AN ABSTRACT OF THE THESIS OF

Allison M. Blackwell for the degree of Honors Baccalaureate of Science in General Science presented on May 23, 2008. Title: Effects of Medial and Lateral Motion of the Foot during a Forward Slip on the Loss and Recovery of Balance.

Abstract approved:

Michael Pavol

Falls, especially those caused by slips, are a major health concern. Past research has examined the mechanisms of preventing a fall from a forward slip; however, the effects of a mediolateral component to the slip have not been thoroughly analyzed. The purpose of this study was to examine how medial or lateral motion of the foot during a forward slip while walking affects the loss and recovery of balance.

A perturbation platform was used to cause 15 young, healthy adults to slip 13 cm while walking. Participants slipped four times across 30 trials, with the final three slips analyzed. Each participant slipped once in the forward, forward-and-lateral, and forward-and-medial directions during their final three slips. All participants were classified as having recovered from the slips. Twenty-five variables, extracted from the recorded motion capture data, were analyzed.

The position and velocity of the participants' center of mass at the end of the slip and at touchdown of the first recovery step differed between slip directions. During a lateral slip, participants lost their balance medially and, during a medial slip, they lost their balance laterally. This caused variations in stepping patterns used in reacting to the different types of balance loss. Participants responded to lateral slips with a significantly shorter, wider, and quicker step whereas, for medial slips, they tended to take a large step across their midline. Adding a mediolateral component to a forward slip was found to not only change the resulting loss of balance, but also change the reaction to the slip.

Key Words: biomechanics, slipping, falls, balance loss, stepping response
Corresponding e-mail address: allison.blackwell@gmail.com

Effects of Medial and Lateral Motion of the Foot

during a Forward Slip on the Loss and Recovery of Balance

by

Allison M. Blackwell

A PROJECT

Submitted to

Oregon State University

University Honors College

In partial fulfillment of
the requirements for the
degree of

Honors Baccalaureate of Science in General Science (Honors Scholar)

Presented May 23, 2008
Commencement June 2008

Honors Baccalaureate of Science in General Science project of Allison M. Blackwell presented on May 23, 2008.

APPROVED:

Mentor, representing Nutrition and Exercise Sciences

Committee Member, representing Nutrition and Exercise Sciences

---

Committee Member, representing Nutrition and Exercise Sciences

---

Dean, University Honors College

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

Allison M. Blackwell, Author

ACKNOWLEDGMENTS

I would like to thank Michael Pavol, my mentor, for his guidance, constructive criticism, and many hours of instruction; without his help this project would not have been possible. I would also like to thank Mark Hoffman for helping with the construction of some of the laboratory materials, and would like to thank him and Cassie Minot for agreeing to be on my committee and for the feedback that they gave. I would like to thank Melissa Mache, Kristof Kipp, Alicia Foster, and Norio Kadono for their help with data collection. I also appreciate the LIFE Scholars program of the Center for Healthy Aging Research and the URISC program of the Research Office at Oregon State University for the funds they contributed to this project. Thank you!

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Effects of Medial and Lateral Motion of the Foot
during a Forward Slip on the Loss and Recovery of Balance

Introduction

Slips are a serious issue. Slips can result in falls, which can lead to health problems, limit activities of daily living, or even cause death (Hall et al., 2000; Hornbrook et al., 1994; Wolinsky et al., 1997). Because slips are a problem, many of the aspects of slipping and the recovery from a slip have been studied. Moyer et al. (2006) studied the pre-slip characteristics that may influence whether or not a person recovers their balance after a slip. Tang et al. (1998) studied the muscles used in the slipping leg to regain balance. Bhatt et al. (2005) studied the compensatory step that occurs after a person slips. These studies generally looked at a slip in which the foot slips forward. One topic that has not been studied enough, however, is the effects on the loss and recovery of balance when a mediolateral component is added to a forward slip. Oftentimes, a slip that occurs when the foot is free to move in any direction will have some sort of mediolateral component to it (Troy & Grabiner, 2006). It is therefore important to know if and how that component may affect the loss and recovery of balance.

In the United States, more than one third of adults who are aged 65 years or older experience a fall each year (Hornbrook et al., 1994). As the population of the United States ages, the problem of falling will only increase. Twenty to thirty percent of people who fall will experience moderate to severe injuries (such as traumatic brain injury or hip fracture), which can decrease mobility and independence (Alexander et al., 1992). Notably, falls cause 95% of the hip fractures sustained by adults 65 and older (Grisso et al., 1991). Severe injuries such as hip fracture can cause serious health problems and lead to reduced quality of life; severe injuries resulting from a fall can even lead to a premature death (Wolinsky et al., 1997; Hall et al., 2000).

There are psychological issues involved with falling as well. Many people who fall develop a fear of falling, even if they were not injured very much (Vellas et al., 1997). The fear of falling can lead to a limitation of activities, which can lead to reduced mobility and less general fitness (Vellas et al., 1997). This actually increases the risk of falling (Vellas et al., 1997).

Falls and fall-related injuries are an enormous burden to the health care system (Stevens, 2005). In 2000, the direct cost (initial medical costs are included, but long-term costs are not) of all fall related injuries for people aged 65 years and older was $179 million for fatal falls and $19 billion for nonfatal falls (Stevens et al., 2006). By 2020, the annual direct and indirect cost of fall injuries is expected to reach $43.8 billion (Englander et al., 1996). Because falls are such an enormous burden, both to the individual and to society, there is a need to fully understand falls in order to help prevent them.

Slips are a common cause of falls, so it is important to know what influences whether a slip will result in a fall (Gabell et al., 1985). Among the factors that are important in determining whether a person will fall or recover are the events that occur before a slip. Moyer et al. (2006) investigated some of the characteristics of gait before a slip occurs. They compared the gait of younger subjects to older subjects, and had all subjects walk onto a tile walkway that had been coated with glycerol and water. Some factors at the beginning of a slip were associated with more severe slips; these included a large step length and a quickly changing angle between the floor and the foot. Age was not a predictor of the severity of a slip; however, older adults had shorter step lengths and more slowly changing foot to floor angles. Thus, if age were not a factor then one would expect older adults to have fewer severe slips, which was not the case. Older and younger adults experienced severe slips at about the same rate. The investigators concluded that some gait variables that occur before a slip can be important factors in the ensuing severity of a slip but that other factors are also important.

Consistent with this, Brady et al. (2000) found that a small leg-to-floor angle at heel-strike, indicative of a long stride length, indicated that a participant was more likely to fall after experiencing a slip. The variable most strongly related to slip outcome in the analysis, however, was slip length; the longer the slip, the less likely one was to recover. Before this study, many researchers believed that if a slip was over 10 cm in length and 50 cm/s in velocity, it was very close to being a slip that could not be recovered from. However, this study showed that, while slip length is an important determinant of the possible severity of a slip, it is possible to recover from a slip of 20 cm and 100 cm/s.

In 2001, Redfern et al. reviewed literature on the biomechanics of gait when slips are involved, to determine differences between slips that lead to a fall and those that result in a recovery. The researchers wrote that the ground reaction force between the shoe and the floor was probably the most critical factor in slips (Redfern et al., 2001). During a slip, ground reaction forces are reduced and it seems that, in trials that result in a fall, body weight is not fully transferred to the slipping leg.

Beyond knowing what gait characteristics influence the severity of a slip, it is important to understand the mechanisms of response to a slip. In 1984, Berger et al. examined the response time to a perturbation during walking. The investigators produced a perturbation by randomly accelerating or decelerating a treadmill or stimulating the tibial nerve and recorded the muscle activations (Berger et al., 1984). The reaction time, 65-75 ms, was too long for the reaction to be a short latency stretch reflex but too short to be a cognitive response. The response to a perturbation during walking thus seems to be a medium to long latency reflex, and is a complex reaction generated at the spinal level.

Cham and Redfern (2001) observed the joint angles and moments of the slipping leg in response to a slip. They found that the initial reactions to a slip included the generation of knee flexion and hip extension moments. The ankle did not seem to play much of a role in the recovery. It seems that knee and hip moments are used to flex the knee and try to bring the slipping foot back towards the body.

In 1998, Tang et al. studied the role of different muscles in the recovery of balance after a slip. Hip and trunk muscles are the muscles mainly in control of balance during normal walking. However, it appears that leg and thigh muscles are important in reacting to a gait disturbance (Tang et al., 1998). The investigators slipped participants by displacing a force plate in the anterior direction. There was more hip and trunk muscle activation upon the first slip than in later trials. The investigators suggested that this could be caused by the nervous system overreacting to a new balance disturbance; the nervous system seems to lessen its reactions over time. They found that hip and trunk muscles did not seem to be more important or react more to the disturbance than leg and thigh muscles in both legs. The investigators showed that leg and thigh muscles and the coordination between the two legs were very important in regaining balance.

Marigold et al. (2003) investigated how the non-slipping leg and the arms are involved in a response to a slip initiated by rollers. The researchers found that the muscles of the non-slipping leg, the upper body, and the arms were recruited at the same time as the muscles in the slipping leg. It seems then, that the nervous system coordinates the reactions of both the upper and lower body in response to an unexpected slip.

Bhatt et al. (2005) investigated the role of the center of mass (COM) position and velocity in stability after a slip and the effect of the recovery step after a slip. Young participants were slipped by a platform that moved in the anterior direction as they walked at a slow, natural, or fast gait speed. At slip onset, the group that walked quickly was the most stable (Bhatt et al., 2005). Both an anterior COM position and a high COM anterior velocity were correlated with greater stability. Those who slipped at a slower speed had a more anterior COM, but this did not compensate for their slower velocity. At the recovery step's touchdown, all groups showed an increase in stability. The group that walked slowly took a smaller recovery step, so their COMs were more anterior to the stepping foot. As a result, at the touchdown of the recovery step, there was no difference in stability among the groups that walked at different speeds. The investigators found that both COM position and velocity affect the severity of a slip. They also found that the recovery step resembled the regular gait pattern in that step length increased as gait speed increased. The investigators believed that this could mean that the motor program involved in normal gait could help determine what happens during the recovery step after a slip.

In 2006, Troy and Grabiner compared slips induced on a slippery surface and those induced with a platform that moved in a forward direction. The investigators found that some variables do differ dependent upon the type of slip induced (Troy & Grabiner, 2006). They found that the acceleration of the slipping foot during the slips caused by the slippery surface was almost two times larger than the acceleration of the foot during the slips caused by the platform. Reaction times were also slower for those slips initiated by a platform. While slips initiated by the slippery surface had a mediolateral component, this was lacking in platform-induced slips because of the nature of the platform. The investigators felt that the slips that occurred as a result of the platform appeared to be less severe than those that were caused by the slippery surface. I believe that the lack of a mediolateral component could have contributed to the platform-induced slips appearing less severe. When people experience a forward slip that also has a mediolateral component, their reaction must compensate for that mediolateral component. Not only must they adjust for their anteroposterior movement, but they must also adjust in the mediolateral direction. This may make slips with a mediolateral component inherently different from those lacking that component, and thus may necessitate a different reaction.

This idea is consistent with the results of Maki et al. (1996), who had subjects stand on a moveable platform that could move in eight different directions. The subjects were instructed to stand on the platform and were then slipped when the platform was moved under their feet. The investigators looked at the effects of slip direction on the stepping response. They found that there were distinct differences in the way subjects stepped dependent on whether there was a lateral component to the slip. Step length, step time, and swing duration all depended on whether there was a lateral component to the slip or not. Thus, this study showed that slips that occur during standing and that have a mediolateral component do result in different stepping responses than those slips that only have an anteroposterior component.

We know that the steps taken before a slip can affect the outcome of a slip (Moyer et al., 2006; Brady et al., 2000). We know that the initial response to a slip seems to be a medium to long latency reflex (Berger et al., 1984) and we know which muscles and patterns of joint moments are used in response to slips (Tang et al., 1998; Marigold et al., 2003; Cham & Redfern, 2001). We even know something about the stepping responses that occur after a slip (Bhatt et al., 2005). Yet most of this knowledge is for mechanically-induced slips that lack a mediolateral component. This is a limitation in that we also know that, during standing, the reactive stepping response to a slip with a mediolateral component is different from the response to one that just has an anteroposterior component (Maki et al., 1996). We therefore need to know more about how a slip with a medial or lateral component that occurs while walking differs from a slip without a mediolateral component, because the results of those different types of slips may differ from one another and may place individuals at differing risks of falling.

Falls can cause injury, and many falls are precipitated by a slip. Therefore, many of the factors associated with recovery or falling upon slipping have been studied. That said, there has been no systematic study of the effect of a mediolateral component on the loss of balance and subsequent recovery from a forward slip. The purpose of this study is thus to investigate the effects that a medial or a lateral component can have on the loss and recovery of balance associated with a forward slip during walking. We hypothesized that the addition of a medial or lateral component to a forward slip would alter the motion of the center of mass (COM) resulting from the slip. We further hypothesized that the reaction to a slip would vary dependent upon the direction of the slip. We felt that adding a mediolateral component to the slip would create the need for a response that would compensate for that mediolateral component by changing the step length and direction, as well as the body position and velocity.

Methods

Participants

Fifteen apparently healthy young adults participated in this study, (6 males, 9 females, mean ± SD: 171.2 ± 7.1 cm in height, 66.3 ± 8.0 kg in mass, and 20.9 ± 2.7 years of age). We asked participants to report any musculoskeletal, neurological, cardiopulmonary, or other systemic disorders, as well as any recent illnesses or pregnancies. We excluded anyone who had any of the previous conditions. In addition, we excluded individuals from participating if they were under the influence of drugs or medications that could impair their physical or mental function. All participants signed an informed consent form that was approved by the Institutional Review Board.

Instruments and Apparatuses

Slips in different directions were induced during walking using a perturbation platform. The platform was embedded at the midpoint of a 5 meter-long by 2.5 meter-wide raised wooden walkway. The flat, circular, metal platform (40 cm in diameter) was capable of sliding horizontally along a set of rails. Normally, the platform stayed in one place when the participants stepped on it. However, when we triggered it to, a piston driven by compressed air at 414 kPa pushed the platform rapidly along the rails to a new position, simulating a slip. To prevent the rails and air cylinder from being seen or stepped on, a thick metal cover plate (74 cm in diameter) was located just below the sliding platform but above the rails and air cylinder. The cover plate was flush with the surface of the raised walkway, and provided a solid, level surface for the participants to walk on. The device was capable of being rotated and locked into any of three different orientations, allowing the sliding platform to move forward, diagonally forward-and-right (45° to the right of forward), or diagonally forward-and-left (45° to the left of forward).

Due to a symmetrical pattern of slots cut into the cover plate, the participants were unable to determine the direction in which the platform would move. In all three of the possible movement directions, the platform moved approximately 13 cm in about 0.19 seconds when inducing the slips.

We used a Labview (National Instruments, Austin, TX) program to trigger the slips. When enabled, the program automatically triggered a slip when 10 % of the participant's body weight was detected by a force plate (Bertec, Columbus, OH) beneath the perturbation platform, and the participant's foot was within a designated contact area determined by the participant's foot length. For a slip to occur, we also had to be holding down a button. Shortly before the heel came in contact with the platform during a planned slipping trial, if it appeared that the heel would touch the platform in the correct position, an investigator would push and hold down the button. When a planned slip was not triggered during a trial, we attempted to induce the slip during the next trial.

For their safety, participants were secured for all trials into a fall arrest system that prevented any part of the body other than the feet from hitting the floor should balance recovery fail. The fall-arrest system consisted of a full-body safety harness that was attached, by two dynamic ropes, to a load cell that was attached, in turn, to a trolley that could move along a ceiling-mounted rail. The load cell (Sensotec, Columbus, OH) measured the force put on the fall-arrest system, and this force was recorded at 600Hz during the trials. The two dynamic ropes were attached to the harness at each shoulder. We adjusted the length of each rope so that the participant's knees could come close to the ground, but could not touch it. During each trial, an investigator pulled a third rope that was attached to the trolley to keep the trolley above the participant as he or she walked.

The movements of the participant during each trial were recorded at 120 Hz by a nine-camera motion capture system (Vicon, Lake Forest, CA). This system tracked the motion of 33 reflective markers of 9 mm diameter that we taped to the participant's skin and clothing. Markers were attached at landmarks that included: the right and left heel, toe, 5^{th} metatarsal, ankle, leg, knee, thigh, shoulder, elbow, and wrist, the pelvis (6), neck, chest (2), and head (4). In addition to the data collected by the motion capture system, a digital video camera obtained a video record of each trial.

Experimental Procedures

Participants began with a short warm-up and, after the reflective markers were attached, performed a sequence of six stretching exercises that encompassed the major muscle groups of the lower limbs. The participants then performed a second warm-up, consisting of stepping up onto a 13 cm-high step and then back down 10 times in each of three directions. Next, in order to determine the participants' dominant foot, we asked the participants to stand still and then take several steps forward upon our command. We noted which foot they stepped with first in two out of three trials. Participants were then secured into the fall arrest system.

After an initial data collection trial of quiet standing in a reference position, each participant walked across the platform for a total of approximately 30 trials. We identified the participant's initial starting location for the walking trials by having the participant stand on the platform and take three steps towards the far end of the wooden walkway. From that starting location, we instructed participants to walk naturally, at a self-selected pace, to the other end of the walkway upon our verbal command, and to stop there until told to return to the starting location. We instructed participants to begin stepping with their dominant foot, so that foot would contact the sliding platform upon the third step. In addition, we told them to look straight ahead at a target on the far wall of the laboratory while walking. We informed participants that they could experience a slip in any direction during any of the upcoming walking trials and that, if they slipped, they should try to recover their balance and continue walking to the end of the walkway. We used a pair of timing lights, spaced 2m apart, to monitor the participants' walking speed across the platform. An investigator computed the average walking speed over the first five trials and if, during one of the trials that followed, a participant walked more than 10% faster or slower than that average speed, the investigator asked him or her to slow down or speed up slightly for the next trial, respectively.

We assigned four of the trials to contain a slip in one of the three aforementioned directions: forward, forward-and-medial ("medial"), or forward-and-lateral ("lateral"). The four slips occurred during trial 7 and during a randomly selected trial within trials 11-14, 18-21, and 25-28. Because it was possible that the response to the initial slip would differ from the response to subsequent slips (Pavol et al., 2004), we repeated the slip in the first direction a second time; the slips in the other two directions occurred only once. The order of exposure to the slips in the three directions was counterbalanced across participants.

The motions of the participant, the forces acting on force plate located beneath the sliding platform, and the forces acting on the fall-arrest system were recorded during each trial. In addition, at the end of data collection, we measured the body weight, height, and selected anthropometric dimensions of each participant.

Data Analysis

We analyzed the last three slips of each participant. If, after the slip onset, an average of 5% or more of a participant's body weight was supported by the fall arrest system over any 1-second period, we classified that trial as a fall. Otherwise, the trial was classified as a recovery. The same method of classifying the outcome of a slip was used in a previous study (Pavol et al., 1999).

From the recorded marker position and force data, we computed the values of selected variables associated with a participant's reaction to the slip. We low-pass filtered the marker positions with a fourth-order Butterworth no-lag filter with a cutoff frequency of 13Hz, based on a residual analysis (Winter, 2004). We used a custom BodyBuilder program (Vicon, Lake Forest, CA) to compute the 3-dimensional positions of joint centers from the filtered marker paths using transformations derived from the reference trial of quiet standing and the measured body dimensions. We calculated the position of the body center of mass (COM) from those joint centers and sex-specific anthropometric data (deLeva, 1996) in a 12-segment model of the body.

Four events were of interest. The same investigator visually determined the timing of these events from the marker paths. The investigator classified *slip onset* as the moment after heel touchdown when the heel started to move in a continuous anterior motion. The *end of the slip* was determined to be the time when the entire foot stopped moving as one unit. The investigator determined the instants of *non-dominant and dominant foot touchdown* for the first recovery step by each foot, based on when the first part of the foot appeared to touch the surface of the platform or walkway.

We analyzed 25 dependent variables at or between the events of interest. The COM position and velocity were determined with respect to the dominant (i.e. slipping) foot at slip onset, the end of the slip, and dominant foot touchdown, and were determined with respect to the non-dominant foot at non-dominant touchdown. We computed the anteroposterior distance from the heel to the COM (COM x) in foot lengths. A positive number indicates that the COM is anterior to the heel. We computed the mediolateral distance from the lateral border of the foot at the 5^{th} metatarsal head to the COM (COM y) in body heights (bh), with a positive number indicating that the COM is medial to the 5^{th} metatarsal. We computed the anteroposterior and mediolateral velocities of the COM through numerical differentiation of the COM position. We expressed the velocities as Froude numbers by normalizing them to $\sqrt{(\mathrm{g} \times \text{body height})}$, where g is the acceleration due to gravity. We computed slip time from the onset of the slip until the end of the slip. We computed non-dominant step time from slip onset until the non-dominant foot's touchdown. We measured dominant step time from the non-dominant foot's touchdown until the dominant foot's touchdown. Slip length was measured as the displacement of the slipping foot's heel between slip onset and the end of the slip. For the first recovery step by the non-dominant and by the dominant foot, we determined both the anteroposterior step length and the mediolateral step width in body heights. The length of the step preceding the slip was also determined. Step length and step width were defined as the anteroposterior and mediolateral distances between the two ankle joint centers at the instant of step touchdown. A positive value for step length indicates that the participant stepped anteriorly, and a positive value for step width indicates that the participant stepped laterally relative to the stepping foot.

Statistics

Two of the 15 participants tested exhibited reactions to the slip that were markedly different from all other participants for at least one of the slips of interest. After the slips in question, the two participants made a short, quick step with their non-dominant foot; in at least one case for each participant, the length and duration of the step were 2-2.4 standard deviations below the mean. They then took a second step with their non-dominant foot before taking a step with their dominant foot. Because this was a very different reaction than that exhibited by the other participants, we did not include the data of these two participants in the statistical analyses.

We performed repeated-measures analysis of variance (ANOVA) on each dependent variable, with the slip direction (forward, medial, lateral) as the independent factor. If sphericity was violated, we used a Greenhouse-Geisser correction. Paired t-tests with a Bonferroni correction were used for post-hoc testing. Throughout the analyses, we used a significance level of $\alpha = 0.01$. We performed all of the statistical analyses using SPSS 15.0 (SPSS, Chicago, IL).

Results

All of the participants recovered from all three types of slips. The largest value observed for the peak 1-second-average load put on the safety harness system was 3.2% of the participant's body weight, with the average value across participants being 1.6 ± 0.7% of body weight. The results that follow thus reflect the kinematics of successful recovery from the three types of slips.

In the moments leading up to a slip, the gait variables we analyzed, namely step length, COM position, and COM velocity, did not vary significantly between slip types ($p > 0.01$). The length of the step preceding the slip did not differ between different slip types (0.395 ± 0.025 bh; $p>0.01$). The COM was posterior to the slipping foot's heel (-0.427 ± 0.114 foot lengths) and slightly medial to the slipping foot's 5th metatarsal (0.063 ± 0.009 bh) for all slip types at the onset of the slip. The COM was moving anteriorly (0.314 ± 0.028 $\sqrt{g \cdot \mathrm{bh}}$) and laterally (-0.022 ± 0.006 $\sqrt{g \cdot \mathrm{bh}}$) with respect to the slipping foot at slip onset.

We observed some variation in the characteristics of the slip between directions. The time from the onset to the end of the slip did not differ between slip types (0.19 ± 0.01 s; $p > 0.01$). The distance of the slip, however, differed significantly dependent upon the type of slip induced. Lateral slips (13.4 ± 1.0 cm) were, on average, longer than medial slips (12.3 ± 0.9 cm; $p < 0.01$), whereas neither of these differed in length from forward slips (12.7 ± 1.1cm).

At the end of the slip, there were statistically significant differences in COM position and velocity between slip types (Table 1). The COM was anterior to the heel for medial and lateral slips, but was posterior to the heel, on average, for forward slips. Lateral slips resulted in a COM that was more medial to the 5th metatarsal of the slipping foot than did forward slips which, in turn, resulted in a COM that was more medial than at the end of medial slips. The COM was moving anteriorly at approximately the same velocity at the end of each type of slip. However, the COM was moving more laterally with respect to the slipping foot for medial slips than for lateral slips.

The duration, length, and width of the initial recovery step by the non-dominant foot after lateral slips differed from those after medial and forward slips (Table 2). The step time from the onset of the slip to the touchdown of the non-dominant foot was less for lateral slips than for forward and medial slips. In addition, the step length by the non-dominant foot for lateral slips was less than for forward or medial slips. The step width for lateral slips was greater than for forward slips which, in turn, was greater than for medial slips.

At the touchdown of the initial recovery step by the non-dominant foot, the position of the COM in relation to the foot, as well as the mediolateral velocity of the COM, was still significantly different between slip types (Table 1). At the time of non-dominant touchdown, the COM was more posterior to the heel for forward and medial slips than for lateral slips (Figures 1 – 3). For lateral slips, the COM was more medial to the 5th metatarsal of the non-dominant foot at touchdown than for forward slips, for which the COM was more medial than for medial slips (Figures 4 – 6). At non-dominant touchdown, the COM was moving primarily anteriorly and the difference in anterior velocity between the three slips types was not statistically significant ($p > 0.01$; Figures 1 – 3). However, on average, the COM was also moving medially with respect to the non-dominant foot for medial slips but laterally for forward and lateral slips (Figures 4 – 6).

The first recovery step taken by the dominant foot, corresponding to the second recovery step overall, was not significantly different between slip types with regard to step duration, length, or width (Table 2). The difference in the step time from the non-dominant foot touchdown until the dominant foot touchdown was not statistically significant between slip types ($p > 0.01$). In addition, the differences between the slip types for both step length and step width were not statistically significant ($p > 0.01$).

Similarly, at the time of dominant foot touchdown, the position and the velocity of the COM relative to the foot did not vary between slip types (Table 1; $p > 0.01$). The COM was posterior to the heel of the foot for all slip types, and was medial to the 5th metatarsal for all slip types. The COM was moving anteriorly and laterally with respect to the dominant foot for all slip types at the time of dominant foot touchdown.

Table 1: Mean ± SD Center of Mass (COM) Position and Velocity at Select Events of Interest as a Function of Slip Direction

Variable		**Medial Slip**	**Forward Slip**	**Lateral Slip**
End of slip COM x	(ft.len)	0.107 ± 0.145*	-0.028 ± 0.140†‡	0.155 ± 0.182*
End of slip COM y	(bh)	0.008 ± 0.009*†	0.056 ± 0.010†‡	0.111 ± 0.013*‡
Non-dominant TD COM x	(ft.len)	-0.528 ± 0.204†	-0.620 ± 0.210†	-0.122 ± 0.281*‡
Non-dominant TD COM y	(bh)	0.001 ± 0.018*†	0.073 ± 0.015†‡	0.111 ± 0.020*‡
Dominant TD COM x	(ft.len)	-0.819 ± 0.199	-0.830 ± 0.272	-0.787 ± 0.244
Dominant TD COM y	(bh)	0.074 ± 0.022	0.077 ± 0.026	0.075 ± 0.027
End of slip COM vx	√(g•bh)	0.292 ± 0.034	0.292 ± 0.032	0.292 ± 0.028
End of slip COM vy	√(g•bh)	-0.011 ± 0.009†	-0.009 ± 0.010	0.005 ± 0.017‡
Non-dominant TD COM vx	√(g•bh)	0.299 ± 0.046	0.300 ± 0.029	0.284 ± 0.041
Non-dominant TD COM vy	√(g•bh)	0.061 ± 0.022*†	-0.026 ± 0.012 ‡	-0.050 ± 0.045‡
Dominant TD COM vx	√(g•bh)	0.270 ± 0.046	0.275 ± 0.064	0.286 ± 0.039
Dominant TD COM vy	√(g•bh)	-0.020 ± 0.025	-0.018 ± 0.024	-0.021 ± 0.027

*$p \leq 0.01$ vs. Forward; †$p \leq 0.01$ vs. Lateral; ‡$p \leq 0.01$ vs. Medial

COM x = distance from the heel to the COM; positive numbers indicate that the COM is in front of the heel. COM y = distance from the 5th metatarsal to the COM; positive numbers indicate that the COM is medial to the 5th metatarsal. COM vx = anteriorly-directed velocity of the COM. COM vy = medially-directed velocity of the COM. All values are reported with respect to the dominant (slipping) foot at the end of the slip and at dominant TD. Values are reported with respect to the non-dominant foot at non-dominant TD. TD = touchdown of the foot to the floor; ft.len = foot length; bh = body height; g = acceleration due to gravity.

Table 2: Mean ± SD Time, Length, and Width of the First Recovery Step by the Non-dominant and by the Dominant Foot as a Function of Slip Direction

Variable		**Medial Slip**	**Forward Slip**	**Lateral Slip**
Non-dominant Step Time	(s)	0.563 ± 0.078†	0.581 ± 0.058†	0.355 ± 0.114*‡
Dominant Step Time	(s)	0.492 ± 0.065	0.512 ± 0.085	0.458 ± 0.093
Non-dominant Step Length	(bh)	0.310 ± 0.049†	0.318 ± 0.034†	0.131 ± 0.108*‡
Non-dominant Step Width	(bh)	-0.055 ± 0.039*†	0.068 ± 0.025†‡	0.160 ± 0.039*‡
Dominant Step Length	(bh)	0.321 ± 0.048	0.317 ± 0.069	0.334 ± 0.051
Dominant Step Width	(bh)	0.055 ± 0.039	0.073 ± 0.041	0.095 ± 0.050

*$p \leq 0.01$ vs. Forward; †$p \leq 0.01$ vs. Lateral; ‡$p \leq 0.01$ vs. Medial

Non-dominant Step Time = time from slip onset until TD of the non-dominant foot. Dominant Step Time = time from TD of the non-dominant foot until TD of the dominant foot. Step length and width were measured between ankle joint centers at TD, with positive values corresponding to a forward and medial step relative to the contralateral foot, respectively. TD = touchdown of the foot to the floor; bh = body height.

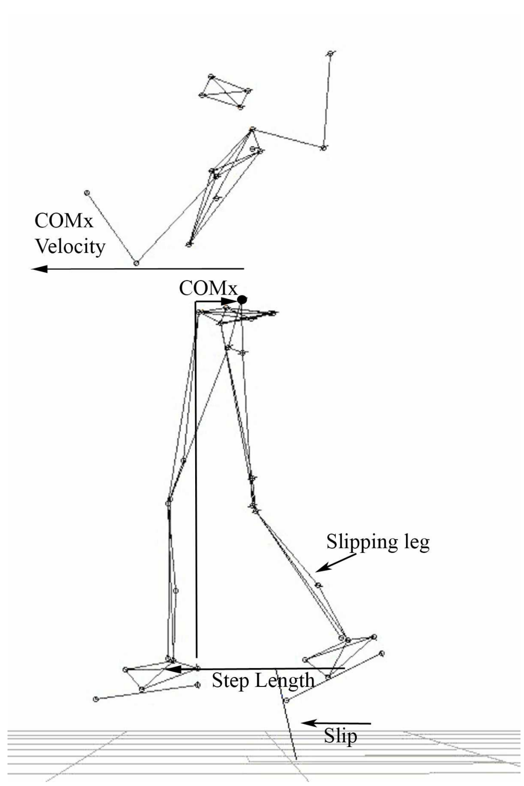

Figure 1: Side View of a Medial Slip at Non-dominant Touchdown

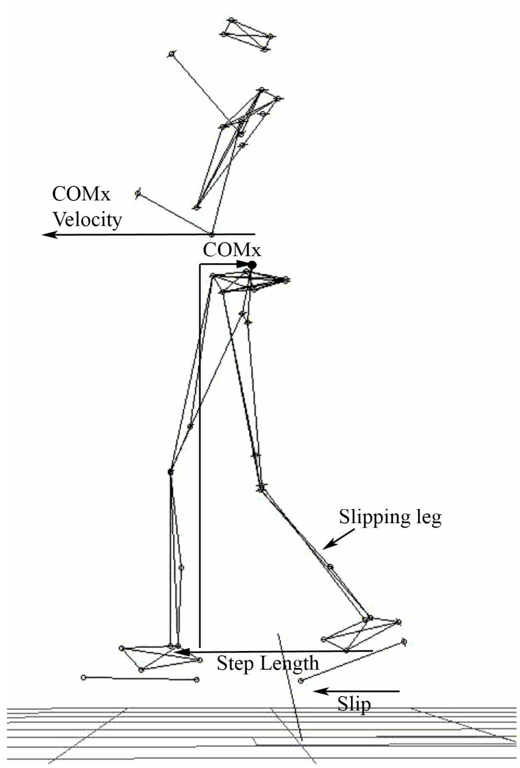

Figure 2: Side View of a Forward Slip at Non-dominant Touchdown

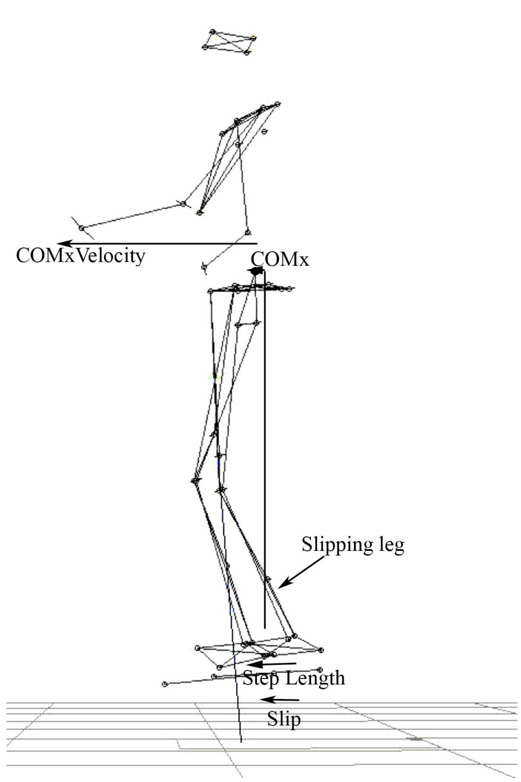

Figure 3: Side View of a Lateral Slip at Non-dominant Touchdown

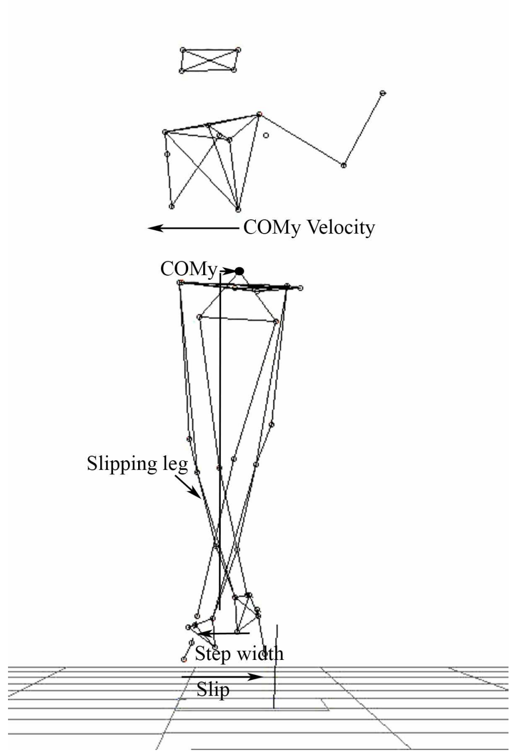

Figure 4: Front View of a Medial Slip at Non-dominant Touchdown

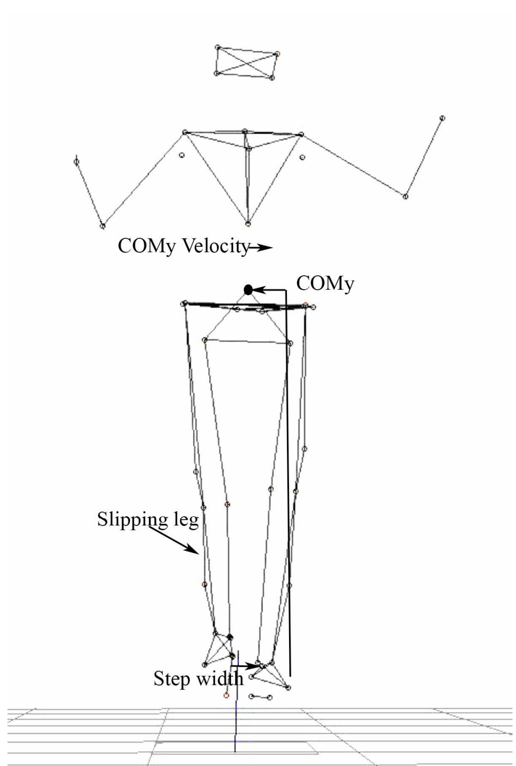

Figure 5: Front View of a Forward Slip at Non-dominant Touchdown

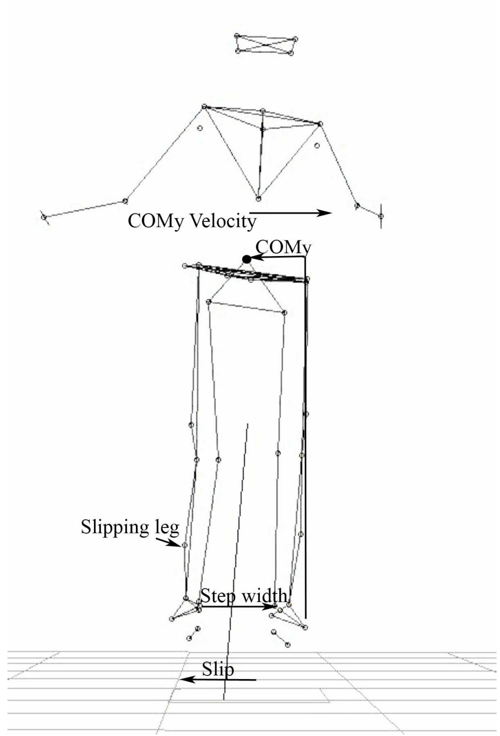

Figure 6: Front View of a Lateral Slip at Non-dominant Touchdown

Discussion

Falling can lead to a serious injury, or even death, in older adults. Slips are a major cause of falls, and the ability to regain balance after a slip greatly determines if and how the person falls (Gabell et al., 1984). This study investigated how medial or lateral motion of the foot during a forward slip affected the loss and recovery of balance. We hypothesized that mediolateral motion of the foot during a forward slip would add a sideways component to the resulting loss of balance, causing individuals to change the way in which they reacted to the slip.

The direction that participants slipped greatly influenced where their COM was in relation to their slipping foot at the end of the slip, both in the anteroposterior and mediolateral direction. In the anteroposterior direction, slips in the forward-only direction (“forward”) resulted in a COM that was posterior to the heel. This was significantly different from slips in the forward-and-medial (“medial”) or forward-and-lateral (“lateral”) direction. At the end of these latter two types of slips, the COM was anterior to the heel. Although all slips were essentially the same length, the forward slip did not have a mediolateral component. As a result, the heel moved more anteriorly during the forward slip than during the other two slip types. This greater anterior motion caused the COM to be posterior to the heel. Notably, the COM moved anteriorly relative to the heel during all types of slips, despite the forward motion of the foot. This is likely due to the large forward velocity of the COM at slip onset, combined with the relatively short length and duration of the slip.

Where the COM was and how it was moving in the mediolateral direction at the end of the slip was also greatly determined by the type of slip undergone. The COM was most medial to the slipping foot for participants who slipped laterally and least medial for those who slipped medially. The COM was moving laterally relative to the slipping foot for medial slips and medially for lateral slips by the end of the slip. The position of the COM with respect to the slipping foot at the end of the slip was as expected, since the foot moved approximately 9 cm away from or towards the body during the slips in the lateral or medial direction, respectively. The direction of the slip, to a great extent, determined where the participants' COM would be in respect to the dominant foot. As one would have expected, the direction of the slip also influenced the participants' COM velocity at the end of the slip. It appears that a shift of the base of support medial or lateral to the COM during a slip caused the weight of the body to produce a torque about the foot that rotated the body in the opposite direction. We hypothesized that adding a mediolateral component to a forward slip would change the effects of the slip, and the way in which balance was lost. The present data shows that the immediate effects of a slip do vary dependent upon what type of mediolateral component is present.

The direction of the slip led to different reactions. After the slip, participants who slipped laterally took a significantly shorter, wider, quicker step with their non-dominant foot than participants who slipped forward or medially. The non-dominant foot stepped medially relative to the slipping foot in forward slips, and more so in lateral slips. In contrast, participants who slipped medially tended to take a large step with their non-dominant foot over their midline. As a result, the non-dominant foot was lateral relative to the slipping foot at step touchdown for medial slips, compared to medial to the slipping foot during forward and lateral slips. These results make sense. When participants started to lose their balance, they placed their foot in the direction of their bodies' movement. It makes sense that participants generally stepped forward after a slip, based on their velocity at the end of the slip. The step length for lateral slips was significantly shorter than for forward or medial slips. The shorter step length could have been an attempt to quickly reestablish mediolateral stability. The response seen in lateral slips would not be possible for medial slips, since, in medial slips, the foot traveled a large distance when it crossed the midline. Thus, we see very different reactions in order to regain one's balance when subjected to different types of slips.

At touchdown of the non-dominant foot, the COM, on average, was posterior to the heel for all three slip types. The COM position after a lateral slip was significantly less posterior to the heel than after the other two slip types. This may make it appear that the non-dominant step after a lateral slip resulted in a COM position that was more stable than the steps after other types of slips. However, the COM was moving anteriorly for all slip types. This allowed participants to maintain their balance. Although their COM was posterior to their heel, their anterior velocity prevented them from falling backward (Pai & Iqbal, 1999).

By the touchdown of the non-dominant foot, participants had different COM positions and velocities in the mediolateral direction dependent upon the type of slip that had occurred. After lateral slips, the COM was moving laterally with respect to the non-dominant (stepping) foot, so participants placed their foot lateral to the COM to stop that movement. This was also the case, but to a lesser magnitude, for forward slips. After medial slips, the COM was moving medially with respect to the stepping foot, so, on average, participants placed the lateral border of their foot directly under the COM. In all three types of slips, participants placed their foot in a position that would allow them to slow down the mediolateral velocity of their COM.

By the time of the dominant foot's touchdown, there were not any variables that we analyzed that differed dependent upon the direction of the slip. The step time, step length, and step width from the non-dominant foot's touchdown until the dominant foot's touchdown was about the same for all three types of slips. The COM was posterior to the heel at step touchdown in all three slip cases. However, the participants did not lose their balance at this point because, in all three types of slips, the COM was moving anteriorly at the time of dominant touchdown (Pai & Iqbal, 1999). For all three slip types, participants placed the dominant foot medially relative to the non-dominant foot. The COM was medial to the dominant foot at step touchdown and moving laterally for all directions of slipping. The lack of differences between the three slip types suggests that by the time of dominant foot touchdown, participants may have recovered from the initial slip. The position and velocity of the COM seem to be similar to what we would see in natural walking. In normal walking, you would expect the COM to be medial to the foot and moving towards the foot that had just stepped on the ground (Bhatt et al., 2005); this is what we saw.

The results of two participants were not evaluated with the rest of the results because the first step with their non-dominant foot after the slip was markedly different from all of the other subjects. The two participants made a short, quick step with their non-dominant foot such that they failed to put their non-dominant foot in front of the dominant foot. Their COM was moving anteriorly relative to their heel at touchdown, and their more posterior foot placement would have led to faster forward rotation of the body during stance, due to the greater moment arm of the weight about the foot. This appears to have caused them to take another step with their non-dominant foot before they stepped with their dominant foot. One of the participants used this mechanism to recover her balance during a forward slip, and the other reacted in this manner in recovering from both forward and lateral slips. This could signify that there are a variety of reactions that people may exhibit to the same slip stimulus.

The reaction of stepping twice with the same foot because the first step did not move the foot anteriorly enough to regain balance was seen in a minority of cases in this study. In only two other cases did a participant place the stepping foot posterior to the slipping foot, but only slightly so and they then stepped with the contralateral foot. In a previous study, however, most of the subjects, when faced with a forward slip while walking at a natural speed, placed their non-slipping foot posterior to both the slipped foot and to their COM (Bhatt et al., 2005). The slips induced in that study were larger, 35.2 ± 0.63 cm, than the slips in this study, 12.7 ± 1.1cm for forward slips. Stepping behind one's COM would be an appropriate response to a backward balance loss. On the other hand, a backward balance loss following a slip can be prevented if the COM is moving forward fast enough, and the velocity required to prevent a backward balance loss is smaller for smaller slips (Pai & Iqbal, 1999). The fact that few of our participants stepped posterior to their slipping foot suggests that, in our study, participants may not have lost their balance backwards and depended on their forward velocity to carry them over the platform until they put their foot down in front of their COM.

In our study, we added a mediolateral component to a forward, platform-induced slip. A mediolateral component to a slip is not frequently studied in platform-induced slips, and may make platform-induced slips more similar to real life slips. A previous study noted that slips induced by a perturbation platform vary from slips that occur on a slippery surface where the foot is free to slip in any direction for any distance (Troy & Grabiner, 2006). In that study, slips that occurred on a slippery surface seemed to be more severe than slips that occurred on a platform. Most notably, the slips caused by the slippery surface exhibited considerable mediolateral motion of the slipping foot (4.2 cm). This mediolateral portion of the slip has been missing in many studies of platform-induced slips to date (Troy & Grabiner, 2006) and, as the present results indicate, can have a considerable impact on the resulting loss and recovery of balance. Other differences have been found to exist between the slips that occurred due to a perturbation platform and those that occurred on an artificial ice surface (Troy & Grabiner, 2006). Those differences include a higher acceleration of the foot during slipping and a faster response time to slips that occur on artificial ice. However, the platform still provides a reasonably realistic slip experience and is much easier to control. Participants in the previous study by Troy and Grabiner (2006) were also able to recover from the different types of slips at the same rate. Nevertheless, the previous study did not look at forward slips that were initiated by a platform with a mediolateral component, as in the present study. Based on the present results, we believe that platform-induced slips with a mediolateral component are inherently different than those that just have a forward component and may resemble slips that occur on a slippery surface more closely.

Slips with a mediolateral component elicited a very different reaction than a normal step. Those types of slips may be more difficult to recover from. It seems that the very large step that was seen in medial slips could be difficult to produce if one had limited strength, mobility, or reaction time. The lateral slip could also be more difficult to recover from than a forward slip due to quick nature of the step in reaction to the slip. Although all of the participants were able to recover from the slips, there were differences in the reactions dependent upon the type of slip. The reaction to a medial slip usually involved the non-dominant foot taking a large step over the slipping foot. The reaction to the lateral step was usually a very short, quick step, resulting in the COM slightly posterior to the heel and medial to the fifth metatarsal of the non-dominant (stepping) foot. Forward slips elicited a response that oftentimes looked like the participant placed the non-dominant foot where it would have been placed in a normal step, or close to it. It would seem that if, while walking, a person slipped forward, but the slipping foot also moved in the mediolateral direction, that slip may be more difficult to recover from than if the slip was solely in the anterior direction.

Previous studies have found that the reaction to a slip is a postural reflex that seems to be preprogrammed (Nashner, 1977). It is apparent that the reaction time, in one study 65-75 ms, is too long for the reaction to a perturbation to be a short latency stretch reflex; however, it is too short to be a cognitive response (Berger et al., 1984). Previous research has found that the reaction to a perturbation is a long latency reflex, and is a complex reaction generated at the spinal level (Berger et al., 1984). It has also been noted that the type of reaction is dependent on the type and direction of the perturbation (Berger et al., 1984). This is consistent with our findings that the reaction to a slip differed depending on the type of slip that occurred.

Limitations and Future Studies

There are some limitations to our study. After analyzing the data, we found that slip length differed significantly between medial and lateral slips. Lateral slips were approximately one centimeter longer than medial slips, which corresponds to a difference of 8% of the average slip length of about 13 cm. With the apparatus we used, driven and stopped by air pressure, there was bound to be some variation in the slips. It is also possible that, during lateral slips, participants pushed the platform with their dominant foot in the lateral direction while they were trying to regain their balance. This could be due to the nature of the slip. The mediolateral distance between the foot and COM increased during lateral slips, but decreased during medial slips, causing the body to be inclined medially at a greater angle during lateral slips. This greater body angle could make it so that the foot would have been more likely to push the platform laterally. It is possible that the extra distance traveled by the dominant foot during lateral slips may have affected the results of this study. However, in the end, 1 cm extra length should not drastically change any results. Future studies should look into how to make slips in different directions the same length and to see if a 1 cm difference would affect the severity of the slip.

We used a platform that was pushed by air pressure to ensure that we could get repeatable slips with a mediolateral component. If we had used a platform on top of rails that was pushed by the participants' feet, we would have been able to easily obtain forward slips and even medial slips. However, a lateral slip might not have always occurred. Using a platform powered by air pressure induced a slight time delay so that the platform did not start moving exactly at the point of heel contact. Generally, a participant had already started to lift their non-dominant foot off the ground by the time the platform started moving. This slight time delay could have changed the reaction to regain balance that we observed from what would have occurred if the platform had started to move at the instant of heel contact. Future studies could investigate whether that small amount of time significantly changes the slipping responses.

All of the participants knew that a slip would occur, however they did not know when or in what direction it would occur. We believe that by having the participants walk over the perturbation platform multiple times without any slipping, and by changing the directions of the slip, we limited the amount of pre-slip planning the participants could achieve. Although laboratory settings cannot perfectly recreate real life experiences, we believe that the participants in this study were not able to guess accurately when or how a slip would occur.

We did not include the results of the first slip in this study, as the first slip may differ significantly from slips that occur afterwards, because the participant has some knowledge of and direct experience with what will occur (Pavol et al., 2004). All slips were approximately the same length and speed, and the perturbation platform was plainly visible. Therefore, after the first slip, participants realized approximately where their foot would be when they were slipped, and could guess how severe future slips might be. To combat possible order effects, however, we used counterbalancing. Therefore the three slips should be comparable to one another. Future studies should examine the initial slip. It would be interesting to know if the results found in this study are similar to those that would be found if the initial slips were analyzed.

The results of this research can be generalized to healthy young adults in a laboratory setting. It may not be possible to generalize this study to slips that occur during activities other than walking or to other methods that cause people to lose their balance. Older adults may not react the same way that young adults do. Older adults also have been found to exhibit diminished reactive responses in comparison to young adults (Pavol & Pai, 2007). Nonetheless, if a certain type of slip is difficult for a young person to recover from, it could be assumed that a similar type of slip would also be difficult for an older person to recover from. Future studies may want to look at how older adults react to slips occurring in different directions during walking.

Conclusion

At the beginning of this study, we hypothesized that the addition of a mediolateral component to a forward slip would change both the way in which subjects lost their balance and the way that they reacted in order to regain their balance. We found that this was indeed the case. At the end of the slip and at the non-dominant foot's first touchdown, some variables, including the COM position and velocity in the mediolateral direction differed dependent upon the slip type. During a lateral slip, participants lost their balance medially, and in a medial slip, participants lost their balance laterally. This caused variations in the reactive stepping patterns used in response to the different types of balance loss. To recover from a lateral slip, participants quickly placed their non-dominant foot lateral and slightly anterior to their COM. To recover from a medial slip, participants on average placed their foot more anterior to their COM than for lateral slips, and placed their foot so that the lateral border of the foot was under the COM. After a forward slip, participants placed their foot more anteriorly but less laterally to the COM than for lateral slips. By the first touchdown of the dominant foot, however, most of the variables we measured, such as COM position and velocity relative to the dominant foot, did not differ significantly from each other. The values for these variables seemed similar to normal walking, suggesting that most participants had recovered from the slip by that point. We felt that the medial slips appeared to be especially difficult to recover from, as they required the non-dominant leg to take a large step across the midline so that it was almost lateral to the dominant foot's fifth metatarsal. This type of slip could therefore potentially be difficult to recover from for those who have weak leg and hip strength, lack mobility, or have poor response times. In this study, we found that adding a mediolateral component to a forward slip changes not only the slip itself, but the subsequent reaction to that slip.

Bibliography

Alexander BH, Rivara FP, Wolf ME. (1992). The cost and frequency of hospitalization for fall-related injuries in older adults. *American Journal of Public Health, 82*(7), 1020–1023.

Berger W, Dietz V, Quintern J. (1984). Corrective reactions to stumbling man: neuronal coordination of bilateral leg muscle during gait. *Journal of Physiology, 357,* 109-125.

Bhatt T, Wening JD, Pai YC. (2005). Influence of gait speed on stability: recovery from anterior slips and compensatory stepping. *Gait and Posture, 21*(2), 146-156.

Brady RA, Pavol MJ, Owings TM, Grabiner MD. (2000). Foot displacement but not velocity predicts the outcome of a slip induced in young subjects while walking. *Journal of Biomechanics, 33*, 803-808.

Cham R, Redfern MS. (2001). Lower extremity corrective reactions to slip events. *Journal of Biomechanics, 34,* 1439-1445.

deLeva P. (1996). Adjustments to Zatsiorsky-Seluyanov's segment inertia parameters. *Journal of Biomechanics, 29,* 1223-1230.

Englander F, Hodson TJ, Terregrossa RA. (1996). Economic dimensions of slip and fall injuries. *Journal of Forensic Science, 41*(5), 733–746.

Gabell A, Simons MA, Nayak US. (1985) Falls in the healthy elderly: predisposing causes. *Ergonomics, 28*, 965-975.

Grisso JA, Kelsey JL, Strom BL, Chiu GY, Maislin G, O'Brien LA. (1991). Risk factors for falls as a cause of hip fracture in women. *New England Journal of Medicine, 324* (19), 1326–1331.

Hall SE, Williams JA, Senior JA, Goldswain PR, Criddle RA. (2000). Hip fracture outcomes: quality of life and functional status in older adults living in the community. *Australian and New Zealand Journal of Medicine, 30*(3), 327–332.

Hornbrook MC, Stevens VJ, Wingfield DJ, Hollis JF, Greenlick MR, Ory MG. (1994). Preventing falls among community-dwelling older persons: results from a randomized trial. *The Gerontologist, 34*(1), 16–23.

Maki BE, McIlroy WE, Perry SD. (1996). Influence of lateral destabilization on compensatory stepping responses. *Journal of Biomechanics, 29*(3), 343-353.

Marigold DS, Bethune AJ, Patla AE. (2003). Role of the unperturbed limb and arms in the reactive recovery response to an unexpected slip during locomotion. *Journal of Neurophysiology, 89*, 1727-1737.

Moyer BE, Chambers AJ, Redfern MS, Cham R. (2006). Gait parameters as predictors of slip severity in younger and older adults. *Ergonomics, 49*(4), 329-343.

Nashner LM. (1977). Fixed patterns of rapid postural responses among leg muscles during stance. *Experimental Brain Research*, *30*, 13-24.

Pai YC, Iqbal K. (1999). Simulated movement termination for balance recovery: can movement strategies be sought to maintain stability in the presence of slipping or forced sliding? *Journal of Biomechanics*, *32*(8), 779-786.

Pavol MJ, Owings TM, Foley KT, Grabiner MD. (1999). The sex and age of older adults influence the outcome of induced trips. *Journal of Gerontology: Medical Sciences*, *54A*(2), M103-M108.

Pavol MJ, Pai YC. (2007). Deficient limb support is a major contributor to age differences in falling. *Journal of Biomechanics*, *40*(6), 1318-1325.

Pavol MJ, Runtz EF, Pai YC. (2004). Young and older adults exhibit proactive and reactive adaptations to repeated slip exposure. *Journal of Gerontology: Medical Sciences*, *59A*(5), 494-502.

Redfern MS, Cham R, Gielo-Perczak K, Gronqvist R, Hirvonen M, Lanshammar H, Marpet M, Pai YC, Powers C. (2001). Biomechanics of slips. *Ergonomics,44*(13), 1138-1166.

Stevens JA. (2005). Falls among older adults-risk factors and prevention strategies. *Journal of Safety Research*, *36*, 409-411.

Stevens JA, Corso PS, Finkelstein EA, Miller TR. (2006). The costs of fatal and nonfatal falls among older adults. *Injury Prevention*, *12*, 290–295.

Tang PF, Woollacott MH, Chong RKY. (1998). Control of reactive balance adjustments in perturbed human walking: roles of proximal and distal postural muscle activity. *Experimental Brain Research*, *119*, 141-152.

Troy KL, Grabiner MD. (2006). Recovery responses to surrogate slipping tasks differ from responses to actual slips. *Gait and Posture, 24*, 441-447.

Vellas BJ, Wayne SJ, Romero LJ, Baumgartner RN, Garry PJ. (1997). Fear of falling and restriction of mobility in elderly fallers. *Age and Ageing, 26*, 189–193.

Winter, DA. (2004). *Biomechanics and motor control of human movement* (3rd ed.). Hoboken, NJ: John Wiley and Sons.

Wolinsky FD, Fitzgerald JF, Stump TE. (1997). The effect of hip fracture on mortality, hospitalization, and functional status: a prospective study. *American Journal of Public Health, 87*(3), 398–403.