ADAPTIVE POSTURAL STRATEGIES: IMPACT OF AGING

by

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Falls threaten the quality of life of older adults and are associated with tremendous economic costs. Slips and trips are the two major causes of falls during locomotion and each requires a different postural response to prevent falling. However, a critical requirement in maintaining balance in either is the ability to generate proactive postural adjustments. Older adults have been shown to adopt proactive postural adjustments during repeated exposure to initially novel perturbations. However, the extent to which such learning applied to gait was unknown. This dissertation investigated reducing the incidence of falls in older adults through learning anticipatory adjustments to perturbations during gait based on a systems model theory. Potential associations between age and anticipatory postural strategies when repeatedly exposed to forward slips were studied. Forward vs. backward walking slips were also compared to examine the impact of gait novelty on the ability to generate proactive adjustments. The impact of knowledge of the type of perturbation on the ability to generate proactive adjustments and whether such adjustments change with experience and when the nature of the perturbation was also investigated. Subjects were exposed to multiple slip and trip perturbations to investigate these differences and to compare how young and older adults alter their proactive adjustments. As anticipatory behavior improves perturbation recovery outcomes, changes in measures of severity with increased exposure were also analyzed. This study found young and older adults adopt proactive postural adjustments when repeatedly exposed to forward slips and make internal representations applicable to a novel task. Awareness of a perturbation proved sufficient to induce proactive adaptations and with experience, adaptations became perturbation specific to reduce slip and trip risk in both age groups. Perturbation recovery improved with multiple exposures in both age groups as decreases in severity measures were observed. This study opens the door to studies evaluating the retention of postural control motor skills adapted through training and prior experiences and sheds light on the benefits of a systems model theory based fall intervention program for slips and trips.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

PREFACE

There is no telling how many miles you will have to run while chasing a dream.

~Author Unknown

This has truly been a journey. Through this process I have evolved both as an individual and a researcher. For that I am grateful. I would first like to thank my advisor, Dr. Rakié Cham. Over the years she has pushed me to achieve my potential and I appreciate her setting the bar for excellence. In addition, I am also thankful for my committee members, Dr. McCrory, Dr. Perera, Dr. Redfern and Dr. Van Swearingen, whom have demonstrated a diverse set of expertise while each supporting me with a unique perspective to reach the finish line. Each of you has contributed to this work to help me develop a very insightful project that has significance for the field. I thank each of you for your continued support, time, guidance, advice and insight. Dr. Borovetz and Dr. Wosu, I appreciate your steadfast support throughout my studies at the University of Pittsburgh. Each of you has helped me through situations that made it possible to get to the current point. To my Pitt family, Ms. Allen, Ms. Moore and Dominique, thank you for being a family away from home. I will miss those spontaneous office visits and heart-to-hearts that became a part of my daily life. I would also like to give a special thank you to April Chambers, Wilshaw Stevens and the members of the HMBL for their continued support. Without your help completion of this project would have been very difficult. For the friendships I have formed in graduate school, Kurt Beschorner and Peter Sandrian, I believe we will be friends forever. Thank you for all of the memories that made the difficult times less gloomy. And lastly, to thank the people behind the scenes, my family and friends. To my mother and bestfriend, Mrs. Felix Harper, the day has come. THANK YOU. You have held my hand every step of the way and because of your support I never gave up. To my family, thank you for believing in me even at moments when I didn't believe in myself. To Tiffany, thank you for helping me maintain a balance. Your support truly made the difference in the final stretch. Every aforementioned person has made the completion of this work possible. I appreciate you all. This dissertation is dedicated to Clark Kingston. Thank you for supporting mommy and being my guiding light to the finish line.

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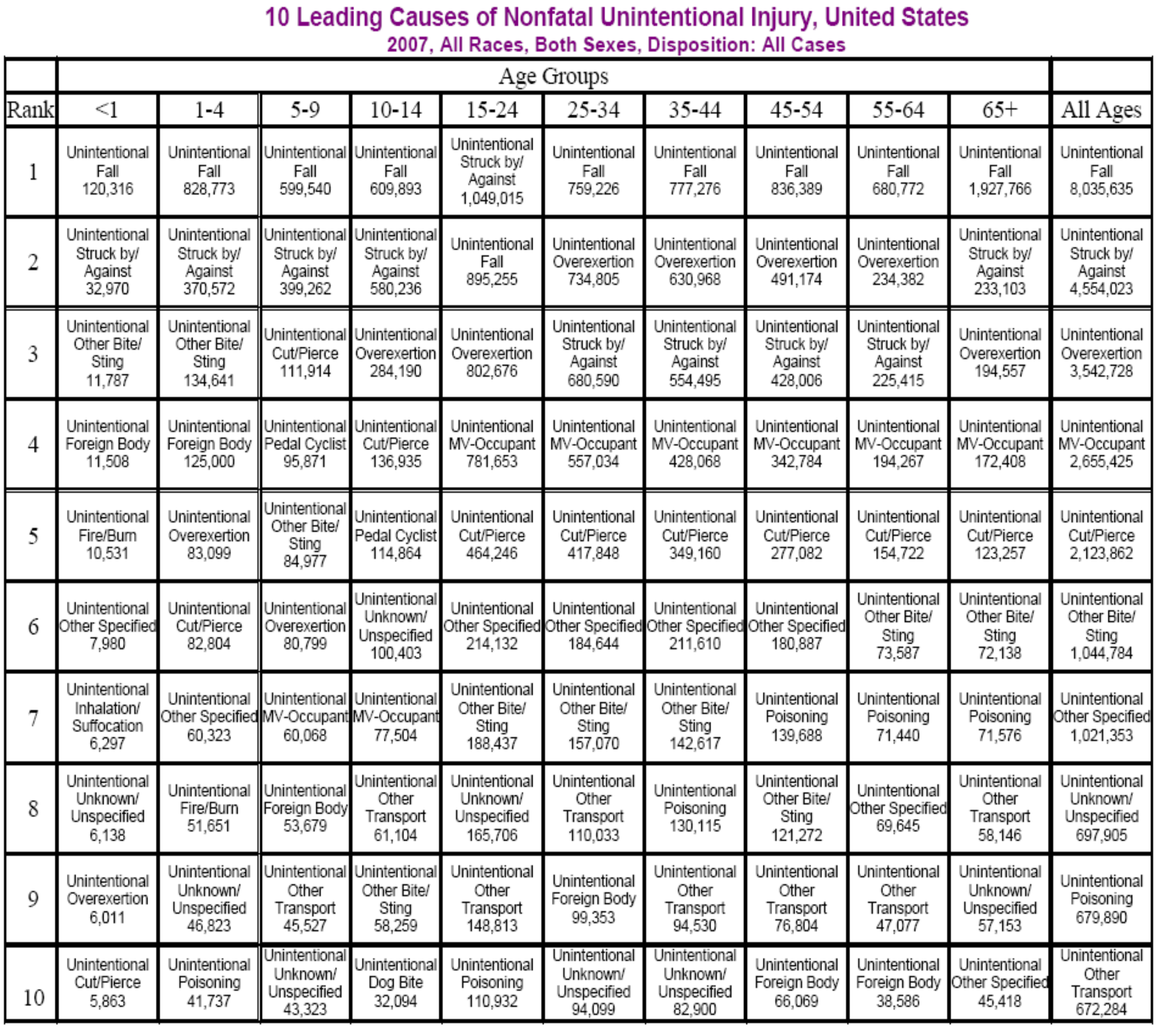
1.0 BACKGROUND

Falls threaten the quality of life of older adults and are associated with tremendous economic cost. The aging of the population is expected to aggravate these falls-related concerns. To date, fall prevention programs have had limited success minimizing the risk of falls in the elderly. Research into the basic underlying reasons for aging-related worsening of postural control performance can provide new directions for clinicians and therapists in their attempt to minimize their patients' risk of falling and to improve the likeliness of recovery when falls do occur. This chapter reviews the problem and significance of slip, trip and fall accidents (Section 1.1), the contributing factors to slip, trip and fall accidents (Section 1.2), an approach to motor learning and the importance of proactive postural adjustments (Section 1.3), previous findings and voids in the literature (Section 1.4), backward walking as a novel task (1.5), and the current state of training, retention and the journey towards the development successful intervention programs (1.6).

1.1 PROBLEM STATEMENT AND SIGNIFICANCE

Falls are a major health problem in the elderly. The average annual risk of falling for an older adult over 65 years ranges from 30 to over 50%, i.e. at least 1 in 3 older adults falls each year [1, 2]. Consequences of falls include injury, fear of falling, decreased activity, functional deterioration, social isolation, depression, reduced quality of life, institutionalization and death [3]. Muscle weakness, gait and balance deficits increase fall risk by 440%, 290% and 290%, respectively, and all of these factors are correlated with the natural process of aging [4]. The problem to date is that the incidence of falls remains on the rise. Fall induced injuries in persons aged 50 and older increased from 5,622 in 1970 to 21,574 in 1995, a 284% increase [5] and this number continues to grow. In 2007, more than 18,000 older adults died as the result of unintentional fall injuries [6]. In the following year, 2.1 million nonfatal fall related injuries (Figure 1.1) among older adults were treated in the emergency room with an alarming estimated 559,000 requiring hospitalization [7]. This apparent problem also reaches new dimensions of complexity and concern when considering the aging workforce. By the year 2050, the estimated population of older adults is expected to increase by more than 50 million [8]. In the year 2000, direct medical costs had already spiraled to $200 million dollars in fatal falls and $19 billion dollars in nonfatal injuries [7]. Thus, there is an imperative need to develop intervention programs reducing the incidence of falls and associated health care costs. To achieve this goal, it is necessary to understand the factors that contribute to the probability of falling for a postural disturbance as well as the factors associated with the ability to recover from such a postural disturbance [9]. This research proposes to focus on one of these factors, the ability to adapt one’s gait when faced with environmental hazards, e.g. slipping/tripping hazards. The goal of such work is to establish the validity that postural control motor skills can be adapted and retained through training in the form of prior experiences which can potentially serve as the foundation for intervention programs focused on task specific motor learning capabilities.



10 Leading Causes of Nonfatal Unintentional Injury, United States

2007, All Races, Both Sexes, Disposition: All Cases

	Age Groups										
Rank	<1	1-4	5-9	10-14	15-24	25-34	35-44	45-54	55-64	65+	All Ages
1	Unintentional Fall 120,316	Unintentional Fall 828,773	Unintentional Fall 599,540	Unintentional Fall 609,893	Unintentional Struck by/ Against 1,049,015	Unintentional Fall 759,226	Unintentional Fall 777,276	Unintentional Fall 836,389	Unintentional Fall 680,772	Unintentional Fall 1,927,766	Unintentional Fall 8,035,635
2	Unintentional Struck by/ Against 32,970	Unintentional Struck by/ Against 370,572	Unintentional Struck by/ Against 399,262	Unintentional Struck by/ Against 580,236	Unintentional Fall 895,255	Unintentional Overexertion 734,805	Unintentional Overexertion 630,968	Unintentional Overexertion 491,174	Unintentional Overexertion 234,382	Unintentional Struck by/ Against 233,103	Unintentional Struck by/ Against 4,554,023
3	Unintentional Other Bite/ Sting 11,787	Unintentional Other Bite/ Sting 134,641	Unintentional Cut/Pierce 111,914	Unintentional Overexertion 284,190	Unintentional Overexertion 802,676	Unintentional Struck by/ Against 680,590	Unintentional Struck by/ Against 554,495	Unintentional Struck by/ Against 428,006	Unintentional Struck by/ Against 225,415	Unintentional Overexertion 194,557	Unintentional Overexertion 3,542,728
4	Unintentional Foreign Body 11,508	Unintentional Foreign Body 125,000	Unintentional Pedal Cyclist 95,871	Unintentional Cut/Pierce 136,935	Unintentional MV-Occupant 781,653	Unintentional MV-Occupant 557,034	Unintentional MV-Occupant 428,068	Unintentional MV-Occupant 342,784	Unintentional MV-Occupant 194,267	Unintentional MV-Occupant 172,408	Unintentional MV-Occupant 2,655,425
5	Unintentional Fire/Burn 10,531	Unintentional Overexertion 83,099	Unintentional Other Bite/ Sting 84,977	Unintentional Pedal Cyclist 114,864	Unintentional Cut/Pierce 464,246	Unintentional Cut/Pierce 417,848	Unintentional Cut/Pierce 349,160	Unintentional Cut/Pierce 277,082	Unintentional Cut/Pierce 154,722	Unintentional Cut/Pierce 123,257	Unintentional Cut/Pierce 2,123,862
6	Unintentional Other Specified 7,980	Unintentional Cut/Pierce 82,804	Unintentional Overexertion 80,799	Unintentional Unknown/ Unspecified 100,403	Unintentional Other Specified 214,132	Unintentional Other Specified 184,644	Unintentional Other Specified 211,610	Unintentional Other Specified 180,887	Unintentional Other Bite/ Sting 73,587	Unintentional Other Bite/ Sting 72,138	Unintentional Other Bite/ Sting 1,044,784
7	Unintentional Inhalation/ Suffocation 6,297	Unintentional Other Specified 60,323	Unintentional MV-Occupant 60,068	Unintentional MV-Occupant 77,504	Unintentional Other Bite/ Sting 188,437	Unintentional Other Bite/ Sting 157,070	Unintentional Other Bite/ Sting 142,617	Unintentional Poisoning 139,688	Unintentional Poisoning 71,440	Unintentional Poisoning 71,576	Unintentional Other Specified 1,021,353
8	Unintentional Unknown/ Unspecified 6,138	Unintentional Fire/Burn 51,651	Unintentional Foreign Body 53,679	Unintentional Other Transport 61,104	Unintentional Unknown/ Unspecified 165,706	Unintentional Other Transport 110,033	Unintentional Poisoning 130,115	Unintentional Other Bite/ Sting 121,272	Unintentional Other Specified 69,645	Unintentional Other Transport 58,146	Unintentional Unknown/ Unspecified 697,905
9	Unintentional Overexertion 6,011	Unintentional Unknown/ Unspecified 46,823	Unintentional Other Transport 45,527	Unintentional Other Bite/ Sting 58,259	Unintentional Other Transport 148,813	Unintentional Foreign Body 99,353	Unintentional Other Transport 94,530	Unintentional Other Transport 76,804	Unintentional Other Transport 47,077	Unintentional Unknown/ Unspecified 57,153	Unintentional Poisoning 679,890
10	Unintentional Cut/Pierce 5,863	Unintentional Poisoning 41,737	Unintentional Unknown/ Unspecified 43,323	Unintentional Dog Bite 32,094	Unintentional Poisoning 110,932	Unintentional Unknown/ Unspecified 94,099	Unintentional Unknown/ Unspecified 82,900	Unintentional Foreign Body 66,069	Unintentional Foreign Body 38,586	Unintentional Other Specified 45,418	Unintentional Other Transport 672,284

Figure 1.1 Unintentional injury in the year 2007 by age group in the United States.

1.2 CONTRIBUTING FACTORS TO SLIP, TRIP AND FALL ACCIDENTS

Normal walking necessitates the performance of complex processes involved in the initiation of movements and balance maintenance. Two major causes of falling, slips and trips, will be investigated in this dissertation. These two perturbations require different postural responses to prevent falling. To prevent the initiation of slipping, the retarding or frictional forces at the foot-floor interface must be sufficient to counteract shear forces generated by the forward motion of the foot as it hits the floor and body weight is transferred to it. Since the shear forces are highest shortly after heel contact, the ground reaction forces occurring at that time are of critical importance in determining whether the frictional capabilities of the foot-floor interface will be sufficient to prevent slips. Specifically, an increased risk of slipping is assumed as the peak shear to normal ground reaction force ratio, also called peak required coefficient of friction ($RCOF_{peak}$), exceeds the measured or available foot-floor coefficient of friction (COF) [10, 11]. In order to avoid a fall after a slip is initiated, the body must generate a quick and effective corrective response to re-establish dynamic balance and maintain an upright posture while continuing with the locomotion task [12].

Recovery following a trip is also a dynamic task involving concentric and eccentric joint moments. Evidence linking increased risk of trip-initiated falls with decreased lower extremity strength and slower responses following the perturbation has been shown [13-16]. Other factors associated with increased risk of trip-precipitated falls included faster walking speed at trip onset, stooped gait, delayed recovery responses (e.g. landing of the tripped foot and responses of the lower extremity muscles), inadequate positioning of the recovery foot during the positioning phase, inability to arrest trunk flexion, changes in neural control and reduced toe clearance [9, 13, 17-19]. Pavol and colleagues also underlined the critical role of the hips in recovering from a trip and the ability to effectively use the support limb to slow the fall appears to be of equal importance in determining the outcome of a trip [13, 20].

1.3 AN APPROACH TO MOTOR LEARNING AND THE IMPORTANCE OF PROACTIVE POSTURAL ADJUSTMENTS

One approach in treating individuals with balance disorders is to expose patients to varied gait experiences on different surfaces in different situations. The underlying theory of such a therapeutic approach, referred to as the systems model theory, indicates that balance is not based on a fixed set of equilibrium reflexes ("feedback" reflexes) but on flexible, functional motor skills that can adapt with training and prior experiences [21] emphasizing goal-directed neural organization of multiple interacting systems [21, 22]. Thus, in the context of this systems model theory, the classification of balance as a motor skill suggests that balance can be improved with repeated exposures. Specifically, when equilibrium is unexpectedly challenged, "online" sensory inputs and cortical inputs providing stored information based on previous experiences partially determine reactive motor balance recovery responses. This study investigated the possibility of reducing the incidence of falls in older adults through learning to better recover based on a systems model theory. In this study, short-term evaluations of this approach were conducted in situations where subjects are aware of the type of perturbation and, more importantly, when participants are uncertain of the nature of the balance-challenging event. The findings of this study can open the door to studies evaluating the long-term benefits of systems model theory based fall interventions. For example, one could foresee the potential benefits of therapeutically exposing individuals at risk of falling to slippery surfaces at the beginning of the winter season to improve their chance of recovering from a slip on ice.

The central nervous system (CNS) must routinely compensate for external perturbations that occur during gait to maintain balance. Compensation can take the form of feedforward or feedback (e.g. reflexes) control. Feedforward responses, or proactive postural adjustments, precede the onset of a predictable perturbation and attempt to counteract the expected destabilizing effect of the perturbation [23, 24]. One critical requirement for maintaining balance during gait is the ability to generate proactive postural adjustments in the face of external perturbations. These adjustments might include alterations in the body's center of mass (COM) state (e.g. repositioning of the COM with respect to the base of support, modifying the COM's velocity) and changes in gait patterns (e.g. increased knee/hip flexion). Feedforward control can significantly reduce the reliance on reactive responses triggered by the onset of the perturbation ("feedback control"). There is evidence from novel tasks indicating that, when exposed to perturbations of some known characteristics or nature, the CNS adapts its feedforward control [25-27]. However, it is presently unclear how the CNS might feasibly employ feedforward adjustments to reduce the likelihood of a balance loss in the event of an external perturbation during gait.

1.4 PREVIOUS FINDINGS AND VOIDS IN THE LITERATURE

Several studies have investigated repeated and multiple exposures to slips [27-42]. Pavol and colleagues investigated proactive strategies using a perturbed sit-to-stand testing paradigm [28]. Early studies found older adults to initially be at greater risk than young adults to fall from a novel and unexpected perturbation [28]. However, healthy older adults learned to avoid falling comparable to young adults with no evidence in age-related limitations in the acquisition of motor skills. In more recent studies, repeated exposures to slips produced in laboratory settings mimicking real-life situations has been tested to explore the effectiveness of training reducing balance loss and improving stability [26, 27, 30, 43, 44]. With repeated exposure to perturbed and non-perturbed conditions, subjects began to adapt towards an optimal strategy that allowed a balance loss to be avoided under both conditions [26]. This same group later showed reduced fall incidence to be achieved through both proactive adaptations of the sit-to-stand performance and adaptive changes in the reactive response to slipping [27, 30]. This indicates that healthy older adults appear fully capable of learning to better recover from or adjust to a perturbation through repeated exposure. In addition, a related study found proactive adjustments in pre-slip stability to influence post-slip decreases in the base of support (BOS) velocity which resulted in overall improvements in stability [26]. Such improvements from the repeated exposure training were suggested to persist even in unperturbed conditions [26]. Adaptations to perturbations that persisted in subsequent trials in the absence of the perturbation were later referred to as "aftereffects" [33]. These adaptations to repeated exposures were rapidly acquired, age–independent and other studies also reported similar proactive gait adjustments adopted in environments perceived to be slippery including reduced heel velocity and foot floor angle at foot contact, decreased step length, changes in knee and hip moments, increased cadence and elevation in vertical COM position [34, 35, 38, 39, 43, 45-48].

Despite extensive research, questions still remain regarding the ability of repeated exposure learning to transfer over different types of perturbations. It is also currently unclear how the CNS responds to multiple exposures to different types of perturbations when presented randomly and without knowledge. This has been part of our motivation for this study. Previous trip studies have indicated that the probability of successful balance recovery after a trip is much lower in elderly individuals compared to young adults [18, 19]. But the answer to the question as to why older adults fall from a trip more is unknown. Repeated exposures to trips have been studied to a lesser extent. Most studies investigating tripping have either only exposed subjects to one trip [9], studied only young adults [20, 49] or focused on the recovery responses and reactive mechanisms after tripping [14, 15, 17, 50-52]. Pavol et al. were amongst the first to study trips in older adults [9, 13, 53] where they found lower extremity strength to play both a beneficial and maladaptive role. On the one hand lower extremity strength enabled the execution of an adequate trip recovery response. However, as stronger people walk faster, walking too fast was shown to increase recovery demands following a trip [13]. Other studies involving multiple trips have focused on the obstructed swing limb and descriptions of recovery kinematics and muscle responses [13, 17, 49, 54-56]. Pavol et al. ascribed falls after tripping to the slower execution of the recovery strategy in older adults which was shown to be related to the ability to generate large ankle and hip extension moments, an ability diminished in older adults and especially fallers. In general, contribution of the support limb to recovery is also limited in older adults [50]. More recent studies have investigated arm movement differences in young and older adults and found young adults to rely on arm movements to elevate the body COM as a means of reducing forward angular momentum of the body [57]. Although much information has been disseminated regarding differences in trip recovery between young and older adults, limited information is available regarding age-related proactive adaptation differences observed during tripping and how these adaptations may differ with concurrent presentation of another type of perturbation.

The role of prior knowledge and experience on proactive postural adjustments has also been largely investigated. Previous studies have shown subjects to behave differently after one exposure [34, 35, 38, 58]. Large foot floor angles at foot contact prior to the unexpected slips were reduced in remaining slip trials. Heiden et al. found subjects to adapt optimally with both awareness of and experience with the perturbation [41]. In a related study, actual mechanisms of adaptation did not differ much between age groups with the exception that foot floor angle was significantly reduced in older adults [58]which is evidence of older adults' likeliness to adopt a more cautious gait when aware of a potential threat to balance. In tripping, Pijnappels et al. found gait kinematics of younger adults to be minimally affected by anticipation when forewarned of a trip. No study has simultaneously investigated the effect of multiple exposure, knowledge and experience on slips and trips on the same set of subjects.

1.5 BACKWARD WALKING AS A NOVEL TASK

In addition to forward gait, this study tested backward walking activities. This choice of task is based on two factors. First, in the therapeutic systems model theory approach mentioned previously, successful balance maintenance during walking requires the ability to adjust motor postural responses to various environmental and task constraints. Changing the direction of locomotion is one way to vary the task constraints and this method has been explored in various gait/mobility research and in clinical and therapeutic settings [59-64]. Indeed, although backward walking is not a commonly performed task, such activity can provide information concerning the ability of the CNS to generate and to adjust postural motor responses when performing unfamiliar tasks. In contrast to forward walking, backward walking is not a preprogrammed activity and thus it might be associated with greater demands for attentional resources [59]. Also, the dynamical sensory cues (e.g. visual, proprioceptive) will be different between the two gait activities resulting in potentially different strategies for maintaining balance [59]. In spite of the task-related differences, research supports that forward and backward walking are run from the same motor program which facilitates the comparison of postural motor responses between the two gait activities. Specifically, Winter suggested that “backward walking is almost a simple reversal of forward walking” [65]. Others have put forward the idea that a central program for locomotion regulates reflex pathways [60] and kinematic patterns [62] for both forward and backward walking. Thus, this study shed light on the capabilities of the CNS to process/integrate sensory information that is relevant to balance while performing familiar (forward walking) and non-familiar (backward walking) gait activities and to generate and adjust postural responses when balance is challenged.

1.6 THE CURRENT STATE OF TRAINING, RETENTION AND THE JOURNEY TOWARDS THE DEVELOPMENT OF SUCCESSFUL FALL INTERVENTION PROGRAMS

To date, fall intervention programs have had limited success. Several exercise interventions have been proposed to prevent falls in older adults including resistance training, endurance training and balance training [17, 66-70]. However, the most effective method of training considering exercise intensity and type has yet to be determined. Some programs have had a prophylactic effect, others have had no effect and others have actually increased the incidence of falls [67, 71-73].

As opposed to the commonly practiced exercise based interventions, research is moving in the direction of motor learning based interventions. Pai and Bhatt refer to repeated exposure training as one of the potentially most beneficial yet underutilized intervention strategies available [33]. Through motor training in situations resembling real-life, it is believed that older adults can strengthen their own neuromuscular protective mechanisms to reduce fall incidence. The maintenance of posture and balance during locomotion necessitates the need for human beings to readily and constantly be able to adapt to changing environmental and task constraints. The ability to transfer motion state adaptations to changing environmental and task constraints has been said to be one of three critical components in motor learning along with acquisition and retention [74]. Practicing movements is one way that individuals can relearn. In fact, greater challenges to posture and balance have been associated with increased motor learning abilities [75].

Bhatt and Pai have led the way in repeated exposures to slipping as a means of motor learning. Past studies have shown that with just one to two trials, loss of balance incidence was reduced 80% [43, 44]. In addition, adaptive motor improvements were shown to be retained for several months. The primary objective of a more recent study was to determine whether gait stability improvements acquired on a repeated slip exposure trained limb could transfer immediately to the untrained contralateral limb [32]. Partial immediate transfers of gait stability were observed on the untrained contralateral limb. The untrained limb also continued to show improvements which persisted for up to 1-month but started to deteriorate over a long-term 4-month interval [32]. These improvements were accomplishable with only one slipping exposure on the untrained side per retest session. This study provided evidence that information acquired through repeated exposure training can be generalized, applied to the contralateral (untrained) side and retained for an extended period of time. A later study also supported that the CNS could generalize neuromechanical responses acquired through motor training in different environmental contexts, i.e. different types of forward slips (moveable platform vs. slippery floor) [31, 76]. Both of the aforementioned training protocols were conducted on young adults.

However, to assess whether aging-related declines affected the ability to learn in postural tasks involving different functional requirements, a study was conducted on young and old comparing acquisition of motor skills in sit-to-stand slips versus movable platform slips [58, 77]. With repeated slip exposure in both tasks, older adults learned to resist falls comparably to and just as rapidly as young adults. In fact, large reductions in fall incidence were observed after only one slip exposure in each task and adaptation rates were not shown to differ between the tasks. This study did not investigate retest sessions. Therefore, the ability of older adults to retain learned motor skills over an extended period of time remains to be determined. This study shed light on adaptation abilities across tasks. However, the transfer of adaptations acquired in a specific task to recovery from different types of perturbations and directions of perturbations remains unknown.

Other groups have investigated trip training to improve recovery and reduce the number of falls occurring as the outcome of a trip. One approach exposed older subjects to a simulated trip that necessitated a recovery step to clear the obstacle resembling recovery following an actual trip [66]. Repeated exposure to a simulated trip on a treadmill was used to enable subjects to learn a strategy that would improve recovery kinematics following a trip. This study provided evidence that motor skills acquired through repeated exposure training on a treadmill proved beneficial in improving recovery kinematics following a trip while walking over ground [66]. Resistance training targeted to increase muscle strength and therefore improve the push-off reaction and thus trip recovery was carried out in another trip training pilot study [19]. Strength measures increased over the marked training period, however, significance in the trip recovery measures were not observed although slight improvements were seen. This study gave further merit to the question of whether strength training, task-specific training of motor skills or a combination of both would prove most effective in developing a training tool specific to trips. The determination of optimal parameters for motor learning across different perturbations and considerate of age remains to be achieved.

2.0 OBJECTIVE OF RESEARCH

Balance maintenance during walking requires the ability to adjust postural responses to various environmental and task constraints. One critical requirement in maintaining balance when exposed to an external perturbation, a slip/trip, is the ability to generate a proactive postural adjustment. Such adjustments precede the onset of a predictable perturbation in attempts to counteract any destabilizing effect that a slip/trip may have. This study aimed at investigating this ability among younger and older adults in different conditions. The overall effect of postural adjustments was assessed using derivations of the motion analysis data collected in the laboratory. Comparisons of familiar and novel tasks yielded insight into the CNS' ability to perform and adjust postural motor responses in gait activities that are not preprogrammed. Simultaneously investigating proactive adaptations to slips and trips in the same group of young and old adults showed whether knowledge and experience have the capacity to improve anticipatory performance in one, none or each of the presented perturbations.

2.1 PURPOSE AND LONG TERM GOAL

The purpose of this study was to gain a better understanding of abilities to generate proactive postural adjustments in balance-challenging environments. Specifically, potential associations between aging and the ability to generate these proactive postural adjustments were of particular interest. Proactive postural adjustments have been studied in older adults during slips, but to a lesser extent in trips. This study investigated how repeated exposures to perturbations, multiple exposures to perturbations, familiarity versus novelty of gait tasks, knowledge, experience and uncertainty each play a role in the ability to generate proactive postural adjustments as well as the ability to successfully employ optimal perturbation recovery responses. The goal of this research was to provide evidence to suggest that task specific training in the form of repeated and/or multiple exposures to both slip and trip perturbations, the two main causes of falls, is effective in helping adults adopt beneficial proactive adaptations that reduce the incidence of falls. The long-term goal of this research is to aid in the development of intervention and rehabilitation regimens that focus on a motor learning approach to help older adults reduce the incidence of falls in a cost-effective, easily implemented fashion.

2.2 RESEARCH QUESTIONS

2.2.1 Research Question #1

How might the CNS feasibly employ feedforward adjustments to reduce the likelihood of a balance loss in the event of an external perturbation during gait? How might the CNS feasibly employ feedforward adjustments to reduce the likelihood of a balance loss during a novel task?

2.2.2 Research Question #2

Could the systems model theory applied to perturbations during gait be an effective component in the enhancement of interventions to reduce the incidence of falls?

2.2.3 Research Question #3

Is this effective for different types of perturbations simultaneously investigated?

2.3 SPECIFIC AIMS

2.3.1 Specific Aim #1

To investigate potential associations between aging and anticipatory postural strategies when repeatedly exposed to slip or when exposed multiple times to slip/trip stimuli while walking forward.

2.3.2 Specific Aim #2

To examine the impact of the novelty of the gait activity on proactive postural adjustments in the face of slipping hazards and to compare the findings between young and older adults.

2.3.3 Specific Aim #3

To compare how young and older adults optimize their anticipatory gait adjustments when uncertain of the nature of the perturbation.

2.3.4 Specific Aim #4

To investigate potential associations between aging and perturbation recovery responses when exposed multiple times to slip and trip stimuli while walking forward and to compare how young and older adults optimize their perturbation recovery responses when uncertain of the nature of the perturbation.

3.0 POSTURAL ADAPTATIONS DURING REPEATED EXPOSURE TO FORWARD AND BACKWARD SLIPPING IN HEALTHY YOUNG AND OLDER ADULTS

3.1 ABSTRACT

Balance maintenance during walking requires the ability to adjust postural responses to various environmental and task constraints. This study investigated the differences in proactive postural adjustments adopted when exposed to a slip during a familiar gait task, walking forward, and an unfamiliar gait task, walking backward. Furthermore, this study aimed to describe aging-related differences observed in these proactive strategies. Eighteen younger (ages 21-35) and thirteen older (ages 65-75) adults participated in this study. Subjects experienced an unexpected slip followed by five repeated, known slips in each direction. Postural adaptations, changes in COM state and slip-risk related kinematic data, were evaluated 50 ms before foot contact. In the forward direction older adults exhibited gait alterations of greater magnitudes and took more exposures to reach a steady state. Older adults executed cautious strategies in the novel task demonstrated by immediate significant changes compared to more gradual changes observed in young adults. The CNS was able to make internal representations to a novel task for both young and older adults.

3.2 INTRODUCTION

Aging is associated with the loss of pre-programmed motor patterns involved in functional stability and balance [78]. As a result, older adults over the age of 65 have a 30 to 50% chance of experiencing a fall each year [1, 79]. The financial toll for older adult falls is expected to increase as the population ages, possibly reaching an estimated $54.9 billion by the year 2020 [6, 80]. These anticipated costs could potentially be reduced with the successful development of interventions targeted at reducing fall incidence in older adults. One approach in treating individuals with balance disorders is to expose patients to varied gait experiences on different surfaces in different situations. The underlying theory of such a therapeutic approach, referred to as the systems model theory, indicates that balance is not based on a fixed set of equilibrium reflexes but rather on flexible, functional motor skills that can adapt with training and prior experiences [21]. On the basis of this theory and classifying balance as a motor skill, it is believed that balance can be improved with repeated exposure to a particular perturbation [21, 22].

To maintain balance, the central nervous system (CNS) must routinely compensate for external perturbations during gait. One form of such compensation is feedforward control, referred to as proactive postural adjustments, which precedes the onset of a known perturbation in attempts to counteract the expected destabilizing effect of the perturbation [28, 31]. One critical requirement for maintaining balance during gait is center of mass (COM) control. COM adaptations were shown to be impacted by both experience with and knowledge of a slip perturbation [33, 41, 58]. In a recent study, the ability to rapidly acquire fall-resisting skills on repeated slip exposure remained intact at older ages and across different tasks [58]. It is presently unclear how the CNS might feasibly employ proactive postural adjustments to reduce the likelihood of a balance loss in the event of a perturbation during a novel gait task.

Successful balance maintenance during walking requires the ability to adjust postural responses to various task constraints such as changing the direction of locomotion [59-64]. The literature supports that forward and backward walking are run from the same motor program [61, 81] and this facilitates a comparison between forward and backward walking as a familiar and novel task, respectively. Information regarding the ability of the CNS to generate and adjust postural responses when performing unfamiliar tasks as well as whether abilities to generate proactive adjustments are task specific may emerge from such comparisons. To date, potential associations between aging and the ability to generate proactive postural adjustments when balance is challenged during a novel gait task has not yet been investigated [26-28, 33].

The purpose of this study is two-fold: (1) To investigate potential associations between aging and anticipatory postural strategies when repeatedly exposed to a familiar task, a slip while walking forward and (2) To examine the impact of the novelty of the gait activity, a slip while walking backward, on proactive postural adjustments and to compare the findings between young and older adults. Adaptations to whole body COM state, foot floor angle and cadence were compared when repeatedly exposed to the same slip perturbation in the forward and backward directions for both young and older adults. This was done to observe changes in proactive strategies with knowledge and increased exposure to the perturbations. The findings of this study add further insight to potential long-term benefits of systems model based interventions.

3.3 METHODS

Eighteen young (ages 21-35) and thirteen old adults (ages 65-75) screened for neurological and musculoskeletal abnormalities were recruited for participation (Table 3.1). Written informed consent was obtained prior to participation according to the University of Pittsburgh Institutional Review Board. Exclusion criteria included a clinically significant condition that would impede normal/independent gait and balance.

Table 3.1 Subject characteristics.

			Age (years)		**Height (cm)**		**Body mass (kg)**	
	Female	Male	Mean	SD	Mean	SD	Mean	SD
Young	8	10	27.9	4.9	174.8	7.0	72.7	13.5
Old	5	8	68.9	3.1	172.7	8.9	77.8	11.7

3.3.1 Subjects, experimental equipment and conditions, protocol

Subjects walked along an 8.5 m long vinyl-tiled walkway. An eight M2-camera VICON® 612 (VICONPeak, Lake Forest, California) 612 motion measurement system recorded three-dimensional motion data captured at 120 Hz from 81 reflective markers placed on the body and shoes (Figure 3.1). All subjects wore the same shoes. Ground reaction forces captured at 1080

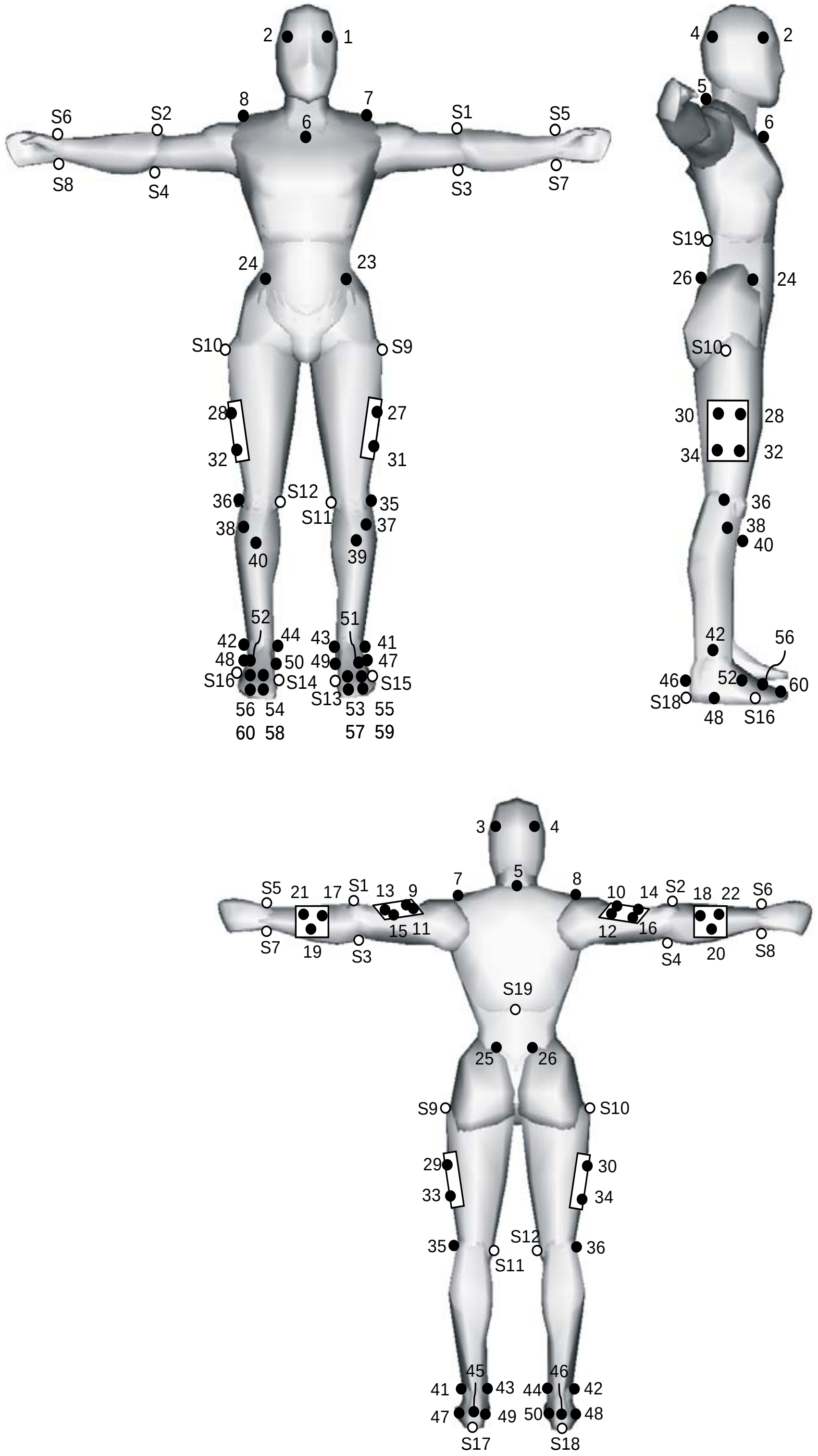


Figure 3.1 Human Movement and Balance Laboratory custom marker set. All markers are present for calibration in the static trial. In dynamic trials, all markers with an S are removed due to common obstructions of these markers.

Hz were measured on two Bertec® (Bertec Corporation, OH, USA) type 4060a force plates embedded into the walkway 3 and 4 meters from the start of the walkway for the right foot and left foot, respectively. Subjects were equipped with a safety harness during all trials to prevent them from hitting the ground in the event that an irrecoverable loss of balance occurred. The trolley was operated by a lab staff member to stay above the subject while walking and did not impede gait. Slips were induced with a 40-ml sample of glycerol solution (90% glycerol: 10% water) applied uniformly by the same experimenter in all slip trials for consistency over the second force plate (60 x 40 cm) such that the left foot came in contact with the slippery area. Contact paper was also applied to the bottom of the shoes in all trials to enhance slipperiness. The testing environment was illuminated by ceiling mounted halogen lights which were dimmed throughout the experiment to reduce visibility of contaminant in unaware trials.

Experimental conditions included two walking directions, forward (FW) and backward (BW), at a self-selected speed. The presentation order of these conditions was randomized. After baseline gait data were collected within each walking direction, subjects were exposed to one unexpected slip immediately followed by five repeated slips. In the unexpected slip (US), subjects had no knowledge that the glycerol had been applied to the floor and expected a dry, non-slippery floor. In the five repeated slips (RS1…RS5), subjects were told they would experience the same type of perturbation consecutively and to try to regain their balance and continue walking. Only three slips within each walking direction were included in the analyses, namely, US, RS1 and RS5. The rationale of the selected trials was the US served as a baseline, RS1 was the first trial with knowledge of the upcoming slips with minimal experience and RS5 had knowledge and the greatest level of exposure to the perturbation.

3.3.2 Data analysis and statistics

Center of mass (COM) position and velocity in the anterior-posterior (COM_{AP}), medial-lateral (COM_{ML}) and vertical (COM_{V}) directions, cadence and foot floor angle at heel contact in FW and toe contact in BW were the dependent variables of interest. COM position was calculated using a weighted average of 13-segmental COM locations [39] with the following equation:

$$COM_{body} = \frac{\sum m_i a_i}{\sum m_i} \qquad \textbf{(1)}$$

where m is the mass of the segment, a is the location of the segment center of mass and i represents the individual segment. Segment masses and segment COM locations were determined as per de Leva [82]. COM position was measured with respect to the ankle of the slipping foot 50 milliseconds prior to foot contact to investigate COM adaptations. COM_{AP} and COM_{V} were normalized to leg length prior to analyses. COM position was first filtered using a zero-phase low pass filter passband 6 Hz, stopband 15 Hz and then derived to compute COM velocity. Foot contact was determined from minimum vertical velocity of the heel in FW and of the toe in BW. Foot floor angle was always taken at foot contact of the slipping foot and cadence was determined from the first and last foot contact points in the trial.

JMP® 8 (SAS Institute Inc.) was used for all statistical analyses. A mixed linear model was fit to each dependent variable (COM state, cadence and foot floor angle) as the response variable; age group (YA/OA), direction (forward/backward), trial (US/RS1/RS5) and interactions as fixed effects; and subject as a random effect. Appropriate contrasts were constructed to make comparisons of interest. Statistical significance was set at α=.05.

3.4 RESULTS

Associations between aging and anticipatory postural strategies when repeatedly exposed to a familiar task, a slip while walking forward were observed. The unexpected slip served as a baseline and old adults had a more superiorly located COM_V position (p = .0421) (Table 3.2). No other differences existed between age groups in the FW unexpected slip. Old adults immediately reduced COM_{AP} velocity .13 m/s (p = .0208; Figure 3.2) while young adults reduced foot floor angle 9º (p = .0032; Figure 3.2) in the first repeated exposure slip, RS1, with knowledge that the slip would occur and minimal slip experience (1 prior slip). With increased exposure in FW RS5 (5 prior slips), the COM of old adults was less posterior to the ankle (p = .0138) as they continued to reduce COM_{AP} velocity compared to young adults (p =.0003). Young versus old difference in how adaptations to COM_{AP} velocity were affected by repeated exposure was -.178 m/s (p = .016). Both young and old adults significantly reduced foot floor angle (p < .001 and p < .0001, respectively) in the FW RS5 trial. Age group differences were found to be significant in three of the eight dependent variables in the FW RS5 trial. These variables include the COM_{AP} velocity (p = .0063), COM_V velocity (p = .0003) and foot floor angle (p = .05) (Table 3.2).

Table 3.2 Center of mass state, cadence and foot floor angle mean values (standard deviation) for both age groups and directions.

	Forward					
	Young			**Old**		
Variables	Unexpected slip	Repeated slip Mean (*SD*)	5th Repeated slip	Unexpected slip	Repeated slip Mean (*SD*)	5th Repeated slip
COM$_{ML}$ position (cm)	72.2 (30.7)	81 (34.6)	77.1 (34.2)	86.1 (20.3)	89.7 (14.5)	91.2 (22.2)
COM$_{AP}$ position (/leg length)	.286 (.146)	.269 (.111)	.251 (.153)	.352 (.055)	.294 (.0691)	.270 (.0675)
COM$_{V}$ position (/leg length)	.879 (.335)	.893 (.341)	.893 (.341)	1.03 (.0355)	1.05 (.0373)	1.05 (.0398)
COM$_{ML}$ velocity (m/s)	-.0462 (.0422)	-.0693 (.0343)	.0463 (.0449)	-.0479 (.0369)	-.0689 (.0515)	-.0398 (.0556)
COM$_{AP}$ velocity (m/s)	1.26 (.174)	1.23 (.233)	1.24 (.246)	1.18 (.267)	1.05 (.313)	.972 (.319)
COM$_{V}$ velocity (m/s)	-.190 (.0510)	-.193 (.0511)	-.200 (.0695)	-.150 (.0586)	-.147 (.0813)	-.115 (.0739)
Cadence (steps/minute)	109 (16.7)	115 (18.3)	122 (22.4)	111 (18.8)	116 (21.3)	119 (23.9)
Foot floor angle (deg)	19.3 (9.00)	10.5 (8.94)	9.36 (9.27)	15.8 (10.0)	9.38 (9.85)	2.02 (8.96)

	Backward					
	Young			**Old**		
Variables	Unexpected slip	Repeated slip Mean (*SD*)	5th Repeated slip	Unexpected slip	Repeated slip Mean (*SD*)	5th Repeated slip
COM$_{ML}$ position (cm)	93.3 (21.9)	98.0 (24.7)	91.5 (22.5)	73.3 (36.1)	77.5 (33.4)	75.9 (31.1)
COM$_{AP}$ position (/leg length)	.344 (.0547)	.344 (.0497)	.330 (.0812)	.287 (.141)	.300 (.118)	.265 (.114)
COM$_{V}$ position (/leg length)	.935 (.0455)	.951 (.0388)	.956 (.0463)	.911 (.241)	.917 (.236)	.926 (.239)
COM$_{ML}$ velocity (m/s)	.114 (.0455)	.101 (.0653)	.100 (.0458)	.0894 (.0423)	.0625 (.0758)	.0804 (.0584)
COM$_{AP}$ velocity (m/s)	.918 (.218)	.862 (.228)	.877 (.264)	.823 (.325)	.676 (.306)	.693 (.346)
COM$_{V}$ velocity (m/s)	-.121 (.0729)	-.102 (.0445)	-.123 (.101)	-.0890 (.0611)	-.0648 (.0351)	-.0592 (.0493)
Cadence (steps/minute)	109 (32.1)	116 (35.8)	122 (35.9)	111 (24.1)	121 (34.7)	111 (38.9)
Foot floor angle (deg)	43.0 (11.2)	37.5 (13.8)	34.5 (12.1)	35.8 (12.0)	27.6 (12.6)	28.9 (8.27)

Center of mass (COM) position and velocity in the anterior-posterior (COM$_{AP}$), medial-lateral (COM$_{ML}$) and vertical (COM$_{V}$) directions. Positive COM$_{ML}$ position and velocity indicates COM medial to the ankle of the slipping foot and COM$_{ML}$ is moving medially over time, respectively. Positive COM$_{AP}$ position and velocity indicates COM posterior to the ankle of the slipping foot and COM$_{AP}$ is moving anteriorly (where anterior refers to the direction of motion) over time, respectively. Positive COM$_{V}$ position and velocity indicates COM located superiorly to the ankle of the slipping foot and COM$_{v}$ is moving superiorly over time, respectively. Positive foot floor angle indicates a toes-up position in the forward direction and a toes-down position in the backward direction.

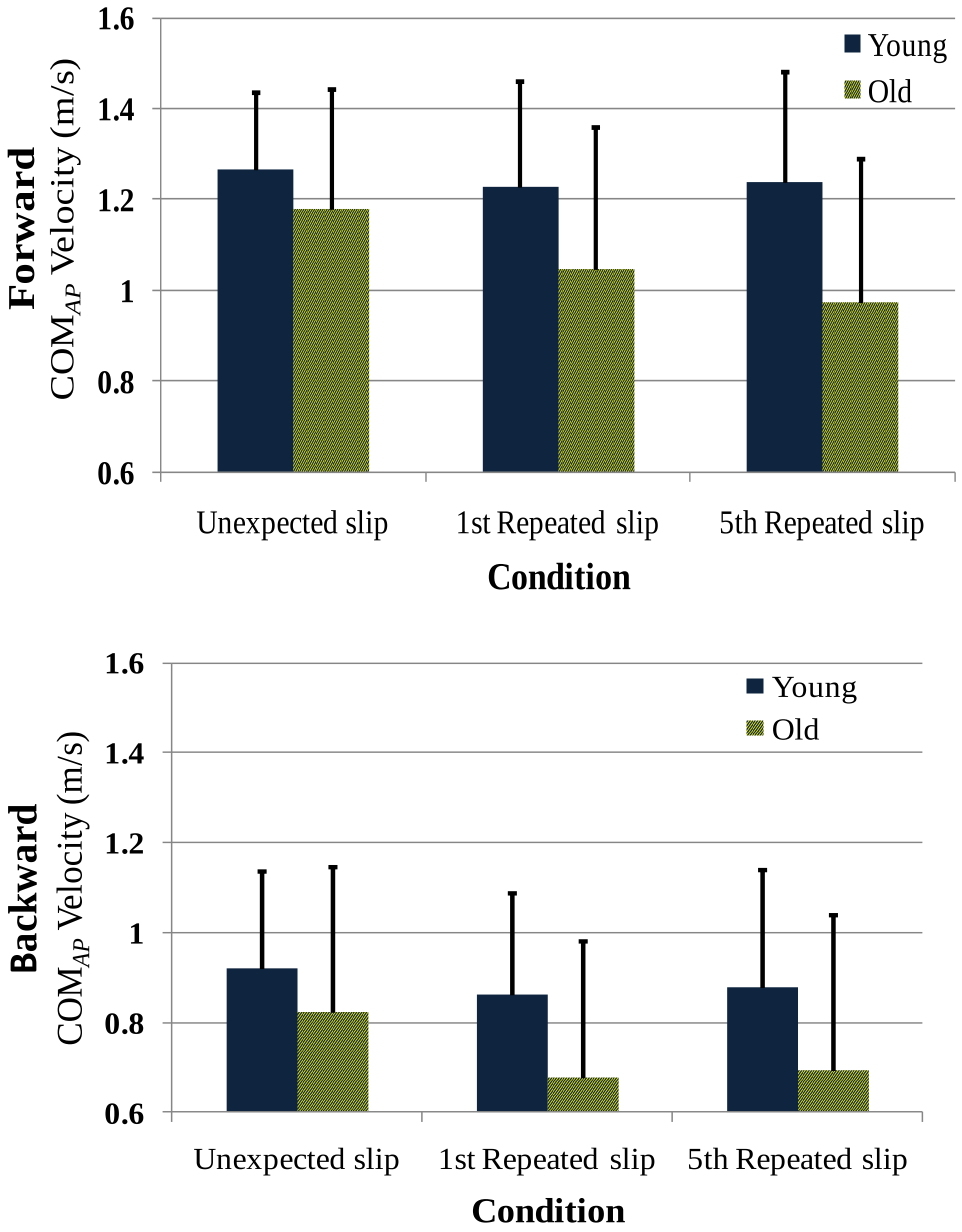


Figure 3.2 COM$_{AP}$ velocity for the forward (top) and backward (bottom) directions across repeated exposure trials. Old and young adults are depicted as striped and solid bars, respectively. Standard deviations are represented. Positive indicates the COM$_{AP}$ velocity is moving anteriorly. Old adults significantly reduced COM$_{AP}$ velocity in the forward and backward directions. No change was observed in COM$_{AP}$ velocity for young adults in either direction.

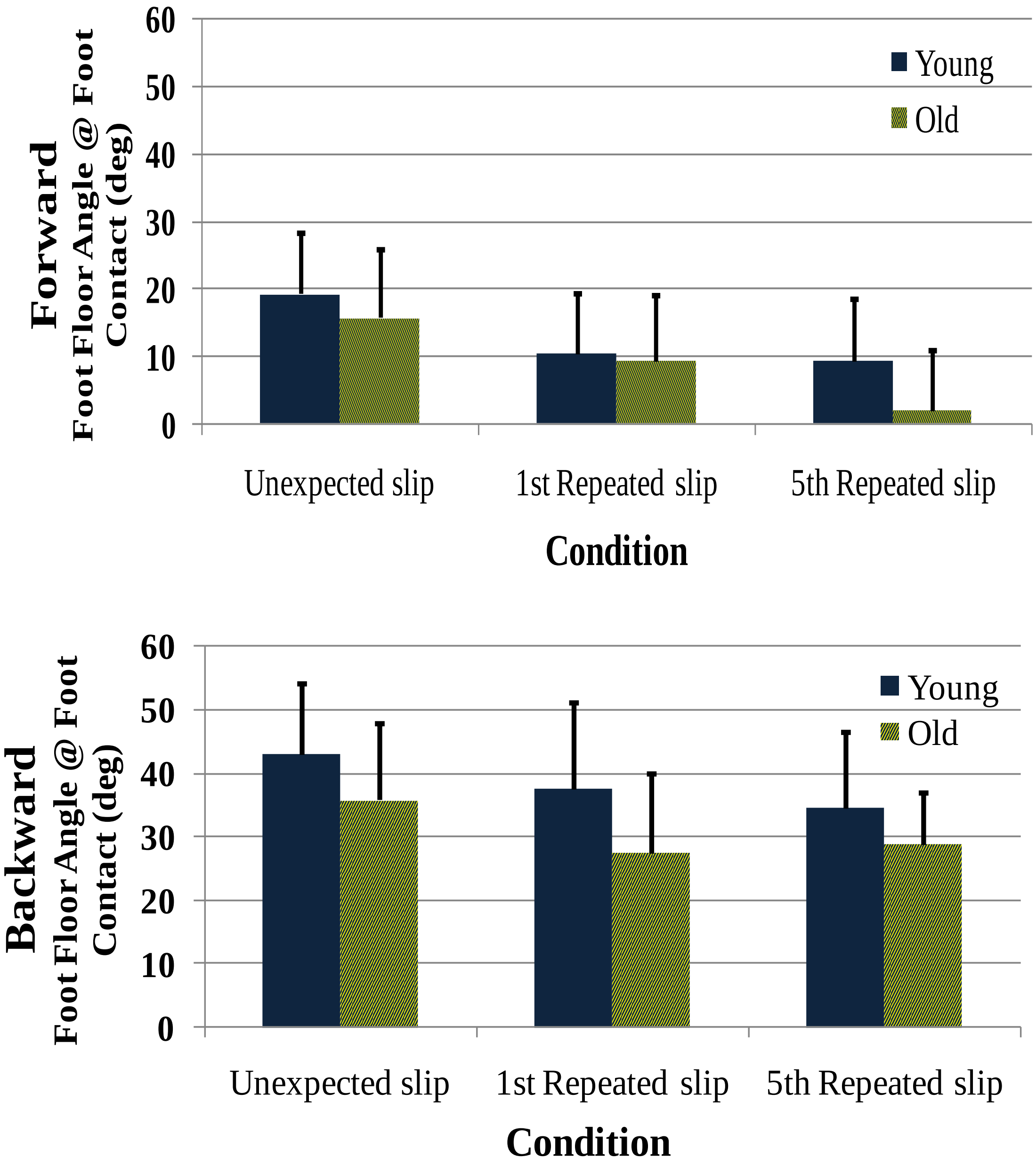


Figure 3.3 Foot floor angle for the forward (top) and backward (bottom) directions across repeated exposure trials. Old and young adults are depicted as striped and solid bars, respectively. Standard deviations are represented. Positive foot floor angle indicates toes-up in the forward direction and toes-down in the backward direction at foot contact. Both young and old adults significantly reduced foot floor angle in both directions.

Proactive adaptations were impacted by age in the backward walking slip, novel task. In the BW unexpected slip, the COM in young adults was 20 cm more medial to the ankle and they walked with a 7º larger foot floor angle at toe down. No other differences existed between age groups in the BW unexpected slip. Age group differences in the BW RS1 trial were observed for COM_{ML} position (p = .0322) and velocity (p = .0312), COM_{AP} velocity (p = .0328) and foot floor angle (.0097). Young adults' COM was more medial to the ankle and moved .04 m/s faster medially and .2 m/s faster anteriorly while having a 10º larger foot floor angle at toe down. In comparison, old adults significantly reduced COM_{AP} velocity .15 m/s (p = .0093) and foot floor angle 8º (p = .0202) in the BW RS1 trial. Old adults continued to reduce COM_{AP} velocity in the BW RS5 trial (Figure 3.2). In addition, both young and old adults significantly reduced foot floor angle by almost 10º (p = .0047 and p = .0501, respectively; Figure 3.3). Old adults had a .06 m/s slower COM_{V} velocity compared to young adults (p = .0062) and was the only significant difference between age groups in the BW RS5 trial.

When comparing whether adjustments differed when performing the novel as opposed to the familiar task significant observations were made. Unexpected slip trial adaptations significantly differed between directions in all variables except COM_{V} position and cadence in young adults and COM_{ML} position and cadence in old adults (Table 3.2). The following were observed in the BW US compared to the FW US. COM_{AP} position increased 6% in young adults (p = .0376) and decreased 7% in old adults (p = .0504). COM_{AP} velocity decreased .3 m/s in young adults (p < .0001) and .4 m/s in old adults (p < .0001). COM_{ML} position increased 21 cm in young adults (p = .001). COM_{ML} velocity increased .07 m/s in young adults (p < .0001) and .04 m/s in old adults. COM_{V} position decreased 12% in old adults (p = .0498). COM_{V} velocity decreased .07 m/s in young adults (p < .0001) and .06 m/s in old adults (p = .001). Foot floor angle increased 24° in young adults ($p < .0001$) and 20° in old adults ($p < .0001$). Age groups adapted similarly between conditions and there were no age differences in how novelty of the gait task impacted proactive adaptations.

3.5 DISCUSSION

The present study investigated potential associations between aging and anticipatory postural strategies when repeatedly exposed to a familiar task, a slip while walking forward and examined the impact of the novelty of the gait activity, a slip while walking backward, on such associations. Our hypothesis that repeated exposure to a familiar task would result in a greater number of trials needed to achieve steady state adaptations in older adults was supported. However, our hypothesis that gait alterations would be of smaller magnitude in older adults was not supported. We also hypothesized subsequent exposures to a novel balance-perturbing task compared to a largely pre-programmed activity would result in postural adjustments of different magnitude. This hypothesis was also not supported. Comparable to other studies, it was found that both young and older adults were capable of adapting with repeated exposures in both directions [26-28, 33, 58]. However, the mechanisms of adaptation were found to differ with age.

Older adults did take a greater number of exposures to reach steady state in the forward direction; however, the overall magnitudes of their gait alterations were actually greater. Their adaptations occurred gradually in the familiar task compared to immediately in the novel task. As the novel task represented an activity with which subjects were less familiar, it is possible that older adults adapted more rapidly using cautious strategies to promote balance maintenance.

Older adults immediately made significant adaptations in the novel task which may be attributed to delivery of the script at the beginning of the repeated exposure trials informing subjects they would now experience the same perturbation consecutively. This agrees with previous studies that found adaptations to occur within one slip trial and gait to be more cautious when subjects had awareness of and experience with the perturbation [33, 34, 38, 41, 58]. This observation was also unique to older adults providing support that the warning may affect young and older adults differently in an unfamiliar situation which can be associated with heightened anxiety due to a known threat to balance [1]. Young adults made more gradual changes to establish a strategy for balance maintenance in both directions with foot floor angle adaptations being the exception.

As differences were observed between the forward and backward directions in the unexpected slip trials before any within direction slips had been performed, gait changes were induced by the nature of the task alone. Age groups adapted similarly between directions with some exceptions. In the novel task, young adults had an increased safety margin between the COM and boundaries of the supporting area provided by a widened base of support represented by COM_{ML} position. As mediolateral stability has also been used to discriminate fallers from non-fallers and to predict the likeliness of falls to the side [45, 83, 84], this finding may suggest mediolateral stability to discriminate age-related proactive capability differences when performing a novel task. Postural adjustments did not differ with subsequent exposure in a novel compared to a familiar task.

Adaptive mechanisms differed within each direction between age groups. Although both groups reduced COM_{AP} velocity in the novel task, young adults did not modulate it within directions like older adults. Slower walkers have been shown to be more unstable at slip onset

[85] and restricted in the mechanisms and magnitudes with which one can adapt. Such cautious behavior observed only in older adults could therefore be a maladaptive strategy.

Several studies have investigated repeated exposure to slips [27, 28, 33, 85], novel task slips [27, 28, 33], slips resembling real-life slips [31, 34, 58] and the effects of knowledge and experience [38, 41]. However, this is the first study to our knowledge that looks at slipping while walking forward, a highly pre-programmed activity, and slipping while walking backward, a novel activity that utilizes the same central pattern generator (CPG), on the same group of subjects inclusive of both healthy young and old adults. Only 65-75 year olds meeting all inclusion criteria with health comparable to the young adults were tested in this study and our subject population appeared to be very robust. It is likely that with a subject pool inclusive of older and frailer adults, stronger differences in the COM state and cadence would emerge between age groups. The slips used in this study were extremely slippery and highly resembling of real-life slips. Subjects were informed the study would entail slipping when consented; however, we do not feel this to be a limitation based on their lack of familiarity with the protocol. It is feasible that proactive adjustments observed in this study could be applied to the nature of gait to be expected by people knowingly walking outside on a sheet of ice. It may be a limitation that subjects were only truly naïve in their first slipping direction. However, we randomized direction order to minimize this impact. Also, it should be stated that adaptations observed in the present study reflected what subjects actually did and not their capabilities.

The CNS was able to create internal representations [33], generalized motor programs resulting in adaptive changes in gait, applicable to a novel task for both young and older adults. Adaptations with repeated exposure were more impacted by age than novelty of the task. Young adults did not modulate gait speed and increased mediolateral stability, both of which are known to be beneficial adaptations. Overall, both young and older adults demonstrated proactive postural strategies in response to challenges to balance during familiar and unfamiliar tasks. These results are insightful because with repeated exposure older adults can learn to adapt to maintain balance even in novel gait tasks having had no prior training and/or experience comparable to young adults. It is insightful that older adults were able to immediately generate proactive adaptations during an unfamiliar task. Such rapid adaptations in the unfamiliar task are associated with an increased challenge and a greater threat to balance in older adults. This may support familiar tasks presented with greater complexity in repeated exposure trainings may expedite motor learning capabilities and possibly long-term retention. Further investigation must be done to yield support for this approach in consideration for the development of long-lasting, effective interventions to reduce the incidence of falls in older adults.

4.0 PROACTIVE ADAPTATIONS TO SLIPS AND TRIPS: DOES KNOWLEDGE AND/OR EXPERIENCE WITH FALLING HAZARDS MATTER?

4.1 ABSTRACT

This study investigated proactive strategies adopted in anticipation of slips and trips when knowledge of and experience with the specific perturbation was provided. Differences in the proactive strategies adopted when uncertain of the nature of the perturbation were also of interest. Aging-related differences in the alterations of these anticipatory gait adjustments were also compared. Sixteen young and thirteen older healthy adults participated. Subjects experienced slip and trip perturbations where knowledge/no knowledge was provided. Dependent variables included foot-floor angle and minimum toe clearance due to the correlations of these gait variables with the risk of slip/trip-initiated falls. Proactive adaptations to slips and trips were found to be perturbation specific as evident by a modulation in responses known to benefit perturbation recovery. This study provides insight into possible avenues for the improvement of perturbation performance which could easily be incorporated into fall intervention programs.

4.2 INTRODUCTION

Falls and fall-related injuries are the origin of many adverse outcomes affecting socialization, mental and physical health and related health care costs. In 2000, direct medical costs totaled \$179 million for fatal falls and \$19 billion for nonfatal fall injuries [7]. With an aging workforce, balance challenging environments encountered in the workplace pose an even greater threat and therefore an increased concern for falls in the elderly. Such environments include slipping and tripping hazards, which account for over 50% of falls in the elderly [86-88]. Nearly 5% of all falls result in fracture and 5-11% result in other serious injuries [5]. In the year 2000, 2.6 million non-fatal fall injuries required medical treatment in older adults [7].

Postural responses required to recover from a slip are different than those needed to recover from a trip. However, for both slipping and tripping perturbations, the ability to generate proactive postural adjustments prior to the onset of the perturbation is critical to the maintenance of balance. Proactive adaptations precede a predictable perturbation which means knowledge of the perturbation must be provided. Knowledge of the perturbation has induced proactive adaptations in both slips and trips. Older adults have been shown capable of exhibiting proactive adjustments to the center of mass comparable to those of young adults in repeated exposure to slipping [27]. Anticipatory behavior has also been observed in tripping where differences in step width and foot clearance were found to be affected by being forewarned that a trip would occur [89]. It has also been reported that experience with a perturbation also improves proactive capabilities [35, 38, 41]. The strategies adopted by older adults in anticipation of a slip and with repeated exposure to slips has been described [27-29, 31-33, 39, 43, 44]. However, to date, studies on tripping are limited in that they either involved only one exposure to a trip, tested only young adults or focused on recovery responses [9, 17, 20, 56, 89].

A better understanding of differences in postural adjustments adopted by young and older adults in anticipation of a tripping hazard is needed.

In summary, the goal of this study is to investigate the differences in proactive strategies adopted in anticipation of slips and trips when knowledge of the specific perturbation is provided. Aging-related differences in these abilities will also be investigated. To our knowledge no study exists that simultaneously investigates proactive postural adaptations to slipping and tripping on the same group of subjects inclusive of young and older adults. Changes in foot floor angle are a known anticipatory adjustment specific to slipping. When knowledge is provided that a slip will occur or after individuals have experienced a slip, foot floor angle is typically reduced to decrease the risk of slipping in consequent trials [34, 35, 38, 39]. In tripping, a known anticipatory adjustment involves toe clearance [18]. With knowledge that a trip will occur or after experiencing a trip, individuals have been shown to increase minimum toe clearance in efforts to reduce impact with the obstacle or to clear the obstacle with the toe [9, 56, 89-91]. Thus, in this study we will focus on foot-floor angle and toe clearance due to the correlations of these gait variables with the risk of slip/trip-initiated falls, respectively.

4.3 METHODS

4.3.1 Subjects, experimental equipment and design, protocol

Sixteen younger (YA) (ages 21-35) and thirteen older (OA) adults (ages 65-75), screened for neurological and musculoskeletal abnormalities, were recruited for participation (see Table 4.1 for subject characteristics).

Table 4.1 Subject characteristics and spatial-temporal values (mean ± standard deviation).

Variable	Young (*n* =16; 9M,7F)	Old (*n* =13; 8M,5F)
Age (yrs)	27 ± 5	70 ± 3
Height (cm)	175 ± 8	173 ± 9
Weight (kg)	72 ± 13	77 ± 11
Gait speed (m/s)	1.2 ± 0.2	1.1 ± 0.2
Cadence (steps/minute)	104 ± 11	106 ± 13

Written informed consent was obtained prior to participation according to the University of Pittsburgh Institutional Review Board. Exclusion criteria included a clinically significant neurological, musculoskeletal, cardiovascular and/or orthopedic disease and the presence of any difficulty that would impede normal walking or an ability to walk and stand independently. Additionally, older adults were screened for osteoporosis (T-score ≤ -2.5) to minimize the risk of testing those with osteoporosis.

Participants were instrumented with reflective markers and walked across a vinyl tile walkway while whole-body motion and kinetic data were captured at 120 and 1080 Hz, respectively [39]. Subjects were equipped with a safety harness during all trials to prevent them from hitting the ground in the event that an irrecoverable loss of balance occurred. All subjects wore the same tight-fitting outfit and shoes. Next, subjects were allowed to practice walking prior to data collection and instructed to walk at a comfortable pace while looking straight ahead in a dimmed environment to reduce the possible detection of a contaminant placed on the floor in the slippery condition.

The experimental design consisted of four blocks of trials (Table 4.2). Block 1 was always presented first. In Block 1, the baseline block, five unperturbed gait trials were collected.

Subjects were assured that no perturbation would occur during these trials. The following two blocks of trials, Blocks 2 and 3, were presented in a random order.

Table 4.2 Description of four trial blocks.

Block	Prior Knowledge	Perturbation Type
(1) 5 unperturbed trials – Baseline	Yes, subject was reassured that no perturbation would occur in the next set of trials	None
(2) 3 slips randomly inserted into a series of 5 unperturbed trials	Yes, subject informed of the type of perturbation at the beginning of the block but not exact timing	Slip, None
(3) 3 trips randomly inserted into a series of 5 unperturbed trials	Yes, subject informed of the type of perturbation at the beginning of the block but not exact timing	Trip, None
(4) 3 trips and 3 slips randomly inserted into a series of 10 unperturbed trials	No, subject was not informed of the specific type of perturbation (slips/trips were mixed)	Slip, Trip, None

In these blocks, subjects were informed of the type of perturbation they would experience, slip or trip, however no knowledge of the exact timing of the perturbation was provided. At the beginning of the block before any trials had taken place subjects were told the following script, “In the next set of trials, at some point you will experience a (slip/trip).” In each of the perturbation blocks, slip block or trip block, 3 perturbation trials were randomly inserted into 5 unperturbed gait trials. In these blocks, an unperturbed walking trial was always the first trial in the block and at least one unperturbed walking trial separated perturbations. In the final block, Block 4 - the combo block, 3 slips and 3 trips were randomly inserted into a series of 10 unperturbed walking trials. In Block 4, subjects were not informed of the specific type of perturbation (combination of slips and trips) they would experience nor were they aware of the exact timing of the perturbations. Therefore, in Block 4, subjects had no prior knowledge. Before all trials in Blocks 2, 3 and 4, subjects were instructed to turn and face the wall 1-2 minutes while listening to loud music in the headphones and completing a word find puzzle.

This was done to maintain uncertainty as to the timing of the perturbations by distracting subjects from the later application of contaminant/preparation for the trips.

4.3.2 Perturbation paradigms

Slips were induced with a glycerol solution (90% glycerol: 10% water) [39]. Additionally, contact paper was applied to the bottom of all shoes to make the floor more slippery. Trips were induced by an in-house designed apparatus (Figure 4.1). Detection of center of pressure in excess of 15 N on the forceplate immediately following right heel contact triggered activation of a solenoid driven obstacle system embedded in a wooden box on the floor adjacent to the force plate. The pull solenoid released a caliper-eyebolt-spring mechanism that pushed out a 37¼” L x 1¼” W x 3½” H trip slide approximately 90 ms after heel contact. Eight foam covered plexiglass trip obstacle slides were hidden over a 60 cm distance and the appropriate slide based on location of the center of pressure shot out to catch the subject at midswing of the left foot.

Figure 4.1 Tripping device (bottom side up (left) and solenoid-caliper-eyebolt-spring assembly (right).

4.3.3 Data analysis and statistics

For each subject only the last baseline trial (Baseline), the walking trial immediately following the script (Knowledge) and the walking trial before the last perturbation (Experience) in each block were analyzed. We focused on these trials specifically because of our research interests in (*i*) baseline gait patterns representing the subject's natural walking, (*ii*) the impact of the warning script before any perturbations on gait adaptations and lastly (*iii*) gait adaptations that occur with experience with two known perturbations (in the slip and trip blocks) and with mixed perturbations (in the combo block). As mentioned previously, dependent variables included common measures of the risk of slips and trips. More specifically, sagittal foot floor angle at heel contact was evaluated due to the established correlation of this variable with slips [38, 39] and minimum toe clearance for its relation to trips [18, 92-94].

JMP 8 was used for all statistical analyses. A mixed linear model was fit with foot floor angle or minimum toe clearance as the response variable; age group (YA/OA), condition (Baseline / Slip Knowledge / Slip Experience / Trip Knowledge / Trip Experience / Combo Knowledge / Combo Experience), interaction between these variables as fixed effects; and subject as a random effect to account for the same subject performing under multiple conditions. Appropriate contrasts were constructed for comparisons of interest (see Appendix A). Statistical significance was set at α=.05.

4.4 RESULTS

4.4.1 Slip block observations

In the slip block, (Block 2 or 3, knowledge provided), slip risk was reduced compared to natural walking. Foot floor angle was significantly reduced in both the knowledge and experience trials compared to the baseline trial ($p < .01$) for old adults. Adaptations to foot floor angle were made and persisted throughout the block. Old adults reduced foot floor angle by as much as 16º in the knowledge trial and reduced foot floor angle by 9º compared to baseline in the experience trial. Figure 4.2 shows the change in foot floor angle across conditions and between age groups. Baseline values of foot floor angle did not differ between age groups. However, older adults had a significantly reduced foot floor angle in the slip knowledge condition than younger adults ($p = .0001$). There was a significant difference in young and old adults' adaptations with knowledge of the slip. Specifically, young versus old difference in how foot floor adaptations changed with knowledge was -14º ($p = .0004$). No differences existed between the groups in the slip experience condition ($p = .4914$) as both young and old continued to significantly modulate foot floor angle from the baseline and knowledge conditions to the slip experience conditions ($p = .002$; .0167 and $p = .0018$; .0266, respectively). There was a significant difference in young and old adults' adaptations from only knowledge to knowledge plus experience with the slip. Young versus old difference in changes in foot floor angle from knowledge to knowledge plus experience was 13º ($p = .0013$). Similar trends were not observed for toe clearance in the slip block. Figure 4.3 highlights the changes in toe clearance across conditions and between age groups. No significant differences in toe clearance were observed for any trials in the slip block.

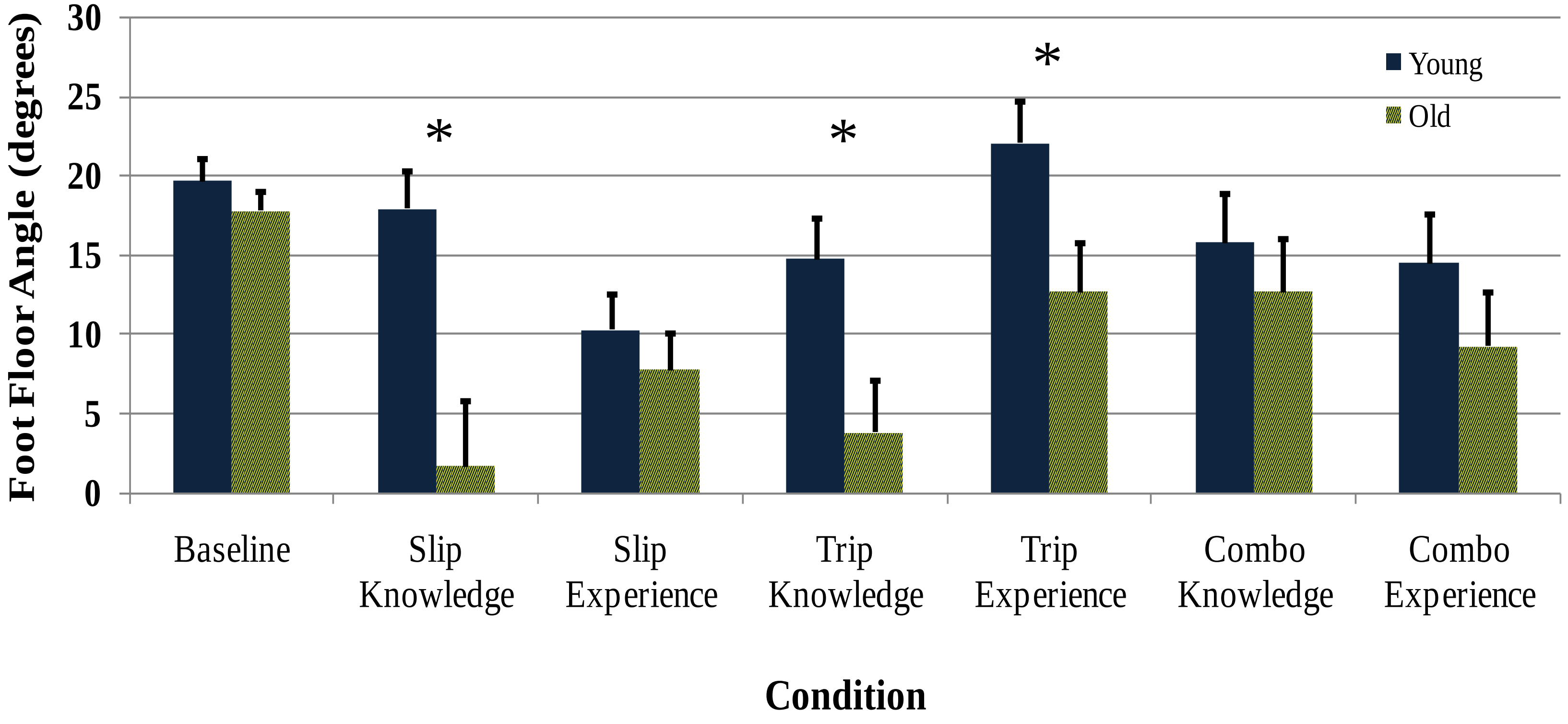


Figure 4.2 Changes in foot floor angle across conditions is shown for young (solid) and old (striped) adults. The asterisk indicates a significant difference between age groups ($p < .05$) in the slip knowledge, trip knowledge and trip experience conditions. Standard error bars are presented.

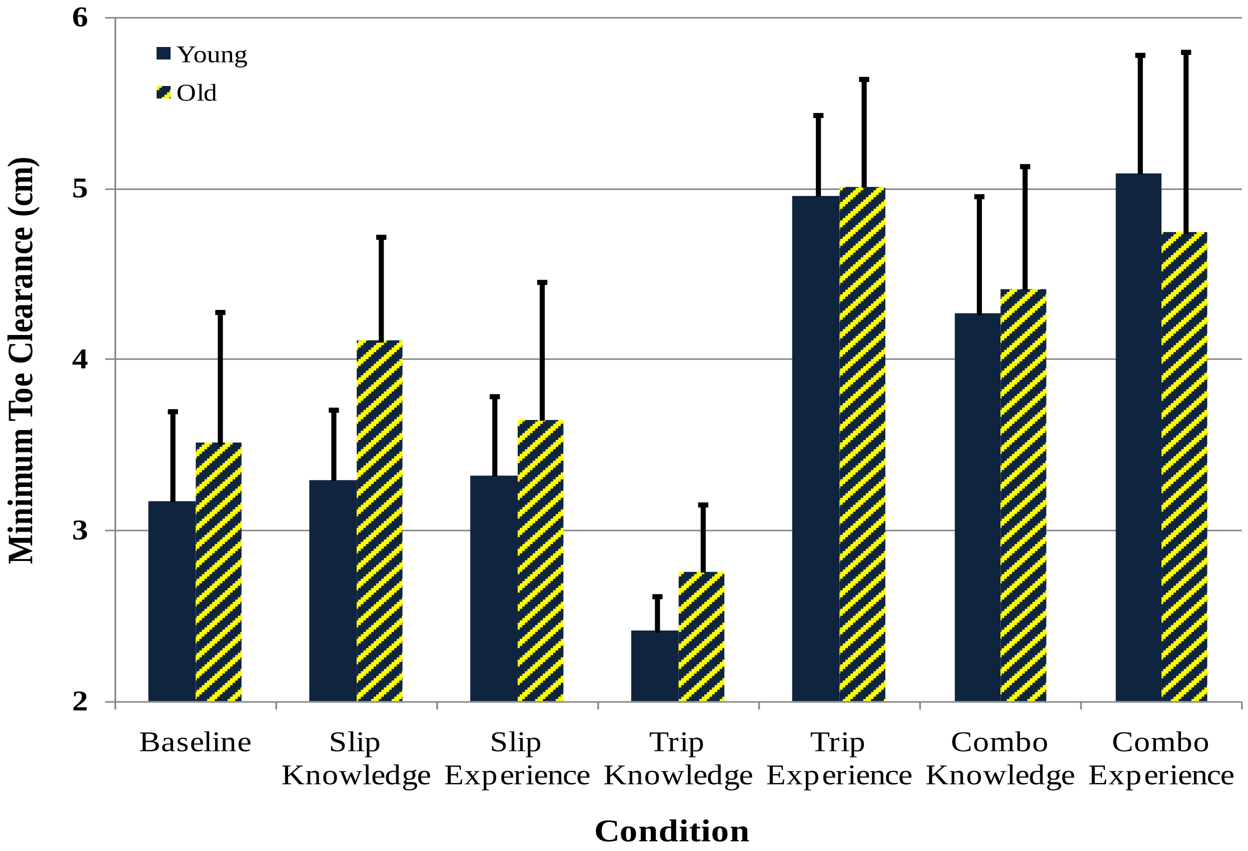


Figure 4.3 Changes in minimum toe clearance across conditions is shown for young (solid) and old (striped) adults. No significant differences existed between age groups within conditions. Standard error bars are presented.

4.4.2 Trip block observations

In the trip block, (Block 2 or 3, knowledge provided), trip risk was also reduced compared to natural walking. Initial changes in toe clearance, a decrease of 0.8 cm in the knowledge trial, did not differ from baseline. However, in the experience trial, toe clearance increased for old and young adults 1.8 cm and 1.5 cm, respectively, compared to baseline and these changes were found to be significant ($p = .059$ and $p = .013$) (Figure 4.3). This later increase in toe clearance in the trip experience condition was also significantly different from the knowledge trial as young adults increased toe clearance by 2.5 cm ($p = .0004$) and old adults 2.2 cm ($p = .0048$). No significant age group differences in toe clearance or age related changes in adaptations from knowledge to knowledge plus experience were observed. In the trip block, after being warned that a trip would occur old adults significantly reduced foot floor angle 14º in the knowledge trial compared to baseline ($p < .0001$) (Figure 4.2). Young adults showed a trend for significance and reduced foot floor angle 5º in the trip knowledge condition compared to baseline ($p = .0585$). Knowledge of the trip impacted young and old differently. Young versus old difference in the impact of knowledge on foot floor angle was 9º ($p = .0225$). After experiencing two trips and several unperturbed walking trials, foot floor angle in the trip experience condition returned to baseline values for both young and old adults. Beneficial adaptations in toe clearance were made throughout the trials within the trip block while adaptations to foot floor angle did not persist.

4.4.3 Combo block observations

In the combo block (Block 4, no knowledge provided), both slip and trip risks were reduced. Although no knowledge was provided at the beginning of the combo block, subjects began walking with a slightly reduced foot floor angle and a slightly increased toe clearance in the knowledge trial compared to baseline. The magnitude of the combo knowledge foot floor angle was less than baseline values but still greater than the initial reductions in foot floor angle that had been observed in either the slip or trip blocks (Blocks 2-3) where knowledge of the perturbations had been provided (Figure 4.2). Older adults' foot floor angle was significantly increased 11° in the combo knowledge condition compared to the slip knowledge condition ($p = .0003$). There was also a difference in how young and old adults changed their foot floor angle when uncertain of the nature of the perturbation. Young versus old difference in change in foot floor angle when no knowledge was provided compared to when knowledge was provided was 13° ($p = .0012$) in the slips and 8° ($p = .0482$) in the trips. For toe clearance, it was not until the combo experience condition that a significant increase compared to baseline occurred in young adults ($p = .0084$). Young adults increased toe clearance by 1.9 cm in the combo experience condition (Figure 4.3). There was a significant difference in how no knowledge compared to knowledge affected adaptations. Both young ($p = .0097$) and old ($p = .0369$) adults had a significantly greater minimum toe clearance in the combo knowledge condition compared to the trip knowledge condition. With experience, minimum toe clearance also increased significantly compared to the trip knowledge condition and this was observed for young ($p = .0003$) and old adults ($p = .0126$).

When comparing the adaptations made across conditions, post hoc comparisons show that initial changes in foot floor angle did not differ between slips and trips, but slips and trips did significantly differ from the knowledge trial of the combo block . The achieved toe clearance in the combo block was significantly different from that of the experience condition of the slip block (p = .0149) in young adults, but found to be similar to the experience condition of the trip block for both young (.839) and old (.737).

4.5 DISCUSSION

The purpose of this study was to investigate the differences in proactive strategies adopted in anticipation of slips and trips when knowledge of the specific perturbation was provided. We also sought to compare aging-related differences in the optimization of these anticipatory gait adjustments known to reduce falls precipitated by slips and trips. Present results show that both young and older adults are able to reduce slip and trip risk with knowledge of and experience with the perturbations. In both slips and trips, awareness of an upcoming perturbation alone was sufficient to induce proactive adaptations. In addition, experience with the perturbation in the absence of knowledge regarding the nature of the perturbation to be encountered (Block 4) proved sufficient in enabling both groups to adopt optimal anticipatory strategies that reduced the risk of falling from a slip or a trip when either was randomly presented.

One main finding of this study is proactive adaptations were found to be perturbation specific. For example, when warned of slipping, significant adaptations were observed in foot floor angle only and when warned of tripping, significant adaptations persisted in toe clearance only. However, when both slips and trips were presented without warning, significant adaptations in both foot floor angle and toe clearance were observed. As in other studies, actual mechanisms of adaptation did not differ much between age groups with the exception that foot floor angle was significantly reduced in older adults [58]. This is evidence of older adults' likeliness to adopt a more cautious gait. Our foot floor angle results agree with previous findings where foot floor angles at foot contact prior to the unexpected slip were reduced in remaining slip trials [34, 35, 38, 58].

Results of this study imply that older adults are capable of adopting strategies (reduced foot floor angle at heel contact) known to reduce the risk of slipping when anticipating a slippery floor. Other studies also reported similar findings [32, 34, 35, 38, 39, 58, 95]. In contrast, both older and younger adults lacked an immediate adaptation following the script in trip trials. Upon receipt of knowledge that subjects would experience a trip in the next set of trials, subjects did not immediately adopt a more cautious walking adaptation inclusive of increased toe clearance. This may suggest a lack of internal, preprogrammed strategies to utilize in anticipation of a trip. Repeated exposures to trips have been studied to a lesser extent than slips. Most studies investigating tripping have either only exposed subjects to one trip [9], studied only young adults [20, 49]or focused on the recovery responses and reactive mechanisms after tripping [14, 15, 17, 51, 52, 96]. Although much information has been disseminated regarding differences in trip recovery responses between young and older adults, limited information is available regarding age-related differences in proactive adaptation differences during tripping.

Another main finding of this study is knowledge of a known threat to balance is sufficient to activate the execution of proactive adaptations even when adults lack experience with the specific perturbation. When subjects were warned that they would experience a slip or trip perturbation (Blocks 2 and 3), gait patterns immediately deviated from baseline levels. However, adaptations specific and beneficial to the perturbation were only observed in knowledge trials where subjects had prior experience with the perturbation, in the current study, the slip block. A limitation to the study is that subjects had previously experienced the slipping paradigm in a previous visit so even when only knowledge was provided; the subjects were not completely naïve as to the conditions of the perturbation. Immediate responses observed in the slip and trip blocks were a result of knowledge whereas those in the combo block were adaptations that had been adopted due to prior experience in the current testing session. In the combo block, adaptations specific to slipping and tripping were maintained because both perturbations were occurring in the block. Although no knowledge was provided in this block it can be argued that after a subject had experienced one of each of the perturbations within the block naivety was gone and they were then anticipating both perturbations. As subjects continued to apply these adaptations with no knowledge of the type of perturbation ahead it can be said that an optimal strategy inclusive of both increased toe clearance and reduced foot floor angle was adopted by both old and young adults to minimize destabilization caused by the perturbations. These anticipatory strategies also increased the probability of successfully recovering balance in each type of perturbation. Previous studies have shown subjects to behave differently after one exposure [34, 35, 38, 58]. Other studies found subjects to adapt with both experience and awareness of the perturbation [40, 41]. Our results support these findings as our subjects had knowledge and experience with both perturbations when the most optimal adaptations were observed.

The process by which adaptations became perturbation specific was a unique observation. Adaptations immediately following the script, knowledge trials, were similar regardless of perturbation type. However, as subjects gained experience with the specific perturbations, later responses, as represented by those in the experience responses, became perturbation specific. When subjects were warned that they would experience a trip, foot floor angle was also initially reduced. However, after experiencing two trips and several unperturbed walking trials, a key observation is that subjects did not continue to reduce foot floor angle. In fact, foot floor angle returned to baseline values. This suggests that subjects did not continue to adapt foot floor angle in the tripping block because it was not an adaptation beneficial to tripping. With experience, the presence or absence of knowledge was no longer the driving force behind observed adaptations. This relates to other studies where subjects were similarly said to rely more on experience than knowledge [38, 40, 41]. This may suggest a tendency to initially execute all cautious strategies familiar to the individual when threatened of a balance-challenging environment, especially in older adults. Experience with the perturbation may enable the discontinuation of adaptations not beneficial to the perturbation while beneficial adaptations are continuously adopted. In this manner, the adaptations become curtailed to the specific type of perturbation as observed in the slip and trip blocks investigated in this study.

Studies investigating proactive strategies generated in anticipation of a threat to balance have described anticipatory postural adjustments that happen prior to the onset of a perturbation to reduce the destabilizing effects of the perturbation [28, 31-35, 38, 40, 41, 44, 46, 89]. The central nervous system seems capable of interpreting information about the expected environment and generating anticipatory adjustments to maintain postural control. One highly supported mechanism of how the central nervous system achieves this is by its development of internal models. If we accept that prior perturbation experience is more influential than knowledge or awareness alone, it may further support the existence of internal models in postural adaptations during gait as those that have been shown in arm movements and grip-force-load-force coupling [97-99]. The neuroplastic capabilities of the CNS are believed to generate representations of the human body and the environment with which it interacts known as internal models [100]. In these internal models, feedforward control is used to generate adaptations reflecting demands of a postural task [101]. As interaction increases with greater exposure to environments, the neural representations evolve to reflect the continuous learning that takes place. Kawato et al. hypothesized these internal models may play a part in generating anticipatory actions and later found fMRI evidence that the cerebellum acquires multiple, context specific internal models to adapt to different environmental situations [97, 102]. In addition, with adequate exposure to a robot generated perturbation force, unimpaired subjects were able to counteract the robot force during arm reaching movements [103, 104]. Similarly in the current study, with multiple exposures, subjects were able to adopt anticipatory postural adjustments that reduced their slip and trip related risk. It is highly likely that multiple and repeated exposures to slipping and tripping perturbations also create a preprogrammed response that is retained and later called upon in similar situations of postural threat in efforts to maintain balance and not be as destabilized by external perturbations. The existence of such a model would provide insight on the effectiveness of repeated (or multiple) exposure therapy as a means of fall prevention training.

In conclusion, with an aging workforce, the probability of increased occupational slip and trip accidents are of growing concern. This study has shown that knowledge alone can generate anticipatory strategies when forewarned of an upcoming perturbation. Further, with multiple exposures to the perturbation, postural adaptations to reduce falls risk are continuously adopted. It has also been shown that both young and old adults are capable of generating beneficial adaptations with limited training and that older adults tend to adopt even more cautious strategies when they have had experience with the particular perturbation. Old and young adults were able to have successful recovery outcomes when randomly presented with slips and trips based on their ability to adopt an optimal proactive strategy that prepared them for either perturbation. Lastly, proactive postural adjustments were found to be perturbation specific. With further research into the theory of repeated/multiple exposure training to foster the development of internal models along with the retention capabilities of such training, a feasible, cost-effective fall prevention tool could be on the horizon for implementation in occupational safety procedures.

5.0 MEASURES OF SEVERITY: DOES KNOWLEDGE AND EXPERIENCE IMPROVE SLIP AND TRIP RECOVERY?

5.1 ABSTRACT

More than one in three older adults fall each year and fall related injuries in older adults are often treated medically with the direct costs totaling an estimated $19 billion dollars [7]. This study investigated how the severity of a trip changes with awareness of the environmental hazard (knowledge) and/or with prior exposure. The impact of aging on this effect was also investigated. Sixteen young and thirteen older adults participated. Three blocks of gait perturbations were presented to each subject. In the first two (a slip or trip block), subjects were exposed to either slip or trip perturbations randomly inserted into unperturbed walking trials. At least one unperturbed walking trial separated all perturbation trials. Knowledge regarding the type of perturbation (slip or trip) was provided to the subject at the beginning of the first two blocks, however timing of the perturbation was not provided. In the third and final block, termed the “combo” block, subjects were not provided any information related to the perturbation type or the timing and a combination of slips and trips were randomly inserted into unperturbed walking trials. Dependent variables reflecting the severity of the trip perturbation included sagittal and frontal planes trunk kinematics (excursion and angular velocity). Overall, the results showed the destabilizing effects of the perturbations to diminish with prior exposure to trip

perturbations as both young and old adults were able to establish optimal postural responses to maintain balance even when uncertain about the nature of the balance perturbation.

5.2 INTRODUCTION

More than one in three older adults fall each year and fall related injuries in older adults are often treated medically with the direct costs totaling an estimated $19 billion dollars [7]. In addition to escalated economic costs, consequences of falls include fear of falling, decreased activity, functional deterioration, social isolation, depression, reduced quality of life and institutionalization [3]. Thus, there is an imperative need to develop intervention programs that reduce the occurrence of fall accidents. To achieve this, it is first necessary to establish that postural control motor skills can be adapted and retained through training and prior experiences which will later serve as the foundation for fall intervention programs.

Normal walking necessitates the performance of complex processes involved in the initiation of movements and balance maintenance. In these processes, the central nervous system (CNS) must routinely compensate for external perturbations that occur during gait to maintain balance. Such compensation can take the form of feedforward or feedback control. Feedback responses are quick, corrective responses generated immediately after a balance perturbation to re-establish balance and maintain upright posture while continuing the locomotor task [48, 105]. On the other hand, feedforward, or proactive, responses precede the onset of a predictable perturbation and attempt to counteract the expected destabilizing effect of the perturbation [26, 28]. Proactive postural adjustments, also called anticipatory strategies, generate flexible, motor skills that can adapt with training and prior experiences.

CNS compensation during two major causes of falling, slips and trips, have been previously investigated. Specifically, proactive strategies during repeated exposure to a perturbed sit-to-stand slipping paradigm found subjects began to adapt toward an optimal movement strategy that allowed balance loss to be avoided under perturbed and non-perturbed conditions [26, 28]. This and other studies also found young and older adults to be able to learn to avoid falling at similar rates [28, 38, 41]. In tripping, changes in spatial gait parameters were observed in young subjects when forewarned that a trip would occur [89]. When knowledge is provided regarding a particular perturbation, it is expected that proactive strategies in consequent trials will be observed. It is also expected that such anticipatory behavior will improve perturbation performance and therefore increase the chances of recovery.

In a recent study, proactive adjustments during slipping and tripping were found to be perturbation specific [46]. Subjects were provided knowledge as to the type of perturbation they would experience. In trials where they knew they would experience a slip, decreased foot floor angle was observed. Likewise, in trials where it was known that a trip would occur, increases in toe clearance were observed during swing. In a block that contained both slips and trips, both reduced foot floor angle and increased toe clearance were observed. It was apparent that with knowledge and prior exposure to the perturbation, there was a modulation in these perturbation specific adaptations in attempts to reduce the destabilizing effects of the perturbations. However, it is currently unknown whether the presence of such proactive adaptations was actually effective in reducing balance perturbations when exposed to slip and trip hazards.

The purpose of this study was three-fold: (1) to determine whether trip severity decreases with prior exposure; (2) to determine the effect of knowledge related to the nature of the perturbation (slip or trip) on the severity of such perturbation; and (3) to determine if increased exposure helps reduce trip severity when knowledge related to the nature of the perturbation (slip or trip) is not available. The presence of age-related differences in the aforementioned objectives was also investigated.

5.3 METHODS

Sixteen younger (YA) (ages 21-35) and thirteen older (OA) adults (ages 65-75), screened for neurological and musculoskeletal abnormalities, were recruited for participation (see Table 5.1 for subject characteristics). Written informed consent was obtained prior to participation according to the University of Pittsburgh Institutional Review Board. Exclusion criteria included a clinically significant neurological, musculoskeletal, cardiovascular and/or orthopedic disease and the presence of any difficulty that would impede normal walking or an ability to walk and stand independently. Additionally, older adults were screened for osteoporosis (T-score ≤ -2.5) to minimize the risk of bone fracture.

Table 5.1 Subject characteristics.

Variable	Young (*n* =16; 9M,7F)	Old (*n* =13; 8M,5F)
Age (yrs)	27 ± 5	70 ± 3
Height (cm)	175 ± 8	173 ± 9
Weight (kg)	72 ± 13	77 ± 11
Gait speed (m/s)	1.2 ± 0.2	1.1 ± 0.2
Cadence (steps/minute)	104 ± 11	106 ± 13

5.3.1 Subjects, experimental equipment and design

Participants were instrumented with reflective markers and walked across a vinyl tile walkway while whole-body motion and kinetic data were captured at 120 and 1080 Hz, respectively [39]. Subjects were equipped with a safety harness during all trials to prevent them from hitting the ground in the event of an irrecoverable loss of balance. All subjects wore the same tight-fitting outfit and shoes. Next, subjects were allowed to practice walking prior to data collection and instructed to walk at a comfortable pace while looking straight ahead in a dimmed environment to reduce the possible detection of a contaminant placed on the floor in the slippery condition.

Table 5.2 Description of the four trial blocks.

Block	**Prior Knowledge**	**Perturbation Type**
(1) 5 unperturbed trials – Baseline	Yes, subject was reassured that no perturbation would occur in the next set of trials	None
(2) 3 slips randomly inserted into a series of 5 unperturbed trials	Yes, subject informed of the type of perturbation at the beginning of the block but not exact timing	Slip, None
(3) 3 trips randomly inserted into a series of 5 unperturbed trials	Yes, subject informed of the type of perturbation at the beginning of the block but not exact timing	Trip, None
(4) 3 trips and 3 slips randomly inserted into a series of 10 unperturbed trials	No, subject was not informed of the specific type of perturbation (slips/trips were mixed)	Slip, Trip, None

The experimental design consisted of four blocks of trials (Table 5.2). Block 1 was always presented first. In Block 1, the baseline block, five unperturbed gait trials were collected. Subjects were assured that no perturbation would occur during these trials. The following two blocks of trials, Blocks 2 and 3, were presented in a random order. In these blocks, subjects were informed of the type of perturbation they would experience, slip or trip, however no knowledge of the exact timing of the perturbation was provided. At the beginning of the block before any trials had taken place subjects were told the following script, “In the next set of trials, at some point you will experience a (slip/trip).” In each of the perturbation blocks, slip block or trip block, 3 perturbation trials were randomly inserted into 5 unperturbed gait trials. In these blocks, an unperturbed walking trial was always the first trial in the block and at least one unperturbed walking trial separated perturbations. In the final block, Block 4 - the combo block, 3 slips and 3 trips were randomly inserted into a series of 10 unperturbed walking trials. In Block 4, subjects were not informed of the specific type of perturbation (combination of slips and trips) they would experience nor were they informed of the exact timing of the perturbations. Therefore, in Block 4, subjects had no prior knowledge. Before all trials in Blocks 2, 3 and 4, subjects were instructed to turn and face the wall 1-2 minutes while listening to loud music in the headphones and completing a word find puzzle. This was done to maintain uncertainty as to the timing of the perturbations by distracting subjects from the later application of contaminant/preparation for the trips.

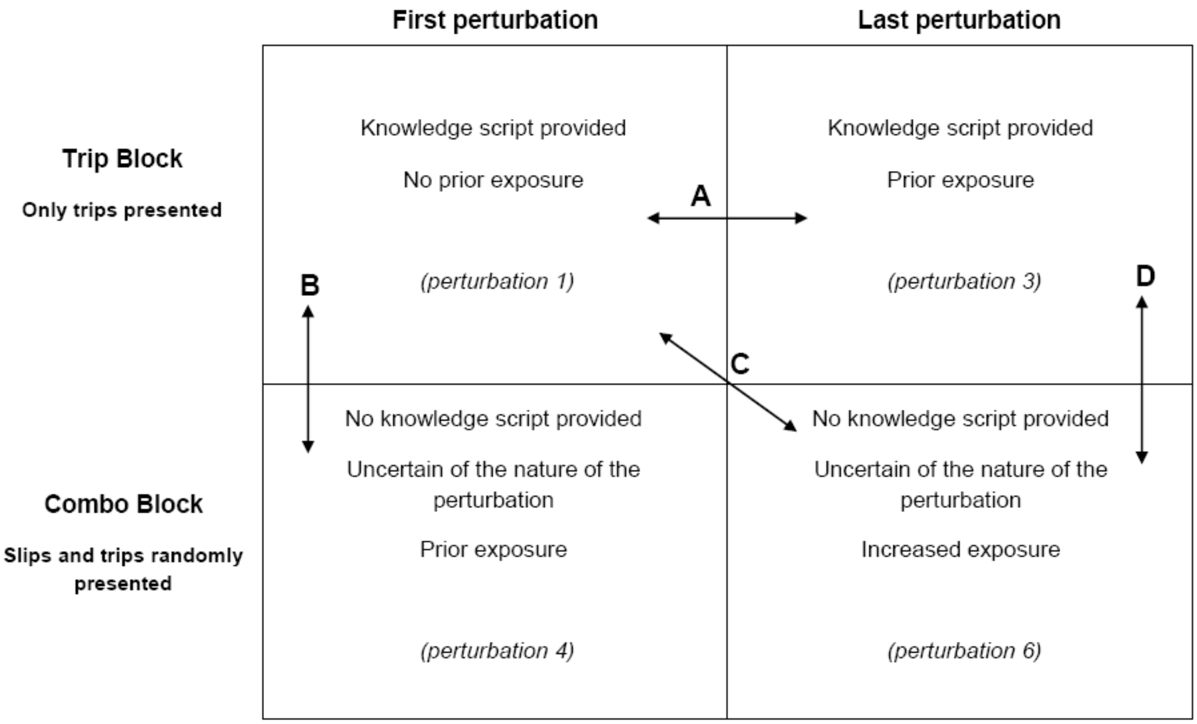
5.3.2 Perturbation paradigms

Slips were induced with a glycerol solution (90% glycerol: 10% water) [39]. Additionally, contact paper was applied to the bottom of all shoes to make the floor more slippery. Trips were induced by an in-house designed apparatus. Detection of center of pressure in excess of 15 N on the forceplate immediately following right heel contact triggered activation of a solenoid driven obstacle system embedded in a wooden box on the floor adjacent to the force plate. The pull solenoid released a caliper-eyebolt-spring mechanism that pushed out a 37¼” L x 1¼” W x 3½” H trip slide approximately 90 ms after heel contact. Eight foam-covered plexiglass trip obstacle slides were hidden over a 60 cm distance and the appropriate slide based on location of the center of pressure shot out to catch the subject at midswing of the left foot.

5.3.3 Data analysis and statistics

For each subject, only the first and last perturbation in the trip block and the first and last trip perturbation in the combo block were analyzed. The trials to be analyzed are described in Figure 5.1 and categorized by the knowledge and prior exposure conditions. Dependent variables included measures trip severity. Trunk kinematics play a critical role in the recovery outcome of trip perturbations and were the focal point of interest to gauge changes in severity of the perturbation with multiple exposures. Sagittal and frontal plane trunk kinematics were analyzed for the trips. Specifically, maximum instantaneous trunk flexion angle in the sagittal plane and maximum instantaneous angular deviation towards the ipsilateral side of the perturbed foot in the frontal plane were investigated. The time window was taken from obstacle impact to landing of the recovery foot. For a stable estimate of the angular velocities, mean trunk flexion and ipsilateral deviation velocities were also evaluated over the same time window. Trunk angle was defined as the angle between the trunk segment (midpoint of the shoulders and the posterior-superior iliac spine) and vertical. Trunk angular velocity was the time derivative of trunk angle.

JMP 8 was used for all statistical analyses. A mixed linear model was fit with each dependent variable (trunk flexion angle, trunk flexion velocity, angular ipsilateral deviation, angular ipsilateral deviation velocity); age group (YA/OA), condition (first trip, last trip, first combo trip, last combo trip), interactions between them as fixed effects; and subject as a random effect to account for the same subject performing under multiple conditions. Appropriate contrasts were constructed for comparisons of interest. Statistical significance was set at α=.05.



Planned comparisons

A: The impact of prior exposure given knowledge vs. knowledge

B: The impact of uncertainty of the nature of the perturbation given prior exposure vs. knowledge

C: The impact of increased exposure when uncertain of the nature of the perturbation vs. knowledge

D: The impact of increased exposure (6 perturbations) when uncertain of the nature of the perturbation vs. prior exposure (3 perturbations) given knowledge

Figure 5.1 Test matrix highlighting the planned comparisons (A-D) used to identify changes in perturbation severity. Figure adapted from [41].

5.4 RESULTS

Changes in measures of trip severity were influenced by prior exposure (3 tripping perturbations), knowledge of the nature of the perturbation and increased exposure (6 tripping perturbations). Prior exposure with the tripping perturbation affected trunk flexion angle at recovery foot contact. The greatest trunk flexion angles of 43º and 35º at recovery foot contact for young and old adults, respectively, were observed in the first trip condition of the trip block when only knowledge that subjects would experience a trip in the following set of trials had been provided. Young adults decreased trunk flexion angle at recovery foot contact 26º on their third exposure to a trip in the last trip of the trip block (p = .0001) compared to a reduction of only 6º in older adults. Figure 5.2 shows a typical unexpected trip at various time points. Figure 5.3 shows trunk flexion angle at recovery foot contact across tripping conditions for both young and old adults.

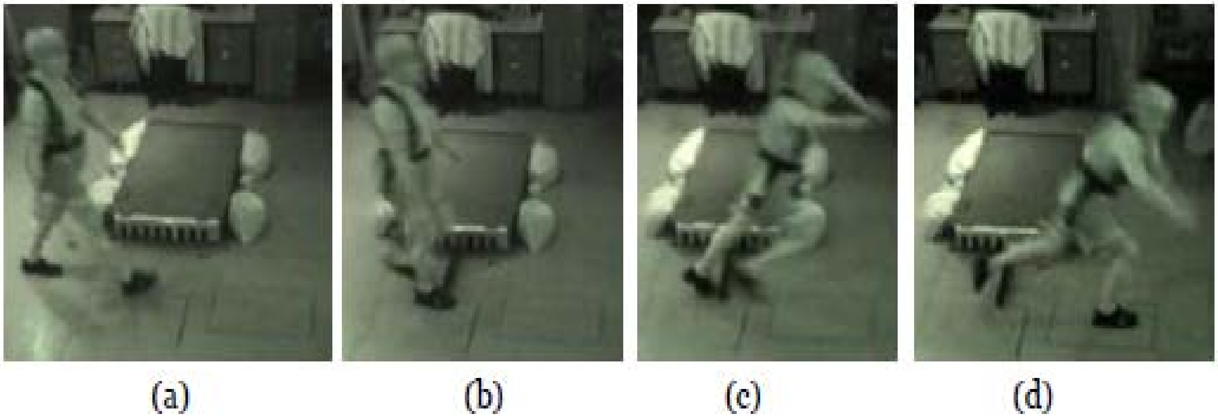


Figure 5.2 Unexpected trip pictured for one subject at a) right heel contact b) just before impact with the obstacle c) immediately after impact and d) landing of the recovery foot.

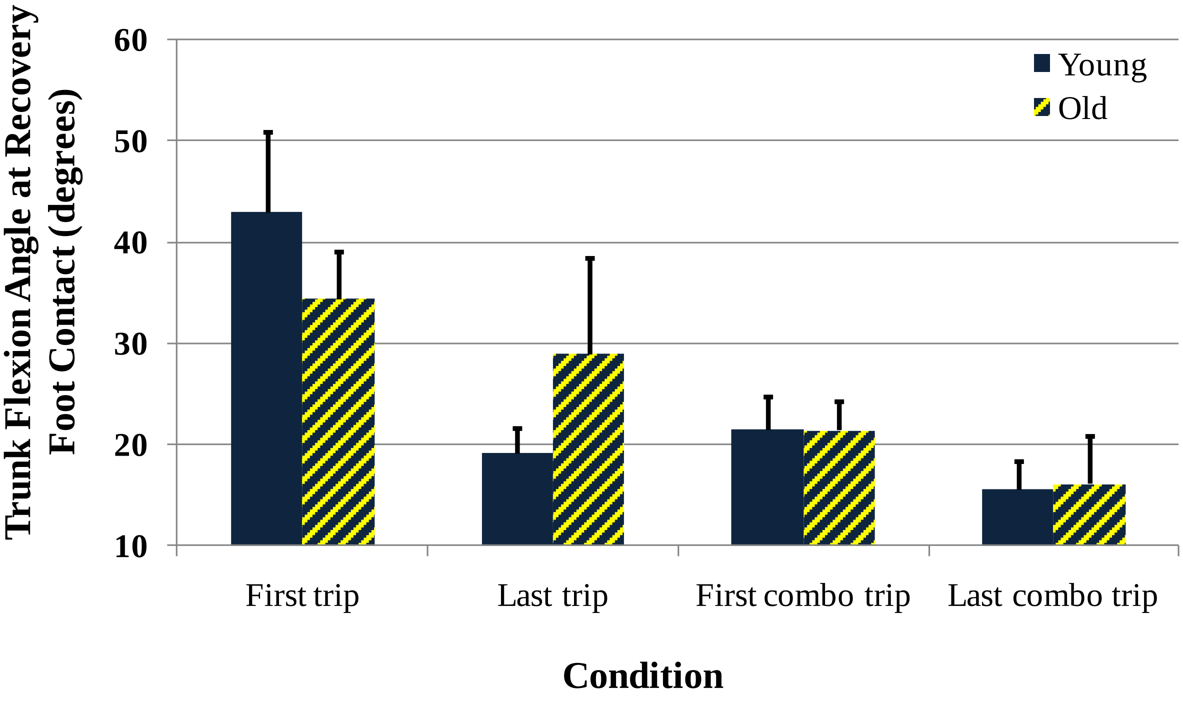


Figure 5.3 Trunk flexion angle at recovery foot contact during tripping is shown for young (solid) and older adults (striped) in the first trip of the trip block (knowledge provided), last trip of the trip block (knowledge + prior exposure – 3 perturbation exposures), first trip of the combo block (no knowledge of the nature of the perturbation + prior exposure – 4 perturbation exposures) and last trip of the combo block (no knowledge of the nature of the perturbation + increased exposure – 6 perturbation exposures). Young and older adults significantly differed in how prior exposure affected trunk flexion angle (p = .0278).

In addition, age group differences in how prior exposure affected trip perturbation recovery were also observed. Young versus old differences in how prior exposure impacted trunk flexion angle at recovery foot contact was 21º (p = .0278). Young adults were also able to significantly reduce trunk flexion angle 23º when no knowledge regarding the nature of the perturbation was provided in the first combo trip compared to the first trip of the trip block (p = .0004). Although older adults reduced their trunk flexion angle in the first trip of the combo block compared to the first trip of the trip block, this reduction of 13º only showed a trend for significance (p = .0565).

Increased exposure to the tripping perturbation and therefore more experience proved to significantly improve trunk flexion angle for both age groups and no differences were observed between age groups. From the first trip of the trip block to the last trip of the combo block young adults reduced trunk flexion angle 29º ($p < .0001$) and old adults 18º ($p = .0087$). Figure 5.4 shows a typical young subject improving in the ability to arrest trunk flexion with increased exposure. The top figure demonstrates the severity of the perturbation in the first trip and the bottom shows how the subject has reduced trunk flexion by the last combo trip.

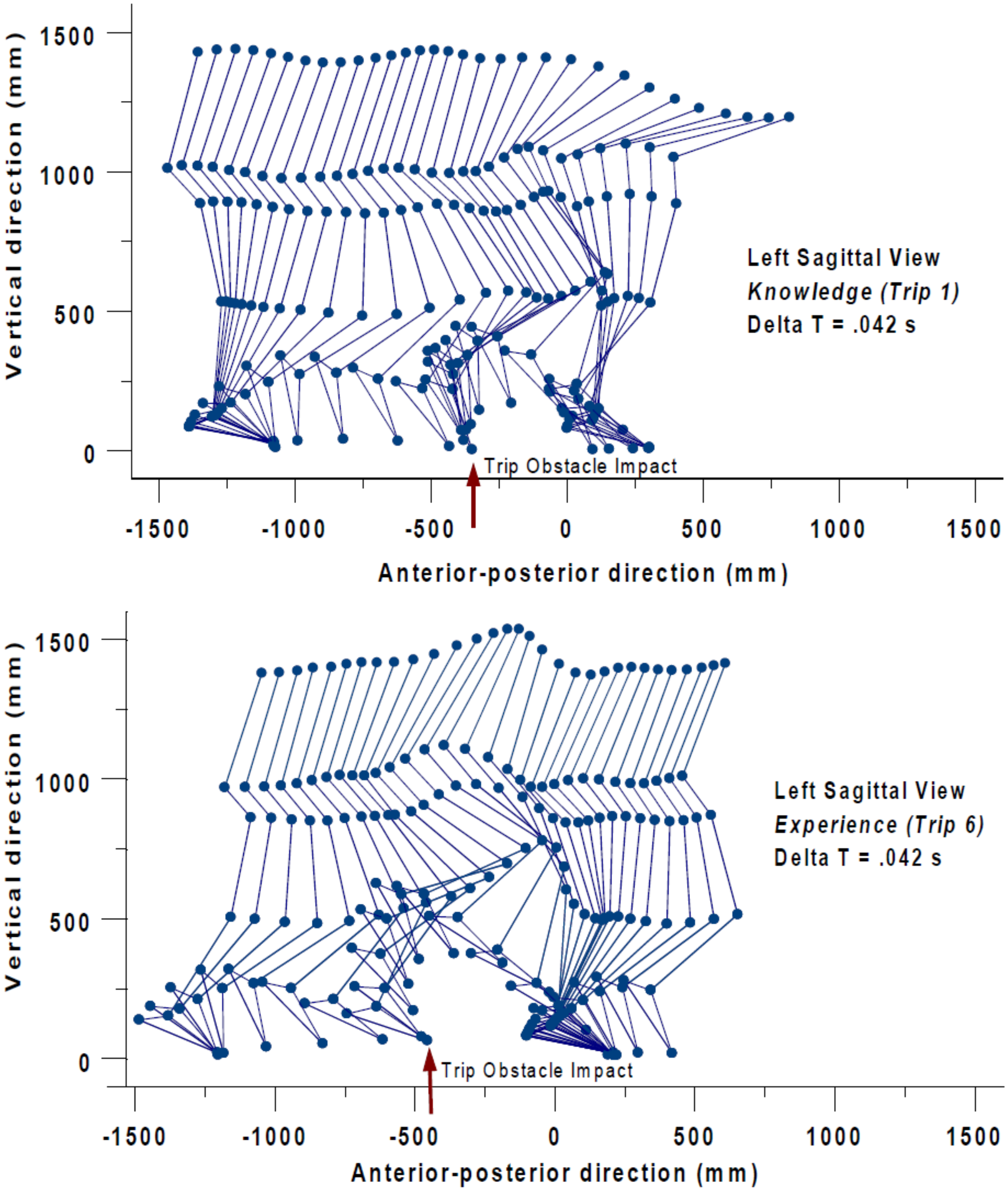


Figure 5.4 Sagittal views of the marker position data for a typical participant from the instant just before trip obstacle impact to just after recovery foot landing for (a) the first "unexpected" trip of the trip block and (b) the last trip of the combo block. Dots from top to bottom represent the acromion, posterior superior iliac spine, greater trochanter, lateral epicondyle, malleolous, heel and toe of the left side, respectively.

Mean trunk flexion velocity improved with prior exposure in young adults. Figure 5.5 shows mean trunk flexion velocity across conditions for young and old. Young adults reduced mean trunk flexion velocity 38 deg/s with prior exposure compared to the first trip in the trip block ($p = .0023$). When no knowledge regarding the nature of the perturbation was provided, both young and old adults were able to successfully reduce mean trunk flexion velocity. Young adults reduced mean trunk flexion velocity 46 deg/s ($p = .0002$) and old adults 27 deg/s ($p = .0401$) in the first trip of the combo block. When comparing the first trip of the trip block to the last trip of the combo block both young and old adults continued to significantly reduce mean trunk flexion velocity where young adults decreased 54 deg/s ($p < .0001$) and old adults 36 deg/s ($p = .0071$). In addition, old adults showed a significant difference in mean trunk flexion velocity with increased exposure. Specifically, old adults reduced mean trunk flexion velocity 26 deg/s from the last trip condition of the trip block to the last trip condition of the combo block.

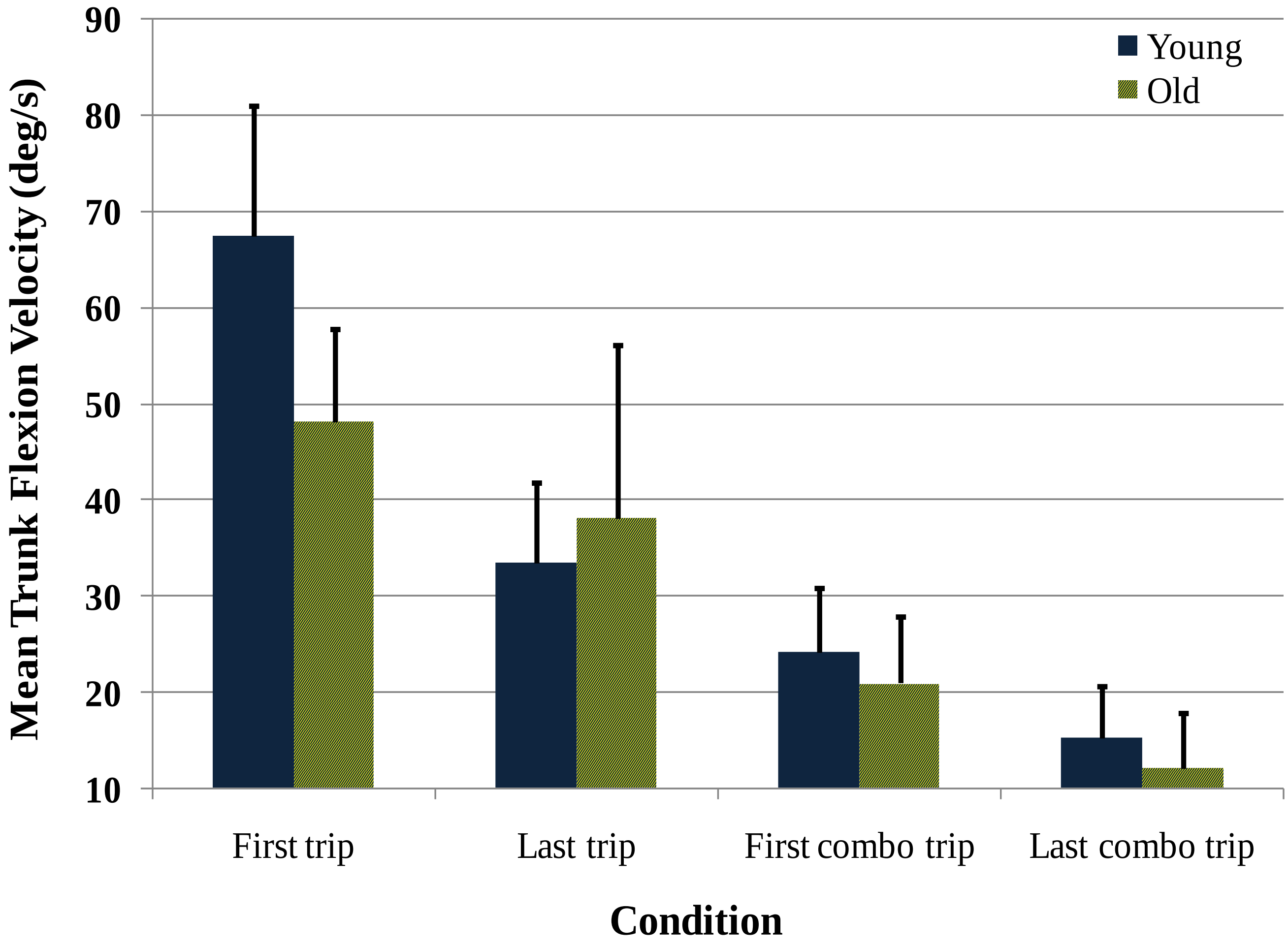


Figure 5.5 Mean trunk flexion velocity during tripping is shown for young (solid) and older adults (striped) in the first trip of the trip block (knowledge provided), last trip of the trip block (knowledge + prior exposure – 3 perturbation exposures), first trip of the combo block (no knowledge of the nature of the perturbation + prior exposure – 4 perturbation exposures) and last trip of the combo block (no knowledge of the nature of the perturbation + increased exposure – 6 perturbation exposures). Both young and older adults were able to use increased exposure to the perturbation to significantly reduce mean trunk flexion velocity ($p < .0001$ and $p = .0071$, respectively).

Prior exposure also improved perturbation response in maximum trunk deviation ipsilateral to the tripped foot side for both young and old adults. Figure 5.6 shows maximum trunk deviation in the frontal plane across tripping conditions for both age groups. Both young and older adults experienced their greatest deviation in the first trip condition. Young adults had a more negative maximum deviation which indicates a greater perturbation of the trunk towards the tripped foot (left) side (-ZY plane with respect to vertical). Absolute values were taken for graphical purposes only. Young and old adults significantly decreased maximum trunk deviation in the frontal plane, 11º ($p < .0001$) and 5º ($p = .0401$), respectively, in the last trip of the trip block. There was no age group difference in how prior exposure impacted maximum ipsilateral trunk deviation. When no knowledge regarding the nature of the perturbation was provided, both young and older adults significantly decreased maximum ipsilateral trunk deviation. Young adults decreased 9º ($p = .0002$) and old adults 6º ($p = .0123$) compared to the first trip condition where knowledge was provided. Increased exposure to the tripping perturbation only significantly improved maximum ipsilateral trunk deviation for young adults that increased 13º ($p < .0001$) by the last trip of the combo block.

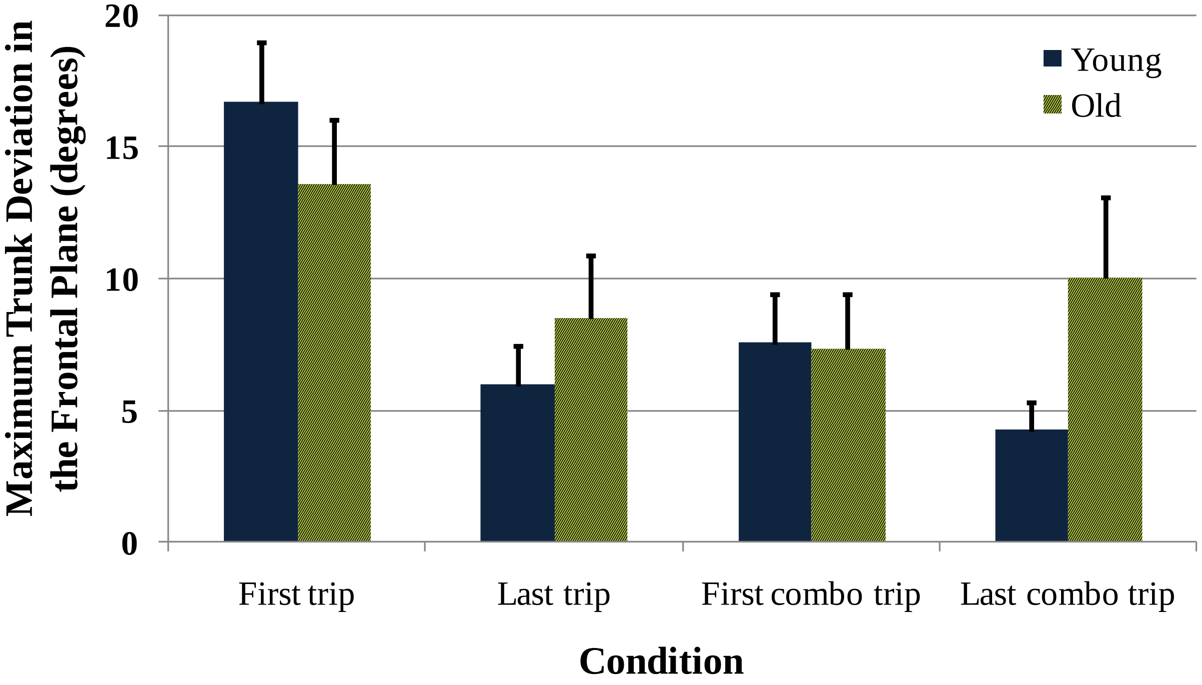


Figure 5.6 Maximum trunk deviation in the frontal plane during tripping is shown for young (solid) and older adults (striped) in the first trip of the trip block (knowledge provided), last trip of the trip block (knowledge + prior exposure – 3 perturbation exposures), first trip of the combo block (no knowledge of the nature of the perturbation + prior exposure – 4 perturbation exposures) and last trip of the combo block (no knowledge of the nature of the perturbation + increased exposure – 6 perturbation exposures). Positive values indicate deviation ipsilateral to tripped foot side (left) as absolute values of the trunk deviation were plotted for representation. Young and older adults significantly differed in how increased exposure to the perturbation affected maximum ipsilateral trunk deviation (p = .0073).

Contrast comparisons revealed a significant difference in the last combo trip condition between young and old adults. This significant improvement observed only in young adults resulted in an age group difference in how increased exposure affected postural responses. Maximum ipsilateral trunk deviation was not different in the last trip of the combo block compared to the first trip of the trip block for older adults (p = .1485). Young adults reduced maximum ipsilateral trunk deviation significantly from the first trip, -16.6°, to the last combo trip condition, -4.2°, compared to older adults' 10° in the last trip of the combo block which was not different from the first trip of the trip block -13.6° (p = .1485). Young versus old difference in how increased exposure affected maximum ipsilateral trunk deviation was -9º ($p = .0073$). No other trip severity measures differed significantly between age groups or conditions.

5.5 DISCUSSION

This study sought to examine whether multiple exposures to perturbations improved perturbation postural response performance. Specifically, we sought to determine whether differences in knowledge and prior exposure conditions reduced perturbation severity during trips in young and older adults. Overall, the results showed the destabilizing effects of the perturbations to diminish with exposures as both young and old adults were able to establish optimal postural responses to maintain balance even when uncertain about the nature of the balance perturbation.

Trunk kinematics play a critical role in the recovery outcome of both slip and trip perturbations and were the focal point of interest to gauge changes in severity of the perturbation with multiple exposures. Based on the nature of perturbations, it is likely that the first encounter with the perturbation will likely be the most severe perturbation as it is the most unexpected or naïve response. The more severe the perturbation is, the greater the destabilizing effect of the perturbation. Once a perturbation becomes predictable, proactive adaptations are often adopted preceding the perturbation onset to minimize the effect of the perturbation. Also, with exposure to the perturbation knowledge regarding the conditions of the perturbation is gathered which further improve a person's proactive adaptation generating capabilities as well as feedback responses. The maintenance of dynamic stability during slips involves minimizing a backward loss of balance whereas in trips the forward rotation of the trunk must be arrested. Grabiner et al. have suggested that avoiding a fall subsequent to a large postural disturbance that causes posteriorly-directed motion of the body is more challenging than disturbances causing anteriorly- and laterally-directed motion, especially in older adults. Therefore, there is inherent direction-related specificity in the recovery responses to these perturbations [106].

Trips and slips activate different trunk postural responses. In trips, the momentum of the perturbation rotates the trunk forward often beyond the base of support. For this reason, trunk flexion angle was one measure selected to represent severity of the trip perturbation. More severe trips result in larger trunk flexion angles in the sagittal plane with respect to vertical and often an inability to arrest this rotation results in a forward fall. As subjects gained experience with the perturbation, it was expected that trunk flexion angle would decrease as they would be less perturbed by the tripping perturbation. Another key finding of this study was that older adults had greater difficulty in arresting their forward momentum after a trip. With experience older adults still had not attained optimal trunk control. In fact, a significant reduction in trunk flexion angle did not occur for older adults until the last trip in the combo block after experiencing six trip perturbations. The same trends were observed for mean trunk flexion velocity. With increased exposure to the tripping perturbation, mean trunk flexion velocity continued to decrease for both age groups.

Both young and old adults continued to improve trip perturbation recovery with each exposure. Perhaps this suggests that with each trip exposure, subjects were training a response that improved recovery and would eventually reach an optimal recovery strategy beyond which significant improvement would not be possible. This may show that a large number of perturbation exposures are needed in trips to fully optimize postural responses. This differs from our results in slipping where prior exposure and increased exposure did not significantly improve postural response. As subjects had no past tripping experience an ideal follow-up study would investigate knowledge trips in the same group of participants to determine whether optimal retention of postural responses was apparent by the limitations in postural response improvement.

An interesting finding was in the trip postural response in the frontal plane. Deviation in the frontal plane has been used to differentiate faller from non-fallers as well as the probability of falling to the side [107]. Therefore, frontal plane stability has been shown to be even more significant in older adults. However, in our findings, frontal plane stability of old adults was comparable to young adults. In fact, old adults were able to decrease maximum trunk deviation in the frontal plane with minimal exposure. The exception was in the last trip of the combo block. In the last trip of the combo block old adults exhibited maximum ipsilateral trunk deviation similar to initial trip magnitudes. The lack of similar destabilization in the sagittal plane in the last trip of the combo block shows that old adults were still improving trip postural responses. However, this may suggest that the maintenance of sagittal plane stability is prioritized in older adults especially when the two types of perturbations (slips and trips) are randomly presented. The particular trial where this is observed represents the greatest level of exposure to trips perturbation of all tested conditions. A limitation is that due to the nature of the study the true causation of this cannot be isolated. However, it is possible that this difference can be attributed to the fact that older people were less able to respond after having experienced such a large number of mixed perturbations.

One main finding of this study is no knowledge regarding the nature of the perturbation did not affect older adults during tripping. However, in a separate analysis of the slip trials collected in this same protocol (unpublished data), older adults were affected when no knowledge regarding the nature of the perturbation was provided. Older adults experienced their most severe slip, as determined by their greatest level of perturbation, in the first slip of the combo block where no knowledge of the perturbation had been provided. This shows that prior exposure with the perturbation in the absence of knowledge was not sufficient in controlling the trunk to be less perturbed. At the first slip of the combo block, old adults had adequate exposure to and experience with the perturbation and had been less perturbed in previous trials. This may suggest that older adults were initially more perturbed in the uncertain condition because they were not explicitly told there would be a perturbation in the following set of trials. These results agree with a previous study that found young adults to have a more cautious gait encountering a slippery perturbation when they had both awareness and experience with the perturbation [41]. The fact that old adults had been less perturbed when knowledge had been provided and did not exhibit this ability in the absence of knowledge shows the importance, and perhaps reliance, of older adults on awareness to achieve optimal recovery performance as experience was present in both conditions and in the uncertain slip subjects actually had more experience. The fact that this was not observed in trips is a promising result. It is likely that since subjects were experiencing trips for the first time, the amount of exposures necessary to develop an internal representation had not yet been achieved. In the absence of such a motor program, it is likely that the CNS continues to expect the perturbation and therefore whether knowledge was provided or not, subjects continued to improve proactive and reactive responses. However, once an internal representation has been created through training, such as the previous repeated slip training that subjects experienced in a prior session, it is likely that the CNS turns the program off in the absence of external cues or explicit instructions which would enable explain a difference in postural response when there was no knowledge of the perturbation.

With the past slipping experience, a repeated exposure paradigm, it is possible that subjects developed an internal representation of a motor response specific to improve the chances of recovery upon slipping. However, based on the results of our study, it remains unknown if such an internal representation exists, is it only activated with some degree of expectance of the particular perturbation. Even though knowledge was provided in the slip block, there remained some degree of uncertainty as to the actual timing of the perturbation and how many perturbations would occur. It seems that knowledge in general makes a substantial difference in the activation of any existing models. Although there was still no knowledge provided in the last slip of the combo block, the first combo slip experience may have been enough to anticipate more perturbations activating proactive adaptations and turning on the motor command for slipping both of which would result in less destabilization by the perturbation and an enhanced recovery performance. In a previous study, these same older adults were shown to be capable of generating proactive adaptations in foot floor angle with experience with the perturbation in the absence of knowledge. This may show that after exposure to a perturbation older adults walk with a cautious gait, aftereffect of the perturbation whether it is present or not [33]. However, these proactive adaptations may be programmed automatically whereas the feedback responses needed for recovery are activated only in the presence of the perturbation or when the perturbation is predictable.

Increased challenge of task-specific training has been shown to improve motor learning capabilities. Repeated exposure to the same perturbation can serve as task-specific training especially in cases where the perturbations resemble real-life perturbations. It can be suggested that the random presentation of either a slip or trip with no knowledge of the nature, timing or number of exposures increased the challenge of the perturbations in this study. A further investigation involving how the sequence of perturbations influences the adaptations and recovery kinematics of older adults is necessary and will be done in a subsequent analysis. This would enhance our understanding of the paradigm complexity and how it influences the biomechanical modulation of gait during complex locomotor tasks in the older population compared to younger adults. The structure of this protocol may also yield insight into the prioritization or retention of motor programs in older adults. As the combo block was mixed with slips and trips, it is possible that subjects performed better in the perturbation they experienced first as this would be the perturbation they continued to anticipate. We observed visually during testing sessions that for both age groups, but in particular older adults, when first presented with the other perturbation type in the combo block, for some it was equally if not more unexpected than the first presentation of that particular perturbation. It is evident from previous studies that older adults can adopt proactive adaptations to slipping and tripping, foot floor angle and an increase in minimum toe clearance, to anticipate a challenge to balance. However, more research is needed to further understand older adult recovery capabilities when knowledge is not provided and more than one specific gait task is explored to better characterize kinematic and kinetic variables that could possibly identify the existence of overlap in responses to slips and trips. Identification of such overlap could serve as the foundational components of a task-specific training tool that capable of improving slip and trip recovery.

To our knowledge, no study has simultaneously investigated two perturbations, slips and trips, occurring during forward directed locomotion on the same group of subjects inclusive of young and old adults. Therefore, this study is novel in that it enabled the observation of effects of uncertainty and experience on slip and trip recovery responses in the same group of subjects. These perturbations have been investigated individually on young and old adults, but often the differences in paradigm and subject populations make it difficult to interpret how applicable results will be in different scenarios. The ability to observe changes in behavior across conditions specifically in old adults provides insight for more specific questions for future research. Overall, this study showed that the mechanisms by which uncertainty and increased experience affect young and old adults with slip and trip perturbations differs. However, at recovery in the last perturbation trials generally resulted in improved recovery outcomes for both young and old adults.

6.0 DISCUSSION AND FUTURE WORK

6.1 ADAPTIVE POSTURAL STRATEGIES IN YOUNG AND OLDER ADULTS

In just 40 years, the population of older adults in America alone is expected to increase by more than 50 million [8]. Falls and fall-related injuries are the origin of many adverse outcomes affecting socialization, mental and physical health and related health care costs. With an aging workforce, balance challenging environments encountered in the workplace pose an even greater threat and therefore an increased concern for falls in the elderly.

This dissertation was focused on understanding the proactive adaptations adopted in repeated exposures to slips resembling real-life during forward walking and backward walking as well as multiple exposures to trips while walking forward. As proactive postural adjustments are known to be a direct influence in the generation of adequate feedback responses and improved recovery, this work supported efforts to identify beneficial tools for integration into a fall intervention program. The insight from this study can inform future intervention approaches in the development of fall intervention and rehabilitation regimens that focus on a motor learning approach to help older adults reduce the incidence of falls in a cost-effective, easily implemented fashion. However, the techniques presented in this work have only been tested in those that are not at greatest risk for falling. The relation of the test findings to falling has not been established. Therefore, older adults at greatest risk for falling, including frail and mobility impaired individuals may not respond similarly or may even be at risk for injury from such an intervention. Further research must be done to draw further conclusions about the effectiveness of repeated exposures therapy in populations resembling those at greatest risk.

6.2 SIGNIFICANT FINDINGS

This dissertation aimed to provide evidence that a systems model theory based approach to motor learning, repeated or multiple exposures to perturbations, can potentially serve as an effective tool in the development of fall intervention programs designed to reduce the incidence of falls.

In chapter 3.0, repeated exposure to slips while walking forward were investigated and compared between young and older adults. A highly preprogrammed activity, walking forward, was also compared to a novel gait activity, backward walking, and aging effects were also investigated. Based on knowledge that both gait tasks utilize the same central pattern generator, observed differences in adaptability would be said to be independent of neural limitations. Therefore, the findings of this study suggested the CNS' ability to generate proactive postural adjustments to be dependent upon the nature of the task being performed. The CNS was able to make internal representations to a novel task for both young and older adults.

After investigating whether a novel task with common neural circuitry to the familiar task impacted the ability to adapt with repeated exposures, it was then of interest to determine the effect of different types of perturbations. Proactive adaptations adopted in anticipation of slips and trips were analyzed in Chapter 4. In two blocks, the slip and trip blocks, knowledge was provided. However, it was also of interest to observe the adaptations that occurred when the nature of the perturbation was uncertain, i.e. no knowledge was provided. In all conditions subjects gained experience with increased exposure and the effect of experience was also considered. Aging-related differences in the optimization of anticipatory gait adjustments were also compared. The most important finding of this component of the study was that proactive adaptations were found to be perturbation specific. This was evident by a modulation in adaptations known to benefit recovery. Knowledge of a known threat to balance was also sufficient to activate the execution of proactive adaptation even when adults lacked experience with the perturbation. However, as the knowledge condition trials were the first trials following the script, no experience with the perturbation had yet been obtained. Adults were capable of adopting a strategy known to reduce the risk of slipping when anticipating a slippery floor, but no such ability to adopt a strategy reducing trip risk was achievable with only knowledge and anticipation of being tripped. This is a highly significant observation and directly relates to the initial component of the study. In the first gait testing session, subjects experienced repeated exposure to forward slips. After a period of at least 2 weeks but not exceeding 2 months, subjects returned for the second gait testing session where they experienced slips and trips. At this point subjects had prior experience with the forward slips, but no prior experience with the tripping perturbation. As subjects were able to immediately adopt appropriate proactive strategies when warned of slipping, this may suggest and provide evidence that an internal representation of slipping was formed and retained over the elapsed time window. This study focused only on foot angle with regard to slipping. In a future investigation it would be wise to focus on observed proactive adaptations in other kinematic variables to determine the similarities, if present, between knowledge trial (first slip gait session 2) and RS5 of the forward slip trials(last forward slip gait session 1) responses. If this trend was upheld in other variables it would provide further support to say an internal model for slipping was created from repeated exposure to forward slipping in young and older adults while also providing some evidence of capabilities for retention. Other studies have marked 1-month retest sessions as significant retention landmarks so this could potentially have therapeutic implications as well. Such information would be the strongest support of internal models in postural adaptations yielding insight on the effectiveness of the systems model theory based approach to fall prevention training.

As proactive postural adjustments reduce the reliance on feedback responses for successful recovery outcomes, it was the goal of Chapter 5 to determine if recovery outcomes improved. This was measured by reductions in perturbation severity. Although recovery from slip and trip perturbations requires different postural responses, both involve control of the trunk in maintaining balance. For this reason, measures of instantaneous trunk angle and angular velocity were evaluated in the sagittal and frontal planes for both trips and slips. Destabilizing effects of the perturbations diminished with exposures and both young and older adults were able to establish optimal recovery responses to maintain balance even when different challenges were presented without knowledge. One significant finding from this study, however, was that when the nature of the perturbation was uncertain and subjects were not explicitly told they would experience a perturbation, older adults experienced a more severe slip. This is an important observation because older adults have been shown to exhibit a waning effect in responses when not expecting the perturbation. However, immediately in the next slip trial under the same conditions, responses improved to previous levels. Although we have evidence that an internal representation for forward walking was formed, this may suggest that for older adults it is only activated with some degree of expectance of the particular perturbation (i.e., an explicit script or current slip experience is enough to anticipate more perturbations and the increase the level of attention/awareness in the trial immediately following a perturbation). As evidence is acquired for the existence of internal models being formed perhaps this study finding is a very preliminary indication that such motor commands have an on/off switch that may be associated with age.

6.3 FUTURE RESEARCH DIRECTION

The results of this research open the door to the continued research of the systems model theory based approach to increase learning to avoid falls through repeated and multiple exposure training. Although some differences in mechanisms of change in adaptations were age-related, this dissertation only tested 13 older adults ages 65-75 all of whom were robust. Even though these adults fall into the range where a concentrated focus on falls has been stressed in the research, such older adults willing to come into the laboratory to be slipped and tripped multiple times most likely do not resemble the population at greatest risk for falls, recurrent falls and those most likely to show large differences in adaptation capabilities compared to healthy young adults. Another limitation to the current study was the random trial sequence in the combo block (slips and trips) for each subject. Trial sequences were generated using a Matlab code and so although every subject experienced the same number of total perturbations, the order was random for each. Without further investigation the random presentation of slips and trips in our combo block makes it difficult to interpret findings related to how the presence of two different perturbations affects the optimization of proactive and reactive responses in young and older adults. The work of this dissertation was but a poke at the potential findings of the current dataset. Several future analyses remain to be performed.

Short term research goals include:

1. The investigation of retention utilizing the investigation of the first unexpected slip trial (first slip of the first gait testing session) compared to the first slip trial of the second gait testing session.
2. To investigate the differences in upper extremity contributions to perturbation recovery between slips and trips and to determine whether aging differences exist.
3. To investigate and compare lower extremity muscular anticipation between slips and trips as well as aging related differences.
4. To investigate and compare lower extremity muscular anticipation between no knowledge (unexpected), knowledge (first repeated slip) and knowledge (first perturbation of retest/2nd gait testing session) and aging related differences.
5. To investigate the effects of trial sequence in the combo block by grouping subjects with matching trial sequences and running between subject comparisons to make general pre- and post-perturbation kinematic observations.
6. To investigate the effects of trial sequence in the combo block by analyzing the first perturbation of the second perturbation type following the first presented perturbation in the block. For example, given the sequences below:

   A) S W S W T W S W T W T

   B) T W T W T W S W S W S

   C) T W S W S W T W S W T

   The highlighted trials in A - C would be compared to the first perturbation of that type in the knowledge (slip/trip) block.

7. To compare the first unexpected slip to the first slip of the combo block and the first slip following a trip in the combo block (when applicable).
8. To investigate COM state adaptations and COM control after perturbations in the mixed perturbation block.

These investigations will foster a greater understanding of the retention capabilities of repeated exposure to forward walking slips using a slippery floor paradigm as a training tool. Also, the muscle onsets and latencies will enable determination of anticipatory muscular contributions common to both slipping and tripping. Such contributing muscles could be targeted in a training program to be combined with task specific training. Inspection of the effect of trial sequence on observed adaptations and reactions will shed light on the prioritization of tasks. As an individual's expectation of an upcoming event has been shown to be dependent upon their most recent experience, such knowledge would better explain how subjects can readily transition between tasks in the case where the lack of expectation for a particular perturbation destabilizes them comparably or worse to a knowledge perturbation where the exact timing is uncertain. Objective 7 would yield insight as to the presence of internal representations developed with training and experience and how they are retained in the absence of knowledge and in the presence of another type of perturbation. Each of these conditions is still unexpected as the subject has no knowledge. However, in the first slip of the combo block the subject is either not expecting any perturbation or is expecting a trip because they have already experienced a trip. The same is expected in the first slip following a trip because the subject may then continue to expect a trip. In that case the subject may be confused and choose to adopt an optimal anticipatory behavior not knowing which perturbation to expect and therefore having to prepare for either. Elucidation of an optimal whole-body proactive strategy that fosters successful outcomes in the face of either perturbation would be extremely beneficial to the advancement of training tools for intervention purposes. In addition, it is hopeful that in subsequent biomechanical analyses experimental data from the current work can be used to drive model simulations exploring slipping and tripping on the same subject in efforts to generate a set of parameters common to an optimized outcome in both perturbations. With the establishment of such parameters simulation models could be manipulated to determine overlapping regions of stability and balance thresholds considerate of both perturbations. Weight and gender are also covariates of interest for future study, especially with regard to trips.

Long-term extensions of the current work expand into further areas and become a bit more integrating of the neuroscience, electrical engineering and biomechanics disciplines. In order to ever have an accurate assessment of what the CNS is truly doing in these situations, both the brain and postural mechanisms have to be evaluated and measured simultaneously. A future study conducting repeated exposure perturbation training while also recording electroencephalogram (EEG) or quantitative electroencephalogram (QEEG) would be a valuable tool in drawing direct CNS conclusions on the observed biomechanic adaptations. As brain mapping measures electrical activity of the brain, such brainwave signatures may provide insight as to how activity changes once the task has been "programmed." A limitation to this proposed inspection is that EEG/QEEG requires subjects to be very still while wearing the silicone cap. With an interdisciplinary approach, it is quite possible that researchers could come together to formulate a protocol capable of addressing similar questions despite the inherent limitations. The results of such a study would be a major link in the biomechanical and neuroscience data and advancement for clinically supported validation of repeated exposure training.

As the target goal of all falls research is to reduce the incidence of falls in older adults, research would most benefit from conducting studies on a population most resembling those at greatest risk. This, however, has been a problem and remains a problem for many researchers as the identification of subjects in that population willing to volunteer and fulfilling of all of the inclusion/exclusion criteria mandated by the Institutional Review Boards across the world to ensure human subject safety is an arduous task. A future study (similar in aims to the current work) investigating slips and trips on a pool of healthy older subjects split into a control group and a group made to look "unhealthy" would be of interest and merit. Removing a sensory system (visual, proprioceptive or vestibular), inducing extreme fatigue before perturbation presentation, having subjects perform a dual task while walking or taping down the arms during testing so as not to be accessible in generating recovery responses would be a few ways to make otherwise healthy older adults less robust when generating their proactive adaptations and recovery responses. It is possible that findings from such a study would yield more representative results of what those who are frail, lacking balance confidence and/or mobility-limited older adults would actually do if exposed to a similar protocol. In another potential study it would also be interesting to see if adults, young or old, were capable of adopting optimal responses as observed in the current work when performing slips/trips in a virtual environment where the scene changes from trial to trial but the perturbation does not (perturbation duration and severity in terms of paradigm remain constant). Such observations would provide insight on how cognition and reality impact the ability to make adaptations and recovery responses. Failing to observe similar abilities from scene to scene would show that adults are affected by the change of scenery moreso than the perturbation itself. The implications of a study such as this would be of benefit to the rehabilitation community as real life perturbations seldom occur in the same setting. Changes in scenery and surrounding environments provide a different set of contextual cues and it is known that these can influence balance maintenance. Repeated exposure to the same task in different visual environments may teach us something about the roles awareness and familiarity with the environment may also play in reducing fall incidence.

APPENDIX A

ABBREVIATIONS

Abbreviation	**Definition**
BOS	Base of support
CAD	Cadence
COM	Center of mass
COM_{AP}	Anterior-posterior center of mass
COM_{AP} velocity	Anterior-posterior center of mass velocity
COM_{ML}	Medial-lateral center of mass velocity
COM_{ML} velocity	Medial-lateral center of mass velocity
COM_{V}	Vertical center of mass velocity
COM_{V} velocity	Vertical center of mass velocity
COP	Center of pressure
FC	Foot contact
FFA	Foot floor angle
PPA	Proactive postural adjustments
PSV	Peak slip velocity
RHC	Right heel contact

APPENDIX B

TRIPPER DETAILS

Tripper Design and Operation

The tripping device was designed to trip an individual's left foot during midswing. At contact, the foot encounters one of eight wood slides that serve as the tripping obstacles (see Figures 1 and 2). These slides are 3.5" tall standing 4.5" from the zeroed floor. Each slide is 37¼" long and when triggered travels approximately 70 cm (10 cm onto the forceplate) ensuring that the left foot contacts the slide (for those with narrow stepwidths).

The device is triggered once 15-N force is detected on the force plate (60 cm L x 40 cm W). At this time, the anterior-posterior position of the center of pressure is calculated using the equation:

$$COP_{A\text{-}P}=[(-F_y * h)M_x]/ F_z \qquad (1)$$

where F_y is the shear force, h is the thickness of the forceplate, M_x is the moment about the x-axis and F_z is the normal force. The forceplate is divided into eight, 7.5 cm sections that are each associated with a specific slide. The Labview coding selects the corresponding region for the calculated COP and releases the appropriate slide.

The trigger assemblies (mechanical components of slides, see Figures 2 -5) are each activated by a solenoid. The signal from the computer is relayed to one of eight solenoids wired in series. The solenoids are each pull type with intermittent duty.

Once activated, the solenoid pin pulls back on the notch of an archery trigger. Inside the head of the triggers is an eyebolt which is pushed in place by compressing a spring. The wood slides are aligned and at rest against the spring. At activation of the solenoid, the pin pulls back, the notch pulls back opening the trigger head thus releasing the eyebolt, the spring releases from compression and drives the wood slide forward. The wood slides have wheels at the top that roll along a metal track giving the slides their speed. The tripping slide travels out and perturbs the left foot at midswing.

Figure A.B.1. Tripping device (bottom side up).

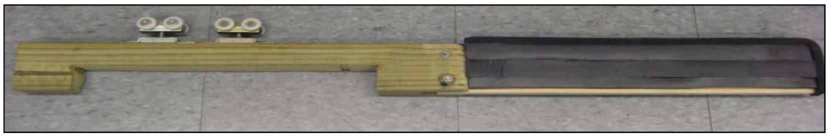


Figure A.B.2. Wood tripper slide with padding.

Figure A.B.3. Solenoid and trigger with eyebolt locked in trigger head.

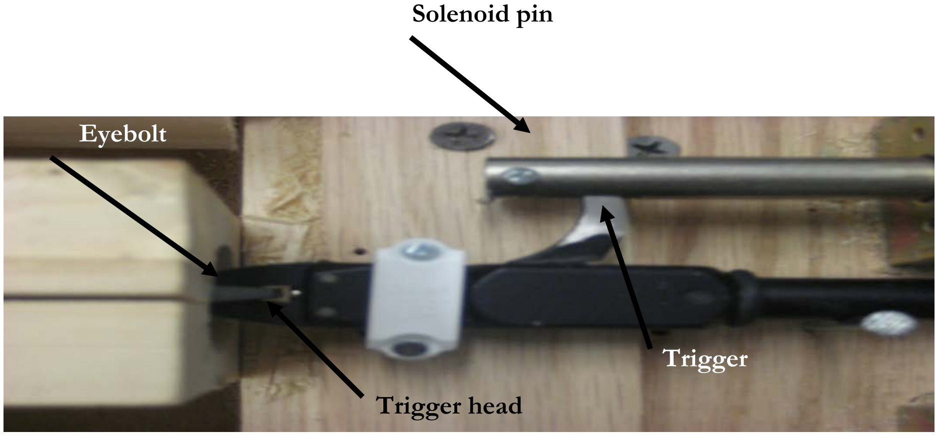


Figure A.B.4. Trigger, eyebolt, and solenoid pin.

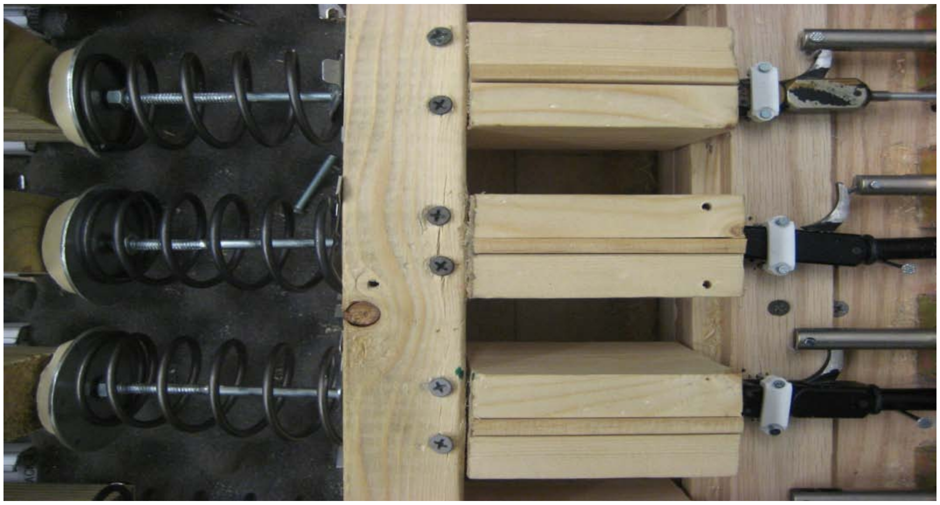


Figure 5. Complete trigger assembly: solenoid, trigger, eyebolt, spring, slide.

Circuit Info

The tripper circuit is triggered by a computer parallel port. A signal is sent to a single pin on the parallel port which is then amplified. The amplified signal travels to a relay switch which triggers a separate power source of 18 volts. The 18 volts is sent through a serial port cable to activate the appropriate solenoid.

APPENDIX C

FUNDING SOURCE

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