FINAL PROGRESS REPORT

Biomechanics of Human Reactions to Slip Events
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Rakié Cham, PhD (PI)
Mark Redfern, PhD (Co-I)

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Human Movement and Balance Laboratory
Department of Bioengineering
University of Pittsburgh
740 Benedum Hall
3700 O'Hara Street
Pittsburgh, PA 15261
E-mail: chamr@upmc.edu
Tel: (412) 624-7227

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List of Abbreviations

Abbreviation	Definition
SD	Slip distance measured at the left heel (leading / slipping leg)
PSV	Peak slip velocity measured at the left heel
FFA	Angle between the left foot and the floor
FFAS	Rate of change of FFA
CAD	Cadence
GS	Gait speed
V_VEL	Vertical velocity of the left heel measured at heel contact onto the slippery floor
H_VEL	Horizontal velocity of the left heel measured at heel contact onto the slippery floor
SLR	Step length normalized to leg length
HS	Heel strike
TO	Toe Off
COM	Center of mass
NH	Non hazardous slip (PSV > 1m/s)
H	Hazardous slip (PSV > 1m/s)
AD	Alert Dry
BD	Baseline Dry
US	Unexpected Slip
BOS	Base of Support
CCI	Co-contraction Index
EMG	Electromyography
iEMG	Integrated EMG
MG	Medial Gastrocnemius
MH	Medial Hamstring
TA	Tibialis Anterior
VL	Vastus Lateralis

Abstract

Slip and fall accidents have been recognized to be of major importance in occupational health. Epidemiological studies have reported this problem being even more serious in older workers. In light of the aging dynamics of the labor force, the long term goal of this research project is directed at reducing slip-precipitated falls among older adults. The specific aims were (1) to investigate the differences in the biomechanics of slipping between young and older adults and (2) to examine the effect of slippery surfaces warnings on slip-related postural responses.

Forty subjects (21 F, 19 M) divided by gender and into two age groups were recruited in this study: "young" between the ages of 20 and 35 years and "older" aged 55 to 70 years old. Each subject was asked to walk on dry and glycerol-contaminated vinyl tile floors, while varying the extent of the a-priori knowledge of the floor's contaminant condition. Specifically, subjects were exposed to the following experimental conditions: (1) baseline

dry floors (subjects knew the floor was dry); (2) unexpected slippery floor (contaminant was applied to floor without subjects' knowledge); (3) alert dry or slippery (subjects were uncertain of the floor's condition), (4) known slippery (subject is aware of the slippery condition). Whole body data were collected at 120 Hz and synchronized with ground reaction forces and electromyographic data sampled at 1080 Hz. A 3D whole body model was developed, validated and used to derive various kinetic and kinematic gait parameters, which were entered as dependent variables in ANOVAs investigating age and warning safety conditions. Also, differences in these biomechanical variables were compared between hazardous and non-hazardous slips. This slip classification was based on a 1.0 m/s PSV threshold.

The analysis was divided into 2 parts. The first part related to Aim 1 and considered responses to an unexpected slip (reactive strategies). To date, the results based on the electromyographic (EMG) recordings made from the major muscles of the stance leg (leading / slipping leg) indicated that slip-initiated postural reactive strategies were similar in patterns between young and older adults. However, when experiencing a severe slip, young adults demonstrated a longer, more powerful response compared to older adults. Specifically, the patterns of the reactive strategies consisted of the activation of the Medial Hamstring and the Vastus Lateralis approximately 175 and 240 ms after HS onto the slippery floor, respectively. Corrective responses were scaled to slip severity with more severe slips generating longer, higher magnitude responses. Delayed Vastus Lateralis latency and Medial Hamstring cessation were associated with an increased slip severity as quantified by PSV.

The second part relates to Aim 2, i.e. the impact of slippery floors anticipation on gait biomechanics. The results based on the EMG recordings made from the major muscles of the stance leg, indicated that anticipation of a slippery surface resulted in a general increase in muscle activation magnitude (48% increase) and in ankle/knee co-contraction (30% increase), as well as earlier onsets and longer durations of posterior muscles. Young adults demonstrated earlier onsets and longer muscle activity duration than older adults reducing their slip potential.

Finally, we also have results linking slip severity to baseline gait characteristics. This information indicated that adults who normally walk with decreased CAD, greater SLRs, increased FFAs and faster FFASs are at a higher risk of experiencing a hazardous slip. A logistic regression model relating SLR and cadence to slip severity predicted ($R^2 = 0.45$, $\chi^2 = 15.30$, $p < 0.001$) that increased SLR and decreased cadence would result in increased probability of hazardous slip. A second logistic regression model relating FFA with slip severity predicted (chi-Square = 16.55; p = 0.005) that increased FFA would result in increased probability of hazardous slip. Additionally, adults with normal gait characterized by greater ankle co-contraction and delayed Tibialis Anterior onset near HS were predisposed to experience less severe slips when encountering an unexpected slippery floor. These findings indicate that older adults' natural gait predisposes them to experience a less hazardous slip. However, both young and older adults experienced hazardous slips at the same rate. These results indicate that baseline gait characteristics, i.e. initial conditions, are not the only contributors to slip severity in older adults. Furthermore, when initial conditions results are combined with the findings of Aim 1, it appears that post-slip reactions in older adults are the main contributors to slip severity in

The data analysis of the biomechanical data (e.g. joint moments) is not completed yet. We expect to have more results within the next few months.

Highlights and Significant Findings

To date, the findings can be summarized as follows:

1. The muscle activation patterns collected in unexpected slips support the hypothesis that post-slip corrective reactions generated at the knee and hip joints are most important in a successfully recovery attempt.

2. Reactive strategies consisted of activation of the MH followed by the VL muscles in the stance leg. The success of this strategy depended on the magnitude and timing of this response. Specifically, a delayed VL latency and MH cessation were associated with increased slip severity. Corrective responses were scaled to slip severity with hazardous slip reactions consisting of longer and magnitude responses.

3. Young and older adults adopted similar strategies to recover from unexpected slips. When experiencing a hazardous slip, young adults demonstrated a longer, more powerful response compared to older adults implying that older adults may have a higher incidence of falls because they cannot react with the power needed during a hazardous slip.

4. When adapting to a potentially slippery surface, adults significantly change their muscle activation patterns during gait. Specifically, anticipation of a slippery surface resulted in earlier onsets and longer durations of flexors muscles. Younger adults exhibited a greater ability to generate such adaptations compared to older adults. Additionally, alerting older and young adults of the possibility of a slippery surface resulted in increased muscle activations and co-contraction at the ankle and knee.

5. Gait characteristics under normal conditions (known dry) can be useful in the identification of individuals at a greater risk of experiencing a hazardous slip (longer steps, decreased ankle muscle co-contraction, decreased cadence and increased foot floor angle at heel strike).

6. Gait characteristics under normal conditions (known dry) are not the only predictors of slip severity. For example, in our study although older adults walked in a slip-related safer way compared to young adults, both age groups experienced the same number of hazardous slips, suggesting post-slip reactions are also important.

Translation of Findings

Although the data analysis procedures have not been completed yet, the results derived to date provide a better understanding of the reasons for epidemiolgical findings suggesting increasing in slip-initiated falls among older adults. For example, it appears that similar slip-initiated recovery responses are adopted by young and older adults. However, for severe slips, the magnitude of postural responses is greater in young adults than in older participants. Such specific deficiencies of slip-initiated responses in older adults can be the focus of more effective fall prevention and training programs. Additionally, by understanding the impact of slippery surfaces anticipation on gait, the results of this study may have direct implications in the possible implementation of safety warning guidelines. The complete potential for translational findings will be reported explicitly in publications when the data analysis is completed.

Scientific Report

Project Status

As mentioned in the Abstract section, the specific aims of this project were (1) to investigate the differences in the biomechanics of slipping between young and older adults and (2) to examine the effect of slippery surfaces warnings on slip-related postural responses. Although we feel we have reached several milestones in this project, we also acknowledge progress was made at a slower rate than originally anticipated. In addition to a major upgrade of our motion analysis system during the period of the project, the main source of the delay relates to the data processing procedures. The time required to process 3D biomechanical data was simply unforeseen, thus we proposed an unrealistic original timeline based on our experience processing 2D data. Also, personnel training to process 3D biomechanical data also took longer than expected.

The following milestones were achieved:

1. Data collection has been completed. We collected more variables than originally proposed. For example, EMG recordings from the major muscle groups in the trailing leg and leading/stance leg have been sampled.

2. Data processing is complete. To process the motion and kinetic data, a 3D whole body biomechanical model was developed and tested (a technical report describing not only the model but also the overall data processing flow is available if needed).

3. Data analysis and results write-up are only partially completed as reported in "Scientific Report 1" and "Scientific Report 2". We expect to complete and publish the remaining of the results within the next year (the reader is referred to the section entitled "Publications / in preparation" for a list of anticipated manuscripts).

Scientific Report 1: Findings related to Aim 1 and Aim 2

The first set of findings reported in Scientific Report 1 relates to Aim 1 and Aim 2 of the project and is focused on muscle activation patterns of the stance/leading/slipping (left) leg generated in response to slipping and in anticipation of slippery surfaces. Muscle activation patterns reveal insights into how corrective reactions are generated and carried out when balance is unexpectedly perturbed by an unanticipated slip (reactive strategies). We also differentiated lower extremity muscle responses between slip events that are likely to lead to a fall (hazardous slips by a PSV greater than 1.0 m/s) and successful gait strategies (non-hazardous slips characterized by a PSV less than 1.0 m/s). Also, investigating the correlation between muscle activation patterns when anticipating a slippery floor provides information about how people change their gait to reduce the likelihood of a slip (proactive strategies).

As mentioned previously, we have not completed all analyses yet. We expect to publish the results within the next year.

Objectives

Objective 1 (reactive strategies): To identify the stance leg's muscle activation patterns in the stance leg generated in response to an unexpected slip, and to investigate differences in these patterns between young and older adults.

Objective 2 (proactive strategy): To investigate the proactive activation patterns of stance leg muscles in anticipation of a slippery floor, and to examine differences in these patterns between young and older adults.

Background: Scope of the problem of falls

Falls precipitated by slipping are a major cause of injury. Slips accounted for the second cause of death resulting from accidents in the United States [30]. In 1999, over one million people in the United States suffered a slip, trip or falling injury. The National Safety Council reported 14,500 deaths due to falls and listed falls as the third ranked cause of unintentional injury deaths in the general population of the United States [69]. Slips are the most frequent event leading to fall and overexertion injuries in Sweden [22] and the most common fall initiating event for employees in the United Kingdom [31]. Britain ranked slips, trips and falls as the most frequent type of event, accounting for 29.8% of all reported injuries occurring on the same floor level [38].

Injuries afflicted by falls are common and often severe. The Bureau of Labor Statistics reported 303,800 occupational fall injuries in 2000. Nearly 30% of workers that sustained falling injuries missed 31 days at work or more [6]. Approximately one-fifth of injury-related emergency department visits, the single largest fraction of such visits, are attributed to falls [61]. Falls are often listed as the leading cause of work-related disabling conditions including about 44% of fractures and 45% of multiple injuries. The severity of fall-related injuries partially explains their substantial contribution to medical care costs associated with compensation payments in US industry. Leamon and Murphy attributed 24% of the direct cost of all claims filed during the years 1989 and 1990 to fall-related injuries. Over 65% of these claims were contributed to falls resulting in an average cost of $4,363 per claim [48]. According to the United States Department of Labor, 15% of accidental deaths in the workplace are caused by slips, trips and falls accounting for 12 to 15% of all Workers' Compensation costs [6]. The annual direct cost of all fall-related occupational injuries in the US alone was estimated to be approximately six billion dollars [22]. Thus, the prevention of such injuries is a high occupational and public health priority.

The incidence, as well as severity, of falls increases with age in the general population. Slips and trips cause 32% of falls sustained by the young while causing 67% in the elderly [50]. A ten-fold increase in the incidence of falls was reported in the elderly (65+) compared to younger individuals [106]. Estimates of the average annual risk of falling in older adults over the age of 65 years range from 30% to over 50% [5,91,108,109]. Falls are often listed among the leading causes of serious unintentional injuries, disability and death among older adults [23,45,45,46,46,56,56,89,89]. Injury is the fifth leading cause of death in older adults. The majority of these fatal injuries are related to falls [40,42,89,107]. Based on the demographic aging trends of the United States population in 1995, Englander et al. have projected the number of falls to increase by more than 25%

between 1995 and 2020 [28]. This can also been seen in other industrialized societies with aging populations [40,41,107]. Thus, as the labor force ages, falls among older adult workers are becoming an increasingly serious health problem.

This trend can already be seen as the fraction of occupational-related non-fatal injuries and deaths attributed to falls increases with age [6]. More than 30% of the total economic cost of falls in the older population in the United Kingdom is attributed to falls [92]. Personick and Windau suggested that older workers are at a greater risk of non-fatal injuries resulting from slips [79]. The risk of a slip, trip or fall accident is 1.5 times greater in workers over the age of 56 years compared to workers between the ages of 21 and 25 years [8]. Older adult workers are at a higher risk of facing fatal fall-related work injuries.

In summary, epidemiological findings indicate that slips, trips and falls are a leading cause of injuries and source of high economic costs, both of which increase with age. Slips and falls are of major importance in occupational health as well. Findings suggest that older workers are less able than young workers to recover balance after a slip resulting in higher injury and fatality rates. The aging workforce creates occupational environments and demographics that did not exist previously. However, the increase in occupational fatal falls cannot be explained merely by demographic changes [43]. It is important for injury prevention to gain a clearer understanding of the factors responsible for slipping and recovery. Specifically, the neuromuscular and biomechanical factors associated with failed slip recoveries in older adults remain unclear. The first set of findings focused on the impact of slipping on leg muscle activation patterns and the effects of age and anticipation of slippery surfaces. The insight gained from this project may provide an understanding of the underlying neuromuscular and biomechanical factors that contribute to the epidemiology findings summarized in this section. Additionally, this information may be important in the development of fall prevention programs.

Background: Previous experimental research

Gait involves the integration of complex processes necessary to initiate human movement and maintain balance [9,10,63,78,86,87,99]. In particular, walking requires the ability to change locomotion patterns in response to external perturbations that threaten dynamic equilibrium [93]. Much research has been done investigating the biomechanical responses during base of support translations [57,100-102], trips [75,76], and release from forward lean [103,105,114,115]. Researchers have also considered corrective reactions during support surface translation protocols designed specifically to simulate real slip events [37,100-102]. However, it is unclear whether active anterior BOS translation, used in these investigations to simulate naturally occurring slips, actually evoke motor muscle patterns [15,17,67,71].

In order to avoid a fall after an unexpected slip event, the body must generate a quick and effective corrective response to re-establish dynamic balance and maintain an upright posture while continuing locomotion (reactive strategies). Slip-initiated reactive strategies first included increased flexion moments at the knee and extensor activity at the hip around 25% stance followed by knee extension moment and hip flexion moments around 40% stance [12]. The initial reaction of increased knee flexion and forward rotation of the shank were seen in an attempt to bring the foot back towards the body [12]. Secondary reactions of knee extension are thought to be a compensatory reaction to avoid knee buckling and continue gait by progressing the center of mass over the BOS [12]. The ankle was found to act as a passive joint and was not important in a successfully recovery attempt [12]. Therefore, for the purpose of this project, it was hypothesized that increased magnitude and activation of the muscles responsible for corrective reactions at the knee and hip, VL and MH, would be important in recovering from an unexpected slip.

Surface EMG analysis has been used successfully to study the neuromuscular characteristics of reactions strategies elicited in response to an external perturbation during gait. In contrast to responses to standing perturbations, recent evidence suggests that there exists a more active control of the hip and knee compared to the ankle of reactive strategies during tripping [27] and mechanical perturbations consisting of a forward translation [29]. Tang found, using a BOS translation, that both the lower leg and thigh muscles demonstrated earlier onset, higher magnitude, and longer duration compared to normal gait [60,100-102]. Additionally, Oates recorded increased activity in both the upper and lower leg muscles during a slip to provide support to the lower limbs and correct balance [70]. In general, a reactive strategy to an unexpected perturbation, BOS translation, in young healthy adults consists of an early (60-90 ms) and coordinated postural response of considerable magnitude (4-9 times normal walking) from both legs [25-27,68,70,101]. Based on the literature regarding muscle responses to perturbations during gait and preliminary findings of this research, there should exist significant differences in temporal and magnitude aspects of muscle activity during a naturally occurring slip compared to gait on dry floors.

Proactive strategies are defined as balance control mechanisms that take place before the body encounters a potential disturbance [60,74,102]. Individuals have demonstrated a modification of their gait and response strategies when knowledge is provided about the surface characteristics [14,14,67,118]. Rand et al. noted a change in step length and anterior-posterior sway as an adaptation to treadmill perturbations [82]. Modifications of step width and foot clearance were demonstrated after forewarning of a possible trip [80]. Feedforward adaptations were seen in controlling the center of mass during sit-to-stand perturbations. Subjects adapted their performance in a manner that significantly decreased their overall likelihood of balance loss [72]. Tang showed that the use of proximal muscles faded away with repeated exposure, suggesting the fine-tuning of a proactive strategy and possible overcompensation during the initial simulated "slip" [101]. Increased duration and coordination of lower leg muscle activity was also seen as an adaptation [82]. Shortened stride length was noted when walking on oily floors [67]. Reduction in stance duration, reduced foot-floor angle and slower vertical heel velocity at HS were noted during anticipation of a slippery surface [14,17]. These gait adaptations led to a significant reduction in joint moments at the knee (extension) and hip (flexion) [14]. These adaptations resulted in an overall reduction in slip potential [9,10,14,34,84,85,99].

Little is known about aging effects on biomechanical and neuromuscular variables affecting recovery from an unexpected naturally occurring slip (reactive strategies). Lockhart et al. have investigated the effects of age on a limited number of gait variables during walking on oily floors and reported increases in heel velocity at HS, SD and slipping velocity in older adults [54,55]. Unfortunately, this study did not investigate the biomechanics and temporal profiles of corrective responses. These differences in the recovery biomechanics are postulated to be one of the underlying reasons for the older workers' reduced ability to prevent slip-initiated falls.

It is possible that the high rate of fall incidence might be reduced by training older adults to better recover from or adapt to perturbations, i.e. improving proactive strategies. Older adults typically exhibit poorer performance [47] and are unable to adapt [96]. Given these differences in older and young adults, it should be determined whether older adults adjust differently to a naturally occurring slip by choice or necessity. Pavol has found that older adults learned to avoid falling through a proactive strategy similar to that used by young adults [73,74]. This is not always the case. Woollacott found that older adults shortened their stride length after a perturbation compared to young adults. This can be partially accounted for by the increased co-contraction of the upper leg in older adults. Older adults also showed a decrease in duration of muscle activation compared to their younger counterparts [116]. Thus, it was hypothesized that older adults would demonstrate delayed onsets accompanied by shorter durations and increased co-contraction compared to their younger counterparts.

Methods

Subjects: Two age groups of participants (55 to 66 years old AND 20 to 26 years old) participated in this project (Table 1). Prior to participation, each individual signed a consent form approved by the University of Pittsburgh Institutional Review Board. Initially, a 30-minute neurological screening was performed by Dr. Joseph Furman, a neurologist specializing in balance disorders. Exclusionary criteria included a history of neurological, orthopedic, cardiovascular, pulmonary abnormalities and pregnancy as well as any other difficulties hindering normal gait. During the gait session, participants were equipped with a safety harness to prevent them from hitting the ground in case of an irrecoverable balance loss. This harness has been used in previous research and has proven to be safe without impeding natural walking [34,86].

Table 1: Subject Characteristics

Mean (SD) [Range]	Young	Old
Age (yrs)	23.27 (1.95) [81]	60.44 (3.50) [81]
Weight (kg)	70.53 (13.82) [81]	72.33 (14.44) [45.54-86.82]
Height (m)	1.71 (.06) [1.64-1.86]	1.64 (.08) [81]

Environment: The Human Movement and Balance Laboratory at the University of Pittsburgh is designed to capture and analyze human motion especially gait. The data acquisition system used to collect gait variables consisted of the two Bertec force plates (type 4060a) and a Vicon 612 system that employs eight IR M2-cameras. Bilateral leg muscle EMGs for the VL, MH, TA and MG muscles were collected using bipolar Ag/AgCl surface EMG electrodes (Noraxon) and a Noraxon Telemyo 8-channel electromyography system, internal cutoffs 10-500 Hz. Analog signals were recorded at 1080 Hz from a 12-bit National Instruments A/D converter and synchronized to the marker data, collected at 120 Hz using the Vicon Motion Analysis System. Additionally, a SONY digital camcorder was used to collect videos of each trial.

Gait Path: Participants walked along a level vinyl tile (Armstrong commercial tile pattern 51903) pathway which allows for a walking distance of approximately 8 m. Two Bertec force plates are embedded into the floor midway along the gait path such that one foot hits each plate. Both plates are equipped with the same vinyl tile as the floor. Both plates measure 0.6m x 0.4m however, the second plate was extended by 15 centimeters to allow for longer slip distances (Figure 1). The data acquisition system consisted of the two Bertec force plates mentioned previously and a Vicon 612 system with eight, IR M2-cameras collecting data at 1080 Hz and 120 Hz, respectively. The eight Vicon cameras were positioned around the room such that a capture volume of 6.6 m x 2 m x 2 m was generated above the force plates.

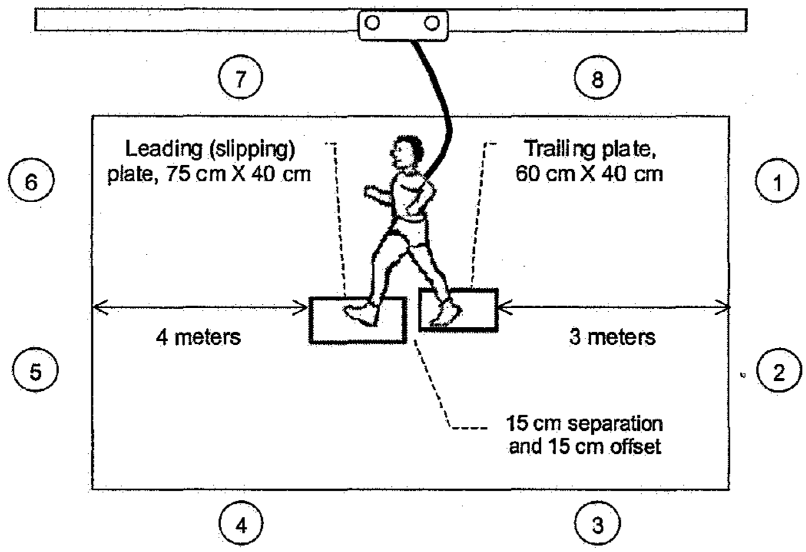

Figure 1: Schematic gait path layout. Circled numbers represent camera placement. Rectangles are embedded force plates. Trolley and harness system are also shown.

Electromyography Setup: Bilateral leg muscle EMG data, VL, MH, TA and MG, were collected using bipolar Ag/AgCl surface EMG electrodes (Noraxon) and a Noraxon Telemyo 8-channel electromyography system, internal cutoffs 10-500 Hz. The participant's skin was shaved, if necessary, abraded and cleaned with an alcohol swab before the electrodes were positioned. Electrodes were positioned over the muscle belly with an inter-electrode distance of 3 cm (Figure 2). Proper placement was confirmed using a simple exertion test. Analog signals, sampled at 1080 Hz, were synchronized to the Vicon marker data, collected at 120 Hz.

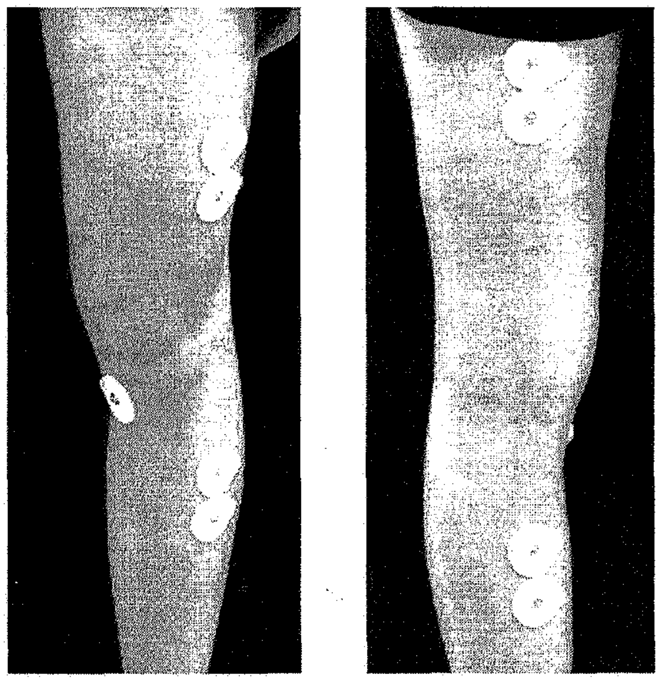

Figure 2: Picture of the stance (left) leg EMG placement. Frontal view is provided on the left showing VL, TA and ground electrodes. Posterior view is provided on the right showing MH and MG electrodes.

Harness: As mentioned previously, a harness system coupled to an overhead trolley system was employed in case of an irrecoverable balance loss. The trolley is controlled by a trained researcher to match the forward progression of the participant. This type of harness system has been proven to fit comfortably without impeding participants' movement in a number of gait studies [34,86]. It prevents contact with the ground and any resulting injury after a loss of balance.

Subject Clothing: All participants wore spandex shorts and a sleeveless spandex top to optimize marker placement and minimize motion artifacts. Additionally, participants all wore the same brand and model of polyvinyl chloride soled shoes, a common shoe sole material in the workplace. Multiple sizes were available to assure a comfortable fit. To prevent cross-contamination between trials, participants wore a clean pair of shoes after each contaminated trial. All heels and soles were mechanically abraded to simulate normal wear prior to use.

Contaminant: To generate slips a contaminant was uniformly applied to the leading force plate, which was contacted by the left foot. The contaminant consisted of a 75% glycerol to 25% water solution. Glycerol is water soluble, clear, and odorless allowing its application to be easily concealed from the subject. Glycerol has been widely used in slip resistance testing [20]. The slip index of the vinyl tile, with and without the contaminant, was measured with the English XL slip meter device. The dry vinyl tile was measured as .55, while the tile with the contaminant was measured at .03.

Experimental protocol: All participants were exposed to the same walking protocol. The participant's body was instrumented with the electrodes and reflective markers. The participant was then equipped with the safety harness and allowed to practice walking as the researcher varied the starting point. This was done such that each foot struck one plate, with the left foot hitting the leading plate that would be contaminated during the slippery conditions. During this process, the participant was instructed to look straight ahead and walk as naturally as possible at a self-selected comfortable pace throughout the experiment.

The lights were dimmed to minimize unwanted reflections and detection of a contaminant by the participant. Once a participant comfortably negotiated the gait path with both feet repeatedly hitting the appropriate force plates naturally, the data collection began. The participant was instructed (prior to each gait trial included in the experiment) to walk to the start of the gait path, face away from the walkway and listen to loud music for one minute, distracting him or her from the possible application of a diluted glycerol solution onto the floor. At the end of this one-minute waiting period, the participant turned and walked forward while data were recorded.

The participant was informed that the first few trials would be non-slippery to ensure natural gait. Two to three dry trials were collected, "baseline dry" (BD). Then, without the participant's knowledge, the diluted glycerol solution (75% glycerol: 25% water) was applied to the floor of the leading, left foot, force plate and another gait trial was conducted, "unexpected slip" (US). After the unexpected slippery trial, no more information regarding the floor's contaminant condition was revealed for the next six trials. Thus the subject did not know the floor's condition, but was informed that there was a possibility of the contaminant being applied. Five dry trials were collected, "alert dry" (AD) followed by one "alert slip" trial and a "known slip" (subject is fully aware of slippery nature of the floor). Only US and the first two trials in the AD conditions were considered for here to minimize any adaptation effects AD trials were analyzed here

Data Processing: Heel contact and toe off were identified from ground reaction forces. EMGs were rectified and filtered at 50 Hz using a phase-less elliptical filter [35]. After filtering, EMGs were time normalized with respect to the left foot with 0% being HS and 100% as TO. The mean stance duration was 834 (341) ms. Each channel was peak normalized within subject using the average maximum calculated across the BD condition during the gait cycle [39].

Dry Trials: Onsets and offsets were determined automatically using a threshold of two standard deviations above activity during a typically quite period of the gait cycle and visually confirmed (Table 2). Duration was calculated from the difference of the offset and onset for each muscle. The magnitude of muscle activity was determined from the integrated EMG (iEMG), calculated by taking the integral from onset to offset. Co-contraction index (CCI) was calculated based on the integrated (from -20% to HS and from HS to 20% into stance) ratio of the EMG activity of antagonist/agonist muscle pairs (TA/MG and VL/MH) using a modified version of the equation proposed by Rudolph [90]. The equation was modified slightly to account for time (Equation 1). Lower EMG refers to the level of activity in the less active muscle and Higher EMG refers to the activity of the more active muscle. This was done to avoid division by zero. The ratio was then multiplied by the sum of the activity found in the muscle pair. This provides an estimate of the relative activation of the two muscles as well as the magnitude of the co-contraction. The resulting curve was then integrated over the pre-HS (-20% to HS) and post-HS (HS to 20%) time periods. This value was divided by the time period, 20%, and the resulting index has a maximum value of two.

Table 2: Dependent Variables: Dry Trials

Temporal	Integrated	Other
Onset	CCI	Slip Outcome[§]
Offset	Magnitude	PSV
Duration		

[§]Each slip was classified as Non-Hazardous or Hazardous.

$$CCI = \frac{\int_{i=0\%}^{i=20\%} \frac{Lower\ \ EMG_i}{Higher\ \ EMG_i} \times \left(Lower\ \ EMG_i + Higher\ \ EMG_i\right)}{20\%} \quad \text{(Equation 1)}$$

Contaminated Trials: Contaminated trials were categorized into non-hazardous (NH) and hazardous (H) by considering PSV. Peak slip velocity (PSV) was identified as the first local maximum horizontal velocity after 50 ms from heel strike using the velocity of the slipping heel virtual marker. Hazardous slips were defined as having a PSV greater than 1.0 m/s. The last trial of the BD condition was subtracted from the US trial within subject providing a difference in muscle activation during slipping. Reactive onset and cessation were determined automatically using a threshold of two standard deviations above activity of the difference during a quite period of gait and visually confirmed. In certain cases, muscle activation continued after a fall occurred. In these situations, cessation was set to the time at which a fall occurred. Latency is defined as the time between HS and reactive onset. The reactive duration was calculated from the difference of the cessation and reactive onset for each muscle. The reactive magnitude of muscle activity was determined using the iEMG of the difference in activation during slipping, calculated by taking the integral from onset latency to cessation (Table 3).

Table 3: Dependent Variables: Contaminated Trials

Temporal	Integrated	Other
Latency	Reactive Magnitude	Slip Outcome[§]
Cessation		PSV
Reactive Duration		

[§]Each slip was classified as Non-Hazardous or Hazardous.

Statistical analysis: An outlier analysis and normality check was performed on all experimental data. A significance level of $p \leq 0.05$ was used throughout the analysis. In objective 1, in order to differentiate the EMG response to the slip from baseline gait activity, the muscle activity collected during the BD trial immediately preceding the slip was subtracted from the data recorded in the unexpected slip. Latency, cessation and reactive magnitude were found. Linear ANOVA models were fit with the latency, cessation and reactive magnitude as an outcome (one model per outcome variable), and with age (young/old), hazard (H/NH) and muscle as explanatory fixed effects (between muscle model). This model also included the first order interaction terms of these fixed effects. Appropriately constructed post-hoc Tukey comparison tests were also performed as needed.

Additional analyses (within-muscle) were conducted to achieve objective 1. Linear ANOVA models were fit with the muscle-specific EMG response variable of interest as outcome (one model/outcome), and age (young/old), hazard (H/NH) as fixed effects including their interaction term. If the interaction term of age group and hazard was significant, appropriately constructed post-hoc Tukey comparison tests allowed statistical comparisons between young and older subjects in terms of difference in outcomes when subjected to hazardous and non-hazardous slips.

In objective 2, mixed linear ANOVA models were fit with the muscle-specific EMG response variable of interest as outcome, anticipation condition (BD/AD) and age group (young/old) as fixed effects, subject within the age group as a random effect (two to three baseline trials per subject were averaged while two alert trials were averaged and included in the model), and fixed effect interaction terms. If the interaction term of age group and anticipation condition was significant, appropriately constructed post-hoc Tukey comparison tests allowed statistical comparisons between young and older subjects in terms of difference in outcomes under BD and AD conditions.

Results: Objective 1

Young and older adults experienced hazardous slips at about the same rate: 64% (7/11) for younger subjects and 67% (6/9) for older subjects. None of the slip events that were classified as non-hazardous based on the 1 m/s PSV threshold resulted in falls, while hazardous slips resulted in some recoveries, some falls, slips off the force plate, or harness-assisted recoveries.

Qualitative Description To determine the sequence of muscle activations utilized in a reactive strategy, linear ANOVAs were conducted on the latency using age (young/old), hazard (H/NH), muscle and their interaction effects as independent variables. The initial reaction to an unexpected slip consisted of the activation of the MH (21.9% stance, 175 ms), TA (24.2% stance, 189 ms), MG (26.1% stance, 219 ms) and VL (29.1% stance, 239 ms). Overall, the MH was activated significantly sooner than VL and MG and the VL was activated after the MH and TA ($p = .0021$, Figure 3).

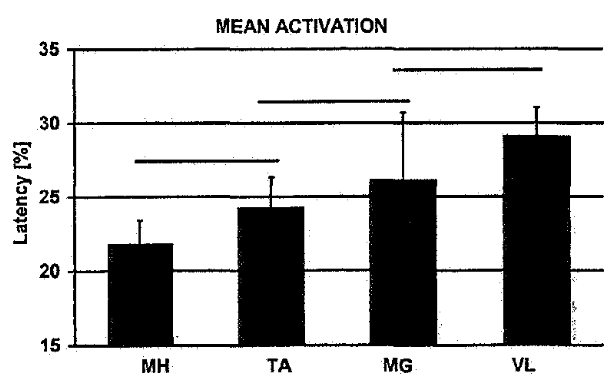

Figure 3: Mean activation latencies of postural reaction in percent time of stance leg muscles in response to a slip. Non-significant results of post-hoc Tukey tests are provided (-). SE bars given.

Linear ANOVAs were conducted on the cessation and reactive duration using age (young/old), hazard (H/NH), muscle and their interaction effects as independent variables. In general, hazardous slips were associated with significantly later cessations ($p = .0113$) and longer reactive durations ($p = .0165$, Figure 4, Figure 5). Young adults showed significantly later cessations ($p = .0230$) and longer reactive durations ($p = .0234$) during hazardous slips compared to older adults.

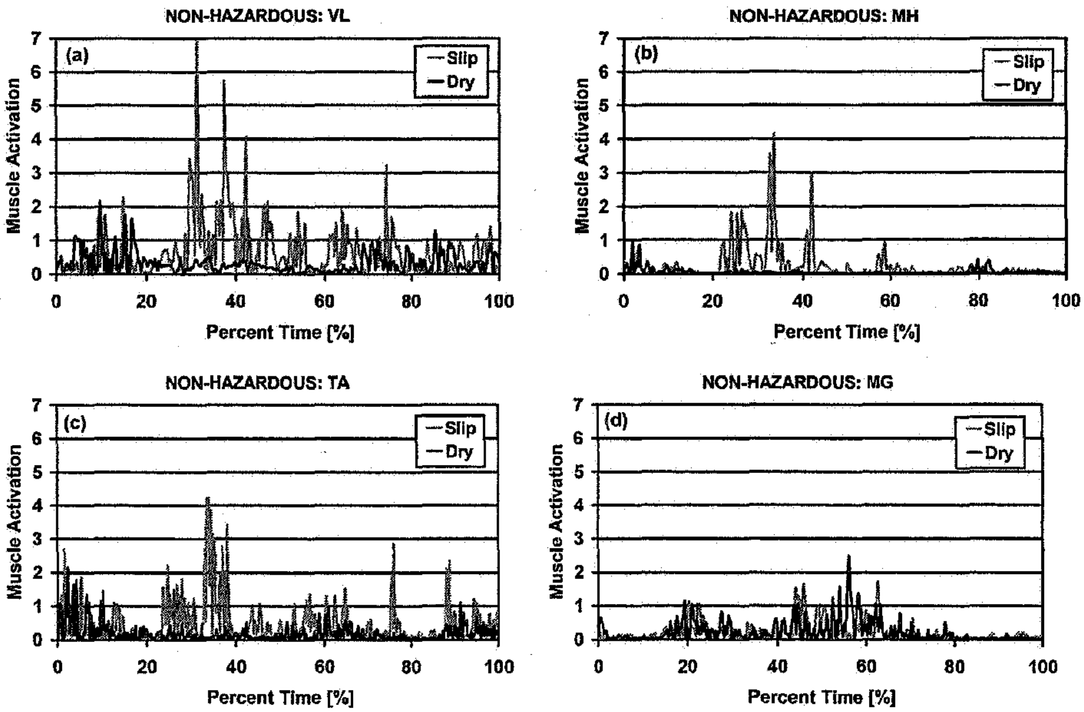

Figure 4: Typical muscle activation patterns during a non-hazardous slip (gray) and one baseline dry gait trial (black). (a): VL, (b): MH, (c): TA, (d): MG. Muscle activity was magnitude normalized to the peak during baseline gait and time normalized to stance with HS being 0% and TO as 100%. The end of slip was recorded at 27.4 % stance.

It was noted that all muscles demonstrated a positive reactive magnitude during slipping (Figure 4, Figure 5). Overall, hazardous slips had increased reactive magnitude compared to non-hazardous slips ($p = .0001$, Figure 4, Figure 5). Generally, adults activated their upper leg muscles with significantly more reactive magnitude, compared to their activity during normal gait, than their lower leg muscles ($p < .0001$). Hazardous slips were also characterized by higher reactive magnitude across muscles compared to non-hazardous slips in young adults compared to older adults ($p = .0288$).

EMG differences between Hazardous and Non-Hazardous Events: Trials were categorized into hazardous and non-hazardous by considering the peak velocity of the heel during a slip. Hazardous slips were defined as having a PSV greater than 1.0 m/s. Young adults experienced hazardous slips at a rate of 64% (7/11). Older adults experienced hazardous slips at a rate of 67% (6/9).

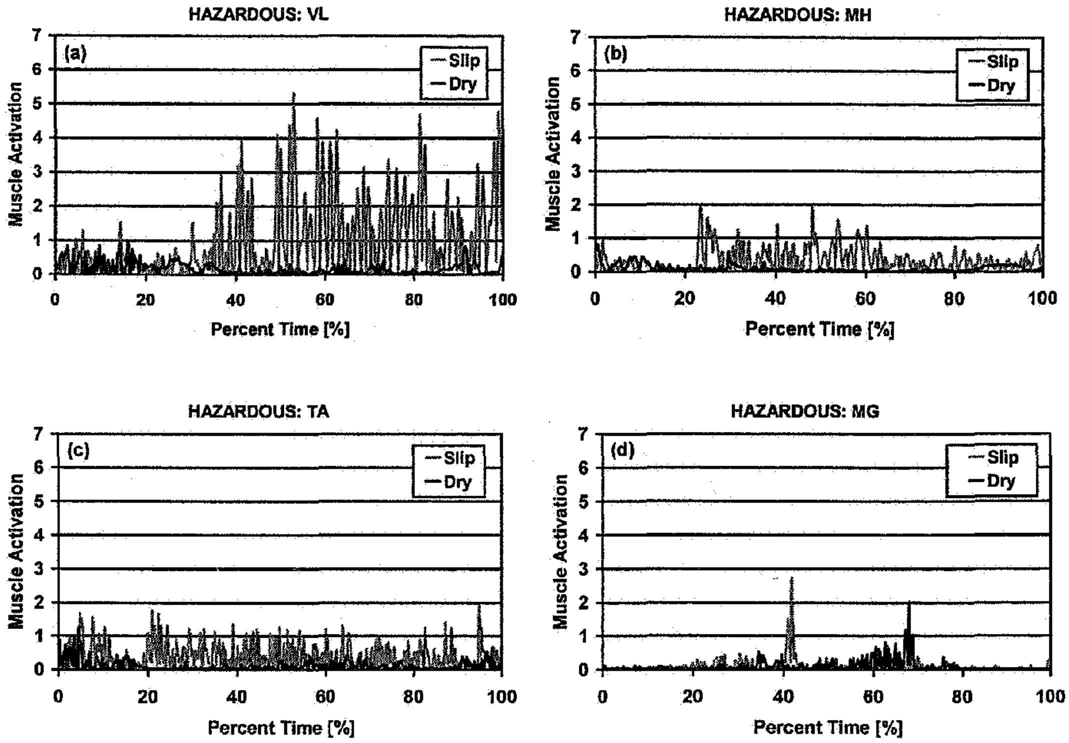

Figure 5: Typical muscle activation patterns during a hazardous slip (gray) and one baseline dry gait trial (black). (a): VL, (b): MH, (c): TA, (d): MG. Muscle activity was magnitude normalized to the peak during baseline gait and time normalized to stance with HS being 0% and TO as 100%. The end of slip was recorded at 54.4 % stance.

Temporal Aspects of Muscle Activity: Similar temporal patterns of muscle activation strategies were noted between young and older adults (Figure 6). Linear ANOVAs were conducted on the latency using age group, hazard (H/NH) and their interaction effect as independent variables to investigate differences in corrective reactions between hazardous and non-hazardous slip. Interestingly, adults that experienced hazardous slips activated their VL significantly later than those who experienced non-hazardous slips (Figure 6a, Table 4).

Young adults showed later cessations and longer reactive durations compared to older adults. Specifically, ANOVAs conducted on the cessation and duration using age group, hazard (H/NH) and their interaction effect as independent variables revealed that significantly longer reactive duration and delayed cessation were noted in the TA during hazardous slips (Figure 6, Table 5). This tended to occur in the MH as well (Table 4).

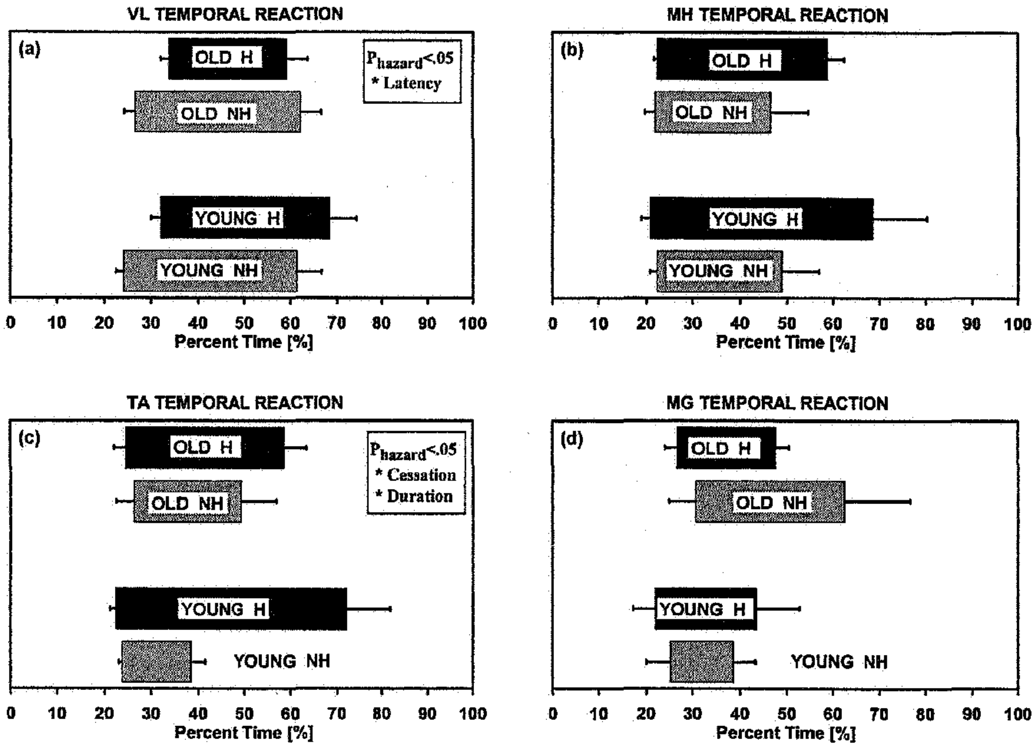

Figure 6: Temporal aspects of muscle activation during reaction to an unexpected slip. (a): VL, (b): MH, (c): TA, (d): MG. The BD trial before the US trial was subtracted from the US trial leaving the reactive activity. Bars represent reactive onset and cessation of muscle activity. Older adults are shown on the top while young adults are on the bottom. Black bars correspond to hazardous slips and gray bars are non-hazardous slips. Overall significance is given in top right corner of each graph. SE bars given.

Table 4: Temporal Reaction Statistics: Upper Leg Muscles

	VL			MH		
	Latency	Cessation	Reactive Duration	Latency	Cessation	Reactive Duration
Age						
Hazard	.0021				.0609	
Interaction						

** Only p values < 0.1 are presented.*

Table 5: Temporal Reaction Statistics: Lower Leg Muscles

	TA			MG		
	Latency	Cessation	Reactive Duration	Latency	Cessation	Reactive Duration
Age					.0820	
Hazard		.0057	.0041			
Interaction		.0843				

** Only p values < 0.1 are presented.*

Reactive Magnitude: Linear ANOVAs conducted on the reactive magnitude using age group, hazard (H/NH) and their interaction returned both MH and TA as having significant increases in reactive magnitude during hazardous slips (Figure 7, Table 6).

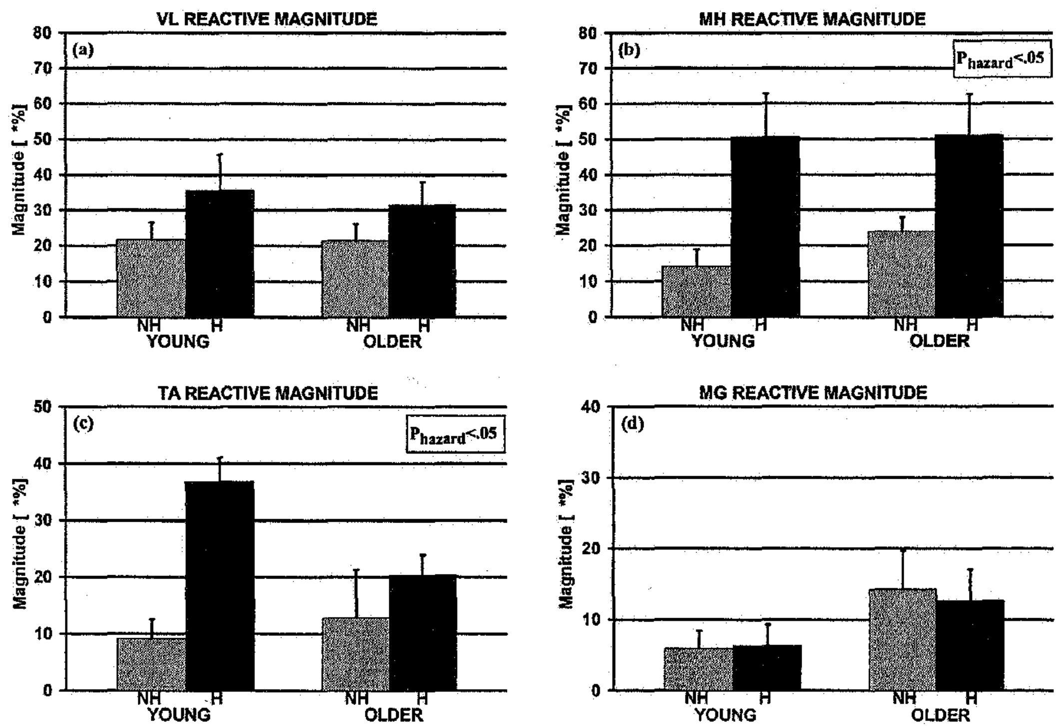

Figure 7: Reactive magnitude of muscle activation during reaction to an unexpected slip. (a): VL, (b): MH, (c): TA, (d): MG. The BD trial before the US trial was subtracted from the US trial leaving the reactive activity. Bars represent reactive magnitude. Young adults are shown left while older adults are on the right. Black bars correspond to hazardous slips and gray bars are non-hazardous slips. Overall significance is given in top right corner of each graph. SE bars given.

Table 6: Reactive Magnitude Statistics

	VL	MH	TA	MG
Age				
Hazard		.0124	.0026	
Interaction			.0527	

** Only p values < 0.1 are presented.*

Results: Objective 2

Following an unexpected slip, no more information regarding the floor's contaminant condition was revealed for the next trials. The participant did not know the floor's condition, but was informed that there was a possibility of the contaminant being applied.

Only the dry trials will be analysed. Onset, offset, duration and magnitude of muscle activity were determined. Anticipation effects were investigated using mixed linear ANOVAs conducted on the onset, offset, duration, magnitude and ankle and knee co-contraction using age (young/older) and anticipation condition (BD/AD) as fixed effects, subject within the age groups as a random effect and their interaction terms as independent variables. Tukey comparison tests were performed to further investigate differences due to the effect of interaction, if the factor was significant.

Temporal Aspects of Muscle Activity: Younger adults activated their MH significantly earlier in stance compared to older adults (Table 7). Additionally, younger adults activated their MH significantly longer when anticipating a slippery surface compared to older adults (Figure 8b, Table 7). Younger adults tended to utilize a similar strategy when activating their TA longer during AD (Figure 8c, Table 8).

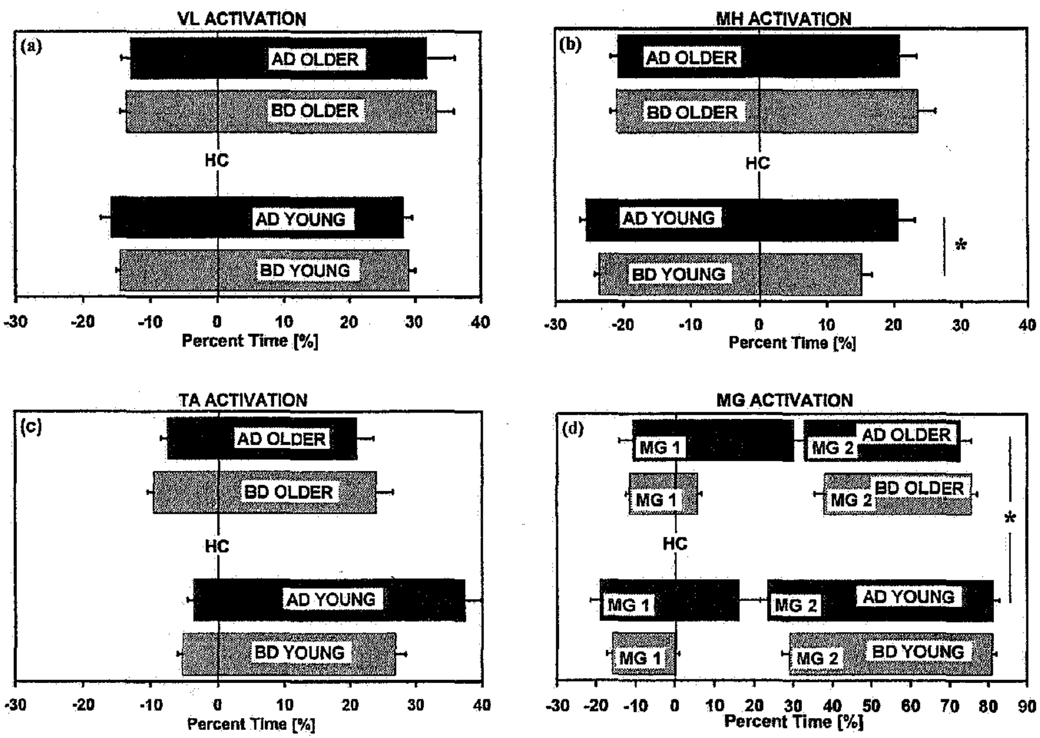

Figure 8: Temporal effect of anticipation on muscle activations during gait. Bars represent reactive onset and offset of muscle activity. (a): VL, (b): MH, (c): TA, (d): MG, MG 1 shown on left and MG2 shown on right. MG 1, was found in 54% of young adults and 67% of older adults. Older adults are shown on the top while young adults are on the bottom. Black bars correspond to alert dry and gray bars are baseline dry. Please see tables 7 and 8 for significance. Significant results of post-hoc Tukey tests of offset are provided (*). SE bars given.

During AD condition, notably more subjects activated their MG around HS, termed MG 1. In addition to the four young adults and one older adult who adopted these patterns during normal conditions (known dry), two more young adults and five additional older adults activated their MG around HS, resulting in a total of six young adults (54%) and six older adults (67%) that utilized this strategy. Activation of the MG 1 lasted significantly longer during AD compared to BD (Table 8). Regardless of MG 1 activation, younger adults tended to activate their MG 2 sooner than older adults as well as significantly longer (Table 8). When warned of the possibility of a slippery surface, both young and older adults activated their MG 2 significantly sooner and maintained activation for a longer period of time (Figure 8d, Table 8). Additionally, when anticipating a slippery surface, older adults' offset occurred significantly sooner in stance than young adults (Table 8). Anticipation had no significant effect on the activity of the VL in both the young and older adults (Figure 8a, Table 7).

Table 7: Temporal Aspects of Muscle Activity Statistics: Upper Leg Muscles

	VL			MH		
	Onset	**Offset**	**Duration**	**Onset**	**Offset**	**Duration**
Age				.0214		
Condition						
Interaction					.0060	.0011

Only p values < 0.1 are presented.

Table 8: Temporal Aspects of Muscle Activity Statistics: Lower Leg Muscles

	TA			MG 1			MG 2		
	Onset	**Offset**	**Duration**	**Onset**	**Offset**	**Duration**	**Onset**	**Offset**	**Duration**
Age							.0642	.0205	.0003
Condition					.0580	.0323	.0006		.0401
Interaction		.0769	.0509					.0465	

Only p values < 0.1 are presented.

Magnitude and Co-contraction: Magnitude was calculated as the iEMG from onset to offset of each muscle. In general, except for TA, alerting older and younger adults of the possibility of a slippery surface resulted in increased magnitude of activation (Table 9). The greatest increase in magnitude was noted in MH and MG 1 (Figure 9). Also, young adults increased their MH magnitude significantly more than older adults when anticipating a slippery surface (Table 9).

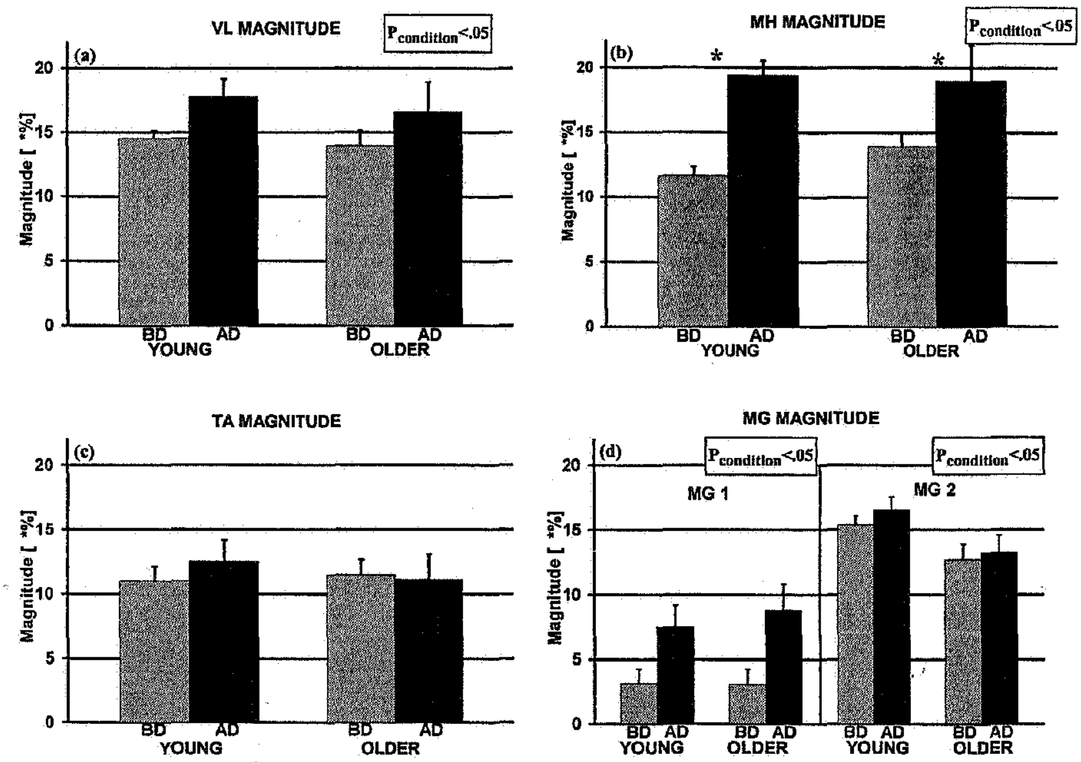

Figure 9: Magnitude effect of anticipation on muscle activations during gait. (a): VL, (b): MH, (c): TA, (d): MG, MG 1 shown on left and MG 2 shown on right. Young adults are shown on the left while older adults are on the right. Black bars correspond to alert dry and gray bars are baseline dry. Overall significance is given in top right corner of each graph. Significant results of post-hoc Tukey tests are provided (*). SE bars given.

Table 9: Magnitude Statistics

	VL	MH	TA	MG 1	MG 2
Age					
Condition	.0007	<.0001		.0462	.0552
Interaction		.0119			

Only p values < 0.1 are presented.

Anticipation resulted in a significant increase of co-contraction at the ankle and knee in both age groups (Figure 10, Table 10). There were no interaction effects of age and condition. Pre-HS co-contraction increased by an average of 27.5 % at the ankle and 27.7% at the knee during AD conditions across both age groups (Figure 10a, Figure 10c). Similarly, anticipation resulted in an average increase of 30.5 % at the ankle and 35.9% at the knee of post-HS co-contraction (Figure 10b, Figure 10d).

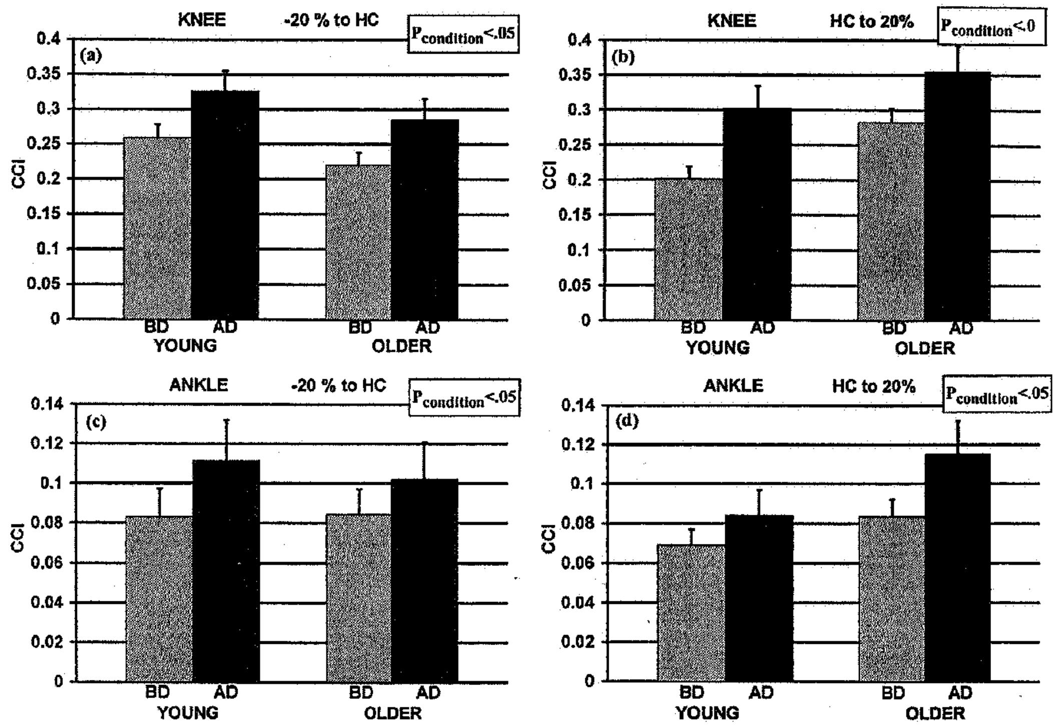

Figure 10: Effect of anticipation on co-contraction during gait. (a): co-contraction at the knee pre-HS, (b): co-contraction at the knee post-HS, (c): co-contraction at the ankle pre-HS, (d): co-contraction at the ankle post-HS. Young adults are shown on the left while older adults are on the right. Black bars correspond to alert dry and gray bars are baseline dry. Overall significance is given in top right corner of each graph. SE bars given.

Table 10: CCI Statistics

	-20% to HS		HS TO 20%	
	Knee	Ankle	Knee	Ankle
Age				
Condition	<.0001	.0039	<.0001	.0023
Interaction				

** Only p values < 0.1 are presented.*

In summary, anticipating slippery surfaces affected temporal aspects, magnitude and co-contraction of the stance leg muscles.

Discussion

This research focused on muscle activation patterns generated in response to slipping and anticipation of slippery surfaces. Muscle activation patterns reveal insight into how corrective reactions are generated and carried out when balance is unexpectedly perturbed by an unanticipated naturally occurring slip (reactive strategies). This project, which focused on the muscle activation patterns of the stance/slipping leg, differentiated lower extremity muscle responses of the VL, MH, TA and MG between hazardous and non-hazardous slips. Additionally, muscle activity when anticipating slippery floors during gait on dry surfaces was examined to provide information about how people change their gait to reduce the likelihood of a slip (proactive strategies). Age-related differences in both reactive and proactive strategies were also investigated. Initially, subjects were informed that the first few trials would be dry, ensuring natural walking (BD). The contaminant was applied without the subjects' knowledge (US). Subjects were then informed of the possibility of encountering a slippery floor prior to each trial (AD). In summary, this study investigated the relationship between the muscle activation patterns of the stance leg and slipping severity, as well as the impact of anticipation and aging on this relationship.

Reactive strategies: Significant differences in temporal and magnitude aspects of muscle activity during a naturally occurring unexpected slip compared to gait on dry floors were found. Similar temporal patterns of muscle activation strategies were noted between young and older adults. The initial reaction to a slip consisted of the mean activation of the MH (21.9%), followed by the TA (24.2%), MG (26.1%) and finally, the VL (29.1%). VL latency was an important aspect of the corrective reaction as adults that experienced hazardous slips activated their VL significantly later than those who experienced non-hazardous slips. Additionally, MH cessation was also important in the corrective reaction as adults tended to have a delayed cessation during hazardous slips compared to non-hazardous. In general, the response to an unexpected slip was scaled to its severity. Hazardous slips were associated with significantly later cessations and longer reactive durations, as well as, increased reactive magnitude compared to non-hazardous slips, specifically seen in both MH and TA. Age-related differences were noted as young adults demonstrated a longer more, powerful muscle response to hazardous slips compared to older adults.

Previous studies on the kinematics and kinetics of slip events noted the onset of corrective reactions around 25% of stance and continue through 45% of stance [12]. Therefore, muscle activations in response to an unexpected slip should have latencies around 20% stance. The latencies reported here, with mean activations of the MH (21.9%), TA (24.2%), MG (26.1%) and VL (29.1%), were consistent with previously reported corrective joint moments. Additionally, increased magnitude was noted in the lower leg muscles during a simulated slip which has been seen previously [24,25,27,68,70,101]. Recent research suggests that more active control of the hip and knee compared ankle, which acts as a passive joint with no net moment, is important in successfully reacting to a perturbation [12,27,29]. Reactive strategies included increased knee flexion moment and hip extension moment. Increased knee flexion and forward rotation of the shank were also seen in an attempt to bring the foot back towards the body [12]. This research supported the importance of knee and hip corrective reactions compared to the ankle in a successfully recovery attempt during an unexpected slip.

Slips were categorized using a PSV threshold of 1.0 m/s into hazardous and non-hazardous. This threshold of 1.0 m/s was chosen based upon velocities for larger slips reported in previous studies [54,97]. Classifying slip severity rather than differentiating falls from recoveries avoids slip outcome determination issues for hazardous slips where recovery efforts are potentially assisted through reliance on the safety harness, slipping completely off of the contaminated force plate, or other indeterminate ground contact. None of the slip events classified as non-hazardous resulted in falls, while hazardous slips resulted in some recoveries, some falls, slips completely off of the force plate, or harness-assisted recoveries. A PSV rather than a SD threshold was chosen to avoid distance underestimates resulting from similar potential assistance, which do not affect the PSV for larger slips. Young and older adults experienced hazardous slips at about the same rate for this study: 64% (7/11) for younger subjects and 67% (6/9) for older subjects.

The initial reaction to an unexpected slip consisted of the activation of the MH (21.9% of stance), TA (24.2% of stance), MG (26.1% of stance) and VL (29.1% of stance). Overall, the MH was activated significantly sooner than VL and MG. Increased magnitude of the MH was also present during an unexpected slip. This initial activation of the MH would result in increased knee flexion and an increased knee flexion moment. Both of which have been reported as the initial phase of the corrective reaction to a slip. This flexion reaction of the knee resulted in a rearward motion of the foot towards the body to stop the slip. Increased knee flexion occurred with an increased hip extension moment [12]. This can be attributed to the continued muscle activation of the MH and increased reactive magnitude of the MH demonstrated by adults.

Previous literature reported a secondary phase of the corrective reaction which consisted of knee extension and hip extension [12]. In order to accomplish this, adults would have to turn off their MH and activate their VL. The VL was consistently activated last by both young and older adults. This delayed activation of the VL, a knee extensor, supports the secondary corrective reaction mentioned above. This secondary reaction allows subjects to translate their COM over their BOS, a more stable position [71]. Thus, progressing the COM forward and continuing the gait cycle. This strategy also advances the subject off of the slippery surface quicker.

Overall, the response to an unexpected slip was scaled to its severity. Hazardous slips were associated with significantly later cessations and longer reactive durations, as well as, increased reactive magnitude compared to non-hazardous slips. It is worth noting that it is difficult to comment on the cessation and duration of hazardous slip reactions. In the case of a fall, cessation and duration are actually greater than the calculated parameters since cessation was stopped at the end of the slip defined as the point where a subject slipped off the force plate or was assisted by the harness. This was done to avoid issues surrounding hazardous slips were recovery efforts are potentially assisted through reliance on the safety harness or other indeterminate ground contact. Thus, it is probable that longer reactive durations and delayed cessations were present in muscles during hazardous slips but not found due to the premature cessation time. This is also the case for reactive magnitudes since the end point of integration is cessation. In other words, a premature cessation would result in a larger than reported reactive magnitude.

Specifically, significantly longer reactive duration and delayed cessation were noted in the TA during hazardous slips. This tended to occur in the MH as well. However, with the previously mentioned limitations, it is probable that MH cessation and duration would be significantly delayed in hazardous slips. In addition, both MH and TA showed significant increases in reactive magnitude during hazardous slips. Interestingly, adults that experienced hazardous slips activated their VL significantly later than those who experienced non-hazardous slips. In addition, VL latency was highly correlated to PSV.

An attempt was made to identify EMG characteristics that are associated with a successful reactive strategy, i.e. decreased PSV. VL latency and MH cessation, neither of which was highly correlated to each other, were used in a regression model to predict PSV after a stepwise regress analysis identified these variables as potential predictors of slip severity. The overall model resulted in a R^2 value of 0.78. The analysis revealed a significant relationship between PSV and VL latency. Specifically, increases in VL latency were associated with more severe slips as measured by the PSV. Delayed MH cessations tended to increase slip severity as well. This result may have been affected by the limitations of cessations when considering falls.

A delayed VL activation in response to a slip would result in a delayed secondary phase of the corrective reaction, increased knee extension and increased hip flexion. Activating the VL later, as was the case in hazardous slips, would result in a greater distance between the COM and BOS later in the slip, an unstable position [71]. The later MH cessation would also cause an overall increase in knee flexion and hip extension later in the slip, the exact opposite of the result achieved by the secondary phase of a successfully corrective reaction. It is also not efficient to maintain MH activation when trying to achieve knee extension. Previous research found that decreased knee extension later in stance was pronounced in fall cases [12]. This decreased knee extension later in stance does not aid in forward progression of the COM and continuation of the gait cycle. Therefore, the subject would remain on the slippery surface longer, possibly increasing the severity of the slip that they were trying to recover from and eventually fall. An increase in the duration and severity of a slip would require a longer reaction, resulting in delayed cessations and increased reactive magnitude, both of which were noted in hazardous slips.

Significant contributions at the ankle in response to an unexpected slip were not found. An increased magnitude of the TA, as well as delayed cessation and longer duration, was noted during hazardous slips. These changes in the lower leg were only demonstrated during hazardous slips and may be attributed to the scaled response seen during hazardous slips. This activation of the TA during hazardous slips would result in the delayed achievement of foot-flat, an important aspect in slip recovery and continuation of gait. Aspects of TA activation were not found to be important in the successfully corrective reactions to a slip and may have hindered a recovery attempt. Researchers have previously reported a less active role at the ankle compare to the knee and hip in response to a slip [12,27,29]. It is also possible that increased reactive magnitude noted in the lower leg muscles resulted in an increase in co-contraction at the ankle. Stiffening of the ankle may be an important reaction in hazardous slips. The ankle was found to act as a passive joint with no net moment [12]. It is important to note that increased co-contraction, which could be beneficial to a slip reaction, would still result in no net moment at the ankle. Results reported here support these findings that a more active control of the hip and knee compared to the ankle is critical to corrective reactions during an unexpected slip.

Age-related differences were noted as young adults showed significantly later cessations and longer reactive durations compared to older adults. Overall, hazardous slips tended to be associated with higher reactive magnitude compared to non-hazardous slips in young adults compared to older adults. When experiencing a hazardous slip, young adults demonstrated a longer, more powerful response. Similar age-related limitations in temporal and reactive magnitude in response to a perturbation have been reported previously [1,100,102]. This difference might be directly related to the reduced lower extremity strength or ability to generate powerful, fast responses reported in older adults [65,104,115]. Implying that older adults have a higher incidence of falls because they simply can't react with the power needed to recover from an unexpected slip.

Proactive strategies: Anticipating slippery surfaces affected temporal aspects, magnitude and co-contraction of the stance leg muscles. In general, anticipation of a slippery surface resulted in earlier onsets and longer durations of flexors muscles as well as other temporal age-related differences. Notably more subjects activated their MG around HS, MG 1. Anticipation had no significant effect on the activity of the VL. Except for TA, alerting older and younger adults of the possibility of a slippery surface resulted in increased magnitude of activation. Anticipation also resulted in a significant increase of co-contraction at the ankle and knee in both age groups.

Previously published literature has shown that when provided with knowledge about possible surface characteristics, people change their gait [60,74,102]. The EMG results reported here can help explain how these anticipation-related effects are generated. Gait adaptations during anticipation include reduction in stance duration, shorter normalized stride length, reduced foot-floor angle and slower vertical heel velocity at HS [14,17,67]. These adaptations resulted in an overall reduction in the peak required coefficient of friction, thus decreasing slip and fall potentials [9,10,14,34,84,85,99]. Increased activity, as well as temporal changes, of the MH and MG would result in the aforementioned adaptations. Additionally, these gait adaptations led to a significant reduction in joint moments at the knee and hip [14]. A change in joint moments results from an overall change in muscle activity. For example, an increased knee flexion moment and hip extension moment when anticipating slippery surfaces can be partially attributed to increases in MH and MG activation. Thus, changes in muscle activation patterns reported here provide an explanation for the kinematic and kinetic changes previously identified during anticipation [14,17].

Significant changes were noted in the temporal aspects of muscle activation when anticipating a slippery surface. Younger adults activated their MH earlier in stance. The primary MH activation during gait serves to decelerate the swinging leg and slow down the foot. Earlier activation of MH, demonstrated by young adults, would result in a slower foot at HS [113]. This strategy has been seen previously when anticipating a slippery surface and would result in a decreased slip potential [14,17]. Additionally, younger adults' MH activation was significantly longer when anticipating a slippery surface compared to older adults. After HS, the MH serves as a hip extensor to assist in controlling the forward rotation of the thigh and stabilize the pelvis to prevent forward acceleration of the trunk [113]. Only young adults' longer activation of MH aided in this control and stabilization. This age-related difference in muscle activation duration has been noted previously under anticipation effects [116].

No significant changes were found in the temporal aspects of the VL. However, both the VL and MH showed a significant increase in magnitude during anticipation across both age groups resulting in increased co-contraction pre and post HS at the knee. It is unclear if this amount of co-contraction is helpful or harmful in anticipating a slippery surface. A certain amount of increased co-contraction attenuates the upper leg muscles in case a recovery attempt was needed it could be initiated quicker. It is also possible that too much co-contraction would result in stiffening the knee joint, hindering a quick reaction. Interestingly, young adults increased their MH magnitude significantly more than older adults when anticipating a slippery surface. This, in addition to the above mentioned temporal changes found in the MH, would result a slower leg and foot at HS compared to older adults, therefore, decreasing the slip and fall potential in young adults.

Muscle activation adaptations were also found in the lower leg when anticipating a slippery surface. A-priori knowledge of the possibility of a slippery surface resulted in notably more subjects activating their MG around HS, MG 1. In addition to the four young adults and one older adult, two more young adults and five additional older adults demonstrated activation of MG 1, resulting in a total of six young adults, 54%, and six older adults, 67%. Activation of the MG 1 would result in a decrease in foot-floor angle at HS. Overall, activation of the MG 1 lasted significantly longer during anticipation, which would result in achieving foot flat sooner in stance, reducing slip potential [14,17,85]. This strategy was adopted more often in older adults as their offset occurred significantly later in stance than young adults. The primary activation of the MG during gait helps to reach foot flat, fine turns forward rotation of the leg by controlling knee flexion and provides a burst of power to initiate TO. Increasing MG 2 would assure that there is not an excessive amount rotation that would result in an undesired increase in knee flexion [113]. When warned of the possibility of a slippery surface, both young and older adults activated their MG 2 significantly sooner and maintained activation for a longer period of time in attempts to control the amount of knee flexion and advance the gait cycle quicker in preparation for TO.

Younger adults tended to activate their TA longer during AD compared to older adults. The TA typically peaks after HS to control the rotation of the foot to foot flat. After foot flat, it has been noted to play a minor role in pulling the leg forward over the foot [113]. Advancing the center of mass over the BOS quicker shortens the stance duration and allows for continuation of forward progress without great disturbance, if a perturbation occurred, to the normal gait pattern. No significant increase in the magnitude of TA was found during anticipation, however, both MG 1 and MG2 showed significant increases in magnitude. Increased magnitude and occurrence, as well as temporal changes, of the MG 1 resulted in an overall increase of co-contraction pre and post HS at the ankle for both age groups. This co-contraction at the ankle may play a role in the control of foot positioning [36]. Increased co-contraction might also make it more difficult to initiate a slip if the ankle joint is stiffer. Additionally, the increased magnitude of MG 1 without a significant change in TA indicates a possible source for reduction in foot-floor angle at HS, thus decreasing the slip and fall potential in both young and older adults.

Previous research has shown that adaptation to repeated exposure revealed that healthy older adults were fully capable of learning to better recover from or adjust to a perturbation [73,74]. Similarly, both young and older adults adapted their muscle activation patterns during their gait when anticipating a slippery surface. However, certain age-related differences were noted among temporal aspects of the stance leg flexors. Young adults activated their MH and MG significantly sooner and longer than older adults during anticipatory conditions. Increased muscle activation duration of young adults compared to older adults has been previously reported under similar conditions [116]. Additionally, young adults increased the magnitude of their MH significantly more when anticipating a slippery surface compared to older adults. These age-related differences in the stance leg's flexor muscles would result a slower leg and foot at HS compared to older adults. Thus, young adults would be at a decreased risk for a slip and fall when anticipating a slippery surface. This difference in proactive strategies employed by young adults might explain the decreased adaptability seen in older adults.

Scientific Report 2: Additional Investigations

Objectives

Our goal was to investigate the relationship between slip severity and general gait characteristics including initial conditions at heel strike onto an unexpectedly slippery floor. This relationship was evaluated for younger and older subjects. The underlying hypothesis of this study was that pre-slip parameters would differentiate hazardous from non-hazardous slips classified using a peak slipping velocity threshold of 1 m/s. Because these initial condition variables may be modified via training, a greater understanding of the impact of these variables on slip severity may help to reduce fall incidents precipitated by slips.

Background: Importance of baseline gait characteristics and initial conditions

The scope of the problem of slips and falls has been covered in the Background section included in Scientific Report 1.

Why, given the same environmental conditions, are some slips unlikely to lead to falls ("non-hazardous slips", short slipping distance and slow slipping velocity), while other slips are much more likely to lead to falls ("hazardous slips", greater slipping distances and faster slipping velocity)? Although there are clearly other contributors (environmental conditions, subject mindset, etc), two general subjective factors (these are clearly not independent factors) likely contribute to slip severity including (1) the state of the body and, perhaps more importantly, of the perturbed foot at slip initiation, and (2) corrective reactions generated in response to slipping. The findings presented in Scientific Report 2 focus on the first group of factors. Specifically, walking speed, step length, foot angle at heel strike, heel velocity, and cadence as these have previously been implicated as affecting peak slip velocity [98] and thus influencing fall potential [7,11,59,95]. However, these variables have not previously been studied in a systematic way.

Methods

Only the methods specific to the findings reported in Scientific Report 2 are reported here. For more general procedures, the reader is referred to the Methods Section included in Scientific Report 1. Only the BD (known dry) and US (unexpected slip) trials were considered in the analysis.

Variables of interest included kinematic variables calculated from the marker data using a customized routine in Vicon BodyBuilder ® Oxford Metrics. A heel marker was not used during gait trials because it was easily knocked off by contact with the floor. Instead, a rigid-body analysis technique using static calibration markers was used. The location of a heel marker in the local frame of the hind foot segment was recorded along with all other markers during a standing calibration trial. This information was used to reconstruct the trajectory of the heel marker during walking without attaching a physical marker to the heel. The foot-floor angle (FFA) and its derivative (FFAS) were estimated as the angle between the hind-foot segment and the floor. Other variables of interest, calculated using the heel marker (SL_HEEL, Figure 11), were cadence (CAD – steps/min), vertical and horizontal (square root of the sum of the squares of back-to-front and side-to-side) velocity of the left heel at heel strike (V_VEL and H_VEL – m/s), and step length normalized to leg length, i.e., "step length ratio" (SLR – m/m of left leg length). Slip distance (SD - cm) describes the heel marker's travel distance along the floor from heel strike [33] to a stable zero velocity. For hazardous slips, slip distance was determined by accruing the heel's travel distance from heel strike to the time when the subject either slipped beyond the contaminated force plate or he/she relied on the harness to regain balance as determined by visual inspection of the videos.

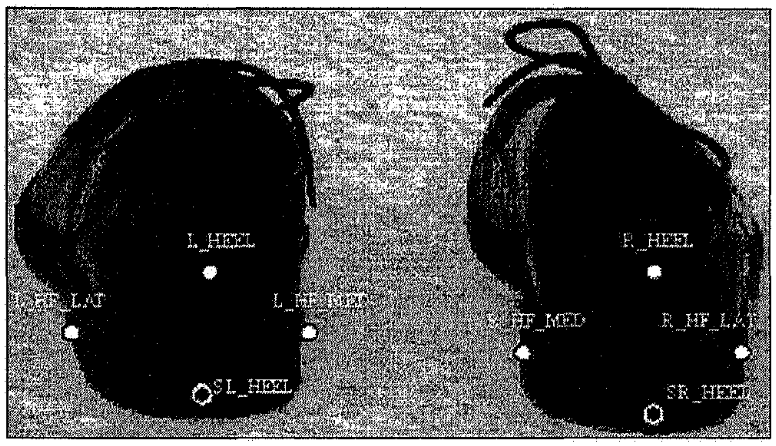

Figure 11: Reflective marker placement. Filled circles represent markers that remain on shoes during dynamic trials and hollow circles represent markers removed after static trails and virtually recreated from other markers during dynamic trials.

Gait speed (GS – m/s) was derived based on the average whole body center of mass velocity along the travel direction prior to slip initiation. A thirteen-segment biomechanical model was used to estimate the whole-body center of mass trajectory. Scaled anthropometry based on Chandler [19] and regression equations from Chaffin and Anderson (Chaffin, Anderson, et al. 1991) were used to determine segment masses, moments of inertia, and centers of mass for the head, upper and lower arms, trunk, pelvis, thighs, shanks, and feet. Segment locations and orientations were determined using at least three, non-collinear reflective markers per segment (Margerum et al. 2005).

Additionally, the EMG variables reported in Scientific Report 1 (Methods Section / "Dry Trials" paragraph) were considered.

Results

None of the slip events classified as non-hazardous based on the 1 m/s PSV threshold resulted in falls (although some of the non-hazardous slips did elicit post-slip responses), while hazardous slips resulted in recoveries, falls, slips completely off of the force plate, or harness-assisted recoveries. Younger and older subjects experienced hazardous slips at about the same rate: 64% (7/11) for older subjects and 69% (11/16) for younger subjects.

Many of the pre-slip baseline-dry gait characterization parameters were strongly correlated (magnitude of $r > 0.5$) as shown by the correlation coefficients summarizing the strength of the linear relationships between each pair of variables in Table 11. PSV was highly correlated with SD ($r = 0.89$ overall) for both for younger ($r = 0.87$) and older subjects ($r = 0.98$) (Figure 12). All trials categorized as hazardous save one also had a slip distance greater than 10.0 cm. There was only weak correlation (magnitude of $r <$

0.3, p = 0.36) between CAD and SLR for these experiments, suggesting that in this study cadence and step length were independently controlled. GS was strongly correlated with SLR and CAD (r = 0.51, p < 0.01 for each) and FFA at heel strike was strongly correlated with SLR (r = 0.67, p < 0.01) as well.

Table 11: Correlations among variables of interest.
Significant correlations (p < 0.05) indicated with *.

PSV	0.89 *	-0.32	0.49 *	0.17	0.48 *	-0.44 *	-0.24	-0.47
	SD	-0.36	0.58 *	0.32	0.45 *	-0.46 *	-0.08	-0.35
		CAD	-0.18	0.51 *	-0.38 *	0.13	0.50 *	0.34 *
			SLR	0.51 *	0.67 *	-0.70 *	-0.26	-0.54
				GS	0.17	-0.43 *	0.24 *	-0.27
					FFA	-0.73 *	-0.13	-0.54
						FFAS	0.33	0.68 *
							H_VEL	0.29
								V_VEL

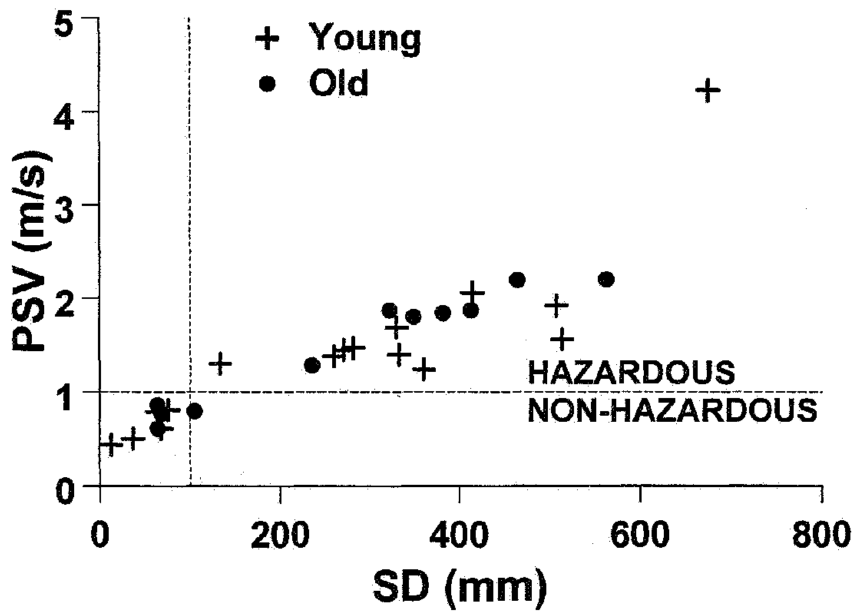

Figure 12: Relationship between peak slip velocity (PSV) and slip distance (SD). Vertical dashed line indicates a potential SD slip severity threshold of 100 mm proposed in the literature while the horizontal dashed line illustrates the actual PSV slip severity threshold of 1.0 m/s used for this report. Note similar results in categorization between the two criteria.

Two-factor ANOVAs were conducted to determine the associations between the pre-slip gait characterization parameters and the independent variables slip severity (H or NH), age group and their interaction (Table 12). Age did not have a significant effect on CAD, H_VEL, or V_VEL ($p = 0.49$, 0.50, and 0.19 respectively). A trend for older subjects to walk slower (GS) than younger subjects did not reach statistical significance ($p = 0.09$). Significant age effects were seen for SLR, FFA at heel strike, and FFAS at heel strike. Specifically, older subjects walked with shorter step lengths relative to their leg length (SLR) ($p = 0.03$), with smaller foot floor angles (closer to flat foot) at heel strike (FFA) ($p < 0.01$), and with slower FFA rate of change (FFAS) at heel strike ($p = 0.02$).

Table 12: Statistical relationship among variables of interest, age group, and slip severity. Significant correlations ($p < 0.05$) indicated with *.

Variable	Age Effect (Y/O)	Slip Severity Effect (H/NH)	Interaction Effect (Y/O x H/NH)
CAD	0.49	0.03 *	0.64
SLR	0.03 *	< 0.01 *	0.46
GS	0.09	0.80	0.93
FFA	< 0.01 *	< 0.01 *	0.48
FFAS	0.021 *	< 0.01 *	0.42
H_VEL	0.50	0.34	0.97
V_VEL	0.19	0.06	0.20

H_VEL and V_VEL were not found to be significantly related to slip severity ($p = 0.34$ and $p = 0.06$) although a trend linking higher vertical velocity to hazardous slips is possible. Significance was found relating slip severity to CAD, SLR, FFA, and FFAS ($p = 0.03$, $p < 0.01$, $p < 0.01$, and $p < 0.01$ respectively). Decreased CAD, longer SLR, higher FFA at heel strike, and faster FFAS at heel strike occurred during hazardous slips. There were no significant interaction effects of slip severity cross age for any of the variables (all $p > 0.2$). The relationships among these variables, age group, and slip severity are illustrated in Figure 13.

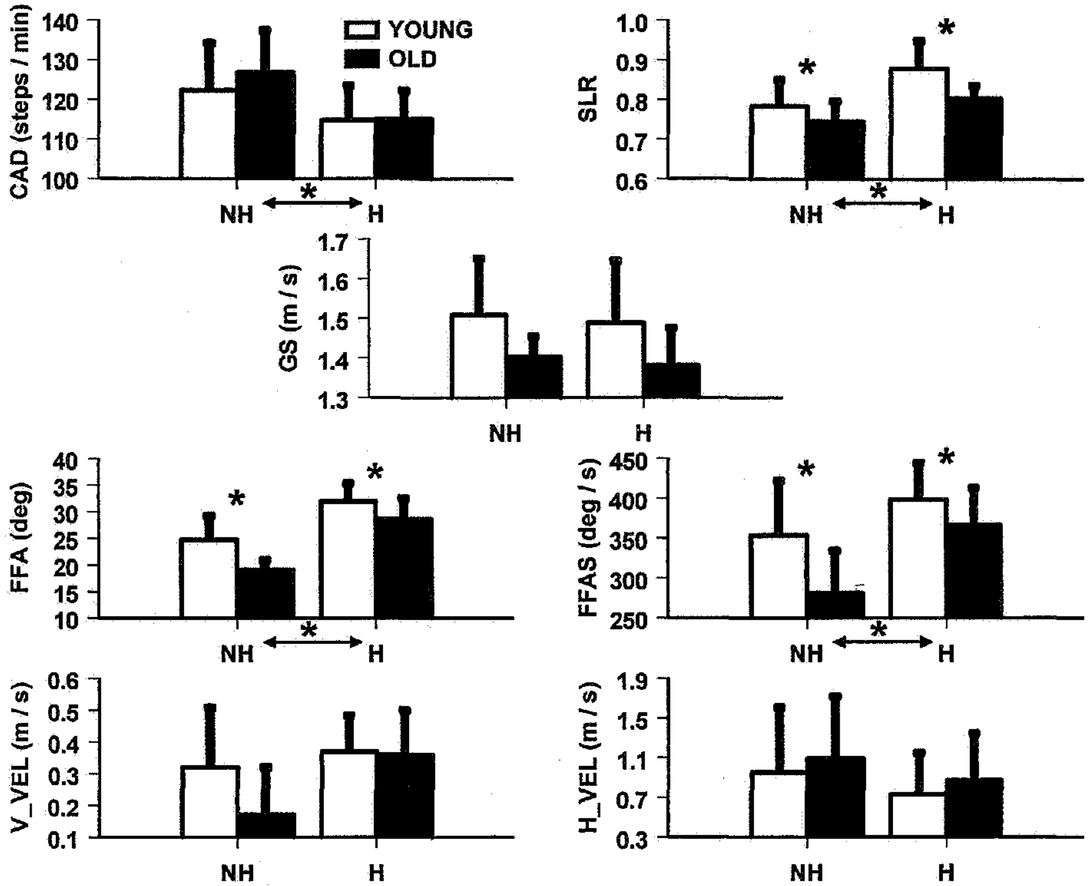

Figure 13: Associations among age-group and variables of interest: unfilled = younger, filled = old; slip type: Non-Hazardous (NH) and Hazardous (H); and variables of interest. Positive foot-floor angle slope (FFAS) indicate decreasing foot-floor angle (FFA). Positive horizontal velocity (H_VEL) in direction of travel. Positive vertical velocity (V_VEL) into floor surface. $p < 0.05$.

A stepwise logistic regression analysis was performed in an attempt to relate common initial conditions and gait characteristics to slip severity (H or NH) for younger and older subjects combined. Initial included variables were CAD, SLR, GS and age group (Y/O). FFA was not included due to high correlations with the other variables. The stepwise regression found two variables (CAD ($p = 0.05$) and SLR ($p = 0.02$)) associated with slip severity. The overall model resulted in a $R^2 = 0.45$ with a likelihood $\chi^2 = 15.30$ ($p < 0.01$). Parameters of the logistic regression model for SLR and CAD were 28.2 and -0.16, respectively. This model resulted in the probability plot shown in Figure 14. Increasing SLR (longer steps) and decreasing CAD (slower steps / min) resulted in increasing probability of a hazardous slip. CAD and SLR were not highly correlated with each other ($r = -0.18$, $p = 0.36$) and therefore supplied relatively independent contributions to the model. GS and age group were not good predictors of slip severity, either alone, or in combination with the other variables.

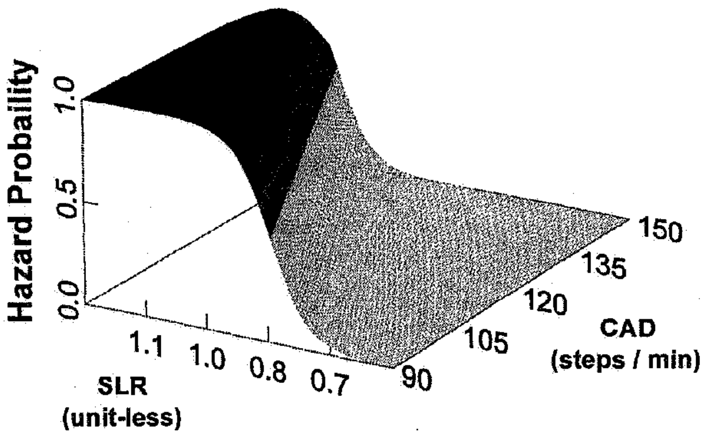

Figure 14: Probability of hazardous slip during first exposure to slippery environment based upon logistic model including step length ratio (SLR) and cadence (CAD).

An alternative logistic regression analysis was conducted using a single initial condition variable, FFA, and age group, since FFA was well correlated with SLR, CAD, and FFAS, all of which were statistically related to slip severity (Table 11). This analysis showed a strong logistic relationship for FFA and no age group significance ($R^2 = 0.53$, $\chi^2 = 16.55$; $p < 0.01$). The probability model is given in Figure 15. Increasing FFA resulted in increasing probability of a hazardous slip.

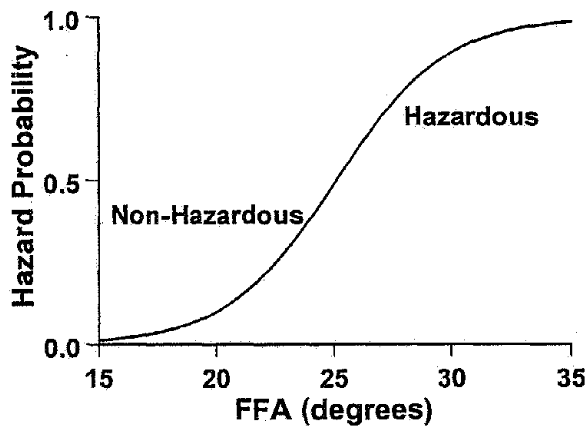

Figure 15: Logistic relationship between hazardous slip event and foot-floor angle (FFA) at heel strike.

Finally, to investigate differences in EMG characteristics during baseline dry gait between participants that experienced hazardous and non-hazardous slips, linear ANOVAs were conducted on temporal aspects, EMG magnitude and co-contraction using hazard (N/NH), age (young/old) and their interaction as independent variables. Co-contraction at the ankle pre-HS ($p = .0357$) and post-HS ($p = .001$) was significantly different between hazardous and non-hazardous groups. Adults that normally walked on dry floors with greater co-contraction around HS at the ankle experienced non-hazardous slips (Figure 16).

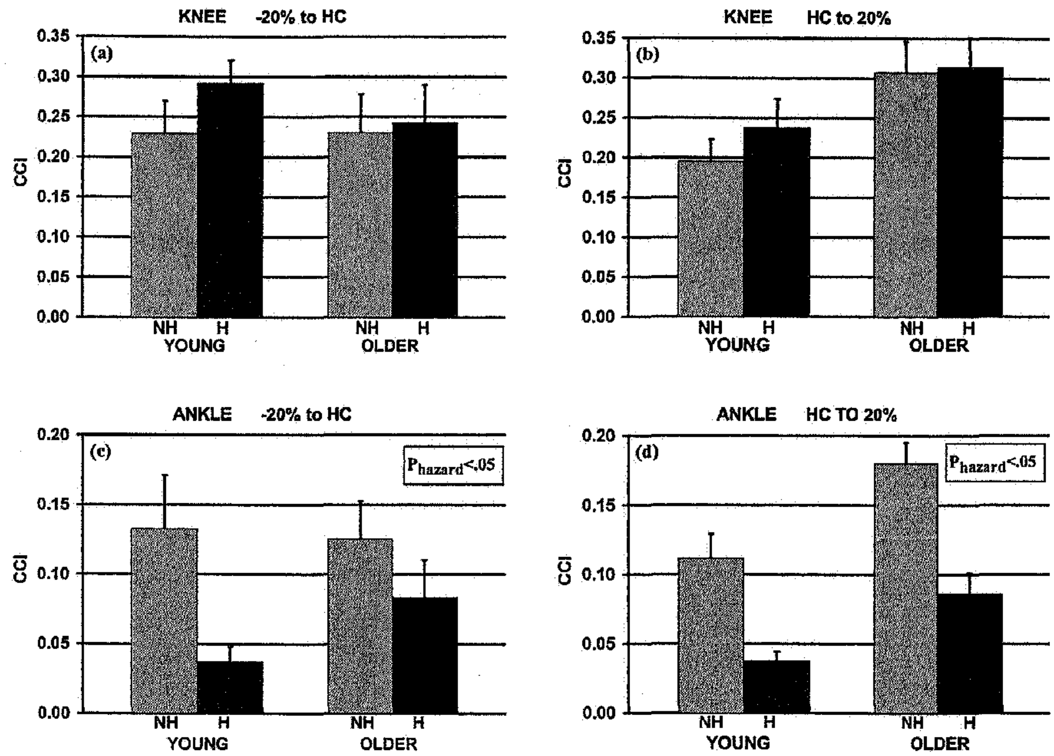

Figure 16: Effect co-contraction during gait on slip severity as measured by hazardous condition. (a): co-contraction at the knee pre-HS, (b): co-contraction at the knee post-HS, (c): co-contraction at the ankle pre-HS, (d): co-contraction at the ankle post-HS. Young adults are shown on the left while older adults are on the right. Black bars correspond to hazardous slips and gray bars are non-hazardous slips during the unexpected slip. Overall significance is given in top right corner of each graph. SE bars given.

Discussion

The findings reported in Scientific Report 2 suggest that initial conditions contribute to the severity of slips. In particular, cadence, normalized step length, and the angle of the foot relative to the floor were found to be important. Decreased cadence, longer step lengths normalized to leg length, higher foot-floor angle at heel strike, and faster foot-floor angular velocity at heel strike were found during hazardous slips. Older subjects were found to have gait that was generally less-hazardous as characterized by smaller step length ratios, smaller foot-floor angles at heel strike, and slower rates of change of the foot-floor angle at heel strike as compared to younger subjects, even though older subjects had equivalent numbers of hazardous slips.

Hazardous slips were associated with longer steps (SLR) compared to non-hazardous slips. This agrees with the previously reported relationship between step length and slip risk [2,7,13,49,53,62,66]. The effect of longer step length on slip severity may be due to increases in the ratio of required shear to normal force at heel strike for longer steps [13,33]. Additionally, longer steps imply greater excursions of the foot with respect to the center of mass, causing the foot to accelerate faster than it would for shorter steps and suggesting an increase in the magnitude of any required action needed to arrest resulting sliding motion of the foot. Finally, taking long steps modifies the tension of lower extremity muscles (e.g., stretching the hamstrings), which may impact the ability to generate faster reflexive torque responses of appropriate magnitude in the face of external perturbations.

Increasing FFA at heel strike was a contributor to slip severity as well, a finding in support of previously published reports [7,16,18,58,83,98]. This finding may be due to a number of factors. First, decreased FFA at HS increases the shoe-floor contact area at landing. Also, foot-flat gait reduces the braking impulse at heel strike. Finally, decreased FFA, along with faster cadences and shorter step length ratios impact the dynamics of the center of mass excursions, increasing the center of mass to base of support safety margin, decreasing inertial loading on the foot at heel strike, and thus reducing the frictional requirements needed to prevent a slip [33].

Gait speed did not appear to differentiate between hazardous and non-hazardous slips. However, several researchers have previously reported that peak slip velocities exceeding gait speed increased the likelihood of falls [16,33,53,77,98,117]. For this study, subjects walked at self-selected gait speeds ranging from 1.2 to 1.8 m/s for both hazardous and non-hazardous slips classified based on a PSV threshold of 1.0 m/s. Thus, the range of speeds was not great and it is therefore understandable that a significant relationship between severity and GS was not found. Perhaps this relationship would be a more valuable differentiator of recoveries and falls.

While the correlation analysis confirmed a number of suspected relationships among gait variables, it also revealed interesting interactions that appear to be in disagreement with previously published literature. For example, in this study CAD and SLR were not well correlated with each other ($r = -0.18$, $p = 0.36$), which is in contrast to significant positive correlations reported in the literature (i.e., [110]). Our lack of correlation is probably due to the limited range of GS induced by the self-paced constraint. Thus, within the self-paced limits it appears that CAD and SLR are independently controlled. Some effects were similar to those reported in the gait literature (Brady et al. 2000) such as larger foot-floor angles (more vertical orientation of the foot) occurring as longer steps are taken ($r = 0.67$, $p < 0.01$) and a slower cadence is adopted ($r = -0.38$, $p = 0.048$).

Horizontal heel velocity at heel contact (H_VEL) was not found to have a significant effect on slip severity. In contrast, other studies have shown that greater H_VEL results in greater numbers of slips and falls [7,51,52,111]. However, there tends to be variability in H_VEL during gait, with the heel either slipping forward, backward, or matching ground speed [111]. This variability is probably a function of the instructions to the subject in the experiment and the subjects' mindset (i.e., anticipation of the environmental conditions). Measurements of the coefficient of friction have been shown to be impacted by the velocity of the tests, with greater velocities resulting in lower coefficients of friction (see [21] for review) thus one would anticipate that H_VEL would have an effect on the available coefficient of friction with higher H_VEL more likely to result in hazardous slips. However, our expectation that H_VEL would predict slip severity was not verified in the experiments.

Two logistic regression models were considered to predict slip hazardousness. The choice of predictor variables was based on three factors. First, the explanatory variables were general gait variables that are conventionally thought of affecting slip potential and/or outcome. Second, significant differences in the predictor variables were found between hazardous and non-hazardous slips. Third, independent variables included in the same model were only weakly correlated with each other. The first logistic model included CAD and SLR, both of which are widely used in gait research. These variables were also predictive of slip severity and they were not strongly correlated with each other in this investigation ($r = -0.18$, $p = 0.36$); therefore SLR and CAD were deemed to be good choices for the first logistic regression model (Figure 14). The second model considered only FFA as an explanatory variable predicting slip hazardousness. Because FFA was correlated with both SLR and CAD, and because significant differences in FFA were found between H and NH slips, it seemed a reasonable choice to use FFA as a single predictor of slip severity (Figure 15).

Age group was not found to be primarily associated with the classification of the slip. Thus, gait characteristics dominated the association with slip classification. However, even though younger and older subjects experienced hazardous slips at about the same rate (64% (7/11) for older subjects and 69% (11/16) for younger subjects), older subjects appeared to adopt "safer" gait styles, with shorter SLR, shallower FFA at heel strike, slower FFAS and increased ankle CCI. This cautious gait behavior in older adults has been noted in previous literature [3,4,32,44,54,64,88,94,112]. Thus, there may be some influence of age that is counteracted by the changes in gait characteristics seen in older adults. Some possibilities include other unmeasured gait characteristics, psychophysical differences related to concern about slipping that could affect the mental set in this experiment, biomechanical differences, or possible reflexive response differences. In addition, our older subjects were as a group slightly heavier than our younger subjects (increased BMI) which could be a covariate for future investigation. Deficiencies in reactive responses to slips have been cited as explanations for slips resulting in falls [55]; however, as PSV occurs within the first 200 ms after HS, it is unlikely that non-reflexive responses would influence slip hazard as defined in this research. Further research is needed to understand the interplay among initial gait characteristics, postural control responses, hazardous slips and aging.

One of potential long-term benefits of this study is its contribution to our understanding of the interplay among fundamental gait parameters, slip potential, and age. The "human factors" involved in slipping are an important component that deserves increased attention. The results of this study suggest that hazardous slip potential can be reduced by modifying specific gait parameters. This finding may influence training regimens to reduce hazardous slips. Importantly, it appears that adjusting gait may be equally useful across the age groups tested here, although future research is needed to determine if the same associations hold for very old adults. This research will also significantly contribute to definitions of important human factors that may some day be incorporated into new methods of slip resistance testing. There is general agreement within the slip testing community that increasing the 'biofidelity' of slip resistance testing will improve the tests ability to define useful slip measures towards preventing falls. Further understanding of the relation of human gait parameters to slip hazard could be useful in this regard. Finally, the concept of using hazardous versus non-hazardous slips instead of falls and recoveries could benefit future studies investigating interactions of floors and human locomotion. Other human slip studies may want to include this concept in defining the impact of floor condition, age, etc on the potential for slip-related injurious, not only due to falls but also due to the larger responses required to recover from hazardous slips.

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Publications

Peer-reviewed journals

Published, in press or accepted

1. Chambers AJ, Margerum S, Redfern MS, Cham R: "Kinematics of the foot during slips," Occupational Ergonomics, vol. 3, pp. 225-234, 2003.

2. Moyer BE, Chambers AJ, Redfern MS and Cham, R; "Gait parameters as predictors of slip severity in young and older adults"; Accepted in Ergonomics; 2005.

In preparation

1. Chambers AJ and Cham R; "Stance leg slip-related muscle activation patterns", Manuscript will be submitted to Gait and Posture by 10/31/2005.

2. 3D-biomechanics of lower extremity responses to an unexpected slip in young and older adults (Part 1: Kinematics and Part 2: Kinetics)

3. Anticipated and unexpected slips: Bilateral lower extremity bomechanical adaptations in young and older adults

4. Slip-related biomechanics of the upper body in young and older adults

5. Center of mass dynamics during unexpected and anticipated slips in young and older adults

Peer-reviewed conference proceedings

1. Cham R, Moyer B, Redfern MS: "Whole body biomechanics of responses to slips," Poster presentation and published in the Proceedings of the American Society of Biomechanics (ASB) in conjunction with IVth World Congress of Biomechanics, Calgary, Alberta, August 2002.

2. Moyer B, Cham R, Redfern MS: "Slip anticipation effects on ground reaction forces," Poster presentation and published in the Proceedings of the American Society of Biomechanics (ASB) in conjunction with IVth World Congress of Biomechanics, Calgary, Alberta, August 2002.

3. Redfern MS, Cham R: "Utilizing biomechanics to prevent slips and falls," Podium presentation and published in the Proceedings of the American Society of Biomechanics (ASB) in conjunction with IVth World Congress of Biomechanics, Calgary, Alberta, August 2002.

4. Cham R, Moyer B, Redfern MS: "Whole body biomechanics of responses to slip events," Podium presentation and published in the Proceedings of XXVII^{ème} Congrès de la Société de Bioméchanique, Valenciennes, France, September 2002. Published

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5. Cham R, Moyer B, Redfern MS: "Effect of having a-priori knowledge of the floors' contaminant condition on the biomechanics of slips," Podium presentation and published in the Proceedings of the Human Factors and Ergonomics Society (HFES), Baltimore, Maryland, vol. 1, pp. 1181-1185, September - October 2002.

6. Cham R, Moyer B, Redfern MS: "Anticipation of slippery floors and biomechanics of slips," Podium presentation and published in the Proceedings of the International Society for Postural and Gait Research (ISPGR), Sydney, Australia, pp. 59, March 2003. Published in a special issue of Gait and Posture, 2003.

7. Bieryla K, Chambers A, Cham R: "Slip anticipation effects on hip/knee kinematics – Part 1: gait on dry floors," Poster presentation and published in the Proceedings of the American Society of Biomechanics (ASB), Toledo, Ohio, September 2003.

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9. Margerum S, Moyer B, Bieryla K, Cham R: "Kinematics of the slipping foot," Poster presentation and published in the Proceedings of the American Society of Biomechanics (ASB), Toledo, Ohio, September 2003.

10. Moyer B, Chambers A, Redfern MS, Cham R: "Initial condition variables and age group as determinates of slip severity," Poster presentation and published in the Proceedings of the American Society of Biomechanics (ASB), Portland, Oregon, September 2004.

11. Margerum S, Cham R: "Center of mass kinematics at slip onset and slip severity," Poster presentation and published in the Proceedings of the International Society of Posture and Gait Research (ISPGR), Marseille, France, May-June 2005. Published in a special issue of Gait and Posture, 2005.

12. Chambers AJ, Cham R: "Anticipation of slippery floors: Muscle onsets and co-contraction of the stance leg," Poster presentation and published in the Proceedings of the American Society of Biomechanics (ASB) in conjunction with IVth World Congress of Biomechanics, Cleveland, Ohio, September 2005.