THE IMPACT OF SLIP EXPOSURE ON GAIT

by

April Jeannette Chambers

BS, University of Pittsburgh, 2003

MS, University of Pittsburgh, 2005

Submitted to the Graduate Faculty of

Swanson School of Engineering in partial fulfillment

of the requirements for the degree of

Doctor of Philosophy

University of Pittsburgh

2011

UNIVERSITY OF PITTSBURGH

SWANSON SCHOOL OF ENGINEERING

This dissertation was presented

by

April Jeannette Chambers

It was defended on

March 10, 2011

and approved by

Steven Abramowitch, Ph.D., Assistant Professor, Department of Bioengineering

Jennifer Brach, Ph.D., Assistant Professor, Department of Physical Therapy

Arash Mahboobin, Ph.D., Research Assistant Professor, Department of Bioengineering

Mark S. Redfern, Ph.D., Professor, Department of Bioengineering

Dissertation Director: Rakié Cham, Ph.D., Associate Professor, Department of Bioengineering

THE IMPACT OF SLIP EXPOSURE ON GAIT

April Jeannette Chambers, PhD

University of Pittsburgh, 2011

Slips and falls are a major cause of injury in young and older adults. This research focused on investigating proactive strategies generated after experiencing a slippery surface without any additional awareness (Aim 1) and with awareness (Aim 2). The influence of aging was examined. Slip risk was assessed using required coefficient of friction (RCOF), center of mass (COM) state and general gait parameters. Slip severity was quantified using peak slip velocity. In Aim 3, a sensitivity analysis was performed on the lower extremity muscles included in a three-dimensional simulation of gait. Additionally, a preliminary comparison of the simulated muscle excitations between baseline and anticipation conditions provided insight into proactive strategies.

(Aim 1) Fifty-two adults from two age groups (young/older) experienced an unexpected slip. Multiple dry trials were conducted to assess recovery gait and a second unexpected slip was collected. (Aim 2) Thirty-one young/older adults walked across a dry surface before and after experiencing a slip and with warning of another slippery surface. Slip risk and slip severity were analyzed for dry and slip trials, respectively. Overall, older adults maintained a more conservative proactive strategy than young regardless of the amount of awareness provided. This resulted in older adults experiencing less severe slips upon second exposure with and without awareness. Young adults appear to be affected by the specificity of knowledge provided. With no

threat of a slippery surface, young adults eventually return to baseline levels of slip risk and a second unexpected slip can be generated. The addition of awareness resulted in young adults adopting a more conservative proactive strategy with decreased peak RCOF, amplified gait adaptations and increased COM stability compared to young adults without awareness. Consequently, young adults with awareness experienced a reduction in slip severity upon second exposure.

A sensitivity analysis of a three-dimensional gait simulation revealed that the removal of one muscle was compensated by muscles in the same functional group or antagonistic muscle group. Additionally, the model was most sensitive to perturbations in tendon slack length. These findings highlight the importance of model selection and obtaining accurate estimates of muscle model parameters when modeling gait.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

PREFACE

This research would not have been possible without the support and guidance of my committee, Dr. Rakié Cham, Dr. Steven Abramowitch, Dr. Jennifer Brach, Dr. Mark Redfern, and Dr. Arash Mahboobin. I am especially thankful to my advisor, Dr. Cham, and to Dr. Mahboobin for all the extra effort that was put into making this possible. Additionally, there are several members of the HMBL team that contributed directly to this work throughout the years. Thank you to everyone who has assisted in data collection, labeling, processing, etc. Without your hard work this would have taken a lot longer and not been nearly as enjoyable. This dissertation is dedicated to my grandfather, who always wanted to see this milestone achieved. This work was supported by research grants from the National Institute of Occupational Safety and Health (NIOSH R03 OH007533 and NIOSH R01 OH007592).

1.0 SPECIFIC AIMS

The long-term goal of this research is slips and falls prevention in older adults. Maintaining balance during walking in challenging environments requires two types of postural strategies, reactive and proactive. Reactive strategies are generated after balance is perturbed by an external hazard such as a slip or trip. Proactive strategies are generated when expecting the potential of being perturbed. Since proactive adjustments can reduce or even eliminate the need for a reactive response, a fundamental understanding of these proactive strategies is necessary, especially in older adults.

Proactive strategies can result from prior experience with a given hazard (slip/trip) and/or from being aware of the possible presence of a hazard prior to exposure. The individual impact of experience and awareness on proactive strategies and on their effectiveness in reducing the severity of a perturbation are unclear. Understanding proactive strategies is important in the development of slip paradigms and successful fall prevention programs.

The proposed research will focus on investigating the proactive strategies generated after experiencing a slippery surface without any additional awareness (Aim 1) and with awareness (Aim 2). The influence of aging on the findings in Aims 1 and 2 will also be examined. The risk of slipping will be assessed using the required coefficient of friction, center of mass state and general gait parameters, all of which are important factors in predicting slip severity. Slip severity will be quantified using the peak slip velocity measured at the heel of the slipping foot shortly after heel contact onto the contaminated floor.

Current modeling techniques can be utilized to provide insights into proactive strategies. In Aim 3, a sensitivity analysis will be performed to examine how simulated muscle excitations change due to the number of muscles included in a simulation of gait. Additionally, the sensitivity of simulated muscle excitations to perturbations in muscle model parameters will be evaluated. Following these analyses, preliminary modeling simulations will be used to provide insight into proactive strategies. The specific aims of this project and hypotheses that will be tested are described below.

Specific Aim 1: To investigate the effect of experience (without awareness) on proactive strategies generated after being exposed to an unexpected slip.

Hypothesis 1.1: Slip experience alone will initially result in gait adaptations to minimize slip risk. With no warning of future slips, proactive strategies will diminish and subjects will eventually return to normal gait.

Hypothesis 1.2: Experience alone will not result in reduced slip severity of subsequent slips given there is appropriate time between exposures.

Hypothesis 1.3: Older adults will adopt more cautious proactive strategies and experience less severe slips upon subsequent exposure compared to young adults.

Specific Aim 2: To explore the additional effect of awareness on proactive strategies generated after experiencing an unexpected slip.

Hypothesis 2.1: Awareness, in addition to experience, will result in increased proactive strategies to minimize slip risk compared to experience alone.

Hypothesis 2.2: Increased awareness, in addition to experience, will result in reduced slip severity of subsequent slips.

Hypothesis 2.3: Older adults will adopt more cautious proactive strategies and experience less severe slips upon subsequent exposure compared to young adults.

Specific Aim 3: To generate simulations of gait during baseline and anticipation conditions in order to provide a preliminary comparison of the simulated muscle excitations utilized during proactive strategies. Additionally, sensitivity analyses will be performed to examine how simulated muscle excitations change due to the number of muscles included in a simulation of gait and due to perturbations in muscle model parameters.

2.0 BACKGROUND AND SIGNIFICANCE

2.1 SCOPE OF THE PROBLEM

Falls are a major cause of injury, death, and disability in young and older adults. From 2004-2005 falls were the leading cause of injuries and emergency room visits regardless of age (Bergen *et al.* 2008). Falls accounted for 12% of all injury deaths and 25% of non-fatal injuries in 2006 (NCHS 2009). In 2007, more than 7.9 million Americans were injured by a fall (NSC 2009). Slips are often a common fall initiating event in the workplace, a finding that is consistent of many industrialized countries (Courtney *et al.* 2001, Gao and Abeysekera 2004). For example, slips have been reported as the most frequent event leading to fall and overexertion occupational injuries in Sweden (Courtney *et al.* 2001). Britain ranked slips, trips and falls as the most frequent type of injury event in employees with most falls being initiated by slipping (Gao and Abeysekera 2004). Same-level falls were the second leading cause of disabling injury among American workers in 2008 (Liberty Mutual 2010) (Figure 1). Nearly 50% of occupational fall-related fatal and non-fatal injuries have been caused by slipping (Courtney *et al*. 2001).

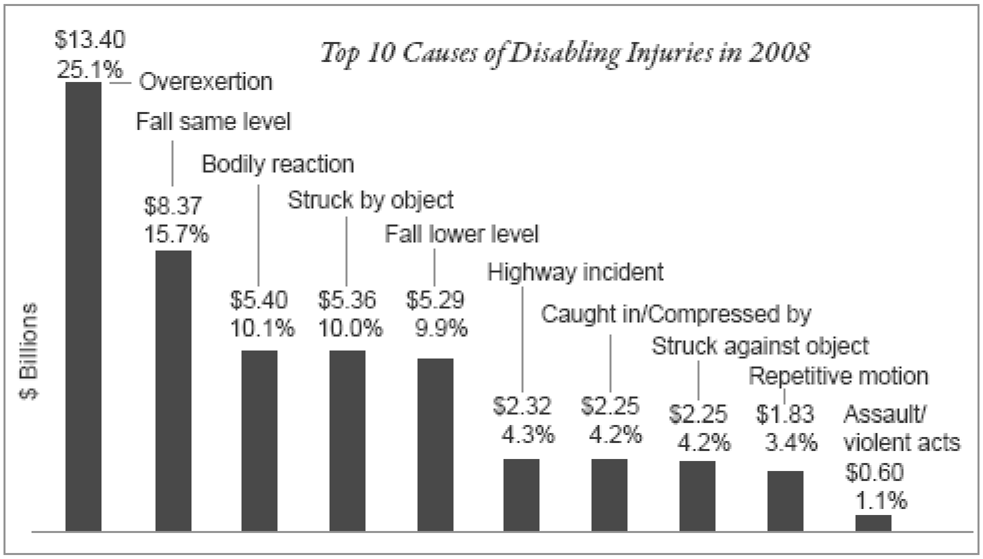


Figure 1: Top 10 causes of disabling injuries in 2008 (Liberty Mutual 2010).

Injuries afflicted by slips, trips, and falls on the same level are often severe and carry with them a high economic burden. In 2006, over 27 million emergency room visits among the general population were due to unintentional injuries of which falls were a leading cause (NSC 2008). Occupational falls on the same level require more time to recuperate than the median time required for all injuries. Slip and fall injuries typically result in 10 days away from work (BLS 2008). Nearly 30 percent of same-level falls resulted in more than 21 workdays lost (NSC 2008). The severity of fall-related injuries and loss of workplace productivity aid in explaining the high medical care costs and compensation payments associated with slips and falls. The overall injury burden from falls in the United States exceeded $89 billion in 2000 (Corso *et al.* 2006). The cost of same-level falls in the workplace has increased 42% over a ten year period from 1998 to 2008. In 2008 disabling injuries from same-level falls in the workplace cost $8.37 billion in the United

States (Liberty Mutual 2010) (Figure 1). The prevention of slip and fall injuries is a high occupational and public health priority.

The incidence, severity, and cost of falls increase with age. One out of three adults over the age of 65 falls each year (Hausdorff *et al.* 2001). In older adults, falls were among the leading causes of unintentional fatal and non-fatal injuries (Dellinger and Stevens 2006, CDC 2010). In 2009, over 2.2 million older adults who had a fall-related injury required an emergency room visit. Fall-related injuries are often severe in older adults. Over 80% of fall deaths were among adults 65 and older (CDC 2010). The total direct cost of fall-related injuries in adults over the age of 65 exceeded $19 billion in 2000 (Stevens *et al*. 2006). The cost of non-fatal injuries nearly doubles in older adults suggesting an increased burden with increasing age (Stevens and Sogolow 2005). Based on aging trends in the United States population, the rate and cost of falls is expected to worsen. By 2020, the number of falls is projected to increase more than 25% over a twenty-five year period and fall-related injury costs in older adults are expected to reach $54.9 billion (Englander *et al.* 1996).

An aging population suggests that the scope of this problem can be expected to increase in industry as well (Woolf and Pfleger 2003). Previous research has suggested that older workers are at a greater risk of incurring slip and fall-related injuries than their younger counterparts (Buck and Coleman 1985, BLS 2008). Injuries become more severe as age increases. This is reflected in the amount of time older workers miss after an injury (Figure 2). Older workers required 15 days away from work while workers younger than 35 years old only required 5 days on average (BLS 2008).

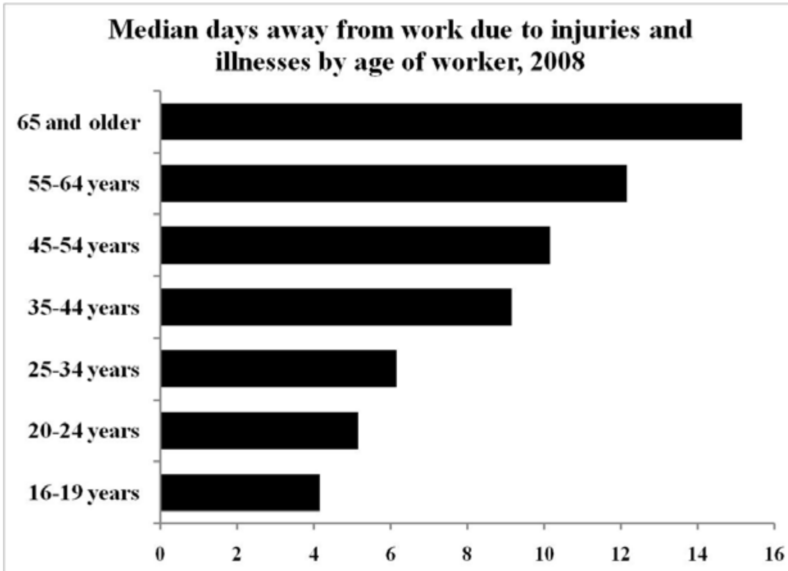


Figure 2: Median days away from work due to injuries and illnesses by age of worker, 2008 (BLS 2008).

In summary, slips and falls are a leading cause of injury and source of high economic costs, both of which increase with age. The high injury rates and costs associated with falls make them a strong prevention target. An aging workforce creates occupational challenges that did not previously exist. A clearer understanding of the factors responsible for minimizing slip risk is important for injury prevention. The impact of prior knowledge, whether experience or awareness, on proactive strategies is not well understood and has been cited as a limitation in many slip and fall experiments (Heiden *et al*. 2006, Oates *et al*. 2010). This doctoral dissertation provides a better understanding of how prior knowledge affects proactive strategies in order to correctly interpret slip experiments and provide insights on mechanisms used to reduce slip risk and slip severity. Additionally, this project used a novel modeling approach to provide a greater understanding of proactive strategies used to minimize slip risk and slip severity. The insight gained from this project may provide a better understanding of proactive strategies that help reduce the rate and severity of slip and fall accidents.

2.2 EXPERIMENTAL RESEARCH BACKGROUND

With approximately two-thirds of falls occurring during walking, it is not surprising that the aspects of gait are an important component of fall prevention research (Berg *et al.* 1997, Menz *et al.* 2003, Delbaere *et al*. 2009). Gait involves the integration of multiple complex processes that are necessary to initiate movement and maintain balance (Buczek and Banks 1996, Redfern *et al.* 2001). Investigating the neurological, biomechanical, physiological and psychological factors related to slip-precipitated falls during gait are critical in fall prevention research (Redfern *et al.* 2001). Encountering a slippery environment requires a corrective response to prevent falling. These reactive responses are complex and involve time critical motor skills (Cham and Redfern, 2001, Redfern *et al.* 2001, Lockhart and Kim 2006, Liu and Lockart 2009). Avoiding a fall can be challenging and becomes increasingly difficult with age (Lockhart and Kim 2006, Troy *et al.* 2008).

2.2.1 Causes of Slips and Falls

Slip-initiated falls involve the interaction of multiple environmental and human factors (Courtney *et al.* 2001, Redfern *et al.* 2001, van Dieen and Pijnappels 2008). Human factors include gait biomechanics, expectation, sensory information processing, neuromuscular and vestibular mechanisms involved in maintaining balance during walking (Redfern *et al.* 2001, van Dieen and Pijnappels, 2008). Environmental factors include the frictional properties of the foot-floor interface, material properties of the surface/shoes, and lighting (Courtney *et al.* 2001, Redfern *et al.* 2001, van Dieen and Pijnappels 2008).

Most slips occur when the amount of friction at the shoe-floor interface, a major environmental factor, is less than the friction biomechanically required to walk without slipping (Hanson *et al.* 1999, Burnfield and Powers 2006). It has been shown that slips occur due to a high ratio of shear to normal ground reaction forces applied on a floor surface immediately following heel contact (Hanson *et al.* 1999, Cham and Redfern 2002, Lockhart *et al.* 2003, Burnfield and Powers 2006). The ratio of shear to normal ground reaction forces, termed the required coefficient of friction (RCOF), represents the minimum required friction at the foot-floor interface to prevent the initiation of a slip (Redfern and DiPasquale 1997, Hanson *et al.* 1999). Specifically, the peak RCOF value during 10-30% of stance has been used to determine slip potential (Redfern and DiPasquale 1997, Cham and Redfern 2002, Lockhart *et al.* 2007). A lower peak RCOF has been linked to a reduced slip risk during gait (Redfern and DiPasquale 1997, Cham and Redfern 2002, Lockhart *et al.* 2007, Fong *et al.* 2008).

Certain temporal and spatial gait characteristics have been linked to falls (Berg *et al.* 1997, Menz *et al.* 2003, Delbaere *et al.* 2009). Significant differences in gait were found between fallers and non-fallers with increased gait variability predicting fall risk (Berg *et al.* 1997, Menz *et al.* 2003). Falling history has also been associated with decreased gait speed, increased stance time and increased temporal variability (Hausdorff *et al.* 2001). Changes in spatial gait parameters have also been noted in fallers. These include reduced step length, increased step width, increased step length variability and too little or too much step width variability (Lord *et al.* 1996, Maki 1997, Hausdorff *et al.* 2001, Brach *et al.* 2005). Hazardous slips have been associated with increased step length, decreased cadence, greater foot-floor angles at heel contact (Moyer *et al.* 2006) and decreased ankle muscle co-contraction (Chambers and Cham 2007). Researchers have also reported that decreased gait speed is associated with increased fall risk and a faster gait may allow for increased chances of a successful balance recovery from a slip (Hausdorff *et al.* 2001, You *et al.* 2001, Bhatt *et al.* 2005).

2.2.2 Proactive Strategies

Previous research has found that after walking on a contaminated flooring surface ('experience') or if a slippery surface warning is provided ('awareness'), gait adjustments are made to reduce the likelihood of a slip (Cham and Redfern 2002, Marigold and Patla 2002, Siegmund *et al.* 2006, Lockhart *et al.* 2007, Fong *et al.* 2008). Proactive strategies are balance control mechanisms that take place before encountering a potential disturbance and are an important aspect of fall prevention research (Cham and Redfern 2002, Pavol *et al.* 2004, Chambers and Cham 2007, Lockhart *et al.* 2007). They serve to counteract the destabilizing effect of a disturbance. Proactive strategies have been shown to reduce slip probability and reliance on reactive strategies in avoiding a fall (Cham and Redfern 2002, Pavol *et al.* 2004, Chambers and Cham 2007, Lockhart *et al.* 2007).

2.2.3 Combined Effects of Experience and Awareness of a Slippery Surface

Several studies have found that a combination of experience and awareness of a slippery surface results in several gait adaptations in young adults. Kinematic gait changes included shortened step length (Cham and Redfern 2002, Gao and Abeysekera 2004, Bhatt *et al.* 2005) and reduced foot-floor angle (Cham and Redfern 2002, Marigold and Patla 2002, Heiden *et al.* 2006, Fong *et al.* 2008). Altered kinetic parameters were also noted including reduced ground reaction forces and peak RCOF (Cham and Redfern 2002, Marigold and Patla 2002, Heiden *et al.* 2006, Lockhart *et al.* 2007, Fong *et al.* 2008) as well as altered lower extremity muscle activity and joint moments (Cham and Redfern 2002, Marigold and Patla 2002, Heiden *et al.* 2006, Chambers and Cham 2007). Experience and awareness of a slippery surface additionally resulted in feedforward changes in the center of mass state including increased margin of stability in both the medial-lateral and anterior-posterior directions (Marigold and Patla 2002, Bhatt *et al.* 2005). These aforementioned adaptations can result in decreased frictional requirements, thus reducing slip potential (Strandberg and Lanshammar 1981, Buczek and Banks 1996, Hanson *et al.* 1999, Cham and Redfern 2002, Burnfield and Powers 2007).

The combined effect of experience and awareness of a slippery surface may result in slightly different proactive strategies employed by older adults compared to young. Some research has found that older adults avoid falling through a proactive strategy similar to one used by young adults during sit to stand perturbations (Pavol *et al.* 2004). This is not always the case, as it was also found that older adults, age 70-85 years, shortened their step length after a mechanical perturbation more than young adults (Woollacott and Tang 1997). It has also been suggested that adults age 65 and older adopt a more cautious adjustment strategy than younger adults when walking over a known slippery surface, requiring more time to adjust their gait (Lockhart *et al.* 2007). A combination of experience and awareness of a slippery surface also resulted in older adults utilizing different muscle activity patterns than young adults (Lockhart *et al.* 2007, Chambers and Cham 2007). Further exploration is needed into possible age-related differences in proactive strategies generated in response to a real slippery surface, as they may be an important step in reducing the high rate of falls in older adults.

2.2.4 Effect of Awareness of a Slippery Surface

Awareness of a slippery surface is defined as knowledge that a surface will or may have the potential to be slippery. The effects of awareness are evident when we compare stepping onto an icy skating rink versus stepping on black ice we did not see, or walking differently in the presence of a wet floor sign. Recently, studies have attempted to distinguish the independent effects of experience and awareness. Awareness, by itself, seems to have minimal impact in assisting a novice person during a perturbation. In whiplash perturbations, awareness has played only a minor role in neck adaptations (Magnusson *et al.* 1999, Siegmund *et al.* 2003a). Nonetheless, it was found that participants aware of a pending whiplash perturbation were at a lower injury potential than unaware participants (Siegmund *et al.* 2003b). Being aware of a slippery floor alone produced limited kinematic changes similar to a combination of awareness and prior experience of a slippery floor (Heiden *et al.* 2006). These changes included a decrease in knee and foot-floor angle at heel contact. However, awareness alone did not produce any significant decrease in peak RCOF. It was concluded that awareness, in isolation, had no effect on either slip risk or slip distance (Heiden *et al.* 2006).

Awareness by itself may result in adopting a more cautious gait, especially in older adults (Pai *et al.*2003). Cautious gait has been defined as widened base of support, reduced gait speed, shortened step length and increased gait variability (Maki 1997, Menz *et al.* 2003, Lockhart *et al.* 2007). These cautious gait adaptations might be similar to those seen in older adults with concern over falling or fear of falling. Slower gait speed, shorter step length, increased step width, and increased double limb support time were found to be associated with a fear of falling (Maki 1997, Menz *et al.* 2003, Chamberlin *et al.* 2005, Delbaere *et al.* 2009). Gait variability has also been associated with numerous physiological and psychological factors including age and concern over falling (Adkin *et al.* 2002, Delbaere *et al.* 2009). Aging results in greater gait variability and slower gait with shorter steps (Lockhart *et al.* 2003, Menz *et al.* 2003, Shkuratova *et al.* 2004). It has been suggested that older adults, even those without fear of falling, are compensating for reduced physical and neuromuscular capabilities by adopting a more cautious gait (Maki 1997, Menz *et al.* 2003). However, these cautious gait adaptations have also been noted as risk factors for falls and may increase fall risk, rather than protect against it (Menz *et al.* 2003, Menz *et al.* 2007, Delbaere *et al.* 2009).

2.2.5 Effect of Experience of a Slippery Surface

Previous research has shown that experiencing a slip is an important aspect of developing a proactive strategy and minimizing slip risk (Bhatt *et al.* 2006, Heiden *et al.* 2006, Siegmund *et al.* 2006). While being aware of a slippery floor alone did not reduce slip risk or slip distance, a subsequent slip experience resulted in decreased peak RCOF similar to that of a simultaneous change in awareness and experience (Heiden *et al.* 2006). This suggests that experiencing a slip provides critical information necessary to develop a proactive strategy that minimizes slip risk.

Repeated exposure to a perturbation has been used to develop adaptive strategies that minimize slip risk and slip severity of later slips (Marigold and Patla 2002, Bhatt and Pai 2005, Pai and Bhatt 2007). Often after one experience of a slippery surface gait, adaptations emerge, reducing slip risk and slip severity. These proactive adaptations included a diminished muscular response, decreased foot-floor angle and an elevated center of mass (Tang *et al.* 1998, Marigold and Patla 2002, Marigold *et al.* 2003, Bhatt *et al.* 2005).

2.2.6 Experimental Research Gaps

Maintaining balance during walking in challenging environments requires two types of postural strategies: reactive and proactive (Tang and Woollacott 1998, Pavol *et al.* 2004, Chambers and Cham 2007). Reactive strategies are generated in response to a perturbation, such as a slip or trip. Proactive strategies are generated when expecting the potential of being perturbed. The ability of the motor control system to develop proactive strategies that allow adaptations in challenging environments is crucial to fall prevention (Cham and Redfern 2002, Pavol *et al.* 2004, Lockhart *et al.* 2007). Gait adjustments of proactive strategies can reduce the likelihood of a slip (slip risk) and improve the likelihood of a recovery if a slip occurs (slip severity) (Cham and Redfern 2002, Marigold and Patla 2002, Chambers and Cham 2007). Since proactive adjustments can reduce or even eliminate the need for a reactive response, a fundamental understanding of these proactive strategies is necessary, especially in older adults.

Proactive strategies can result from prior experience with a given hazard (slip/trip) and/or from awareness that a hazard is possible prior to exposure (Marigold and Patla 2002, Heiden *et al*. 2006). Most studies that have investigated proactive strategies combine the effects of experience and awareness (Cham and Redfern 2002, Marigold and Patla 2002, Lockhart *et al*. 2007). The independent impact of experience or awareness on proactive strategies has only recently been investigated in young adults. It was noted that awareness altered how the slip-limb approaches the floor but had no effect on either slip risk or slip severity, while experience and awareness altered anticipatory muscle activation and foot-floor interactions (Heiden *et al.* 2006). It has also been shown that repeatedly experiencing a slippery surface develops adaptive strategies that minimize slip risk and slip severity of later slips (Marigold and Patla 2002, Bhatt and Pai 2005, Pai and Bhatt 2007). Previous research has shown that experiencing a slip provides critical information necessary to develop a proactive strategy that minimizes slip risk (Marigold and Patla 2002, Bhatt and Pai 2005, Bhatt *et al.* 2006, Heiden *et al*. 2006, Siegmund *et al.* 2006, Pai and Bhatt 2007).

Previous research has not investigated the effect of experience alone. Further exploration is necessary to determine the effect of experiencing a slip on changes in gait without additional awareness or repeated exposure. Additionally, the effect of experience alone on proactive strategies has not been investigated in older adults. Possible age-related differences in proactive strategies after experiencing a slip may be an important component in reducing the high rate of falls in older adults. Previous research has also concluded that laboratory subjects should be limited to a single slip if real-world slips are desired due to gait adaptations noted after experiencing a single slip (Heiden *et al.* 2006, Oates *et al*. 2010). However, this may not be the case as it is unknown whether adults of any age return to normal gait patterns after experiencing a slip with no awareness of a pending slippery surface. Specific Aim 1 addressed these questions by investigating the proactive strategies generated after experiencing a slippery surface without any additional awareness in both young and older adults.

The impact of prior knowledge, whether experience or awareness, on proactive strategies is not well understood and has been cited as a limitation in many slip and fall experiments (Heiden *et al*. 2006, Oates *et al*. 2010). A better understanding of how prior knowledge affects proactive strategies is needed to correctly interpret slip experiments and provide insights on mechanisms used to reduce slip risk and slip severity. The effects of awareness are evident when we compare stepping onto an icy skating rink versus stepping on black ice or walking differently in the presence of a wet floor sign. However, awareness, in isolation, seems to have minimal impact on reducing slip risk or slip distance (Heiden *et al*. 2006).

Previous research has found that a combination of experience and awareness are incorporated into developing proactive strategies (Marigold and Patla 2002, Heiden *et al.* 2006). What has yet to be examined is the added effect of awareness after experiencing a slip. Awareness, in addition to experience, might be a critical factor in developing or retaining proactive adaptations. Developing proactive strategies that minimize slip risk is especially important in older adults since once a slip is initiated, avoiding a fall becomes increasingly difficult with age (Lockhart and Kim 2006, Troy *et al.* 2008). It has been suggested that older adults adopt a more cautious adjustment strategy than younger adults. However, this cautious strategy may further increase risk of slipping (Menz *et al.* 2003, Lockhart *et al.* 2007, Menz *et al.* 2007, Delbaere *et al.* 2009). While age-related differences in proactive strategies have been examined in sit to stand perturbations (Pavol *et al.* 2004) and mechanical slips (Woollacott and

Tang 1997), only the effect of walking on a known slippery surface has been investigated in older adults (Lockhart *et al.* 2007). Further exploration is needed into possible age-related differences in proactive strategies generated in response to real slippery surfaces as it may be another important step in reducing the high prevalence of slip-related falls in older adults. Specific Aim 2 investigated the proactive strategies generated after experiencing a slippery surface with additional awareness in both young and older adults.

2.3 MODELING RESEARCH BACKGROUND

Experimental gait studies alone cannot investigate the direct effect of an individual component of a proactive strategy, e.g. increased activation of a given muscle or co-contraction, on the effectiveness of reducing slip severity. This is due to the complexity of the musculoskeletal system and its large number of degrees of freedom, challenging the feasibility of cause and effect type of investigations based on experimental data alone. Additionally, experimental gait studies do not take into account the coupled dynamics of the human body that permit muscles of one joint to accelerate or decelerate another joint or the body center of mass. The musculoskeletal system is mechanically redundant and net joint moments have the potential to be produced by various combinations of muscle forces. The use of experimental gait studies alone does not allow for individual muscle contributions to be determined thus providing limited explanations of how gait is controlled (Kepple *et al.* 1997, Zajac *et al.* 2003, Pandy and Andriacchi 2010). Recently, human gait models have provided insights into the complex neuromuscular interactions involved in controlling locomotion (Anderson and Pandy 2003, Zajac *et al.* 2003, Liu *et al.* 2006, Siegel *et al.* 2006, Liu *et al.* 2008, Mahboobin *et al.* 2010, Pandy and Andriacchi 2010).

One aim of this project is to examine the role of lower extremity muscles utilized during proactive strategies. Muscle contributions to body support and slowing forward progression are important in slip-initiated falls prevention. In order to avoid a fall after a slip, the body must generate a quick and effective response to re-establish center of mass stability and maintain an upright posture while continuing locomotion. Previous research has determined that corrective reactions to slip events are aimed at bringing the slipping foot closer to the body center of mass while maintaining an upright posture (Cham and Redfern 2001, Marigold and Patla 2002, Lockhart *et al.* 2003, Yang and Pai 2010). The forward velocity of the slipping foot is a key factor that impacts the recovery outcome of a slip (Redfern *et al.* 2001, Cham and Redfern 2002, Lockhart *et al*. 2003, Bhatt *et al*. 2006, Moyer *et al.* 2006). Corrective moments at the knee and hip have been associated with slowing the slipping foot in an attempt to bring it closer to the body center of mass (Cham and Redfern, 2001, Yang and Pai 2010). Preventing contact with the ground, i.e. vertical support, is also a key component in avoiding a slip-initiated fall. Previous research has found that inadequate support greatly hinders a successful recovery attempt (Pai *et al*. 2006, Pai and Bhatt 2007). Increased vertical support may result in an elevated center of mass which has been noted in strategies used to reduce slip severity in repeated exposure to a slip (Marigold and Patla 2002).

During gait, some muscles work to accelerate the center of mass upward against the downward accelerations of gravity (Kepple *et al*. 1997, Anderson and Pandy 2003, Pandy and Andriacchi 2010). Various modeling techniques have been employed to determine which muscles are contributing to vertical body support. These studies have found that the hip and knee extensors were the main contributors to support in early stance (Kepple *et al*. 1997, Anderson and Pandy 2003, Neptune *et al.* 2004, Pandy and Andriacchi 2010). At heel contact, before the foot was placed flat on the ground, the ankle dorsiflexors of the ipsilateral leg and the plantarflexors of the contralateral leg made important contributions to support as well (Anderson and Pandy 2003, Liu *et al*. 2006). Additionally, it has been noted that the muscles providing vertical support also act to slow the forward progression of the body center of mass during the first half of stance (Liu *et al*. 2006).

2.3.1 Modeling Research Gaps

While the experimental gait studies provide a valuable description of the proactive strategies used after experiencing a slippery surface with and without additional awareness, modeling simulations are able to provide additional information on how each muscle or muscle group is contributing to a proactive strategy. Previous research using modeling simulations has provided a better understanding of how individual muscles/muscle groups or net joint moments control locomotion and certain causes of gait deficiencies (Kepple *et al*. 1997, Anderson and Pandy 2003, Siegel *et al*. 2006). Modeling simulations have the potential to reveal findings that are not easily discerned and that may even be counterintuitive. Previous research has concluded that modeling simulations are a valuable tool in understanding balance responses during standing and the causes of movement in healthy gait and in different pathologies (Siegel *et al*. 2006, van Asseldonk *et al*. 2007, Pandy and Andriacchi 2010).

This project uses modeling simulation techniques to aid in understanding gait and proactive strategies. While including as many muscles as possible in a model may seem more physiologically realistic, it would also require more model parameters to be specified and increased computational time (Xiao and Higginson 2010). Furthermore, simulated muscle excitations are typically generated using generic muscle model parameters (Delp *et al.* 1990). The use of these generic muscle parameters has been shown to negatively impact simulation results in certain populations (Piazza 2006). The response of a model is influenced by the specifics of the model selected and the values assumed for its parameters (Xiao and Higginson 2008, Pandy and Andriacchi 2010, Xiao and Higginson 2010). In order to place confidence in the results of a simulation, it is important to understand the model's sensitivity to variations in the number of muscles and the assumed muscle model parameters.

In Specific Aim 3, a sensitivity analysis will be performed to examine how simulated muscle excitations change due to the number of muscles included in a simulation of gait. Additionally, the sensitivity of simulated muscle excitations to perturbations in muscle model parameters will be evaluated. Following these analyses, preliminary modeling simulations will be used to provide insight into proactive strategies. Specifically, simulated muscle excitations generated during proactive strategies used to minimize slip risk will be explored. A better understanding of proactive strategies is needed to correctly interpret slip experiments and provide insights on mechanisms used to reduce slip risk and slip severity.

3.0 ABBREVIATIONS

Table 1: Abbreviations

AD	Anticipation Dry
AdMg	Distal Adductor Magnus
AP	Anterior-Posterior
AS	Anticipation Slip
BD	Baseline Dry
BOS	Base of Support
CMC	Computed Muscle Control
COM	Center of Mass
COM BOS ANG	Center of Mass Base of Support Angle
EMG	Electromyography
Gem	Gemellus
Grac	Gracilis
HC	Heel Contact
IK	Inverse Kinematics
ML	Medial-Lateral
O	Older
Pect	Pectineus
Piri	Piriformis
PSV	Peak Slip Velocity
QdFm	Quadriceps Femoris
RCOF	Required Coefficient of Friction
RD	Recovery Dry
RRA	Residual Reduction Analysis
Sar	Sartorius
SI	Superior-Inferior
TbPo	Tibialis Posterior
Tfl	Tensor Fasciae Latae
TO	Toe Off
US	Unexpected Slip
US1	First Unexpected Slip
US2	Second Unexpected Slip
Y	Young

4.0 METHODS

The research methods necessary to accomplish the three specific aims of this project included experimental and modeling procedures. Two experimental studies were collected as part of an Institutional Review Board approved 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 & R01 OH007592, Principal Investigator: Rakié Cham, Ph.D.). Experimental data from these studies were utilized to answer Aims 1 and 2. Specifically, 83 healthy adults (N=83) divided into young (20 to 33 years old) and older (50 to 67 years old) groups were recruited for participation. Subjects walked on dry and slippery floors with varying amounts of experience and awareness while ground reaction forces and whole body motion data were collected. Aim 3 was accomplished using musculoskeletal modeling techniques. Experimental data collected in Aim 2 were used in a sensitivity analysis to examine how simulated muscle excitations change due to the number of muscles included in a simulation of gait and due to perturbations in muscle model parameters. Additionally, simulated muscle excitations generated during proactive strategies were explored.

4.1 EXPERIMENT 1

4.1.1 Subject Population

Twenty-seven young (20-31yrs) and twenty-five older adults (50-65 yrs) were recruited for participation in this study (Table 2). Written informed consent approved by the University of Pittsburgh Institutional Review Board was obtained prior to participation. Participants were screened for neurological, orthopedic, cardiovascular and pulmonary abnormalities, as well as any other condition that would hinder normal gait.

Table 2: Subject sample characteristics

Mean (SD) [Range]	Young (N = 27)	Older (N = 25)
Age [yrs]	23.9 (2.7) [20-31]	56.0 (4.8) [50-65]
Mass [kg]	69.3 (11.5) [51.5-89.0]	81.6 (13.9) [55.5-111.8]
Height [m]	1.73 (0.08) [1.59-1.87]	1.71 (0.09) [1.57-1.91]

4.1.2 Experimental Environment

The Human Movement and Balance Laboratory at the University of Pittsburgh is designed to capture and analyze human motion, especially gait. The data acquisition system used to collect gait variables consisted of the two Bertec force plates (4060A, Bertec, Inc, Columbus, OH) and a Vicon 612 system that employs eight IR M2-cameras (Vicon, Centennial, CO, USA). 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. Subjects walked along a level vinyl tile walkway which allows for a walking distance of approximately 8.5 meters. Two force plates are embedded into the floor midway along the gait path such that one foot hits each plate (Figure 3).

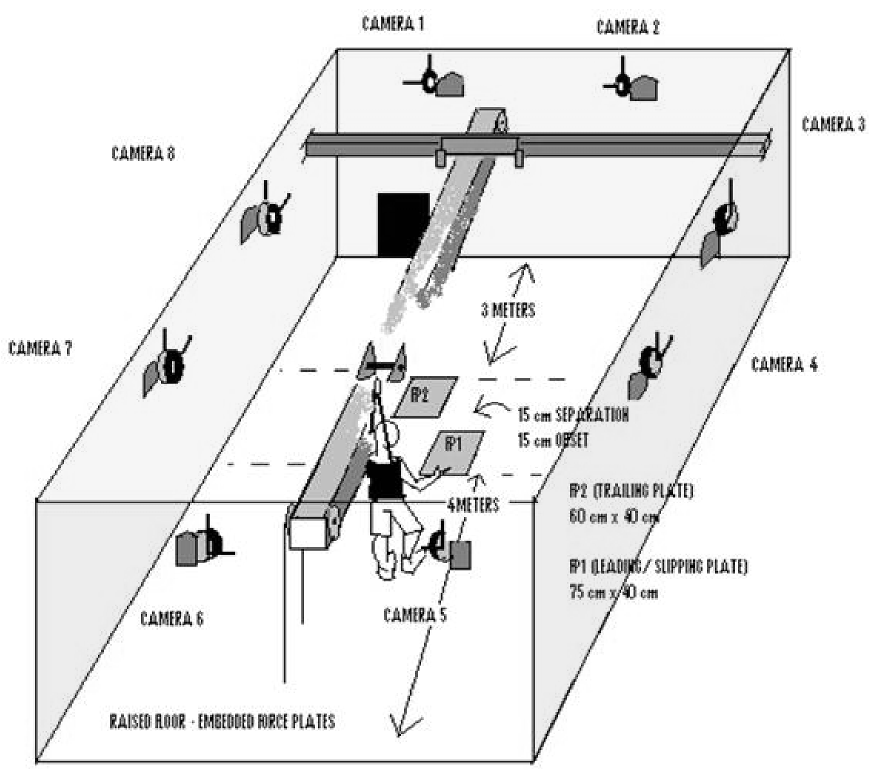


Figure 3: Schematic gait path layout. Vicon motion capture cameras are shown. Rectangles represent embedded force plates. Trolley and harness system are also shown.

The subject's body was instrumented with a custom set (n=79) of reflective markers (Moyer 2006, Moyer *et al.* 2006). Nineteen markers, referred to as "static markers", were only present during a static posture calibration trial, collected at the beginning of each session (Figure 4). The location of these markers relative to other markers on the same rigid bodies will be later used to approximate static marker trajectories during dynamic trials. The passive characteristics of the system allowed subjects to walk naturally (no wires). Additionally, a digital camcorder was used to tape each trial, serving as a visual record.

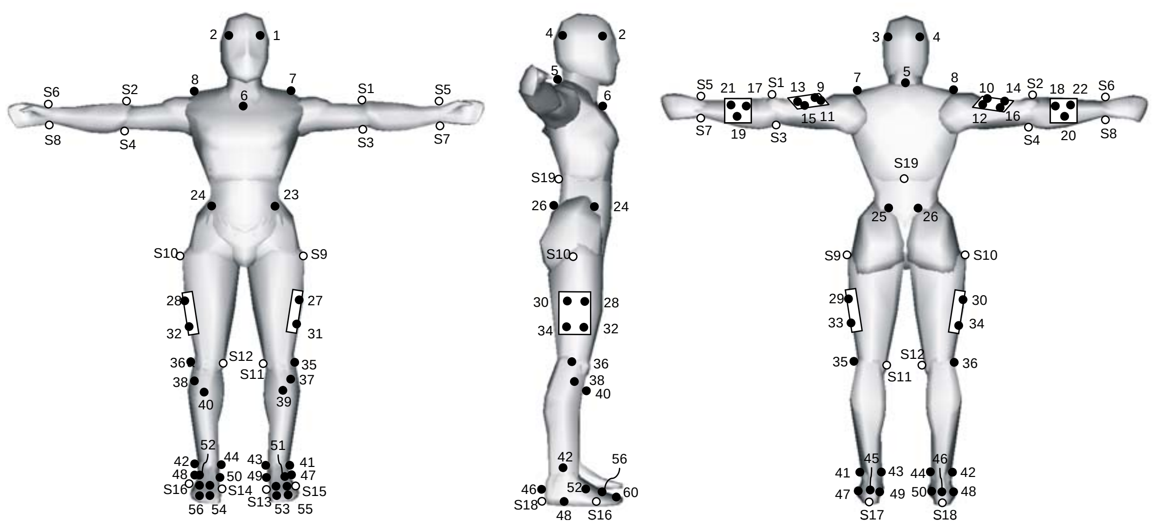


Figure 4: Motion capture markers. Solid circles represent markers present in all gait trials. Hollow circles illustrate static markers present in calibration trial only and later reconstructed based on rigid body assumptions.

All participants wore spandex shorts and a sleeveless spandex top to optimize marker placement and minimize motion artifacts. Participants were equipped with a safety harness and the same polyvinyl chloride soled shoes. The harness was attached to an overhead trolley system, used to catch the subject, thus preventing injury and contact with the ground in case of an irrecoverable balance loss. The harness system has been used previously and shown to not hinder normal gait (Redfern and DiPasquale 1997, Cham and Redfern 2002, Moyer *et al.* 2006).

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 was chosen because it is water soluble, clear, and odorless, allowing its application to be easily concealed from the subject. Glycerol has been previously used in slip testing (Moyer *et al*. 2006, Chambers and Cham 2007). Coefficients of friction for the dry and slippery conditions at the shoe-floor interface were 0.53 and 0.03, respectively, measured by the English XL VIT Slipmeter (ASTM F1679).

4.1.3 Experimental Protocol

All participants were exposed to the same walking protocol. The participant's body was instrumented as described previously. Participants were instructed to look straight ahead and walk at a self-selected pace across an 8.5 m vinyl tile walkway. The lights were dimmed just enough to minimize unwanted reflections and detection of a contaminant. Next, subjects were allowed to practice walking while a researcher adjusted the starting point to ensure that the right foot contacted the first force plate and the left foot contacted the second force plate. Prior to each trial, participants faced away from the walkway and listened to loud music for one minute, distracting them from the possible application of a contaminant. Participants then turned and walked forward while data were recorded.

Participants were informed that the first few trials would be dry to ensure natural gait and two to three dry trials were collected, baseline dry (BD). Without the participant's knowledge, the diluted glycerol solution (75% glycerol : 25% water) was applied, by the same researcher to ensure uniformity, to the left/leading foot-floor interface and another trial was conducted, unexpected slip (US1). Participants were then informed that the next few trials would be dry but no further specific information related to the slipperiness of the floor was revealed. Fifteen recovery dry (RD) trials were then conducted on a dry surface, followed by a second unexpected slip (US2). To summarize, the conditions included in the protocol were the following:

- Baseline Dry (BD) - The subject was informed that the first few trials would be dry, ensuring natural walking with no fear of slipping. Three to five good (both feet contact one and only one force plate) trials were collected.
- Unexpected Slip (US1) – The contaminant (75:25) was applied without the subject's knowledge. One slip trial was collected. After this trial, the subject was given clean shoes and the floor was cleaned.
- Recovery Dry (RD) – The subject was informed that the floor would be dry prior to each trial for the first 5 trials. After the 5th dry trial, no more information about the floor's contaminant was given to the subjects. A total of fifteen dry trials were collected.
- Unexpected Slip (US2) – The contaminant (75:25) was applied without the subject's knowledge. One slip trial was collected.

The experimentation session 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. Additionally, seated rest was provided following each slip trial while the floor was cleaned. This effort is well below exertions that could lead to physical fatigue. However, subjects were reminded that if a break was needed during testing it would be provided to them.

4.1.4 Data Processing and Analysis

Ground reaction forces and motion data were processed to retrieve specific kinetic and kinematic gait variables relevant to slip/fall biomechanics. Variables that assess slip risk were calculated during dry trials. These include required coefficient of friction (RCOF), center of mass (COM) stability, and other general gait variables such as gait speed and stride length (Cham and Redfern 2002, Marigold and Patla 2002, Pai *et al.* 2003, Moyer *et al.* 2006, Burnfield and Powers 2007, Lockhart *et al*. 2007). Slip trials were categorized by slip severity using the peak slip velocity (PSV) of the heel (Moyer *et al*. 2006).

Slip risk was determined by calculating the peak RCOF for each dry trial. RCOF was analyzed by taking the ratio of anterior-posterior shear to normal ground reaction forces (Cham and Redfern 2002). Time was normalized to stance duration, with 0% at heel contact (HC) and 100% at toe off (TO). HC and TO were identified from ground reaction forces. The peak RCOF value during 10-30% of stance was selected for this analysis due to its importance in determining slip potential (Redfern and DiPasquale 1997, Cham and Redfern 2002, Lockhart *et al.* 2007). Peak RCOF was determined during the stance phase of both right (non-slipped) and left (slipped) foot.

General spatiotemporal gait characteristics were derived from motion data for each dry trial. HC and TO for kinematic variables were identified using heel and toe marker data with a foot velocity algorithm similar to previous research (O'Connor *et al.* 2007). Temporal variables included stance duration (ms), gait speed (m/s), and cadence (steps/min). Gait speed was defined as the average velocity of the sternum marker in the direction of travel. Step length (cm) was calculated as the anterior-posterior distance between two consecutive heel strikes, determined using the heel markers. Mean temporal and spatial gait variables were determined from all of the steps recorded over BD and RD trials.

COM stability was assessed using several methods associated with evaluating slip and fall potential. COM was estimated using the mid-point of the four pelvis markers located on the left/right superior and anterior iliac spines (Appendix A). Base of support (BOS) was estimated using the left heel marker at left HC. Margin of stability in the medial-lateral (ML) and anterior-posterior (AP) directions was determined. ML margin of stability was defined as the minimum distance between the COM and the border of the BOS. A line running through the center of the foot perpendicular to the ML heel position at left HC defined the BOS in the ML direction (Marigold and Patla 2002). AP margin of stability was calculated as the distance between the COM and the BOS in the AP direction (Oates *et al*. 2010). A smaller AP margin of stability reflects an anterior shift in the COM position. The vertical position of the COM (COM vertical) at left HC was also reported. Center of mass base of support angle (COM BOS angle) was defined as the angle formed by the COM, BOS and the vertical projection of the COM onto the ground (Burnfield and Powers 2007). The position of the COM relative to the BOS at HC of the left (slipped) foot was calculated in the ML direction, AP direction, and vertical directions. The COM BOS ANG was determined using the following equation (1).

$$COMBOSANG = ArcTan\frac{\sqrt{(COMml - BOSml)^2 + (COMap - BOSap)^2}}{COMvert} \quad (1)$$

Peak slip velocity (PSV) was used to determine slip severity of US1 and US2 (contaminated trials). For each unexpected slip trial PSV was defined as the first local maximum of horizontal heel velocity 50 ms after heel contact (Moyer *et al*. 2006).

A preliminary analysis consisted of investigating age-related and foot-related differences in the frictional requirements of baseline walking. Specifically, mean peak RCOF was used as the response variable, with age group (young/older), foot (left/right) and their interaction as fixed effects. Subject was included as a random effect.

The main statistical analysis consisted of multiple parts. Analysis A: age- and baseline/recovery-related differences in each dry trial variable of interest, peak RCOF, gait parameters and COM stability were determined. Specifically, each gait variable of interest was compared between baseline dry and recovery dry conditions using mixed-linear regression models using age group (Y/O), condition (BD/RD) and their interaction effects as independent fixed effects. Subject was included as a random effect. Statistical significance was set at 0.05.

In Analysis B, RD trial number-related differences in peak RCOF, gait parameters and COM stability variables were determined within age groups. Specifically, dependent variables for the dry trials were compared between BD and each RD trial number conditions using mixed-linear regression models with RD trial number condition (BD/RD trial number) as an independent fixed effect. Subject was included as a random effect. Statistical significance was set at 0.05.

Analysis C was conducted to determine the effect of experiencing a slip on the slip severity of a subsequent slip, quantified by PSV. PSV was compared within age between slip conditions (US1/US2) using mixed-linear regression models with condition (US1/US2) as an independent fixed effect. Subject was included as a random effect. Statistical significance was set at 0.05.

4.2 EXPERIMENT 2

4.2.1 Subject Population

Eighteen young (20-33 yrs) and thirteen older adults (55-67 yrs) were recruited for participation in this study (Table 3). Written informed consent approved by the University of Pittsburgh Institutional Review Board was obtained prior to participation. Participants were screened for neurological, orthopedic, cardiovascular and pulmonary abnormalities, as well as any other condition that would hinder normal gait.

Table 3: Subject sample characteristics

Mean (SD) [Range]	Young (N = 18)	Older (N = 13)
Age [yrs]	23.9 (3.29) [20-33]	61.1 (3.66) [55-67]
Mass [kg]	69.5 (13.4) [53.3-105.5]	76.5 (11.8) [55.5-92.7]
Height [m]	1.76 (0.03) [1.59-1.94]	1.65 (0.08) [1.54-1.79]

4.2.2 Experimental Environment

Experiment 2 was performed at the University of Pittsburgh Human Movement and Balance Laboratory and data acquisition was the same as previously mentioned in Experiment 1. Similarly, all subjects were instrumented as in Experiment 1 with markers for motion capture, a safety harness and the same polyvinyl chloride soled shoes. To generate slips the same contaminant was used as in Experiment 1. The 75% glycerol to 25% water solution was uniformly applied to the leading force plate, which was contacted by the left foot.

4.2.3 Experimental Protocol

All participants were exposed to the same walking protocol. The participant's body was instrumented as described previously. Participants were instructed to look straight ahead and walk at a self-selected pace across an 8.5 m vinyl tile walkway. The lights were dimmed just enough to minimize unwanted reflections and detection of a contaminant. Next, subjects were allowed to practice walking while a researcher adjusted the starting point to ensure that the right foot contacted the first force plate and the left foot contacted the second force plate. Prior to each trial, participants faced away from the walkway and listened to loud music for one minute, distracting them from the possible application of a contaminant. Participants then turned and walked forward while data were recorded.

Participants were informed that the first few trials would be dry to ensure natural gait and at least three dry trials were collected, baseline dry (BD). Then, without the participant's knowledge, the diluted glycerol solution (75% glycerol : 25% water) was applied, by the same researcher to ensure uniformity, to the left/leading foot-floor interface (four meters from the start) and another trial was conducted, unexpected slip (US). After the unexpected slip, subjects were then made aware that all remaining trials might be slippery but no further specific information was provided. The combined effect of experience and awareness was termed anticipation. Five additional dry trials were collected, anticipation dry (AD). After again being made aware of the possibility of a slippery surface, the diluted glycerol solution (75% glycerol : 25% water) was applied to the left/leading foot-floor interface and another trial was conducted, anticipation slip (AS). To summarize, the conditions included in the protocol were the following:

• Baseline Dry (BD) -The subject was informed that the first few trials would be dry, ensuring natural walking with no fear of slipping. Three to five good (both feet contact one and only one force plate) trials were collected.

• Unexpected Slip (US) – The contaminant (75:25) was applied without the subject's knowledge. One slip trial was collected. After this trial, the subject was given clean shoes and the floor was cleaned.

• Anticipation Dry (AD) – After experiencing an unexpected slip, the subject was made aware of the possibility of encountering a slippery floor prior to each of the next five dry trials. Five dry trials were collected.

• Anticipation Slip (AS) – After experiencing an unexpected slip, the subject was made aware of the possibility of encountering a slippery floor prior to this trial. The contaminant (75:25) was applied and one slip trial was collected.

The experimentation session 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. Additionally, seated rest was provided following each slip trial while the floor was cleaned. This effort is well below exertions that could lead to physical fatigue. However, subjects were reminded that if a break was needed during testing it would be provided to them.

4.2.4 Data Processing and Analysis

All data processing of experimental ground reaction forces and motion data were similar to that which was described in Experiment 1. Variables that assess slip risk were calculated during dry trials. These included peak RCOF, COM stability, and temporal/spatial gait parameters. Again, slip trials were categorized by slip severity using PSV.

Only the first two AD trials were used and compared to the baseline trials in this analysis. The statistical analysis consisted of multiple parts. Analysis D: age- and baseline/anticipation-related differences in each dry trial variable of interest, peak RCOF, gait parameters and COM stability, were determined. Specifically, each gait variable of interest was compared between baseline dry and anticipation dry conditions using mixed-linear regression models using age group (Y/O), anticipation condition (BD/AD) and their interaction effects as independent fixed effects. Subject was included as a random effect. Statistical significance was set at 0.05.

When anticipating slippery floors, participants can modulate gait speed by changing their cadence or step length. Beneficial adaptations to reduce slip risk include increasing cadence and reducing step length (Cham and Redfern 2002, Lockhart *et al*. 2003, Moyer *et al*. 2006, Lockhart *et al*. 2007). Analysis E, consisting of a multiple regression analysis, was performed to determine the proportion of variability in gait speed that was explained by modulations in cadence and step length. Gait speed was regressed on step length and cadence both individually and simultaneously in different regression models. The behavior of each models' R^2 was examined to quantify (1) step length contributions alone, (2) cadence contributions alone, and (3) the simultaneous contribution of cadence and step length. The added value of step length to explaining gait speed variability above that by cadence was derived by computing the R^2 difference between regression Models (3) and (2). Similarly, the added value of cadence to explaining gait speed variability above that by step length was derived by computing the R^2

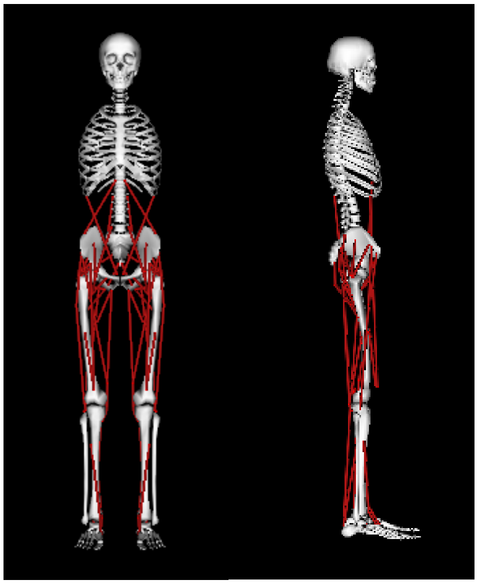
difference between regression Models (3) and (1). This analysis was conducted within age groups and anticipation conditions to reveal potential differences in how young and older adults control their gait speed during normal walking and when anticipating slippery floors.

Analysis F was conducted to determine the effect of experiencing a slip and awareness of a slippery surface on the slip severity of a subsequent slip, quantified by PSV. PSV was compared between slip conditions (US/AS) using mixed-linear regression models with age group (Y/O), anticipation condition (US/AS) and their interaction effects as an independent fixed effect. Subject was included as a random effect. Statistical significance was set at 0.05.

4.3 MODELING

4.3.1 Simulations

Measured motions and ground reaction forces collected during Experiment 2 were formatted to be used in OpenSim (http://SimTK.org, Delp *et al*. 2007). OpenSim is a biomechanical modeling software system that allows users to develop musculoskeletal models and create dynamic simulations of any movement. A three-dimensional OpenSim model with 10 segments, 54 muscles, and a total of 23 degrees of freedom was used in this project (Delp *et al*. 1990, Anderson and Pandy 1999) (Figure 5).



Muscles	
Anterior Gluteus Medius	Iliacus
Middle Gluteus Medius	Psoas
Posterior Gluteus Medius	Sartorius
Biceps Femoris Long Head	Soleus
Biceps Femoris Short Head	Gracilis
Superior Gluteus Maximus	Pectineus
Middle Gluteus Maximus	Piriformis
Inferior Gluteus Maximus	Gemellus
Distal Adductor Magnus	Tibialis Anterior
Quadriceps Femoris	Tibialis Posterior
Rectus Femoris	Internal Oblique
Vastus Intermedius	External Oblique
Medial Gastrocnemius	Erector Spinae
Tensor Fasciae Latae	

Figure 5: Frontal and side view of OpenSim model with 54 muscles and 23 degrees of freedom used for modeling of gait trials. Muscles included in model are also provided (Delp *et al.* 1990, Anderson and Pandy 1999).

Muscle excitations were generated using a multi-step process (Figure 6). Step 1: Subject-specific linked-segment models were created by scaling a generic model. Specifically, the generic model was scaled to match each participant's anthropometry using the static calibration data collected during motion capture, as well as the participant's mass and height, to adjust the mass, length and inertial properties of each segment.

Step 2: Joint angles were computed in OpenSim using the inverse kinematics (IK) tool such that the errors between the measured and theoretical marker trajectories were minimized (Delp *et al*. 2007). In other words, a weighted least-squares problem is formulated where marker error, distance between an experimental marker and the corresponding model virtual marker, is minimized. The specific weights corresponding to each marker was varied accordingly to best represent gait motion.

Step 3: Due to modeling assumptions, noise, and perhaps other errors from motion capture data, the ground reaction forces and accelerations estimated from measured kinematics do not satisfy Newton's second law. This may lead to dynamic inconsistency. In order to make the model joint coordinates derived from IK more dynamically consistent with experimental ground reaction forces, a residual reduction analysis (RRA) was performed. Locations of the segment centers of mass were adjusted as part of the RRA procedure, a technique available in OpenSim (Delp *et al*. 2007). Specifically, RRA is an algorithm used to reduce the residual forces and moments required for dynamic consistency. To reduce the residual forces and moments, RRA makes small adjustments to the torso COM of the subject-specific model and permits the kinematics of the model to vary in order to be more dynamically consistent with the ground reaction force data (Delp *et al*. 2007).

Step 4: Finally, muscle excitations were derived by OpenSim using the computed muscle control (CMC), an optimization-based control technique (Thelen and Anderson 2006, Delp *et al*. 2007). CMC generated a set of muscle excitations that produce a coordinated muscle-driven simulation of gait. Simulated muscle excitations were validated using electromyography (EMG) data, when available, and previous literature.

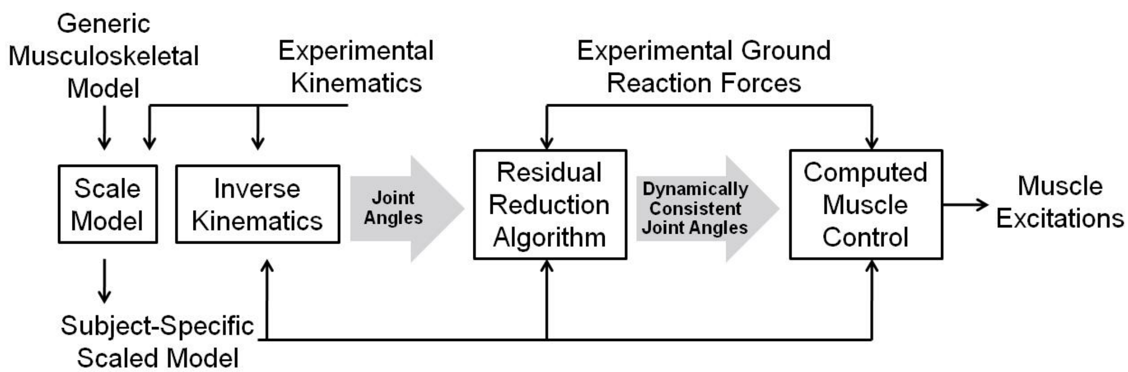


Figure 6: Steps for generating muscle excitations. A musculoskeletal model, experimental kinematics, and experimental ground reaction forces were inputted into OpenSim. Experimental kinematics were used to scale the generic musculoskeletal model. Model joint angles were found using an inverse kinematics approach. A residual reduction algorithm was used to refine the model kinematics. Muscle excitations were generated using a computed muscle control algorithm (Delp *et al*. 2007).

4.3.2 Sensitivity Analysis: Number of Muscles

In order to examine how simulated muscle excitations change due to the number of muscles included in a simulation of gait, a sensitivity analysis was performed. Specifically, muscles not known to significantly contribute to gait were systematically removed, individually, from the simulation (Winter 2004, Liu *et al*. 2006, Neptune *et al*. 2009, Pandy and Andriacchi 2010). Thirty-six muscles known to contribute to gait were included in the model throughout the sensitivity analysis (Table 4). Eighteen muscles were removed bilaterally one at a time and simulated muscle excitations were generated for the remaining muscles using CMC. Finally, all eighteen muscles were removed at once and the simulated muscle excitations for the remaining muscles were generated.

Table 4: Muscle Sensitivity Analysis

Muscles Included	Muscles Removed
Gluteus Medius (Anterior, Middle, Posterior)	Sartorius
Biceps Femoris Long Head	Distal Adductor Magnus
Biceps Femoris Short Head	Tensor Fasciae Latae
Gluteus Maximus (Superior, Middle, Inferior)	Pectineus
Iliacus	Gracilis
Psoas	Quadriceps Femoris
Rectus Femoris	Gemellus
Vastus Intermedius	Piriformis
Medial Gastrocnemius	Tibialis Posterior
Soleus	
Tibialis Anterior	
Erector Spinae	
Internal Oblique	
External Oblique	

Simulated muscle excitations were smoothed and resampled to 100 Hz for analysis. A portion of the data from 50 ms before left HC to 150 ms after left HC was then selected for further examination. This period of time was selected due to its importance in evaluating slip risk before any reactive strategies are generated (Cham and Redfern 2001, Chambers and Cham 2007). The resulting lower extremity simulated muscle excitations were compared to those generated from the full muscle model. Relative error was calculated using equation 2. The relative error was defined as the difference between two values of the different excitation curves at the same point in time divided by the maximum of both values, reported as a percent (Dao *et* *al*. 2009). The mean relative error across the time period of interest, 50 ms before left HC to 150 ms after left HC, was reported. Experimental data from Subject 2 BD were used in this sensitivity analysis (Table 6).

$$\text{Mean}\left[\frac{C_i - C_i^0}{\max(C_i, C_i^0)}\right]_{t_{-50}}^{t_{150}} \qquad (2)$$

4.3.3 Sensitivity Analysis: Muscle Properties

A sensitivity analysis was performed to determine the impact of the Hill-type muscle model parameters on simulated excitations. Specifically, values of the maximum isometric force, optimal fiber length, and tendon slack length were perturbed by ± 10 % from their nominal values for the inferior gluteus maximus and rectus femoris (Table 5). No other muscles were perturbed in this preliminary sensitivity analysis. Simulated muscle excitations were generated for each perturbation and processed as previously described.

Table 5: Default Muscle Parameters (Delp *et al*. 1990, Anderson and Pandy 1999)

Muscle Parameter	Inferior Gluteus Maximus	Rectus Femoris
Maximum Isometric Force [N]	552	1169
Optimal Fiber Length [m]	0.144	0.114
Tendon Slack Length [m]	0.145	0.310

The resulting lower extremity simulated muscle excitations were compared to those generated from the original muscle model (Delp *et al*. 1990, Anderson and Pandy 1999). The sensitivity, ε, of an individual muscle excitation to the muscle parameter perturbation was quantified as the normalized change in one muscle excitation due to the normalized muscle parameter change (Equation 3).

$$\varepsilon_i = \frac{\frac{A_i - A^0}{A^0}}{\frac{p_i - p^0}{p^0}} \qquad (3)$$

A value of |ε| greater than 1 was used to define if a muscle was sensitive to the perturbation (Xiao and Higginson 2010). Each muscle's sensitivity, inferior gluteus maximus and rectus femoris, was examined to its own parameter perturbation. Additionally, the effect of one muscle's perturbation on other muscles was also explored. Experimental data from Subject 2 BD were used in this sensitivity analysis (Table 6).

4.3.4 Simulated Proactive Strategies

Two adults from Experiment 2 were chosen for participation in Specific Aim 3 (Table 6). The BD trial immediately preceding US and the AD trial immediately following US were selected for this analysis.

Table 6: Subject sample characteristics

	Subject 1 (Young Male)	Subject 2 (Older Female)
Age [yrs]	24	64
Mass [kg]	67.73	56.36
Height [m]	1.72	1.63

Modeling simulations were processed and simulated muscle excitations were derived as described previously using OpenSim. A portion of the data from 50 ms before left HC to 150 ms after left HC was then selected for further examination. Simulated muscle excitations were smoothed and resampled to 100 Hz for analysis. Simulated muscle excitations were compared across conditions (BD/AD).

5.0 RESULTS

5.1 EFFECT OF EXPERIENCE ON PROACTIVE STRATEGIES

Specific Aim 1 investigated the impact of unexpectedly slipping on a contaminated floor (‘experience’) on the risk of slipping and slip severity when subjects are not warned of an additional pending slippery floor (‘awareness’). Additionally, age-related differences were examined.

5.1.1 Gait on Dry Floors Following Slip Experience

The preliminary analysis of baseline gait characteristics of peak RCOF values conducted across age groups and feet revealed that both young and older adults walked with similar frictional requirements for both feet. Specifically, the average mean BD peak RCOF across age groups and left/right feet was 0.195 ± 0.031 ($p_{age} > 0.05$, $p_{foot} > 0.05$, $p_{agexfoot} > 0.05$).

Analysis A revealed significant changes in peak RCOF during RD (Figure 7). A significant age-condition interaction effect ($p = 0.03$) revealed differences in the right foot peak RCOF. In young adults the right foot showed no statistically significant difference in peak RCOF values between BD and RD conditions with a mean across all trials of 0.193 ± 0.036. However, in older adults the right foot peak RCOF significantly decreased on average 0.006 during RD

(Table 7). On the left (previously slipped) foot, there was a significant difference in BD/RD condition ($p < 0.01$) in both young and older adults (Figure 7B). Both young and older adults decreased their left foot peak RCOF 0.016 after experiencing a slip (Table 7).

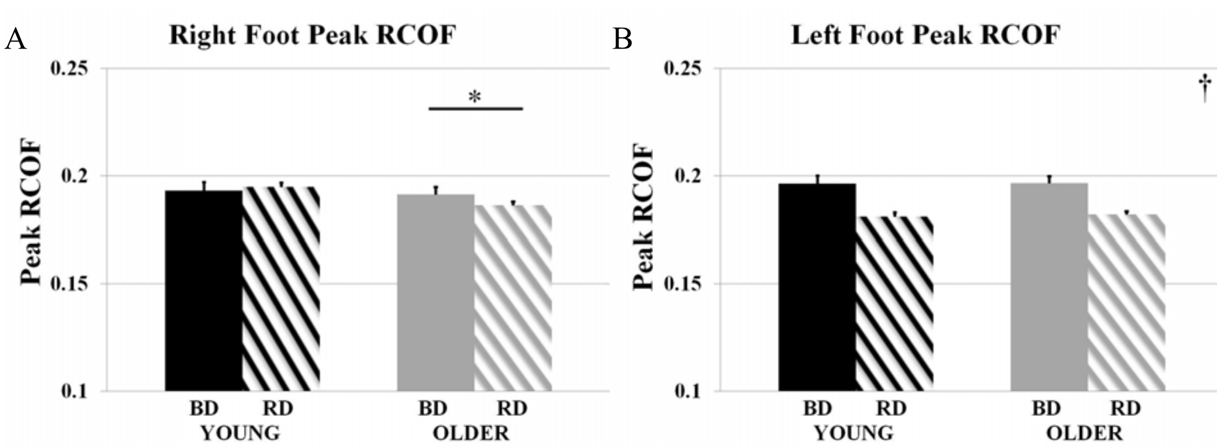


Figure 7: Effect of experience on peak RCOF, (A) right foot peak RCOF and (B) left foot peak RCOF. Baseline dry (BD) shown as solid bars and recovery dry (RD) as hashed bars with young adults in black and older adults in gray. Significance is provided in the top right corner with † denoting experience condition. * represents a significant interaction effect. Standard errors are provided.

Table 7: Peak RCOF Within Subject Differences

Mean (SE)	Young	Older
Right Foot Peak RCOF	0.004 (0.002)	-0.006 (0.002) *
Left Foot Peak RCOF †	-0.016 (0.002)	-0.016 (0.001)

† Denotes experience condition (BD/RD) significant. * Denotes significant interaction effect.

Analysis B revealed that RD trial number on the left (previously slipped) foot was significant in young adults and older adults. RD trials 1-8 were significantly lower than the mean BD peak RCOF values in young adults on the left (previously slipped) foot (Table 8). For older adults, almost all 15 RD trials peak RCOF values were significantly lower than the mean BD peak RCOF (Table 8). In other words, after approximately 8 RD trials young adults returned to baseline gait levels of slip risk on their left foot, while the slip risk of older adults remained lower in the RD condition compared to BD characteristics on their left foot after 15 trials (Figure 8).

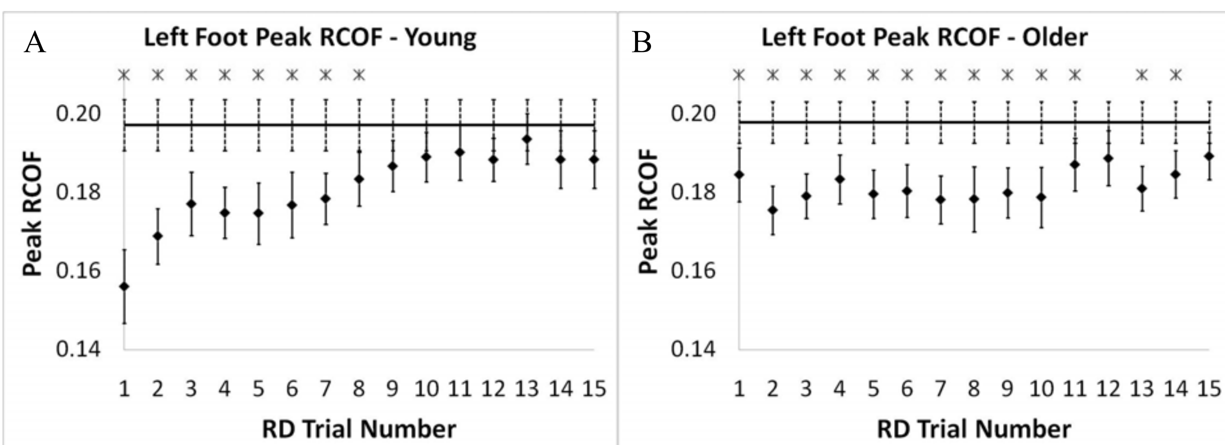


Figure 8: Mean peak RCOF during RD trials on the left (previously slipped) foot in young (A) and older (B) adults. Mean baseline peak RCOF for the age group is shown as the solid horizontal line. Significant trial effect is provided along the top with * denoting significance for each RD trial.

Table 8: Left Foot Peak RCOF Within Subject Differences

Mean (SE)	Young	Older
RD 1	-0.039 (0.008) *	-0.017 (0.005) *
RD 2	-0.028 (0.006) *	-0.020 (0.004) *
RD 3	-0.021 (0.007) *	-0.023 (0.005) *
RD 4	-0.022 (0.005) *	-0.017 (0.005) *
RD 5	-0.022 (0.008) *	-0.019 (0.004) *
RD 6	-0.020 (0.007) *	-0.019 (0.006) *
RD 7	-0.019 (0.006) *	-0.019 (0.005) *
RD 8	-0.014 (0.005) *	-0.019 (0.006) *
RD 9	-0.011 (0.006)	-0.017 (0.006) *
RD 10	-0.007 (0.006)	-0.017 (0.007) *
RD 11	-0.007 (0.006)	-0.011 (0.005) *
RD 12	-0.005 (0.006)	-0.009 (0.006)
RD 13	-0.00 4(0.006)	-0.016 (0.006) *
RD 14	-0.010 (0.006)	-0.012 (0.005) *
RD 15	-0.007 (0.006)	-0.009 (0.006)

* Denotes significant difference from BD for each RD trial

Analysis A found that age group and experience condition impact gait parameters. Overall, older adults had longer stance durations, slower gait speeds, and shorter step lengths than young adults ($p = 0.01$, $p = 0.01$, $p = 0.03$, respectively). Experiencing a slippery floor during gait impacted all gait parameters of interest. Experience resulted in shorter mean stance duration ($p < 0.01$, Figure 9A). Young adults decreased their stance duration significantly more, 20.71 ms, than older adults, 17.25 ms ($p = 0.01$, Table 9). These temporal changes are likely due to changes in gait speed. Both young and older adults increased their gait speed during RD ($p < 0.01$). However, the increase in gait speed was significantly more in young adults ($p < 0.01$, Figure 9B). Young adults increased gait speed 0.05 m/s after experiencing a slip while older adults only increased gait speed 0.02 m/s (Table 9). Cadence increased in both young and older adults after experiencing a slip ($p < 0.01$, Figure 9C). It was also noted that only young adults increased step length ($p < 0.01$, Figure 9D). Specifically, young adults increased their step length by 1.14 cm (Table 9).

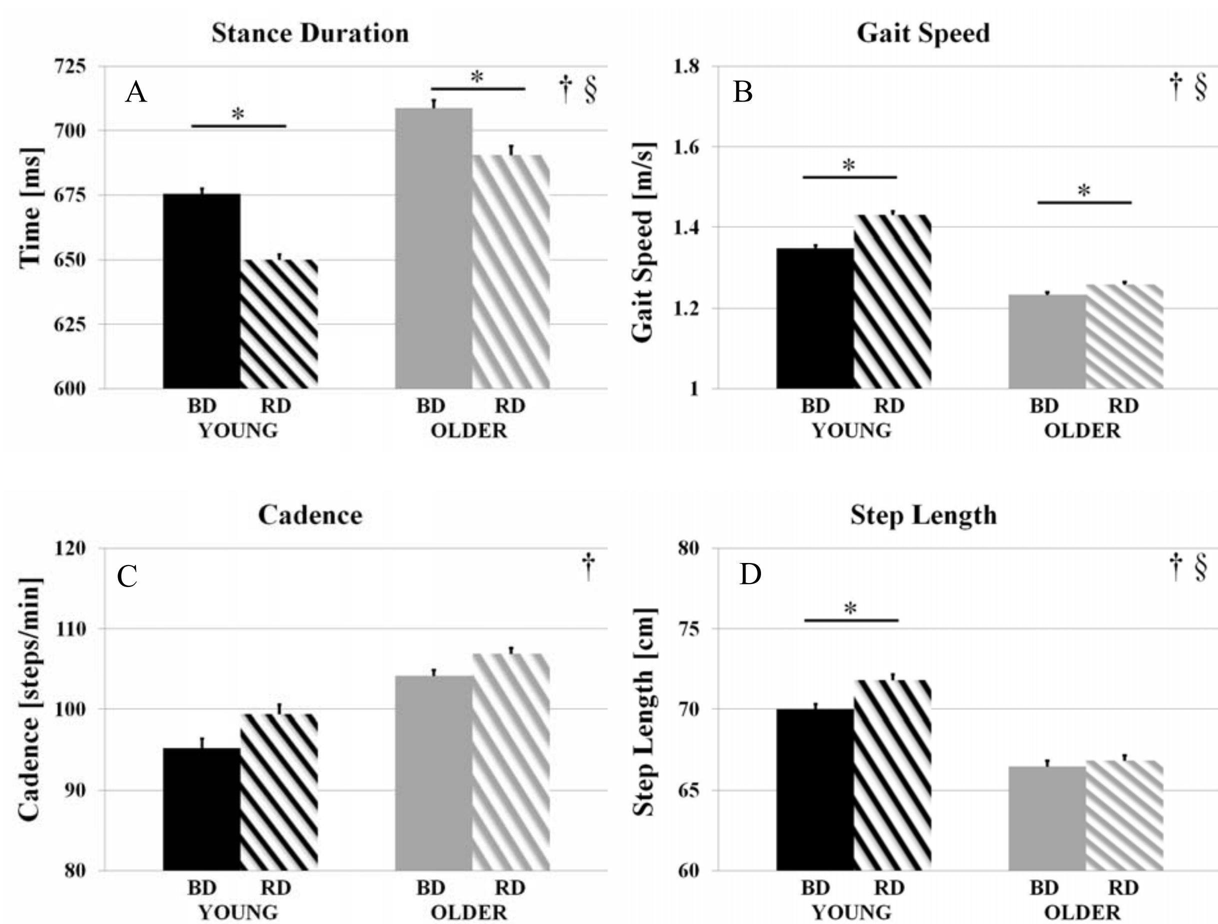


Figure 9: Effect of experience on mean gait parameters, (A) stance duration, (B) gait speed, (C) cadence and (D) step length. Baseline dry (BD) shown as solid bars and recovery dry (RD) as hashed bars with young adults in black and older adults in gray. Significance is provided in the top right corner with † denoting experience condition and § denoting age group. * represents a significant interaction effect. Standard errors are provided.

Table 9: Gait Parameters Within Subject Differences

Mean (SE)	Young	Older
Stance Duration [ms] † §	-20.71 (1.35) *	-17.25 (2.17) *
Gait Speed [m/s] † §	0.05 (0.01) *	0.02 (0.01) *
Cadence [steps/min] †	1.92 (0.20)	2.49 (0.23)
Step Length [cm] † §	1.14 (0.17) *	0.41 (0.15)

† Denotes experience condition (BD/RD) significant. § Denotes age group significant. * Denotes significant interaction effect.

In Analysis B, RD trial number condition was significant for several of the temporal/spatial gait parameters of interest. Specifically, stance duration was significantly decreased during the majority of RD trials in both young and older adults (Figure 10A,B, Table 10). Gait speed was significantly increased during RD trials 2-15 in young adults (Figure 10C). Meanwhile, older adults significantly changed gait speed from BD in only RD trial 12 (Figure 10D, Table 10). Cadence was significantly increased from BD during the majority of RD trials in both young and older adults (Figure 10E,F, Table 10). RD trial number condition was significant in young adults but not in older adults for step length. Young adults showed an increase from BD in step length during the majority of later RD trials, starting around RD trial 9 (Figure 11, Table 11). Experiencing a slip did not cause any significant change in step length among older adults.

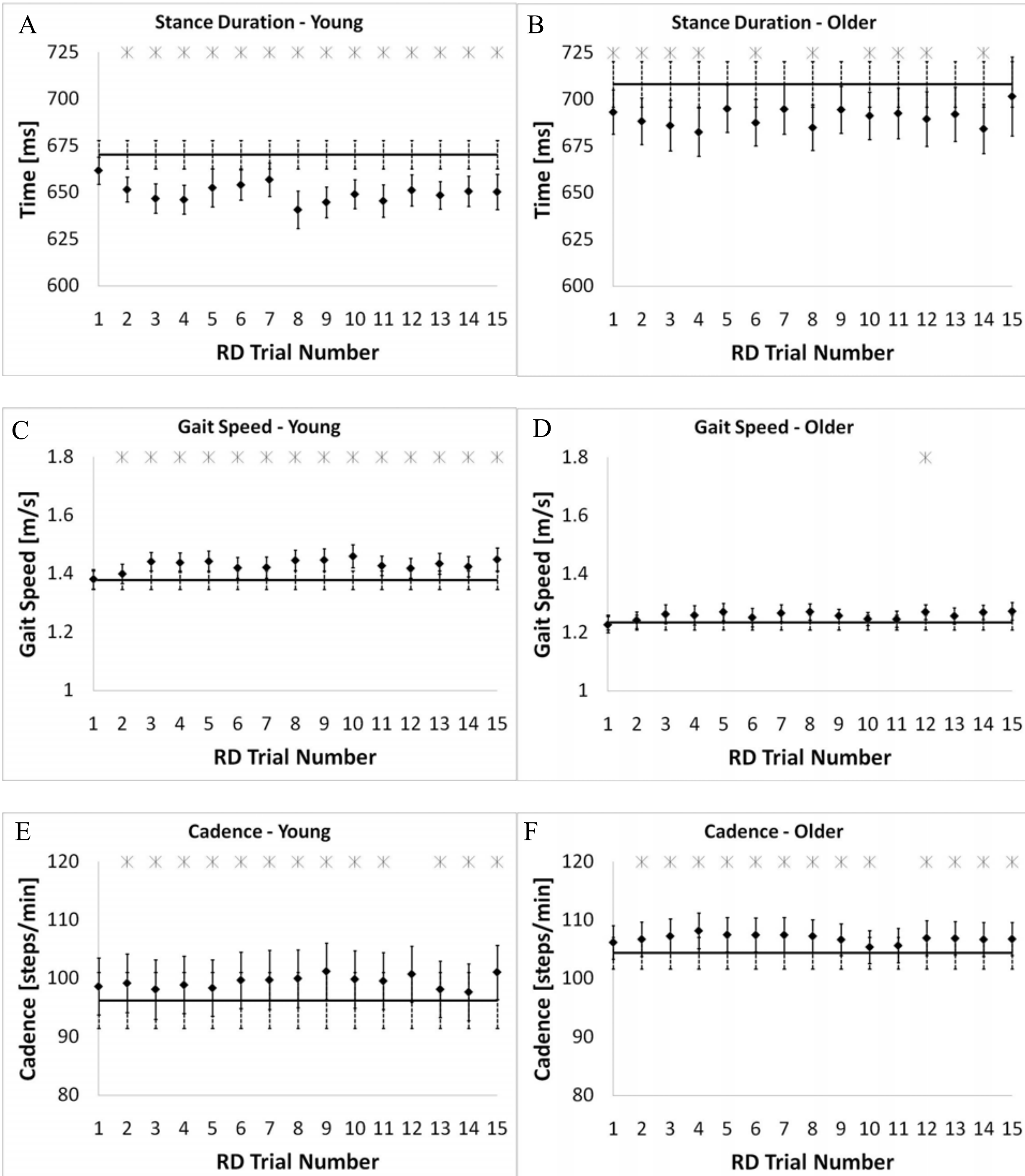


Figure 10: Temporal gait parameters, mean stance duration of RD trials in young (A) and older (B) adults. Mean baseline stance duration for the age group is shown as the solid horizontal line. Mean gait speed of RD trials in young (C) and older (D) adults. Mean baseline gait speed for the age group is shown as the solid horizontal line. Mean cadence of RD trials in young (E) and older (F) adults. Mean baseline cadence for the age group is shown as the solid horizontal line. Significant trial effect is provided along the top with * denoting significance for each RD trial.

Table 10: Temporal Gait Parameters Within Subject Differences

Mean (SE)	Stance Duration [ms]		Gait Speed [m/s]		Cadence [steps/min]	
	Young	Older	Young	Older	Young	Older
RD 1	-9.70 (5.08)	-10.85 (5.31)	0.01 (0.01)	-0.01 (0.02)	0.89 (0.86)	1.39 (0.84)
RD 2	-20.97 * (3.89)	-19.90 * (6.62)	0.04 * (0.02)	0.01 (0.02)	2.11 * (0.77)	2.37 * (0.64)
RD 3	-24.67 * (4.93)	-22.19 * (7.13)	0.08 * (0.02)	0.03 (0.02)	2.60 * (0.92)	2.90 * (0.95)
RD 4	-24.16 * (4.47)	-25.70 * (7.23)	0.06 * (0.01)	0.03 (0.02)	2.66 * (0.84)	3.82 * (1.04)
RD 5	-17.80 * (4.74)	-13.02 (7.30)	0.06 * (0.01)	0.03 (0.02)	2.13 * (0.64)	3.16 * (0.98)
RD 6	-16.26 * (5.72)	-20.55 * (8.87)	0.04 * (0.02)	0.02 (0.02)	1.96 * (0.67)	3.13 * (1.18)
RD 7	-13.47 * (5.68)	-13.24 (7.79)	0.04 * (0.02)	0.03 (0.02)	2.01 * (0.84)	3.13 * (1.08)
RD 8	-29.51 * (5.93)	-23.14 * (7.38)	0.07 * (0.01)	0.04 (0.02)	2.25 * (0.78)	2.92 * (0.73)
RD 9	-25.51 * (4.30)	-13.54 (8.29)	0.07 * (0.02)	0.02 (0.02)	1.84 * (0.92)	2.32 * (0.91)
RD 10	-21.25 * (5.06)	-21.76 * (7.59)	0.08 * (0.02)	0.02 (0.02)	2.12 * (0.70)	1.75 * (0.75)
RD 11	-24.82 * (4.79)	-15.48 * (6.79)	0.05 * (0.02)	0.01 (0.02)	1.83 * (0.83)	1.31 (0.91)
RD 12	-19.10 * (6.02)	-18.54 * (7.84)	0.04 * (0.01)	0.04 * (0.02)	1.35 (0.82)	2.31 (0.92)
RD 13	-21.79 * (5.42)	-15.98 (8.74)	0.06 * (0.01)	0.02 (0.02)	1.91 * (0.73)	2.55 * (0.92)
RD 14	-19.70* (5.95)	-22.34 * (6.95)	0.05 * (0.01)	0.03 (0.01)	1.44 * (0.70)	2.26 * (0.85)
RD 15	-21.72 * (6.02)	-2.44 (17.46)	0.07 * (0.02)	0.03 (0.02)	1.69 * (0.83)	1.99 * (0.85)

* Denotes significant difference from BD for each RD trial

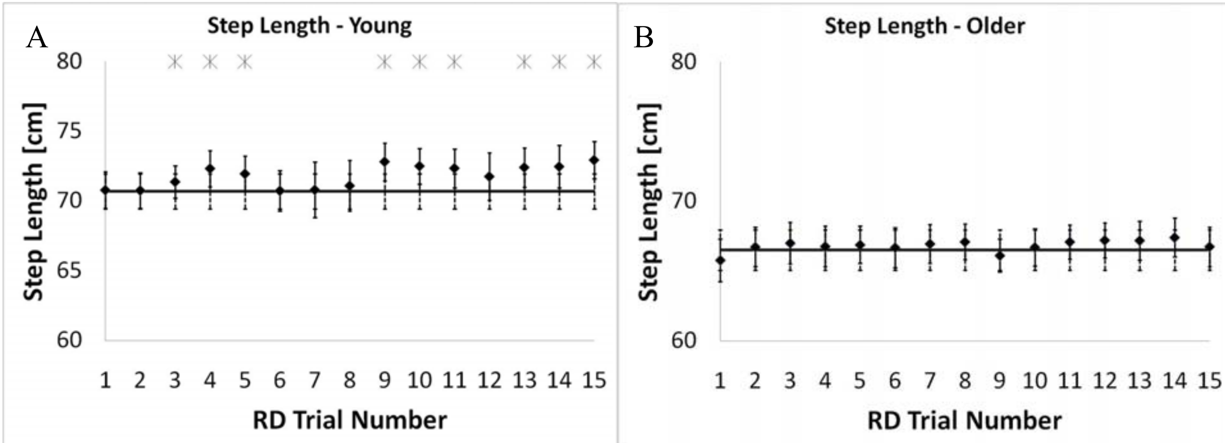


Figure 11: Spatial gait parameter, mean step length of RD trials in young (A) and older (B) adults. Mean baseline step length for the age group is shown as the solid horizontal line. Significant trial effect is provided along the top with * denoting significance for each RD trial.

Table 11: Spatial Gait Parameters Within Subject Differences

	Step Length [cm]	
Mean (SE)	Young	Older
RD 1	-0.16 (0.41)	-0.30 (0.43)
RD 2	0.73 (0.41)	0.52 (0.52)
RD 3	1.18 (0.32) *	0.80 (0.45)
RD 4	1.63 (0.32) *	0.56 (0.58)
RD 5	1.25 (0.30) *	0.38 (0.49)
RD 6	0.04 (0.59)	0.18 (0.67)
RD 7	0.11 (1.35)	0.45 (0.57)
RD 8	0.40 (1.13)	0.60 (0.54)
RD 9	2.11 (0.44) *	-0.39 (0.73)
RD 10	1.81 (0.48) *	0.33 (0.62)
RD 11	1.65 (0.47) *	0.59 (0.58)
RD 12	1.06 (0.90)	0.71 (0.56)
RD 13	1.71 (0.50) *	0.69 (0.48)
RD 14	1.77 (0.69) *	0.69 (0.52)
RD15	1.77 (0.38) *	0.37 (0.82)

* Denotes significant difference from BD for each RD trial

Experiencing a slippery floor during gait resulted in several significant changes in COM stability (Figure 12). A significant age-condition interaction effect ($p = 0.04$) revealed that ML margin of stability significantly decreased in young adults only. Specifically, ML margin of stability decreased 0.38 cm during RD in young adults (Table 12). Overall, older adults had a smaller AP margin of stability than younger adults ($p = 0.04$). Experience also resulted in AP margin of stability significantly decreasing ($p < 0.01$), reflecting an anterior shift in the COM at left HC (Figure 12B). Young and older adults decreased their AP margin of stability 0.67 cm and 0.87 cm, respectively (Table 12). COM vertical significantly decreased during recovery trials in both young and older adults ($p < 0.01$). It was also found that COM vertical decreased significantly more in older adults, 0.81 cm, than in young, 0.49 cm, after experiencing an unexpected slip ($p < 0.01$, Table 12). COM BOS angle significantly decreased during RD ($p < 0.01$, Figure 12D). This decrease was noted in both young, 0.30°, and older adults, 0.31° (Table 12).

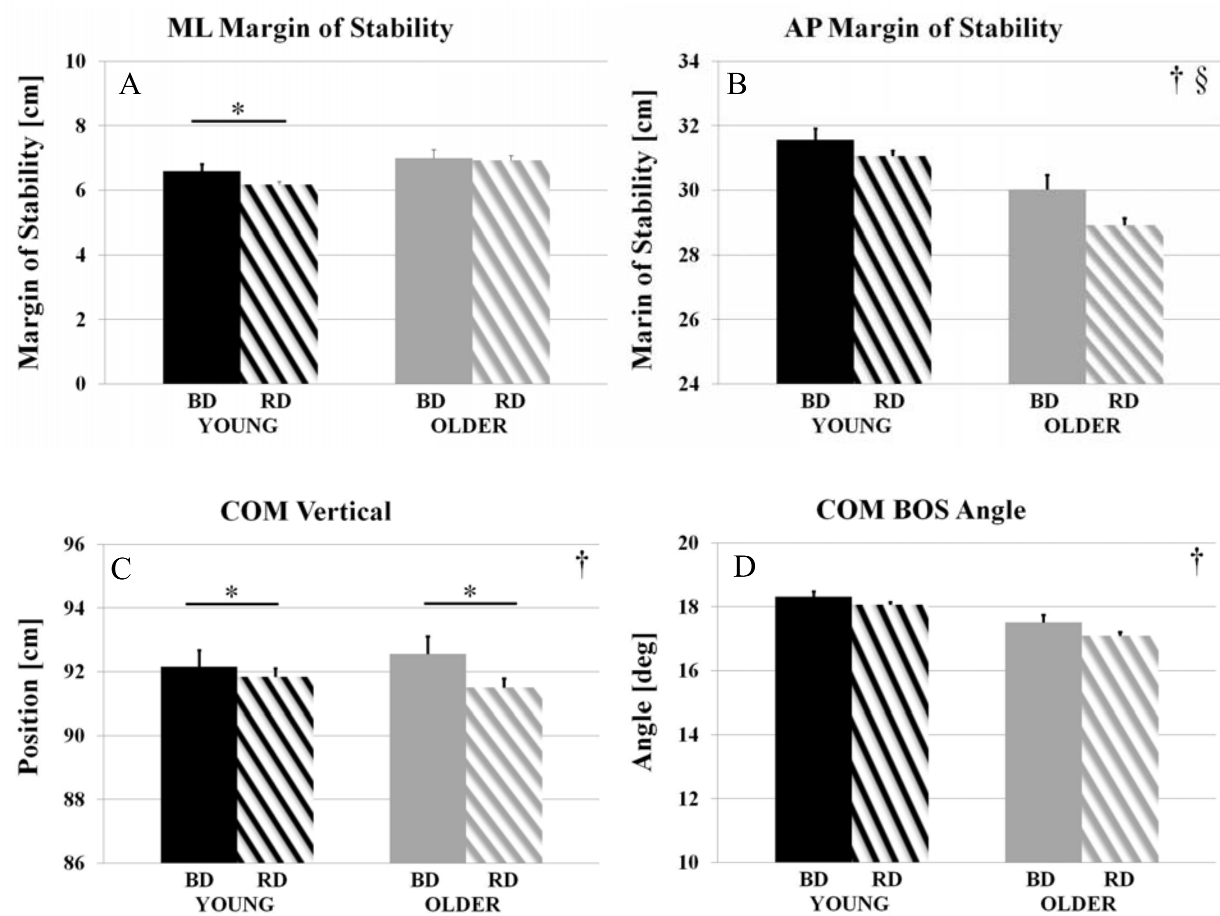


Figure 12: Effect of experience on COM stability, (A) ML margin of stability, (B) AP margin of stability, (C) COM vertical, and (D) COM BOS Angle. Baseline dry (BD) shown as solid bars and recovery dry (RD) as hashed bars with young adults in black and older adults in gray. Significance is provided in the top right corner with † denoting experience condition and § denoting age group. * represents a significant interaction effect. Standard errors are provided.

Table 12: COM Stability Within Subject Differences

Mean (SE)	Young	Older
ML Margin of Stability [cm]	-0.38 (0.08) *	0.13 (0.11)
AP Margin of Stability [cm] † §	-0.67 (0.10)	-0.87 (0.11)
COM vertical [cm] †	-0.49 (0.05) *	-0.81 (0.07) *
COM BOS ANG [deg] †	-0.30 (0.06)	-0.31 (0.06)

† Denotes experience condition (BD/RD) significant. § Denotes age group significant. * Denotes significant interaction effect.

Analysis B revealed that RD trial number condition was significant for AP margin of stability in young and older adults. Specifically, young adults had 4 RD trials that were significantly less than BD while older adults had 9 RD trials (Figure 13A,B). In general, AP margin of stability was decreased during more RD trials in older adults than in young compared to baseline (Table 13). RD trial number was also significant in both young and older adults for COM vertical. All RD trials had significantly lower COM vertical than BD in older adults. Similarly, the majority of RD trials had significantly lower COM vertical than BD in young adults (Figure 13C,D, Table 13). In young and older adults RD trials number was significant for COM BOS angle. Both young and older adults decreased COM BOS angle in a few of the RD trials compared to baseline values (Figure 13E,F). No RD trials after RD trial 8 were significantly different than baseline for COM BOS angle (Table 13).

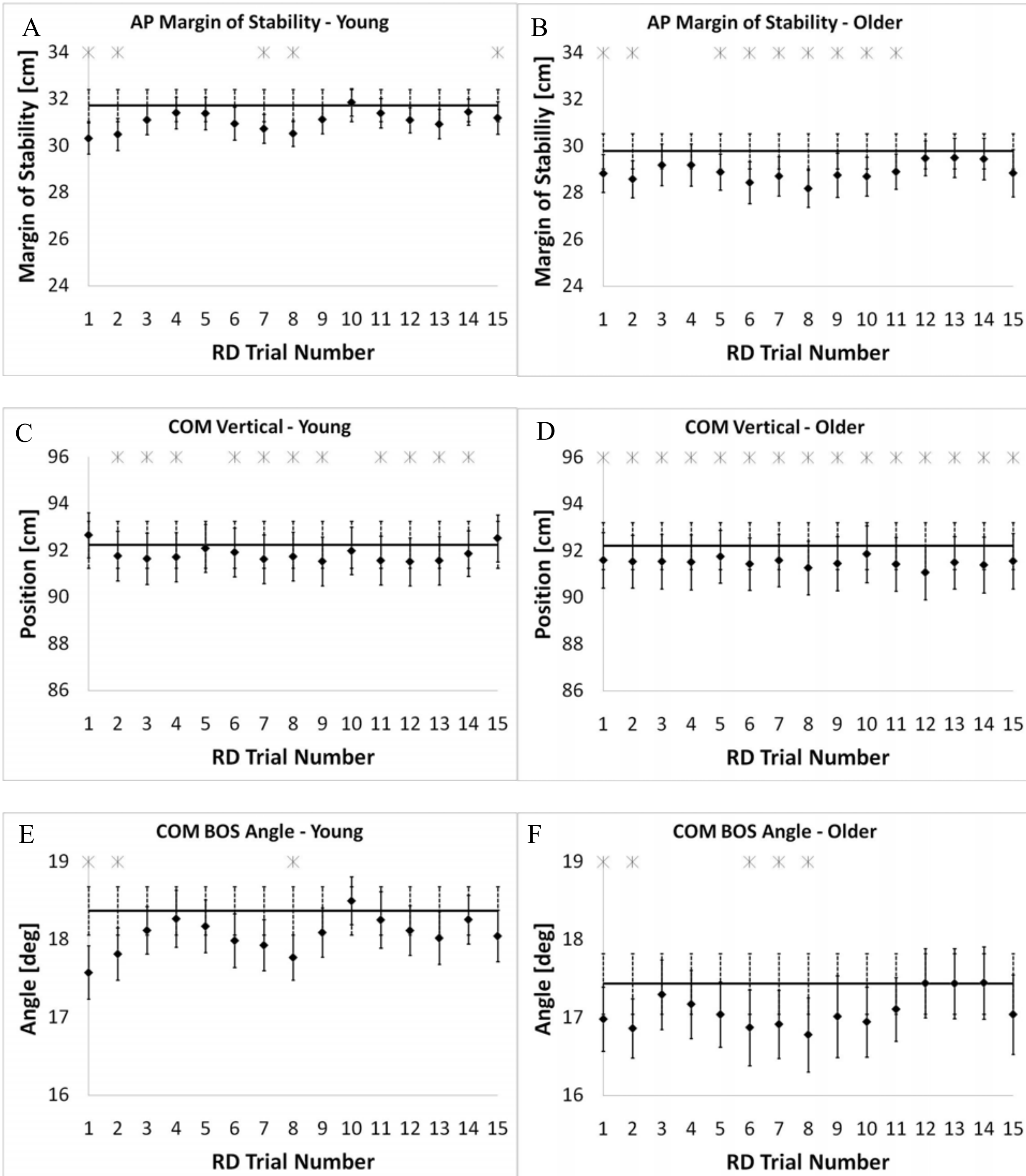


Figure 13: COM stability, mean AP margin of stability of RD trials in young (A) and older (B) adults. Mean baseline AP margin of stability for the age group is shown as the solid horizontal line. Mean COM vertical of RD trials in young (C) and older (D) adults. Mean baseline COM vertical for the age group is shown as the solid horizontal line. Mean COM BOS angle of RD trials in young (E) and older (F) adults. Mean baseline COM BOS angle for the age group is shown as the solid horizontal line. Significant trial effect is provided along the top with * denoting significance for each RD trial.

Table 13: COM Stability Within Subject Differences

Mean (SE)	AP Margin of Stability [cm]		COM Vertical [cm]		COM BOS Angle [deg]	
	Young	Older	Young	Older	Young	Older
RD 1	-1.60 * (0.37)	-0.85 * (0.30)	0.01 (0.19)	-0.62 * (0.25)	-0.83 * (0.21)	-0.34 * (0.16)
RD 2	-0.97 * (0.37)	-1.04 * (0.34)	-0.43 * (0.16)	-0.86 * (0.23)	-0.43 * (0.22)	-0.45 * (0.17)
RD 3	-0.36 (0.35)	-0.44 (0.27)	-0.55 * (0.19)	-0.86 * (0.26)	-0.13 (0.19)	-0.01 (0.18)
RD 4	-0.31 (0.33)	-0.59 (0.45)	-0.53 * (0.20)	-0.81 * (0.24)	-0.10 (0.19)	-0.22 (0.21)
RD 5	-0.34 (0.34)	-0.90 * (0.39)	-0.15 (0.20)	-0.57 * (0.26)	-0.20 (0.18)	-0.37 (0.19)
RD 6	-0.78 (0.45)	-1.51 * (0.50)	-0.33 (0.23)	-0.69 * (0.26)	-0.38 (0.25)	-0.65 * (0.25)
RD 7	-1.00 * (0.45)	-1.08 * (0.37)	-0.62 * (0.19)	-0.73 * (0.30)	-0.44 (0.27)	-0.50 * (0.18)
RD 8	-1.20 * (0.45)	-1.77 * (0.46)	-0.51 * (0.18)	-0.85 * (0.28)	-0.60 * (0.24)	-0.75 * (0.26)
RD 9	-0.60 (0.42)	-1.19 * (0.49)	-0.71 * (0.17)	-0.67 * (0.31)	-0.28 (0.23)	-0.51 (0.29)
RD 10	0.13 (0.42)	-1.04 * (0.45)	-0.26 (0.21)	-0.87 * (0.29)	0.13 (0.23)	-0.38 (0.25)
RD 11	-0.33 (0.39)	-0.89 * (0.39)	-0.68 * (0.19)	-0.90 * (0.26)	-0.12 (0.22)	-0.31 (0.20)
RD 12	-0.63 (0.42)	-0.46 (0.41)	-0.73 * (0.17)	-1.05 * (0.29)	-0.25 (0.24)	-0.09 (0.20)
RD 13	-0.80 (0.42)	-0.28 (0.34)	-0.68 * (0.18)	-0.82 * (0.26)	-0.35 (0.24)	0.02 (0.18)
RD 14	-0.48 (0.37)	-0.33 (0.25)	-0.78 * (0.18)	-0.93 * (0.28)	-0.15 (0.20)	0.05 (0.14)
RD 15	-0.80 * (0.36)	-0.68 (0.71)	-0.40 * (0.21)	-1.00 * (0.26)	-0.35 (0.20)	-0.14 (0.37)

* Denotes significant difference from BD for each RD trial

5.1.2 Gait on Slippery Floors Following Slip Experience

Analysis C investigated the difference in slip severity between US1 and US2. Slip severity was not significantly different between US1 and US2 in young adults, implying that young adults experienced a slip of similar magnitude upon second exposure after 15 dry trials (Figure 14). In fact young adults on average were found to have a 0.07 m/s decrease in PSV upon second exposure (Table 14). However, older adults experienced a less severe slip in US2 compared to US1 (p=.0473, Figure 14). Slip severity decreased 0.31 m/s, over 40%, in older adults upon second unexpected exposure to a slippery floor (Table 14).

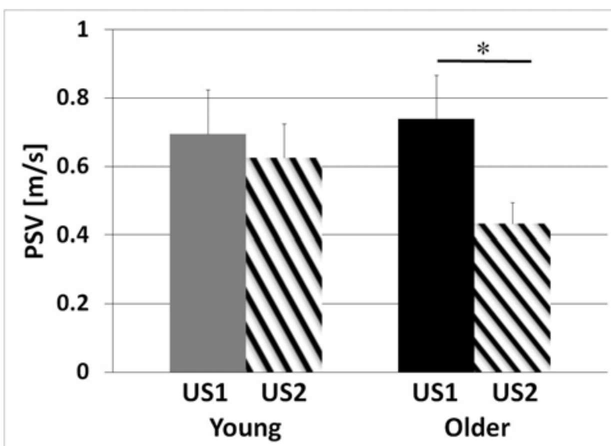


Figure 14: Mean peak slip velocity (PSV) in young (gray) and older (black) adults. First unexpected slip, US1, shown as solid bars and second unexpected slip, US2, as hashed bars. Standard errors are provided. * denotes PSV significantly different between US1/US2.

Table 14: PSV Within Subject Differences

Mean (SE)	Young	Older
PSV [m/s]	-0.07 (0.09)	-0.31 (0.15) *

* Denotes significant condition (US1/US2) effect

5.2 EFFECT OF EXPERIENCE AND AWARENESS ON PROACTIVE STRATEGIES

Specific Aim 2 examined the effect of warning subjects that a slippery floor is possible (‘awareness’) on proactive strategies generated after unexpectedly slipping on a contaminated floor (‘experience’) on the risk of slipping and slip severity. The combined effect of experience and awareness was termed anticipation. Additionally, age-related differences were examined.

5.2.1 Gait on Dry Floors Following Slip Experience with Awareness

Analysis D revealed that anticipating a slippery floor resulted in a significant decrease in peak RCOF (Figure 15). This decrease was noted on both the right and left (previously slipped) feet ($p < 0.01$, $p < 0.01$, respectively). Anticipation resulted in young adults decreasing their peak RCOF 0.032 on the right foot and 0.041 on the left foot (Table 15). Older adults also decreased their peak RCOF 0.034 on the right foot and 0.034 on the left foot after experiencing a slippery floor and while aware of a pending slip (Table 15).

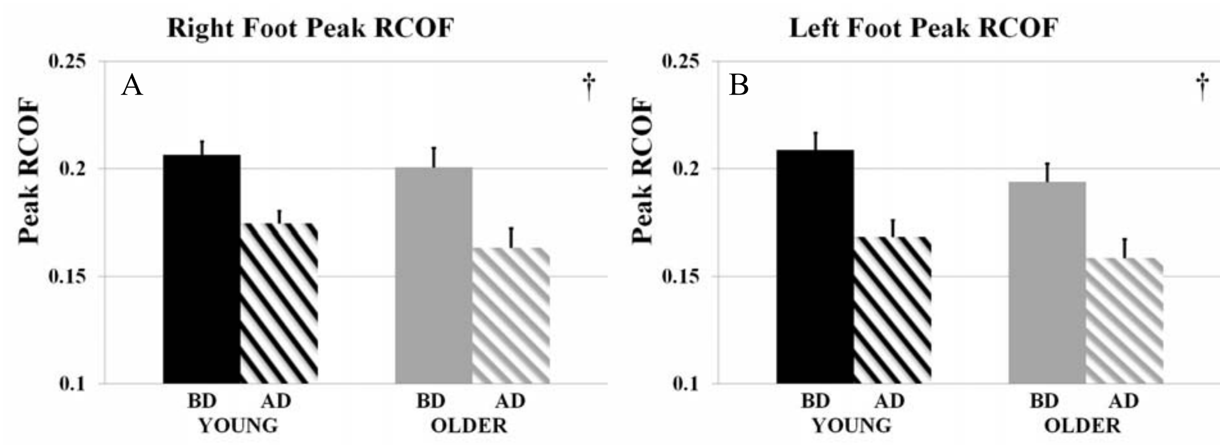


Figure 15: Effect of awareness and experience on mean peak RCOF on the right foot (A) and left foot (B) in young and older adults. Baseline dry (BD) shown as solid bars and anticipation dry (AD) as hashed bars with young adults in black and older adults in gray. Significance is provided in the top right corner with † denoting anticipation condition. Standard errors are provided.

Table 15: Peak RCOF Within Subject Differences

Mean (SE)	Young	Older
Right Foot Peak RCOF †	-0.032 (0.005)	-0.034 (0.008)
Left Foot Peak RCOF †	-0.041 (0.006)	-0.034 (0.008)

† Denotes significant awareness condition (BD/AD) effect

Analysis D also demonstrated that experience and awareness (‘anticipation’) of slippery floors resulted in significant changes in spatiotemporal gait parameters. Anticipation increased cadence ($p < 0.01$) and gait speed ($p < 0.01$) in both young and older adults (Figure 16B,C). In general, young adults walked faster than older adults ($p < 0.01$). Young adults showed a greater increase in gait speed during AD, 0.09 m/s, than older adults, 0.03 m/s (Table 16). Likely due to increased gait speed, shorter mean durations of stance were also reported with an average decrease of 31 ms with anticipation (Table 16). Overall, young adults took significantly longer steps than older adults ($p < 0.01$). Step length significantly increased ($p < 0.001$) 2.98 cm in young adults during AD trials (Table 16, Figure 16D).

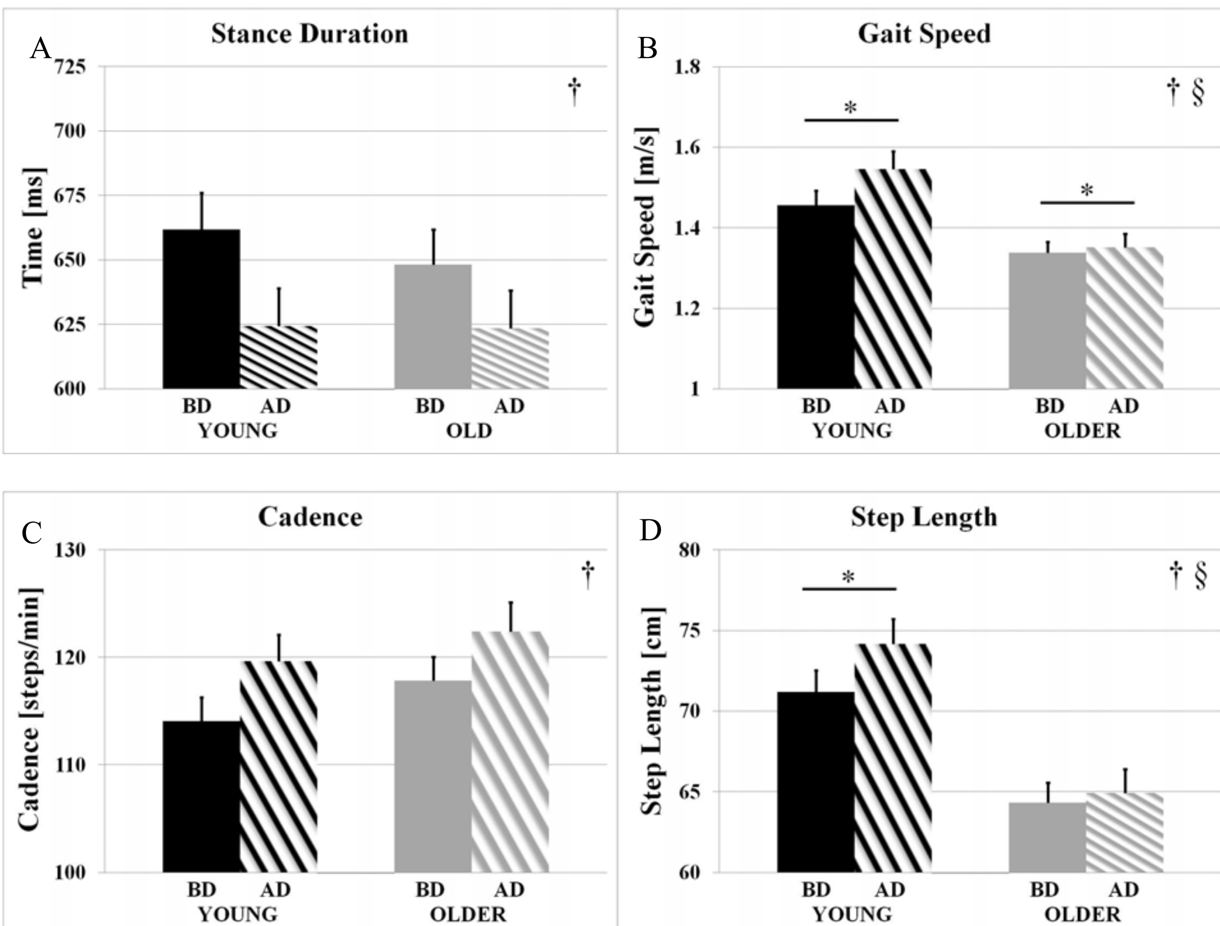


Figure 16: Effect of awareness and experience on mean gait parameters, (A) stance duration, (B) gait speed, (C) cadence and (D) step length. Baseline dry (BD) shown as solid bars and anticipation dry (AD) as hashed bars with young adults in black and older adults in gray. Significance is provided in the top right corner with † denoting anticipation condition and § denoting age group. * represents a significant interaction effect. Standard errors are provided.

Table 16: Gait Parameters Within Subject Differences

Mean (SE)	Young	Older
Stance Duration [ms] †	-37.44 (6.35)	-24.77 (10.48)
Gait Speed [m/s] † §	0.09 (0.02) *	0.03 (0.02) *
Cadence [steps/min] †	5.60 (1.10)	4.48 (1.65)
Step Length [cm] † §	2.98 (0.42) *	0.59 (0.90)

† Denotes anticipation condition (BD/AD) significant. § Denotes age group significant. * Denotes significant interaction effect.

As mentioned previously, Analysis E was performed to reveal how young and older adults modulate gait speed when anticipating slippery floors compared to baseline gait. The contribution of cadence to explaining gait speed variability during baseline walking and when anticipating slippery floors above the contribution of step length was equal to 53% and 34% in young adults, respectively (Table 17). In older adults, cadence explained an additional 72% of gait speed variability above and beyond the contribution of step length during baseline walking and 49% during anticipation (Table 17). While the role of cadence in controlling gait speed was more prominent during baseline walking compared to anticipation, in general, older adults relied more on cadence control strategies to modulate gait speed than young participants did. In contrast, step length explained 39% and 59% of the variability in gait speed during baseline walking and when anticipating slippery floors, respectively, above and beyond the contributions of cadence in young adults (Table 17). The additional contribution of step length to explaining gait speed variability above and beyond cadence contributions was equal to 59% during baseline walking, and 55% when anticipating slippery floors in older subjects, a proportion similar to the result found in young participants (Table 17). This implies that the contribution of step length above and beyond the contribution of cadence to explaining gait speed increased 20% when anticipating slippery floors compared to baseline in young adults while it decreased 4% in older adults.

Table 17: R2 values obtained by regressing gait speed on step length alone (Model 1), cadence alone (Model 2) and on step length and cadence combined (Model 3) in young and older adults during baseline dry (BD) and anticipation dry (AD). The added value of step length is quantified using the R^2 difference between Models (3) and (2). The added value of cadence is quantified using the R^2 difference between Models (3) and (1). Statistical significance is noted for the contribution of step length and/or cadence in each Model.

Independent variable(s) → Group ↓	Step Length (1)	Cadence (2)	Step Length & Cadence (3)	ΔR^2 Step Length (3 – 2)	ΔR^2 Cadence (3 – 1)
Young BD	0.34^{α}	0.48^{β}	$0.87^{\alpha\beta}$	0.39	0.53
Young AD	0.58^{α}	0.33^{β}	$0.92^{\alpha\beta}$	0.59	0.34
Older BD	0.13	0.26	$0.85^{\alpha\beta}$	0.59	0.72
Older AD	0.45^{α}	0.39^{β}	$0.94^{\alpha\beta}$	0.55	0.49

$^{\alpha}$ Denotes $p_{Step\ Length} < .05$ $^{\beta}$ Denotes $p_{Cadence} < .05$

Analysis D also examined changes in COM stability across anticipation conditions and age groups. Anticipation of slippery surface during gait resulted in a significant change in COM stability (Figure 17). No significant difference was noted in ML margin of stability. In general, older adults had a smaller AP margin of stability than younger adults ($p = 0.01$). Anticipation resulted in AP margin of stability significantly decreasing ($p < 0.01$), reflecting an anterior shift in the COM at left HC. Specifically, young adults decreased their AP margin of stability 2.38 cm while older adults decreased theirs 2.53 cm (Table 18). COM vertical tended to increase during anticipation in both young and older adults ($p = 0.12$). COM BOS angle significantly decreased ($p < 0.01$) during anticipation gait. This decrease was seen in both young, 1.23°, and older adults, 1.34° (Table 18).

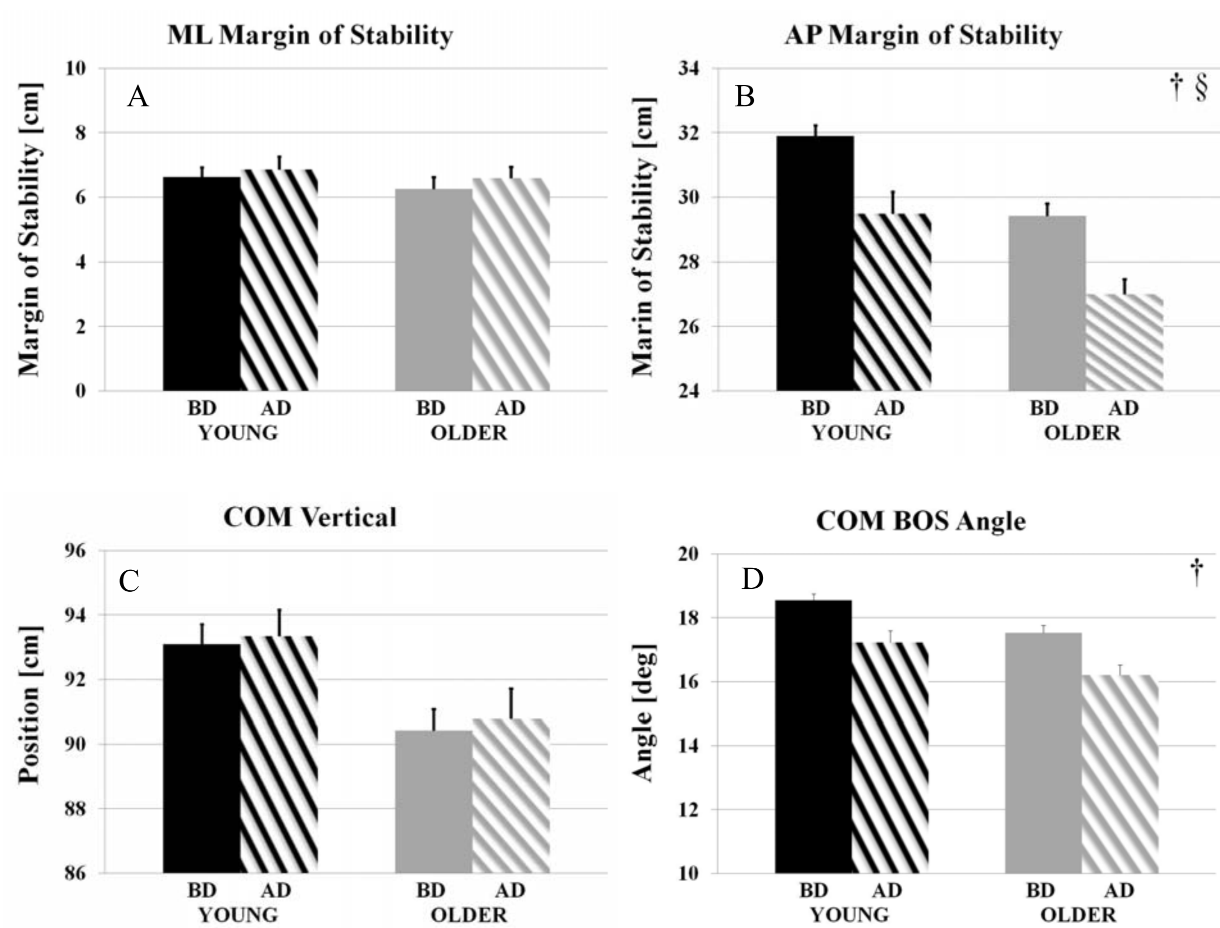


Figure 17: Effect of awareness and experience on COM stability, (A) ML margin of stability, (B) AP margin of stability, (C) COM vertical, and (D) COM BOS Angle. Baseline dry (BD) shown as solid bars and anticipation dry (AD) as hashed bars with young adults in black and older adults in gray. Significance is provided in the top right corner with † denoting anticipation condition and § denoting age group. * represents a significant interaction effect. Standard errors are provided.

Table 18: COM Stability Within Subject Differences

Mean (SE)	Young	Older
ML Margin of Stability [cm]	0.11 (0.40)	0.13 (0.42)
AP Margin of Stability [cm] † §	-2.38 (0.54)	-2.53 (0.39)
COM vertical [cm]	0.10 (0.14)	0.02 (0.20)
COM BOS ANG [deg] †	-1.23 (0.30)	-1.34 (0.22)

† Denotes anticipation condition (BD/AD) significant. § Denotes age group significant.

5.2.2 Gait on Slippery Floors Following Slip Experience with Awareness

Analysis F found that slip severity was significantly different between US and AS in both young and older adults ($p < 0.01$). Both young adults and older adults experienced a less severe anticipation slip than unexpected slip (Figure 18). Young adults on average were found to have a 0.57 m/s decrease in PSV upon second exposure with awareness (Table 19). Similarly, slip severity decreased 0.61 m/s in older adults upon second exposure to a slippery floor with awareness (Table 19).

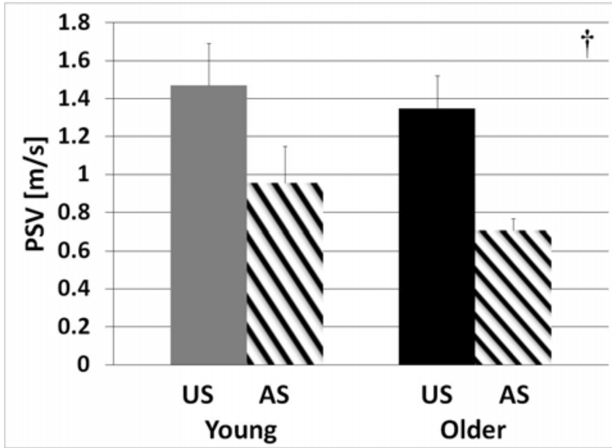


Figure 18: Mean peak slip velocity (PSV) in young (gray) and older (black) adults. Unexpected slip, US, shown as solid bars and anticipation slip, AS, as hashed bars. Standard errors are provided. Significance is provided in the top right corner with † denoting anticipation condition.

Table 19: PSV Within Subject Differences

Mean (SE)	Young	Older
PSV [m/s] †	-0.57 (0.11)	-0.61 (0.17)

† Denotes significant anticipation condition (US/AS) effect

5.3 MODELING

In Aim 3, a sensitivity analysis was performed to examine how simulated muscle excitations change due to the number of muscles included in a simulation of gait. Additionally, the sensitivity of simulated muscle excitations to perturbations in muscle model parameters was evaluated. Finally, preliminary modeling simulations were used to provide insight into proactive strategies.

5.3.1 Simulation Validation

The simulated muscle excitations for Subject 2 BD were compared to previously reported EMG data (Chambers 2005) and literature (Winter 2004). A period from left HC to left TO was examined for validation purposes. When comparing simulated muscle excitations to available EMG and previous literature, scale should not be considered due to differences in normalization procedures. Simulated muscle excitations vary from 0 to 1. EMG data was normalized to the peak magnitude during a gait cycle (Chambers 2005). Previous literature was EMG mean normalized (Winter 2004). Simulated left tibialis anterior peaked after HC then its activity decreased after foot flat (Figure 19). This is similar to what was found previously and for the available EMG data for this participant (Figure 19). The simulated medial gastrocnemius also agrees with EMG data and previous literature, with the majority of its activity occurring in the latter half of stance (Figure 20).

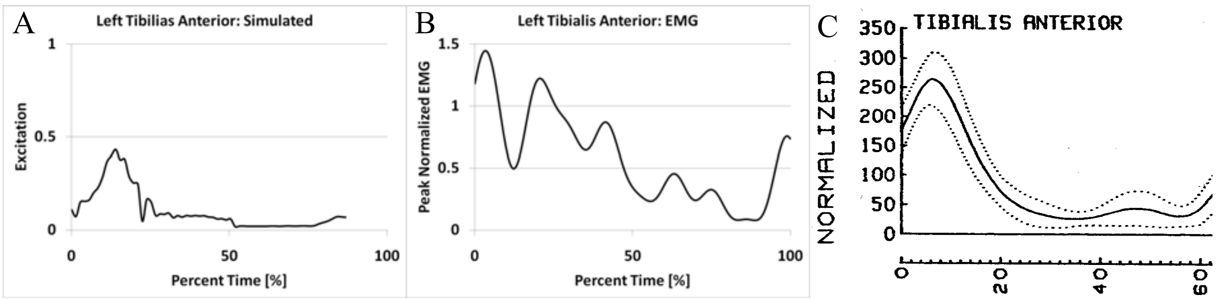


Figure 19: Muscle activity of the left tibialis anterior during stance with 0% as left HC and 100% as left TO, (A) simulated muscle excitations, (B) corresponding peak normalized EMG (Chambers 2005), (C) typical mean normalized EMG (Winter 2004). Simulated muscle excitations were unavailable at TO due to modeling procedures used.

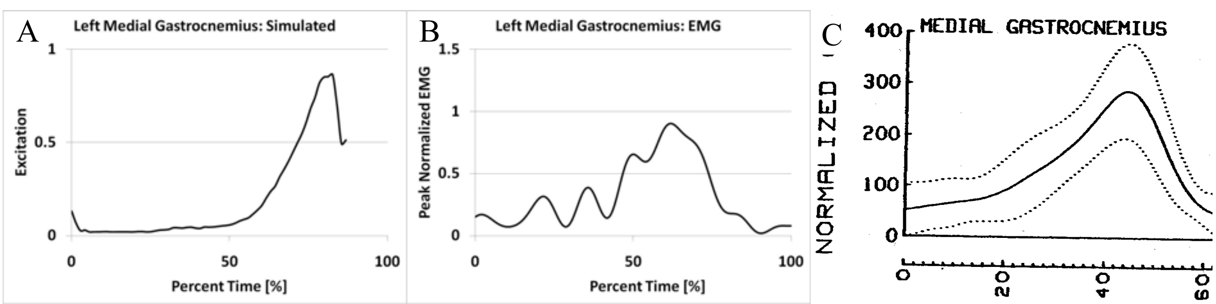


Figure 20: Muscle activity of the left medial gastrocnemius during stance with 0% as left HC and 100% as left TO, (A) simulated muscle excitations, (B) corresponding peak normalized EMG (Chambers 2005), (C) typical mean normalized EMG (Winter 2004). Simulated muscle excitations were unavailable at TO due to modeling procedures used.

Left soleus is activated just before TO in both the simulated excitations and previous literature (Figure 21A, B). The majority of left rectus femoris activity has been previously found to occur immediately following HC, while minor activity was present around TO (Winter 2004). This pattern of activity was true for the simulated left rectus femoris as well (Figure 21C, D). Previous research found that gluteus maximus activity peaks after HC (Winter 2004). Similar patterns were also noted in the simulated gluteus maximus excitations (Figure 21 E, F). In general, the patterns of the simulated muscle excitations of the major muscles involved in controlling gait agree with previous literature and available EMG.

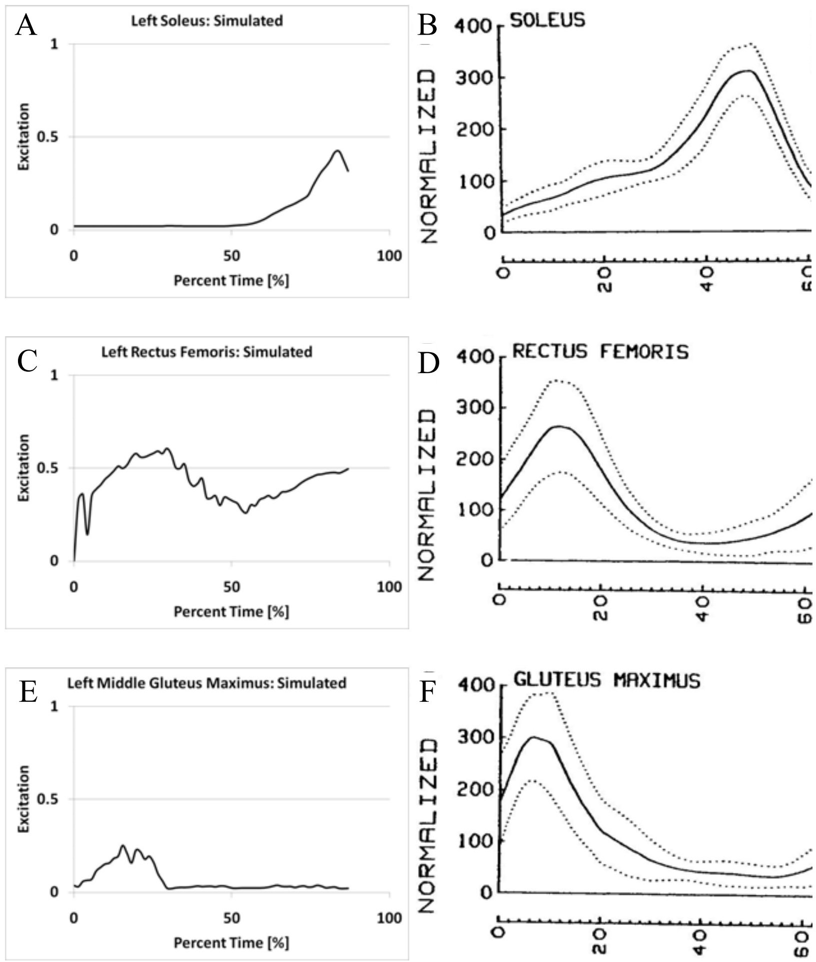


Figure 21: Muscle activity during stance with 0% as left HC and 100% as left TO, (A) simulated left soleus muscle excitations, (B) left soleus typical mean normalized EMG (Winter 2004), (C) simulated left rectus femoris muscle excitations, (D) left rectus femoris typical mean normalized EMG (Winter 2004), (E) simulated left gluteus maximus muscle excitations, (F) left gluteus maximus typical mean normalized EMG (Winter 2004). Simulated muscle excitations were unavailable at TO due to modeling procedures used.

5.3.2 Sensitivity Analysis: Number of Muscles

A sensitivity analysis was performed to reveal the impact of removing certain muscles from a three-dimensional simulation of gait. Including all 54 muscles resulted in simulated muscle excitations that were comparable to gait muscle patterns found previously, as discussed earlier. At left HC, removing all the muscles of interest had the greatest impact, nearly 94% mean relative error, on left inferior gluteus maximus excitations (Figure 22B). In general, this resulted in the left inferior gluteus maximus having higher excitations. This increased excitation was noted throughout the time period of interest for all muscles removed except for the distal adductor magnus. Removing the distal adductor magnus resulted in higher left inferior gluteus maximus excitations at HC but had no impact after HC (Figure 22A). Excitation of the left inferior gluteus maximus was least affected, approximately 34% mean relative error, by removal of the distal adductor magnus (Figure 22B). Removing the distal adductor magnus had a similar minimal impact on left biceps femoris long head excitation (Figure 22C). Removing all muscles had a slightly greater impact on left biceps femoris long head excitation than removing the remaining muscles individually (Figure 22C). This difference was most noticeable after the burst of excitation at left HC.

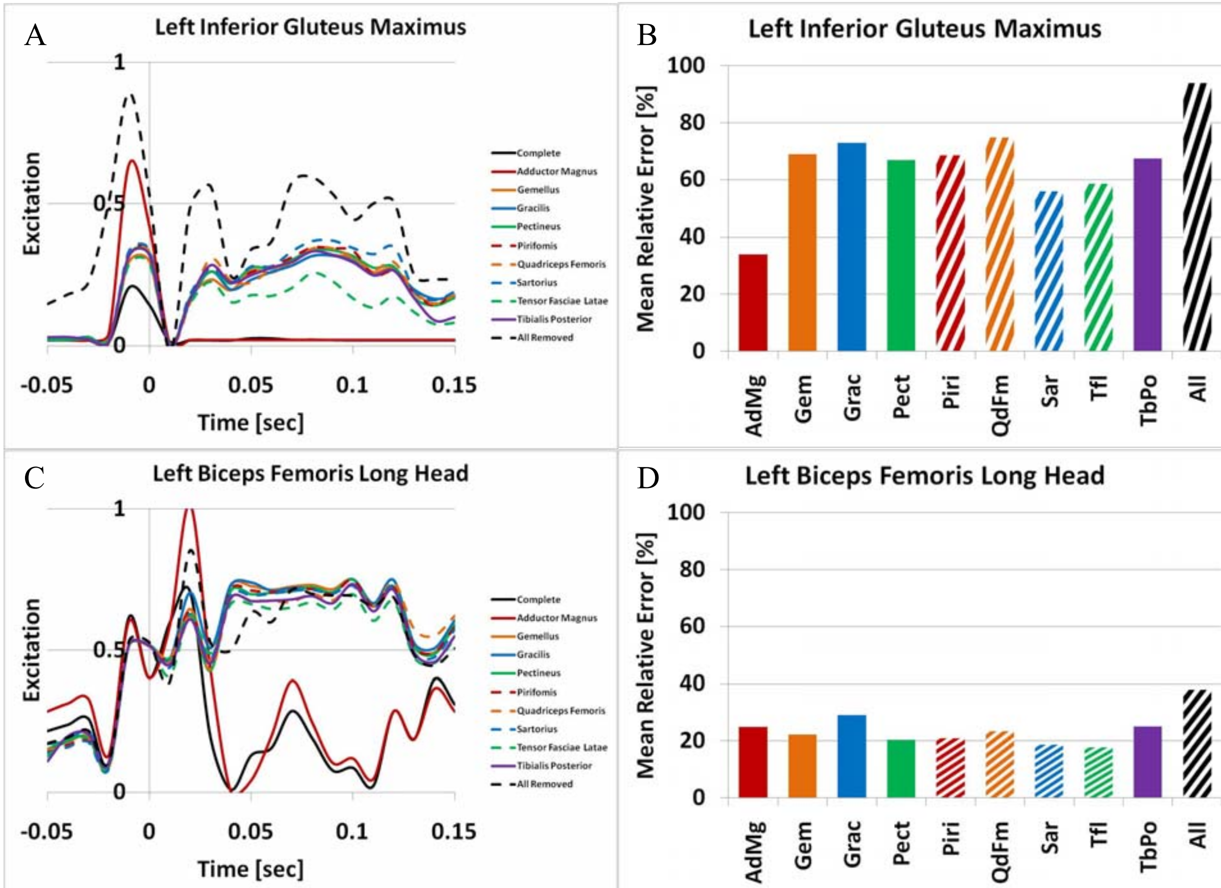


Figure 22: Sensitivity analysis of simulated muscle excitations from 50 ms before left HC (0 ms) to 150 ms after left HC of (A) left inferior gluteus maximus and (C) left biceps femoris. Mean relative errors of each removed muscle simulation compared to complete model for (B) left inferior gluteus maximus and (D) left biceps femoris.

Removing the distal adductor magnus had the least impact on left anterior gluteus medius activity (Figure 23A,B). Removal of the remaining muscles, individually or together, resulted in a similar temporal yet increased excitation pattern of the left anterior gluteus medius (Figure 23A). Excitation of the left psoas was most affected, approximately 70% mean relative error, by removal of all muscles of interest (Figure 23D). Removing the muscles individually, excluding the distal adductor magnus, resulted in a decreased left psoas excitation before HC and increased excitation after HC (Figure 23C). In general, removing the distal adductor magnus caused increased left psoas excitation until 50 ms after HC when its removal had little effect. In addition, removing the distal adductor magnus had minimal impact on excitations of the left rectus femoris (Figure 23E,F). In general, removing any of the muscles of interest, individually or as a group, had little impact on left rectus femoris excitation until 50 ms after left HC. However, after 50 ms their removal resulted in increased left rectus femoris excitation (Figure 23E).

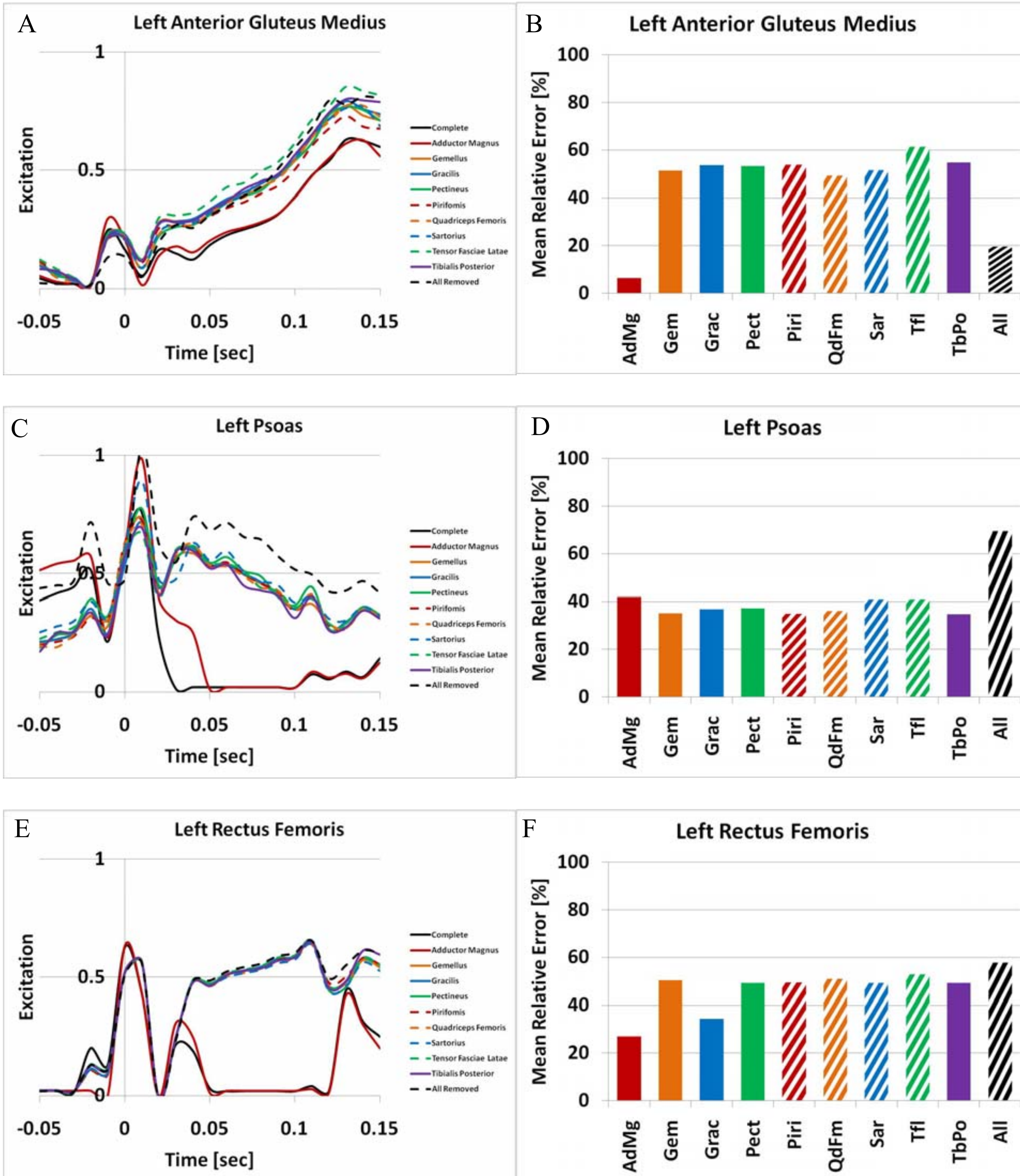


Figure 23: Sensitivity analysis of simulated muscle excitations from 50 ms before left HC (0 ms) to 150 ms after left HC of (A) left anterior gluteus medius, (C) left psoas, and (E) left rectus femoris. Mean relative errors of each removed muscle simulation compared to complete model for (B) left anterior gluteus medius, (D) left psoas, and (F) left rectus femoris.

Lower leg muscle excitations were not sensitive to the muscles of interest being removed, individually or as a group (Figure 24). All mean relative errors for left medial gastrocnemius and left tibialis anterior were less than 2% and 8%, respectively (Figure 24).

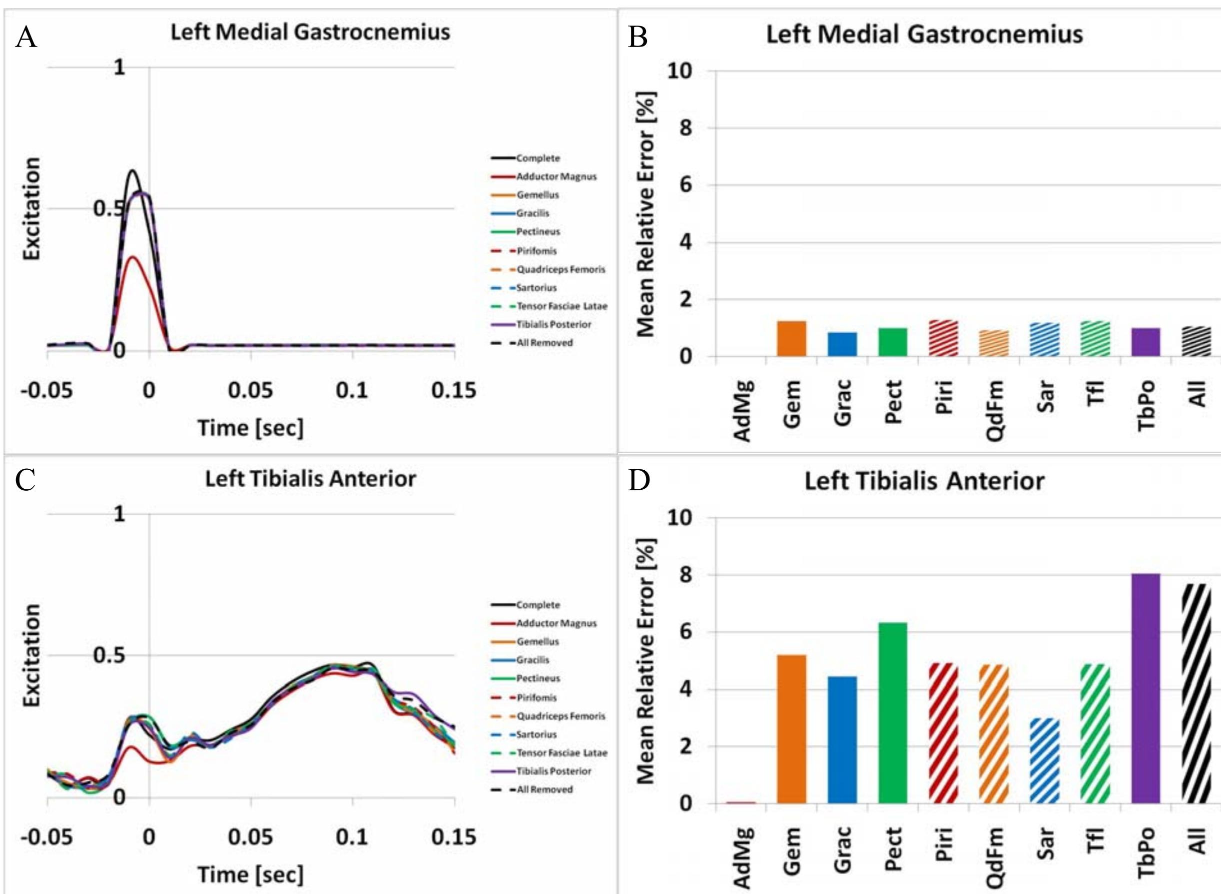


Figure 24: Sensitivity analysis of simulated muscle excitations from 50 ms before left HC (0 ms) to 150 ms after left HC of (A) left medial gastrocnemius and (C) left tibialis anterior. Mean relative errors of each removed muscle simulation compared to complete model for (B) left medial gastrocnemius and (D) left tibialis anterior.

5.3.3 Sensitivity Analysis: Muscle Properties

Another sensitivity analysis was performed to examine the impact of individual muscle model parameters on simulated muscle excitations during gait. Specifically, values of maximum isometric force, optimal fiber length, and tendon slack length were bilaterally perturbed by ± 10% for the inferior gluteus maximus and rectus femoris. The inferior gluteus maximus muscle was sensitive to deviations in its maximum isometric force (Figure 25A,C). Interestingly, the inferior gluteus maximus was also sensitive to deviations in the maximum isometric force of the rectus femoris muscle (Figure 25F). The rectus femoris muscle was not sensitive to deviations of its own maximum isometric force (Figure 25B,D,F). In general, no other muscles (Table 20) were sensitive to perturbations in the maximum isometric force of inferior gluteus maximus or rectus femoris. The model was not sensitive to perturbations in optimal fiber length of inferior gluteus maximus or rectus femoris (Figure 26).

Table 20: Stance Leg Muscle Abbreviations

Abbreviation	Muscles
BF	Biceps Femoris Long Head
GMAX	Gluteus Maximus (Inferior)
GMED	Gluteus Medius (Anterior)
PSO	Psoas
RF	Rectus Femoris
MG	Medial Gastrocnemius
TA	Tibialis Anterior

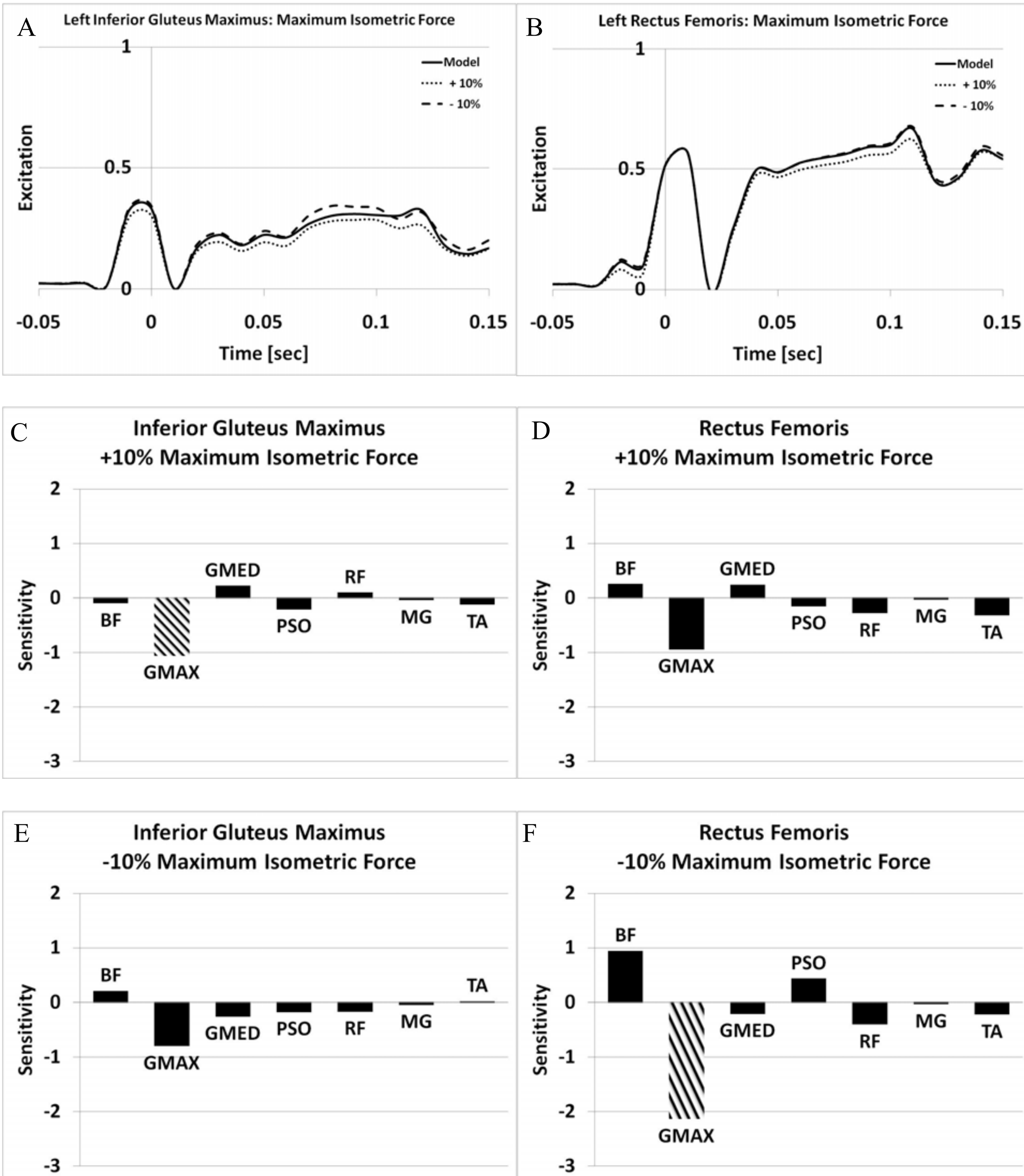


Figure 25: Individual muscle sensitivities to perturbations in maximum isometric force of inferior gluteus maximus (A,C,E) and rectus femoris (B,D,F). Simulated muscle excitations from 50 ms before left HC (0 ms) to 150 ms after left HC of (A) left inferior gluteus maximus and (B) left rectus femoris. Unperturbed model, +10%, and -10% shown as solid, dotted, and dashed lines, respectively. Sensitivity of muscles to perturbations in inferior gluteus maximus of (C) +10% and (E) -10%. Sensitivity of muscles to perturbations in rectus femoris of (D) +10% and (F) -10%. Dashed bars denote that a muscle was considered sensitive to perturbation, $|\varepsilon| > 1$.

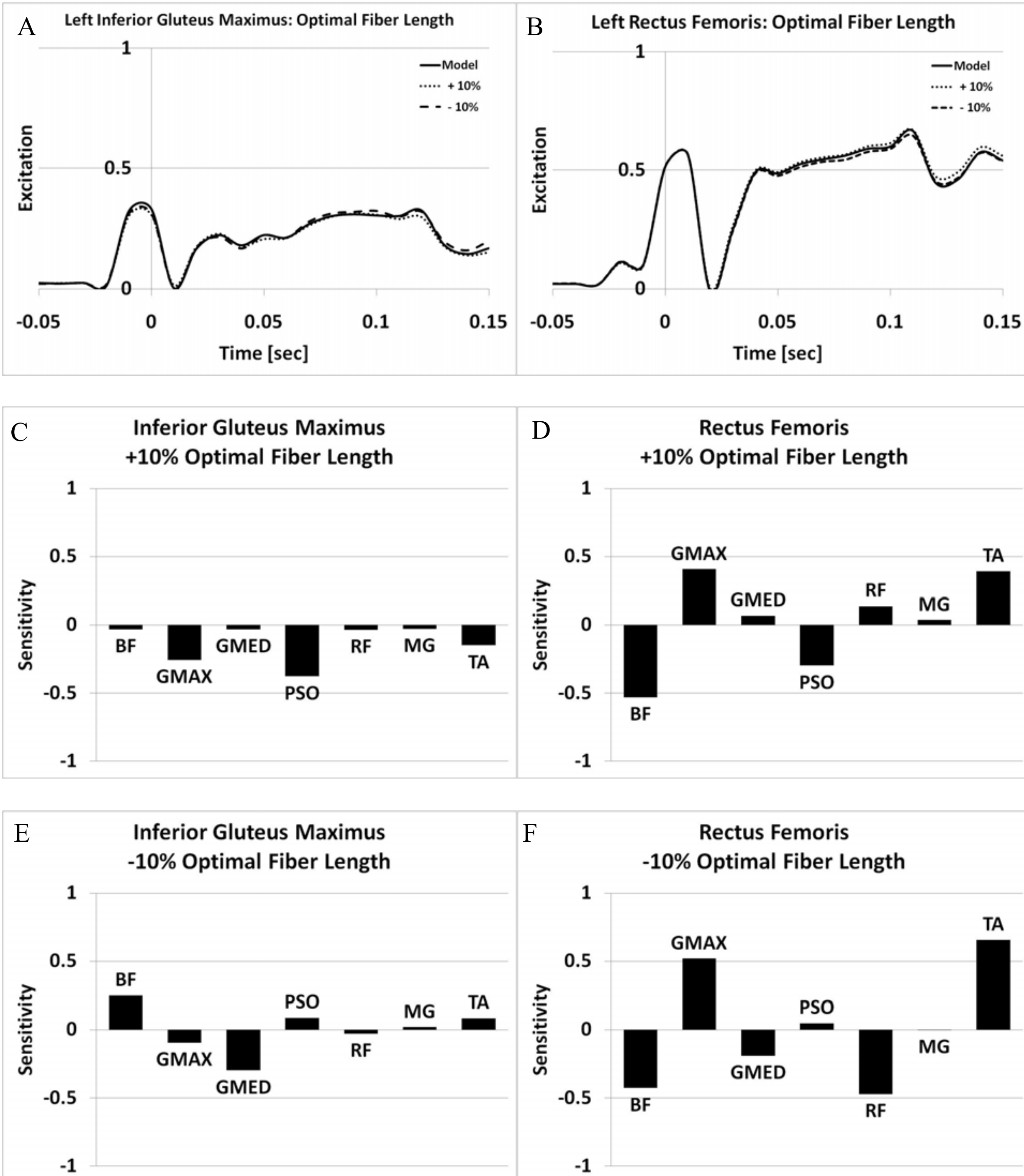


Figure 26: Individual muscle sensitivities to perturbations in optimal fiber length of inferior gluteus maximus (A,C,E) and rectus femoris (B,D,F). Simulated muscle excitations from 50 ms before left HC (0 ms) to 150 ms after left HC of (A) left inferior gluteus maximus and (B) left rectus femoris. Unperturbed model, +10%, and -10% shown as solid, dotted, and dashed lines, respectively. Sensitivity of muscles to perturbations in inferior gluteus maximus of (C) +10% and (E) -10%. Sensitivity of muscles to perturbations in rectus femoris of (D) +10% and (F) -10%. Dashed bars denote that a muscle was considered sensitive to perturbation, $|\varepsilon| > 1$.

The model was sensitive to changes in tendon slack length. Inferior gluteus maximus muscle excitations were sensitive to deviations in the muscle's tendon slack length (Figure 27A,E). Overall, no other muscles were sensitive to perturbations in tendon slack length of the inferior gluteus maximus muscle (Figure 27C,E). Muscle excitations of the rectus femoris were slightly sensitive to deviations in its tendon slack length (Figure 27B,D,F). In addition, stance leg biceps femoris, inferior gluteus maximus, and tibialis anterior were sensitive to rectus femoris tendon slack length deviations (Figure 27D).

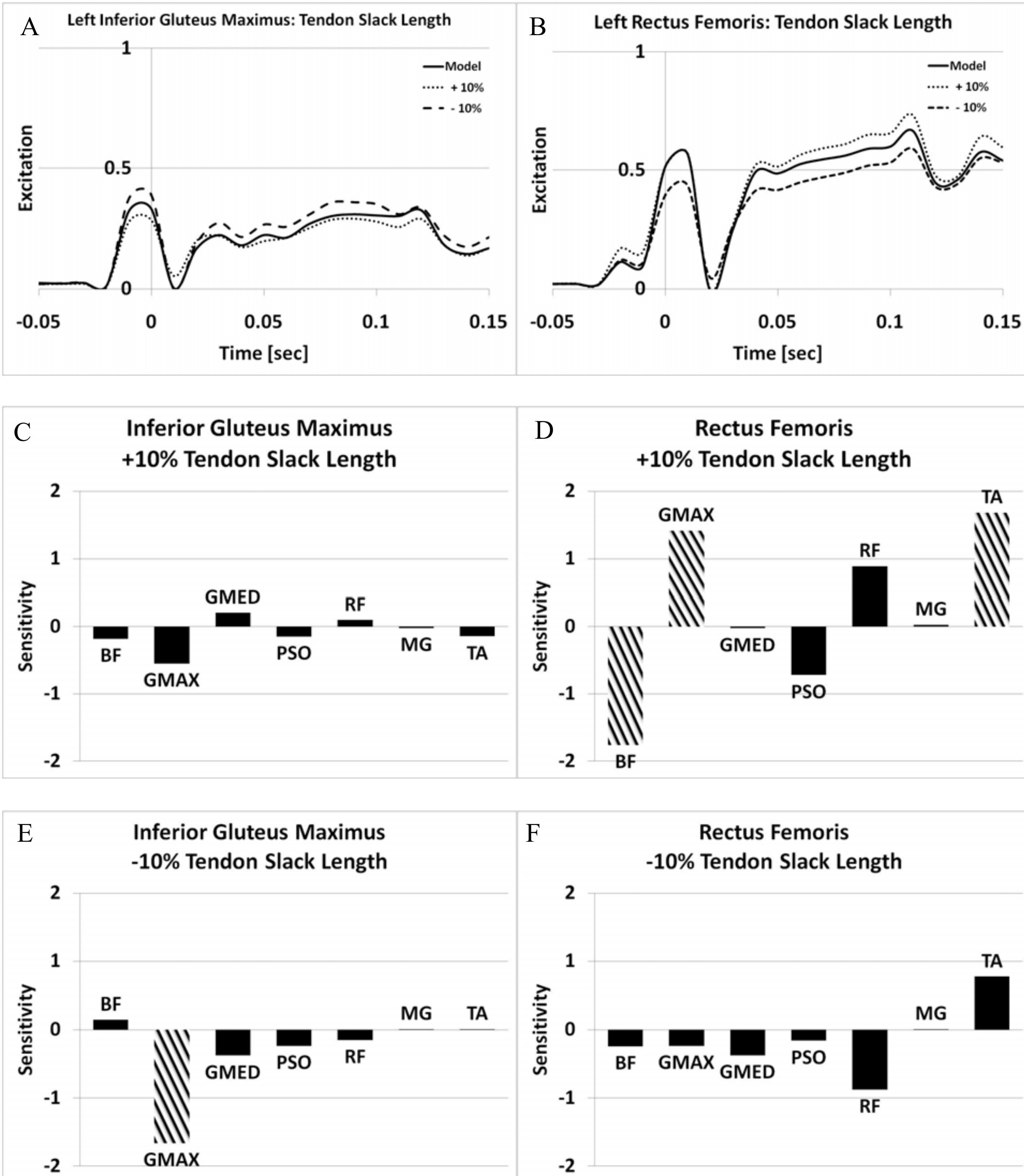


Figure 27: Individual muscle sensitivities to perturbations in tendon slack length of inferior gluteus maximus (A,C,E) and rectus femoris (B,D,F). Simulated muscle excitations from 50 ms before left HC (0 ms) to 150 ms after left HC of (A) left inferior gluteus maximus and (B) left rectus femoris. Unperturbed model, +10%, and -10% shown as solid, dotted, and dashed lines, respectively. Sensitivity of muscles to perturbations in inferior gluteus maximus of (C) +10% and (E) -10%. Sensitivity of muscles to perturbations in rectus femoris of (D) +10% and (F) -10%. Dashed bars denote that a muscle was considered sensitive to perturbation, |ε| >1.

5.3.4 Simulated Proactive Strategies

Two subjects from Experiment 2 were selected due to their differences in proactive strategies utilized during anticipation trials. Subject 1 (Young) was a young adult who walked during AD with a 0.15 m/s increase in gait speed and a 5.58 cm increase in step length compared to BD. The young subject walked during BD with a peak RCOF of 0.24 and 0.21 on the right and left feet, respectively. During AD the young subject decreased his peak RCOF to 0.16 and 0.14 on the right and left feet, respectively. Subject 2 (Older) was an older adult who walked with a 0.10 m/s increase in gait speed and a 1.94 cm increase in step length during AD compared to BD. Additionally, the older subject walked with a right foot peak RCOF of 0.19 and a left foot peak RCOF of 0.18 during BD. When anticipating a slippery floor, the older subject decreased her peak RCOF to 0.14 on both feet.

The simulated muscle excitations of several lower extremity muscles were different between baseline and anticipation conditions. The left inferior gluteus maximus had higher excitations before and after HC in both young and older subjects (Figure 28A,B). A slight increase in the left biceps femoris long head excitation was seen in the young subject before HC. In general, there was no difference in simulated biceps femoris long head excitations between BD and AD for the older subject (Figure 28C,D).

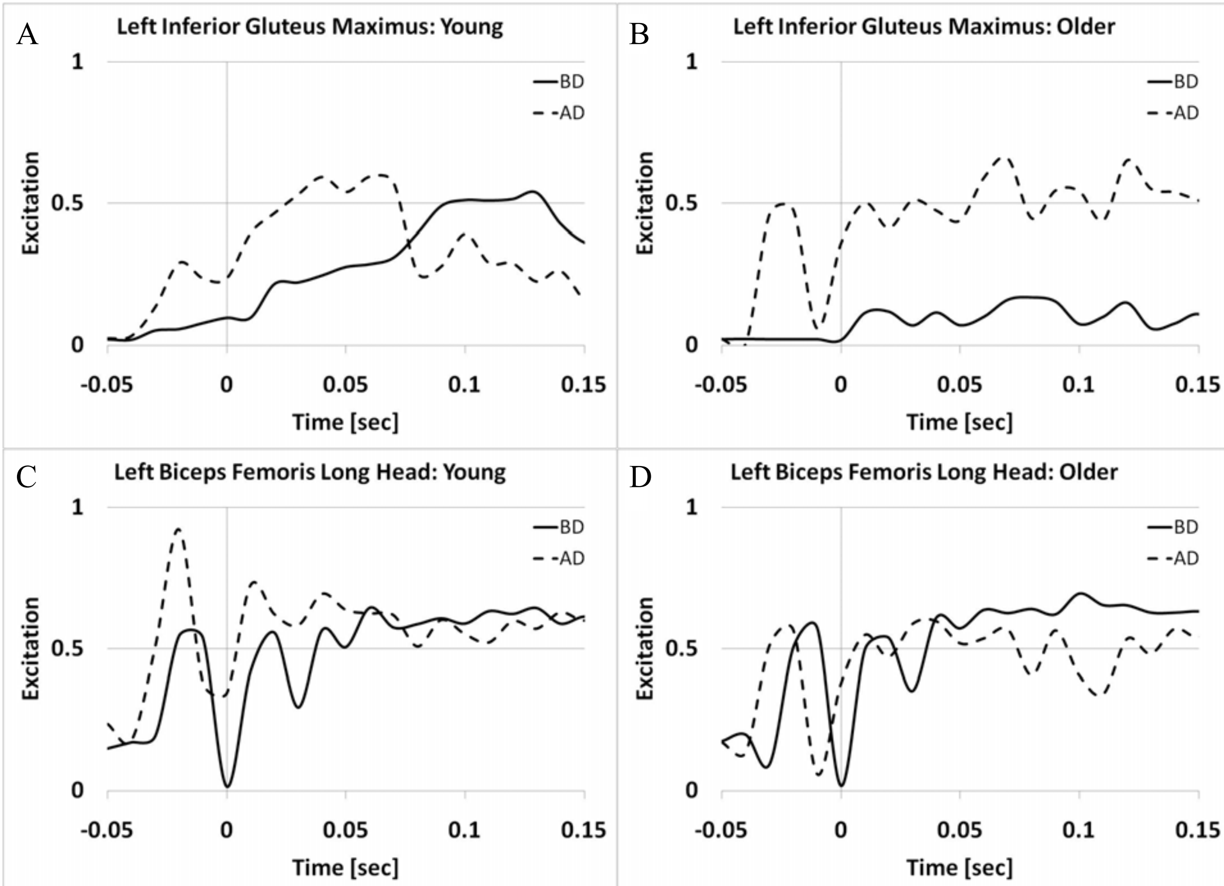


Figure 28: Simulated muscle excitations from 50 ms before left HC (0 ms) to 150 ms after left HC of baseline dry (BD) and anticipation dry (AD) for (A) left inferior gluteus maximus, young, (B) left inferior gluteus maximus, older and (C) left biceps femoris, young, (D) left biceps femoris, older.

Age-related differences were seen in the left anterior gluteus medius and left psoas muscle excitations. The older subject had elevated left anterior gluteus medius excitations when anticipating a slippery floor, while the young subject did not (Figure 29A,B). Additionally, the young subject had decreased left psoas excitations around HC. However, the older subject had slightly higher left psoas excitations (Figure 29C,D). Both the young and older subjects were found to have a minor burst of left rectus femoris activity before HC during AD that was not present in BD (Figure 29E,F). During the remainder of the time period of interest, there were little differences in left rectus femoris across anticipation conditions.

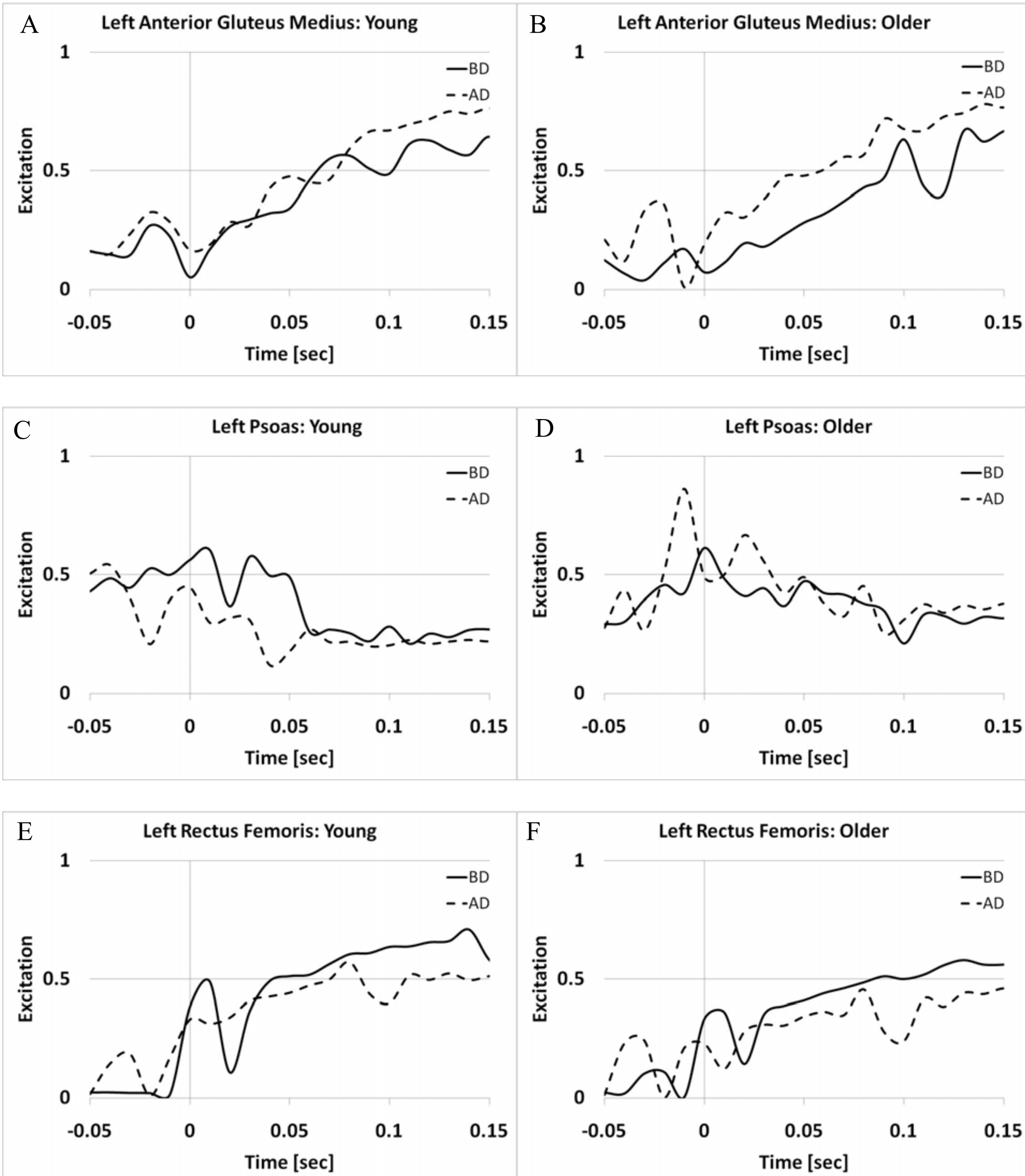


Figure 29: Simulated muscle excitations from 50 ms before left HC (0 ms) to 150 ms after left HC of baseline dry (BD) and anticipation dry (AD) for (A) left anterior gluteus medius, young, (B) left anterior gluteus medius, older, (C) left psoas, young, (D) left psoas femoris, older, and (E) left rectus femoris, young, (F) left rectus femoris, older.

The most noticeable differences in simulated excitations between baseline and anticipation conditions were discovered in the lower leg muscles. The young subject had a major burst in left medial gastrocnemius excitation activity before HC during anticipation that was not present in BD (Figure 30A). The older subject had a minor burst in left medial gastrocnemius before HC during BD. However, this excitation was increased and occurred earlier when anticipating a slippery floor (Figure 30B). Interestingly, both the young and older subjects also had an increased burst in left tibialis anterior excitations before HC during AD (Figure 30C,D). Increased tibialis anterior excitations were also found shortly after HC during AD in both young and older adults. It appears as though the peak of tibialis anterior excitation noted around 100 ms during BD occurs earlier, ~50 ms, when anticipating a slippery floor (Figure 30C,D).

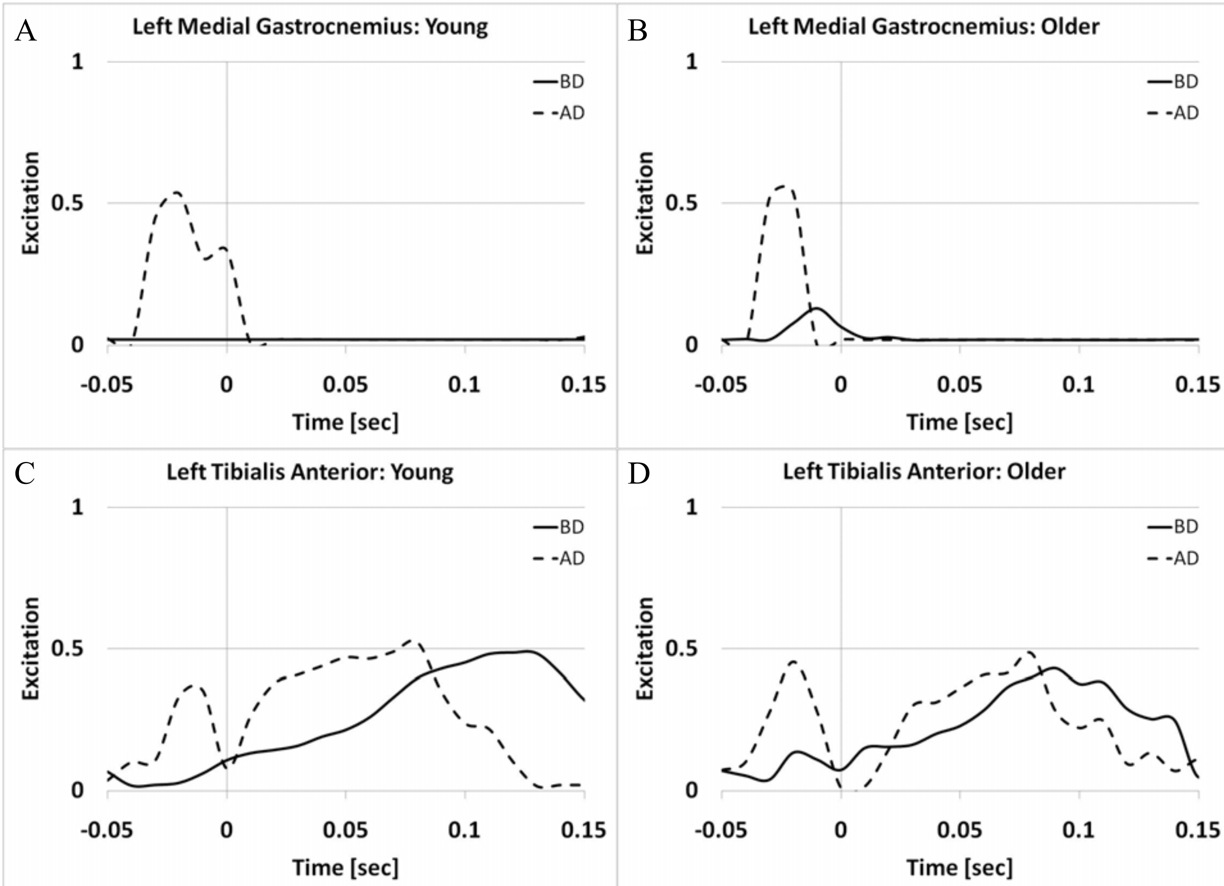


Figure 30: Simulated muscle excitations from 50 ms before left HC (0 ms) to 150 ms after left HC of baseline dry (BD) and anticipation dry (AD) for (A) left medial gastrocnemius, young, (B) left medial gastrocnemius, older and (C) left tibialis anterior, young, (D) left tibialis anterior, older.

6.0 DISCUSSION

6.1 EFFECT OF EXPERIENCE ON PROACTIVE STRATEGIES

The goal of Specific Aim 1 was to examine the impact of unexpectedly slipping on a contaminated floor (‘experience’) on the risk of slipping when subjects are not warned of an additional pending slippery floor. Additionally, age-related differences were examined. It was found that experiencing a slippery surface significantly alters peak RCOF, gait parameters and COM stability in both young and older adults.

Both young and older adults walked with similar frictional requirements for both the left and right feet with a mean baseline peak RCOF value of 0.195 ± 0.031. This finding is comparable with results published in previous literature reporting peak RCOF for normal gait typically ranging from 0.17 to 0.20 (Redfern *et al.* 2001).

One measure of slip risk was defined as the peak RCOF for each baseline dry trial (BD) before an unexpected slip (US1) and after US1, recovery dry trial (RD). It is important to note that following the slip, participants were informed that the next few trials would be dry but no further specific information was revealed. This allowed the effect of experiencing a slip alone, without the impact of additional verbal warning or awareness, to be examined, which has not been done previously. After experiencing a slip, young adults reduced their slip risk only on the left (previously slipped) foot by decreasing peak RCOF. Right foot peak RCOF was not significantly different than baseline during RD in young adults. However, with no additional awareness of a pending slippery surface, young adults adopt baseline gait characteristics. More specifically, nine trials after the unexpected slip exposure, left foot peak RCOF values returned to BD levels in young adults and remained at baseline levels for the remainder of the RD trials. This implies that upon exposure to a second unexpected slip (US2) young adults possessed a slip risk similar to the risk at first exposure (US1).

After experiencing a slip, older adults, unlike young adults, adjusted their slip risk on both the right (non-slipped) and left (previously slipped) feet. Lockhart et al. (2007) found that older adults made gait adjustments, including reduced RCOF, on the step prior to a known slippery surface. It is unknown whether these adjustments were limited to only the step preceding a slippery surface. It is possible that older adults adopt a more conservative strategy throughout the entire trial, as may also be the case in the older adults presented here. Previous research concerned with walking on dry floors concluded that older adults, not young, adopted a safer gait strategy simply because the informed consent document made them aware of slippery conditions on another testing visit (Kim *et al.* 2005). In general, when provided with a combination of experience and awareness of a slippery surface, previous research has found that older adults adopt a more cautious proactive strategy than young adults (Chambers and Cham 2007, Lockhart *et al*. 2007).

While the right foot (not previously slipped foot) displayed a statistically significant peak RCOF reduction of approximately 3% averaged across RD, peak RCOF reduced over 8% on the left (previously slipped) foot in older adults. A reduction in peak RCOF of this magnitude has been reported previously following exposure to slips on ramps (Cham and Redfern 2002). These results suggest that while older adults are adopting a more conservative strategy than young adults, they may still be prioritizing the foot that was previously slipped. However, with no additional awareness of a pending slippery surface, older adults do not appear to return to baseline like their younger counterparts did. In almost all fifteen RD trials after experiencing an unexpected slip, older adults walked with a peak RCOF that was significantly lower than in the BD condition. This implies that upon exposure to a second unexpected slip (US2) older adults were at a lower slip risk than at first exposure (US1), even after being exposed to a significant number of non-slippery conditions.

Significant changes in the temporal aspects of gait were found after experiencing a slip even though there was no awareness of a pending slippery surface. Experiencing a slippery floor resulted in shorter mean stance durations in both young and older adults. Decreased stance duration has been associated with reduced peak RCOF (Cham and Redfern 2002). Decreased stance duration was likely due to changes in gait speed. Both young and older adults increased their gait speed during RD. However, the increase in gait speed was significantly greater in young adults. Young adults showed a 6% increase in gait speed after experiencing a slip while older adults only increased gait speed by 2% compared to baseline. Slower gait speeds have been linked to increased fall risk and a faster gait may allow for a successful recovery from a slip (Hausdorff *et al.* 2001, You *et al*. 2001, Bhatt *et al*. 2005). After experiencing a slip, cadence was also increased in both young and older adults. Previous research has associated decreased slip severity with increased cadence (Moyer *et al*. 2006). Based on previous research, the temporal gait adaptations noted in both young and older adults after experiencing a slip implies that they utilized proactive strategies to reduced slip risk even though there was no threat of a pending slippery surface.

Interestingly, it was found that only young adults increased step length after experiencing a slip. Increased step length may not positively contribute to an effective proactive strategy aimed at reducing slip risk since increased step length has been associated with an increased peak RCOF (Myung *et al*. 1992, Cham and Redfern 2002, Lockhart *et al*. 2003, Kim *et al*. 2005, Lockhart *et al.* 2007). Hazardous slips have also been associated with increased step length (Moyer *et al*. 2006). Aside from a few early RD trials, Analysis B revealed that young adults walked with a longer step length compared to baseline during the majority of later RD trials, starting around RD Trial 9. It is possible that the increased step length seen in later RD trials contributed to the peak RCOF values returning to BD levels in young adults discussed earlier. Previous research has found that increased step length was a significant factor contributing to increases in peak RCOF among young adults (Kim *et al*. 2005). Experiencing an unexpected slip did not cause any significant change in step length among older adults. The lack of a longer step length after slip experience, in combination with previously discussed adaptations, places older adults at a reduced slip risk compared to young.

Aim 1 also noted that experiencing an unexpected slip resulted in several significant changes in balance measures previously related to COM stability. ML margin of stability, distance between the COM and the border of the BOS in the ML direction at left HC, decreased during RD in young adults but not in older adults. Previous research noted that subjects walking on a known dry floor had a decreased ML margin of stability compared to subjects that were unsure of the flooring surface. Additionally, subjects increased ML margin of stability on a known slippery surface (Marigold and Patla 2002). This implies that a decreased ML margin of stability was not the choice of subjects who might have been or were walking on a slippery surface. After experiencing an unexpected slip, young adults decreased ML margin. It is possible that the decrease in ML margin of stability found in young adults is related to an increase in gait speed as it would be challenging to walk faster with wider steps. Additionally, the decreased ML margin of stability seen in young adults might be related to their return to baseline levels of peak RCOF. The return to baseline slip risk implies that young adults may have believed that there was no threat of a slippery surface. As mentioned previously, subjects walking on a known dry floor had a decreased ML margin of stability (Marigold and Patla 2002). The fact that older adults did not decrease their ML margin of stability suggests that they were more conservative after experiencing a slip compared to young.

Experiencing a slippery floor also resulted in AP margin of stability, distance between the COM and the BOS in the AP direction at left HC, significantly decreasing in both young and older adults, reflecting an anterior shift in the COM at left HC. In general, AP margin of stability was decreased compared to baseline during more RD trials in older adults than in young. Previous research has found that AP margin of stability is associated with step length (Bhatt *et* *al*. 2005, Oates *et al*. 2010). Age-related differences in step length likely contribute to young adults having less RD trials with decreased AP margin of stability than older adults. Previous research has found that a decreased AP margin of stability increases COM stability and is a component of a successful proactive strategy (Pai and Patton 1997, You *et al*. 2001, Bhatt *et al*. 2005, Oates *et al*. 2010).

COM vertical, vertical position of the COM at left HC, significantly decreased after experiencing an unexpected slip in both young and older adults. Additionally, it was noted that COM vertical decreased significantly more in older adults than in young. Previous research found that subjects chose to lower COM vertical for an unexpected slip which served to increase stability as the COM was closer to BOS (Marigold and Patla 2002). However, researchers have also shown that lowered hip height, an estimate of COM, greatly hinders a successful recovery attempt (Pai *et al*. 2006, Pai and Bhatt 2007). Differences seen in COM vertical at left HC might also be contributed to a temporal phase shift in the sinusoidal pattern of superior-inferior COM position. Further examination of the effect of COM vertical on COM stability is needed. Both young and older adults significantly decreased COM BOS angle, angle formed by the COM, BOS and the vertical projection of the COM onto the ground, after experiencing an unexpected slip. Previous research has associated smaller COM BOS angles with reduced peak RCOF (Burnfield and Powers 2007). The decreased COM BOS angle noted after experiencing a slip may contribute to a lower slip risk due to reduced peak RCOF.

In summary, while young and older adults demonstrated similar proactive strategies after experiencing a slip, several key components differed. With no awareness of a pending slippery surface, young adults eventually adopt baseline gait characteristics that are key factors in determining slip risk. Specifically, increased step length and decreased ML margin of stability were noted in young adults. Most importantly, peak RCOF values returned to BD levels in young adults. This implies that upon second exposure to an unexpected slip (US2) young adults possessed a slip risk similar to the risk at first exposure (US1). With a similar slip risk preceding both unexpected slips (US1/US2) one would presume that the magnitude of slips experienced would be alike.

PSV was determined during slip trials to assess the slip severity (Moyer *et al*. 2006). As expected, with a similar slip risk preceding both unexpected slips (US1/US2), the slip severity was not significantly different between US1 and US2 in young adults. This suggests that after young adults returned to baseline levels of peak RCOF, it is possible to generate a second unexpected slip in a laboratory environment. Studying unexpected slips in a laboratory environment has always been challenging. The ability to generate only one unexpected slip often limits researchers (Cham and Redfern 2001, Marigold and Patla 2002, Chambers and Cham 2007, Oates *et al*. 2010). A slip event being novel or unexpected is an important distinction. Previous literature has found that unexpected slips consistently produce biomechanical responses that are significantly different than all subsequent slips (Cham and Redfern 2001, Marigold and Patla 2002, Bhatt *et al*. 2006). Unexpected slips are a more challenging event to study since awareness or repeated exposure generally increases stability and decreases subsequent slip severity (Marigold and Patla 2002, Bhatt *et al*. 2006, Heiden *et al*. 2006). The possibility of generating more than one unexpected slip would allow researchers to further investigate this unique event in order to prevent falls.

Contrary to their younger counterparts, older adults do not appear to return to baseline gait characteristics even with no awareness of a pending slippery surface. In addition to other adaptations, older adults did not increase step length and continued to walk with a decreased peak RCOF during all the RD trials following slip experience. This implies that upon second exposure to an unexpected slip (US2) older adults were at a lower slip risk than at first exposure (US1). With a reduced slip risk preceding US2 one would presume that older adults should experience a less severe second slip.

Accordingly, the slip severity significantly decreased between the first and second unexpected slips in older adults. It appears that US2 might not qualify as 'unexpected' in older adults since they experienced a 40% reduction in slip severity compared to US1. This is likely due to older adults maintaining a reduced slip risk compared to baseline even when there was no warning or awareness of a potentially slippery surface. The reasons behind older adults choosing to maintain a lower slip risk after experiencing a slip but with no pending threat of an additional slip is likely due to a combination of factors. Cautious gait adjustments in older adults have been associated with numerous physiological and psychological factors including reduced physical or neuromuscular capabilities (McGibbon and Krebs 2001, Menz *et al*. 2003, Lockhart and Kim 2006) and concern over falling (Maki 1997, Chamberlin *et al*. 2005, Delbaere *et al*. 2009).

6.2 EFFECT OF EXPERIENCE AND AWARENESS ON PROACTIVE STRATEGIES

The goal of Specific Aim 2 was to examined the effect of warning subjects that a slippery floor is possible ('awareness') on proactive strategies generated after unexpectedly slipping on a contaminated floor ('experience') on the risk of slipping and slip severity. The combined effect of experience and awareness was termed anticipation. Additionally, age-related effects were investigated. It was found that both young and older adults significantly altered their peak RCOF, gait parameters and COM stability while anticipating a potentially slippery floor. Gait speed control strategies were also revealed, i.e. whether humans control cadence or step length to modulate gait speed when anticipating a slippery environment.

Anticipating a slippery floor resulted in a significant decrease in peak RCOF in both young and older adults. This decrease was noted on both the right and left (previously slipped) feet. As previously mentioned, a lower RCOF has been linked to a reduced slip potential during gait (Redfern and DiPasquale 1997, Cham and Redfern 2002, Lockhart *et al*. 2007). Reduced ground reaction forces and peak RCOF have been reported previously after first exposure to a slippery surface with awareness or repeated exposure (Cham and Redfern 2002, Marigold and Patla 2002, Heiden *et al*. 2006, Lockhart *et al*. 2007, Fong *et al*. 2008). The majority of these researchers have focused on reporting peak RCOF of the previously slipped foot (left foot in this project). A reduction in the previously slipped foot peak RCOF of similar magnitude has been reported previously following exposure to multiple slips with awareness of a potential slippery surface on ramps (Cham and Redfern 2002). A combination of slip experience on varying surfaces and awareness resulted in decreased peak RCOF of the previously perturbed limb. After experiencing a slip combined with the knowledge that a flooring surface is slippery also results in both young and older adults reducing their previously slipped foot peak RCOF (Lockhart *et al*. 2007).

As mentioned previously, it was found that both young and older adults decreased their peak RCOF on the right foot (non-slipped). Only one other study (Lockhart *et al*. 2007) examined the peak RCOF of the foot preceding the slippery surface (right foot in this project). It was noted that only older adults reduced their peak RCOF on the step before a known slippery surface combined with previous slip experience (Lockhart *et al*. 2007). Aim 1 revealed age-related differences in peak RCOF following slip experience. After experiencing a slip and with no risk of a pending slippery surface, only older adults significantly decreased right foot peak RCOF. While the addition of awareness (Aim 2) resulted in both young and older adults reducing right foot peak RCOF. It is likely that adults in Aim 2 decreased right foot peak RCOF because they were made aware of the potential of experiencing another slip but its exact location/occurrence was unknown.

In young adults, the right (non-slipped) foot peak RCOF appears to be affected by the amount of slippery surface knowledge provided (aware vs. unaware). Similar conclusions can be drawn about the left (previously slipped) foot peak RCOF. Aim 1 found that with no threat of a pending slippery surface, young adults return to baseline levels of slip risk on their left foot. Based on these results and previous research, it appears that the specificity of knowledge provided to young adults impacts right (non-slipped) and left (previously slipped) foot peak RCOF utilized during proactive strategies. Meanwhile, older adults maintain more conservative right and left foot peak RCOF values thus lowering their slip risk regardless of the amount of awareness provided.

Previous literature has found that certain changes in gait spatial and temporal variables have important effects, such as decreased shear forces and thus decreased RCOF, leading to a reduction in slip risk (Cham and Redfern 2002, Lockhart *et al*. 2007). Specifically, decreased step length and stance duration are linked to a reduction in peak RCOF during walking (Myung *et al*. 1992, Cham and Redfern 2002, Lockhart *et al*. 2003, Lockhart *et al*. 2007). Moyer et al. (2006) found that non-hazardous slips were associated with shorter step lengths and increases in cadence. Researchers have also reported that decreased gait speed is associated with increased fall risk and a faster gait may allow for increased chances of a successful balance recovery from a slip (Hausdorff *et al*. 2001, You *et al*. 2001, Bhatt *et al*. 2005). Based on this evidence, it would appear that the gait parameters associated with a successful proactive strategy, utilized to reduce slip potential, should consist of increased gait speed and cadence, as well as decreased step length and stance duration.

Specific Aim 2 also examined the impact of anticipating slippery floors on spatiotemporal gait characteristics and revealed gait speed control strategies, i.e. do humans control cadence or step length to modulate gait speed when anticipating a slippery environment. It was found that both young and older adults significantly altered the spatiotemporal characteristics of gait while anticipating a potentially slippery floor. Anticipation increased gait speed and cadence while decreasing stance duration, all of which may be important factors in reducing slip risk. Decreasing stance duration while walking on potentially dangerous slippery surfaces has been linked to a reduced slip potential (Cham and Redfern 2002). Decreases in the temporal aspects of gait found in the present study where highly correlated with increases in cadence in both young and older adults.

While anticipating a slippery surface, both young and older adults increased gait speed and cadence. At first glance and based on previous findings, an increased gait speed should be a valuable component of a successful proactive strategy. However, it should be of interest how this increase in gait speed was achieved. Previous research has found that gait speed is a product of cadence and step length (James 1983, Soames 1985). The addition of cadence contributed more to explaining gait speed variability during anticipation in older adults than in young. Step length, which was significantly less in older adults compared to young adults, was not significantly increased during anticipation trials in older adults. Also, additional step length contributions to explaining gait speed in older adults decreased 4% when anticipating slippery floors. This implies that that older adults increased their gait speed primarily through an increase in cadence when anticipating slippery floors. In contrast, young adults increased their gait speed and step length significantly more than older adults during anticipation trials. Also, additional step length contributions to explaining gait speed in young adults increased 20% when anticipating slippery floors. Even though increased cadence during anticipation was noted, based on these results, the increased gait speed in young adults was likely due to increases in step length.

While slower gait speeds have been related to increased fall risk (Hausdorff *et al*. 2001, Cromwell and Newton 2004) and increased slip probability (Bhatt *et al*. 2005), it is important how faster gait speeds are achieved. The distinction between how young and older adults increased gait speed becomes important when modifications in step length are considered. Step length significantly increased 4.2% in young adults during anticipation trials and contributed significantly more to explaining changes in gait speed than did cadence. Previous research has noted similar associations between step length, gait speed and RCOF during walking in young adults. It was found that increased step length and increased gait speed were a significant factors contributing to increases in RCOF among young adults (Kim *et al*. 2005).

However, increased step length as a component of a proactive strategy to reduce slip risk might be maladaptive. Increased step length has been linked to increased RCOF and thus increased slip risk (Myung and Smith 1997, Cham and Redfern 2002, Lockhart *et al*. 2003, Moyer *et al*. 2006, Lockhart *et al*. 2007). Recently, Espy et al. (2010) discovered that decreases in step length have comparable if not stronger influences on reducing slip risk than increases in gait speed. Moyer et al. (2006) found that while gait speed alone was not a good predictor of slip severity, decreasing step length and increasing cadence resulted in decreasing the probability of a hazardous slip. At self-selected walking speeds, previous research found differences in how step length and gait speed impact stability during slipping. Faster gait speeds increased slip onset stability, thus reducing initial slip risk. However, shorter step lengths increased stability during the recovery phase of a slip, thus reducing the magnitude of a reactive strategy necessary to prevent a fall (Bhatt *et al*. 2005, Espy *et al*. 2010). This implies that in a high slip risk group such as older adults, beneficial proactive strategies to reduce slip risk should include shorter step length and increased gait speed achieved through increasing cadence. Theoretically, this combination of gait adaptations may result in overall increased stability throughout a future slip event.

Older adults in the current study were able to implement a more conservative proactive strategy consisting of increased gait speed by increasing cadence without significantly increasing step length. While studying the relationship between step length, gait speed and peak RCOF, Kim et al. (2005) concluded that age-related differences noted in step length and gait speed were due to older adults adopting a safer gait strategy while young adults did not. It is worth noting that while the gait speed increases seen in older adults (0.03 m/s) were statistically significant, they may not be clinically significant concerning fall risk. Previous research has associated a 0.1 m/s increase in gait speed with clinically significant health improvements (Hardy *et al*. 2007). It is also important to note that older adults were walking at gait speeds of 1.33 m/s and 1.35 m/s during BD and AD, respectively. In general, adults who walk faster than 1.0 m/s are not typically in high risk populations (Cesari *et al*. 2005, Hardy *et al*. 2007). Significant increases in gait speed as a component of a proactive strategy to decrease slip risk may not be recommended in older adults who are in a high-risk population due to their decreased physical and neuromuscular capabilities (McGibbon and Krebs 2001, Menz *et al*. 2003, Tirosh and Sparrow 2005, Lockhart and Kim 2006).

Young adults may not have reduced step length because proactive strategies are not the only type of effective response used to reduce slip-initiated fall risk. Based on previous research, young adults in this study should have increased stability during slip onset due to faster gait speeds reported when anticipating slippery floors. However, they may also have decreased stability during the recovery phase of a slip due to longer step lengths noted during AD. This would imply that young adults would need to employ a more robust reactive strategy in order to prevent a fall during a future slip event. Indeed, young adults are capable of generating faster, more powerful reactions to slip events than older adults (Chambers and Cham 2007). However, increasing gait speed through increased step length may still result in higher slip risk compared to increasing gait speed through other methods such as increased cadence (Moyer *et al*. 2006, Espy *et al*. 2010).

The combined effect of experience and awareness of a slippery surface on temporal/spatial gait characteristics were similar to those noted with only experience of a slippery surface. It should be noted that the addition of awareness resulted in amplified differences compared to experience alone. It appears that the addition of awareness resulted in larger proactive gait adaptations. For example, cadence increased 2.21 steps/min, average for young and older adults, after experiencing a slip without awareness (Aim 1) but increased 5.04 steps/min after experiencing a slip with awareness (Aim 2). Age-related differences were seen in step length regardless of awareness where young adults increased step length and older adults did not. Based on this, it is possible that similar age-related gait speed control strategies are being employed by the participants in Aim 1.

COM stability was also examined across anticipation conditions and age groups. Anticipation of a slippery surface during gait resulted in a significant change in COM stability. In general, older adults had a smaller AP margin of stability than young adults. This is likely due to age-related differences in step length, which was significantly less in older adults compared to young. Previous research has found that decreased AP margin of stability is associated with shorter step lengths (Bhatt *et al*. 2005, Oates *et al*. 2010). Anticipation resulted in AP margin of stability significantly decreasing, reflecting an anterior shift in the COM at left HC. Previous research has found that an anterior shift in the COM reflects an increase in COM stability (Pai and Patton 1997, You *et al*. 2001, Bhatt *et al*. 2005). During a slip event, a smaller AP margin of stability can allow the COM to catch up with the slipping foot, thus avoiding a fall (Pai and Patton 1997, You *et al*. 2001). A decreased AP margin of stability has also been seen as a component of successful proactive strategies used during gait termination on a slippery surface (Oates *et al*. 2010). Therefore, young and older adults should have increased COM stability when anticipating a slippery floor due to their decreased AP margin of stability.

In both young and older adults, COM vertical tended to increase while anticipating a slippery surface. Previous research on COM vertical and slipping is conflicting. Marigold and Patla (2002) claim that the CNS chose to lower COM vertical for an unexpected slip which served to increase stability as the COM was closer to BOS. However, other researchers have shown that lowered hip height, an estimate of COM, greatly hinders a successful recovery attempt (Pai *et al*. 2006, Pai and Bhatt 2007). In theory, a higher COM vertical allows for more time before contacting the floor, i.e. a fall, because you are further away from the BOS which is located on the floor. Additionally, a higher COM is likely to result from other postural changes that minimize slip risk including shortened step length and decreased AP margin of stability. Upon closer examination of the results of Marigold and Patla (2002), participants are not always lowering COM vertical as was concluded. Repeated exposure to slip resulted in increased COM vertical after the first exposure. In addition, knowledge of the flooring surface impacted COM vertical. On known dry floors, subjects lowered COM vertical compared to subjects that were unsure of the flooring surface. On a known slippery surface, rollers, subjects increased COM vertical (Marigold and Patla 2002). Interestingly, subjects that were uncertain whether or not a slip would occur walked with an elevated COM vertical even on dry floors, a strategy similar to subjects that knew a slip would occur. Based on this, it appears that knowledge of or the potential for a slippery surface led to elevated COM vertical. This is in agreement with the results of Aim 2 that reported a tendency of both young and older adults to elevate their COM vertical during anticipation trials.

COM BOS angle significantly decreased during anticipation in both young and older adults. COM BOS angle mathematically encompasses all previously reported COM stability parameters of interest and are likely highly correlated to previously discussed parameters. Previous research has established a positive relationship between COM BOS angle and peak RCOF, i.e. larger COM BOS angles are associated with increased peak RCOF (Burnfield and Powers 2007). Therefore, a decreased COM BOS angle with anticipation may contribute to decreased peak RCOF and reduced slip risk. Previous research also proposed that increasing gait speed by increased step length would likely lead to a larger COM BOS angle and may contribute to a higher peak RCOF, while increasing gait speed through increased cadence should not result in a higher peak RCOF (Burnfield and Powers 2007). This theory agrees with the conservative proactive strategy chosen by older adults which consisted of increased gait speed by increasing cadence. Older adults also reported a decreased COM BOS angle and lower peak RCOF. However, young adults increased gait speed by increasing step length during anticipation. Based on previous research, these postural adjustments may lead to a larger COM BOS angle and higher peak RCOF. This was not the case though as COM BOS angle and peak RCOF both decreased with anticipation in young adults. It is possible that other postural adjustments not investigated, such as foot-floor angle, joint moments, and muscle forces, may help to explain the ability of young adults to walk with longer steps while maintaining a decreased COM BOS angle and peak RCOF.

The combined effect of experience and awareness of a slippery surface (Aim 2) had a different impact on COM stability than experience alone (Aim 1). Experiencing a slippery surface resulted in decreased ML margin of stability in young adults but not in older adults. As mentioned previously, this adaptation may contribute to an increased slip risk. The addition of awareness resulted in young adults not decreasing ML margin of stability. The addition of awareness resulted in larger proactive adaptations that further increase COM stability. After experiencing a slip without awareness, AP margin of stability and COM BOS angle decreased 0.77 cm and 0.31°, respectively. Subjects who experienced a slip with awareness decreased AP margin of stability and COM BOS angle 2.46 cm and 1.29°, respectively. COM vertical significantly decreased after experiencing a slip but tended to increase after experiencing a slip with awareness. Previous research claimed that lower COM vertical increases stability (Marigold and Patla 2002) but also greatly hinders a successful recovery attempt (Pai *et al*. 2006, Pai and Bhatt 2007). Postural adjustments not investigated, such as foot-floor angle, joint moments, and muscle forces, may help to explain the effect of COM vertical on COM stability.

Temporal/spatial gait adjustments, decreased peak RCOF, and an overall increase in COM stability were noted as components of proactive strategies utilized in young and older adults when anticipating a slippery floor. These adjustments caused by experience and awareness of a slippery floor have been shown to reduce slip risk. This implies that upon second exposure to a slip with awareness (AS) both young and older adults were at a lower slip risk than at first unexpected exposure (US). With a reduced slip risk before AS one would presume that both young and older adults should experience a less severe second slip. Accordingly, the slip severity significantly decreased between US and AS in both young and older adults. Young experienced over a 35% reduction in slip severity between US and AS. Older adults experienced a 48% less severe anticipation slip than unexpected slip.

Older adults experienced a less severe slip upon second exposure with experience alone (Aim 1) and with experience and awareness (Aim 2). This is likely due to their selection of a more conservative proactive strategy regardless of awareness. As previously mentioned, young adults without awareness experienced a second slip of similar magnitude to their first. However, a decrease in slip severity was seen in young adults between US and AS. Aim 2 noted that the addition of awareness after experiencing a slip resulted in young adults adopting a more conservative proactive strategy compared to young adults without awareness (Aim 1). The addition of awareness (Aim 2) resulted in young adults utilizing a proactive strategy with decreased peak RCOF, amplified gait adaptations and increased COM stability compared to young adults without awareness (Aim 1). Consequently, the additional awareness also resulted in young adults reducing their slip severity upon second exposure to a slippery surface with awareness.

6.3 MODELING

The goal of Specific Aim 3 was to perform a sensitivity analysis to examine how simulated muscle excitations change due to the number of muscles included in a simulation of gait. Additionally, the sensitivity of simulated muscle excitations to perturbations in muscle model parameters was evaluated. Finally, preliminary modeling simulations were used to provide insight into proactive strategies. As a method of validating the OpenSim three-dimensional gait model, simulated muscle excitations for Subject 2 BD were compared to previously reported EMG data (Chambers 2005) and previous literature (Winter 2004). A period from left HC to left TO was examined. While amplitudes could not be examined due to differing normalization methods, temporal patterns of activity were compared. In general, simulated muscle excitations of the lower extremities followed similar activation patterns as the available EMG (Chambers 2005) and previous literature (Winter 2004).

A sensitivity analysis was performed to reveal the impact of removing certain muscles, previously not found as significant contributors to gait, from a three-dimensional simulation of gait. Previous studies found that the hip and knee extensors, as well as the ankle dorsiflexors, of the stance leg are the main contributors to vertical support and forward progression in early stance (Kepple *et al.* 1997, Anderson and Pandy 2003, Neptune *et al.* 2004, Liu *et al.* 2006, Pandy and Andriacchi 2010). Therefore, these muscles were not removed during the sensitivity analysis and their excitations were examined to determine the impact of removing other muscles from the simulation.

Overall, removing the distal adductor magnus had little to no impact on muscle excitations. Gluteus medius maintained a similar muscle excitation pattern with the removal of the selected muscles and only the magnitude of excitation was increased. Previous literature that examined the number of muscles in a model found that most of the muscles achieved the same patterns with differences in magnitude (Xiao and Higginson 2010). This is similar to what was noted in anterior gluteus medius. Previous research has also shown that some of the muscles chosen for removal (gemellus, piriformis, quadriceps femoris, and tensor fascia latae) make small contributions to the overall joint moments. It was concluded that these muscles are not likely to alter simulation results of joint function (Arnold *et al*. 2010). Similarly, removing these muscles from a simulation of gait resulted in slightly elevated anterior gluteus medius excitations, but no temporal differences were found.

Contrary to previous research, the remaining hip muscles examined, excluding the anterior gluteus medius, were sensitive to the number of muscles included in the simulation. Inferior gluteus maximus excitations were most sensitive to removing muscles, except distal adductor magnus. Hip muscle excitations were noted to have similar temporal patterns with varying magnitude during bursts of activity around HC. However, an increased excitation was found beginning around 50 ms after HC in the stance leg inferior gluteus maximus, biceps femoris, psoas and rectus femoris. The complete muscle model simulation generated little to no excitations of these muscles during this time period. The selection of muscles removed during the sensitivity analysis likely impacted the differences found in the remaining hip muscle excitations. The majority of muscles removed are involved in controlling the hip. Once removed, the model likely increases the excitations of the remaining hip muscles in order to maintain a successful gait simulation. Previous research has found similar results such that the change of one muscle force was compensated by muscles in the same functional group or antagonistic muscle group (Xiao and Higginson 2010).

The muscles of the lower leg were not sensitive to the muscles of interest being removed individually or as a group. Again, this might be contributed to the selection of muscles removed. Only one removed muscle, tibialis posterior, is involved primarily in controlling the lower leg. The gracilis and sartorius, also removed, have minor contributions to knee flexion. The remaining removed muscles, including gracilis and sartorius, are involved in controlling the hip (Winter 2004). As stated previously, removing mostly hip muscles would likely be compensated by muscles in the hip functional group. In other words, there may not be a need to alter the excitations of the lower leg muscles. Similar differences in model sensitivity between thigh and lower leg muscles have been noted previously (Xiao and Higginson 2008). It was found that while the majority of hip muscles had different excitations between a two-dimensional and three-dimensional model, the knee and ankle excitations were similar (Xiao and Higginson 2008).

A second sensitivity analysis was performed to examine the impact of individual Hill-type muscle model parameters on simulated muscle excitations during gait. Specifically, values of maximum isometric force, optimal fiber length, and tendon slack length were bilaterally perturbed by ± 10% for the inferior gluteus maximus and rectus femoris. Deviations of ± 10% were selected to provide useful information regarding sensitivity while still allowing the model to accurately reproduce the experimental gait data (Xiao and Higginson 2010). This analysis was limited to examining the model's sensitivity to deviations in maximum isometric force, optimal fiber length, and tendon slack length. Other muscle parameters in a Hill-type model, e.g. activation rise time, can also influence simulated muscle excitations during walking and should be examined in future work.

The inferior gluteus maximus muscle was sensitive to deviations in its maximum isometric force and to deviations in the maximum isometric force of the rectus femoris muscle. Previous research has also found that the gluteus maximus muscle was sensitive to deviations in its maximum isometric force during gait. However, the gluteus maximus muscle was not seen to be sensitive to deviations in the maximum isometric force of the rectus femoris (Xiao and Higginson 2010). The rectus femoris muscle was not sensitive to deviations of its own maximum isometric force. In general, other than the inferior gluteus maximus, no other muscles were sensitive to perturbations in the inferior gluteus maximus or rectus femoris maximum isometric force. These findings are consistent with previous literature that noted sensitivities for only the gluteus maximus muscle to deviations in maximum isometric force (Xiao and Higginson 2010).

The model was more sensitive to perturbations in inferior gluteus maximus or rectus femoris tendon slack length than optimal fiber length. Changes in tendon slack length have been found previously to impact the muscles of a gait simulation more than changes in optimal fiber length (Redl *et al.* 2007, Xiao and Higginson 2010). Only the inferior gluteus maximus muscle excitations were sensitive to deviations in the muscle's tendon slack length. Previous research also found that changes in gluteus maximus tendon slack length only impacted the gluteus maximus muscle (Xiao and Higginson 2010). However, deviations in the rectus femoris tendon slack length impacted multiple stance leg muscles including the biceps femoris, inferior gluteus maximus, and tibialis anterior. Perturbations in the rectus femoris tendon slack length have been found previously to impact other muscles including the biceps femoris and adductor magnus (Xiao and Higginson 2010). Additionally, changes in the tendon slack lengths of the knee extensors had the most significant impact of simulated muscle forces (Redl *et al.* 2007).

In summary, each muscle responded differently to deviations in muscle model parameters. In a Hill-type muscle model, each muscle has a different set of muscle parameters and its own force-generating characteristics. Muscle force depends on the muscle's force-length relationship (Zajac 1989). Therefore, certain muscles might be more sensitive to changes in fiber length depending on where they are acting on the curve during gait (Xiao and Higginson 2010). These results apply only to normal gait in healthy adults. Gait simulations in other populations, such as elderly adults, may respond differently to deviations in muscle model parameters. Previous research has shown the potential importance of accounting for age-related changes in muscle parameters when simulating movements in elderly adults (Thelen 2003). Additionally, it is likely that the results of any sensitivity analysis would change depending on the task and range of motion being analyzed (Redl *et al*. 2007, Xiao and Higginson 2010). Previous research has also suggested that inter-subject variations in gait could potentially exceed the model's sensitivity to changes in muscle model parameters (Pandy and Andriacchi 2010). Additional research is necessary to determine the importance of population-specific and task-specific muscle model parameters used in simulations.

Finally, a preliminary comparison of the simulated muscle excitations between baseline and anticipation conditions was performed to provide insight into proactive strategies. Specific Aim 2 revealed that older adults implemented a more conservative proactive strategy consisting of increased gait speed without increasing step length. Meanwhile, young adults utilized a potentially more risky proactive strategy consisting of increasing gait speed through increased step length. Two subjects, one young and one older, were selected from Experiment 2 who exemplified these age-related differences found in proactive strategies. Subject 1 (Young) was a young adult who walked during AD with a 0.15 m/s increase in gait speed and a 5.58 cm increase in step length compared to BD. Subject 2 (Older) was an older adult who walked with a 0.10 m/s increase in gait speed and a 1.94 cm increase in step length during AD compared to BD.

The simulated excitations of stance leg hip extensors were different between baseline and anticipation conditions. Anticipation trials were found to have higher excitations of the left inferior gluteus maximus before and after HC in both young and older subjects. A slight increase in the left biceps femoris excitation was also seen in the young subject before HC with anticipation. Both the inferior gluteus maximus and biceps femoris serve as hip extensors. They act at HC during gait to control hip flexion and assist in controlling trunk forward acceleration and pelvis stabilization (Winter 2004). The importance of increased hip extensor excitations around HC is evident when previous findings are explored. Hip extensors have been linked to improving COM stability during slipping (Yang and Pai 2010). Hip extensor activity has also been found as a key component in a successful recovery reaction to a slip (Cham and Redfern 2001, Chambers and Cham 2007). Additionally, simulation studies have determined that the stance leg hip extensors are a main contributor to vertical support during gait immediately following HC (Anderson and Pandy 2003, Neptune *et al.* 2004, Liu *et al*. 2006, Pandy and Andriacchi 2010). Based on previous research, it is likely that increased hip extensor excitations noted during anticipation trials, especially inferior gluteus maximus, would be associated with reduced slip risk. Further investigation is necessary to explore the differences in inferior gluteus maximus excitations found when anticipating a slippery floor.

Age-related differences in simulated muscle excitations of the other left leg hip muscles were also seen. The older subject had elevated left anterior gluteus medius and left psoas excitation around HC when anticipating a slippery floor. However, the young subject had little change in left anterior gluteus medius and decreased left psoas excitations when anticipating a slippery floor. The anterior gluteus medius acts during gait as a hip abductor to control the drop of the pelvis during weight acceptance and assists in hip extension by controlling hip flexion (Winter 2004). The psoas contributes to hip flexion and stabilization of the pelvis. These age-related differences in excitations might be associated with the differences in gait kinematics seen between young and older adults. Older adults did not significantly increase step length during anticipation. On the contrary, young adults were found to significantly increase step length during anticipation. Specifically, the older subject used for these simulations walked with a 1.94 cm increase in step length during AD ,while the young adult walked with a 5.58 cm increase in step length. Walking with different step lengths would likely result in different body orientation around HC. Previous findings have emphasized that the function of a muscle can depend strongly on body orientation (Anderson and Pandy 2003, Liu *et al*. 2008, Pandy and Andriacchi 2010). Further examination is necessary to explore the contributions of these hip muscles to gait during proactive strategies.

Both the young and older subjects were found to have a minor burst of left rectus femoris activity before HC during AD that was not present in BD. The rectus femoris acts during gait to extend the leg and foot prior to HC. It then acts as a knee extensor to control knee flexion and cause knee extension (Winter 2004). Previous studies found that the knee extensors of the stance leg are among the main contributors to vertical support early in stance (Kepple *et al.* 1997, Anderson and Pandy 2003, Neptune *et al.* 2004, Liu *et al.* 2006, Pandy and Andriacchi 2010). The increased knee extensor excitations seen during AD before HC might be contributing to increased vertical support, which should be beneficial if a threat to ones balance was present, as was the case during anticipation trials. Additionally, the increased excitation before HC might contribute to increased co-contraction at the knee. Previous research has seen increased knee co-contraction around HC during proactive strategies aimed at reducing slip risk (Chambers and Cham 2007).

The most noticeable differences in simulated excitations between baseline and anticipation conditions were discovered in the lower leg muscles. During baseline, the older subject had a minor burst in left medial gastrocnemius before HC and the young subject did not have any activity at all. However, when anticipating a slippery floor, both young and older subjects were found to have a major burst in left medial gastrocnemius excitation before HC. The stance leg medial gastrocnemius is a knee flexor and ankle plantarflexor that acts to control forward rotation of the leg and knee flexion during gait (Winter 2004). Previous research revealed that the plantarflexors contribute to support during the first half of stance (Neptune *et al.* 2004, Liu *et al.* 2006). The knee flexors were also found to improve COM stability during slipping (Yang and Pai 2010). Additionally, increased activity of the medial gastrocnemius around HC when anticipating a slippery floor, which has been found experimentally, would likely result in a decreased foot-floor angle at HC and a reduced slip risk (Cham and Redfern 2001, Redfern *et al*. 2001, Marigold and Patla 2002). Based on previous findings, it appears as though the increased medial gastrocnemius excitations noted before HC when anticipating a slippery floor would lead to reductions in slip risk.

Both young and older subjects also increased left tibialis anterior excitations before HC when anticipating a slippery floor. Increased tibialis anterior excitations were also found shortly after HC during AD in both young and older adults. The tibialis anterior is an ankle dorsiflexor that serves to keep the foot dorsiflexed at HC, then controls the lowering of the foot to the ground (Winter 2004). Previously, the ankle dorsiflexors of the stance leg were found to contribute to vertical support around HC (Kepple *et al*. 1997, Anderson and Pandy 2003, Neptune *et al.* 2004, Liu *et al*. 2006, Pandy and Andriacchi 2010). The increased excitations noted during AD may also contribute to vertical support, which might be an important component in reducing slip risk. The increased excitations in tibialis anterior combined with the increased medial gastrocnemius activity when anticipating a slippery floor likely contribute to increased co-contraction at the ankle around HC. Increased ankle co-contraction around HC has been found previously when anticipating a slippery surface. Increased ankle co-contraction has also been associated with less severe slips (Chambers and Cham 2007). Based on previous findings, the differences found in simulated excitations of the tibialis anterior would likely reduce slip risk when anticipating a slippery floor.

Changes in gait speed were not considered during this preliminary comparison. Future work should take gait speed differences into account. Gait speed should be considered when evaluating muscle contributions as previous research has shown that speed impacts muscle function (Liu *et al*. 2008, Neptune *et al*. 2008, Pandy and Andriacchi 2010). During slower walking speeds, vertical body support was primarily provided by a straighter limb posture such that the skeletal alignment of the stance leg provided resistance to the downward pull of gravity (Liu *et al*. 2008, Pandy and Andriacchi 2010). As walking speed increases, muscle contributions increase (Liu *et al*. 2008, Neptune *et al*. 2008). In early stance, greater knee flexion during self-selected and fast walking speeds caused increased knee extensor force. This contributed to providing vertical body support and slowing progression (Liu *et al*. 2008). Gait speed-related differences in muscle contributions also highlight the importance of body position. Previous research has revealed that the function of a muscle can depend strongly on body positioning (Anderson and Pandy 2003, Liu *et al*. 2008, Pandy and Andriacchi 2010).

7.0 LIMITATIONS

Although study participants were informed to walk naturally and provided ample practice trials, it is impossible to determine the effect of the experimental conditions in a laboratory environment on the subjects' gait parameters. A brief comparison of kinematic data at heel contact showed no significant differences between baseline dry trials and the unexpected slip (Moyer *et al*. 2006). However, slip anticipation may have influenced all gait trials included in the testing session. Several subjects were excluded from Experiment 1 (19 out of 71) and Experiment 2 (1 out of 32) if they did not experience both slips during testing. Specifically, subjects were excluded if they did not have a clean contact with the contaminant covered force plate, i.e. foot did not land completely on the force plate. Due to laboratory constraints, the gait parameters calculated were based on a limited number of steps. Additionally, the older subject group was arguably not sufficiently old enough to demonstrate significantly altered gait parameters compared to the young subject group. Different trends in proactive strategies might be seen in elderly adults.

The sensitivity analyses provided information such that a moderate level of confidence can be placed in the preliminary results of the proactive strategies comparison. It is also important to note that the findings of the preliminary simulation results were in agreement with previous experimental research. The sensitivity analysis of the number of muscles included in a three-dimensional gait simulation found that the majority of hip muscles examined were sensitive to the number of muscles included in the simulation. However, the muscles of the lower leg were not sensitive to muscles being removed individually or as a group. Due to the model's sensitivity to muscles being removed, the complete model with 54 muscles was utilized during the preliminary comparison of proactive strategies to provide higher quality simulation results. A second sensitivity analysis revealed that each muscle responded differently to deviations in muscle model parameters and that changes in one muscle's model parameters could alter excitations of another muscle. The secondary sensitivity analysis was limited to exploring the model's sensitivity to deviations in maximum isometric force, optimal fiber length, and tendon slack length. Other muscle parameters in a Hill-type model can also influence simulated muscle excitations during walking and should be examined in future work.

The simulation results were based on a very limited number of subjects and apply only to normal gait in healthy adults. Since muscle function is task-dependent, it is likely that the results of any sensitivity analysis would depend on the task and range of motion being analyzed (Redl *et al*. 2007, Xiao and Higginson 2010). Future work should also take gait speed differences into account since previous research has shown that gait speed impacts muscle function (Liu *et al*. 2008, Neptune *et al*. 2008, Pandy and Andriacchi 2010). As previously mentioned, gait simulations in other populations, such as elderly adults, may respond differently to deviations in muscle model parameters (Thelen 2003).

The accuracy of a simulation depends on numerous assumptions made in the musculoskeletal model and throughout the simulation process (Delp *et al*. 2007). Musculoskeletal modeling requires assumptions regarding anatomy, muscle physiology, force application, and ground contact. Experimental data is typically used to validate model output. However, additional investigation is necessary to aid in model validation standards (Neptune *et al*. 2009). Thus, conclusions drawn from simulations must critically consider the limitations of the model. The analysis of simulation results also depend on the specifics of the musculoskeletal model (Liu *et al*. 2006). The details of findings may change for a different set of muscles or model type. Previous research has suggested that a 3D model is more appropriate for estimating certain muscles during walking compared to a 2D model (Xiao and Higginson 2008). While a 3D model was used in this dissertation work, the musculoskeletal model had other limitations. The head, arms, and trunk were modeled as one segment. It is possible that modeling these segments separately would result in different lower extremity muscle excitations during walking. Future simulation work will likely address these assumptions and develop more complex musculoskeletal models.

8.0 CONCLUSIONS

Proactive strategies can reduce the likelihood of a slip (slip risk) and improve the likelihood of a recovery if a slip occurs (slip severity) (Cham and Redfern 2002, Marigold and Patla 2002, Chambers and Cham 2007). Previous research had not investigated the effect experience of a slippery surface, alone, has on slip risk and slip severity in young or older adults. Age-related differences in proactive strategies after experiencing a slip may be an important component in reducing the high rate of falls in older adults. Previous research had also concluded that laboratory subjects should be limited to a single slip if real-world slips are desired due to gait adaptations noted after experiencing a single slip (Heiden *et al.* 2006, Oates *et al.* 2010). However, this may not be the case as it is unknown whether adults of any age return to normal gait patterns after experiencing a slip with no awareness of a pending slippery surface. Specific Aim 1 addressed these gaps in the literature by investigating the proactive strategies generated after experiencing a slippery surface without any additional awareness in both young and older adults.

While young and older adults demonstrated similar proactive strategies after experiencing a slip, several key components differed. Immediately following an unexpected slip, both young and older adults reduced their slip risk by decreasing peak RCOF on the left (previously slipped foot), modifying temporal/spatial gait parameters and increasing COM stability. With no warning of encountering an additional slippery surface, young adults appear to eventually return to baseline levels of slip risk by adopting gait characteristics that are key factors in determining slip risk. Specifically, increased step length and decreased ML margin of stability were noted in young adults. Most importantly, peak RCOF values returned to BD levels in young adults. Upon second unexpected exposure to the same slippery surface, young adults experienced a slip similar in magnitude to their first slip. The possibility of generating more than one unexpected slip would allow researchers to further investigate this unique event in order to prevent falls. Future research should focus on to determining if these slips share similar recovery characteristics.

Unlike young adults, older adults continued walking more cautiously with a decreased slip risk after experiencing a slip even with no awareness of a pending slippery surface. In addition to other proactive adaptations, older adults did not increase step length and continued to walk with a decreased peak RCOF following slip experience. Following this, older adults experienced over a 40% decrease in slip severity upon second exposure. This is likely due to older adults walking with a reduced slip risk compared to baseline even when there was no warning or awareness of a potentially slippery surface. Additional research should examine how these cautious proactive adaptations contribute to a reduced slip severity as they may be a key component in fall prevention training.

Previous research had found that a combination of experience and awareness are incorporated into developing successful proactive strategies aimed at reducing slip risk (Marigold and Patla 2002, Heiden *et al.* 2006). However, the added effect of awareness after experiencing a slip was unknown. Awareness, in addition to experience, might be a critical factor in developing or retaining proactive adaptations. While age-related differences in proactive strategies had been previously examined in other perturbation types (Woollacott and Tang 1997, Pavol *et al.* 2004, Lockhart *et al*. 2007), exploration was needed into those generated in response to real slippery surfaces. This is another important step in reducing the high prevalence of slip-related falls in older adults. Specific Aim 2 investigated the proactive strategies generated after experiencing a slippery surface with additional awareness in both young and older adults.

The combined effect of experience and awareness of a slippery floor was associated with gait adaptations that are beneficial to a decreasing slip potential. Specifically, temporal/spatial gait adjustments, decreased peak RCOF, and an overall increase in COM stability were components of proactive strategies utilized in young and older adults when anticipating a slippery floor. Interestingly, older adults were able to implement a more conservative proactive strategy consisting of increased gait speed through increased cadence without increasing step length. Young adults implemented a potentially more risky proactive strategy consisting of increasing gait speed through increased step length. These gait parameters combined with decreased peak RCOF and increased COM stability placed both young and older adults at a lower slip risk after experiencing a slip with awareness. Accordingly, both young and older adults experienced a significant decrease in slip severity of a subsequent slip with awareness.

Overall, older adults chose to maintain a more conservative proactive strategy than young regardless of the amount of awareness provided. This resulted in older adults experiencing less severe slips upon second exposure with and without awareness. On the contrary, young adults appear to be affected by the specificity of knowledge provided about the slippery surface. For example, Aim 1 found that with no threat of a pending slippery surface, young adults return to baseline levels of slip risk and a second unexpected slip can be generated. However, Aim 2 noted that the addition of awareness after experiencing a slip resulted in young adults adopting a more conservative proactive strategy with decreased peak RCOF, amplified gait adaptations and increased COM stability compared to young adults without awareness (Aim 1). Consequently, young adults with awareness experienced a reduction in slip severity upon second slip exposure. Further research should investigate if similar trends are found in elderly adults or other high risk fall groups.

In Specific Aim 3, preliminary modeling simulations provided insights into proactive strategies. Specifically, simulated muscle excitations generated during proactive strategies used to minimize slip risk were compared. Previous research has shown that the results of a model are influenced by the specifics of the model selected and the values assumed for its parameters (Xiao and Higginson 2008, Pandy and Andriacchi 2010, Xiao and Higginson 2010). In order to place confidence in the simulation results, it was important to understand the model's sensitivity to variations in the number of muscles and the assumed muscle model parameters. Therefore, a sensitivity analysis was be performed to explore how simulated muscle excitations change due to the number of muscles included in a simulation of gait and due to perturbations in muscle model parameters.

Model simulations generated muscle excitations similar to those previously reported during gait. A sensitivity analysis of the number of muscles included in a three-dimensional gait simulation found differences in sensitivity between thigh and lower leg muscles. The majority of hip muscles examined were sensitive to the number of muscles included in the simulation. However, the muscles of the lower leg were not sensitive to muscles being removed individually or as a group. A second sensitivity analysis revealed that each muscle responded differently to deviations in muscle model parameters. Overall, the model was most sensitive to perturbations in tendon slack length. Other muscle parameters in a Hill-type model can also influence simulated muscle excitations during walking and should be examined in future work. It was also noted that changes in one muscle's model parameters could alter excitations of another muscle. These findings highlight the importance of model selection and obtaining accurate estimates of tendon slack length and other muscle model parameters when modeling gait.

A preliminary comparison of the simulated muscle excitations between baseline and anticipation conditions provided insight into proactive strategies. The simulated excitations of stance leg hip extensors were increased between baseline and anticipation conditions. Based on previous research, it is likely that these elevated excitations, especially inferior gluteus maximus, would be associated with reduced slip risk. Age-related differences in simulated muscle excitations of other left leg hip muscles might be associated with the differences in gait kinematics seen between young and older adults. Future research should explore the contributions of these hip muscles to slip risk during proactive strategies. The most noticeable differences in simulated excitations during anticipation were discovered in muscles of the lower leg. When anticipating a slippery floor, both young and older subjects increased excitations of the left medial gastrocnemius and left tibialis anterior around HC. These differences in simulated muscle excitations are likely associated with increased ankle co-contraction and decreased foot-floor angle, both of which reduce slip risk.

While the experimental gait studies provided a valuable description of the proactive strategies used after experiencing a slippery surface with and without additional awareness, future modeling work should further analyze these events to aid in fall prevention research. This work should include an induced acceleration analysis. An induced acceleration analysis is an analytic method that allows quantification of the contributions of individual muscles or net joint moments utilized during gait. Previous research using this approach has provided a better understanding of how individual muscles/muscle groups or net joint moments control locomotion (Kepple *et al*. 1997, Neptune *et al*. 2001, Anderson and Pandy 2003, Siegel *et al*. 2006). An induced acceleration analysis allows for a thorough assessment of the impact certain postural adjustments have on all segments of the model and body center of mass. Future work using an induced acceleration analysis would be able to quantify how each muscle or muscle group is contributing to body support and heel deceleration, important factors in assessing slip risk.

APPENDIX A

ESTIMATED COM ANALYSIS

COM was estimated using the mid-point of the four pelvis markers located on the left/right superior and anterior iliac spines. Estimated COM was compared to actual COM. Actual COM was determined from custom model using a weighted average of segmental COM locations (Moyer 2006). Within subject differences between estimated COM and actual COM were determined at left HC in the ML, AP and SI directions for the BD and AD trials of five subjects from Experiment 2 (n=27 trials). Baseline/anticipation-related differences in COM difference were determined to ensure that estimated COM followed similar trends to actual COM during both BD and AD. Specifically, COM difference in the ML, AP and SI directions were compared between BD and AD conditions using mixed-linear regression models with anticipation condition (BD/AD) as an independent fixed effect. Statistical significance was set at 0.05.

The analysis of the difference between estimated COM and actual COM values conducted revealed that estimated COM in all directions of interest behaved similarly during BD and AD as actual COM at left HC (Figure 31). Specifically, the average ML COM difference during BD was 3.32 ± 0.18 cm while AD was 3.28 ± 0.26 cm ($p = 0.78$). The average AP COM difference during BD was 0.45 ± 0.06 cm while AD was 0.46 ± 0.06 cm ($p = 0.78$). The average SI COM difference during BD was -2.11 ± 0.64 cm while AD was -2.13 ± 0.54 cm ($p = 0.82$). The consistent offset within subjects between estimated COM and actual COM in the ML, AP and SI directions across BD and AD conditions allows estimated COM to be used in this project in order to evaluate COM stability.

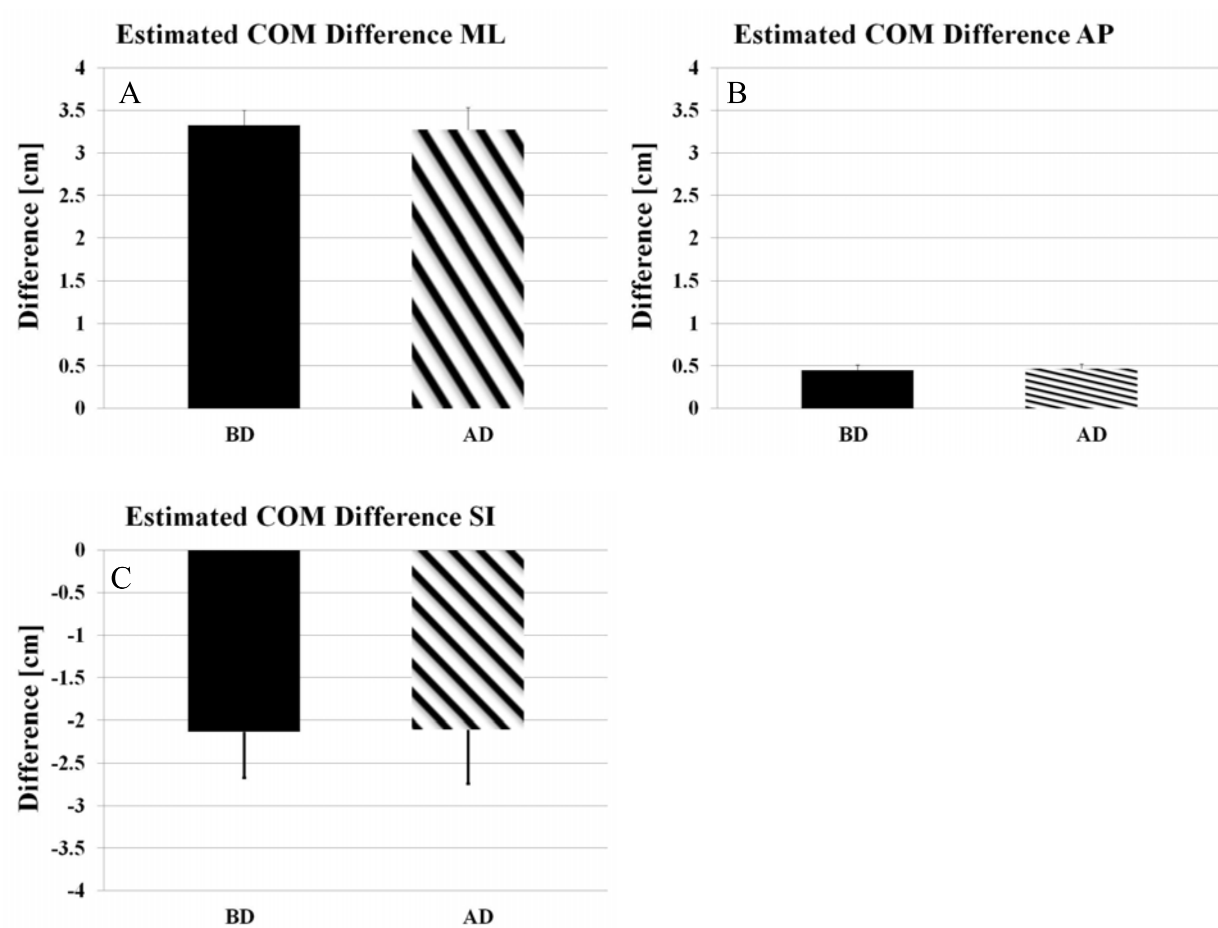


Figure 31: Difference between estimated COM and actual COM in the (A) ML direction, (B) AP direction and (C) SI direction. Baseline dry (BD) differences shown as solid bars and anticipation dry (AD) differences as hashed bars. Standard errors are provided.

BIBLIOGRAPHY

Adkin, A.L., Frank, J.S. et al., 2002. Fear of falling modifies anticipatory postural control. *Exp Brain Res,* 143(2), 160-170.

Anderson, F.C. and Pandy, M.G., 1999. A dynamic optimization solution for vertical jumping in three dimensions. *Comp Meth Biomech Biomed Eng*, 2, 201-231.

Anderson, F.C. and Pandy, M.G., 2003. Individual muscle contributions to support in normal walking. *Gait Posture*, 17(2), 159-69.

Arnold, E.M., Ward, S.R. et al., 2010. A model of the lower limb for analysis of human movement. *Ann Biomed Eng*, 38(2), 269-279.

Berg, W.P., Alessio, H.M. et al., 1997. Circumstances and consequences of falls in independent community-dwelling older adults. *Age and ageing*, 26(4), 261-268.

Bergen, G., Chen, L. et al., 2008. Injury in the united states: 2007 chartbook. *National Center for Health Statistics*, Hyattsville, MD.

Bhatt, T. and Pai, Y.C., 2005. Long-term retention of gait stability improvements. *J Neurophysiol*, 94(3), 1971-1979.

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

Bhatt, T., Wening, J.D. et al., 2006. Adaptive control of gait stability in reducing slip-related backward loss of balance. *Exp Brain Res*, 170(1), 61-73.

BLS, 2008. Survey of Occupational Injuries and Illnesses. *Bureau of Labor Statistics: U.S. Department of Labor*, www.bls.gov.

Brach J.S., Berlin J.E. et al., 2005. Too much or too little step width variability is associated with a fall history in older persons who walk at or near normal gait speed. *J Neuroeng Rehabil*, 2, 21-29.

Buck, P.C. and Coleman, V.P., 1985. Slipping, tripping and falling accidents at work: a national picture. *Ergonomics*, 28, 949-958.

Buczek, F.L. and Banks, S.A., 1996. High-resolution force plate analysis of utilized slip resistance in human walking. *J Testing Evaluation,* 24(6), 353-358.

Burnfield, J.M. and Powers, C.M., 2006. Prediction of slips: an evaluation of utilized coefficient of friction and available slip resistance. *Ergonomics*, 49(10), 982-995.

Burnfield, J.M. and Powers, C.M., 2007. The role of center of mass kinematics in predicting peak utilized coefficient of friction during walking. *J Forensic Sci,* 52(6), 1328-1333.

CDC, 2010. Web–based Injury Statistics Query and Reporting System (WISQARS). *Centers for Disease Control and Prevention: National Center for Injury Prevention and Control,* www.cdc.gov.

Cesari, M., Kritchevsky, S.B. et al., 2005. Prognostic value of usual gait speed in well-functioning older people--results from the Health, Aging and Body Composition Study. *J Am Geriatr Soc*, 53(10), 1675-1680.

Cham, R. and Redfern, M.S., 2001. Lower extremity corrective reactions to slip events. *J Biomech,* 34(11), 1439-1445.

Cham, R. and Redfern, M.S., 2002. Changes in gait when anticipating slippery floors. *Gait Posture,* 15(2), 159-171.

Chamberlin, M.E., Fulwider, B.D. et al., 2005. Does fear of falling influence spatial and temporal gait parameters in elderly persons beyond changes associated with normal aging? *J Gerontol A Biol Sci Med Sci*, 60(9), 1163-1167.

Chambers, A.J., 2005. Slip-related muscle activation patterns of the stance leg during gait. M.S. Thesis, University of Pittsburgh.

Chambers, A.J. and Cham, R., 2007. Slip-related muscle activation patterns in the stance leg during walking. *Gait Posture*, 25(4), 565-572.

Corso, P., Finkelstein, E. et al., 2006. Incidence and lifetime costs of injuries in the United States. *Inj Prev*, 12(4), 212-218.

Courtney, T.K., Sorock, G.S. et al., 2001. Occupational slip, trip, and fall-related injuries-can the contribution of slipperiness be isolated? *Ergonomics,* 44(13), 1118-1137.

Cromwell, R.L. and Newton, R.A., 2004. Relationship between balance and gait stability in healthy older adults. *J Aging Phys Act*, 12(1), 90-100.

Dao, T.T., Marin, F. et al., 2009. Sensitivity of the anthropometrical and geometrical parameters of the bones and muscles on a musculoskeletal model of the lower limbs. *Proceedings of the 31st Ann Int Con IEEE EMBS.*

Delbaere, K., Sturnieks, D.L. et al., 2009. Concern about falls elicits changes in gait parameters in conditions of postural threat in older people. *J Gerontol,* 64, 237-42.

Dellinger, A.M. and Stevens, J.A., 2006. The injury problem among older adults: mortality, morbidity and costs. *J Safety Res*, 37(5), 519-522.

Delp, S.L., Anderson, F.C. et al., 2007. OpenSim: open-source software to create and analyze dynamic simulations of movement. *IEEE Trans Biomed Eng*, 54(11), 1940-1950.

Delp, S.L., Loan, J.P. et al., 1990. An interactive graphics-based model of the lower extremity to study orthopaedic surgical procedures. *IEEE Trans Biomed Eng*, 37, 757-767.

Englander, F., Hodson, T.J. et al., 1996. Economic dimensions of slip and fall injuries. *J Forensic Sci*, 41, 733-746.

Espy, D.D., Yang, F. et al., 2010. Independent influence of gait speed and step length on stability and fall risk. *Gait Posture*, 32(3), 378-382.

Fong, D.T., Mao, D.W. et al., 2008. Greater toe grip and gentler heel strike are the strategies to adapt to slippery surface. *J Biomech*, 41(4), 838-844.

Gao, C. and Abeysekera, J., 2004. A systems perspective of slip and fall accidents on icy and snowy surfaces. *Ergonomics*, 47(5), 573-598.

Hanson, J.P., Redfern, M.S. et al., 1999. Predicting slips and falls considering required and available friction. *Ergonomics,* 42(12), 1619-1633.

Hardy, S.E., Perera, S. et al., 2007. Improvement in usual gait speed predicts better survival in older adults. *J Am Geriatr Soc*, 55(11), 1727-1734.

Hausdorff, J.M., Rios, D.A. et al., 2001. Gait variability and fall risk in community-living older adults: a 1-year prospective study. *Arch Phys Med Rehabil*, 82(8), 1050-1056.

Heiden, T.L., Sanderson, D.J. et al., 2006. Adaptations to normal human gait on potentially slippery surfaces: the effects of awareness and prior slip experience. *Gait Posture,* 24(2), 237-246.

James, D.I., 1983. Rubbers and plastics in shoes and flooring: the importance of kinetic friction. *Ergonomics,* 26(1), 83-99.

Kepple, T.M., Siegel, K.L. et al., 1997. Relative contributions of the lower extremity joint moments to forward progression and support during gait. *Gait Posture*, 6, 1-8.

Kim, S., Lockhart, T.E. et al., 2005. Relationship between age-related gait adaptations and required coefficient of friction. *Saf Sci,* 43(7), 425-436.

Liberty Mutual, 2010. 2010 Workplace safety index. *Liberty Mutual Research Institute for Safety*, www.libertymutual.com/researchinstitute.

Liu, J. and Lockhart, T.E., 2009. Age-related joint moment characteristics during normal gait and successful reactive-recovery from unexpected slip perturbations. *Gait Posture*, 30(3), 276-281.

Liu, M.Q., Anderson, F.C. et al., 2006. Muscles that support the body also modulate forward progression during walking. *J Biomech*, 39(14), 2623-2630.

Liu, M.Q., Anderson, F.C. et al., 2008. Muscle contributions to support and progression over a range of walking speeds. *J Biomech*, 41(15), 3243-3252.

Lockhart, T.E. and Kim, S., 2006. Relationship between hamstring activation rate and heel contact velocity: factors influencing age-related slip-induced falls. *Gait Posture,* 24(1), 23-34.

Lockhart, T.E., Spaulding, J.M. et al., 2007. Age-related slip avoidance strategy while walking over a known slippery floor surface. *Gait Posture*, 26(1), 142-149.

Lockhart, T.E., Woldstad, J.C. et al., 2003. Effects of age-related gait changes on the biomechanics of slips and falls. *Ergonomics*, 46(12), 1136-1160.

Lord, S.R., Lloyd, D.G. et al., 1996. Sensori-motor function, gait patterns and falls in community-dwelling women. *Age Ageing*, 25, 292-299.

Maki, B.E., 1997. Gait changes in older adults: predictors of falls or indicators of fear. *J Am Geriatr Soc,* 45(3), 313-320.

Magnusson, M.L., Pope, M.H. et al., 1999. Cervical electromyographic activity during low-speed rear impact. *Eur Spine J*, 8(2), 118-125.

Mahboobin, A., Cham, R., et al., 2010. The impact of a systematic reduction in shoe-floor friction on heel contact walking kinematics-- A gait simulation approach. *J Biomech,* 43(8), 1532-1539.

Marigold, D.S. and Patla, A.E., 2002. Strategies for dynamic stability during locomotion on a slippery surface: effects of prior experience and knowledge. *J Neurophysiol*, 88(1), 339-353.

Marigold, D.S., Bethune, A.J. et al., 2003. Role of the unperturbed limb and arms in the reactive recovery response to an unexpected slip during locomotion. *J Neurophysiol*, 89(4), 1727-1737.

McGibbon, C.A. and Krebs, D.E., 2001. Age-related changes in lower trunk coordination and energy transfer during gait. *J Neurophysiol* 85(5), 1923-1931.

Menz, H.B., Lord, S.R. et al., 2003. Age-related differences in walking stability. *Age Ageing*, 32(2), 137-142.

Menz, H.B., Lord, S.R. et al., 2007. A structural equation model relating impaired sensorimotor function, fear of falling and gait patterns in older people. *Gait Posture*, 25(2), 243-249.

Moyer, B.E., 2006. Slip and fall risks: pre-slip gait contributions and post-slip response effects. Ph.D. Thesis, University of Pittsburgh.

Moyer, B.E., Chambers, A.J. et al., 2006. Gait parameters as predictors of slip severity in younger and older adults. *Ergonomics*, 49(4), 329-343.

Myung, R. and Smith, J.L., 1997. The effect of load carrying and floor contaminants on slip and fall parameters. *Ergonomics*, 40(2), 235-246.

Myung, R., Smith, J.L. et al., 1992. Slip distance as an objective criterion to determine the dominant parameter between static and dynamic COFs. *Proceedings of the human factors society 36th annual meeting.*

NCHS, 2009. Injury fact sheet. *National Center for Health Statistics: Centers for Disease Control and Prevention,* www.cdc.gov.

NSC, 2008. Injury facts. *National Safety Council,* www.nsc.org.

NSC, 2009. Injury facts. *National Safety Council,* www.nsc.org.

Neptune, R.R., Kautz, S.A. et al., 2001. Contributions of the individual ankle plantar flexors to support, forward progression and swing initiation during walking. *J Biomech*, 34(11), 1387-1398.

Neptune, R.R., McGowan, C.P. et al., 2009. Forward dynamics simulations provide insight into muscle mechanical work during human locomotion. *Exerc Sport Sci Rev*, 37(4), 203-210.

Neptune, R.R., Sasaki, K. et al., 2008. The effect of walking speed on muscle function and mechanical energetics. *Gait Posture*. 28(1), 135-143.

Neptune, R.R., Zajac, F.E. et al., 2004. Muscle mechanical work requirements during normal walking: the energetic cost of raising the body's center-of-mass is significant. *J Biomech*, 37(6), 817-825.

O'Connor, C.M., Thorpe, S.K. et al., 2007. Automatic detection of gait events using kinematic data. *Gait Posture*, 25(3), 469-474.

Oates, A.R., Frank, J.S. et al., 2010. Control of dynamic stability during adaptation to gait termination on a slippery surface. *Exp Brain Res*, 201(1), 47-57.

Pai, Y.C. and Bhatt, T.S., 2007. Repeated-slip training: an emerging paradigm for prevention of slip-related falls among older adults. *Phys Ther*, 87(11), 1478-1491.

Pai, Y.C. and Patton, J., 1997. Center of mass velocity-position predictions for balance control. *J Biomech*, 30(4), 347-354.

Pai, Y.C., Wening, J.D. et al., 2003. Role of feedforward control of movement stability in reducing slip-related balance loss and falls among older adults. *J Neurophysiol*, 90(2), 755-762.

Pai, Y.C., Yang, F. et al., 2006. Mechanisms of limb collapse following a slip among young and older adults. *J Biomech,* 39(12), 2194-2204.

Pandy, M.G. and Andriacchi, T.P., 2010. Muscle and joint function in human locomotion. *Ann Rev Biomed Eng*, 12, 401-433.

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

Piazza, S.J., 2006. Muscle-driven forward dynamic simulations for the study of normal and pathological gait. *J NeuroEng Rehab*, 3, 5-11.

Redfern, M.S., Cham, R. et al. 2001. Biomechanics of slips. *Ergonomics,* 44(13), 1138-1166.

Redfern, M.S. and DiPasquale, J., 1997. Biomechanics of descending ramps. *Gait Posture*, 6(2), 119-125.

Redl, C., Gfoehler, M. et al., 2007. Sensitivity of muscle force estimates to variations in muscle-tendon properties. *Hum Mov Sci*, 26(2), 306-319.

Shkuratova, N., Morris, M.E. et al., 2004. Effects of age on balance control during walking. *Arch Phys Med Rehabil*, 85(4), 582-588.

Siegel, K.L., Kepple, T.M. et al., 2006. Using induced accelerations to understand knee stability during gait of individuals with muscle weakness. *Gait Posture,* 23(4), 435-440.

Siegmund, G.P., Heiden, T.L. et al., 2006. The effect of subject awareness and prior slip experience on tribometer-based predictions of slip probability. *Gait Posture*, 24(1), 110-119.

Siegmund, G.P., Sanderson, D.J. et al., 2003a. Rapid neck muscle adaptation alters the head kinematics of aware and unaware subjects undergoing multiple whiplash-like perturbations. *J Biomech,* 36(4), 473-482.

Siegmund, G.P., Sanderson, D.J. et al., 2003b. Awareness affects the response of human subjects exposed to a single whiplash-like perturbation. *Spine,* 28(7), 671-679.

Soames, R.W., 1985. Foot pressure patterns during gait. *J Biomed Eng*, 7(2), 120-126.

Stevens, J.A., Corso, P.S. et al., 2006. The costs of fatal and non-fatal falls among older adults. *Inj Prev*, 12(5), 290-295.

Stevens, J.A. and Sogolow, E.D., 2005. Gender differences for non-fatal unintentional fall related injuries among older adults. *Inj Prev*, 11(2), 115-119.

Strandberg, L. and Lanshammar, H., 1981. The dynamics of slipping accidents. *J Occ Accidents*, 3: 153-162.

Tang, P.F. and Woollacott, M.H., 1998. Inefficient postural responses to unexpected slips during walking in older adults. *J Gerontol A Biol Sci Med Sci*, 53, 471-480.

Tang, P.F., Woollacott, M.H. et al., 1998. Control of reactive balance adjustments in perturbed human walking: roles of proximal and distal postural muscle activity. *Exp Brain Res*, 119(2), 141-152.

Thelen, D.G., 2003. Adjustment of muscle mechanics model parameters to simulate dynamic contractions in older adults. *J Biomech Eng*, 125, 70-77.

Thelen, D.G. and Anderson, F.C., 2006. Using computed muscle control to generate forward dynamic simulations of human walking from experimental data. *J Biomech*, 39(6), 1107-1115.

Tirosh, O. and Sparrow, W.A., 2005. Age and walking speed effects on muscle recruitment in gait termination. *Gait Posture*, 21(3), 279-288.

Troy, K.L., Donovan, S.J. et al., 2008. Modifiable performance domain risk-factors associated with slip-related falls. *Gait Posture*, 28(3), 461-465.

van Asseldonk, E.H., Carpenter, M.G. et al., 2007. Use of induced acceleration to quantify the (de)stabilization effect of external and internal forces on postural responses. *IEEE Trans Biomed Eng*, 54(12), 2284-2295.

van Dieën, J.H. and Pijnappels, M., 2008. Falls in older people. *J Electromyogr Kinesiol*, 18(2), 169-171.

Winter, D.A., 2004. Biomechanics and Motor Control of Human Movement. New York, NY, Wiley & Sons Inc.

Woolf, A.D. and Pfleger, B., 2003. Burden of major musculoskeletal conditions. *Bull World Health Organ,* 81(9).

Woollacott, M.H. and Tang, P.F., 1997. Balance control during walking in the older adult: research and its implications. *Phys Ther,* 77(6), 646-660.

Xiao, M. and Higginson, J.S., 2008. Muscle function may depend on model selection in forward simulation of normal walking. *J Biomech*, 41, 3236-3242.

Xiao, M. and Higginson, J.S., 2010. Sensitivity of estimated muscle force in forward simulation of normal walking. *J Appl Biomech*, 26(2), 142-149.

Yang, F. and Pai, Y.C., 2010. Reactive control and its operation limits in responding to a novel slip in gait. *Ann Biomed Eng,* 38(10), 3246-3256.

You, J., Chou, Y. et al., 2001. Effect of slip on movement of body center of mass relative to base of support. *Clin Biomech*, 16(2), 167-173.

Zajac, F.E., 1989. Muscle and tendon: properties, models, scaling, and application to biomechanics and motor control. *Crit Rev Biomed Eng*, 17, 359-411.

Zajac, F.E., Neptune, R.R. et al., 2003. Biomechanics and muscle coordination of human walking: part II: lessons from dynamical simulations and clinical implications. *Gait Posture*, 17(1), 1-17.