SLIP-RELATED MUSCLE ACTIVATION PATTERNS OF THE STANCE LEG DURING GAIT

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Falls precipitated by slipping are a major cause of injury, death and disability in the elderly. This research focused on muscle activation patterns generated in response to slipping and anticipation of slippery surfaces. The goal was to identify the muscle activation patterns of the stance leg in response to an unexpected slip (reactive strategies) and investigate muscle activity when anticipating slippery floors during gait on dry surfaces (proactive strategies). Additionally, age-related differences were examined. Electromyographic recordings were made from the Vastus Lateralis, Medial Hamstring, Tibialis Anterior and Medial Gastrocnemius of eleven young and nine older adults. Participants walked during the following conditions: (1) baseline dry (subjects knew the floor was dry); (2) unexpected slip (contaminant was applied to floor without subjects' knowledge); (3) alert dry (subjects were uncertain of the floor's condition). Reactive strategies, which were similar among young and older adults, consisted of activation of the Medial Hamstring at around 21% stance (~ 175 ms) followed by the Vastus Lateralis at around 29% stance (~ 240 ms). Corrective responses were scaled to slip severity with more severe slip reactions consisting of longer, higher magnitude responses. Delayed Vastus Lateralis latency and Medial Hamstring cessation were associated with an increased slip severity as quantified by peak slip velocity. Additionally, when experiencing a severe slip, young adults demonstrated a

longer, more powerful response compared to older adults. Anticipation of a slippery surface resulted in increased magnitude of activation (48% increase) and ankle/knee co-contraction (30% increase), as well as earlier onsets and longer durations of posterior muscles. Young adults demonstrated earlier onsets (3% stance, 24 ms) and longer durations (10% stance, 83 ms) than older adults reducing their slip potential. Finally, adults with baseline gait on dry floors characterized by greater ankle co-contraction at heel contact and delayed Tibialis Anterior onset were predisposed to experience less severe slips when encountering an unexpected slippery floor. Older adults' natural gait predisposes them to experience a less hazardous slip. However, once a slip occurs, older adults cannot react with the long, powerful response needed to prevent balance loss whereas young adults are capable of this response.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1.0 SPECIFIC AIMS

The long-term goal of this research is slip and fall prevention, especially in older adults, through a better understanding of the biomechanical reactions during slipping. This thesis research focused on muscle activation patterns 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). This project also differentiated lower extremity muscle responses between slip events that are likely to lead to a fall (hazardous slips defined as having a peak slip velocity greater than 1.0 m/s) and successful gait strategies (non-hazardous slips defined as having peak slip velocity 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).

This research focused on the muscle activation patterns of the stance/leading/slipping (left) leg. The following aspects were of particular interest: (1) the difference in slip-initiated muscle responses (Vastus Lateralis, Medial Hamstring, Tibialis Anterior and Medial Gastrocnemius) between hazardous and non-hazardous slips (reactive strategies), (2) muscle activity when anticipating slippery floors during gait on dry surfaces (proactive strategies), and (3) the influence of age on the findings in (1) and (2). Thus, the Specific Aims are as follows:

Specific Aim 1: 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.

H.1) In a response to an unexpected slip, the normalized reactive magnitude and latencies of the Medial Hamstring and Vastus Lateralis will be critical to a successful reaction, and furthermore, the knee flexors will have a faster latency than the knee extensors**.**

H.2) Responses associated with non-hazardous slips will have shorter latencies and greater magnitude compared to reactions associated with hazardous outcomes.

H.3) Young adults will react to unexpected slips with shorter latencies and a greater magnitude compared to older adults.

Specific Aim 2: 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.

H.1) Slippery surface warnings will result in earlier onsets and longer durations of the Medial Hamstring and Medial Gastrocnemius activity as well as increased co-contraction of both the upper and lower leg muscles compared to findings in locomotion on known dry surfaces.

H.2) Slippery surface warnings will result in greater co-contraction, delayed onsets and shorter durations of muscle activity in older than in young adults.

H.3) Baseline gait muscle activation patterns characterized by earlier onset of the Medial Gastrocnemius and increased co-contraction will result in less severe slips as quantified by peak slip velocity.

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.

2.0 BACKGROUND AND SIGNIFICANCE

2.1 SCOPE OF THE PROBLEM

Falls precipitated by slipping are a major cause of injury. Slips are the most frequent event leading to fall and overexertion injuries in Sweden [21] 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 [39]. 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 [67].

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 [7] (Figure 1). Approximately one-fifth of injury-related emergency department visits, the single largest fraction of such visits, are attributed to falls [59]. 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 [51]. 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 [7]. The annual direct cost of all fall-related occupational injuries in the US alone was estimated to be approximately six billion dollars [21]. Thus, the prevention of such injuries is a high occupational and public health priority.

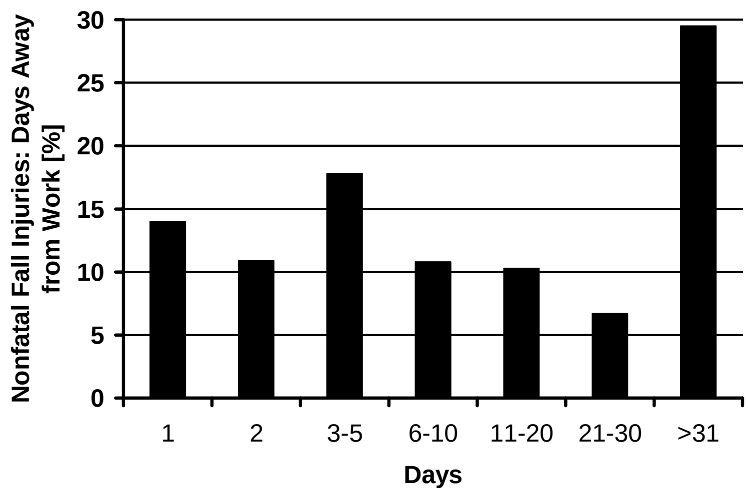

Figure 1: Number of days away from work due to falls on same level [7]

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 [52]. A ten-fold increase in the incidence of falls was reported in the elderly (65+) compared to younger individuals [103]. Estimates of the average annual risk of falling in older adults over the age of 65 years range from 30% to over 50% [5,89,105,106]. Falls are often listed among the leading causes of serious unintentional injuries, disability and death among older adults

[22,46,47,55,87]. Injury is the fifth leading cause of death in older adults. The majority of these fatal injuries are related to falls [41,43,87,104]. 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 [41,42,104]. 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 (Figure 2) and deaths (Figure 3) attributed to falls increases with age [7]. More than 30% of the total economic cost of falls in the older population in the United Kingdom is attributed to falls [90]. Personick and Windau suggested that older workers are at a greater risk of non-fatal injuries resulting from slips [77]. 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 [11]. Older adult workers are at a higher risk of facing fatal fall-related work injuries.

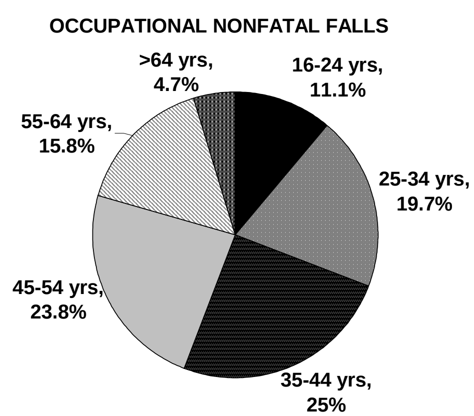

Figure 2: Occupational nonfatal falls on same level grouped by age [7]

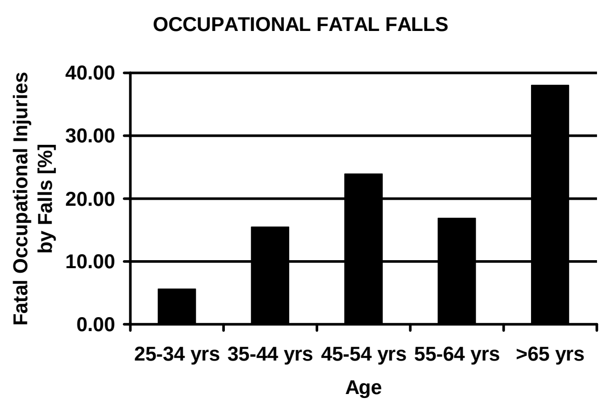

Figure 3: Occupational fatal falls on same level grouped by age [7]

Women especially experience a higher incidence rate ratio (old/young) of fatal fall-related work injuries, 14, compared to men, 3.3 (Figure 4) [48]. In general, injury rates from falls were higher among women, with fracture rates being 2.2 times greater than in men [94]. In 1996, over one-fourth of occupational fatal fall victims were 55 years and older, double that age group's share of the work force [6]. Fatality rates from falls showed a significant increase for workers as young as 45 to 54 years old [1]. Specifically, nearly half of the fatal falls in the US workforce occur in adults aged 45 years and older [105]. The number of fall-induced deaths of adults 50 years or older nearly doubled over the last 30 years in Finland. Following the current trends in Finland (Figure 5), the number of fall-related fatalities will increase 108% by the year 2030 [44].

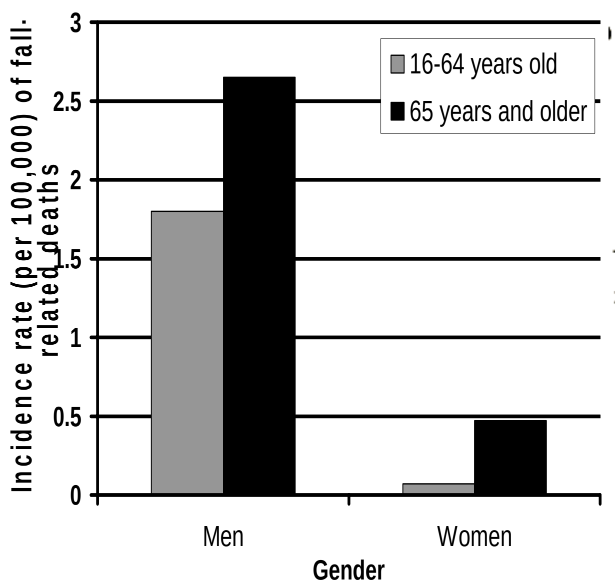

Figure 4: Incidence rate of fall-related deaths at work [48]

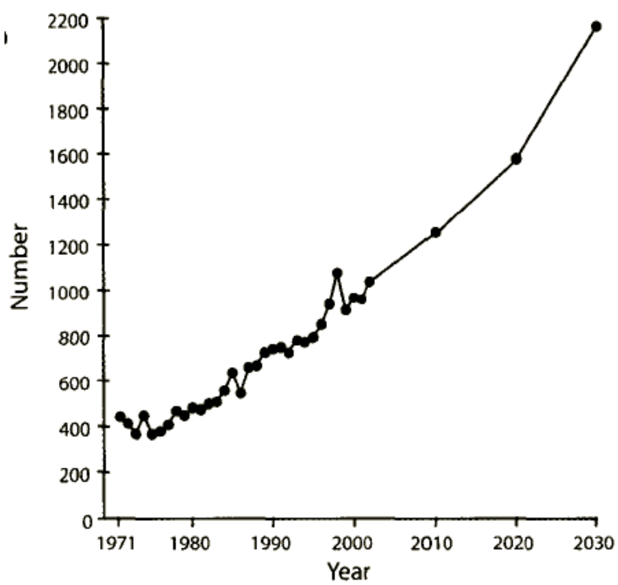

Figure 5: The number of fall-related deaths between 1971 and 2002 and the prediction of development until the year 2030 [44].

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 [44]. 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. This thesis project 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.

2.2 EXPERIMENTAL RESEARCH BACKGROUND

Gait involves the integration of complex processes necessary to initiate human movement and maintain balance. [12,13,60,76,84,85,96] Gait studies have improved our understanding of the complex relationship between gait biomechanics and slip-precipitated falls and thus have become critical in slips/falls prevention research [12,13,35,60,76,84,85,96]. Factors that must be considered in balance recovery are anatomical, biomechanical, physiological and cognition or behavioral constraints [81]. Included in these factors are muscle activation patterns in reactive and proactive responses, both of which will be considered in this thesis project.

2.2.1 Normal Muscle Activation Patterns during Unperturbed Gait

Numerous attempts have been made to identify normal electromyography (EMG) patterns [20,49,66,70,79,110,115]. Winter developed ensemble averages of EMG profiles. The magnitude of each profile was mean normalized to 100% prior to averaging. The profile was then time normalized to the stride period where toe off (TO) is at 60% (Figure 6). The Vastus Lateralis (VL), in addition to muscles not discussed here, extends the knee and helps to control knee flexion. The major peak of activity of the VL occurs at weight acceptance, 10% stride, and controls the amount of knee flexion. VL then aids in knee extension mid stance. The Medial Hamstring (MH) helps to flex the knee and extend the hip. The major activity begins in late swing phase and continues into weight acceptance. It serves to decelerate the swinging leg and slow down the leg and foot. At heel contact (HC), the MH extends the hip to assist the Gluteus Maximus to control the forward rotation of the thigh and stabilize the pelvis. When activated, the Tibialis Anterior (TA) aids in dorsiflexion of the foot. At HC, the TA activates to keep the foot dorsiflexed as the foot lowers to the ground and then decreases activity after foot flat. It has been noted to play a minor role in pulling the leg forward over the foot. The Medial Gastrocnemius (MG), and additional muscles not discussed here, flexes the knee and plantarflexes the foot when active. It is maximally active around mid push-off and aids achieving foot flat and leg forward rotation [111].

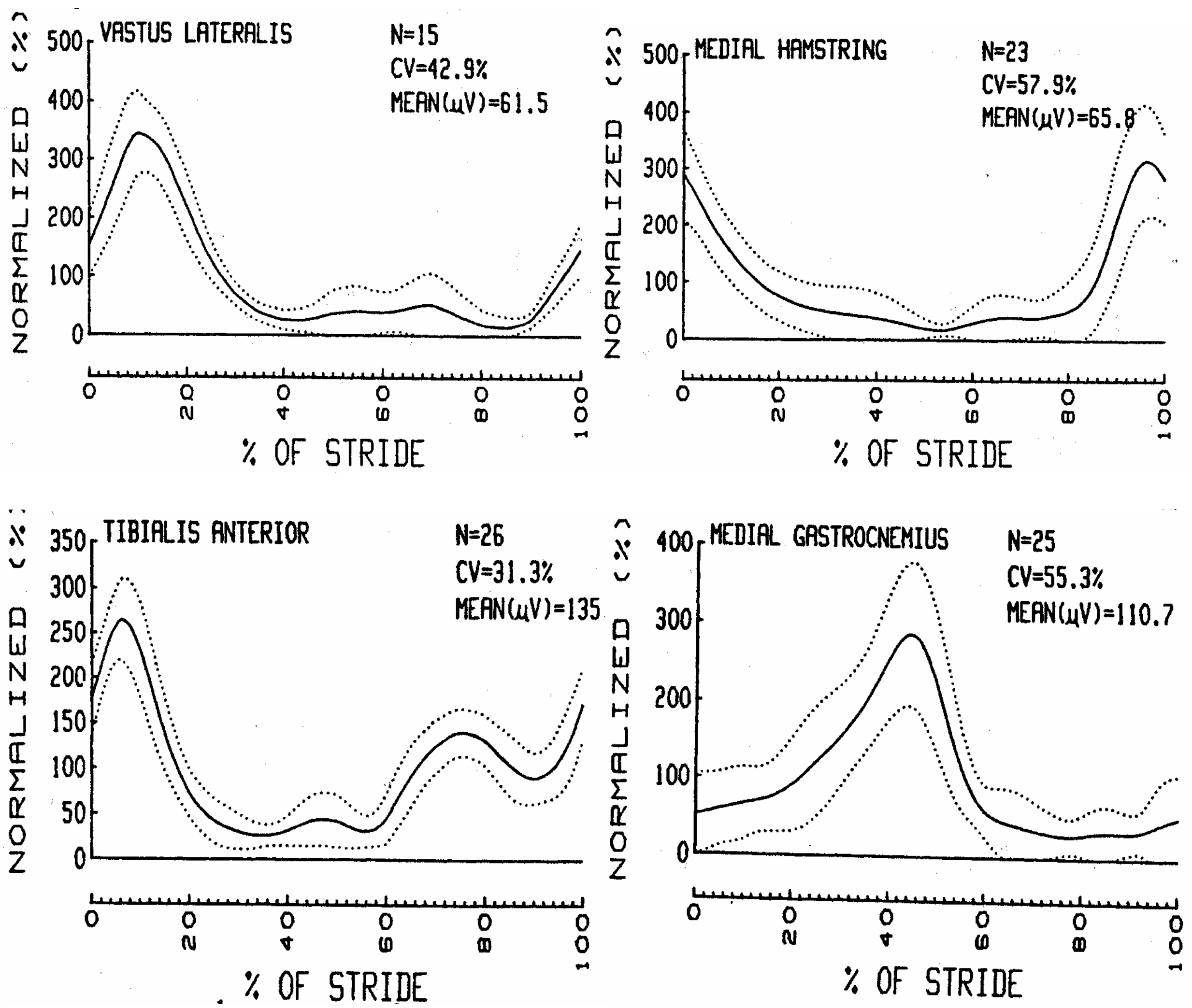

Figure 6: Ensemble average EMG profiles of VL, MH, TA and MG. HC to HC is 0% to 100%. 0% to 60% corresponds to stance time, HC to TO. Profiles were filtered at 10 Hz and magnitude normalized to the mean being 100% [111].

2.2.2 Biomechanics of Recovery Responses during Perturbed Gait

Walking requires the ability to generate and maintain locomotion patterns, maintenance of basic dynamic equilibrium between a shifting center of mass and base of support, and the ability to change locomotion patterns in response to external perturbations that threaten dynamic equilibrium [91]. For example, encountering a slippery environment becomes more challenging due to the additional required corrective responses in order to prevent falling. Therefore, slips and falls involve the interaction of complex environmental and human factors [34]. Environmental factors include the frictional properties of the foot-floor interface, material properties of walking surfaces/shoes (e.g. compliance, roughness) and lighting. Human factors include gait biomechanics, sensory information processing, neuromuscular and vestibular mechanisms involved in maintaining balance during locomotion on dry and contaminated surfaces.

Much research has been done investigating the biomechanical responses during base of support translations [56,97], trips [74,75], and release from forward lean [100,102,112,113]. Researchers have also considered corrective reactions during support surface translation protocols designed specifically to simulate real slip events [38,97-99]. However, it is unclear whether active anterior translation of the base of support (BOS), used in these investigations to simulate naturally occurring slips, actually evoke motor muscle patterns, corrective movements and strategies similar to those recorded during real slips. Hsaio and Robinovitch acknowledged the lack of body dynamics simulated in their standing experiment, a factor that would obviously affect corrective reactions. BOS translations, which are commonly performed at a constant velocity, do not take into account the aspects of heel dynamics on slippery surfaces. During real slips, heel dynamics are unique and critical to slip outcome [17,18,64]. Another difference between naturally occurring slips and BOS translations relates to stability concerns. Pai and Iqbal compared the region of stability (defined as the range of horizontal velocities of the center of mass that can be reduced to zero with respect to the BOS while still allowing the center of mass to traverse within the BOS limits) of both situations using a computer simulation. A substantial overlap of the regions was reported but with a significant difference in the shape of these regions proving that BOS translations are not an accurate model for naturally occurring slips [69].

2.2.3 Reactive Strategies

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 are elicited following unexpected sensory or motor perturbation such as stepping on a slippery surface and are crucial for maintaining dynamic equilibrium and forward progression. It has been suggested that certain strategies exist to maintain balance and restore stability during an unexpected slip [15,68,69]. Specifically, joint moments and postural adaptations during slip events are important for understanding and determining the characteristics of reactions that lead to successful recovery attempts during gait. 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. 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. 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. The ankle was found to act as a passive joint and was not important in a successfully recovery attempt [15]. 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.

2.2.3.1 Strategies of Young Adults Surface EMG analysis has been used successfully to study the neuromuscular reactions to perturbations during gait. Nashner utilized a moveable platform in a walkway to simulate an unexpected perturbation. EMG recordings showed increased TA activity during forward translations and increased MG during backward translations. Based on this information, Nashner hypothesized that muscle stretch of the distal limb provided the principal sensory feedback to elicit a balance response [65]. Following this theory, the distal muscles would be activated first preceding the thigh muscles [32]. Even though a BOS translation is not the same as a naturally occurring slip, as discussed previously, the stretch theory developed by Nashner can be applied to a naturally occurring slip. During a naturally occurring slip, the heel extends beyond the center of mass [116], resulting in a stretch of the posterior muscles starting with the most distal. This would imply an initial response of the MG followed by the MH, in addition to other muscles outside the scope of this project. Similarly, Dietz found that the MG response, ~80 milliseconds, was closely correlated to the magnitude of the disturbance and noted a quick but later response, 100 milliseconds, in the MH [26].

However, the previously mentioned theories were formulated without concurrent investigation of hip and trunk muscles [98] and more 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 [57,97,98,99]. 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 [68]. 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 [25-27,65,68,98]. 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.

2.2.3.2 Strategies of Older Adults The significantly higher incidence rate of falls among older adults compared to the rest of the population has motivated extensive research focused on the effects of age-related changes including neuromuscular, proprioceptive and cognitive systems on the ability of maintaining balance in response to perturbations. Reduced lower extremity strength [62,101,113] and vision, proprioception and vestibular sensory degradation [53,62] in elderly adults have been suggested to influence reactionary biomechanics and lead to increased risk for slips leading to falls. Additionally, older adults demonstrated a combination of slower onset, smaller magnitude of response and longer co-activation which resulted in an inefficient strategy [62,99,100,108]. Older adults activation sequence of muscles was similar to younger adults but with a limited capacity to generate a quick, powerful response [2,97,99]. Therefore, it was hypothesized that young adults would react to unexpected slips with shorter latencies and a greater magnitude of muscle response compared to older adults.

Little is known about aging effects on biomechanical and neuromuscular variables affecting recovery from a naturally occurring slip. As discussed previously, BOS translations are not an accurate model for naturally occurring slips. Thus, the findings for the effects of age on slip recovery are limited. 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 HC, slip distance and slipping velocity among older adults [53,54]. 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.

2.2.4 Proactive Strategies

The aforementioned reactive responses are seen primarily in the first exposure to a slip. Subsequent responses are heavily influenced by proactive adjustments and prior knowledge [57,73,99]. Proactive strategies are defined as balance control mechanisms that take place before the body encounters a potential disturbance. The effects of knowledge about surface characteristics are evident when one steps onto an ice rink versus stepping onto black ice. These strategies serve to counteract the destabilizing effect of a disturbance, reducing the reliance on reactive strategies in avoiding a fall [8,58,107].

2.2.4.1 Strategies of Young Adults Individuals have demonstrated a modification of their gait and response strategies when knowledge is provided about the surface characteristics [16,64,116]. Rand et al. noted a change in step length and anterior-posterior sway as an adaptation to treadmill perturbations [80]. Modifications of step width and foot clearance were demonstrated after forewarning of a possible trip [78]. 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 [71]. Shortened stride length was noted when walking on oily floors [64]. Reduction in stance duration, reduced foot-floor angle and slower vertical heel velocity at HC were noted during anticipation of a slippery surface [16,18]. These gait adaptations led to a significant reduction in joint moments at the knee (extension) and hip (flexion) [16]. These adaptations resulted in an overall reduction in the peak required coefficient of friction, thus decreasing slip and fall potentials [12,13,16,35,82,83,96]. These gait adaptations reflect an increase in activity of the posterior leg muscles. Therefore, it was hypothesized that anticipation of slippery surfaces would result in earlier onsets and longer durations of the MH and MG as well as increased co-contraction compared to normal gait.

These strategies included changes in muscle activation patterns [10]. However, the specifics of these adaptations related to muscle activation patterns are unclear, especially during naturally occurring slips. 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” [98]. Increased duration and coordination of lower leg muscle activity was also seen as an adaptation [80]. When warned of a possible threat to one’s balance, the central nervous system adapts attempting to acquire an optimal movement strategy that reduces the reliance on reactive responses to maintain balance in an uncertain environment [71].

2.2.4.2 Strategies of Older Adults 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. Older adults typically exhibit poorer performance [50] and are unable to adapt [93]. 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 [72,73]. 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 [114]. Thus, it was hypothesized that older adults would demonstrate delayed onsets accompanied by shorter durations and increased co-contraction compared to their younger counterparts.

2.2.5 Initial Conditions

It remains unclear why, given the same environmental conditions, some slips are shorter, slower and require little or no reactive response to stop the slipping foot, while other slips are severe and require large recovery responses. Certain general gait parameters have been implicated as factors affecting peak slip velocity [96] and thus influencing fall potential [9,57]. These parameters include gait speed, step length, foot floor angle at heel contact, heel velocity, cadence and anthropometry [96]. Moyer et al. found that hazardous slips were associated with greater step lengths and decreases in cadence, as well as larger foot-floor angles and faster foot angular velocities. Additionally, it was found that increased foot-floor angle would result in increased probability of hazardous slip [63]. It was hypothesized that muscle activation patterns during normal gait that tend to decrease foot-floor angle would be associated with less severe slips. These initial conditions may affect slip severity and further explain the high prevalence of slip-related falls in older adults. Gait research has found that older adults typically walk slower [3,4,61], take shorter steps [53,61,92], have faster cadences [92], walk with a larger stride width variability [33] and have smaller hip extension during walking [86]. Additional findings have indicated that a redistribution of muscle moments and power occurs with aging resulting in increased output at the hip and decreased output from the ankle compared to young adults [23].

2.2.6 Need for Further Research

Little is known about aging effects on the neuromuscular variables affecting recovery from a naturally occurring slip. These unknown 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. Additionally, the effects of knowledge or anticipating a slippery surface on gait and any age-related differences are unclear. This thesis project will provide possible insight into the high incidence rate of slip and fall related injuries in older adults and may result in the identification of predictive indicators of increased risk for slips and falls. This information can be used to improve training and fall prevention programs aimed at reducing slip-initiated falls and injuries.

3.0 ABBREVIATIONS

Table 1: Abbreviations

AD	Alert Dry
BD	Baseline Dry
BOS	Base of Support
CCI	Co-contraction Index
COM	Center of mass
EMG	Electromyography
H	Hazardous
HC	Heel Contact
iEMG	Integrated EMG
MG	Medial Gastrocnemius
MH	Medial Hamstring
NH	Non Hazardous
PSV	Peak Slip Velocity
SD	Slip Distance
SD	Standard Deviation
SE	Standard Error
TA	Tibialis Anterior
TO	Toe Off
US	Unexpected Slip
VL	Vastus Lateralis

4.0 METHODS

The experimental data were collected as part of an IRB-approved experimental project investigating whole-body biomechanics of slips and falls in healthy young and older adults funded by the National Institute of Occupational Safety and Health (NIOSH R03 OH007533, Principal Investigator: Rakié Cham, Ph.D.)

4.1 SUBJECT POPULATION

A total of 20 healthy adults, 9 older individuals aged 55 to 66 years old (6 females and 3 males) and 11 younger individuals aged 20 to 26 years old (6 females and 5 males) participated in this study (Table 2). 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 [35,84].

Table 2: Subject Characteristics

Mean (SD) [Range]	Young	Old
Age (yrs)	23.27 (1.95) [20-26]	60.44 (3.50) [55-66]
Weight (kg)	70.53 (13.82) [58.18-105.45]	72.33 (14.44) [45.54-86.82]
Height (m)	1.71 (.06) [1.64-1.86]	1.64 (.08) [1.54-1.79]

4.2 EXPERIMENTAL ENVIRONMENT

The Human Movement and Balance Laboratory at the University of Pittsburgh is designed to capture and analyze human motion especially gait.

4.2.1 Data Acquisition Systems

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.

4.2.2 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 7). 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.

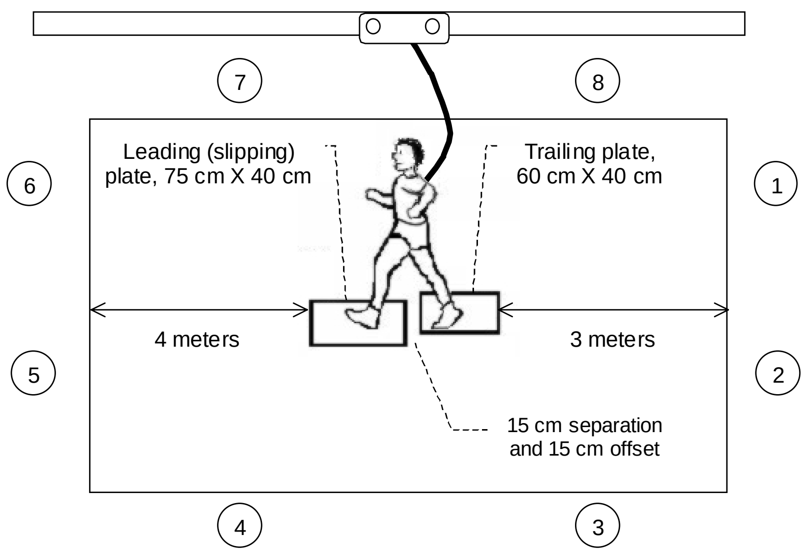

Figure 7: Schematic gait path layout. Circled numbers represent camera placement. Rectangles are embedded force plates. Trolley and harness system are also shown.

4.2.3 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 8). 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.

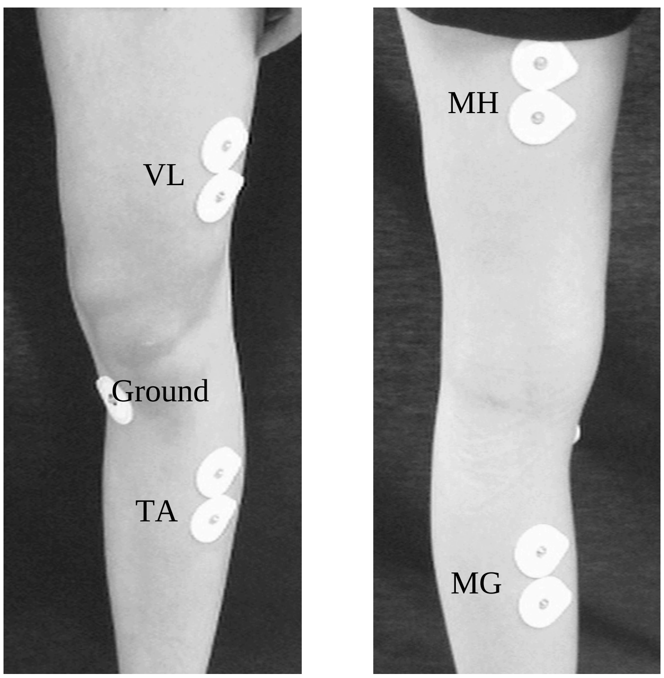

Figure 8: Picture of the stance (left) leg EMG placement. Frontal view is provided on the left showing VL, TA and ground electrodes. Rear view is provided on the right showing MH and MG electrodes.

4.2.4 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 [35,84]. It prevents contact with the ground and any resulting injury after a loss of balance.

4.2.5 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.

4.2.6 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 [19]. 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.

4.3 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.

Once a participant comfortably negotiated the gait path with both feet repeatedly hitting the appropriate force plates naturally, the data collection began. The lights were dimmed to minimize unwanted reflections and detection of a contaminant by the participant. 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).

To summarize, the conditions included in the protocol are the following:

- Baseline Dry (BD) -The participant was informed that the first few trials would be dry, ensuring natural walking with no fear of slipping. Two to three good (both feet contact one and only one force plate) trials were collected.
- Unexpected Slip (US) – The contaminant was applied without the participant’s knowledge. After this trial, the participant is given clean shoes and the floor is cleaned.
- Alert Dry (AD) - The participant was informed of the possibility of encountering a slippery floor prior to each of the next five dry trials.

Only the first two trials in the AD conditions were considered for analysis to minimize any adaptation effects.

The experimentation lasted approximately two hours. During testing, participants walked along the gait path no more than 30 times with rest periods of at least one minute between trials. This effort is well below exertions that could lead to physical fatigue. However, participants were reminded that if a break was needed during testing it would be provided to them.

4.4 DATA PROCESSING AND ANALYSIS

4.4.1 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 [36]. After filtering, EMGs were time normalized with respect to the left foot with 0% being HC and 100% as TO. The mean (SD) 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 [40].

4.4.1.1 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 3). 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 HC and from HC 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 [88]. 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-HC (-20% to HC) and post-HC (HC to 20%) time periods. This value was divided by the time period, 20%, and the resulting index has a maximum value of two.

Table 3: Dependent Variables: Dry Trials

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

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

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

Equation 1: Modified CCI

To summarize, the following EMG characteristic variables were calculated:

- Onset – Start of muscle activation, [percent time]
- Offset – End of muscle activation, [percent time]
- Duration – Difference between the offset and onset, [percent time]
- Magnitude – iEMG from onset to offset, [unit-less * percent time]
- CCI – Integrated (from -20% to HC and from HC to 20%) ratio of the EMG activity of antagonist/agonist muscle pairs (TA/MG and VL/MH) , [unit-less]

4.4.1.2 Contaminated Trials Contaminated trials were categorized into non-hazardous (NH) and hazardous (H) by considering the peak velocity of the heel during a slip. 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 HC 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 4).

Table 4: 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.

To summarize, the following EMG characteristic variables were calculated:

- Latency – Time from HC to start of postural reaction of muscle activations, [percent time]
- Cessation – End of postural reaction of muscle activations, [percent time]
- Reactive Duration – Length of postural reaction of muscle activations, [percent time]
- Reactive Magnitude – iEMG of postural reaction of muscle activations from latency to cessation, [unit-less * percent time]

4.4.2 Statistical Analysis

4.4.2.1 Preliminary Analysis An outlier analysis was performed on all experimental data using the jackknife distance method. The distance for each observation is calculated with estimates of the mean, standard deviation, and correlation matrix that do not include the observation itself. Three adults were excluded after an outlier analysis was performed using the jackknife distance method. Next, plots were made to check for normality. To compare qualitatively the EMG data collected in this experiment to previously published findings in young adults, an ensemble average of the time normalized and low-pass filtered EMG activity was computed for each muscle. Time history plots were generated during the stance period. Additionally, EMG characteristics collected during the BD trials for each subject were descriptively summarized using bar plots, stratified by muscle and age group (young/old).

Typical plots of EMG activation patterns during hazardous and non-hazardous slips were graphically compared to muscle activity collected in unperturbed baseline gait conditions. A correlation analysis was performed on the EMG characteristics and PSV. Scatter plots of each

EMG characteristic were generated using anticipation condition to visualize potential differences. To descriptively summarize how muscle activation patterns during gait in BD conditions may have affected the outcome of a slip (hazardous or non-hazardous) in young and older adults, bar plots were generated with the dependent variable on the y-axis being the EMG variable of interest, stratified by age group (young or older group) and by the hazardousness classification of the slip event on the x-axis.

4.4.2.2 Muscle Activation Patterns during Unperturbed Gait EMG characteristics collected during BD gait trials were statistically compared between young and older subject groups. Mixed linear ANOVA models were fit with the EMG response variable of interest as outcome, age group (young/old) as a fixed effect and subject within the age group as a random effect (two to three baseline trials per subject were averaged and included in the model). A significant effect of the age group factor was an indication of significant differences in baseline EMG characteristics between young and older adults.

4.4.2.3 Reactive Strategies ***Specific Aim 1: 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.***

H.1) In a response to an unexpected slip, the normalized reactive magnitude and latencies of the Medial Hamstring and Vastus Lateralis will be critical to a successful reaction, and furthermore, the knee flexors will have a faster latency than the knee extensors.

As mentioned in the data processing section (Section 4.4.1.2), 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. 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. A significance level of $p \leq 0.05$ was used.

H.2) *Responses associated with non-hazardous slips will have shorter latencies and greater magnitude compared to reactions associated with hazardous outcomes.*

H.3) *Young adults will react to unexpected slips with shorter latencies and a greater magnitude compared to older adults.*

In contrast to the analysis described in the previous section (a between-muscle analysis), the following analysis used within-muscle models. Initially, the muscle-specific EMG variables of interest were descriptively summarized across subjects using bar plots, stratified by age group (young/old), and whether the slip was classified as a hazardous slip or non-hazardous slips (peak slip velocity < 1 m/s). This allowed for an overall visual presentation of reactive strategies between young and older adults, in addition to whether or not the slip outcome was hazardous.

Next, to formally test hypotheses 2 and 3, 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. A significance level of $p < 0.05$ was used.

The effects of PSV on EMG response was investigated using linear ANOVA models with PSV as outcome and age group, EMG characteristic as fixed effects and their interaction term. Finally, a stepwise regression analysis was conducted on peak slip velocity to identify the most critical predictors of slip severity. The correlation between the explanatory variables identified by the stepwise regression was examined and these potential predictors were entered into a linear regression model as appropriate. The outcome in this regression model was peak slip severity. A significance level of $p < 0.05$ was used.

4.4.2.4 Proactive Strategies ***Specific Aim 2: 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.***

H.1) *Slippery surface warnings will result in earlier onsets and longer durations of the Medial Hamstring and Medial Gastrocnemius activity as well as increased co-contraction of both the upper and lower leg muscles compared to findings in locomotion on known dry surfaces.*

H.2) Slippery surface warnings will result in greater co-contraction, delayed onsets and shorter durations of muscle activity in older than in young adults.

First, the muscle-specific EMG variables of interest were descriptively summarized across subjects using bar plots, stratified by anticipation condition (BD/AD) and by age group (young/old). This allowed for an overall visual presentation of proactive strategies adopted by young and older adults.

Second, to formally test Hypotheses 1 and 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. A significant effect of the main anticipation condition factor would imply Hypothesis 1 is true, while H.2 will be accepted if the interaction term of age group and anticipation condition is significant. A significance level of $p \leq 0.05$ was used.

H.3) Baseline gait muscle activation patterns characterized by earlier onset of the Medial Gastrocnemius and increased co-contraction will result in less severe slips as quantified by peak slip velocity.

Quantitative testing of differences in baseline EMG characteristics between hazardous and non-hazardous slips in young and older adults was performed. Specifically, linear ANOVA models were fit with the EMG response variable of interest collected in known dry conditions as outcome (one model/outcome), with 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 hazardous and non-hazardous slips in terms of difference in baseline EMG characteristics in young and older subjects. A significance level of $p < 0.05$ was used.

The effects of EMG characteristics during normal gait on slip severity as measured by PSV were investigated using linear ANOVAs conducted on PSV using age (young/old), EMG parameter during normal gait and their interaction effect. Finally, a stepwise regression analysis was conducted on peak slip velocity to identify the most critical predictors of slip severity collected in known dry conditions. The correlation between the explanatory variables identified by the stepwise regression was examined and these potential predictors were entered in a linear regression model as appropriate with age as a covariate. The outcome in this regression model was peak slip severity. A significance level of $p < 0.05$ was used.

To investigate the impact of MG 1 activation on ankle CCI, linear ANOVA models were fit with ankle co-contraction collected in known dry conditions as outcome (one model/outcome), with age (young/old), MG 1 activation (yes/no) as fixed effects including their interaction term. If the interaction term of age group and activation was significant, appropriately constructed post-hoc Tukey comparison tests allowed statistical comparisons were conducted. A significance level of $p < 0.05$ was used.

5.0 RESULTS

5.1 MUSCLE ACTIVATION PATTERNS DURING UNPERTURBED GAIT

In order to verify BD EMG profiles with previously reported profiles filtered at 10 Hz [111], the data were filtered using the 10 Hz zero-phase elliptical filter and normalized as described in section 4.4.1 (Figure 9). Comparing to Figure 6, it is important to remember that 60% is TO since it is normalized to stride duration. The data presented in this project is normalized to stance with 100% being TO. The young adults' ensemble averaged time series (± 1 SE) are shown in Figure 9. Although secondary minor activity was present during gait, note that only the muscle activation around HC and the MG mid-stance was considered.

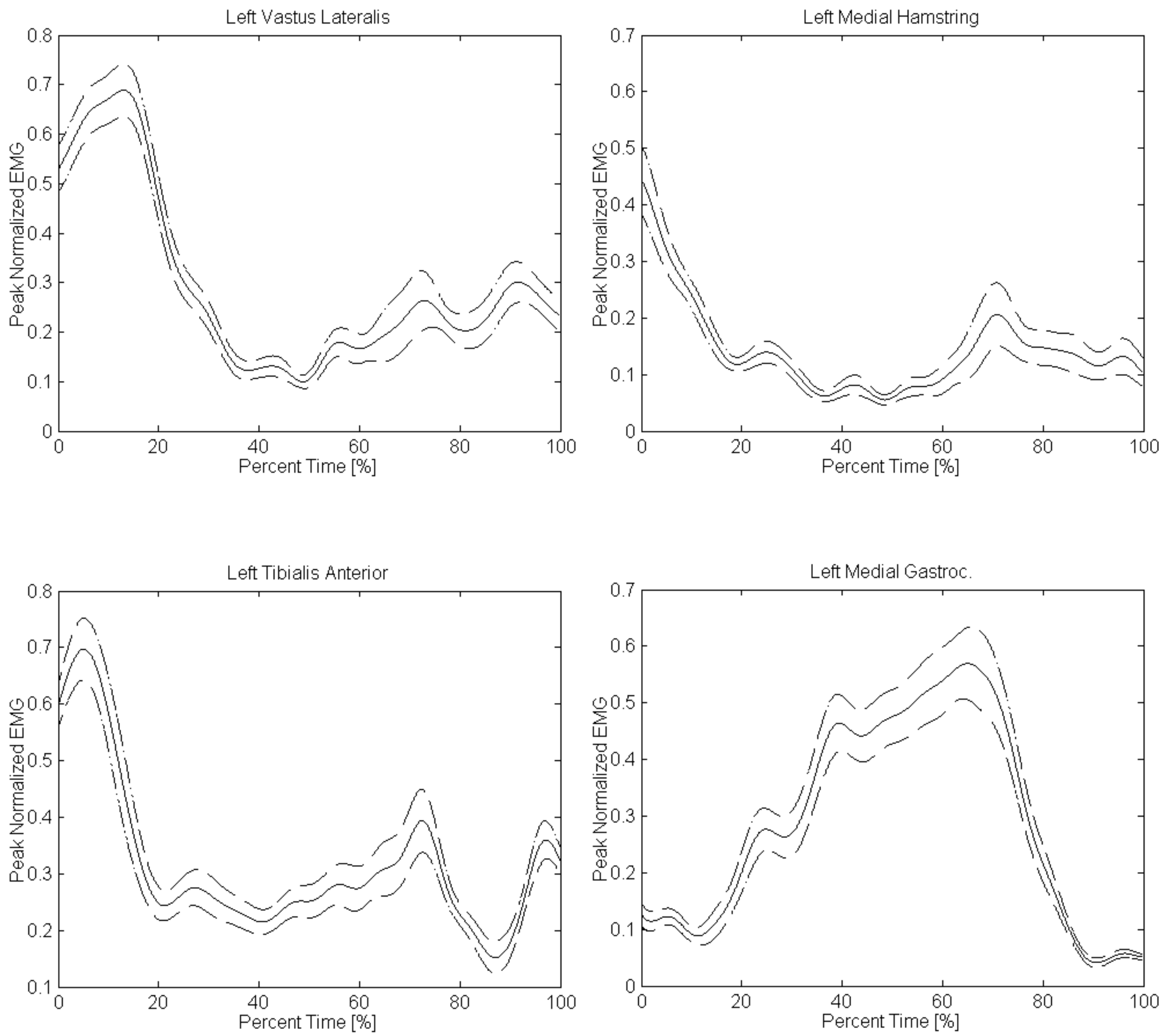

Figure 9: EMG profiles for baseline dry trials of young adults, mean values shown as a solid line. Percent time is from HC to TO with HC being 0% and 100% as TO. Dashed lines represent SE.

Overall, the muscle activation patterns reported here during BD (Figure 9, Figure 10) were similar to those previously reported during gait by Winter [111] (Figure 6). However, increased muscle activity of the MG was found around HC in four young adults (36%) and one older adult (11%) (Figure 10). This is noted as MG 1 in Figure 10. MG 2 refers to activation of the MG around 30% stance, typically seen during gait as the primary muscle activation of the MG.

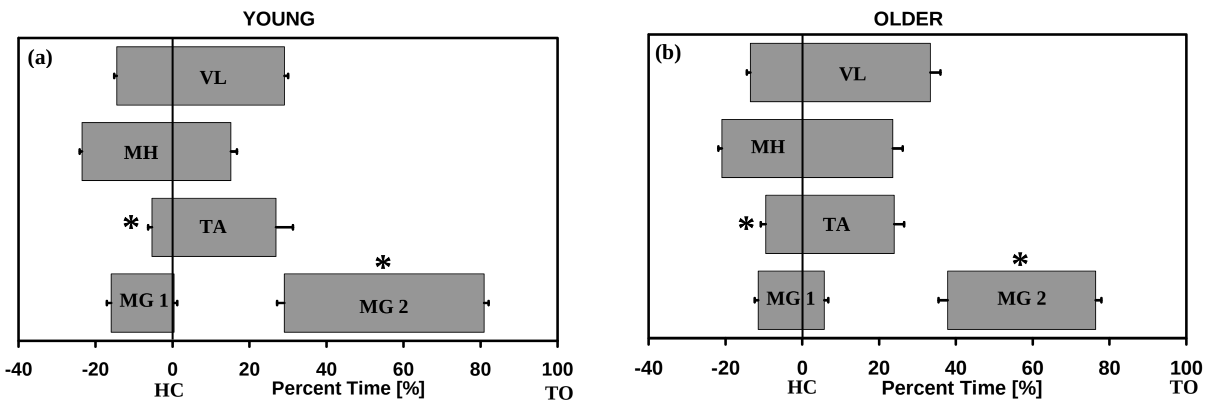

Figure 10: BD muscle activation patterns normalized to percent stance with HC being 0% and 100% as TO. Onset corresponds to the right side of the bar and offset is the left side with duration being the length. Young adults' mean values, a, and older adults' mean values, b, are provided. The non-typical MG activity around HC, MG 1, was found in 36% of young adults and 11% of older adults. * Denotes significant age-related difference in onset (located to the right of the bar) and duration (located above the bars). SE bars shown.

To investigate age-related differences in normal muscle activation patterns during unperturbed gait, mixed linear ANOVAs were conducted. In general, there were few age-related differences in muscle activity during BD gait. It should be noted that older adults (Figure 10b) activated their TA significantly sooner (p=.0336) than younger adults (Figure 10a) and had a shorter activation (p=.0041) of MG 2.

5.2 REACTIVE STRATEGIES

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.

5.2.1 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 11).

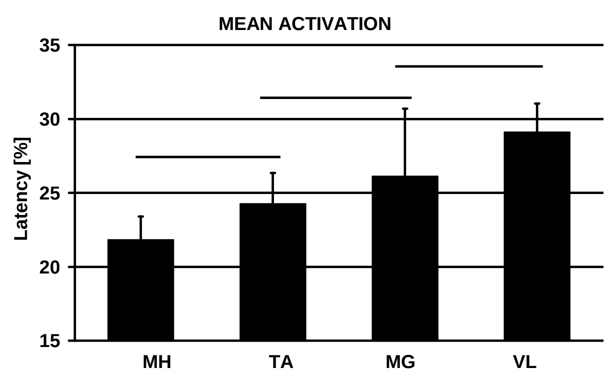

Figure 11: Mean activation latencies of postural reaction in percent time of stance leg muscles in response to a slip. Non-significant results of post-hoc Tukey tests are provided (-). SE bars given.

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 12, Figure 13). Young adults showed significantly later cessations ($p = .0230$) and longer reactive durations ($p = .0234$) during hazardous slips compared to older adults.

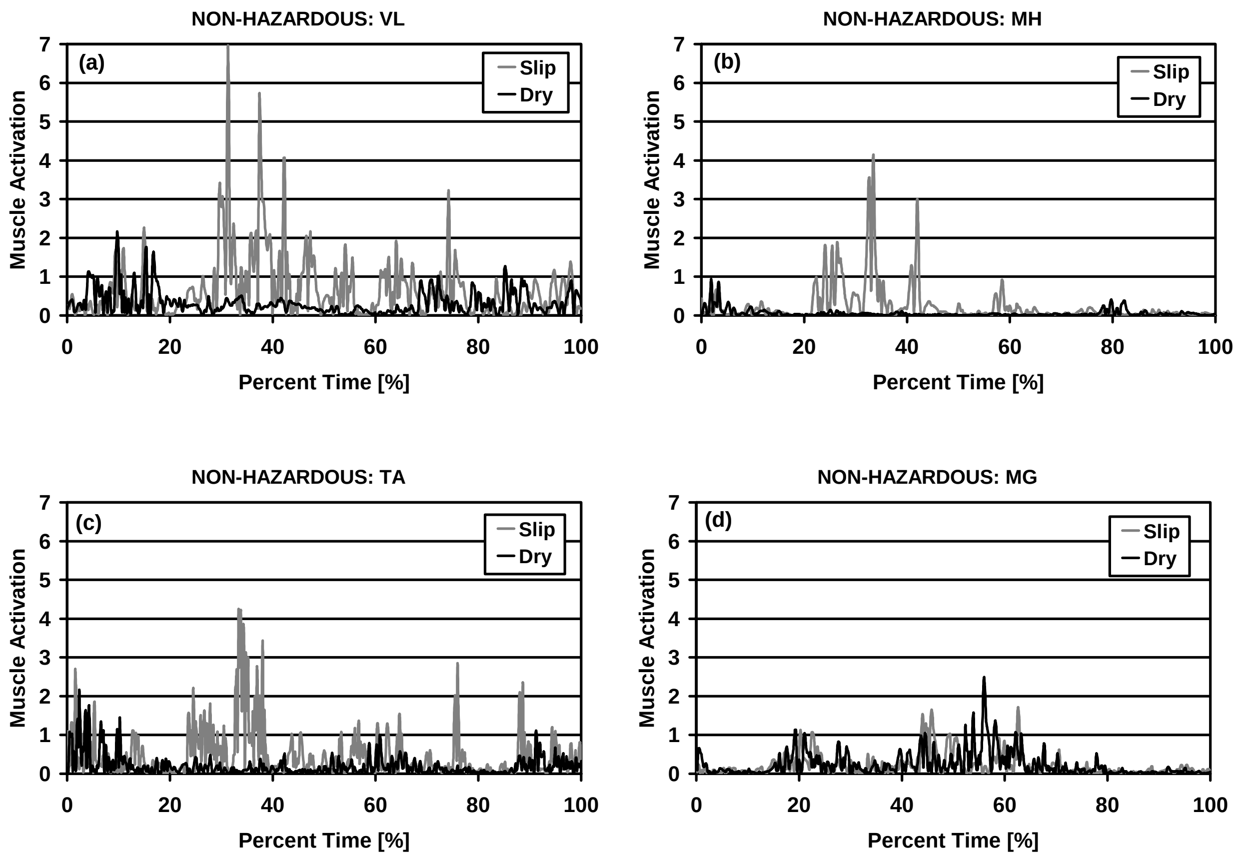

Figure 12: Typical muscle activation patterns during a non-hazardous slip (gray) and one baseline dry gait trial (black). (a): VL, (b): MH, (c): TA, (d): MG. Muscle activity was magnitude normalized to the peak during baseline gait and time normalized to stance with HC being 0% and TO as 100%. The end of slip was recorded at 27.4 % stance.

It was noted that all muscles demonstrated a positive reactive magnitude during slipping (Figure 12, Figure 13). Overall, hazardous slips had increased reactive magnitude compared to non-hazardous slips ($p = .0001$, Figure 12, Figure 13). 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 ($p = .0288$).

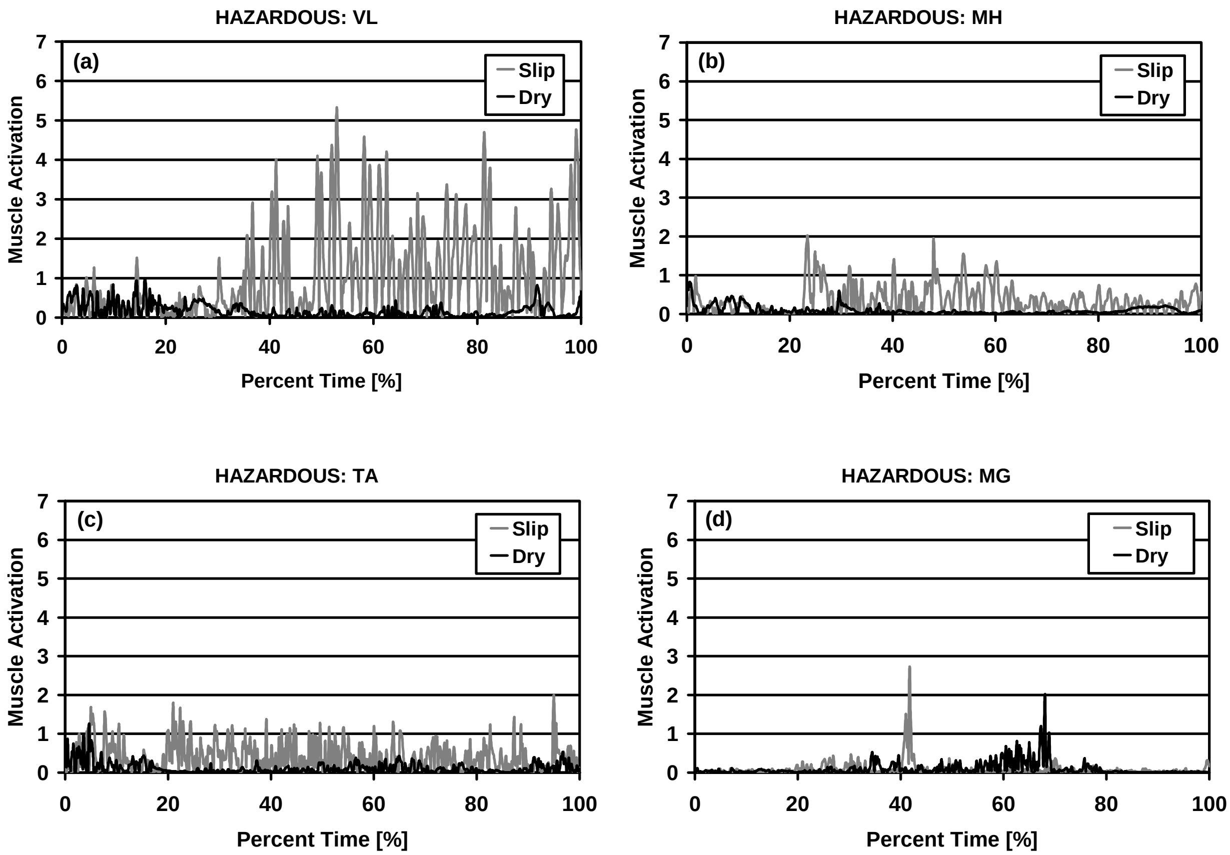

Figure 13: Typical muscle activation patterns during a hazardous slip (gray) and one baseline dry gait trial (black). (a): VL, (b): MH, (c): TA, (d): MG. Muscle activity was magnitude normalized to the peak during baseline gait and time normalized to stance with HC being 0% and TO as 100%. The end of slip was recorded at 54.4 % stance.

5.2.2 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).

5.2.2.1 Temporal Aspects of Muscle Activity Similar temporal patterns of muscle activation strategies were noted between young and older adults (Figure 14). 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 14a, Table 5), effect supported by the relatively high correlation between VL latency and PSV (Table 8).

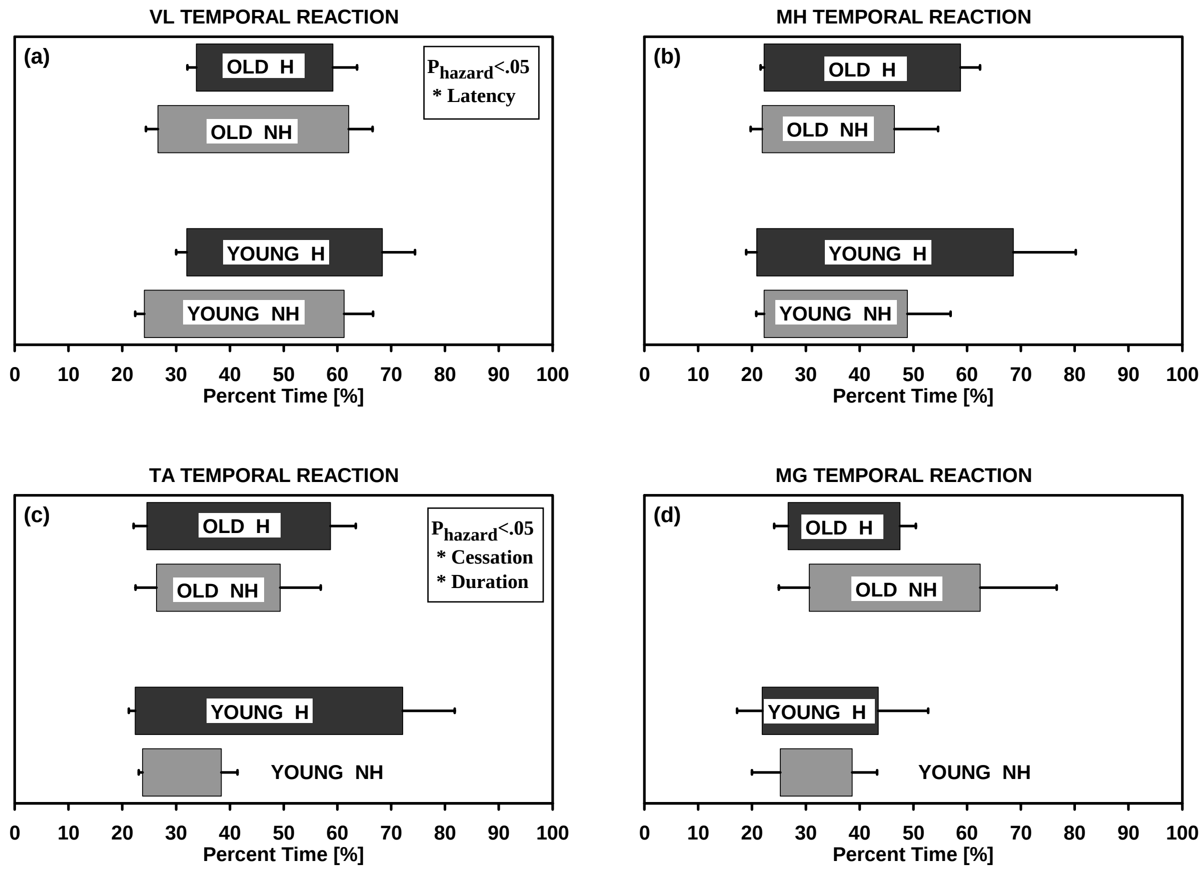

Figure 14: Temporal aspects of muscle activation during reaction to an unexpected slip. (a): VL, (b): MH, (c): TA, (d): MG. The BD trial before the US trial was subtracted from the US trial leaving the reactive activity. Bars represent reactive onset and cessation of muscle activity. Older adults are 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.

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 14, Table 6). This tended to occur in the MH as well (Table 5).

Table 5: 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 6: 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.

5.2.2.2 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 15, Table 7).

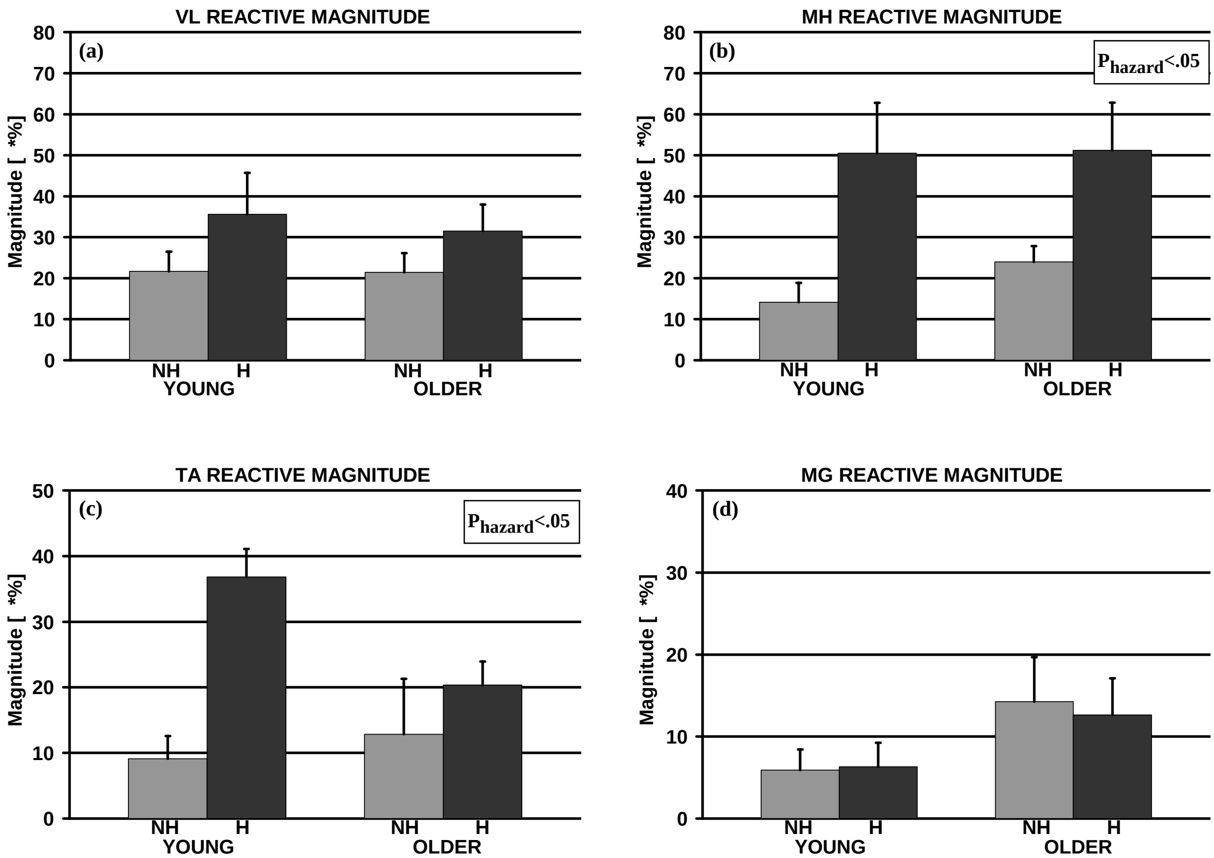

Figure 15: Reactive magnitude of muscle activation during reaction to an unexpected slip. (a): VL, (b): MH, (c): TA, (d): MG. The BD trial before the US trial was subtracted from the US trial leaving the reactive activity. Bars represent reactive magnitude. Young adults are shown left while older adults 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 7: Reactive Magnitude Statistics

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

* Only p values < 0.1 are presented.

5.2.3 EMG characteristics and slip severity as measured by PSV

Certain EMG characteristics were highly correlated to PSV (Table 8). The highest correlation was noted between VL latency and PSV (Table 8). MH cessation and TA cessation were also moderately correlated to PSV (Table 8). Additionally, all reactive magnitudes, except MG, were correlated to PSV (Table 8). Thus, an increased magnitude of reaction was required for slips with greater PSV except at the MG. Reactive magnitude was also correlated to cessation within muscles (Table 8). This is appropriate since cessation was utilized as the end point for integration in calculating reactive magnitude.

Table 8: Correlation of Slip Reaction Variables

			Latency				Cessation				Reactive Magnitude			
		PSV	VL	MH	TA	MG	VL	MH	TA	MG	VL	MH	TA	MG
	PSV	1	.80	-.02	.03	.03	-.02	.38	.55	-.01	.30	.43	.50	.08
Latency	VL		1	.09	-.22	-.08	-.04	.18	.63	-.28	.28	.44	.71	-.01
	MH			1	.18	.71	-.14	-.20	-.11	-.04	-.56	-.45	-.27	-.35
	TA				1	.23	.31	-.11	.04	.49	-.05	-.25	-.32	.24
	MG					1	-.34	-.29	-.27	.47	-.47	-.47	-.43	-.10
Cessation	VL						1	.13	.50	-.01	.40	-.04	.27	.12
	MH							1	.32	.00	.19	.49	.21	-.02
	TA								1	-.15	.57	.38	.80	-.05
	MG									1	.04	.13	-.40	.66
Reactive Magnitude	VL										1	.61	.56	.30
	MH											1	.37	.55
	TA												1	-.19
	MG													1

To investigate the relationship between PSV and highly correlated variables, linear ANOVAs were performed on PSV using age group, EMG characteristic and their interaction effect. A delayed VL latency was associated with more severe slips as measured by the PSV ($p = .0007$, Figure 16a). Additionally, later MH cessations tended to be associated with increases in slip severity ($p = 0.061$, Figure 16b). A delayed silencing of the TA was associated with more severe slips ($p = .0426$, Figure 16c). Similarly, increased reactive magnitude of the TA was seen as PSV increased ($p = .037$, Figure 16c). Age effects and their interaction with these EMG characteristics were not significant.

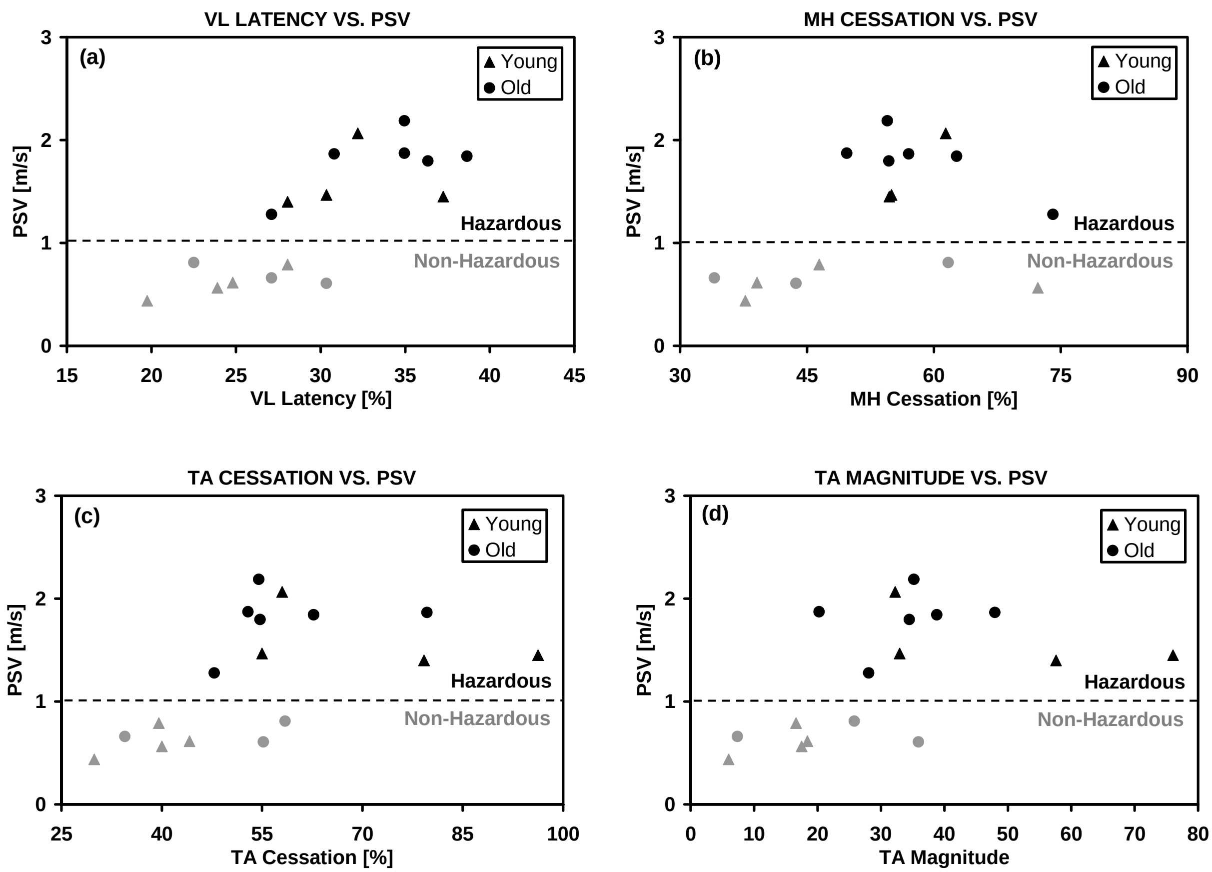

Figure 16: (a): VL Latency vs. PSV, (b): MH Cessation vs. PSV, (c): TA Cessation vs. PSV, (d): TA Magnitude vs. PSV. Young adults are noted by triangles while older adults are noted by a circle. Black symbols correspond to hazardous slips and gray symbols are non-hazardous slips. PSV greater than 1 mm/s signify a hazardous slip.

A stepwise regression analysis was performed in an attempt to identify EMG characteristics that were associated with a successful reactive strategy, decreased PSV. The output of the stepwise regression yielded three variables: VL latency, MH cessation, TA latency. These variables were used as independent variables in a multivariate regression model to predict PSV (Table 8, Figure 17). Note that the dependent variables used in this regression model were not correlated to each other ($|r| < .25$, Table 8) and therefore supplied relatively independent contributions to the model.

The multivariate regression analysis revealed a significant relationship between PSV and VL latency ($p < 0.0001$). Specifically, increases in VL latency were associated with severe slips as measured by the PSV (Figure 17). In addition, later MH cessations tended be associated with increases in slip severity ($p = 0.06$, Figure 17). Finally, there was no significant association between TA latency and PSV ($p = 0.12$). The overall model resulted in a R^2 value of 0.78.

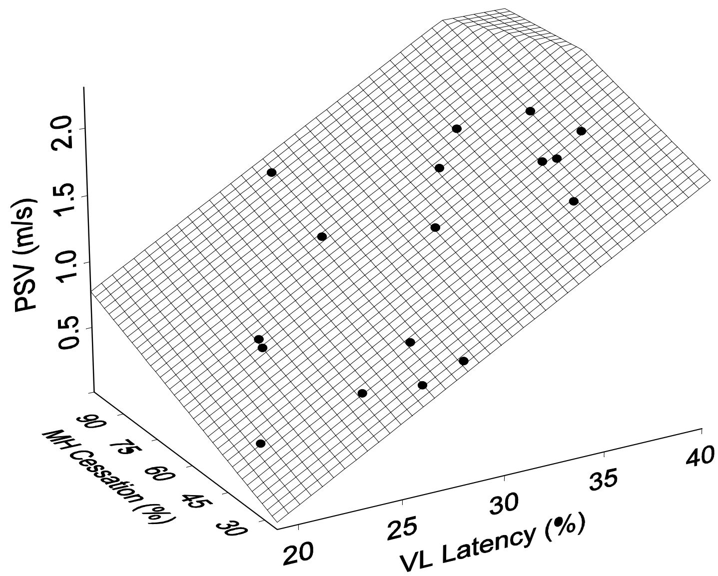

Figure 17: 3D plot of MH Cessation and VL Latency vs. PSV. PSV greater than 1 mm/s signify a hazardous slip. Delayed VL latency and MH cessation were associated with increased PSV. The overall model had a R^2 value of 0.78.

In summary, reactive muscle activation patterns, which were similar among young and older adults, were scaled to slip severity with hazardous slip reactions consisting of longer, higher magnitude responses of the MH and TA. Additionally, a delayed VL latency and MH cessation were associated with an increased slip severity.

5.3 PROACTIVE STRATEGIES

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. 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.

5.3.1 Temporal Aspects of Muscle Activity

Younger adults activated their MH significantly earlier in stance compared to older adults (Table 9). Additionally, younger adults activated their MH significantly longer when anticipating a slippery surface compared to older adults (Figure 18b, Table 9). Younger adults tended to utilize a similar strategy when activating their TA longer during AD (Figure 18c, Table 10).

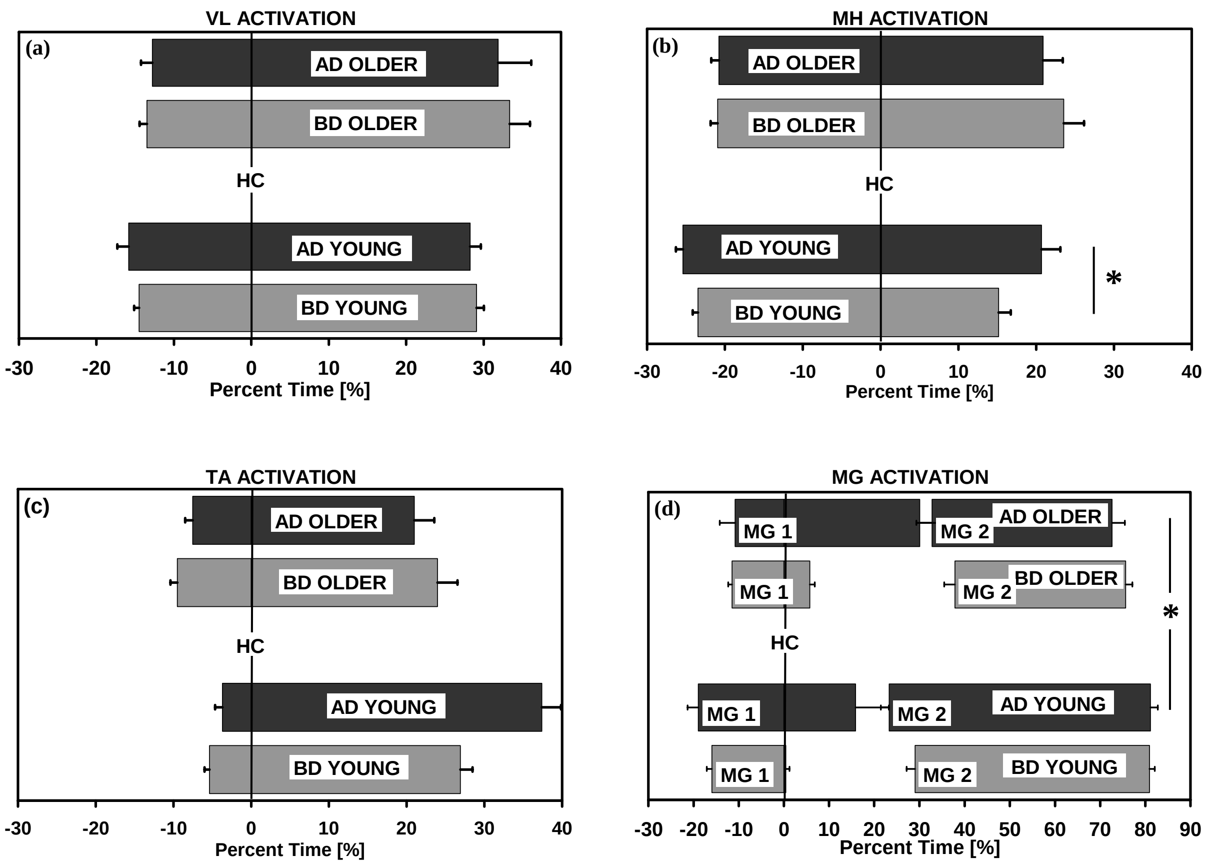

Figure 18: Temporal effect of anticipation on muscle activations during gait. Bars represent reactive onset and offset of muscle activity. (a): VL, (b): MH, (c): TA, (d): MG, MG 1 shown on left and MG2 shown on right. MG 1, was found in 54% of young adults and 67% of older adults. Older adults are shown 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 5 and 6 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 HC, termed MG 1. In addition to the four young adults and one older adult, two more young adults and five additional older adults activated their MG around HC, 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 10). Regardless of MG 1 activation, younger adults tended to activate their MG 2 sooner than older adults as well as significantly longer (Table 10). 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 18d, Table 10). Additionally, when anticipating a slippery surface, older adults' offset occurred significantly sooner in stance than young adults (Table 10). Anticipation had no significant effect on the activity of the VL in both the young and older adults (Figure 18a, Table 9).

Table 9: 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 10: 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.

5.3.2 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 11). The greatest increase in magnitude was noted in MH and MG 1 (Figure 19). Also, young adults increased their MH magnitude significantly more than older adults when anticipating a slippery surface (Table 11).

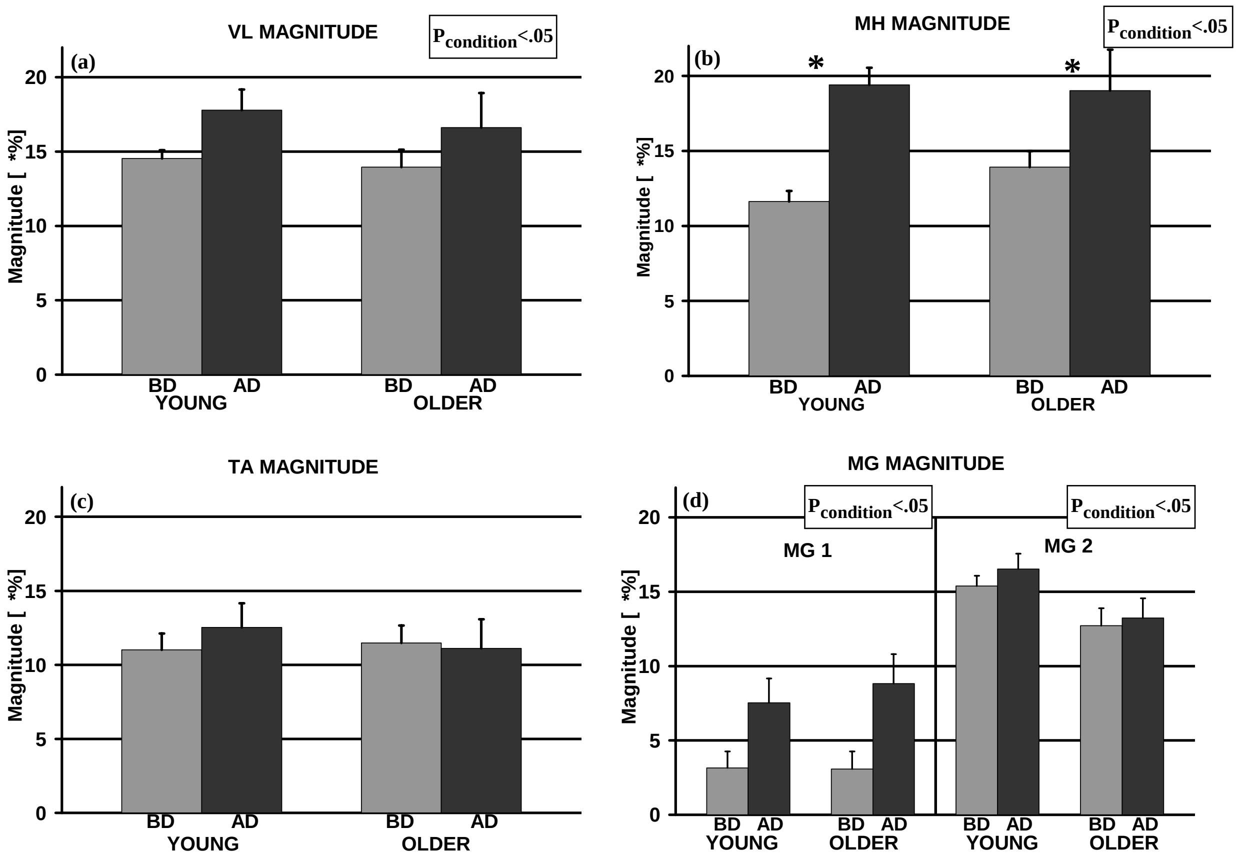

Figure 19: Magnitude effect of anticipation on muscle activations during gait. (a): VL, (b): MH, (c): TA, (d): MG, MG 1 shown on left and MG2 shown on right. Young adults are shown on the left while older adults are on the right. Black bars correspond to alert dry and gray bars are baseline dry. Overall significance is given in top right corner of each graph. Significant results of post-hoc Tukey tests are provided (*). SE bars given.

Table 11: 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 20, Table 12). There were no interaction effects of age and condition. Pre-HC 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 20a, Figure 20c). Similarly, anticipation resulted in an average increase of 30.5 % at the ankle and 35.9% at the knee of post-HC co-contraction (Figure 20b, Figure 20d).

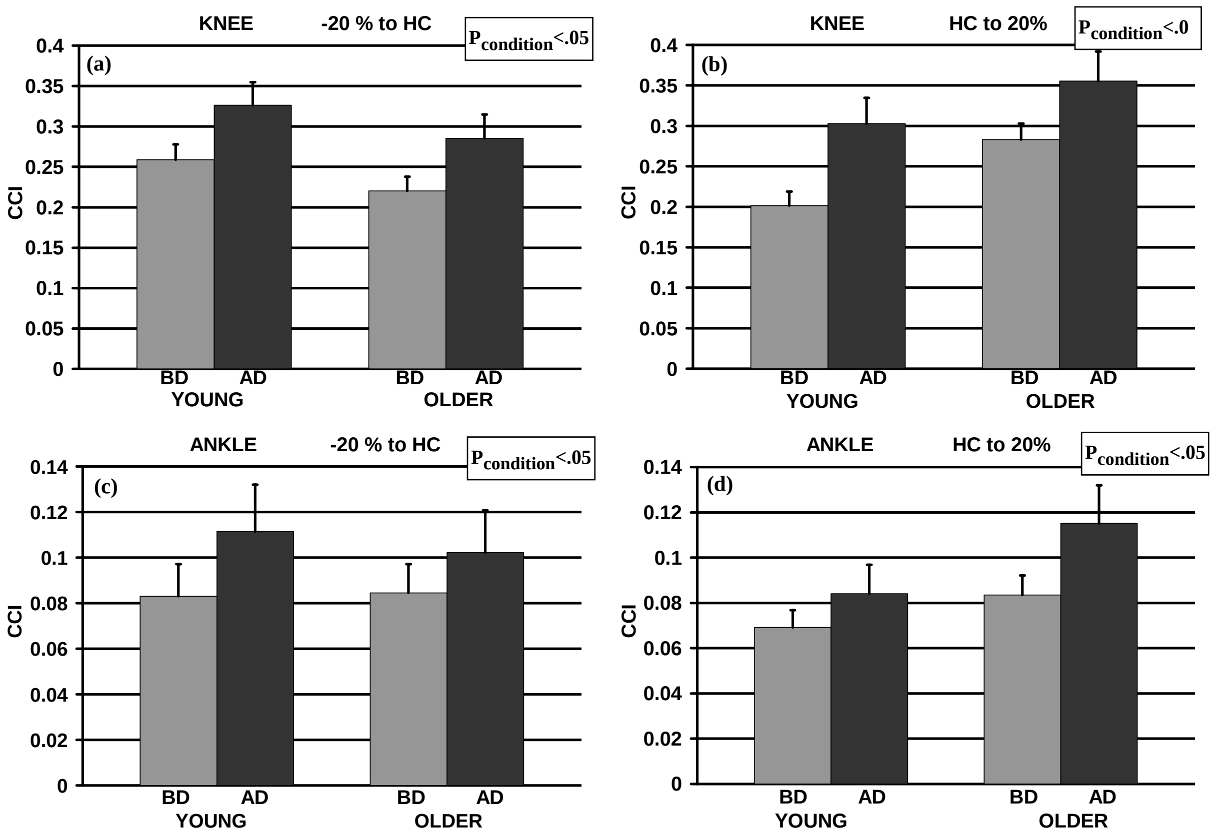

Figure 20: Effect of anticipation on co-contraction during gait. (a): co-contraction at the knee pre-HC, (b): co-contraction at the knee post-HC, (c): co-contraction at the ankle pre-HC, (d): co-contraction at the ankle post-HC. Young adults are shown on the left while older adults are on the right. 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 12: CCI Statistics

	-20% to HC		HC 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.

5.4 INITIAL CONDITIONS

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-HC ($p = .0357$) and post-HC ($p = .001$) was significantly different between hazardous and non-hazardous groups. Adults that normally walked on dry floors with greater co-contraction around HC at the ankle experienced non-hazardous slips (Figure 21).

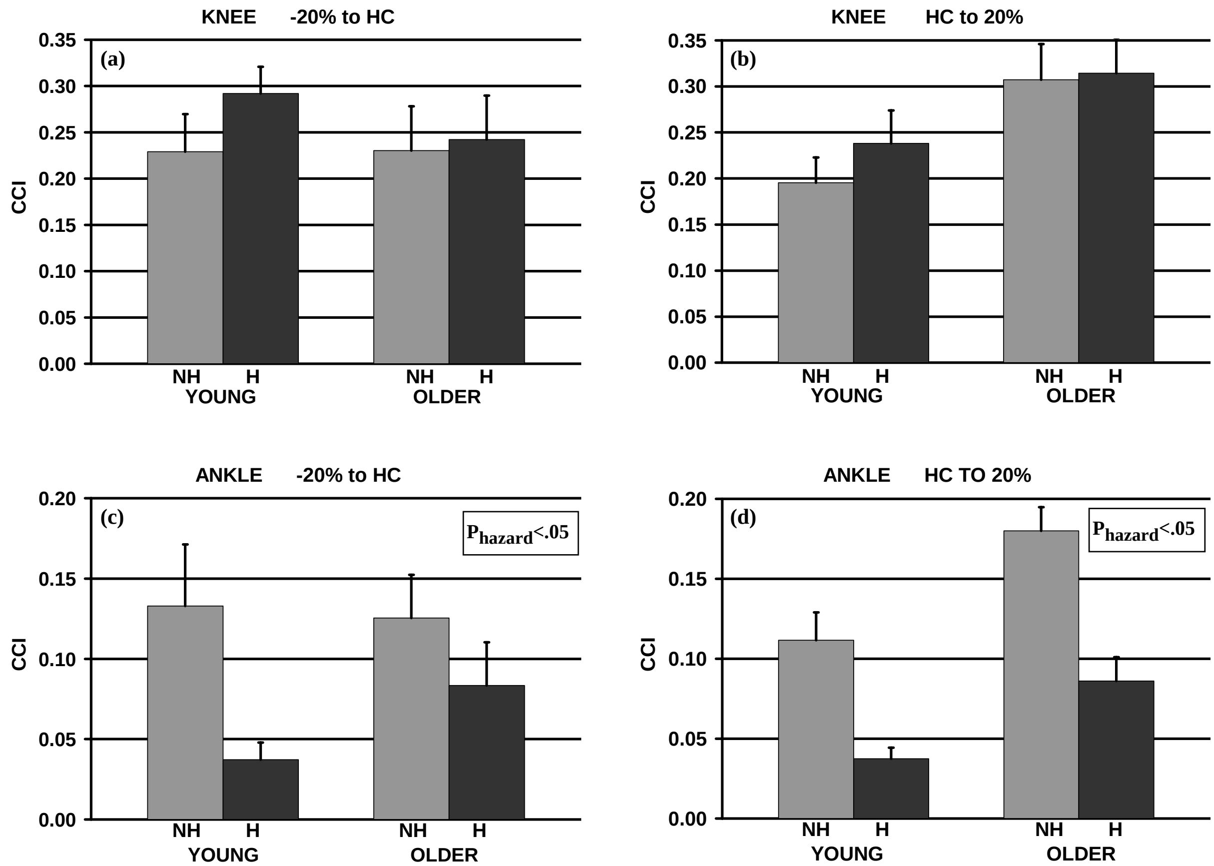

Figure 21: Effect co-contraction during gait on slip severity as measured by hazardous condition. (a): co-contraction at the knee pre-HC, (b): co-contraction at the knee post-HC, (c): co-contraction at the ankle pre-HC, (d): co-contraction at the ankle post-HC. Young adults are shown on the left while 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.

To investigate the effects of EMG characteristics during normal gait on slip severity as measured by PSV, linear ANOVAs were conducted on PSV using age (young/old), EMG parameter during normal gait and their interaction effect. Co-contraction at the ankle pre-HC tended to be greater as PSV decreased (p = .0881, Figure 22). Additionally, ankle co-contraction post-HC was significantly less in adults who experienced more severe slips as measured by PSV (p = .0012, Figure 22). Adults that normally walked on dry floors with less co-contraction around HC at the ankle experienced more severe slips as measured by PSV (Figure 22).

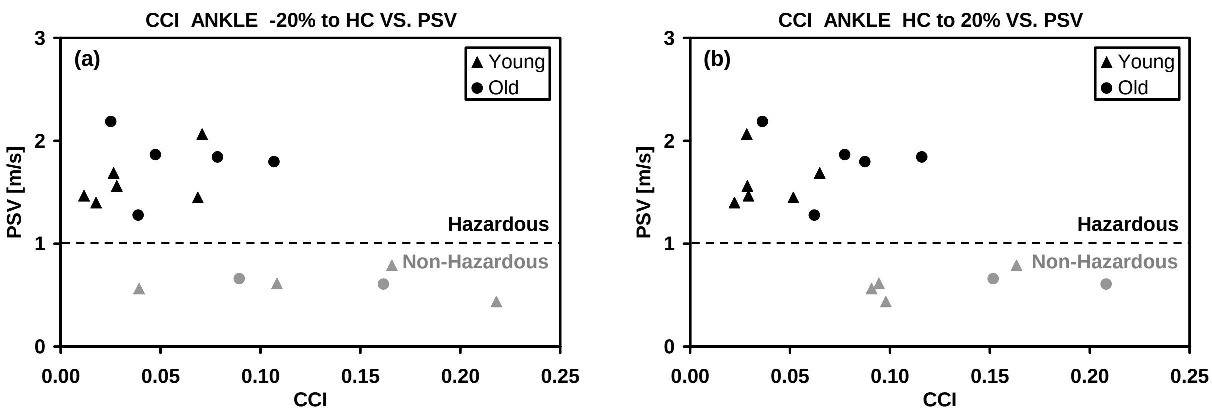

Figure 22: (a): CCI Ankle Pre-HC vs. PSV, (b): CCI Ankle Post-HC vs. PSV. Young adults are noted by triangles while older adults are noted by a circle. **Young adults are noted by triangles while older adults are note**d by a circle. Black symbols correspond to hazardous slips and gray symbols are non-hazardous slips during an unexpected slip. PSV greater than 1 mm/s signify a hazardous slip.

Increased co-contraction at the ankle can be attributed to the activation of MG around HC, MG 1. To investigate the relationship between MG 1 activation and ankle co-contraction, linear ANOVAs were conducted on ankle CCI using age (young/old), MG 1 activation (yes/no) during normal gait and their interaction effect. Both co-contraction at the ankle pre-HC ($p < .0001$) and post-HC ($p = .0010$) were significantly greater when adults activated MG 1 (Figure 23). In addition, age-related differences were noted as older adults demonstrated a higher CCI at the ankle post-HC compared to young adults ($p = .0224$, Figure 23).

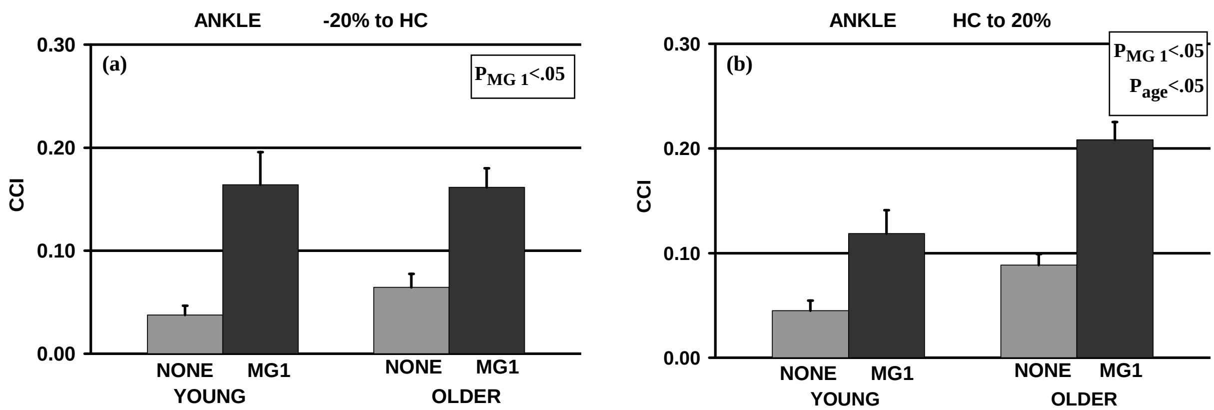

Figure 23: Effect of MG 1 activation on ankle co-contraction during normal gait. (a): co-contraction at the ankle pre-HC, (b): co-contraction at the ankle post-HC. Young adults are shown on the left while older adults are on the right. Black bars correspond to lack of MG 1 activation and gray bars are MG 1 activation. Overall significance is given in top right corner of each graph. SE bars given.

A stepwise regression analysis was performed to identify EMG characteristics of normal gait on dry floors that are associated with decreased slip severity, decreased PSV. The output of the stepwise regression yielded three variables: CCI of the ankle post-HC, TA onset and VL onset. MG 1 could not be included in the analysis due to the small number of subjects that demonstrated activation. These previously mentioned variables were used as independent variables in a multivariate regression model to predict PSV (Table 13, Figure 24). Dependent variables used in this regression model were moderately correlated to each other ($|r| < .5$, Table 13) supplying relatively independent contributions to the model.

Table 13: Partial Correlation: Initial Conditions

	PSV	**CCI Ankle Post-HC**	**TA Onset**	**VL Onset**
PSV	1	-.529	-.188	.004
CCI Ankle Post-HC		1	-.427	-.137
TA Onset			1	.311
VL Onset				1

The multivariate regression analysis revealed a significant relationship between PSV and ankle co-contraction post-HC ($p = .0033$). Specifically, increases in CCI resulted in less severe slips as measured by the PSV (Figure 24). Delayed TA onset also significantly decreased slip severity ($p = 0.031$, Figure 24). There was no significant association between VL onset and PSV ($p = 0.75$). The overall model resulted in a R^2 value of 0.49.

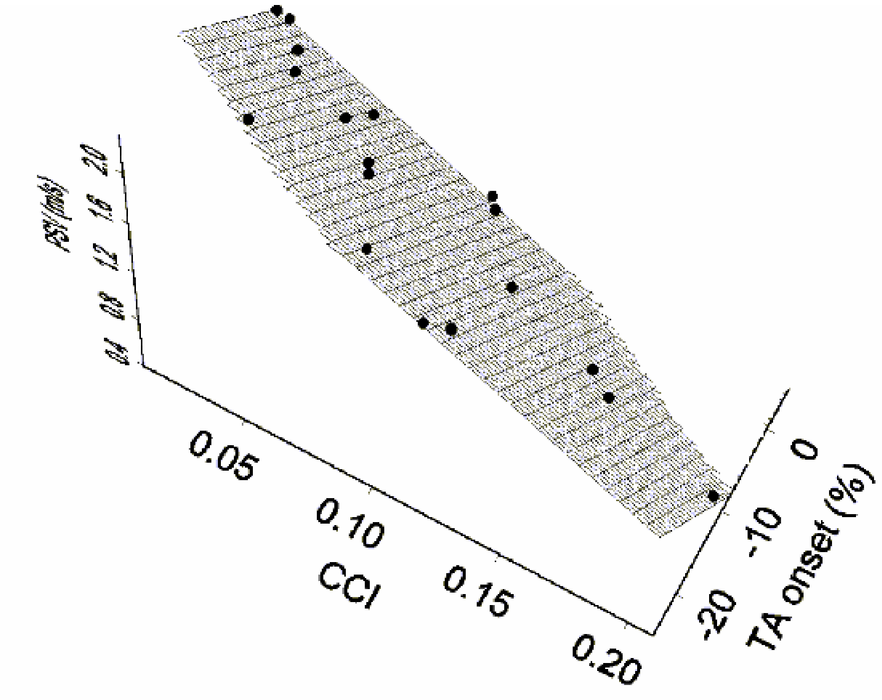

Figure 24: 3D plot of Ankle Co-Contraction Post-HC and TA Onset vs. PSV. PSV greater than 1 mm/s signify a hazardous slip. Increased ankle co-contraction post HCD and delayed TA onset during baseline dry gait were associated with increased PSV during an unexpected slip. The overall model had a R^2 value of 0.49.

In summary, greater co-contraction at the ankle around HC during normal gait resulted in less severe slips. Specifically, decreased ankle co-contraction post-HC and an earlier TA onset during normal gait on dry floors resulted in more severe slips as measured by PSV.

6.0 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.

6.1 MUSCLE ACTIVATION PATTERNS DURING UNPERTURBED GAIT

Overall, experimental EMG profiles during BD were similar to those previously reported [111], thus suggesting that natural gait was achieved during BD conditions. These similarities included the activation of the VL around -20% until 35% stance. MH was typically active from -25% stance until approximately 20% stance. Subjects activated their TA shortly before HC and continued activation until 25% stance. Primary activation of the MG, MG 2, initiated around 30% stance and subsided around 80%. Few age-related differences, for example temporal aspects of the TA and MG 2, in muscle activation patterns during unperturbed gait were found. No previous literature that reported age-related inequalities in EMG during gait was found. Overall, the results reported here show that older adults considered in this study (60.44 yrs) utilized similar muscle activation patterns during unperturbed gait compared to young adults.

Interestingly, there was some atypical increased muscle activity of the MG around HC, MG 1, present in four young adults (36%) and one older adult (11%). This type of variable activity of the plantarflexors around HC has been noted previously during normal gait [37]. The activity contributed to an increase in co-contraction with the TA that might have a role in the control of foot positioning. The appearance of MG 1 might also contribute to decreased foot-floor angle at heel contact which in turn decreases the likelihood of a slip [16,18].

6.2 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 [15]. 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 [24,25,27,65,68,98]. 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 [15,27,29]. 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 [15]. 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 [53,95]. 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 [15]. 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 [15]. 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 [69]. 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 [69]. 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 [15]. 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 [15,27,29]. 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 [15]. 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 [2,97,99]. This difference might be directly related to the reduced lower extremity strength or ability to generate powerful, fast responses reported in older adults [62,101,113]. 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.

6.3 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 HC, 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 [57,73,99]. 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 HC [16,18,64]. These adaptations resulted in an overall reduction in the peak required coefficient of friction, thus decreasing slip and fall potentials [12,13,16,35,82,83,96]. 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 [16]. 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 [16,18].

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 HC [111]. This strategy has been seen previously when anticipating a slippery surface and would result in a decreased slip potential [16,18]. Additionally, younger adults' MH activation was significantly longer when anticipating a slippery surface compared to older adults. After HC, 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 [111]. 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 [114].

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 HC 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 HC 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 HC, 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 HC. Overall, activation of the MG 1 lasted significantly longer during anticipation, which would result in achieving foot flat sooner in stance, reducing slip potential [16,18,83]. 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 [111]. 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 HC 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 [111]. 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 HC at the ankle for both age groups. This co-contraction at the ankle may play a role in the control of foot positioning [37]. 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 HC, 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 [72,73]. 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 [114]. 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 HC 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.

6.4 INITIAL CONDITIONS

Previous research noted certain factors of normal gait that influenced peak slip velocity [96] and thus, fall potential [9,57]. EMG characteristics during normal gait on dry floors were investigated to determine why, given the same environmental conditions, some slips are shorter, slower and require little or no reactive response to stop the slipping foot. It was found that increased co-contraction at the ankle around HC during normal gait was associated with less severe slips. Specifically, decreased ankle co-contraction post-HC and an earlier TA onset during normal gait on dry floors was noted in adults who experienced more severe slips as measured by PSV. These changes in muscle activation patterns represent an increase in foot-floor angle at HC, previously shown to increase slip potential [16,18,63,64].

Co-contraction at the ankle pre-HC and post-HC was significantly greater in adults that experienced non-hazardous slips compared to those who experienced hazardous slip. Similar findings were noted with increased PSV. Adults that normally walked on dry floors with less co-contraction around HC at the ankle experienced more severe slips as measured by PSV. A stepwise regression analysis was performed to identify EMG characteristics of normal gait on dry floors that are associated with decreased slip severity, decreased PSV. A significant relationship between PSV and ankle co-contraction post-HC was revealed. Specifically, increases in CCI were associated with less severe slips as measured by the PSV. In addition, delayed TA onset was also significantly related to decreased slip severity.

It is possible that both increased ankle co-contraction post-HC and delayed TA onset caused decreased foot-floor angle at HC. The TA is a dorsiflexor, so delaying the onset of the TA would result in decreased foot-floor angle at HC. Increased co-contraction at the ankle was shown to be directly related to the activation of MG around HC, MG 1. In other words, adults that demonstrated MG 1 activation had significantly greater ankle co-contraction pre-HC and post-HC. MG 1 was noted in four young adults (36%) and one older adult (11%) during normal gait on dry floors. Therefore, it could not be included in the analysis due to the small number of subjects that demonstrated activation. This type of variable activity of the plantarflexors around HC has been noted previously during normal gait [37]. MG 1 probably contributed more to decreasing foot-floor angle at heel contact as opposed to "stiffening" the ankle. It is possible that increased co-contraction also resulted in a stiffer ankle. A stiffer ankle joint would also make initiating a slip more difficult. Also, decreased foot-floor angle at heel contact decreases the likelihood of a slip [16,18,63]. Therefore, adults that naturally walk with a smaller foot-floor angle or stiffer ankle joint are predisposed to experience less severe slips.

Age-related differences were noted as older adults demonstrated a higher CCI at the ankle post-HC compared to young adults. This implies that older adults should experience less hazardous slips compared to younger adults. Additionally, an earlier onset of the TA was found in older adults compared to young adults during normal gait on dry floors. Earlier onset of the TA in older adults without differences in their offset implies that older adults activated their TA longer than young adults. However, no significant differences were noted in the magnitude of TA activation, suggesting that on average the magnitude per percent time has to be lower in older adults. Therefore, when a fixed time window is considered, HC to 20%, the overall magnitude of the TA would be smaller in older adults resulting in increased CCI post-HC compared to young adults. This implies that older adults employ a more cautious gait under normal conditions thus, are predisposed to experience less hazardous slips. This cautious gait behavior in older adults has been noted in previous literature [3,4,33,45,53,61,86,92,109]. Therefore, initial conditions imply that older adults' natural gait predisposes them to experience a less hazardous slip. However, once they slip, older adults simply can't react with the long, powerful response needed to prevent balance loss. This helps to explain the higher incidence of falls found in the elderly.

7.0 LIMITATIONS

Noise and error exists in all measurements to some extent. This is particularly the case in EMG recordings. Certain factors are crucial to achieving a good EMG signal. Impedance at the electrode-skin interface is important. Moisture, hair and dead skin cells may cause higher impedance, resulting in a low detection of electrical currents. The skin was cleaned and abraded to avoid this. Additionally, any variation in electrode placement between subjects could affect the signal. Crosstalk can be detected in EMG recordings using surface electrodes. This occurs when an excitement from an adjacent muscle reaches the electrodes placed on the muscle of interest. Crosstalk is sometimes difficult to remove due to the human muscular anatomy. The muscles recorded here are not close in proximity, however correct detection of the specific muscle, VL, from the muscle group consisting of several muscles in the same area, quadriceps, may be difficult. The issue of preventing crosstalk was addressed by careful electrode placement.

It was assumed that BD gait corresponded to natural gait on dry floors without any anticipation effects. Subjects were instructed to walk naturally and informed that the first few trials would be dry. However, each participant read and signed an informed consent that specifically stated the use of slippery floors. Also, participants were equipped with a safety harness throughout testing and in an unfamiliar laboratory environment. Therefore, it is impossible to determine which subjects, if any, were suspicious of a slippery floor during the BD condition. Every attempt was made to ease subject concerns and ensure natural gait during BD. The data was also inspected within the BD condition for consistencies. However, it can only be assumed that gait during BD was natural and without anticipation. Additionally, the older subject group was arguably not sufficiently old to impact general EMG characteristic variables.

Co-contraction was presented in the form of an index used to generate a measure that was comparable across subjects. The form of this index has been used previously [88]. However, it is unclear what amount of co-contraction corresponds to a "stiff" joint. A certain amount of increase in co-contraction attenuates the leg muscles in order to initiate a quicker response. Too much co-contraction would result in stiffening the joint, hindering a quick reaction. These limits could not be determined with the data collected for the purpose of this study. A universal co-contraction index with limits defining "stiff" is recommended.

Slips were categorized into hazardous and non-hazardous using a PSV threshold of 1.0 m/s. This threshold was chosen based upon velocities for larger slips reported in previous studies [53,95]. Classifying slip severity avoids slip outcome determination issues for hazardous slips where recovery efforts may be assisted through reliance on the safety harness, slipping completely off of the contaminated force plate, or other indeterminate ground contact. However, not differentiating falls from recoveries limits the conclusions that can be drawn concerning successful reactions. It is possible that non-hazardous slips are over before a reaction is needed and that differences in postural reactions are critical only between recoveries and falls. It would have been difficult to categorize falls and recoveries due a small sample size and lack of load cell data. Only visual confirmation was available to distinguish falls from recoveries which would not have been an accurate tool.

It was difficult to comment on the cessation and duration of hazardous slip reactions. In certain trials, cessation and duration were actually greater than the calculated parameters. This occurred because 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 stance leg muscles during hazardous slips but could not be reported. This would also apply to reactive magnitudes since the end point of integration is cessation.

The unavailability of kinematic and kinetic data made it impossible to state what exactly was happening to the body as a result of the muscle activations. Several possible changes in body dynamics had to be provided with each reported muscle activity. Previously reported kinematic and kinetic changes, identified during unexpected slips and anticipation of slippery surfaces, were used to explain muscle activation patterns reported here. However, the kinematic and kinetic data associated with this study would have provided a justification for certain conclusions that could not be drawn and clarified the effects of changes in muscle activation patterns. This data would have also aided in determining whether or not changes in muscle activations were a cause or effect of the given experimental condition. With the limitations of this study, only associations and relationships between EMG characteristics and slip severity or anticipation could be provided.

Only the stance leg muscle activation patterns were of interest here, however there are numerous other factors affecting the response to a slippery surface, as well as anticipation adaptations. Previous studies have reported the importance of the swing leg and upper body in response to a perturbation [2,15,25,27,29,72,73,98,99]. These changes sum to represent the full body biomechanics needed during a recovery attempt or in anticipation of a slippery floor. It is possible that certain changes seen in the stance leg muscle activation patterns can only be correctly understood by examining the relationship between these changes and changes of the swing leg or upper body.

8.0 CONCLUSION

The muscle activation patterns found here support the hypothesis that corrective reactions surrounding the knee and hip are most important in a successfully recovery attempt. Reactive strategies, which activation patterns were similar among young and older adults, consisted of activation of the MH around 21% stance (~ 175 ms), followed by the VL around 29% stance (~ 240 ms). 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, higher magnitude responses. In addition, 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.

When adapting to a potentially slippery surface, adults significantly change their muscle activation patterns during gait. In general, anticipation of a slippery surface resulted in earlier onsets and longer durations of flexors muscles with young adults demonstrating earlier onsets and longer durations than older adults reducing their slip potential. Notably more subjects activated their Medial Gastrocnemius around heel contact resulting in a decreased foot-floor angle thus, reducing slip potential. Alerting older and younger adults of the possibility of a slippery surface resulted in increased magnitude of activation and co-contraction at the ankle and knee. Overall, these adaptations resulted in decreased slip potential. Young adults demonstrated muscles activation changes that would result a slower leg and foot at HC compared to older adults, therefore, decreasing the slip and fall potential in young adults.

Finally, greater co-contraction at the ankle around heel contact during normal gait resulted in less severe slips. Specifically, increased ankle co-contraction post-HC and delayed TA onset during normal gait on dry floors, which possibly cause decreased foot-floor angle at heel contact and a stiffening of the ankle joint, were associated with less severe slips. Older adults' natural gait predisposes them to experience a less hazardous slip. However, once a slip occurs, older adults can't react with the long, powerful response needed to prevent balance loss whereas young adults are capable of this response. This lack of a powerful reaction may help to explain the higher incidence of falls found in the elderly.

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