes appear to be still intact, the slower, more complex responses tend to decline with age.

Older adults tend to take more steps and use arm movements more than young adults to regain their balance; however, their mechanisms for recovery and their initial step parameters are similar to those of young adults (McIlroy & Maki, 1996; & Maki et al., 2000; Mille et al., 2005). The second step in anteroposterior-directed multi-step recoveries of older adults tends to be more laterally directed than that of younger adults, indicating a decrease in lateral stability with age (McIlroy & Maki, 1996). Older adults are more likely to choose the cross-over method, which is more complex and increases the likelihood of hitting one foot into the other upon a lateral loss of balance (Maki et al., 2000; Mille et al., 2005). Older adults also tend to use more trunk flexion and hip torque to recover from a lateral balance loss than younger adults (Mille et al., 2005). In general, older adults have more difficulty completing successful lateral balance recoveries compared to younger adults (Maki et al., 2000). Older adults are also more likely than the younger adults to use handrails for balance if they are available (Woollacott et al., 1986; McIlroy & Maki, 1996). Effects of aging may cause one factor associated with a successful stepping response, such as range of motion, strength, or sensory organization to decline, but other factors may be able to compensate to make up for that loss (Woollacott et al., 1986; Hsiao & Robinovitch, 1999). In addition to effects of aging, a fear of falling may also

contribute to older adults feeling the need to take more steps, even if they have recovered their balance in fewer steps. Once again, only successful recoveries from balance perturbations have been considered to this point.

#### *How falls occur*

Only recently did researchers begin to examine actual falls (Pavol et al., 2001; Smeesters et al., 2001; Pavol et al., 2004a, 2004b). An early study of young adults found that falls occur most easily in the backwards direction (Hsiao & Robinovitch, 1998). Hsiao and Robinovitch (1998) found that, when perturbed to the rear, participants were only able to recover half as often as for sideways or forward balance perturbations.

Factors associated with both the stepping limb and the support limb appear to be important to the success of reactive stepping responses to balance perturbations (Pavol et al., 2001, 2004a). Pavol et al. (2001) studied actual falls and successful recoveries of older adults who were unexpectedly tripped while walking. In a later study, Pavol et al. (2004a) examined falls and successful recoveries as a result of a slip perturbation administered to adults as they stood up out of a chair. Both studies found that higher hip height, as maintained by the support limb, during the initial recovery step and at the time of the recovery step touchdown was significantly related to the ability to recover on the first novel and unexpected slip or trip (Pavol et al., 2001, 2004a). Those who were able to maintain hip height without dropping were more successful in recovering without a fall. Hip height was maintained by not allowing the support leg to bend excessively underneath the body and/or through

limiting the rotation of the support leg while the stepping leg was in swing phase. Maintaining substantial hip height allowed more time and space for the successful stepping response to take place.

Response times in the supporting limb have been found to be just as fast as those of the swing limb (Pijnappels et al., 2005). In slips while walking on a slippery surface or when unexpectedly tripped while walking, the knee and hip moments reversed compared to non-perturbed trials (Cham et al., 2001; Pijnappels et al., 2005). The hip moments become extension in an attempt to slow the angular velocity of the torso and the knee moments became flexion, potentially to decelerate the forward rotation of the thigh and pull the slipping foot back under the body, essentially buying time for the swing leg to land in a stable location (Cham et al., 2001; Pijnappels et al., 2005). Peak moments about the ankle in the support leg were found to be higher than estimated maximum voluntary isometric moments, reinforcing the importance of this joint in balance recovery (Pijnappels et al., 2005).

The stepping leg also plays an important role in successful recoveries to balance perturbations (Pavol et al., 2001, 2004a). It is important for the initial recovery step to be large enough to create a new base of support that can be used to effectively control the position and velocity of the center of mass (Pavol et al., 2004a). Fallers tended to take shorter steps which did not reach sufficiently past their center of mass, compared to those who recovered (Pavol et al., 2004a). Since the center of mass is dropping as it moves in the direction of the fall, it is also important for the recovery step to be rapid (Pavol et al., 2001). If the duration of the recovery

step is too long, the center of mass will have moved too far for the step to be sufficient to successfully recover balance.

The direction in which a fall will occur depends on a number of factors, including the type of perturbation and walking speed. Trips and unexpected step downs, as well as slips and faints at high walking speeds, were found to be more likely to result in a forward fall (Smeesters et al., 2001). Faints at slow speeds led to side falls, and slips at slow speeds led to backward falls (Smeesters et al., 2001). These balance losses were slightly unrealistic, however, in that participants were told to fall and not make an effort to regain their balance.

Faints and slips are more likely to result in hip impact on the ground, as opposed to trips or unexpected step downs (Smeesters et al., 2001). Eighty-one percent of hip fractures are a result of impact on that hip (Parkkari et al., 1999). Almost all of the backward falls (92%) observed by Hsiao and Robinovitch (1998) resulted in pelvis impact, often at or above velocities known to cause a fracture of an older adult's femur, as compared to only 23% of lateral falls and no anterior falls. Participants avoided hip contact upon lateral falls by rotating their pelvis during the fall to land facing more forward (Hsiao & Robinovitch, 1998). Participants also reduced the amount of force absorbed at the hip by coordinating arm movements to land with the hands at approximately the same time that the hip or knees landed (Hsiao & Robinovitch, 1998; Smeesters et al., 2001). Squatting during a backward fall, as opposed to maintaining extended knees and hips, decreases impact velocity and kinetic energy at impact (Sandler & Robinovitch, 2001; Robinovitch et al., 2004).

Energy is absorbed by the muscles acting across these joints, as evidenced by torques opposing the direction of joint rotation (Robinovitch et al., 2004). In a simulation experiment, falling with a certain technique (squatting and then extending the knees just prior to impact to convert vertical velocity to horizontal velocity) seemed to prove beneficial, despite simulated decreases of 80% in strength (Sandler & Robinovitch, 2001). This indicates that technique may be more important than strength in reducing fall related injuries. Due to the risk of hip fracture from backward slips, it is important to study these types of falls in particular.

#### *Learning to Prevent a Fall*

Owings et al. (2001) and Pavol et al. (2004b) examined repeated exposures to balance perturbations. These studies showed evidence that both proactive adjustments and reactive responses changed over a period of trials to increase the likelihood of a successful response. Proactive adjustments occur prior to the onset of a perturbation to reduce the effect of the perturbation when it does occur and reactive responses occur after the perturbation to counter its effects. Both older and younger adults who fell in the early trials were able to modify their behaviors to become more like those who recovered in their early trials (Owings et al., 2001; Pavol et al., 2004b). The fact that all participants were able to modify their behaviors gives evidence that learning does take place and it may be possible to train or teach people how to recover from a slip or a trip to avoid a fall.

Many participants learned to recover or modify their proactive and reactive behaviors in a positive way as early as the second trial (Pavol et al., 2004b). Pavol &

Pai (2002) induced a slip while participants were standing from a seated position. They found that increased forward position and velocity of the center of mass at seat-off occurred following the first two slip trials and these decreased following no-slip trials (Pavol et al., 2004b). Hip height during the initial recovery step and step length also increased following the first slip trial (Pavol et al., 2004b).

While older adults tend to have a higher incidence of falls when exposed to perturbations, they appear to modify their behaviors in as few trials as younger adults (McIlroy & Maki, 1996; Maki et al., 2000; Owings et al., 2001; Brauer & Burns, 2002; Pavol et al., 2004b). Young adults may actually tend to overcompensate, as they made greater proactive adjustments than older adults after the initial exposure to a slip during a sit-to-stand but the reductions in fall incidence were similar in both groups (Pavol et al., 2004b). In the sit-to-stand study, it was also observed that older adults are able to successfully regain their balance from a smaller range of body center of mass position and velocity at seat-off than younger adults (Pavol et al., 2004b). Despite some differences, it is evident that, given repeated exposure to balance perturbations, both young and older adults are able to adjust both their proactive behaviors and reactive responses to increase their likelihood of avoiding a fall on subsequent balance perturbations.

#### *Role of Unpredictability and Learning to Recover*

In everyday life, when one is aware of a hazard, such as an obstacle or slippery surface, it is either avoided or proactive adjustments to one's movements are made to reduce the risk of falling when negotiating the hazard. As a result,

unexpected hazards are more likely to cause a fall. There is mixed evidence as to whether or not an unpredictable perturbation elicits a different response than predictable perturbations (Gilles et al., 1999; Marigold & Patla, 2002). Both proactive and reactive adjustments are made (feedforward and feedback motor programming) in response to unpredictable movement perturbations (Gilles et al., 1999; Scheidt et al., 2001; Pavol & Pai, 2002; Pavol et al., 2004b).

In studies where either balance or movement was unpredictably perturbed (or potentially not perturbed), participants appeared to use information from the previous one or two trials to determine their proactive adjustments to the imminent perturbation (Scheidt et al., 2001; Pavol & Pai, 2002). In the sit-to-stand study previously described, Pavol and Pai (2002) observed that, in trials following a forward slip trial, the center of mass was more forward and moving forward faster at slip onset and, in trials following a non-slipping trial, the center of mass was farther back and not moving forward as fast (Pavol & Pai, 2002). In early trials, the proactive adjustments following repeated slipping trials overcompensated, and the adjustments following repeated non-slipping trials under-compensated (Pavol & Pai, 2002). Over a period of mixed trials, however, the participants appeared to zero in on an average predictive movement pattern that would be as likely to be successful if there was or was not a perturbation (Pavol & Pai, 2002).

In another study, participants attempted to move a mechanical arm in a straight line (Scheidt et al., 2001). The mechanical arm caused perturbations in unpredictable directions by exerting an external force on the participant's arm during

the movement (Scheidt et al., 2001). As in Pavol and Pai (2002), the proactive adjustments made by the participants generally compensated for the situation that occurred in the previous one or two trials (Scheidt et al., 2001). Movement in the current trial could be accurately predicted by the perturbation encountered on the current and previous trial, as well as the movement error from the previous trial (Scheidt et al., 2001). Also as in Pavol and Pai (2002), over a period of trials, the participants appeared to zero in on an average predictive movement pattern (Scheidt et al., 2001).

Marigold and Patla (2002) found that participants approached a slippery surface differently if they knew it would or might be slippery, as opposed to when they knew it would not be slippery. Evidence of proactive adjustments included decreased foot angle at contact, joint stiffening, and reduced loading rate (Marigold & Patla, 2002). Knowledge of a potential hazard appears to elicit modifications of the recovery response (Marigold & Patla, 2002). However, it is unknown whether the response can be effectively changed if the direction of the perturbation is unknown.

Reactive adjustments to balance perturbations included the addition of a recovery step if one was not used previously, or an increase in recovery step length and decrease in step time over a period of trials (Pavol et al., 2004b). Gilles et al. (1999) found very little difference between responses or response times to perturbations in predictable or unpredictable directions. However, they only used small perturbations in two directions, such that the participant was in little danger of

falling. Perhaps with a larger perturbation a difference would have appeared when the perturbation direction was unpredictable.

### *Rationale*

In order to prevent falls, it is necessary to know what factors are associated with falls and recoveries in response to a slip. Ineffective reactive responses have been shown to contribute greatly to falls (Pavol et al., 2004a, 2004b). Evidence has shown, however, that adaptations of these responses can occur over repeated exposure to predictable postural perturbations and to small, unpredictable perturbations (McIlroy & Maki, 1996; Gilles et al., 1999; Maki et al., 2000; Owings et al., 2001; Pavol et al., 2004b). It is still unknown whether or not these same adaptations can occur in response to large magnitude balance perturbations from unpredictable directions. If adaptations do take place under these conditions, it seems possible that fall incidence could be successfully reduced through training of these reactive responses.

Since most slips occur unexpectedly, it is important to maintain an element of surprise in exposing research participants to slipping, to obtain as realistic a response as possible. While safety precautions are taken to reduce the risk of injury to participants, there is likely some risk involved when testing individuals' ability to respond to balance perturbations. Older adults are at greater risk than young because of their higher incidence of diseases, as well as their general decline in overall function. Therefore, in seeing if it is possible to adapt the reactive stepping response to a balance perturbation when it is of unpredictable direction and is relatively large

in magnitude, we chose to study young adults initially. If such an adaptive response does not exist in young adults, it is not likely to exist in older adults, so there would be no reason to put them at risk as participants.

Testing young adults is justifiable, even though older adults are the primary population of interest for this study, because initial reactions, response strategies, and learning rates have been found to be similar among the different age groups (Stelmach et al., 1989; McIlroy & Maki., 1996; Brauer & Burns, 2002). If successful adaptations are consistently observed among the young adult participants, a similar study of older adults would be suggested.

#### *Purpose Statement*

The purpose of this study was to determine the extent to which apparently healthy young adults are able to learn to recover more efficiently to prevent a fall as a result of perturbations (i.e. slips) in unpredictable directions over repeated trials. Participants were thus exposed to a series of forced slips in differing, unpredictable directions during a simulated lifting task. If learning was evident in young adults, despite the unpredictable direction, then older adults may also be able to learn, justifying a similar study of older adults. Were learning to occur, the variables that differed between successful and failed attempts were to be determined, as well as the changes that occurred over trials in the successful attempts to regain balance. Knowing these differences and changes may help in developing a program to train older adults to improve critical reactions to decrease their risk of falling and suffering a debilitating injury.

### *Research Hypotheses*

Although participants were exposed to forced slips in differing, unpredictable directions, only forward slipping perturbations, which caused a backward loss of balance, were analyzed. We expected that participants might or might not fall from the first, novel and unpredictable, forward perturbation. It was hypothesized that those who did fall would learn to successfully recover from that same perturbation when unpredictably exposed to it in subsequent trials. Furthermore, once a participant successfully recovered from the perturbation, he or she would not fall upon subsequent, unpredictable exposures to the same perturbation. It was expected that successful recoveries from the perturbation would include a stepping response.

It was hypothesized that participants would not alter their performance of the lifting task across trials, but that changes in the initial reactive stepping response would occur among both fallers and those who recovered. Of specific interest were the differences between the first, second, and fifth unpredictable exposures to the forward slip. It was hypothesized that the body center of mass position and velocity at the time of perturbation onset would not differ between trials, nor would the hip height and vertical hip velocity at perturbation onset. However, response time from perturbation onset to step liftoff, as well as step time, should decrease over trials. Maximum hip height during the initial step would likely increase as participants gained more experience with the perturbation, and hip height at the time of step touchdown should be greater for the second and fifth exposures. The latter trials should also show an increase in initial step length relative to the original foot

position, as well as relative to center of mass at touchdown. The initial step would likely occur more in the lateral direction in the latter trials to compensate for unexpectedness of the perturbation direction.

At step liftoff, the body center of mass was hypothesized to be more forward in later trials and moving backward at a slower velocity. Hip height would increase and descending velocity decrease with increasing exposure to the perturbations. At the moment of step touchdown, the hips and body center of mass would likely be moving slower as the participant gained experience.

It was hypothesized that adaptations in the dependent variables over trials would be greater for those who fell in their first trial in comparison to those who successfully recovered on their first trial. Finally it was hypothesized that the adaptations to repeated, unpredictable exposures would not differ from those that result from repeated exposure to the same perturbation. Specifically, the dependent variables would not differ between the fifth unpredictable exposure to the forward perturbation and the last of five, subsequent consecutive exposures to the perturbation.

## Materials and Methods

### *Participants*

Thirty apparently healthy young adult participants (12 men and 18 women) between the ages of 18 and 30 years (mean  $\pm$  SD age:  $23.7 \pm 3.6$  years; height:  $171.0 \pm 10.3$  cm; mass:  $68.3 \pm 9.6$  kg) participated in this study. This study was approved by the Oregon State University Institutional Review Board and all participants signed an informed consent form (see Appendix A).

Participants also completed a health history questionnaire to confirm that they did not have any musculoskeletal, neurological, cardiopulmonary or other systemic disorders (see Appendix B). Participants were also excluded if they were under the influence of drugs or medications that impair physical or mental function. With one exception, participants weighing more than 81.8 kg (180 lbs) were excluded from participation. It was thought that heavier participants might cause the lateral braking forces to exceed the capacity of the experimental apparatus during the sudden stop at the end of the forced slip.

### *Instruments and Apparatus*

A moving platform was constructed to cause a perturbation that simulated a slip while participants were standing on it (Figure 1). This platform, with a radius of 20 cm, was attached to a pneumatic cylinder which was, in turn, attached to a turntable assembly that was bolted to a force plate. Compressed air at 553 kPa to the piston of the cylinder caused the platform to slide horizontally along a pair of rails

when triggered. The pneumatic cylinder and rails were masked by a metal cover plate in such a way that the perturbation direction could not be detected by the participant. This cover plate was flush with a surrounding wooden floor (2.4 m.  $\times$  2.4 m) constructed for this experiment. It was possible to orient the turntable assembly in eight different directions to allow the platform to be driven forward, backward, right, left, or diagonally relative to the participant. The translation of the platform induced a slip that resulted in a loss of balance in the opposite direction. The displacement of the platform was large enough to cause the participant to either take one or more steps to recover or fall into the safety harness system (described below).

In right and left perturbations, the platform translated approximately 20 cm in approximately 0.17 seconds. In all other directions, it moved 30 cm in approximately 0.34 seconds. The smaller perturbations to the side were intended to reduce the likelihood that a participant would sprain his or her ankle. Validity of the platform displacement was obtained by taping a reflective marker to the platform and analyzing the motion of the marker with a motion capture system.

A 40  $\times$  60 cm force plate (Bertec, Columbus, OH) measured reaction forces between the moving platform and the ground. These forces were sampled at 600 Hz in synchrony with the motion capture data for detection of the step liftoff and touchdown. The forces were also used in the triggering of the perturbations.

A Labview (National Instruments, Austin, TX) program was used to control the triggering and length of the perturbations. The program monitored the vertical forces acting on the platform, as measured by the force plate, in real-time, sampling at

120 Hz. These forces were integrated twice with respect to time and used to determine when the participant's center of mass began moving upward during the simulated squat-lifting task being performed. The slip was automatically triggered by the program when the participants' center of mass had risen from its lowest point by 2% of the distance it had traveled downward. This program also monitored center of pressure information in real-time. The slip was only triggered if the center of pressure was within 7 cm of the center of the platform, to avoid impacting the participant's feet with the moving platform.

Participants were secured into a full-body safety harness with dynamic, shock-absorbing ropes attached at each shoulder. These ropes were secured to a trolley fixed to a ceiling-mounted rail. The rope lengths were adjusted so that, when participants "fell," the system would catch them such that their knees, hips, and upper body could not reach the floor. A load cell (Sensotec, Columbus, OH) measured the force exerted by the participant on the ropes of the safety harness system and was sampled at a rate of 600 Hz.

A nine-camera motion capture system (Vicon, Lake Forest, CA) recorded the position of 34 reflective markers at a sampling frequency of 120 Hz. The reflective markers were attached to major joints and body segments (feet, ankle, leg, knee, thigh, pelvis, back, shoulder, elbow, wrist, chest, and head) to total at least three markers per body segment (two markers per upper extremity segment). From these marker positions, data were obtained on body segment position, orientation, and velocity. A digital video camera (Sony, New York, NY) was also used to record

ordinary video of each trial for visual reference and to aid in determining the times of step liftoff and touchdown.

### *Procedures*

All testing took place in the Biomechanics Laboratory of the Department of Nutrition and Exercise Sciences. Informed consent and health history were obtained prior to testing (see Appendices A & B). For data collection, participants wore athletic shoes, tight shorts or pants, and a tank top. Participants began with a warm-up of 5 min of walking on a treadmill. This was followed by light stretching of the plantarflexors, quadriceps, hamstrings, hip flexors, hip adductors, and hip abductors. Reflective markers were then placed on the major body segments and joints of interest, as described earlier. Participants completed their warm-up with step-ups on a 13 cm step. Step-ups consisted of 10 each of forward, left, and right, descending in the opposite direction each time.

Participants were then secured into the safety harness system, in case of a fall. The rope lengths were adjusted and participants were then given an opportunity to test the ropes for proper length and to familiarize themselves with the harness system. The researcher assisted the participant into a kneeling position where the ropes were fully supporting the participant's weight and then helped him or her back to a standing position. This was repeated as many times as necessary until the rope lengths were adjusted such that the knees did not touch the floor and the participant was comfortable with the setup.

The participant was then given the opportunity to practice the lifting activity that he or she would perform repeatedly throughout the experiment. The participant was given a 75 cm-long foam rod with a 3 cm diameter and negligible weight to hold with both hands approximately shoulder-width apart. The lifting activity consisted of the participant squatting to touch the rod to his or her thighs, approximately two-thirds of the way down from the hips to the knees, while keeping his or her back and elbows straight and then returning to the upright position. Feet were placed side-by-side inside a marked circle with their lateral edges approximately 23 cm apart. The participant was asked to execute the downward and upward phases in approximately 0.7 seconds each, with a 1.5 Hz computer-generated tone provided during practice to indicate the desired timing. Once the participant felt comfortable with this exercise and the researcher felt that he or she was doing it correctly, data collection began.

One static trial was performed, recording two seconds of quiet standing in a known reference position to check marker visibility and to allow the determination of joint center positions and body segment orientations in the data analysis. Participants were then told that they would be performing a set of trials of the simulated lifting task and that we would later attempt to make them lose their balance. After four lifting trials with no perturbation, the perturbation platform was triggered to translate forward on the fifth trial (or as soon as feasible thereafter), causing a backward loss of balance. This initial perturbation occurred without demonstration, practice, or explicit warning, to mimic an unexpected slip.

Following the initial perturbation, participants were told that a similar perturbation may or may not occur in any direction during subsequent lifts. They were told to try not to fall and to not let go of the foam rod. Including the first perturbation and the trials that preceded it, each participant was subjected to approximately 36 trials of the lifting task, with 27 of those consisting of a balance perturbation. The perturbations varied unpredictably in five of the eight possible directions and participants were unaware of the direction of each upcoming perturbation. The direction sequence was the same across participants so that comparisons between participants could be made. Following the first forward perturbation on Trial 5, four of Trials 6-29 consisted of forward translations of the platform, with four to six each of backward, left, right, or no perturbations occurring in the remaining trials (Figure 2). The five forward translation perturbations did not occur at equal intervals, nor were they ever back-to-back. Trial 30 consisted of the first diagonal perturbation, causing a backward/left loss of balance. Trials 31-35 all consisted of forward translations. The data from the last forward translation trial (Trial 35) are assumed to be representative of the adaptations to a predictable perturbation.

Following each trial, participants were questioned to make sure that they did not experience any pain during the previous trial and that they were willing and able to continue. The session would have stopped immediately if the participant experienced any pain or chose not to continue. This was never the case, however. Occasionally the platform did not trigger and no perturbation occurred on a trial in

which there was supposed to be a perturbation because the safety harness was supporting part of the participant's weight during the lifting task, which affected integration of the vertical forces. If this happened, the perturbation that was supposed to take place during that trial was given in the next trial. All trials were completed in a single session and participants were allowed to rest as much as desired between trials.

Following the data collection trials, body measurements were obtained. These included foot length, ankle width, knee width, arm width at the shoulder, and sacrum to L<sub>3</sub>L<sub>4</sub> height. Body segment length and width measurements were taken with an anthropometer. Body height and weight were also measured after data collection using a wall-mounted stadiometer and medical scale, respectively.

#### *Data Analysis*

A 3-dimensional marker path reconstruction was done using the motion capture system. Data were low pass filtered with fourth-order, Butterworth, zero-lag filters with a cutoff frequency of 14 Hz to eliminate high-frequency noise. The cutoff frequency was determined through a residual analysis (Winter, 2005). A custom BodyBuilder program (Vicon, Lake Forest, CA) was used to determine the locations of joint centers and the body segment orientations. Both were determined using 3-dimensional coordinate transformations derived from the static trial and the measured body dimensions.

To differentiate between a fall and a successful recovery, a recovery was defined as a trial in which there was a near absence of a load on the safety harness

system, as measured by the load cell. If, over any one second period after perturbation onset, the average load supported by the safety harness system was greater than 10% of the participant's body weight, that trial was classified as a fall. Otherwise, the trial was classified as a recovery. This cutoff was found by graphing the peak one-second average load supported by the safety harness for each participant for the first trial and visually determining where the gap was between "negligible" and "non-negligible" forces. The choice of classification threshold was confirmed through a review of the digital video. In all falls, the hips dropped below 45.5% of body height, however that was the case for some of the recoveries as well.

Three events were of interest. Perturbation onset was defined as the beginning of platform motion, based on the onset of forward motion by markers located on the fifth metatarsal heads. Step liftoff and step touchdown were determined primarily from the respective end and start of a large, rapid mediolateral shift in the center of pressure, with aid and confirmation by the digital video and marker paths. Only the first step in the stepping response was analyzed.

A total of 22 variables were analyzed at or between the events of interest. The position of the body center of mass was calculated from the computed joint center positions and sex-specific anthropometric data in a 12-segment model of the body (de Leva, 1996). The anteroposterior and mediolateral position of the center of mass relative to the base of support were evaluated at perturbation onset and step touchdown, and in the anteroposterior direction only at step liftoff. The position of the center of mass in the anteroposterior direction was expressed in foot lengths in

relation to the more posterior heel at perturbation onset, the non-stepping heel at step liftoff, and the stepping heel at step touchdown. In all cases, a positive position indicated that the center of mass was in front of its respective point of reference. In the mediolateral direction, a positive center of mass position at perturbation onset occurred when the center of mass was to the left of the midpoint between the two ankle joint centers. At step touchdown, the center of mass was referenced to the fifth metatarsal head of the stepping foot and a positive result indicated the center of mass was medial to the fifth metatarsal. The mediolateral center of mass position was expressed in millimeters.

The anteroposterior and mediolateral velocity of the center of mass relative to the base of support was evaluated at perturbation onset, step liftoff, and step touchdown. The anteroposterior velocity was expressed as a Froude number by normalizing it to  $\sqrt{g \times \text{body height}}$ , where  $g$  is the acceleration due to gravity. Positive values indicated a forward velocity relative to the ground or, at step liftoff, the non-stepping heel. In the mediolateral direction, center of mass velocity was positive to the participant's left and reported in millimeters per second. Hip height was defined as the average height of the two hip joint centers above the platform at perturbation onset and step liftoff, and above the wood flooring at step touchdown. Hip height and vertical velocity were evaluated at perturbation onset, step liftoff, and step touchdown and normalized to body height. The maximum hip height above the platform between step liftoff and touchdown was also recorded.

Response time was the time from the perturbation onset to step liftoff and step time was the time from step liftoff to step touchdown. Step length in the posterior direction was determined from the position of the fifth metatarsal reflective marker of the stepping foot relative to that of the non-stepping foot at step touchdown. Step length in the mediolateral direction was measured from the position of the step foot fifth metatarsal marker at step liftoff to the position of the same marker at step touchdown, with positive values corresponding to a laterally directed step. Step lengths were normalized to body height. In total, 16 dependent variables were used to quantify the reactive stepping response to the perturbation and 6 variables were evaluated at perturbation onset to determine if any proactive adaptations existed.

#### *Experimental Design*

A 2x4 (Group x Trial) between/within design with repeated measures on the second factor was used. The groups comprised those who fell on first trial (Fall Group) and those who were able to successfully recover on the first trial (Recovery Group). Participants remained in these groups for all data analysis, regardless of the outcomes of subsequent trials. The four trials of interest were the first, second, fifth, and last (tenth) trials in which a forward translation of the platform (backward loss of balance) occurred.

#### *Statistics*

In order to detect a medium difference among means for each of the dependent variables with a statistical power of at least 0.80 at  $\alpha = 0.05$ , at least 7 participants per first-slip outcome group were required (Kirk, 1982). Since

participants were not assigned to groups until after the first trial, 30 participants were tested to try to ensure that there would be at least seven per group.

For each dependent variable, a 2x4 (Group x Trial) between/within analysis of variance (ANOVA) was performed on the first, second, fifth, and last forward translation trials of the two groups (Fall vs. Recover on the first perturbation). Three effects were of interest. The first was the difference between the Fall Group and Recovery Group. The second was the change across trials, to determine if learning occurred despite the unpredictable direction of the perturbation and to contrast this learning to that upon repeated exposure to the same perturbation. The third effect of interest was whether the difference between groups changed across trials and vice versa. Mauchly's test was performed for each ANOVA and a Greenhouse-Geisser correction was used if the sphericity assumptions were found to be violated. Effects were considered significant at  $p < 0.05$ .

For variables for which there was a significant Group x Trial interaction, post hoc independent t-tests were performed to compare the average values between groups on each trial, with Levene's test used to test for unequal variances. Paired t-tests were also used to look for differences between pairs of trials of interest for each group separately. Trials compared were the first and second, second and fifth, first and fifth, and fifth and last forward perturbations. For variables for which there was a significant Trial effect and no Group x Trial interaction, post hoc paired t-tests between the four pairs of trials of interest were performed on the pooled data for both

groups. A significance level of  $p < 0.0125$  was used in all post hoc testing based on a modified Bonferroni correction for familywise error.

A stepwise forward logistic regression analysis was also conducted on the data from the first trial to determine which, if any variables could best predict a fall versus a recovery. The pool of possible predictors comprised all variables that differed between the two groups on the first trial. The likelihood ratio test at  $p < 0.05$  was used for variable entry and a threshold probability of 0.5 was used for classification. Statistical analyses and tests of the statistical assumptions were performed using SPSS version 13.0 (SPSS, Chicago, IL).

One participant was excluded from analysis because the first forward perturbation was accidentally set to travel the shorter distance intended for lateral perturbations only. Two subjects were missing step data on their last, predictable trial. One of these subjects “rode” the platform and did not step. The other participant took a very delayed step, however the data collection was mistakenly stopped before she stepped. Center of mass data were also missing for two subjects at one of the events of interest in one trial each, due to obstructed markers.

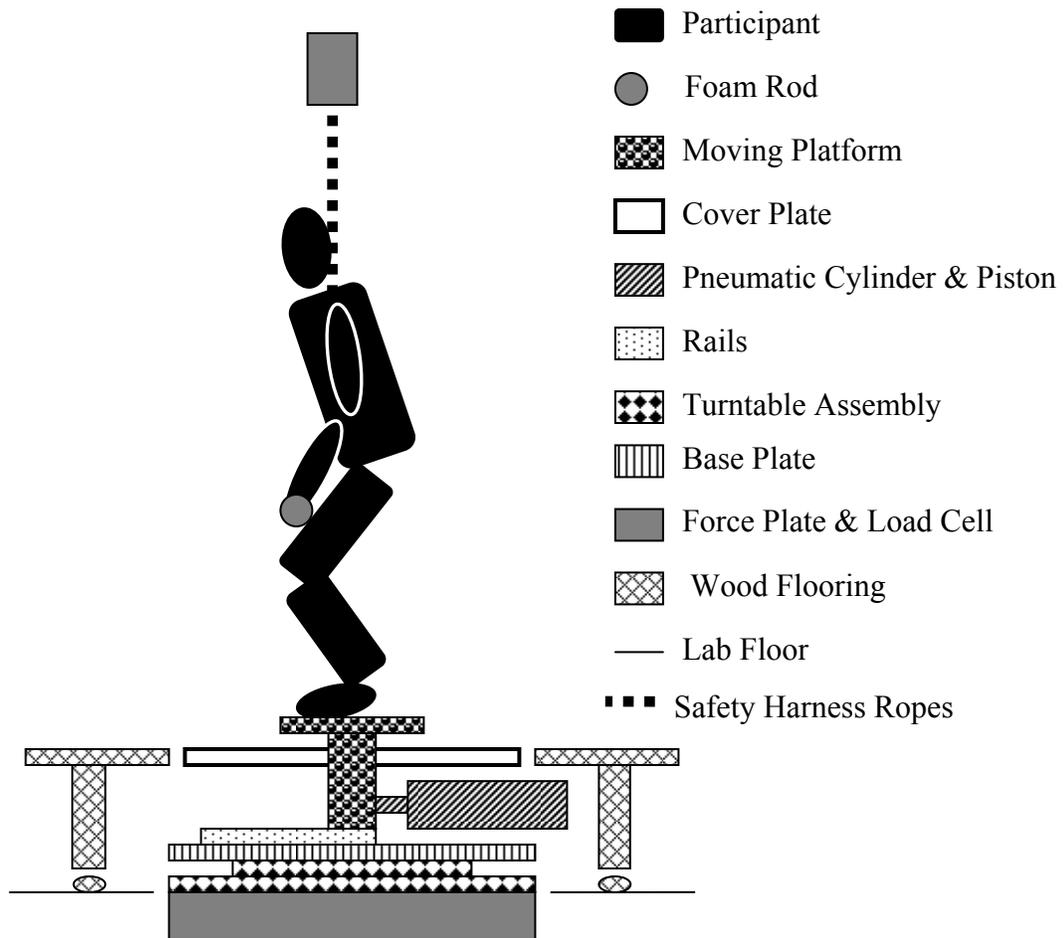


Figure 1: Perturbation platform and related apparatus. Participants performed a simulated lifting task, holding a foam rod, while standing on a circular moving platform. The platform was driven by a pneumatic cylinder and slid along a set of horizontal rails. The rails and pneumatic cylinder were masked by a circular cover plate so the participant could not see what direction the perturbation would occur in. The turntable assembly was bolted to a force plate and allowed the platform to be oriented in any one of eight directions. Wood flooring (2.4 m × 2.4 m) was constructed to be level with the cover plate.

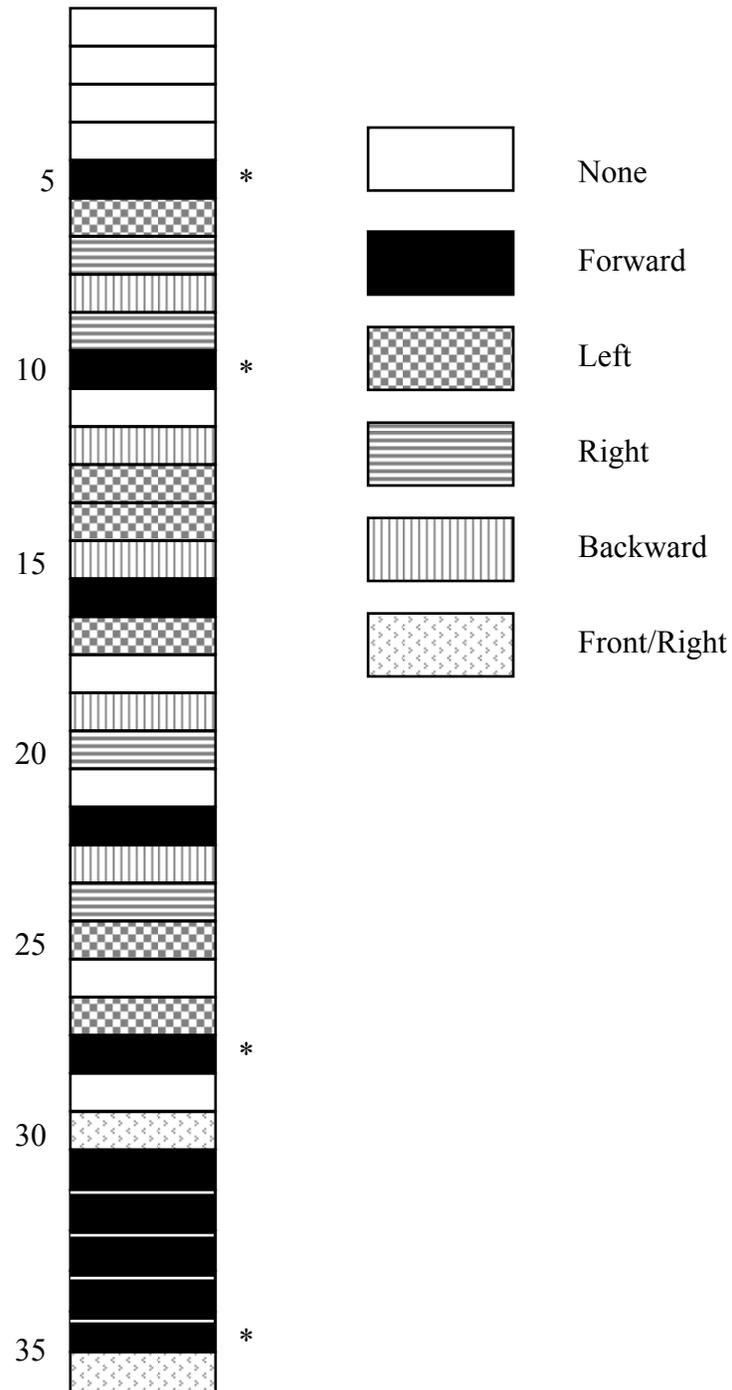


Figure 2: Trial sequence. Directions refer to the direction the platform moved relative to the direction the participant was facing. The motion of the platform induced a loss of balance in the opposite direction. \* Trials analyzed in this study.

## Results

Of the 30 participants tested, 21 recovered on their first, unexpected perturbation and 8 fell into the safety harness. Each participant took at least one step as part of their recovery strategy in the first trial.

### *Similarities and Differences Between Fallers and Those Who Recovered*

On the first unexpected perturbation, those who fell showed marked differences compared to those who recovered. At perturbation onset, the hips of those who fell were slightly higher than in those who recovered (Table 1). There were, however, no differences between the fallers and those who recovered in their center of mass position or velocity, or in their hip vertical velocity, at the onset of the perturbation (Table 1). At step liftoff, the fallers' center of mass was farther back, but moving backwards at a slower rate than those who recovered (Table 2). Notably, the hips of those who fell were dropping almost five times faster at step liftoff than in those who recovered (Table 2). Hip height at step liftoff and response time from the onset of the perturbation to step liftoff did not differ between the fallers and those who recovered in the first trial. At step touchdown, the fallers' hips were 6% of body height lower and dropping faster than those who recovered (Figure 3, Table 3). Finally, those who fell took a shorter step and landed their initial recovery step less far behind their center of mass (Tables 4 & 3). However, their center of mass velocity at step touchdown did not differ from those who recovered on their first trial (Table 3).

Among these group differences, only one variable was needed to predict 100% of the falls in this study. The forward, stepwise, logistic regression analysis found that hip height at step touchdown alone could accurately predict all of the eight falls and 21 recoveries from the first unexpected perturbation.

### *Effects of Trial*

All participants recovered successfully in all subsequent trials after the first unexpected perturbation. Each recovery, with one exception, included a stepping response of one or more steps. In the exception, one participant was able to “ride” the platform on his last predictable trial and successfully recover without stepping. Participant groups are referred to based on the outcome of their first trial only, regardless of the outcome of later trials. The Fall Group is all the participants who fell on their first trial and the Recovery Group is all the participants who successfully recovered on their first trial.

### *Rapid Adaptations Between the First and Second Backward Balance Loss*

From the first, unexpected forward perturbation to the second, unpredictable perturbation in the same direction, the Fall Group made adjustments that resulted in a successful recovery for each of them. At step liftoff in the second trial, the center of mass of the Fall Group was less posterior and moving backwards faster (Table 2). Their hips were also dropping much slower than for the first unexpected perturbation (Table 2). Those who fell in their first trial were also able to increase the height of their hips at step touchdown, as well as reverse the velocity of their hips at step touchdown from dropping to slightly rising in the second trial (Table 3). Each of

these adjustments made the Fall Group similar to the Recovery Group on the second analyzed trial.

The Fall Group also made adjustments to variables that did not differ significantly between groups on the first trial. Response time from the onset of the perturbation to step liftoff was quicker in the second trial (Table 2). In addition, hip height at step liftoff, as well as the maximum hip height achieved during the first step, were both higher for the fallers in their second exposure to the forward perturbation (Tables 2 & 4).

Adjustments on certain of these variables were made by all subjects, regardless of the outcome of their first trial, following the initial balance loss. As in the Fall Group, the Recovery Group's center of mass had not fallen as far back at step liftoff of the second trial and hip height was higher at step touchdown compared to the first (Tables 2 & 3). However, the Fall Group made larger adjustments for these two variables, such that they were not significantly different than the Recovery Group by the second trial (Figure 3). Also like the Fall Group, the response time from the onset of the perturbation to step liftoff decreased in the Recovery Group on the second trial (Table 2). The response time did not differ between the groups in either trial.

Some variables did not change between the first and second forward perturbations. Center of mass anteriorly-directed position and velocity at the onset of the perturbation and at step touchdown and hip height and vertical velocity at perturbation onset did not differ between the first two forward perturbations for either

group (Tables 1 & 3). Step time and step length were also similar between the two trials for both groups (Table 4).

*Later Adaptations Between the Second and Fifth Backward Balance Loss*

The adaptations described above occurred only between the first and second exposures to the backward loss of balance and did not change further between the second and fifth backward losses of balance. Other variables differed between the second and fifth unpredictable forward platform translations, indicating that some adaptations took more than one exposure to learn and developed over time. Both groups increased the duration of their initial step and were able to place their step foot farther behind their center of mass at touchdown of the initial step in the fifth trial as compared to the second (Tables 4 & 3). The Recovery Group was also moving the center of mass slightly forward at the onset of the perturbation in the fifth trial, as compared to moving it slightly backward in their second backward balance loss (Table 1).

*Overall Learning Between the First and Fifth Backward Balance Loss*

Many differences existed between the first and fifth forward platform translations, indicating the learning that resulted from five unpredictable exposures to that perturbation. Both groups decreased their response time and had their center of mass less far behind their heels at step liftoff in the fifth trial compared to the first (Table 2). At step touchdown of the fifth forward perturbation, both groups' hips were higher, with the step foot coming down farther behind their center of mass compared to the first trial (Table 3, Figure 5). With the exception of response time,

the Fall Group made substantially larger adjustments to these variables than did the Recovery Group, such that the initial differences between groups disappeared.

The Fall Group exhibited several additional differences between the first backward balance loss, from which they fell, and the fifth backward balance loss, from which they recovered. At step liftoff of the fifth trial, their hips were higher and dropping more slowly (Table 2). Also, the fallers reached a higher maximum hip height during the initial step in the fifth trial compared to the first (Table 4).

The Recovery Group also made additional adjustments between the first and fifth unpredictable backward balance losses. The center of mass of those who recovered on their first trial was farther forward and moving slightly forward at the onset of the fifth forward perturbation, as opposed to moving slightly backwards at the onset of the first forward perturbation (Table 1).

#### *Effects of Predictability on Backward Balance Losses*

The predictability of the perturbation direction did have some effect on certain variables of interest, even after repeated exposure to perturbations in unpredictable directions. In the last of five forward perturbations in a row, when the perturbation direction was predictable, the center of mass of the Fall Group was farther forward and moving forward faster at perturbation onset as compared to the fifth, unpredictable forward perturbation (Table 1). The center of mass of the Recovery Group was also moving forward faster at perturbation onset in the predictable situation (Table 1). The only other difference related to predictability was that the

fallers' hips were slightly higher at step touchdown in the predictable situation (Figure 3, Table 3).

*Group Differences Remaining After Repeated Perturbation Exposure*

Across the later trials, most of the differences between the Fall and Recovery Groups that existed in the first trial no longer remained. There were, however, a few exceptions where significant differences between the Fall and Recovery Groups from the first perturbation remained present across all trials. At the onset of perturbation, the fallers' hips were consistently slightly higher than those who recovered (Table 1). More notably, the anteroposterior step length was longer, and the anteriorly-directed distance from the stepping heel to the center of mass at step touchdown was greater, in the Recovery Group than in the Fall Group for all trials analyzed (Tables 3 & 4).

The differing influences of perturbation predictability on the Fall and Recovery Groups also resulted in significant differences between the groups on the last of five forward perturbations in a row. The fallers' centers of mass were slightly more forward than those of the Recovery Group at the onset of the perturbation in the last predictable trial (Table 1). At the time of step touchdown on the last predictable trial, the hips of the fallers were slightly higher than those who initially recovered (Table 3).

*Lateral Adaptations to Backward Balance Losses*

Despite the fact that the perturbations analyzed were directed forward, changes in the lateral direction occurred throughout the trials and seemed to be primarily related to the direction of the preceding perturbation. The second forward

perturbation was immediately preceded by a perturbation to the right. Consequently, the center of mass at the onset of the second forward perturbation was farther to the right and moving faster to the right at perturbation onset, step liftoff, and step touchdown as compared to the first perturbation (Tables 1-3). On the other hand, the fifth forward perturbation was immediately preceded by a perturbation to the left, and the lateral changes between trials two and five were opposite to those from trial one to two. The participants' centers of mass were to the left at the onset of the fifth forward perturbation and moving left at perturbation onset and step liftoff (Tables 1 & 2). The lateral position and velocity of the center of mass at perturbation onset were also more to the left in the fifth unpredictable perturbation as compared to the first (Table 1). The change from trials two to five reversed again at the onset of the last, predictable forward perturbation; the center of mass was shifted more to the right and moving slightly rightward compared to the fifth forward perturbation (Table 1). These changes in the mediolateral direction were independent of group.

Finally, step length in the lateral direction increased across trials. Both groups took a more laterally-directed step in the fifth forward perturbation as compared to the first and this change persisted upon the last, predictable forward perturbation (Figure 4 & Table 4).

Table 1: Mean  $\pm$  SD variables representing the proactive adjustments at the moment of perturbation onset for the first, second, and fifth unpredictable, and last predictable, forward perturbations.

Variable at Onset		1st Trial	Forward Perturbation Trial			
		Outcome	1st	2nd	5th	Predictable
COMx	(fl)	Recover	0.425 $\pm$ 0.058	0.436 $\pm$ 0.059	0.469 $\pm$ 0.072*	0.503 $\pm$ 0.080
		Fall	0.391 $\pm$ 0.085	0.429 $\pm$ 0.051	0.477 $\pm$ 0.073	0.599 $\pm$ 0.063 <sup>†¶</sup>
COMy	(mm)	Recover	-1.6 $\pm$ 8.7	-12.6 $\pm$ 12.2 <sup>§</sup>	2.5 $\pm$ 7.9* <sup>¶</sup>	-2.5 $\pm$ 7.2 <sup>¶</sup>
		Fall	-2.0 $\pm$ 8.7	-16.5 $\pm$ 13.2 <sup>§</sup>	3.8 $\pm$ 12.2* <sup>¶</sup>	-3.3 $\pm$ 4.4 <sup>¶</sup>
COMxVel	(F)	Recover	-0.007 $\pm$ 0.007	-0.006 $\pm$ 0.011	0.001 $\pm$ 0.008 <sup>§¶</sup>	0.011 $\pm$ 0.014 <sup>¶</sup>
		Fall	-0.007 $\pm$ 0.013	-0.006 $\pm$ 0.005	0.001 $\pm$ 0.009	0.025 $\pm$ 0.016 <sup>¶</sup>
COMyVel	(mm/s)	Recover	2.5 $\pm$ 14.5	-21.8 $\pm$ 21.3 <sup>§</sup>	18.6 $\pm$ 17.1 <sup>§¶</sup>	1.1 $\pm$ 23.8 <sup>¶</sup>
		Fall	-11.2 $\pm$ 18.5	-16.2 $\pm$ 24.7 <sup>§</sup>	25.8 $\pm$ 32.2 <sup>§¶</sup>	-6.8 $\pm$ 13.5 <sup>¶</sup>
HipHt	(%bh)	Recover	51.8 $\pm$ 2.3	51.6 $\pm$ 1.9	51.8 $\pm$ 1.9	51.7 $\pm$ 2.2
		Fall	53.1 $\pm$ 3.0 <sup>†</sup>	53.5 $\pm$ 2.4 <sup>†</sup>	53.7 $\pm$ 1.8 <sup>†</sup>	53.5 $\pm$ 2.2 <sup>†</sup>
HipzVel	(%bh/s)	Recover	15.1 $\pm$ 7.6	19.2 $\pm$ 7.3	15.8 $\pm$ 5.8	15.9 $\pm$ 7.2
		Fall	14.4 $\pm$ 11.5	14.9 $\pm$ 10.7	16.5 $\pm$ 7.8	13.5 $\pm$ 9.7

\*  $p < .05$  vs. 1st Trial

<sup>†</sup>  $p < .05$  vs. Recover

<sup>§</sup>  $p < .005$  vs. 1st Trial

<sup>¶</sup>  $p < .005$  vs. Previous Trial

Data are reported by variable and outcome of the first perturbation; all participants recovered in subsequent perturbations.

Predictable trial was only compared to the fifth forward perturbation.

COM = body center of mass; x = anterior position with respect to posterior heel; y = mediolateral position to the left of the midpoint between ankle joint centers; Vel = velocity; HipHt = height of average of two hip joint centers above the platform, z = vertical position above the platform; fl = foot lengths; bh = body height; F = Froude number (normalized to  $\sqrt{g \times \text{body height}}$ , where g is the acceleration due to gravity).

Table 2: Mean  $\pm$  SD variables representing the reactive adjustments at the moment of step liftoff for the first, second, and fifth unpredictable, and last predictable, forward perturbations.

Variable at LO		1st Trial	Forward Perturbation Trial			
		Outcome	1st	2nd	5th	Predictable
COMx	(fl)	Recover	-0.364 $\pm$ 0.115	-0.175 $\pm$ 0.153 <sup>§</sup>	-0.110 $\pm$ 0.224 <sup>§</sup>	-0.111 $\pm$ 0.280
		Fall	-0.575 $\pm$ 0.154 <sup>  </sup>	-0.259 $\pm$ 0.080 <sup>§</sup>	-0.066 $\pm$ 0.232 <sup>§</sup>	0.033 $\pm$ 0.224
COMxVel	(F)	Recover	-0.234 $\pm$ 0.098	-0.280 $\pm$ 0.043	-0.254 $\pm$ 0.043	-0.217 $\pm$ 0.103
		Fall	-0.122 $\pm$ 0.103 <sup>†</sup>	-0.295 $\pm$ 0.042 <sup>*</sup>	-0.245 $\pm$ 0.062	-0.244 $\pm$ 0.040
COMyVel	(mm/s)	Recover	6.7 $\pm$ 34.5	-21.1 $\pm$ 48.6 <sup>*</sup>	17.4 $\pm$ 50.4 <sup>¶</sup>	4.4 $\pm$ 64.8
		Fall	-5.5 $\pm$ 23.1	-26.2 $\pm$ 43.9 <sup>*</sup>	18.1 $\pm$ 34.3 <sup>¶</sup>	-15.9 $\pm$ 45.5
HipHt	(%bh)	Recover	53.3 $\pm$ 1.4	53.7 $\pm$ 1.4	53.8 $\pm$ 1.5	53.5 $\pm$ 1.6
		Fall	52.6 $\pm$ 1.6	54.8 $\pm$ 1.3 <sup>§</sup>	55.0 $\pm$ 1.4 <sup>*</sup>	55.2 $\pm$ 1.4
HipzVel	(%bh/s)	Recover	-7.7 $\pm$ 8.9	-3.1 $\pm$ 9.7	-2.9 $\pm$ 7.0	-0.9 $\pm$ 10.0
		Fall	-35.2 $\pm$ 15.0 <sup>  </sup>	-10.3 $\pm$ 8.6 <sup>§</sup>	-5.2 $\pm$ 6.6 <sup>§</sup>	-5.0 $\pm$ 7.0
RespTime	(s)	Recover	0.275 $\pm$ 0.031	0.234 $\pm$ 0.040 <sup>§</sup>	0.229 $\pm$ 0.052 <sup>§</sup>	0.267 $\pm$ 0.112
		Fall	0.307 $\pm$ 0.056	0.236 $\pm$ 0.014 <sup>§</sup>	0.213 $\pm$ 0.055 <sup>§</sup>	0.236 $\pm$ 0.049

\* p < .05 vs. 1st Trial

† p < .05 vs. Recover

§ p < .005 vs. 1st Trial

|| p < .005 vs. Recover

¶ p < .005 vs. Previous Trial

Data are reported by variable and outcome of the first perturbation; all participants recovered in subsequent perturbations.

Predictable trial was only compared to the fifth forward perturbation.

x = anterior position with respect to non-stepping heel; RespTime = response time from onset of perturbation to step liftoff; all other variables are the same as in Table 1.

Table 3: Mean  $\pm$  SD variables representing the reactive adjustments at the moment of step touchdown for the first, second, and fifth unpredictable, and last predictable, forward perturbations.

Variable at TD		1st Trial	Forward Perturbation Trial			
		Outcome	1st	2nd	5th	Predictable
COMx	(fl)	Recover	0.639 $\pm$ 0.419	0.828 $\pm$ 0.432	0.940 $\pm$ 0.373 <sup>§¶</sup>	1.028 $\pm$ 0.372
		Fall	0.106 $\pm$ 0.362 <sup>¶</sup>	0.331 $\pm$ 0.321 <sup>¶</sup>	0.708 $\pm$ 0.398 <sup>§¶¶</sup>	0.530 $\pm$ 0.567 <sup>¶</sup>
COMy	(mm)	Recover	145 $\pm$ 39	161 $\pm$ 54	173 $\pm$ 71	190 $\pm$ 78
		Fall	129 $\pm$ 65	140 $\pm$ 25	168 $\pm$ 54	180 $\pm$ 129
COMxVel	(F)	Recover	-0.120 $\pm$ 0.051	-0.090 $\pm$ 0.053	-0.099 $\pm$ 0.041	-0.115 $\pm$ 0.062
		Fall	-0.132 $\pm$ 0.081	-0.091 $\pm$ 0.027	-0.095 $\pm$ 0.044	-0.056 $\pm$ 0.075
COMyVel	(mm/s)	Recover	14 $\pm$ 141	-80 $\pm$ 213*	-19 $\pm$ 224	-47 $\pm$ 281
		Fall	41 $\pm$ 91	-25 $\pm$ 108*	11 $\pm$ 223	-158 $\pm$ 369
HipHt	(%bh)	Recover	53.3 $\pm$ 1.7	54.1 $\pm$ 1.9 <sup>§</sup>	53.8 $\pm$ 1.6 <sup>§</sup>	53.3 $\pm$ 1.9
		Fall	47.2 $\pm$ 1.9 <sup>¶</sup>	54.0 $\pm$ 1.6 <sup>§</sup>	54.6 $\pm$ 1.4 <sup>§</sup>	55.7 $\pm$ 1.3 <sup>¶‡</sup>
HipzVel	(%bh/s)	Recover	-12.2 $\pm$ 14.3	-11.5 $\pm$ 9.8	-9.7 $\pm$ 10.3	-11.3 $\pm$ 6.8
		Fall	-29.4 $\pm$ 17.1 <sup>†</sup>	0.1 $\pm$ 15.3*	-10.1 $\pm$ 14.1	-7.8 $\pm$ 13.0

\* p < .05 vs. 1st Trial

† p < .05 vs. Recover

‡ p < .05 vs. Previous Trial

§ p < .005 vs. 1st Trial

¶ p < .005 vs. Recover

¶¶ p < .005 vs. Previous Trial

Data are reported by variable and outcome of the first perturbation; all participants recovered in subsequent perturbations.

Predictable trial was only compared to the fifth forward perturbation.

COMx = center of mass anterior position with respect to stepping foot heel; COMy = center of mass medial position with respect to the stepping foot 5<sup>th</sup> metatarsal;

COMyVel is positive to the left; all other variables are the same as in previous tables.

Table 4: Mean  $\pm$  SD variables representing the reactive adjustments during the initial stepping response for the first, second, and fifth unpredictable, and last predictable, forward perturbations.

Variable During Step		1st Trial	Forward Perturbation Trial			
		Outcome	1st	2nd	5th	Predictable
MxHipHt	(%bh)	Recover	53.5 $\pm$ 1.2	54.0 $\pm$ 1.4	54.0 $\pm$ 1.6	53.7 $\pm$ 1.6
		Fall	52.6 $\pm$ 1.6	54.8 $\pm$ 1.3 <sup>§</sup>	55.1 $\pm$ 1.3 <sup>§</sup>	55.5 $\pm$ 1.4
StepTime	(s)	Recover	0.221 $\pm$ 0.091	0.221 $\pm$ 0.073	0.250 $\pm$ 0.077 <sup>¶</sup>	0.288 $\pm$ 0.094
		Fall	0.175 $\pm$ 0.056	0.173 $\pm$ 0.050	0.263 $\pm$ 0.132 <sup>¶</sup>	0.289 $\pm$ 0.236
StepLnx	(%bh)	Recover	25.2 $\pm$ 9.9	26.4 $\pm$ 8.7	27.6 $\pm$ 7.9	29.7 $\pm$ 9.5
		Fall	18.8 $\pm$ 10.1 <sup>  </sup>	18.7 $\pm$ 4.7 <sup>  </sup>	23.7 $\pm$ 7.1 <sup>  </sup>	13.1 $\pm$ 10.5 <sup>  </sup>
StepLny	(%bh)	Recover	1.78 $\pm$ 2.51	3.04 $\pm$ 5.86	4.31 $\pm$ 4.82 <sup>*</sup>	6.29 $\pm$ 6.38
		Fall	0.81 $\pm$ 4.35	0.49 $\pm$ 3.06	4.05 $\pm$ 5.44 <sup>*</sup>	7.36 $\pm$ 12.2

\* p < .05 vs. 1st Trial

‡ p < .05 vs. Previous Trial

§ p < .005 vs. 1st Trial

|| p < .005 vs. Recover

¶ p < .005 vs. Previous Trial

Data are reported by variable and outcome of the first perturbation; all participants recovered in subsequent perturbations.

Predictable trial was only compared to the fifth forward perturbation.

MxHipHt = the maximum height of the average of the two hip joint centers between step liftoff and step touchdown; StepTime = time elapsed between step liftoff and step touchdown; StepLnx = anteroposterior step length from the non-stepping to the stepping 5<sup>th</sup> metatarsal at step touchdown; StepLny = mediolateral step length of the stepping 5<sup>th</sup> metatarsal from step liftoff to step touchdown; all other variables are the same as in previous tables.

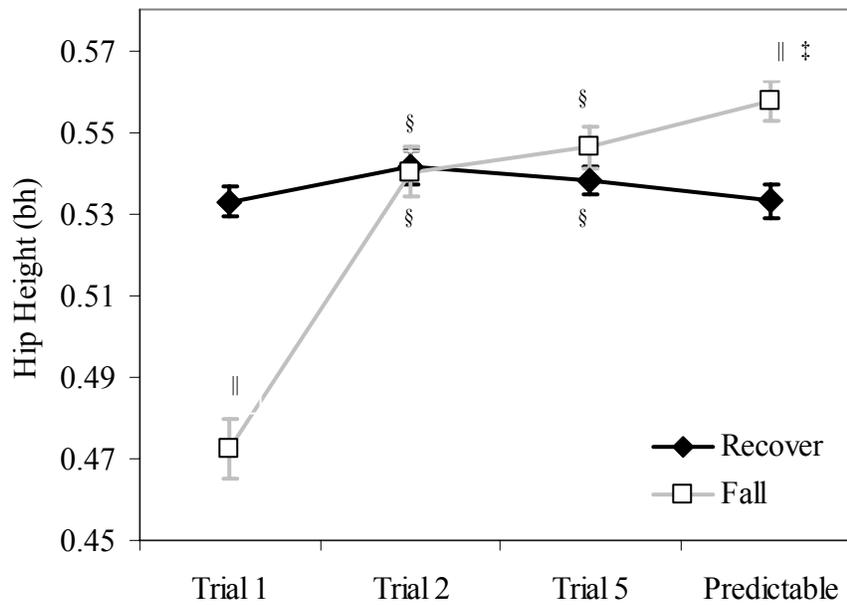


Figure 3: Mean  $\pm$  SE hip height at step touchdown for the Fall Group and Recovery Group in the first, second, and fifth unpredictable, and last predictable, forward perturbations. Hip height is the average vertical height of the two hip joint centers above the platform and is normalized to body height (bh). ‡  $p < .05$  vs. previous trial; §  $p < .005$  vs. Trial 1; ||  $p < .005$  vs. Recover. Note that the predictable trial was only compared to Trial 5.

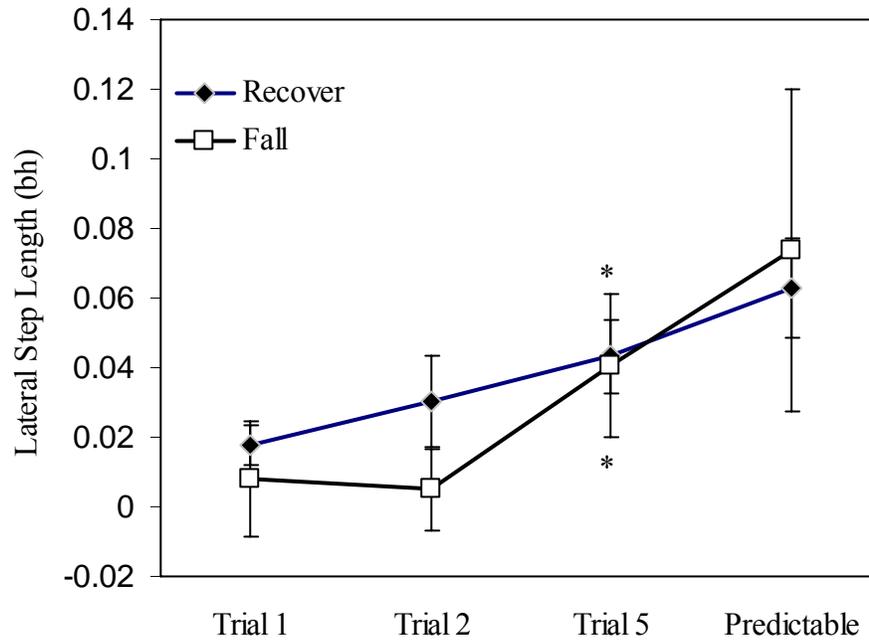


Figure 4: Mean  $\pm$  SE lateral step length, as measured by the displacement of a marker on the fifth metatarsal head, for the Fall Group and Recovery Group in the first, second, and fifth unpredictable, and last predictable, forward perturbations. \*  $p < .05$  vs. Trial 1. Note that the predictable trial was only compared to Trial 5. All other variables are the same as in Figure 3.

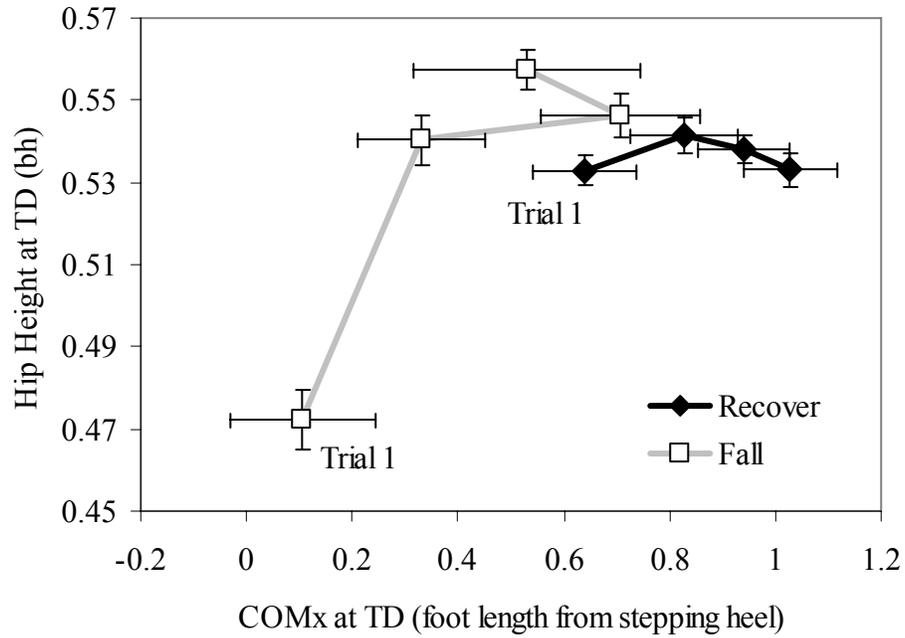


Figure 5: Mean  $\pm$  SE anteriorly-directed center of mass position (COMx) in relation to the stepping foot heel versus hip height at step touchdown (TD) for the Fall Group and Recovery Group in the first, second, and fifth unpredictable, and last predictable, forward perturbations. Center of mass position and hip height were normalized to foot length and body height (bh), respectively.

## Discussion

Since nearly half of the older adult population experiences falls each year, often incurring injuries, at a cost of over seven billion dollars each year, it is imperative to research ways to decrease the overall number and adverse effects of falls (Cummings et al., 1990; Sernbo & Johnell, 1993; Rubenstein & Josephson, 2002). Previous research has shown that differences exist between the reactions of someone who falls and someone who recovers when exposed to a similar perturbation (Owings et al., 2001; Pavol et al., 2001, 2004a). Research has also shown that those who do fall can learn not to fall with very few exposures to the perturbation (Owings et al., 2001; Pavol et al., 2004b). Prior to this study, data did not exist regarding the responses to repeated perturbations large enough to elicit a balance loss and fall in varying, unpredictable directions. The current study exposed participants to large perturbations in varying, unpredictable directions to see if learning patterns similar to those previously observed would still occur. Some participants fell and some recovered in response to the first, unexpected perturbation, however both the fallers and those who recovered made adjustments across trials. This indicates that learning did occur, despite the unpredictable perturbation direction. Those who fell in the first trial made enough of an adjustment that they did not fall in any subsequent trials.

### *Group Differences on the First Unexpected Perturbation*

In the current study, 28% of the participants fell upon their first, unexpected exposure to the forced slipping perturbation. Several factors, especially at step liftoff

and touchdown, appeared to play a large role in whether or not a participant fell on his or her first exposure to the platform perturbation. At step liftoff, those who fell had their center of mass farther behind their base of support, meaning that they were more off balance when they began their recovery step than those who recovered. Also at this time, the fallers were experiencing much faster hip descent, with less backward velocity of the center of mass than those who recovered. Therefore, the fallers were moving more downward while those who recovered were moving more backward at the time their step foot came off the ground. By step touchdown, the fallers' backward motion had become similar to those who recovered, but their hips were still dropping much faster. As a result, hip height at step touchdown on the first perturbation was 6.1% of body height lower for those who fell.

Hip height at step touchdown was the first and only variable selected for inclusion in the stepwise, logistic regression model, meaning it was the variable most related to the outcome of the first perturbation. This variable alone was able to predict 100% of the falls. This is an important factor to consider when developing training programs for fall prevention. They should focus on skills that will help maintain hip height and reduce its downward velocity throughout the recovery step. Pavol et al. (2001, 2004a) also found hip height at step touchdown to be a key factor in both tripping and slipping studies. A lower and faster dropping hip height at step touchdown puts the body in a disadvantaged position for recovery. The stepping leg may touch down in a highly flexed position from which it cannot support the body's weight. In addition, lower hip heights between step liftoff and touchdown can make

it more difficult to take an effective recovery step. This was evidenced by the shorter posteriorly-directed step, which landed less far behind the center of mass for the Fall Group compared to the Recovery Group on the first perturbation. A more effective step could have played a key role in reestablishing stability after the backward loss of balance.

### *Learning Does Occur*

As participants gained experience with the perturbations, they were able to make many adaptations that showed that even though the perturbation direction was unpredictable, learning and improvement in the responses to balance perturbations, specifically slips, does occur. After five unpredictable backward balance losses, both the Fall Group and the Recovery Group had made many changes from their first, unexpected perturbation. The Fall Group made the largest and greatest number of adjustments. Some adaptations were rapid, occurring after only one exposure to the perturbation, while others took longer to develop, occurring between the second and fifth forward perturbations. None of the rapid adaptations changed further between the second and fifth forward perturbations, so the net changes between the first and fifth forward perturbations were a result of either the rapid or the slower adaptations.

In accordance with our hypothesis, no one fell from any perturbations after the first. Fallers adjusted their responses in many of the variables analyzed to make their reactions more like those who recovered on their first trial. By the second forward perturbation, only three of the eight initial differences between the Fall and Recovery Groups remained. This is consistent with the findings of previous studies where

fallers adapted to become more like those who recovered initially, often within one repeat exposure (Owings et al., 2001; Pavol et al., 2004b). All successful recoveries, with one exception, used a stepping strategy, as predicted. In the one exception, the participant managed to stay on the moving platform without either falling or taking a recovery step.

*Rapid Adjustments Between the First and Second Backward Balance Losses*

Participants, especially those who fell in their first trial, made many adjustments at step liftoff between the first and second forward perturbations. By the second forward perturbation, the Fall Group adjusted all of the variables at step liftoff that differed from the Recovery Group in the first forward perturbation. The Recovery Group only made adjustments on one of these three variables between the first and second forward perturbations. In agreement with our hypotheses, the fallers' center of mass was more forward and the hips were 2.2% of body height higher at step liftoff of the second unpredictable backward balance loss compared to the first. Also, by the second trial, the Fall Group's center of mass was moving backward faster and their hips were descending slower at step liftoff. It was hypothesized that the backward velocity of the center of mass would decrease in later trials, but this was not the case. By moving more backwards and less down in the second trial, the Fall Group was able to maintain a higher hip height, which is evidenced by an increase in maximum hip height during the first step, as was hypothesized. Maintaining a higher hip height increased the participants' ability to get their step foot behind their center of mass in a posture where extending that leg could be more effective at reversing the

downward velocity of the hips. The increased backward velocity may be evidence of a more active, controlled backward recovery step as opposed to a passive one. The more active step involved propelling the body into the step prior to liftoff, while the passive step may have been primarily a startle reflex.

Like the Fall Group, the Recovery Group showed a more forward center of mass at step liftoff in the second forward perturbation as compared to the first. This means the participants' center of mass was less far behind their base of support at the time they began their recovery step. Essentially, both groups were less off balance at step liftoff in the second forward perturbation. Since the center of mass position did not differ at the onset of the perturbation, these adaptations took place between the onset of the perturbation and step liftoff.

As further evidence of adaptations of these reactions, both groups decreased their response time between the first and second unpredictable perturbations by approximately 0.05 seconds. This finding was in agreement with our hypothesis that response time would decrease with exposure. A decreased response time means that participants are starting their recovery step sooner after the onset of the perturbation. This means that there is less time for their center of mass to move outside their base of support and less time for their hips to begin dropping before they begin the reactive recovery response. The response times found in the current study are much faster than in previous studies using smaller perturbations to elicit a stepping response (Maki et al., 1996; McIlroy & Maki, 1996). The larger perturbation and the potential threat of a fall in the current study likely elicited a more rapid response.

Adjustments were also evident at step touchdown in the second backward balance loss. The most notable of these changes was the increase in hip height in both groups between the first and second unpredictable perturbations, an increase that was maintained throughout the remaining trials. This is consistent with the findings of Pavol et al. (2004b). They attributed the ability of the support leg to avoid excessive knee flexion and backward rotation as the primary mechanisms for maintaining hip height. The Fall Group increased their hip height by 6.8% of body height after the first trial. The Recovery Group increased less than one percent over that same period. This is in agreement with the hypotheses that hip height would increase over trials and that fallers would make larger adjustments than those who recovered across trials. The Fall Group was also able to decrease the velocity of their hip descent at step touchdown between the first and second trials. As this was considered one of the factors contributing to their fall, it was imperative that they make the adjustment, and they did as hypothesized. It is likely that the increase in hip height and decreased downward velocity of the hips at step touchdown were the result of the observed adjustments at step liftoff, as well as adjustments in the support provided by the stance limb during the step.

#### *Slower Developing Adaptations to Repeated Unpredictable Perturbations*

Some adaptations appeared to take longer to develop and were apparent between the second and fifth backward balance losses. None of the variables at step liftoff changed further after the second forward perturbation. In opposition to our hypothesis, both groups increased their step time by 0.06 seconds between the second

and fifth forward perturbations. This adjustment did not occur between the first and second exposure to the backward loss of balance, consistent with previous research, in which step time did not change between an initial slip and subsequent similar reslip (Pai et al., 2006). The later increase in step time found currently may be a result of other factors, such as increased hip height and decreased hip descent velocity, which allowed more time for a successful recovery step to occur. All step times measured were much faster than those reported in previous research which used smaller, unpredictable balance disturbances to elicit a stepping response (Maki et al., 1996; McIlroy & Maki, 1996). Larger perturbations likely put the participant farther off balance at the time of step liftoff, requiring a quicker step to regain balance to avoid a fall.

Other variables were modified at step touchdown in the later trials. The distance from the step foot to the center of mass increased, as hypothesized, among both groups, although the Recovery Group maintained a larger distance than the Fall Group across all trials. This increase in step distance from the center of mass took place between the second and fifth unpredictable forward perturbations, resulting in a net overall change between the first and fifth perturbations. Since this variable did not change between the first and second trials, whereas the recovery outcome of the Fall Group did, it may not be a major contributor to the falls, despite a group difference. This was contrary to what was originally predicted. The first step appeared to be far enough behind the center of mass on the first trial, however a longer step gave greater assurance of safety as both groups proceeded to increase that

distance. In addition, placing the step foot even farther behind the center of mass gave a mechanical advantage in maintaining hip height, which is strongly correlated to avoiding a fall (Hsiao & Robinovitch, 1999).

#### *Group Differences Remaining Across All Trials*

Although most of the variables that differed between the Fall and Recovery Groups on the first, unexpected perturbation did not differ in later perturbations, there were three variables that continued to differ across all trials. Since these variables did not change significantly between the first and second forward perturbations, and none of the participants fell in any trial after the initial, unexpected trial, a group difference in these variables does not necessarily contribute to a fall or a recovery. Across all trials, fallers had a slightly higher hip height at the onset of the perturbation than those who recovered. Despite a group difference on all trials, neither group changed significantly across trials. It is unclear why the two groups differed, however it did not appear to have an effect on whether or not they fell in the first trial.

On all trials analyzed, the Recovery Group took longer steps and placed their step foot farther behind their center of mass than the Fall Group. This and the fact that these variables did not change significantly by the second trial (in which no one fell), indicates that the Fall Group made other adjustments, such as a more forward and faster moving center of mass at step liftoff and higher hips at step liftoff and touchdown, which negated the need for a longer first step in order to achieve a successful recovery. This is in agreement with previous research, which found that step length differed between fallers and those who recovered on the first slip trial, and

did not change between the first trial and a later trial, in which most of the fallers made a successful recovery (Pavol et al., 2004b). It should also be noted that most participants used multiple steps in their recovery strategy, however only the first recovery step was analyzed. Therefore, the placement of the first step may not be as important when additional steps are used in the recovery.

#### *Variables that Did Not Change Over Time*

Our hypothesis that proactive responses, such as center of mass position and velocity, and hip height and velocity at the onset of the perturbation would not change throughout the experiment held true for the most part. The Recovery Group did make minor adjustments between the first and fifth unpredictable trials by increasing the forward position and velocity of their center of mass by 0.044 foot lengths and  $0.008\sqrt{g \times \text{body height}}$ , respectively. The Fall Group, however, made no proactive adjustments across the unpredictable trials.

In another slipping study, a slip was induced at the moment participants left their seat in a sit-to-stand task (Pavol et al., 2004b). Changes in center of mass anteroposterior position and forward velocity at seat-off (perturbation onset) were cited as main adaptations as fallers learned not to fall. In our study, however, the Fall Group did not adjust the anteroposterior position or velocity of their center of mass at the onset of the perturbation until the last predictable trial. When standing from a sitting position, the center of mass is behind the base of support at seat-off, so the center of mass must be moving forward, even if no perturbation takes place. If perturbed by a slip that causes a backward loss of balance, it is even more important

to be moving forward at seat-off. However, in the current study, the perturbations came from unpredictable directions. In this case, it would be disadvantageous to be moving the center of mass in any one direction at the time the perturbation was triggered, in case the perturbation moved opposite the anticipated direction. Therefore, it makes sense that adaptations to center of mass motion at perturbation onset were not seen in the unpredictable trials of the current study.

Step length was hypothesized to increase as participants gained experience with the perturbation, however this did not occur in the anteroposterior direction. Step length in this direction did not change significantly for either group across the trials. As stated before, the changes in other variables likely negated the need for a longer step in later trials, even though step length differed between the fallers and those who recovered on the first, unexpected perturbation. The anteroposterior step lengths in the Fall Group were similar to those reported by previous research on unpredictable step-inducing balance disturbances, however the Recovery Group had longer steps than previously reported (McIlroy & Maki, 1996). The balance disturbances in the current research were larger and no falls were reported in the previous study (McIlroy & Maki, 1996). Previous research also found that step length did not change over repeated slips (McIlroy & Maki, 1995; Pavol et al., 2004b). This suggests that step length in reflexive reactions, such as balance recovery, may be pre-programmed, making this variable less important of a focus for fall prevention programs.

It was also hypothesized that the posterior-directed velocity of the center of mass would decrease at step touchdown, however this was not the case. There were no significant changes across any of the trials for center of mass velocity at step touchdown. The current study found the velocity of the center of mass to be much smaller compared to a previous study on smaller unpredictable balance perturbations (McIlroy & Maki, 1996). Rather than decrease posterior velocity of the center of mass, participants decreased the downward velocity of their hips. By maintaining a higher hip height there was more time for a successful step (or steps) to take place, reducing the need to decrease backward velocity. Participants were not confined to a single step in their recovery response, so there was no urgent need to decrease backward velocity at the touchdown of the first step because they could use additional steps to decrease that velocity later if needed.

#### *Lateral Adjustments*

Despite the fact that the perturbations analyzed in this study were in the forward direction, participants also made adjustments in the mediolateral direction across the trials. There were no differences between the Fall and Recovery Groups in the variables related to mediolateral motion, however, as a whole, this motion varied across trials. Participants' mediolateral motion, especially at the onset of the perturbation, appeared to be dictated by the direction of the previous trial. The second forward perturbation was immediately preceded by a perturbation to the right. Participants appeared to compensate for this by shifting and/or moving their center of mass toward the right at perturbation onset, step liftoff, and step touchdown of the

second forward perturbation. Such changes would allow them to better resist and recover from a leftward loss of balance if another rightward perturbation occurred. In contrast, the final unpredictable perturbation, which was preceded by a perturbation to the left, showed a shift in center of mass position and velocity towards the left at perturbation onset and step liftoff. This behavior is in agreement with previous research that indicates that participants' proactive and reactive responses will depend on their recent, as well as current, experience (Scheidt et al., 2001; Pavol & Pai, 2002).

Previous research also indicates that, given many differing, unpredictable perturbations, participants will gradually converge their proactive movement pattern towards a moderate behavior that averages all the potential successful behaviors together (Scheidt et al., 2001; Pavol & Pai, 2002). While these previous studies focused on feedforward control, a similar averaging of behaviors is evidenced in the current study by the reactive increase in the laterally-directed component of the initial recovery step between the first and last unpredictable trials (Figure 4). As was originally predicted, participants stepped in a more diagonal direction as they gained experience with the various perturbation directions, allowing their recovery step to be more effective in multiple directions.

Participants in our study took steps with a smaller lateral component in early trials than has been reported in previous research on smaller backward unpredictable balance losses, however they were similar in later trials (McIlroy & Maki, 1996). In the previous study, participants were perturbed enough to make them step, but not

hard enough to make anyone fall (McIlroy & Maki, 1996). The larger perturbations in this study likely caused the participants to take steps more in line with the perturbation direction after the first unexpected perturbation (when the perturbation had only occurred in one direction). However after experiencing perturbations from multiple, unpredictable directions, the lateral component of the initial step became more effective at preventing falls from lateral balance losses, and therefore increased.

#### *Comparing Behaviors in Predictable and Unpredictable Situations*

In comparing the last unpredictable trial to the last predictable one, the effects of increased predictability were almost exclusively limited to proactive changes at perturbation onset. The Fall Group's center of mass was 0.122 foot lengths farther forward at the onset of the predictable, as compared to the unpredictable, perturbation. In addition, both groups were moving forward much faster at perturbation onset in the predictable situation. These findings went against our hypothesis that there would be no difference between the fifth unpredictable backward loss of balance and the last predictable one. However, since participants were more likely to anticipate the direction of the upcoming perturbation in the predictable situation, it makes sense that they would begin moving in a way to counter that perturbation prior to its onset. This was consistent with the research cited earlier by Pavol et al. (2004b) in which the anteriorly-directed center of mass position and velocity at seat-off were significantly greater in subsequent, predictable trials.

Despite the fact that sufficient hip height to maintain balance had been reached by the Fall Group in their second exposure, they continued to increase hip height at step touchdown between the unpredictable and predictable trials. This is the only variable after perturbation onset that continued to change after the last unpredictable trial. Since it is so important a factor in avoiding a fall, participants continued to optimize this variable, even after it had been effectively modified.

#### *Adaptations in Terms of Motor Control and Motor Learning*

Based on the observed response times and step times, the adaptations after perturbation onset measured in this study could potentially involve both reflexive and voluntary reactions. Reaction times from perturbation onset to the onset of muscle activation and the beginning of weight shift were not measured. However, previous research has shown that the initial functional response to a postural perturbation comprises medium- to long-latency reflex and triggered responses (Nashner, 1977; Berger et al., 1984). A spectrum of these responses is thought to exist, with their relative excitability modulated by the central nervous system's "postural set", which is constantly being adapted based on the situation and prior experience (Nashner, 1977; Dietz et al., 1986; Horak & Nashner, 1986; Maki et al., 1996). Hence, different reflexive reactions could occur in response to the same perturbation. The quicker response time and more forward center of mass at step liftoff with experience likely reflect an update of the reflexive response due to a modification of the postural set. The more laterally-directed step in later trials is more indicative of a conscious adaptation, and was likely a voluntary reaction. The results of this study indicate that

the central nervous system can effectively adapt stepping reactions to balance disturbances, even when the perturbation direction is unpredictable. Also, the finding that the reactions to the unpredictable and predictable perturbations were essentially the same suggests that either protocol could potentially be used in a fall prevention training program. However, the unpredictable perturbations more closely approximate the real-world situation, and thus may translate to that setting more effectively.

#### *Assumptions, Limitations and Delimitations*

In this study, it was assumed that the first perturbation experienced by the participants represented a realistic, unexpected slip. Subsequent perturbations were assumed to be expected but unpredictable in direction. Platform translation perturbations have been used in many studies to replicate a slip (Maki et al., 1996, 2000; McIlroy & Maki, 1995, 1996; Pavol et al., 2004a, 2004b; Tang & Woollacott, 1998). While most of these were conducted on standing participants (Maki et al., 1996, 2000; McIlroy & Maki, 1995, 1996), we had participants doing a lifting task with the perturbation timed such that it simulated a slip or loss of balance while beginning to lift a low-lying object. This is more realistic than a slip during standing. The lifting task also kept the participants preoccupied and less likely to anticipate or prepare for the initial perturbation. Finally, the squatted body position at perturbation onset made stepping and successful recovery more difficult. The perturbation was similar to the sit-to-stand slips previously studied (Pavol et al., 2004a, 2004b) but

without the option of falling back onto a stool, forcing participants to try to recover on their own.

Participants knew that an attempt to make them lose their balance would take place at some point, however they did not know when or in what direction. Previous studies have shown that knowing that a perturbation may occur in a known direction affects the actions prior to the perturbation (Marigold & Patla, 2002; Pavol et al., 2004b). This is less realistic because slips that occur in daily activities often occur in unknown directions, with little opportunity for proactive adjustments. It is possible that, since all perturbations occurred at a similar point during the lifting task, participants were more able to anticipate when the perturbation would occur in later trials. We assumed, however, that the unknown direction of these perturbations, as well as the prescribed motions and timing of the lifting task, would eliminate any proactive adjustments. For the most part, this appeared to be a correct assumption.

We also assumed that participants were actually trying to regain their balance. It is possible that participants in the Fall Group could have allowed themselves to fall, even though they could have recovered. Since participants knew that the safety harness was there to catch them, it may not have seemed as critical to give a full effort to regain balance as it would in a situation in which a fall could end in a more dangerous result, such as a slip on jagged rocks or near the edge of a cliff. However, the use of the safety harness could not be avoided.

Finally, the fact that the perturbations induced in the trials immediately preceding the analyzed trials differed (i.e. none, right, left and forward) may have

been a confounding factor in the results. Proactive and reactive responses have been found to be influenced by recent experience (Scheidt et al., 2001; Pavol et al., 2004b). However, except in the case of the predictable trial, none of the trials immediately preceding the analyzed trials included a forward or backward perturbation. This arguably minimized the effects of recent experience on the variables in the sagittal plane, which were those of primary interest.

The results of this study can be generalized to young, healthy, physically mature adults in a controlled lab setting; however, the perturbation was designed to simulate a realistic slip as one begins to lift an object. It may not be possible to generalize the results to slips that occur during other types of activities (walking, running, etc.) or to assume that the learning that occurred will be retained for future balance perturbations. Furthermore, it may not be possible to generalize the results to older adults, who are the true population of concern, since previous research has indicated that older adults respond more slowly when higher level, integrative responses, such as stepping, are required (Woollacott et al., 1986; Stelmach et al., 1989). Older adults have also been found to have decreased lateral stability and are only able to recover from smaller ranges of instability (McIlroy & Maki, 1996; Pavol et al., 2004b). The results of this study are nevertheless important in that, if young adults had been unable to learn, it is almost certain that older adults would not be able to learn either. Since this study has shown that young adults are able to learn to recover more efficiently to prevent a fall with repeated exposure to perturbations of

unpredictable direction, future studies can now proceed to determine whether the same is true of older adults.

In this study, we chose to look at data from perturbations in only one direction. Adaptations and learning may occur differently and at different rates in other directions. We chose to look at backwards balance losses (forward perturbations) because they are the most difficult to recover from (Hsiao & Robinovitch, 1998). Additional trial-to-trial changes as a function of perturbation direction could potentially be examined in future analysis of these data.

Participants could not be placed randomly into groups. Since we grouped participants based on the outcome of the first slipping perturbation, the groups are not equal in size. We tested more participants than needed, given the desired alpha, power, and effect size, in hopes of ensuring that enough participants would be categorized into each of the two groups. Based on a power analysis, at least seven individuals per group were required and we ended up with eight in the Fall Group and twenty one in the Recovery Group. As such, the study should have appropriate power to detect the effects of interest.

#### *What We Now Know*

With the information gathered in this study, it is now known that even when the direction of the upcoming perturbation is varied and unpredictable, young adults can learn to make adjustments over one or more trials to more effectively avoid a fall. Those who did fall were able to adjust their reactions in such a way as to avoid a fall by the very next exposure to that same perturbation, indicating that this learning is

both effective and rapid. Maintaining hip height and decreasing the downward velocity of the hips is imperative in avoiding a fall. From the findings of this and other fall-related research projects, a training program aimed at developing techniques for fall prevention may potentially be developed.

## Conclusion

Falls are a common occurrence among older adults, many times with adverse effects such as decreased self-confidence, fear of falling, broken bones, admission to a long-term care facility, or even death (Tinetti et al., 1988; Kiel et al., 1991; Keene et al., 1993; Berg et al., 1997; Luukinen et al., 2000; Rubenstein & Josephson, 2002). Previous research has found differences in the behaviors of those who fall and those who recover when exposed to balance perturbations (Pavol et al., 2001, 2004a). It has also been previously determined that those who fall can adjust their behaviors in the next predictable perturbation to avoid a fall by responding in a similar manner to those who recovered in the first place (Owings et al., 2001; Pavol et al., 2004b). The purpose of the current study was to show that these adaptations would occur even when the direction of the perturbation was unpredictable.

This study has reinforced that reactive responses differ between those who fall and those who recover when exposed to an unexpected slip-like perturbation. Key differences included the fact that fallers' hips were dropping faster and their center of mass was moving less backward at the liftoff of the recovery step. In addition, the recovery step itself was shorter and landed less far behind the center of mass among fallers. The variable that seemed to have the biggest effect on whether or not a participant would recover, however, was his or her hip height at the time the first recovery step touched down. Those who fell had much lower hips than those who were able to recover.

Participants who fell on their first exposure to the perturbation were able to make rapid adjustments which lead to successful recoveries on all subsequent trials. Among these early adjustments were a less backward center of mass position at step liftoff and a higher hip height and slower downward velocity at step liftoff and touchdown. Those who fell also increased the maximum hip height achieved during the initial recovery step. Those who recovered on their first, unexpected perturbation also made rapid adjustments after their first perturbation exposure. These adaptations included a more forward center of mass at step liftoff and higher hips at step touchdown. Both groups also decreased their response time.

Other adaptations developed more slowly. Both the Fall and Recovery Groups increased their step time and the distance that the stepping foot touched down behind the center of mass. Additionally, both groups increased the lateral component of their initial recovery step with repeated exposure to perturbations in differing unpredictable directions.

The adaptations of both groups give evidence that the central nervous system is capable of preparing a variety of reflexive responses when faced with unpredictable balance perturbations. These responses can be updated with experience and learning. Furthermore, other than the presence of anticipatory behaviors and a small additional increase in hip height at step touchdown when the perturbation direction was more predictable, there were no significant differences between the last unpredictable balance perturbation and the last of a series of five forward perturbations.

Future research should be directed at understanding the responses of older adults to unpredictable balance perturbations. A study similar to this one should be conducted to determine whether older adults show similar differences between fallers and those who recover, as well as similar learning patterns and rates. Since older adults are more at risk of experiencing falls and fall-related injuries, it is important to look at their reactive responses specifically to determine effective ways to prevent falls and fall-related injuries.

Additional features could be added to future studies to gain more knowledge of the specifics of these reactive responses that might be beneficial to fall prevention training. Since maintaining hip height was a key factor in avoiding a fall, it may be helpful to use electromyography (EMG) to determine the activation patterns of muscles and reflexive responses used in maintaining hip height throughout the initial recovery step. Researchers could then look at how these differ between fallers and those who successfully recover, and how they change with experience. This could help guide fall prevention programs with regards to what specific techniques to focus on.

A test/re-test experiment would be useful in determining whether participants are able to retain the techniques they learned in their first session of exposures to this unpredictable slip perturbation series. It would be beneficial to look at responses to the same perturbations after a period of a few weeks or months and compare those to the responses in the first series. It may also be helpful to look at a different type of perturbation to see if the skills learned in the first session would transfer to a different

type of balance loss, such as a trip or waist pull (simulating running into or being struck by something in the upper body or torso). Long-term follow up on actual fall experience outside the experiment could help determine whether or not this experience helps fall prevention in the real world.

There is also a great deal of data from this study that has not been analyzed, but could be important in learning how to prevent future falls. Data regarding lateral losses of balance especially should be analyzed for both this study and a study conducted with older adult participants. Lateral balance losses have been associated with impact to the hip area, which is associated with increased risk for hip fracture (Hsiao & Robinovitch, 1998; Parkkari et al., 1999). Recovery strategies vary between perturbations in different directions. Therefore, it would be beneficial to look at the responses to sideways perturbation when the direction is unpredictable, to see how those reactions change across multiple trials.

The ultimate goal of fall-related research is to find ways to reduce the number of falls experienced by older adults, as well as reduce the incidence and severity of fall-related injuries. These reductions would not only increase the well-being of the older adult population, but also save billions of dollars in fall-related costs each year. This study has found that healthy, young adults are capable of improving their reactions to a balance loss to avoid falls after only one exposure, even when the cause of that balance loss comes from an unpredictable direction. Fall prevention programs should focus on maintaining hip height throughout the initial recovery step once a balance loss has occurred. This could potentially be achieved by building strength in

the leg and core muscles, and more importantly, teaching a proper technique. This technique should include a sufficiently long step to place the foot well ahead of the center of mass along its direction of travel, and maintaining hip height throughout the recovery step. Other improvements, such as decreasing response time and increasing the out-of-plane distance of the initial recovery step, may also be helpful in ensuring a successful recovery. Since these adaptations were made by participants of this study in relatively few exposures to balance perturbations, it may be beneficial for balance training programs to expose participants to repeated balance losses of some type. It may not be necessary for the repeated perturbations to occur in unpredictable directions, however that may help eliminate proactive adjustments and more realistically simulate real-life situations. By improving these techniques through training and experience in a controlled, safe setting, it is hopeful that those at risk for falling and suffering fall-related injuries can increase their likelihood of a successful recovery each time they lose their balance.

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**APPENDICES**

## APPENDIX A

### INFORMED CONSENT DOCUMENT

Project Title: Preventing Falls From Unpredictable Balance Disturbances  
Principal Investigator: Michael Pavol, Ph.D., Dept. of Nutrition & Exercise Sciences  
Research Staff: Lisa Welsh, Brian Higginson

#### **PURPOSE**

This is a research study. The purpose of this research study is to investigate the extent to which young adults can learn to better react to prevent a fall from unpredictable balance disturbances. Falls are a major and growing health concern among older adults. There is thus a need for more effective means of preventing falls. Recent studies have found that young and older adults often fall because their reactions to recover from a loss of balance are poor. This study will investigate whether, in young adults, these reactions might be improved through repeatedly exposing an individual to unpredictable balance disturbances. We expect that, over time, this research will lead to new and effective means of preventing falls through training older adults how to better react to unexpected balance losses. The purpose of this consent form is to give you the information you will need to help you decide whether to be in the study or not. Please read the form carefully. You may ask any questions about the research, what you will be asked to do, the possible risks and benefits, your rights as a volunteer, and anything else about the research or this form that is not clear. When all of your questions have been answered, you can decide if you want to be in this study or not. This process is called “informed consent”. You will be given a copy of this form for your records.

We are inviting you to participate in this research study because you are a healthy adult between 18 and 35 years of age. Approximately 30 subjects will participate in this study.

#### **PROCEDURES**

If you agree to participate, your involvement will last for either one or two sessions of approximately 1-1.5 hours each. The first experimental session will involve the following procedures.

- **Health History Questionnaire:** You will record your health history on a questionnaire that will take approximately 5-10 minutes to complete. It is possible that we may ask you not to participate in this study as a result of the information you provide on this questionnaire.
- **Warm-up and Stretching Exercises:** You will perform sets of exercises to loosen your muscles and prepare them for the tasks to be performed. You will begin with 5 minutes of cycling on a stationary bicycle. You will then perform a series of six stretching exercises for your leg muscles. Finally, you will go up and down a step 10 times forwards and backwards and 10 times to each side.

- **Attachment to a Fall-Arrest System:** To prevent any part of your body except your feet from hitting the ground should you fail to recover from a balance disturbance, you will be secured into a fall-arrest system. You will first be assisted in putting on a full-body safety harness. Three ropes will then be attached from the ceiling to the harness, one rope at each shoulder and one at the buttocks. The ropes will be made taut while you squat down and rest your hands on your knees. Finally, you will kneel down and let your body briefly hang from the ropes to verify that the fall-arrest system is functioning correctly. Adjustments will be made and the system checked again if necessary.
- **Lifting Task:** You will perform several repetitions of a lifting task while your movements and the forces acting on your body are recorded. For this task, you will wear athletic shoes, shorts, and a tank top or T-shirt, as well as the safety harness. In addition, about 35 small, reflective Styrofoam balls will be taped to your skin and clothes for our cameras to see. Loose clothing may be pinned or taped and long hair may be placed in a ponytail. The object to be lifted will be a light, flexible foam rod. You will start by standing with your feet side-by-side, your arms hanging downward, and your hands holding the ends of the rod. When prompted to, you will squat down and touch the rod to your knees, then stand back up while still holding the rod. We will demonstrate the desired technique and you will practice performing the task. After an initial trial of quiet standing, you will perform several trials of the lifting task (10 or less). During each trial, cameras will film the motion of the reflective markers taped to you and sensors will measure the forces between your feet and the ground.
- **Exposure to Unpredictable Balance Disturbances:** Once the above trials of the lifting task are completed, you will perform a set of 25-30 trials in which you will be exposed to unpredictable balance disturbances while you perform the same lifting task. You will stand on a platform that can be moved in different directions. These platform movements will be large and fast enough to cause you to lose your balance. In each trial, the platform may or may not move in any direction at some point during the lifting task; you will not know if, when, or how the platform will move. You will be instructed to try not to fall and to keep holding onto the foam rod being lifted. Should you fail to recover from a balance disturbance, you will be caught by the fall-arrest system before you hit the ground. As before, cameras will film the motion of the reflective markers taped to you and sensors will measure the forces between your feet and the ground.
- **Anthropometric Measures:** Finally, you will have your height, weight, and selected other body dimensions measured. These dimensions will include your foot length, ankle width, knee width, pelvis-to-waist height, and arm width at the shoulder. Body weight will be measured using a scale. Standing height will be measured using a type of wall-mounted ruler. All other body measurements will be made using a special set of calipers designed for this purpose.

You may be invited to return for an optional second experimental session, 90-120 days after the first session. The procedures during the second session, if you choose to return, will be the same as during the first session, except that you will be exposed to the unpredictable balance disturbances for only 10-20 trials.

### **RISKS**

The possible risks associated with participating in this research project are as follows. The most likely risk is that you may experience some muscle soreness in the days following testing. This soreness could be considerable if you are unaccustomed to the types of activities being performed. You could also potentially strain (pull) a muscle while attempting to regain your balance. Similarly, you could potentially sprain or tear a ligament in your ankle or knee. If you were to step into the path of the moving platform, you could bruise or break your foot. Finally, you could break a bone if you were to fall to the floor upon a loss of balance. A number of precautions have been taken to minimize the risk involved in participating in this study, however. First and foremost, you will be secured into a fall-arrest system throughout the experimental trials. This system will prevent any part of your body except your feet from contacting the floor, and will also reduce the risk of muscle or ligament injury by helping to support your weight if your body drops below the lowest point of the lifting task. In addition, the harness and ropes of the fall-arrest system are both designed to absorb shock, and the harness provides support over a large contact area, thereby reducing the size of the forces acting on your body from the fall-arrest system. When disturbing your balance, sideways movements of the platform will be 8" or less, to reduce your risk of spraining an ankle or knee. To further reduce the risk of injury, you will undergo sets of warm-up and stretching exercises to prepare your muscles for the tasks to be performed. Finally, although there is almost no chance that you will step into the path of the moving platform, the platform edges will be padded and the force pushing it will be limited in size.

### **BENEFITS**

There will be no personal benefit for participating in this study. However, the researchers anticipate that, in the future, society may benefit from this study through the development of new and effective methods of preventing falls by older adults. It may be possible to train older adults how to better react to and recover from losses of balance through repeated exposure to balance disturbances.

### **COSTS AND COMPENSATION**

You will not have any costs for participating in this research project. You will receive \$15 as compensation for participating in the first experimental session of this research project. If you participate in the second experimental session, you will receive an additional \$10 as compensation. However, if you withdraw from the study before being exposed to the first balance disturbance of a session, you will receive no compensation for that session.

**CONFIDENTIALITY**

Records of participation in this research project will be kept confidential to the extent permitted by law. It is possible that these records could contain information that personally identifies you. To preserve your anonymity and confidentiality, your data will be identified only by an assigned subject code, and not by name. Only the researchers will have knowledge of your name and code number. Any documents that include your name will be stored in a locked filing cabinet in the Biomechanics Laboratory and will be accessible only to the research staff of this study. In the event of any report or publication from this study, your identity will not be disclosed. Results will be reported in such a way that you cannot be identified.

**VISUAL AND MOTION CAPTURE RECORDINGS**

By initialing in the space provided, you verify that you have been told that both visual and motion capture recordings will be generated during the course of this study. The motion capture recordings will be used to measure your movements during the trials. Only the reflective markers that were attached to you will appear in these motion capture images; you will not be visible. The visual recordings will be used to help evaluate the fall vs. recovery outcome of each balance disturbance; you will be visible in these images. As indicated above, all recordings will be identified only by an assigned subject code. The recordings will be stored on our motion capture system or on CD's in the Biomechanics Laboratory. They will be accessible only to those working in the laboratory and will be kept no longer than 5 years.

\_\_\_\_\_ Participant's initials

**RESEARCH RELATED INJURY**

In the event of research related injury, compensation for medical treatment is not provided by Oregon State University.

**VOLUNTARY PARTICIPATION**

Taking part in this research study is voluntary. You may choose not to take part at all. If you agree to participate in this study, you may stop participating at any time. You may skip any questions on the health history questionnaire that you prefer not to answer. If you decide not to take part, or if you stop participating at any time, your decision will not result in any penalty or loss of benefits to which you may otherwise be entitled. In particular, you may choose not to take part in the second experimental session. Any data collected from you will be saved and may be included in the study results, even if you choose to withdraw partway through the study. As described, if you withdraw before being exposed to the first balance disturbance of an experimental session, you will receive no compensation for that session.

**QUESTIONS**

Questions are encouraged. If you have any questions about this research project, please contact: Michael Pavol, Ph.D., at (541) 737-5928 or by e-mail at [mike.pavol@oregonstate.edu](mailto:mike.pavol@oregonstate.edu). If you have questions about your rights as a participant,

please contact the Oregon State University Institutional Review Board (IRB) Human Protections Administrator, at (541) 737-3437 or by e-mail at [IRB@oregonstate.edu](mailto:IRB@oregonstate.edu).

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Your signature indicates that this research study has been explained to you, that your questions have been answered, and that you agree to take part in this study. You will receive a copy of this form.

Participant's Name (printed):

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(Signature of Participant)

(Date)

There is a chance you may be contacted in the future to participate in an additional study related to this project. If you would prefer not to be contacted, please let the researcher know, at any time.

## APPENDIX B

Subject Code: \_\_\_\_\_

**OREGON STATE UNIVERSITY  
BIOMECHANICS LABORATORY**

Health History Questionnaire

Sex: \_\_\_\_\_ Male      \_\_\_\_\_ Female      Height: \_\_\_\_\_

Age: \_\_\_\_\_ Date of Birth: \_\_\_\_/\_\_\_\_/\_\_\_\_      Weight: \_\_\_\_\_

**Health History:**

Have you ever had:	Yes	No	Explain:	Current symptoms?	Yes	No
Neck or back pain or injury						
Joint pain						
Ligament injury (including sprains)						
Broken bones as an adult						
Arthritis						
Head injury						
Vision problems or eyeglasses/contact lenses						
Balance problems						
Neurological problems or conditions						

**OVER**

Have you ever had:	Yes	No	Explain:	Current symptoms?	Yes	No
Diabetes						
Cancer or tumor						
Heart trouble/heart attack						
Disease of the arteries						
High blood pressure						
Low blood pressure						
Epilepsy						
Asthma or lung disease						
Surgeries/operations						
Other illness or disease						

**Present Symptoms:**

Have you recently had:	Yes	No	Explain:
Back or neck pain			
Chest pain			
Cough on exertion			
Heart palpitations			
Shortness of breath			
Dizziness			
Lightheadedness upon standing up			
Muscle injury or tendonitis			

**OVER**

Painful, stiff, or swollen joints			
Pregnancy			
Cold, sinus, or flu symptoms			
Allergy symptoms			
Ear ache or infection			
Other illness or disease			

### **Drugs and Medications:**

The following types of drugs and medications may impair your judgment, your alertness, your balance, and/or your ability to feel pain, placing you at increased risk of injury during this study:

- Alcohol (2 or more beers, glasses of wine, or “hard” alcoholic drinks)
- Sedatives or anxiety/tension relief medication (e.g. Halcion, Xanax, Phenobarbital)
- Recreational drugs (e.g. marijuana, cocaine)
- Antihistamines or cold medications (e.g. Tylenol PM, Benadryl)
- Anti-inflammatory medication/pain relievers (e.g. aspirin, Ibuprofen)

Have you taken any of the types of drugs and medications listed above within the past 48 hours?

\_\_\_\_\_ Yes

\_\_\_\_\_ No

**Is there any other information that you feel we should know about your health?**

