THE RELATIONSHIP BETWEEN KNEE STRENGTH CAPABILITIES, POSTURAL CONTROL AND SLIP SEVERITY

by

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Slips and falls are serious public health concerns in older populations. Understanding relationships between propensity to slip and biomechanical and physiological characteristics is important to identify factors responsible for slip-initiated falls and to improve slip/fall prevention. Thus, the first goal of this thesis was to investigate the relationship between knee flexion/extension strength and slip severity. Reduced muscle strength is associated with aging and falls. Knee corrective moments generated during slipping assist in balance recovery. Isometric knee flexion/extension peak torque, rate of torque development (RTD), and angular impulse were measured in 30 young and 28 older subjects. Motion data were collected for an unexpected slip during self-paced walking. Slips were characterized as non-hazardous or hazardous based on a 1.0 m/s peak slip velocity threshold measured at the slipping heel. Within-gender regressions relating strength to slip hazardousness and age group revealed significantly greater left knee extension RTD and angular impulse in young males experiencing non-hazardous versus hazardous slips. Findings were not evident in older males, who perhaps implement cautious walking styles, allowing less reliance on post-slip recovery reactions. Other strength variables were not associated with hazardousness. Thus, rapid knee extension force generation may assist balance recovery from hazardous slips.

Decreased postural stability is also associated with aging and falls. Therefore, the second goal of this project was to investigate the association between ability to integrate sensory information important for balance and slip severity. The Sensory Organization Test (SOT) was administered and COP standard deviation (COP ST DEV) and path length (PATH LENGTH) were calculated for each condition. COP ST DEV, PATH LENGTH, and variable ratios were regressed on age group and hazardousness within condition. Significantly greater PATH LENGTH and its subsequent effects on ratio variables associated with Condition 4, in which somatosensation was rendered inaccurate, were evident in individuals experiencing hazardous versus non-hazardous slips. Conditions in which vestibular or visual information was rendered inaccurate or missing were not associated with hazardousness. Somatosensory channels detect slips first at the shoe-floor interface and thus may be especially important in early detection and response to a slip.

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NOMENCLATURE

Angular impulse_vol	Angular impulse calculated beginning at 50 ms after onset of contraction during isometric muscle strength testing
AP	Anterior/posterior
C1-C6	Sensory Organization Test Conditions 1 through 6
COG	Center of gravity
COP	Center of pressure
COP ST DEV	Standard deviation of COP data collected during Sensory Organization Test trials
H	Hazardous slip defined by peak slip velocity > 1.0 m/s
ML	Medial/lateral
MVC	Maximum voluntary contraction calculated during isometric muscle strength testing
NH	Non-hazardous slip defined by peak slip velocity < 1.0 m/s
O	Older subject
PSV	Peak slip velocity of heel during an unexpected slip
RTD	Rate of torque development calculated during isometric muscle strength testing
RTD_vol	Rate of torque development calculated beginning at 50 ms after onset of contraction during isometric muscle strength testing
SOT	Sensory Organization Test
T1-T3	Sensory Organization Test Trials 1 through 3
Y	Young subject

PREFACE

Subject screening was performed by Joseph M. Furman, M.D., Ph.D. Funding was provided by the National Institute of Occupational Safety and Health (NIOSH R03-OH007533 and R01-OH007592).

1.0 INTRODUCTION

1.1 SCOPE OF THE PROBLEM

Falls are a well-acknowledged public health concern that is more prominent with increasing age. Epidemiological estimates of the average annual risk of falling in the elderly indicate that at least one in every three older adults (>65 years) falls each year (Tinetti et al., 1988), a 10-fold increase compared to younger individuals (Thomas and Brennan, 2000). In nursing homes, falling accidents represent a more serious concern: the mean annual incidence rate of falls among older institutionalized patients is 1.5 falls per bed (Rubenstein et al., 1996). Injury-related falls are often serious. In the United States, falls are the leading cause of unintentional injury-related deaths in individuals aged 65 years and older, accounting for about 40% of such incidents in that age group (NCIPC, 2006). Falls are also the leading cause of unintentional nonfatal injury in all individuals aged 25 years and older, accounting for nearly 31% of unintentional nonfatal injuries in that age group (NCIPC, 2006).

Falls in older adults are often attributed to base of support perturbations during walking such as slips, trips and stumbles (Berg et al., 1997; Bloem et al., 2001). One estimate attributes 67% of falls in the elderly to slips and trips (Lloyd and Stevenson, 1992). In an epidemiological study conducted in England and focused on incidence of falls in individuals requiring accident and emergency health care services, slips, trips, and stumbles were reported as the most common cause of falls in four adult age groups over the age of 60 years (Scuffham et al., 2003). Similarly, a study based in northern California reported that 49% of falls with fractures resulted from slipping or tripping (Keegan et al., 2004). Slips specifically are a significant cause of falls in older adults (Sjogren and Bjornstig, 1991; Bjornstig et al., 1997) and account for up to 44% of occupational same-level and 43% of fatal occupational same-level falls (ISA, 1998; USDOL-BLS, 1992-1998). Slip-initiated falls are also a risk factor for fractures, accounting for 10-26% of fall-related hip fractures in older adults (Nyberg et al., 1996; Norton et al., 1997; Luukinen et al., 2000).

1.2 EXPERIMENTAL RESEARCH BACKGROUND

1.2.1 Knee Corrective Reactions in Response to an Unexpected Slip

To regain balance and avoid a slip-initiated fall, the body must generate an immediate, effective corrective response. Two major reactions are generated by the knee of the leading/slipping leg in response to an unexpected slip (Cham and Redfern, 2001; Chambers and Cham, 2007; Moyer et al., 2007). The primary reaction involves the initiation of a corrective knee flexion moment at approximately 100-150 ms after heel strike onto the contaminated floor (Figure 1). This response decelerates the slipping foot, bringing the foot closer to the body center of mass. The secondary reaction, a knee extension moment at approximately 150-200 ms (Figure 1), prevents knee buckling and contributes to the forward movement of the body over the supporting foot to continue normal gait (Cham and Redfern, 2001; Chambers and Cham, 2007; Moyer et al., 2007). These corrective moments generated in response to a slip are active muscle reactions observed in young and older adults (Chambers and Cham, 2007). Thus, it is likely that knee flexor/extensor strength characteristics influence the effectiveness of corrective reactions and, in turn, slip severity.

1.2.2 Relationship between Muscle Strength and Falls in the Elderly

Aging has been associated with decreased muscle strength, including peak and explosive measures such as rate of force/torque development (RFD/RTD) and angular impulse (Larsson et al., 1979; Borges, 1989; Frontera et al., 1991; Thelen et al., 1996; Izquierdo et al., 1999; Johnson et al., 2004; Perry et al., 2007). Both peak and explosive strength capabilities show decreases in fallers compared to non-fallers (Whipple et al., 1987; Gehlsen and Whaley, 1990; Perry et al., 2007). Ability to exert a rapid rise in muscle force in response to external perturbations is suggested to contribute to balance recovery and fall prevention (Thelen et al., 1996; Izquierdo et al., 1999; Aagaard et al., 2002; Chang et al., 2005). Thus, higher explosive strength generation capabilities specifically may help restore dynamic equilibrium and aid in fall prevention in the elderly (Aagaard et al., 2002; Chang et al., 2005). Several studies noted the importance of evaluating strength characteristics, e.g. RTD, during time intervals relevant to a particular functional movement (Abernethy et al., 1995; Aagaard et al., 2002; Andersen and Aagaard, 2006). For instance, it is expected that physiological time intervals corresponding to slip-initiated recovery efforts would be greater than 0-100 ms based on the onset of flexion/extension corrective knee moments.

To our knowledge, only one study has investigated the importance of leg muscle strength in specifically preventing a slip-initiated fall (Lockhart et al., 2005). Results showed that subjects with stronger lower extremities experienced less severe slips, reinforcing that slip recovery ability may be related to lower extremity peak strength. In that study, only overall peak leg strength was examined (Chaffin et al., 1978) and peak and explosive strength measures at individual joints instrumental in slip-recovery efforts, e.g. knee, were not assessed (Lockhart et al., 2005).

As mentioned previously, numerous studies have compared general strength measures in fallers and non-fallers, as well as young and older adults. To our knowledge, however, no previous gait research has examined the direct association between slip severity and strength characteristics at specific joints identified as instrumental in slip-recovery efforts, such as the knee joint. Thus, the first goal of this study was to investigate the relationship between knee flexion/extension strength characteristics and slip severity in young and older adults. Variables considered in this analysis include peak isometric torque, RTD and angular impulse of these individual muscle groups.

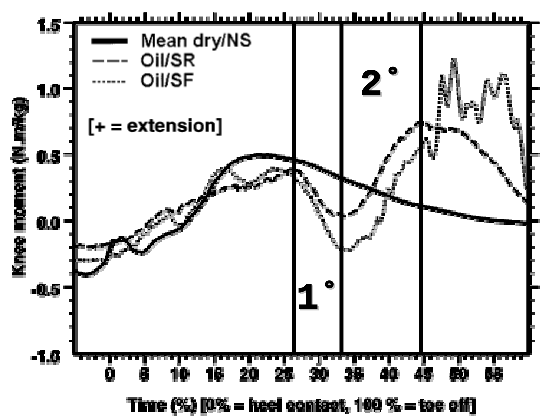


Figure 1: Profile of leading/slipping leg knee moment generated during stance phase on dry floors (mean) and typical slip-recovery (SR) and slip-fall (SF) events on oily floors. Vertical lines denote time periods (% stance) in which primary knee flexion (1º) and secondary knee extension (2º) corrective moments occur. The primary corrective moment acts to pull the slipping foot back near the body, while the secondary moment helps to bring the body over the base of support to avoid knee buckling and continue gait (adapted from Cham and Redfern, 2001).

1.2.3 Postural Control and Integration of Sensory Information Important for Balance

Appropriate postural control involves the acquisition of visual, vestibular, and somatosensory information and the integration of this sensory channel information by the central nervous system in order to generate an appropriate motor response aimed at maintaining postural stability (Nashner et al., 1982; Anacker and Di Fabio, 1992; Peterka, 2002; Horak, 2006). During postural control, visual sensors act to detect orientation of the head and body relative to the visual world, vestibular sensors detect deviations of head orientation from earth-vertical (gravity), and somatosensory cues detect leg orientation relative to the support surface (Peterka, 2002; Lord, 2006; Virk and McConville, 2006). Feedback control loops utilize sensory integration information to update body state and to correct for center of pressure (COP) movements away from equilibrium. Specifically, corrective torque generation acts to resist destabilization from gravity or external perturbation (Peterka, 2002; Peterka and Loughlin, 2004). In a well-lit environment with a stable base of support, healthy individuals typically weight the information from these sensory channels as follows: 70% somatosensory, 10% vision and 20% vestibular (Peterka, 2002; Horak, 2006). A certain amount of redundancy exists among these channels, allowing the individual to maintain postural stability more easily even if one sensory channel is inaccurate or missing (Peterka, 2002; Welgampola and Colebatch, 2002). When presented with conflicting, inaccurate or missing sensory information from one or more of the channels, however, the central nervous system is thought to use a sensory re-weighting strategy to increase sensory weighting of the available accurate sensory channels and decrease that of the inaccurate or missing channels (Peterka, 2002; Peterka and Loughlin, 2004; Mahboobin et al., 2005; Virk and McConville, 2006). This ability to re-weight sensory information depending on sensory context allows an individual to maintain stability when moving from one environment or sensory context to another or adapt when one or two of the sensory inputs are not functioning properly (Horak, 2006; Virk and McConville, 2006).

Decreased postural stability with aging, commonly indicated by increased postural sway, has been well documented (Overstall et al., 1977; Whipple et al., 1993; Baloh et al., 1994; Perrin et al., 1997) and is often considered a risk factor for falling, especially under conditions of conflicting or reduced sensory information (Wolfson et al., 1985; Woollacott et al., 1986; Tinetti et al., 1988; Gehlsen and Whaley, 1990; Anacker and Di Fabio, 1992; Maki et al., 1994; Judge et al., 1995; Fernie et al., 2001; Stalenhoef et al., 2002). A reduced ability to effectively re-weight and integrate sensory information contributes to this decreased postural stability (Horak et al., 1989). In fact, Peterka and Loughlin (2004) predict that any environment change altering the available sensory-orientation cues increases falls risk, even if accurate orientation information is restored during the change. In addition, postural instability in the elderly arises from degradation or failure of the peripheral sensory systems. This degradation reduces the overall amount, as well as the redundancy of information important for sensory integration (Gill et al., 2001; Welgampola and Colebatch, 2002; Low Choy et al., 2003; Vouriot et al., 2004).

As mentioned previously, somatosensory channels, whose major component in postural control is peripheral sensation, are most heavily weighted during maintenance of postural control (Peterka, 2002; Horak, 2006; Bugnariu and Fung, 2007). Peripheral sensation is considered most important in maintaining postural stability regardless of age or falls history, especially under challenging conditions (Lord et al., 1991; Fitzpatrick and McCloskey, 1994; Lord and Ward, 1994; Benjuya et al., 2004; Melzer et al., 2004). However, deterioration and impairment of peripheral sensation with aging due to neuropathy, including degradation of proprioceptive and cutaneous inputs, results in reduced reliance on somatosensory channels (Nakagawa, 1992;

Benjuya et al., 2004; Melzer et al., 2004; Low Choy et al., 2007). The reduced integrity and reliance on somatosensory information is associated with increased falls risk and occurrence (Anacker and Di Fabio, 1992; Melzer et al., 2004; Vouriot et al., 2004). Individuals who fall are reportedly less able than non-fallers to compensate for conflicting or missing somatosensory information during challenging balance conditions (Anacker and Di Fabio, 1992).

As individual somatosensory and vestibular channel function and integration abilities become less efficient with age, vision becomes more instrumental in maintaining postural control, especially under challenging balance conditions when the support surface is not stable, making somatosensory input inaccurate (Perrin et al., 1997; Lord et al., 2000). Elderly individuals and fallers increasingly rely on visual cues into their sixth decade to maintain or recover balance, most likely due to delayed or reduced vestibular and somatosensory functioning (Pyykko et al., 1990; Lord and Ward, 1994; Sundermier et al., 1996; Vouriot et al., 2004; Buatois et al., 2006; Bugnariu and Fung, 2007). Since visual control of postural stability is slower than somatosensory and vestibular control, increased reliance on vision could in turn increase falls risk (Pyykko et al., 1990). Elderly individuals and fallers exhibit greater postural sway than younger individuals and non-fallers, respectively, when vision is occluded or inaccurate (Whipple et al., 1993; Low Choy et al., 2003; Buatois et al., 2006). However, visual acuity also decreases with age, which could lead to overdependence on inaccurate visual information, and thus further decreases in postural stability and increases in fall risk (Lord et al., 2000; Jeka et al., 2006).

Finally, the vestibular system, which senses linear and angular accelerations at the head, is extremely important for sensory integration and postural stability as it provides a reference for body orientation against potentially conflicting visual and somatosensory clues (Nashner et al., 1982; Horak et al., 1990). As reliance and function of somatosensory sensory channels begins to decline with age, individuals may also increasingly rely on vestibular input to maintain postural stability (Welgampola and Colebatch, 2002). However, vestibular loss is also common with age due to peripheral or central vestibular system deterioration, neuropathies, or CNS disorders (Matheson, 1999; Horak, 2006). A decline in vestibular function, then, may cause individuals to reduce reliance on vestibular channels and overweight potentially inaccurate somatosensory and visual channels, further contributing to decreased postural stability (Teasdale et al., 1991a; Peterka, 2002; Welgampola and Colebatch, 2002; Vouriot et al., 2004). Thus, deterioration of vestibular function may also contribute to increased falls risk and occurrence (Woollacott et al., 1986; Kerber et al., 1998; Matheson, 1999).

As detailed above, the accuracy of all three sensory channels declines with age, which in turn decreases the ability to maintain postural stability using sensory re-weighting techniques. The Sensory Organization Test (SOT) is a common test used to reliably assess sensory integration abilities and, therefore, also identify deficits in particular sensory modalities related to sensory re-weighting and integration (Anacker and Di Fabio, 1992; Cohen et al., 1996; Camicioli et al., 1997; Wallmann, 2001; Buatois et al., 2006). The SOT assesses subject ability to effectively weight sensory inputs (visual, vestibular, and somatosensory) while suppressing inaccurate or conflicting sensory information (Vouriot et al., 2004). During the SOT, inaccurate visual and somatosensory cues are applied using sway-referencing techniques. Sway-referencing occurs when the support surface and/or visual surround tilts to directly follow the anterior-posterior center of gravity (COG) sway of the subject (Nashner and Peters, 1990). The SOT collects COP, which is representative of the net neuromuscular response during postural control (Winter et al., 1996) and used in calculation of postural stability and sway measures. Indeed, these measures have been used to reliably assess sway changes with age and between fallers and non-fallers (Cohen et al., 1996; Camicioli et al., 1997; Wallmann, 2001; Shimada et al., 2003; Buatois et al., 2006; Whitney et al., 2006). A common method of assessing postural sway using the SOT is the equilibrium score. An equilibrium score is assigned for each SOT condition based on the ability of the subject to minimize COG sway and maintain upright posture within the limits of stability, estimated as a COG maximum displacement of 12.5 degrees (Nallegowda et al., 2004). Trials in which the maximum COG displacement of a subject extends beyond the limits of stability are considered falls. Because COG and the limits of stability are estimated measures and therefore only indirectly assess postural stability, they may not be as accurate as more directly quantified measures such as COP path length or standard deviation.

To our knowledge, only Lockhart et al. (2005) has investigated the association between sensory integration abilities and slip recovery ability in young (N = 14, 22.6 ± 2.1 year), middle-age (N = 14, 46.9 ± 13.6 years) and older (N = 14, 75.5 ± 6.8 years) adults. In this study, subjects with lower SOT scores, signifying increased postural sway, in each age group experienced longer and thus more severe slips. These results indicate that the ability to integrate sensory information accurately may affect slip recovery capabilities. In addition, SOT scores for older participants were significantly lower than both the scores of young and middle-age participants and SOT scores of middle-age participants were lower than those of the young participants, signifying that postural sway increases with age. In that study, however, only SOT equilibrium scores and not direct measures of postural sway, such as COP standard deviation, were examined. Also, SOT conditions 5 and 6, which utilize inaccurate somatosensory information using sway referencing techniques coupled with either absent or inaccurate vision information, respectively, were not assessed. Decreased performance on these conditions, which cause the subject to rely on vestibular channels only for accurate sensory information, have thus been cited as indicators of vestibular loss (Horak et al., 1990) as well as the best SOT predictors for recurrent falls risk (Buatois et al., 2006). Thus, the study by Lockhart et al. (2005) may have omitted tests that most distinguish individuals at risk of falling during an unexpected slip.

In summary, while numerous studies have compared postural sway measures in young versus older adults and fallers versus non-fallers, to our knowledge no gait research to date has investigated the direct association between slip severity and sensory integration abilities from all three sensory channels important to balance. Thus, the second goal of this research was to investigate the relationship between postural measures representing subject sway during the SOT and slip severity in young and older adults. Postural sway measures considered in this analysis include COP standard deviation and PATH LENGTH.

1.3 SPECIFIC AIMS

The long term goal of this project is to identify biomechanical and physiological factors that affect the ability of an individual to recover from a severe slip. Knowledge of these factors and their influences may aid in the advancement of slip and fall prevention. The first focus of this research project is to investigate the impact of muscle strength on the severity of an unexpected slip. Knowledge of individual joint muscle strength contributions to slip recovery is limited and may be critical to the development of effective fall prevention programs. Specifically, knee corrective moments generated during slipping assist in balance recovery and are modulated by knee flexor/extensor activity. Thus, it is likely that knee flexion and extension strength may influence the ability to recover from an unexpected slip. Given that the ability to generate stronger, more rapid knee corrective moments within a limited time frame during reaction to a slip may be especially important for slip recovery and fall prevention, the relationship between slip severity and both peak and explosive muscle strength measures will be investigated in this study. Specific strength measures examined will include peak torque, rate of torque development and angular impulse. Thus, the first specific aim for this project is as follows:

Specific Aim 1: To investigate the relationship between knee flexion and extension strength and slip severity in young and older adults, including the influences of both peak and explosive strength measures.

H.1.) Increased knee flexion and extension strength will be associated with less hazardous slips.

The second focus of this research project is to examine the influence of individual sensory modalities used to detect an unexpected slip on slip severity. The ability to accurately acquire and integrate somatosensory, vestibular and visual sensory channel information is vital to maintaining postural stability and declines in this ability have been noted with aging and falls incidence. However, specific knowledge of sensory channel contributions and integration abilities regarding the outcome of a slip is lacking and may aid in fall prevention. Somatosensory and vestibular channels specifically contribute most to postural stability and, thus, may influence the ability to detect a slip and produce an appropriate corrective response. The Sensory Organization Test (SOT) was used in this study to assess postural sway measures characterizing the ability to integrate sensory information and identify deficits in the individual sensory channels related to sensory re-weighting and integration. The relationship between these postural sway measures and slip severity will be examined in this study. Specific sway measures will include COP standard deviation and PATH LENGTH. Thus, the second specific aim for this project is as follows:

Specific Aim 2: To investigate the association between the ability to integrate sensory information important for balance and slip severity.

H.2.) Increased sway in conditions requiring the use of vestibular and proprioception channels to maintain balance will be associated with increased slip severity.

2.0 METHODS

2.1 SUBJECTS

Thirty young and twenty-eight older subjects between the ages of 20-31 and 50-65 years old, respectively, were recruited for participation in this study (Table 1). Age group and gender group differences in stature, body mass and age were tested using an ANOVA model including age group (young/older), gender group (male/female) and their interaction as fixed effects. Statistically significant effects are reported in the last column of Table 1. Participants were screened for clinically significant neurological, cardiovascular, pulmonary, and orthopedic abnormalities that affect normal balance and gait. Study protocol was approved by the University of Pittsburgh Institutional Review Board and written informed consent was acquired for each subject prior to participation. Subjects were asked to complete two visits. Strength testing and gait testing were completed in Visits 1 and 2, respectively.

Table 1. Subject population characteristics stratified by age and gender groups. Mean (standard deviation) [minimum - maximum] values are reported.

	Young female (N=14)	***Young male (N=16)***	***Older female (N=15)***	***Older male (N=13)***	***Age / Gender differences***
Age (years)	25 (4) [20-31]	23 (2) [21-26]	55 (3) [50-60]	58 (6) [50-65]	$p_{age} < 0.01$ $p_{agexgender} < 0.05$
Stature (cm)	166 (5) [158-174]	178 (7) [164-190]	164 (5) [157-175]	177 (6) [168-191]	$p_{gender} < 0.01$
Body mass (kg)	63 (12) [52-88]	75 (11) [56-98]	82 (18) [56-112]	88 (13) [61-112]	$p_{age} < 0.01$ $p_{gender} < 0.05$

2.2 GAIT TESTING

2.2.1 Gait Testing Protocol

Subjects were instructed to walk at a self-selected pace along an 8 m vinyl tile walkway, focusing their vision toward an X taped onto the opposite wall. Hindfoot kinematics were tracked using four reflective markers (Figure 2). Subjects were fitted with a safety harness and practiced walking across the walkway. Ground reaction forces were collected at 1080 Hz using two Bertec FP4060 force platforms embedded in the floor (Bertec Co., Columbus, OH) and shoe kinematic data were recorded at 120 Hz using a Vicon 612 motion capture system (Vicon, Lake Forest, CA).

Subjects were exposed to two environmental conditions: a baseline condition in which subjects walked onto a known dry floor and an unexpected slippery condition in which the floor was contaminated with a glycerol-water solution (75%:25%) without the participant's knowledge. Coefficients of friction for the dry and slippery conditions, measured by the English XL VIT Slipmeter ® (ASTM F1679) at the shoe-floor interface, were 0.53 and 0.03, respectively. To prevent the subject from discerning the contaminated floor, the laboratory lights were dimmed. Between all trials (baseline dry and unexpected slip), subjects listened to loud music and faced away from the walkway to distract them from noticing the possible application of the contaminant. Subjects were informed that the first few trials would be dry and two to three baseline trials were first collected to capture normal gait patterns. The leading leg force plate was then covered with the glycerol solution, creating an unexpected slippery condition (Moyer et al., 2006). In this study, only the first unexpected slip trial was analyzed, eliminating effects of anticipation and adaptation.

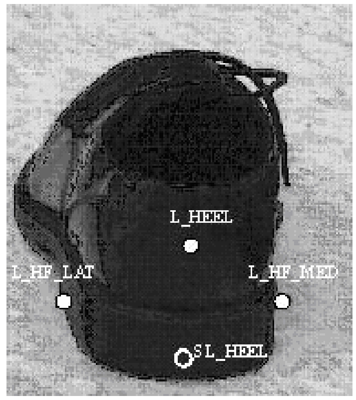


Figure 2. Placement of the markers tracking the kinematics of the hindfoot in the leading/slipping (left) leg. Filled circles (L_HEEL, L_HF_LAT, L_HF_MED) represent markers that remain on the shoes during the static/calibration and dynamic walking trials and the hollow circle (SL_HEEL) denotes the "true" heel marker that is used only in the static/calibration trial. To reconstruct the heel marker position during walking, the three-dimensional relationship between the markers on the rigid heel segment was obtained from the static trial and used to mathematically recreate the trajectory of SL_HEEL during the dynamic gait trials. The kinematics of the SL_HEEL marker were used to determine peak slip velocity for hazardousness categorization. (adapted from Moyer et al, 2006).

2.2.2 Gait Data Processing

Kinematics of the inferior heel marker placed slipping foot (SL_HEEL marker in Figure 2) were used as a basis to quantify slip severity. Because the SL_HEEL marker is easily knocked off during gait, it was physically present only during the static calibration trials. To derive the position of the SL_HEEL marker during gait, a rigid body assumption was used for the hindfoot and the trajectory of the SL_HEEL marker was reconstructed from its three-dimensional relationship with other markers on the hindfoot during the static calibration trial (Moyer et al., 2006). The medial/lateral and anterior/posterior positions of the virtual slipping foot SL_HEEL marker were numerically differentiated to compute heel velocity components. Resultant horizontal heel velocity was then calculated at each time point as the magnitude of the vector containing both anterior/posterior and medial/lateral components. Slip hazardousness, a measure of slip severity, was based on peak slip velocity (PSV), which was determined as the first local maximum horizontal heel velocity approximately 50 ms after heel strike on the slippery surface (Figure 3). All PSV values were visually verified by inspecting the horizontal heel velocity curves. Slip hazardousness was categorized as hazardous (H) or non-hazardous (NH), with H trials having a PSV value of greater than 1.0 m/s (Moyer et al., 2006). Subject trials having a PSV value of greater than 1.5 m/s were considered falls (Redfern et al., 2001).

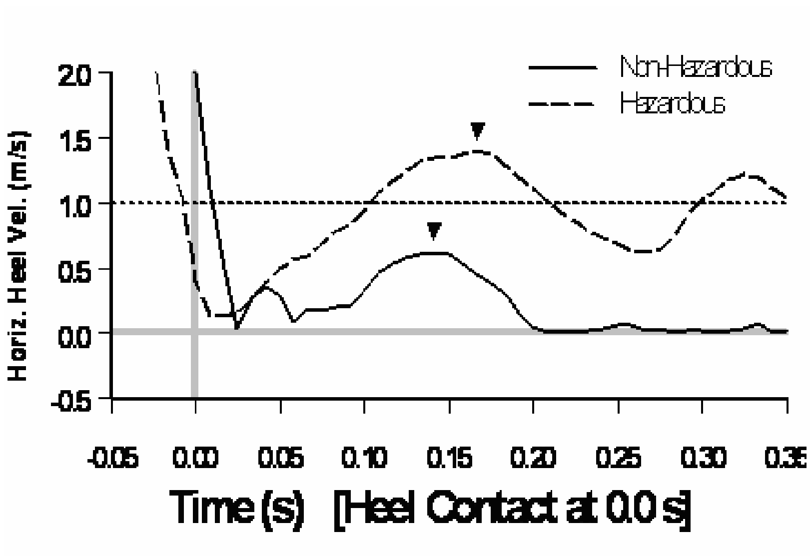


Figure 3. Typical horizontal velocity measured at the heel of the slipping foot in a hazardous and non-hazardous slip. The dashed horizontal line denotes the 1 m/s hazardousness threshold, while downward facing arrows reflect how peak slip velocity was derived, i.e. first local maximum after heel strike (time = 0) (adapted from Moyer et al, 2006).

2.3 MUSCLE STRENGTH

2.3.1 Strength Measurement Protocol

Subjects were seated and isometric knee flexion and extension strength at 45 degrees knee flexion were collected at 1000 Hz using a Biodex AP System 2 (Biodex Medical Systems, Inc., Shirley, NY) (Figure 4). Submaximal trials to approximately 50% of maximum were collected prior to each maximum voluntary contraction (MVC) trial to familiarize subjects with strength testing protocol. For MVC trials, subjects were instructed to contract as hard and fast as possible for five seconds then relax for ten seconds for three repetitions and received standardized verbal coaching by a physical therapist throughout (Chaffin et al., 1999). Knee extension isometric strength was collected first, followed by knee flexion. Only MVC trials were analyzed.

Figure 4. Strength Testing Setup. Subjects were seated with the knee angle set at 45^o flexion. Isometric knee flexion and extension strength were collected at 1000 Hz using a Biodex AP System 2 (Biodex Medical Systems, Inc., Shirley, NY).

2.3.2 Strength Data Processing

Isometric strength data for both the left (slipping) and right (trailing) legs were first lowpass filtered at 20 Hz using a fourth-order zero phase-lag Butterworth filter (Winter, 1990). The mean torque value during the resting period was subtracted from the time series to set the resting period torque to zero (Pohl et al., 2002). The derivative of the torque data, as well as its mean and standard deviation during the resting period, were computed for use in determining the onset of contraction. Specifically, the onset of contraction was defined as the first time point, working backwards from peak torque of each repetition, at which the torque derivative was less than or equal to the mean baseline resting torque derivative value plus two standard deviations and torque value was less than or equal to 2.5% of peak torque value (Aagaard et al., 2002; Pohl et al., 2002). All onsets were visually verified.

Peak torque was determined as the maximum torque value for each repetition. Average peak torque was also calculated across a three-second interval, beginning at two seconds after onset (Chaffin, 1975). All three-second intervals were also visually verified. RTD was calculated as the slope of the torque-time curve for each repetition in the following time period intervals: 0-10, 0-20, …, 0-300 ms, with 0 ms set as the onset of contraction (Andersen and Aagaard, 2006). RTD was computed in different time intervals to verify the time periods related to slip-related balance recovery efforts, as a wide range of time intervals reflects different neurophysiological processes. As mentioned previously, it is expected that RTD time intervals later than 0-100 ms will be relevant to slip-related balance recovery efforts (Cham and Redfern, 2001; Chambers and Cham, 2007; Moyer et al., 2007). Angular impulse was calculated as the area under the torque-time curve for each time interval (Aagaard et al., 2002). Additional RTD and angular impulse variables, RTD_vol and angular impulse_vol, were calculated with intervals beginning 50 ms after onset continuing to 300 ms after onset (e.g. 50-60 ms, 50-70 ms, … , 50-300 ms) to eliminate effects of intrinsic contractile muscle properties (Andersen and Aagaard, 2006). Within-subject ANOVA models revealed similar strength measures across all three repetitions ($p > 0.05$). Thus, mean values across the three repetitions were used in subsequent analyses.

2.3.3 Muscle Strength Statistical Analysis

All data were checked for normality. Those variables not normally distributed underwent a Box Cox transformation. First, knee flexion and knee extension RTD and angular impulse variables were individually entered in a mixed linear regression model with time interval as a fixed effect and subject as a random factor to examine the dependence of RTD and angular impulse on the time interval used in the computation. Second, because gender-related effects on strength have been previously established and the focus of this paper is the relationship between slip hazardousness and strength capabilities in young and older adults, the following main analyses were conducted within each gender group. A linear regression was also run on RTD and angular impulse variables within gender for each time interval using subject nested with age group as a random effect and age group, slip hazardousness, trial type (knee flexion or knee extension), and their interactions as fixed effects. Model significance for all variables regarding trial type indicated that main analyses could be conducted within knee flexion and knee extension trial types.

Specifically, to investigate the association between strength, slip hazardousness and age group, knee flexion/extension peak torque, average peak torque, and RTD and angular impulse variables were individually regressed on slip hazardousness (NH/H), age group (young/older) and their interaction. In addition, correlation analyses were run between left and right leg flexion and extension variables to examine the relationships between slipping and trailing legs and the effects of dominant leg strength capabilities. All analyses were conducted within each time interval for RTD and angular impulse measures. Statistical significance was set at 0.05.

2.4 POSTURAL CONTROL AND SENSORIMOTOR INTEGRATION

2.4.1 Sensory Organization Test Protocol

The Sensory Organization Test (SOT) was administered for all subjects using a computerized dynamic posturography platform (EquiTest, NeuroCom, Clackamas, OR). The SOT evaluates the ability of an individual to effectively apply visual, vestibular, and somatosensory inputs while suppressing any inaccurate sensory information (Vouriot et al., 2004). Inaccurate visual and somatosensory cues during the SOT are generated through the use of sway-referencing techniques in which the support surface and/or visual surround tilts to directly follow the anterior-posterior COG sway of the subject (Nashner and Peters, 1990). Subjects wore their own shoes and were fitted with a safety harness to prevent injury in case of a fall. A laboratory technician was also available to catch the subject in the event of an irrecoverable balance loss. Subjects were positioned with one foot on each of the dual-force plates of the platform, aligning the ankle medial malleoli with the centers of rotation of the force plates. During the SOT, the subject was exposed to six conditions and two to three 20-second trials (T1-T3) were collected at 100 Hz for each condition. SOT conditions can be summarized as follows (Figure 5):

- **Condition 1 (C1):** Eyes open, fixed support surface and surround
    - *Visual, vestibular and somatosensory modalities available and accurate*

- **Condition 2 (C2):** Eyes closed, fixed support surface and surround
    - *Visual input absent*

- **Condition 3 (C3):** Eyes open, fixed support surface, sway-referenced surround
    - *Visual input available but inaccurate*

- **Condition 4 (C4):** Eyes open, sway-referenced support surface, fixed surround
    - *Somatosensory input available but inaccurate*

- **Condition 5 (C5):** Eyes closed, sway-referenced support surface, fixed surround
    - *Visual input absent, somatosensory input available but inaccurate*

- **Condition 6 (C6):** Eyes open, sway referenced support surface and surround
    - *Visual and somatosensory inputs available but inaccurate*

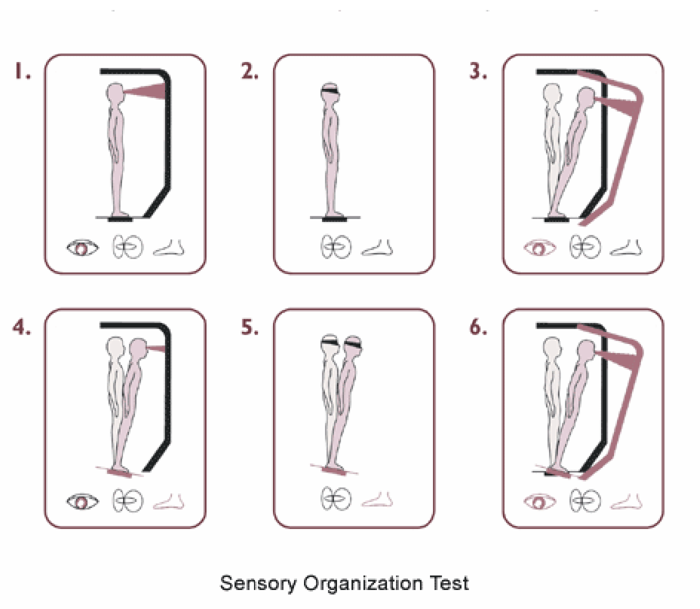


Figure 5. Sensory Organization Test (SOT) conditions. Subjects were exposed to six conditions in which visual, somatosensory, and/or vestibular sensory channels may be missing or inaccurate. Two to three 20-second trials (T1-T3) were collected at 100 Hz for each condition (adapted from NeuroCom International, Inc.).

Subjects were instructed to maintain upright stance during each trial, while trying to limit postural sway and avoid movement of their feet (Vouriot et al., 2004). Trials in which subjects took a step, required the use of the harness, or were caught by the technician were considered falls.

2.4.2 SOT Data Processing

Center of Pressure (COP) position data from each SOT trial was imported into a MATLAB program to calculate measures of postural sway. COP position standard deviation in the anterior/posterior direction (COP ST DEV) was calculated using the following formula:

$$COP\_ST\_DEV = \sqrt{\frac{1}{N}\left(\sum_{i=1}^{N}\left(COP\_AP_i - \overline{COP\_AP}\right)^2\right)}$$

The total change in resultant (both anterior/posterior and medial/lateral) COP position during each trial, known as PATH LENGTH, was also calculated as shown in the equation below:

$$Path\_length = \sum_i \sqrt{(COP\_ML_{i+1} - COP\_ML_i)^2 + (COP\_AP_{i+1} - COP\_AP_i)^2}$$

Note that PATH LENGTH can also be interpreted as a measure of sway velocity.

2.4.3 SOT Statistical Analysis

All data were checked for normality. Those variables not normally distributed underwent a log transformation. Trials classified as falls were removed from the statistical analysis due to difficulty in determining exactly where a fall began during the trials and, thus, where AP COP data was no longer real. Trials removed accounted for approximately 1.4 % of the total data set and occurred only in conditions 5 and 6. Because so few trials were classified as falls, only qualitative differences in balance variables and slip hazardousness between falls and no falls trials have been reported.

For the preliminary analysis, COP ST DEV and PATH LENGTH were first individually entered in a mixed linear regression model with trial (1-3) as a fixed effect and subject as a random factor to examine the dependence of these variables on trial, essentially repeated exposure, within each condition (C1-C6) for each subject. Nearly all variables within each condition showed significant trial effects, warranting the use of subsequent within-trial analyses. A linear regression was then run on COP ST DEV and PATH LENGTH variables within trial using subject nested with age group as a random effect and age group (young/older), slip hazardousness (hazardous/non-hazardous), condition (C1-C6), and their interactions as fixed effects. Significant condition effects for all trials again helped further justify the use of a within-condition main analysis. Also, because the strongest age group and condition main effects, as well as age group by condition interaction effects were seen in T1, subsequent analyses were focused in T1 only.

Thus, the main analyses, conducted within condition and T1, investigated the association between postural sway variables, slip hazardousness and age groups. Specifically, COP ST DEV and PATH LENGTH were regressed on slip hazardousness (NH/H), age group (young/older) and their interaction within condition. To amplify the effects of the individual sensory modalities (visual, vestibular, somatosensory) contributing to postural stability and normalize to baseline sway, ratios of the COP ST DEV and PATH LENGTH variables were also calculated and analyzed. Ratios for the following conditions were calculated for COP ST DEV and PATH

LENGTH: C2 to C1, C3 to C1, C4 to C1, C5 to C2, C6 to C1, C6 to C4, and C6 to C5. These ratios were then also regressed on slip hazardousness, age group and their interaction within condition. In addition, correlation analyses were run between COP ST DEV and PATH LENGTH variables within each condition, as well as for all conditions together to examine the relationship between sway distance and velocity during the SOT. Statistical significance for all analyses was set at 0.05.

3.0 RESULTS

3.1 MUSCLE STRENGTH RESULTS

A relatively even distribution of NH/H slips were experienced across age and gender groups (Table 2). The preliminary analysis examining the dependence of RTD and angular impulse measures on the time intervals used to compute these variables revealed a significant time interval effect ($p < 0.05$, Figure 6). Specifically, RTD and angular impulse values increased with increasing time intervals. This statistically significant time interval effect regarding RTD and angular impulse measures justifies the use of main within-interval analyses for these variables.

Table 2. Distribution of hazardous / non-hazardous slips stratified by age and gender groups

	Young female	***Young male***	***Older female***	***Older male***
Non-Hazardous	6	9	7	7
Hazardous	8	7	8	6

Typical individual subject RTD and angular impulse values across time intervals can be seen in Figure 7. As seen in the figure, RTD and angular impulse profiles for individual subjects demonstrated consistent shape over time intervals. Strength characteristics categorized by fall/recovery are depicted in Figure 8. Due to power issues regarding several small group sizes, no statistics were run regarding fall/recovery status and a more qualitative comparison will be discussed. Overall, males who recovered following the slip demonstrated higher explosive strength (RTD and angular impulse) values than those experiencing falls.

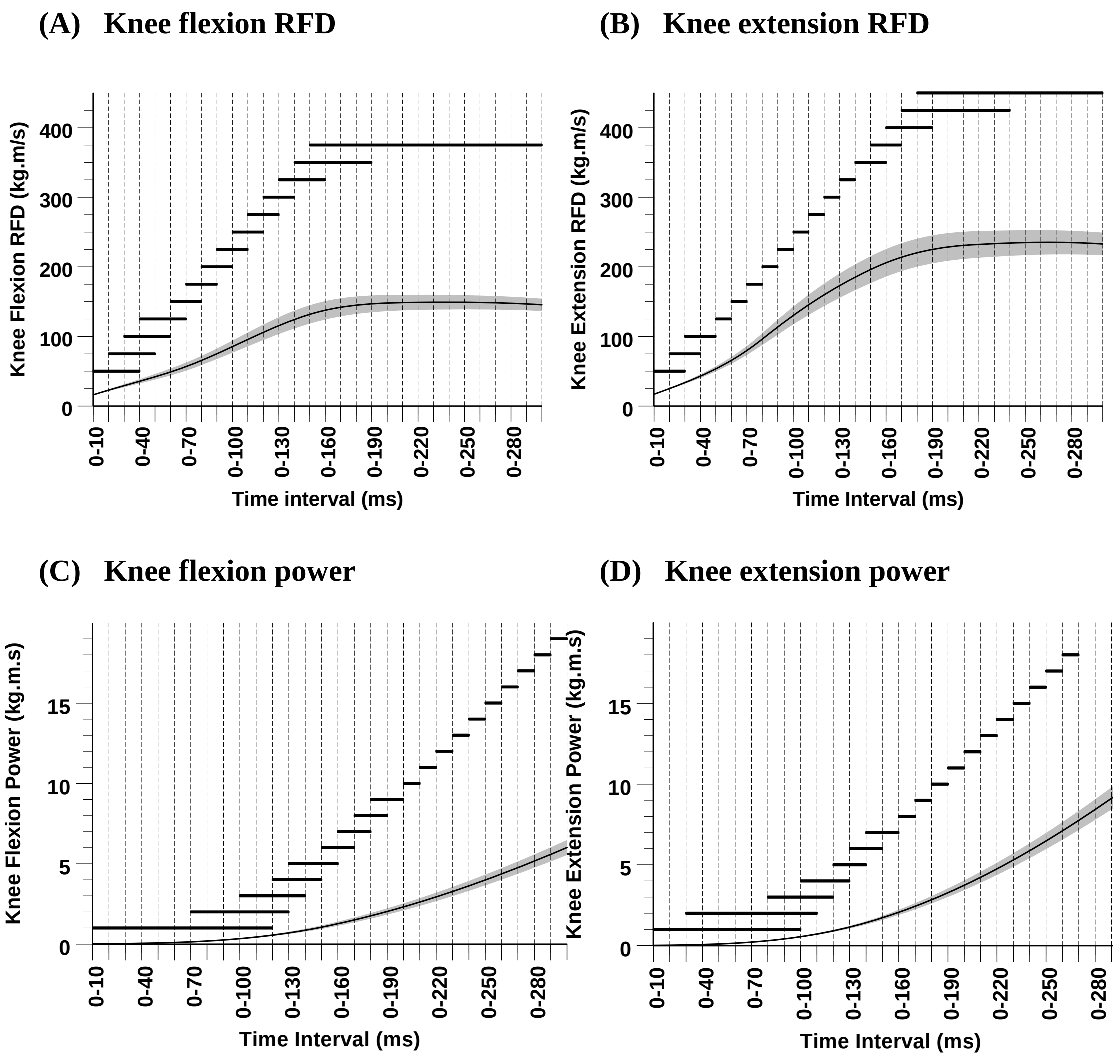


Figure 6. Average (across all subjects) knee flexion RTD (A), knee extension RTD (B), knee flexion angular impulse (C) and knee extension angular impulse (D) versus time interval. Gray shaded areas reflect standard errors. Time interval effects were significant for all strength measures ($p<0.05$). Results of post-hoc tests evaluating differences in strength measures between time intervals are denoted by horizontal lines. Specifically, differences in strength measures between time intervals connected by a line are not statistically significant ($p>0.05$).

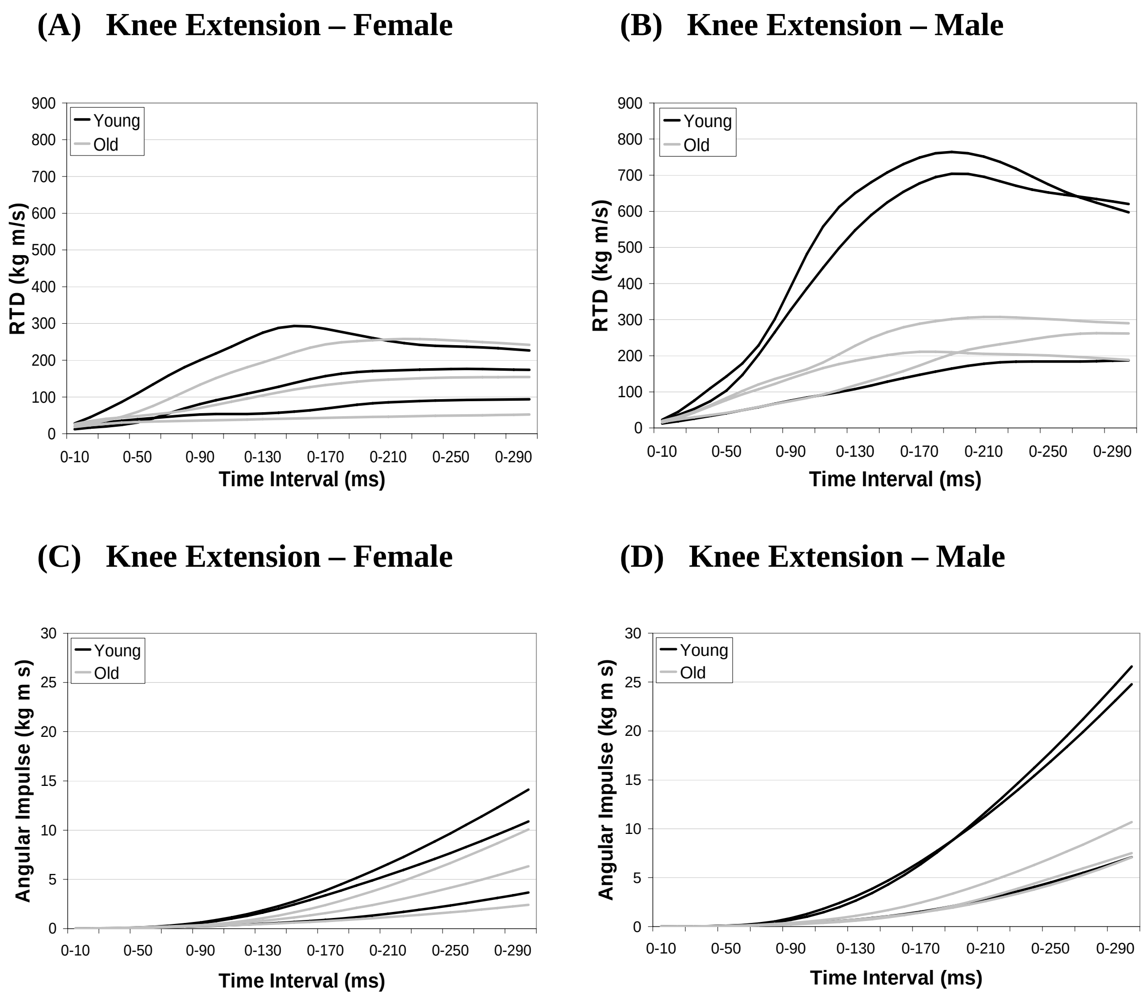


Figure 7. Examples of typical individual subject RTD (A, B) and angular impulse (C, D) values across time interval for three young and three older subjects.

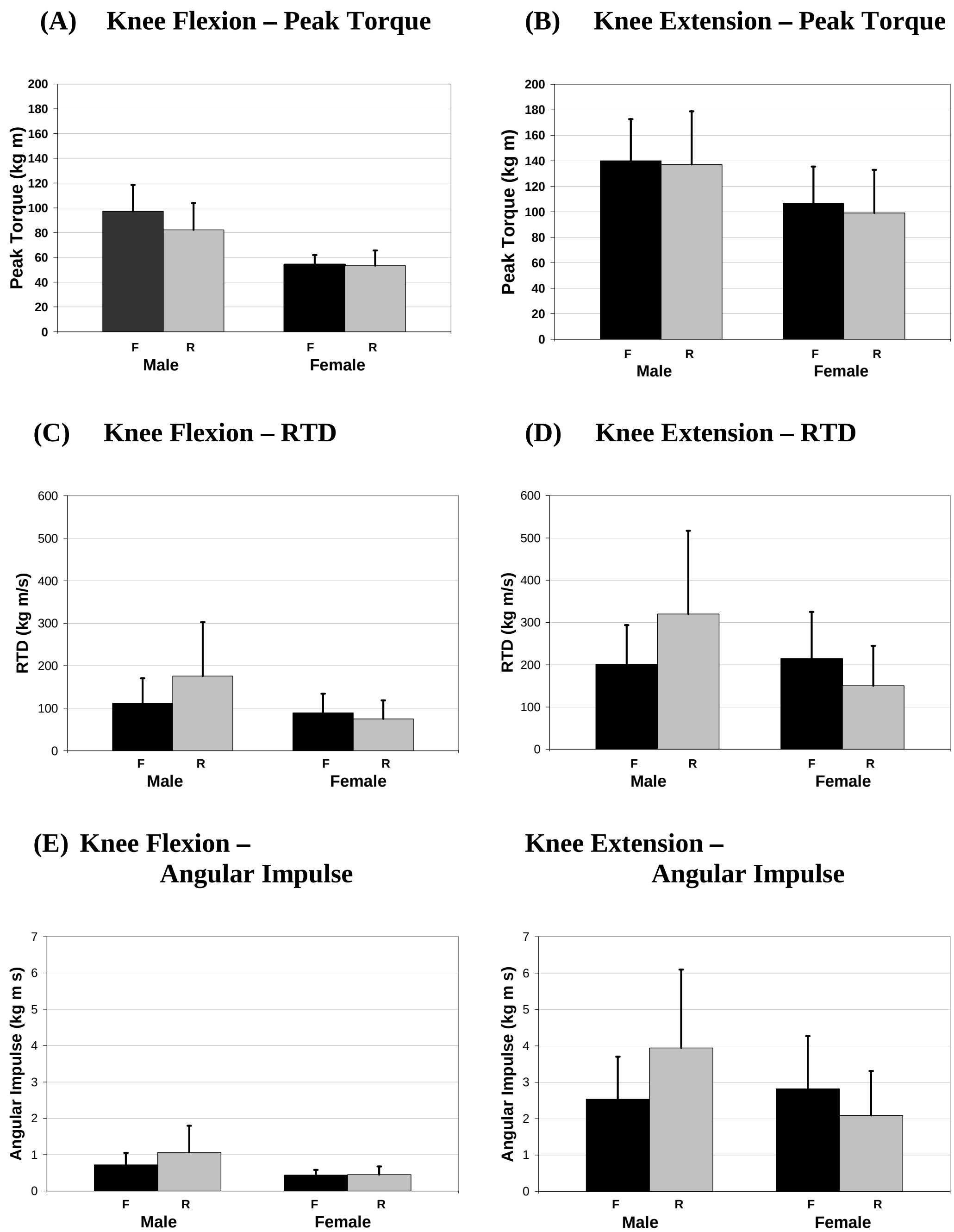


Figure 8 Left leg peak torque (A, B), RTD (C, D), and angular impulse (E, F) stratified by gender and fall status: fall (F) or recovery (R). A peak slipping velocity (PSV) threshold value of 1.5 m/s was used to characterize slips as falls or recoveries. Knee flexion plots (C, E) depict the 0-120 ms time interval, while knee extension plots (D, F) are representative of the 0-180 ms time interval. Standard deviation bars are shown.

RTD and angular impulse variables for both male and female subjects showed model significance regarding trial type beginning with approximately the 0-100 ms time interval and continuing to the 0-300 ms interval. These results helped justify the use of within-trial type main analyses. No other variables in the linear regression were significant for female subjects. RTD and angular impulse variables for both legs in male subjects showed age group significance. In addition, left leg RTD and angular impulse variables in male subjects showed significant hazardousness, age group x hazardousness, and trial type x hazardousness effects. Trial type x age group was also significant for the left leg RTD in male subjects. Time intervals showing the above significant effects are listed in Table 3.

Table 3. Results of preliminary regression analyses investigating the relationship between dynamic strength measures (dependent variable), age group (Young/Older), trial type (knee flexion/knee extension), and slip hazardousness (NH/H). *Significant ($p < 0.05$) time intervals are listed below.*

	RFD				*Power*			
	Male		*Female*		*Male*		*Female*	
	Left	*Right*	*Left*	*Right*	*Left*	*Right*	*Left*	*Right*
Young/Older	0-100 to 0-300 ms	0-40 to 0-90 ms, 0-120 to 0-300 ms			0-90 to 0-300 ms	0-110 to 0-300 ms		
NH/H	0-160 to 0-260 ms				0-200 to 0-300 ms			
Trial Type	0-70 to 0-300 ms	0-140 to 0-300 ms	0-10 to 0-300 ms	0-90 to 0-300 ms	0-90 to 0-300 ms	0-150 to 0-300 ms	0-100 to 0-300 ms	0-90 to 0-300 ms
Young/Older x NH/H	0-70 to 0-250 ms				0-130 to 0-300 ms			
Trial Type x NH/H	0-190 to 0-250 ms							
Trial Type x Young/Older	0-190 to 0-300 ms				0-220 to 0-300 ms			

Knee extension and knee flexion RTD values for all time intervals were significantly correlated within right and left legs between knee flexion and extension values ($p<0.05$). Knee extension vs. knee flexion correlation coefficients ranged from 0.44 to 0.84 and 0.41 to 0.66 for left and right sides, respectively. Right knee flexion angular impulse values were also significantly correlated with right knee extension (r value range: 0.39 to 0.70). Left knee flexion angular impulse values were significantly correlated with left knee extension angular impulse values between the 0-80 to 0-300 ms time intervals (r value range: 0.39 to 0.81). RTD and angular impulse values were also significantly correlated ($p<0.05$) between left and right legs for both knee extension and knee flexion. Correlation coefficients ranged from 0.44 to 0.84 between right and left knee extension RTD values and 0.49 to 0.81 between right and left knee flexion values for all time intervals. Right knee flexion angular impulse values were also significantly correlated with left knee flexion (r value range: 0.37 to 0.78) angular impulse values for all time intervals. Right knee extension angular impulse values were significantly correlated to left knee extension angular impulse values (r value range: 0.37 to 0.82) between the 0-90 and 0-300 ms time intervals.

The main analyses investigated associations between strength measures, age and slip hazardousness within each gender group. Results for peak and average knee flexion and extension torque were similar for both right and left legs. Both peak and average peak knee extension and flexion torque were greater in young male participants compared to their older counterparts ($p_{Y/O} < 0.05$; Tables 4 and 5; Figures 9 and 10). In contrast, such age group differences in peak and average peak torque were not evident in the female participants recruited in this study ($p_{Y/O} > 0.05$; Figures 9 and 10). In both gender groups, the relationship between slip hazardousness and peak knee flexion/extension torque was not statistically significant in young and older participants ($p_{NH/H} > 0.05$; $p_{NH/H\ x\ Y/O} > 0.05$; Tables 4 and 5; Figures 9 and 10).

Table 4. Results of main statistical analyses for the left leg investigating the relationship between strength measures (dependent variable), age group (Young/Older) and slip hazardousness (NH/H) for male participants. Significance (p < 0.05) is denoted by *.

	Peak Torque				*Average Peak Torque*				*RTD*				*Angular Impulse*			
	Male		*Female*		*Male*		*Female*		*Male*		*Female*		*Male*		*Female*	
	KF	*KE*	*KF*	*KE*	*KF*	*KE*	*KF*	*KE*	*KF*	*KE*	*KF*	*KE*	*KF*	*KE*	*KF*	*KE*
Young/ Older	*	*			*	*			* 0-80 to 0-300 ms	*0-100 to 0-300 ms			*0-170 to 0-300 ms	*0-90 to 0-300 ms		
NH/H										*0-160 to 0-280 ms				*0-170 to 0-300 ms		
Young/ Older X NH/H										*0-70 to 0-300 ms				*0-130 to 0-300 ms		

Table 5. Results of main statistical analyses for the right leg investigating the relationship between strength measures (dependent variable), age group (Young/Older) and slip hazardousness (NH/H) for male participants. Significance (p < 0.05) is denoted by *.

	Peak Torque				*Average Peak Torque*				*RTD*				*Angular Impulse*			
	Male		*Female*		*Male*		*Female*		*Male*		*Female*		*Male*		*Female*	
	KF	*KE*	*KF*	*KE*	*KF*	*KE*	*KF*	*KE*	*KF*	*KE*	*KF*	*KE*	*KF*	*KE*	*KF*	*KE*
Young/ Older	*	*			*	*			* 0-150 to 0-300 ms	*0-170 to 0-300 ms			*0-80 to 0-300 ms	*0-230 to 0-300 ms		
NH/H																
Young/ Older X NH/H											*0-10 to 0-150 ms					

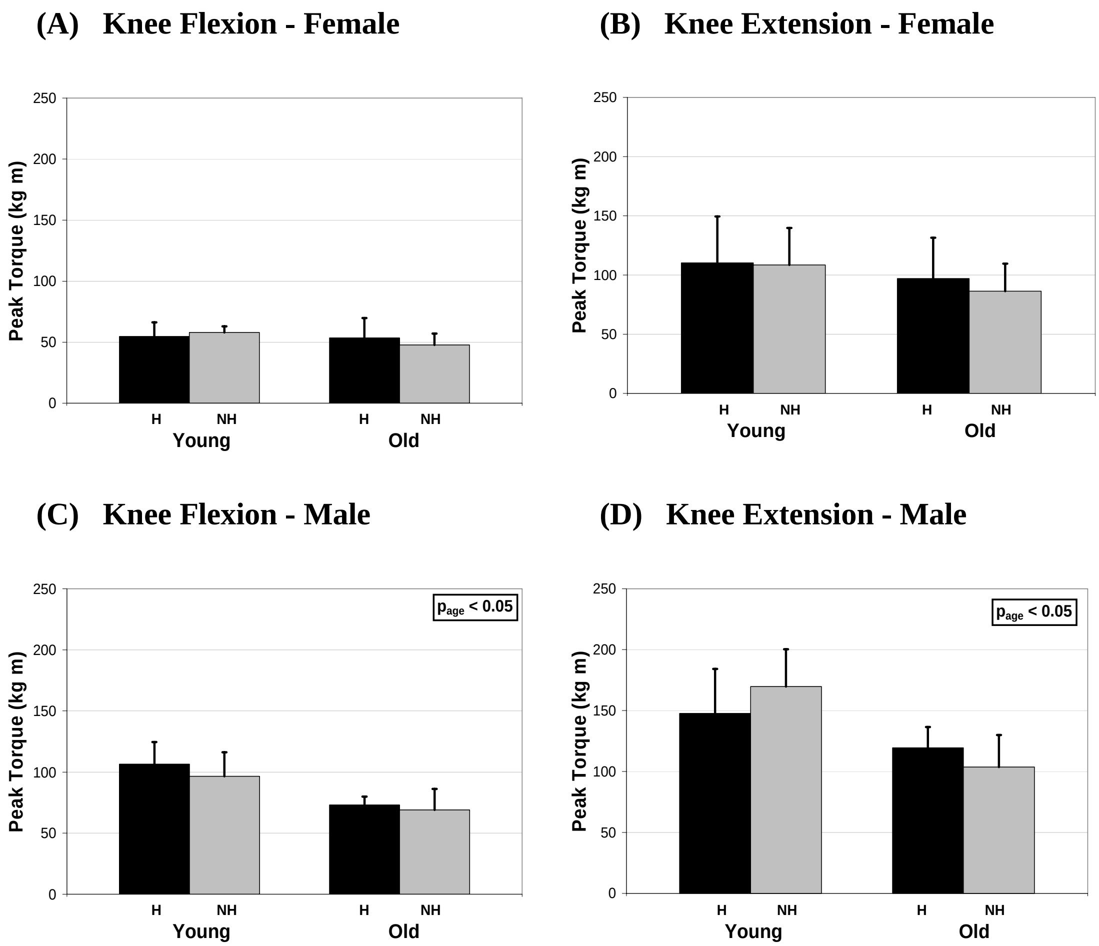


Figure 9. Peak knee flexion (A, C) and extension (B. D) torque stratified by age group and slip hazardousness. In female participants (A, B), main and interaction effects of age and hazardousness on peak knee flexion/extension torque were not statistically significant (p>0.05). In male subjects (C, D), age effects were statistically significant ($p_{Y/O}$ <0.05), with young male subjects generating greater peak knee flexion/extension torque than their older counterparts. As in the female participants, there were no statistically significant associations between strength and slip hazardousness in male subjects. Standard deviation bars are shown.

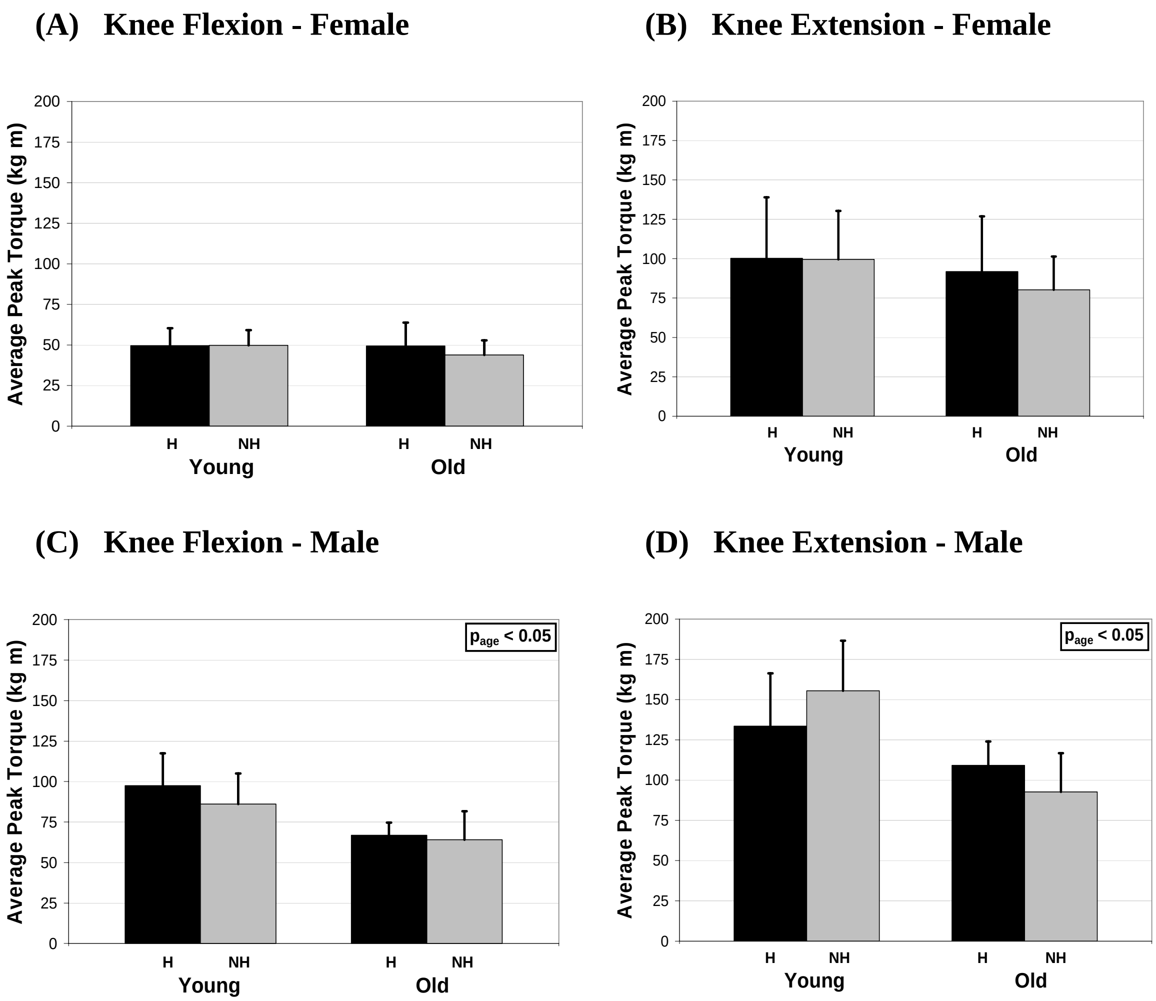


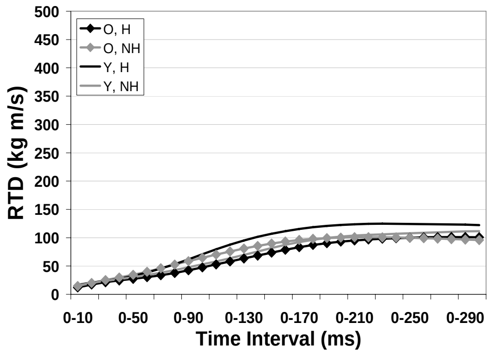
Figure 10. Average peak knee flexion (A, C) and extension (B. D) torque stratified by age group and slip hazardousness. In female participants (A, B), main and interaction effects of age and hazardousness on peak knee flexion/extension torque were not statistically significant (p>0.05). In male subjects (C, D), age effects were statistically significant ($p_{Y/O}$ <0.05), with young male subjects generating greater peak knee flexion/extension torque than their older counterparts. As in the female participants, there were no statistically significant associations between strength and slip hazardousness in male subjects. Standard deviation bars are shown.

The main analyses using RTD as the dependent variable revealed age group effects similar to those found for peak and average peak torque measures. That is, age group effects were statistically significant only for male participants for both right and left leg RTD values.

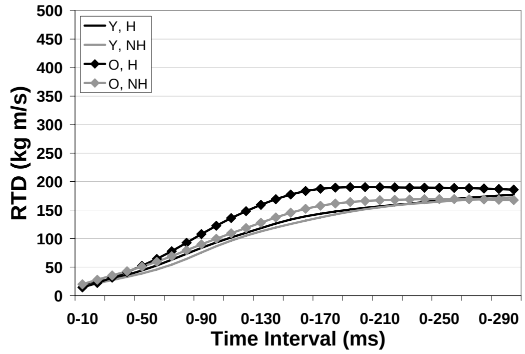
Specifically, young males demonstrated significantly greater knee flexion and knee extension RTD values than older males for both legs ($p_{Y/O} < 0.05$; Figure 11). Tables 4 and 5 list specific time intervals in which age group was significant.

Despite statistically significant correlations between right and left leg variables, results regarding slip hazardousness for the trailing leg differed from those of the slipping leg. Unlike the statistical findings for peak and average peak torque, male participants also showed a statistically significant relationship between main slip hazardousness effects and left knee extension RTD values ($p_{NH/H} < 0.05$; Table 4). These findings were, to a great extent, influenced by the left knee extension RTD results for young male subjects ($p_{NH/H \times Y/O} < 0.05$; Table 4). Specifically, young male subjects experiencing NH slips generated greater left knee extension RTD values than those experiencing H slips in the same age group (Table 4, Figure 11). Table 4 lists specific time intervals in which slip hazardousness and interaction effects were significant for the left leg. These findings relating left knee extension RTD and slip hazardousness in male subjects did not hold for female participants or right knee extension RTD results in male participants (Tables 4 and 5). Furthermore, knee flexion RTD was only significantly correlated with slip hazardousness for right leg values in female subjects. Specifically, female subjects experiencing H slips had significantly higher right knee flexion RTD values than their NH counterparts, as well as older females experiencing H slips. No other age and gender groups exhibited significant relationships between knee flexion RTD and slip hazardousness. Table 5 lists time intervals in which these slip hazardousness interaction effects were significant for the right leg. Results for RTD_vol, calculated beginning at 50 ms after onset, showed similar intervals for age group and hazardousness significance to those found for the original RTD calculation.

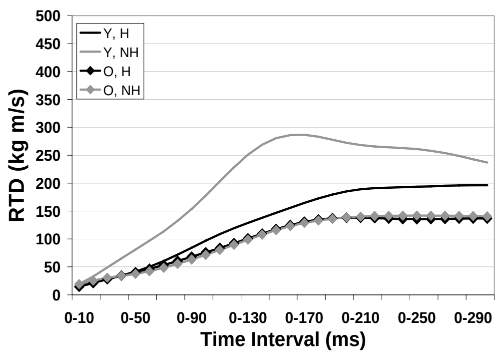
(A) Knee Flexion - Female



(B) Knee Extension - Female



(C) Knee Flexion - Male



(D) Knee Extension - Male

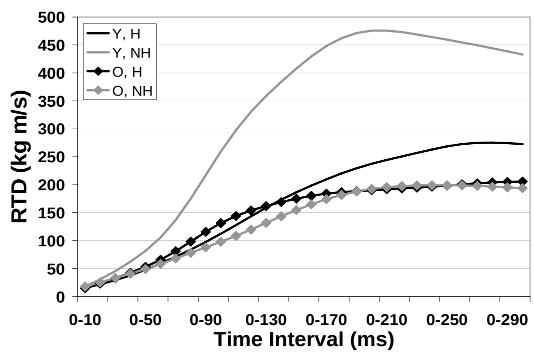


Figure 11. Average isometric knee flexion (A, C) and knee extension (B, D) RTD versus time intervals stratified by age group and slip hazardousness. In female participants (A, B), main and interaction effects of age and hazardousness on average knee flexion/extension RTD were not statistically significant ($p > 0.05$). In male subjects (C, D), age effects were statistically significant ($p_{Y/O} < 0.05$) with young male subjects generating greater knee flexion RTD than their older counterparts. There were no statistically significant associations between knee flexion RTD and slip hazardousness in male subjects. Males experiencing nonhazardous slips showed significantly greater knee extension RTD values ($p_{NH/H} < 0.05$) than those experiencing hazardous. Specifically, young males who experienced nonhazardous slips had significantly greater knee extension RTD values ($p_{NH/H \times Y/O} < 0.05$) reported during strength testing than the other three subject.

The main analyses correlating angular impulse, age group and slip hazardousness revealed results similar to those for the RTD measures. Specifically, young male participants generated greater knee flexion and knee extension angular impulse values than their older counterparts for both right and left legs ($p_{Y/O} < 0.05$; Figure 12). Significant time intervals regarding age group for the left and right legs can be seen in Tables 4 and 5, respectively. Young and older female participants generated similar knee flexion/extension angular impulse values. Similar to RTDs in male participants, only left knee extension angular impulse values were significantly correlated with slip hazardousness ($p_{NH/H} < 0.05$; Table 4; Figure 12). Once again, these findings can be attributed to findings in younger male participants. Specifically, young male subjects experiencing NH slips generated greater left knee extension angular impulse values than young male participants experiencing H slips ($p_{NH/H \times Y/O} < 0.05$; Table 4; Figure 12). Such effects were not found for female subjects or right leg knee extension angular impulse in male subjects. Also, knee flexion angular impulse was not significantly correlated with slip hazardousness in all age and gender groups (Tables 4 and 5). As in RTD_vol, results for angular impulse_vol showed similar intervals for age group and hazardousness significant effects to those found for the original angular impulse calculation.

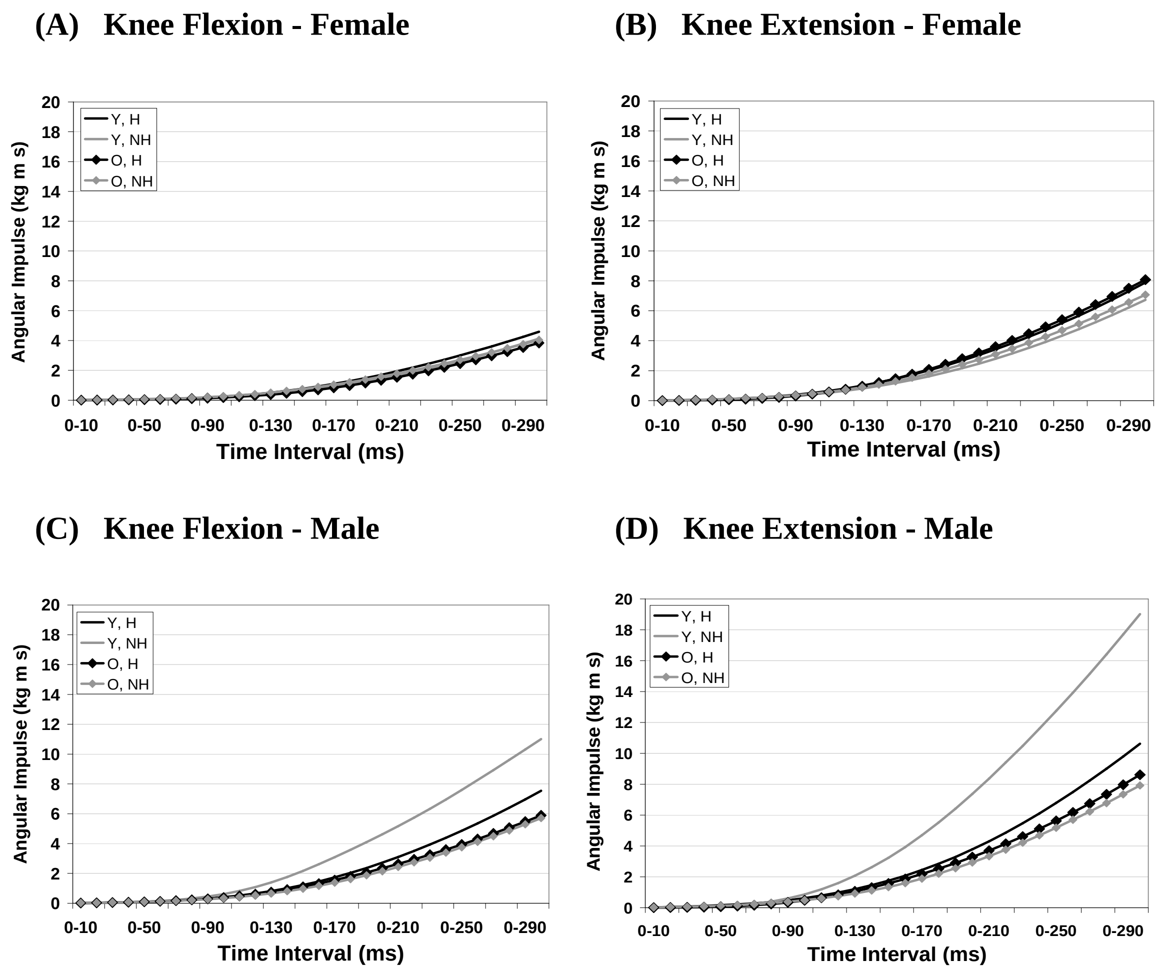


Figure 12. Average isometric knee flexion (A, C) and knee extension (B, D) angular impulse versus time intervals stratified by age group and slip hazardousness. In female participants (A, B), main and interaction effects of age and hazardousness on average knee flexion/extension angular impulse were not statistically significant ($p>0.05$). In male subjects (C, D), age effects were statistically significant ($p_{Y/O} <0.05$) with young male subjects generating greater knee flexion and extension angular impulse than their older counterparts. There were no statistically significant associations between knee flexion angular impulse and slip hazardousness in male subjects. Males experiencing nonhazardous slips showed significantly greater knee extension angular impulse values ($p_{NH/H} < 0.05$) than those experiencing hazardous slips. Specifically, young males who experienced nonhazardous slips had significantly greater knee extension angular impulse values ($p_{NH/H \times Y/O} < 0.05$) reported during strength testing than the other three subject groups.

3.2 SOT RESULTS

Due to the small number of falls during SOT trials, data from these trials were analyzed qualitatively. Any subject who fell according to the above-stated SOT criteria at least once in any of the conditions of the SOT test was classified as a 'faller' and those who did not were classified as 'non-fallers.' According to this categorization, the study included 9 fallers and 49 non-fallers. The risk of experiencing a hazardous slip was about the same in subjects who fell during the SOT versus non-fallers (Table 6). Also, PSV was nearly equal in fallers and non-fallers (Table 6). COP ST DEV and PATH LENGTH were significantly correlated and r values indicated moderate to strong correlations within and across all SOT conditions. Specifically, r values ranged from 0.28 in C1 to 0.80 in C3 (Table 7).

Table 6. Slip characteristics of fallers vs. non-fallers as characterized by falls during the SOT

	Mean PSV ± St Dev (m/s)	*# Non-Hazardous Slips*	*# Hazardous Slips*
Fallers (n = 9)	0.95 ± 0.48	4	5
Non-fallers (n = 49)	1.16 ± 0.76	25	24

Table 7. Results of correlation analysis between COP ST DEV and PATH LENGTH variables. *Variables were significantly (p value < 0.05) and moderately to strongly correlated within each SOT condition (C1-C6), as well as across the entire data set (Total).*

Condition	*R value*	*P value*
C1	0.28	0.0342
C2	0.57	<0.0001
C3	0.80	<0.0001
C4	0.58	<0.0001
C5	0.31	0.0186
C6	0.62	<0.0001
Total	0.78	< 0.0001

The main analysis involved regression of COP ST DEV and PATH LENGTH on age group, hazardousness and their interaction within condition during T1 only. A significant hazardousness effect for C4 PATH LENGTH indicated greater values for individuals experiencing hazardous slips than those experiencing non-hazardous slips (Table 8, Figure 13). In addition, older subjects produced significantly longer PATH LENGTH values than young subjects during all SOT conditions except C1, as well as significantly greater COP ST DEV values in C3 and C6 only (Table 8).

Table 8. Results of regression analyses investigating the relationship between postural sway measures (dependent variable), age group (Young/Older), slip hazardousness (NH/H), and their interactions within condition/condition ratio. *Significant ($p < 0.05$) and borderline significant ($p < 0.10$) p values are listed below. * denote significant p values and '--' denote non-significant p values > 0.10.*

		Young/Older	*NH/H*	*Young/Older x NH/H*
COP ST DEV	*C1*	--	--	--
	C2	0.0564	--	--
	C3	*0.0064	--	--
	C4	--	--	--
	C5	0.0647	--	--
	C6	*0.0305	--	--
Path Length	*C1*	--	--	--
	C2	*0.0033	--	--
	C3	*0.0006	--	--
	C4	*0.0347	*0.0488	--
	C5	*0.0003	--	--
	C6	*0.0006	--	--
COP ST DEV Ratio	*C2-C1*	--	--	--
	C3-C1	--	--	--
	C4-C1	--	--	--
	C5-C2	--	--	--
	C5-C4	--	--	--
	C6-C1	--	--	--
	C6-C4	--	*0.0285	--
	C6-C5	--	--	--
Path Length Ratio	*C2-C1*	*0.0020	--	--
	C3-C1	*0.0004	--	--
	C4-C1	*0.0380	*0.0320	--
	C5-C2	--	--	--
	C5-C4	--	*0.0081	--
	C6-C1	*0.0011	--	--
	C6-C4	--	*0.0350	--
	C6-C5	--	--	--

Next, the individual COP ST DEV and PATH LENGTH ratios were regressed on age group, hazardousness and their interaction. Significant hazardousness effects for PATH LENGTH ratios C4-C1, C5-C4, and C6-C4 indicated greater C4-C1 ratio values and lower C5-C4 and C6-C4 ratio values for individuals experiencing hazardous slips than those experiencing non-hazardous slips (Table 8, Figure 14). A significant hazardousness effect for COP ST DEV ratio also revealed that individuals experiencing hazardous slips produced lower C6-C4 ratio values than those experiencing non-hazardous slips (Figure 15). In addition, significant age group effects were found for PATH LENGTH ratios C2-C1, C3-C1, C4-C1, and C6-C1 with older subjects producing significantly higher PATH LENGTH ratios than younger subjects. No significant age effects were found regarding COP ST DEV ratios.

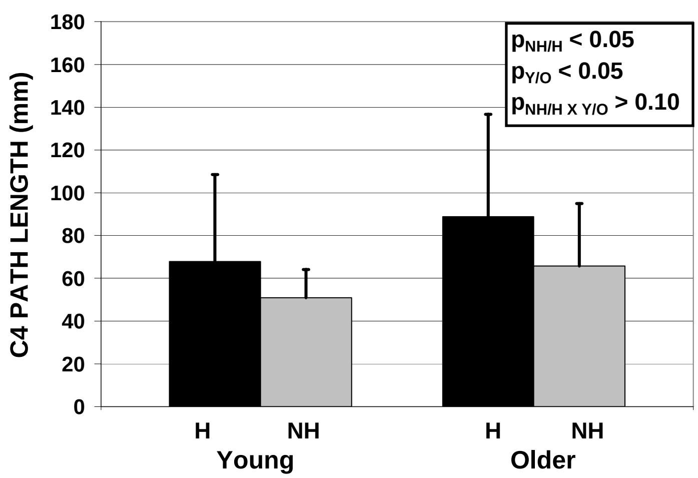


Figure 13. Average C4 PATH LENGTH values for young and older subjects experiencing hazardous (H) and non-hazardous (NH) slips. Subjects experiencing hazardous slips had significantly greater C4 PATH LENGTH values than those experiencing non-hazardous slips ($p_{NH/H} < 0.05$). Older subjects had significantly higher C4 PATH LENGTH values compared to young subjects ($p_{Y/O} < 0.05$). Standard deviation bars are shown.

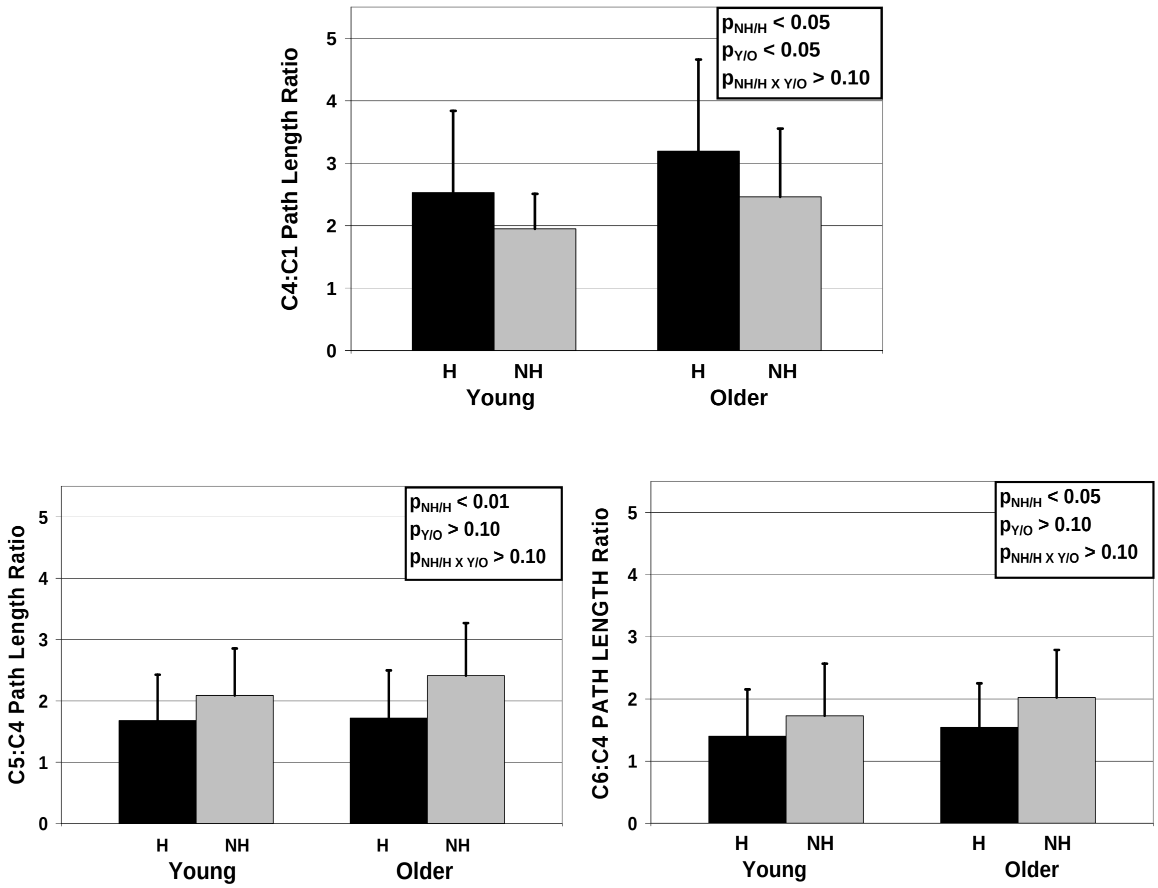


Figure 14. Average C4:C1 (top), C5:C4 (lower, left) and C6:C4 (lower, right) PATH LENGTH ratios for young and older subjects experiencing hazardous (H) and non-hazardous (NH) slips. Subjects experiencing hazardous slips had significantly greater C4:C1 and significantly lower C5:C4 and C6:C4 PATH LENGTH ratios than those experiencing non-hazardous slips ($p_{NH/H} < 0.05$). Older subjects had significantly higher C4:C1 PATH LENGTH ratios compared to young subjects ($p_{Y/O} < 0.05$). Standard deviation bars are shown.

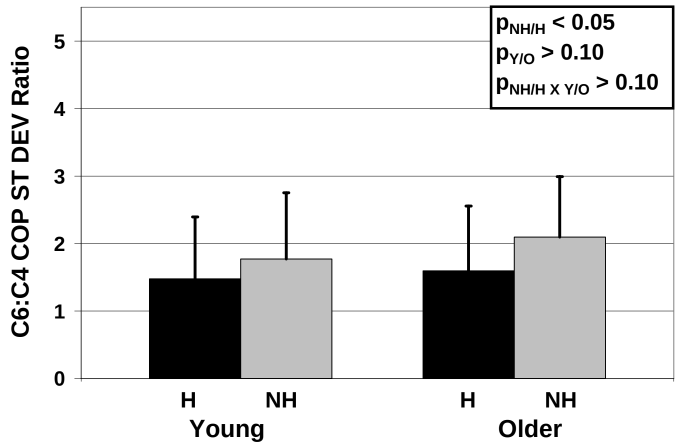


Figure 15. Average C6:C4 COP ST DEV ratio for subjects experiencing hazardous (H) and non-hazardous (NH) slips. Subjects experiencing hazardous slips had significantly lower C6:C4 COP ST DEV ratios than those experiencing non-hazardous slips ($p_{NH/H} < 0.05$). Standard deviation bars are shown.

4.0 DISCUSSION

4.1 MUSCLE STRENGTH AND SLIPPING

The relationship between knee strength characteristics (peak torque and explosive strength variables) and slip hazardousness was investigated in young and older adults. The main analyses were conducted within each gender group. In young and older female participants, both peak torque and explosive strength measures were not significantly associated with slip hazardousness except in knee flexion for the right leg RTD. Furthermore, surprisingly, young and older female subjects recruited to participate in this study exhibited similar strength characteristics. In contrast, age group differences in all strength variables for male subjects were statistically significant, with young males generating greater knee flexion and knee extension peak torque, average peak torque, RTD, and angular impulse values than older males. Only left leg knee extension RTD and angular impulse values computed in time intervals ranging from about 0-100 ms to 0-300 ms were significantly greater in young male subjects experiencing NH slips than those experiencing H slips. Knee flexion strength characteristics were not found to be associated with slip hazardousness in any age/gender groups.

The lack of statistically significant association between knee flexion strength characteristics and slip hazardousness may be unanticipated as the primary reaction generated by the slipping leg in response to an unexpected slip consists of increased activity in the knee flexors in an attempt to bring the slipping foot back near the body (Cham and Redfern, 2001). One explanation for such a finding may be that the slip-initiated knee flexion response generated by the slipping leg is modulated by reflex-like, rather than voluntary, postural control processes. Indeed, the EMG-based latency of the knee flexors' response to unexpected slips occurs early in stance and is similar between NH and H slips (Chambers and Cham, 2007). Also, a minimal knee flexion moment may be needed to bring the foot back near the body as the coefficient of friction of the shoe-floor interface is very low in the slippery environment, causing minimal shear forces opposing the knee flexion response; also, at heel contact, considered the onset of the perturbation, the knee is already producing a flexion moment during gait (Winter, 1991; Cham and Redfern, 2001; Cham and Redfern, 2002).

In contrast to the lack of statistical significance between knee flexion RTD and slip hazardousness, knee extension RTD values were significantly greater in NH than in H slips for male subjects. Based on EMG data, the response of the knee extensors to an unexpected slip is initiated after the knee flexor reaction (~ 65 ms between flexors and extensors) and the latency of such a response is modulated by slip severity (Chambers and Cham, 2007). Thus, these findings suggest that the secondary knee extension reaction to a slip may be modulated by voluntary postural control processes, explaining the importance of knee extensor muscle group strength characteristics in slip reaction. The knee extension reaction of the slipping leg is believed to play at least a partial role in preventing body collapse and knee buckling, as well as bringing the body's center of mass over the base of support and proceeding with the gait cycle (Kepple et al., 1997; Moyer et al., 2007). It is important to note that the knee extensor moment is actually coupled with a hip flexion corrective moment during slip recovery to further aid in bringing the trunk back over the base of support; however, only knee extension is discussed here (Cham and Redfern, 2001).

Peak knee flexion and knee extension torque were not associated with slip hazardousness in any age/gender groups. Average peak torque, used as a comparison method for calculating peak torque values, showed reliable results with similar findings to peak torque results. This finding may be linked to the fact that maximal strength is not utilized during walking (Pohl et al., 2002) nor reached in the small time frame used to generate slip-initiated corrective responses (Cham and Redfern, 2001; Aagaard et al., 2002). Thus, explosive strength measures that reflect the ability to generate muscle force quickly, e.g. RTD and angular impulse, may be more critical than peak strength during balance recovery efforts triggered by external perturbations such as slips (Aagaard et al., 2002; Chang et al., 2005). Therefore, it is important to identify the specific strength characteristics and time intervals that are relevant to a particular functional movement (Abernethy et al., 1995; Aagaard et al., 2002; Andersen and Aagaard, 2006). One relevant study by Lockhart et al. (2005) reported that individuals with weaker lower extremities slipped more than those with stronger lower extremities, inferring that slip recovery efforts may be related to lower extremity peak strength. The apparent discrepancy between the results of Lockhart et al. and the findings of this study may be explained by the differences in strength testing protocols and subject groups. Lockhart et al. employed an overall lower extremity strength testing protocol which evaluated combined leg lifting strength (Chaffin et al., 1978), while the present study isolated strength contributions by the knee flexors and extensors only. Also, the older subject population used by Lockhart and colleagues was older (mean age 75.5 years) than the older subject group in this study and across-gender, rather than within-gender, analyses were reported.

It is somewhat perplexing that the beneficial effect of greater knee extension RTD values was found only in young male participants. We believe such findings were seen in the young male, but not female, participants because the young male participants recruited in this study were much stronger and exhibited a greater range of strength than their female counterparts in the same age group. Interestingly, although a greater sample size is needed to make gender and age group comparisons, 57% of the slips in the young female participants were classified as hazardous compared to 44% in the young male subjects (Table 3). The lack of strength abilities in the young female participants recruited in this study is also supported by the similar strength characteristics found in the young and older group of female subjects. Also, although analyses were not completed comparing strength characteristics of those subjects experiencing falls vs. recoveries due to power issues, qualitative results seem consistent with those for subjects experiencing hazardous vs. non-hazardous slips (Figure 7).

Also unexpected were the significant NH/H x Y/O effects found for trailing leg knee flexion RTD values for female subjects in which young females experiencing H slips produced greater knee flexion RTD values than those experiencing NH slips. This result was especially surprising considering no other significant effects were found for the female subject group in all other analyses. However, these significant effects seem to have resulted from the extremely high RTD values produced by only two young female subjects. When these subjects were excluded from the analysis, the significant interaction effects disappeared. Therefore, these results do not seem to be practically significant. Also, since these slip severity effects occurred in the early time intervals (0-10 to 0-150 ms), significance may not be relevant to the given functional task, i.e. slipping (Andersen and Aagaard, 2006).

With the lack of strength abilities in older, as compared to the young, male subjects, one might also expect that older male participants would be at greater risk of experiencing a H slip than the young males. Yet, a similar relative distribution of H and NH slips was reported in young and older male participants (Table 3). Findings by Moyer et al. (2006) suggest that older adults typically walk with a "safer" gait style based on initial conditions variables that have been shown to impact slip severity, such as shorter step length, reduced foot-floor angle at heel contact, and slower rates of change of the foot-floor angle at heel contact. Thus, while young individuals may need greater strength generation abilities to reduce slip hazardousness, older adults appear to rely more on initially safer gait characteristics and less on strength generation abilities to avoid H slips.

A number of limitations exist in this study. First, because participation in this study involved exposure to a slippery environment and subject safety was a concern, subjects in the older age group were healthy and younger than the age at which the greatest increase in likelihood and occurrence of falls occurs (NCIPC, 2006). Second, strength of joints other than the knee of the leading/slipping leg may be important in slip-recovery efforts. While ankle strength of the leading/slipping foot may not contribute to a greater chance of recovery from severe slips, the hip joint of the same leg has been shown to play an important role in slip recovery efforts (Cham and Redfern, 2001). Hip strength was not measured in this study to minimize fatigue effects. However, knee and hip strength capabilities are reportedly well correlated (Lamoureux et al., 2002). Finally, since the strength capabilities of both female groups and the older male group were comparable, a broader subject base with a greater range of strength capabilities may allow for further analysis of the impact of strength on slipping.

In summary, the ability to rapidly generate muscle force may be more important than peak strength in slip recovery efforts. In particular, findings of this study suggest the ability to rapidly generate knee extension muscle force as reflected by the RTD partially determine the success of avoiding hazardous slips. This may imply that fall prevention programs should include strength training focused not only on improving maximum strength but also muscle force generation abilities in short time intervals. Finally, explosive strength measures such as RTD and angular impulse collected from an isometric strength task can be successfully related to dynamic balance recovery tasks provided the time intervals used for the computation of these strength measures are physiologically relevant to the postural task.

4.2 SENSORIMOTOR INTEGRATION AND SLIPPING

The relationship between postural control variables collected during an SOT (COP ST DEV, PATH LENGTH, and condition ratios) and slip hazardousness was investigated in young and older adults. The risk of experiencing a hazardous slip was relatively the same for both subjects who fell or did not fall during the SOT. COP ST DEV and PATH LENGTH were significantly and moderately to strongly correlated, indicating that subjects exhibiting greater sway distances also experienced higher sway velocities. The main analyses were conducted within condition and T1. Subjects experiencing hazardous slips exhibited significantly greater PATH LENGTH values than those experiencing non-hazardous slips for C4 only. In addition, those experiencing hazardous slips produced significantly greater PATH LENGTH C4-C1 ratios and significantly lower C5-C4 PATH LENGTH, C6-C4 PATH LENGTH, and C6-C4 COP ST DEV ratios than individuals experiencing non-hazardous slips. As expected, older subjects produced significantly greater PATH LENGTH values than young subjects during SOT C2 through C6. Additionally, significantly greater COP ST DEV values in C3 and C6 were reported in older adults. Older adults also produced significantly higher PATH LENGTH ratios than younger subjects for ratios C2-C1, C3-C1, C4-C1 and C6-C1.

The existence of significantly greater C4 PATH LENGTH and subsequent effects on PATH LENGTH ratio variables in subjects experiencing hazardous slips supports the importance of somatosensation in detecting and responding to slips. The significant hazardousness effects regarding C4-C1, C5-C4 and C6-C4 PATH LENGTH ratios shown in Figure 14 are likely all due to the hazardousness effects regarding C4 PATH LENGTH. PATH LENGTH values were similar in C1, C5 and C6 for subjects experiencing both hazardous and non-hazardous slips. Therefore, dividing C4 by C1 led to similar hazardousness effects for the C4-C1 PATH LENGTH ratio. Dividing both C5 and C6 PATH LENGTH values by greater C4 PATH LENGTH values for individuals experiencing hazardous slips further led to lower C5-C4 and C6-C4 PATH LENGTH ratios in these subjects compared to those experiencing non-hazardous slips. Likewise, though no significant hazardousness effects were evident regarding C4 COP ST DEV, greater values for subjects experiencing hazardous slips compared to those experiencing non-hazardous slips again led to significantly lower C6-C4 COP ST DEV ratio values in these subjects due to the placement of greater C4 COP ST DEV in the denominator of the ratio. This result is evident in Figure 15.

Because C4 involves the application of support surface sway referencing which renders somatosensation inaccurate, subjects must increase weighting on vision and vestibular input channels for accurate sensory information regarding sway. Increased postural sway during C4 may demonstrate a deficit in the ability to successfully detect a perturbation to normal balance or the existence of inaccurate somatosensory information. Because the slip occurs at the shoe-floor interface, proprioceptors in the distal musculature detect deviations from the normal joint trajectories first and serve as the primary sensory input for triggering reactive balance adjustments to avoid a fall and continue normal gait (Nashner, 1980). This may suggest that somatosensation is the first sensory modality activated during an unexpected slip. Therefore, the ability to first detect and evoke a response to an unexpected gait perturbation may explain why the somatosensory system is the most highly weighted and important of the three sensory modalities involved in maintaining postural control (Lord et al., 1991; Fitzpatrick and McCloskey, 1994; Lord and Ward, 1994; Benjuya et al., 2004; Melzer et al., 2004). This is supported by previous research which has noted that fallers are less able than non-fallers to compensate for missing or conflicting somatosensory information during challenging balance conditions (Anacker and Di Fabio, 1992).

High dependence on the somatosensory channels due to early slip detection may explain the lack of significant hazardousness effects when only the vestibular or visual sensory modalities are rendered inaccurate or missing during the SOT. It may be likely that the vestibular system, located more proximally in the body in the inner ear, may not be efficient to detect the slipping perturbation early and elicit a corrective response if the slip is sufficiently attenuated by distal reactions. Previous research examining changes in head acceleration and upper body corrective moments has suggested that the vestibular system may act in sensing a fall and initiating an upper body postural response to a slip, if necessary, to avoid a fall (Beschorner et al., 2008). However, it is inconclusive at this time what change in head acceleration is required in order to detect a slip and trigger a corrective response as a result of vestibular sensory input. Also, because detection of an unexpected slip occurs distally to proximally, input to the vestibular system may occur slightly later than in the somatosensory modalities, i.e. the proprioceptors in the leg and thigh musculature. Indeed, onset of upper body reactions to an unexpected slip seems to occur slightly later than onset of lower body reactions (Tang et al., 1998; Beschorner et al., 2008). Therefore, the vestibular system may produce redundant information and corrective reactions occurring later than those already triggered by the distal proprioceptors. Corrective reactions elicited by the visual system likewise occur later than those produced as a result of proprioceptive slip detection and are thus less effective in aiding slip recovery (Pyykko et al., 1990).

Significant age effects indicating increased postural sway with age were expected, as deterioration of the three peripheral sensory channels (somatosensory, vestibular, and visual) as well as central sensory integration and re-weighting processes with aging has been widely reported (Teasdale et al., 1991b; Camicioli et al., 1997; Matheson, 1999; Lord et al., 2000; Melzer et al., 2004; Bugnariu and Fung, 2007; Low Choy et al., 2007). Fewer age effects were evident when examining SOT variable ratios because the ratios acted to normalize the subject postural sway measures calculated for the condition placed in the numerator to those determined for the condition placed in the denominator. The results of this normalization therefore reveal that no interaction exists between conditions, i.e. subjects with worse performance during the conditions placed in the numerator also performed worse during the baseline conditions placed in the denominator.

Several limitations also exist for the postural control and sensory integration portion of the study. First, consistent with the above muscle strength chapter, subject safety was a concern due to exposure to the slippery environment and thus subjects in the older age group were younger than the age at which the risk and occurrence of falls drastically increases and postural control ability decreases (Camicioli et al, 1997; NCIPC, 2006). All subjects were screened for clinically significant disorders affecting normal balance and gait including vestibular disorders, most likely excluding those individuals with individual sensory modality (vestibular, somatosensory and vision), re-weighting and integration deficits that would presumably lead to the greatest changes in postural sway measures.

In summary, the ability to successfully utilize somatosensory information to detect an unexpected slip may be instrumental during slip recovery efforts. Earlier detection by the somatosensory channels as compared to vestibular and visual sensory modalities may make somatosensation especially important in promptly detecting and responding to a slipping perturbation. Thus, the findings of this study may indicate that fall prevention programs should include exercises and practice focused on utilizing accurate somatosensory information to overcome distal perturbations to postural stability, such as slips.

5.0 CONCLUSION

Results from this study indicate that the ability to rapidly generate muscle force may be more important than peak strength in slip recovery efforts. Specifically, young male subjects experiencing non-hazardous slips generated greater knee extension explosive strength (RTD and angular impulse) than young males experiencing hazardous slips, as well as both older male subject groups. Thus, explosive knee extension muscle strength capabilities in particular may determine the success of avoiding hazardous slips. These results indicate that a minimum strength capability threshold, achieved by only young male subjects in this study, may be necessary to impact slip severity. Despite significant strength differences, similar numbers of hazardous and non-hazardous slips were experienced by both young and older male subjects. This could be due to changes in older subject gait initial conditions which enable them to avoid hazardous slips by adopting a safer gait style, while younger subjects may rely on greater strength capabilities to reduce slip hazardousness. Peak torque may be less important in responding to a slip, as maximum strength capabilities are not utilized or reached in the small time frame during reaction to a slip. Fall prevention programs may therefore include strength training focused on force generation in short time intervals. Finally, explosive strength measures from isometric strength testing can be related to dynamic balance recovery tasks in relevant time intervals.

Subjects in this study experiencing hazardous slips also exhibited increased sway during C4 of the Sensory Organization Test compared to those experiencing non-hazardous slips. Since C4 involves the application of support surface sway referencing, increased sway during this condition would indicate a deficit in the ability to detect either a distal perturbation or inaccurate somatosensory information. Thus, the ability to utilize somatosensory information to detect a slip may also be instrumental in slip recovery efforts. Because leg proprioceptors detect a slip at the shoe-floor interface, somatosensation is most likely the first sensory modality to detect a slipping perturbation. This earlier detection may explain why somatosensory channels are considered the most heavily weighted and important of the sensory channels and also why fallers are less able than non-fallers to compensate for missing or conflicting somatosensory information. Although the vestibular system has been suggested to detect falls and initiate upper body postural responses, the change in head acceleration required to sense a fall remains unclear. In addition, slip detection by both vestibular and visual channels occurs later than somatosensory detection, making somatosensation the most efficient sensory channel in slip and fall detection. Therefore, fall prevention programs may also consider including exercises or practice utilizing accurate somatosensory information to overcome distal perturbations such as slips.

APPENDIX A

JOURNAL OF APPLIED BIOMECHANICS MANUSCRIPT

Modified analyses regarding muscle strength and slipping were documented in a manuscript accepted to the Journal of Applied Biomechanics.

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