FINAL PROGRESS REPORT

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2 List of Terms and Abbreviations

Abbreviation *(alphabetical order)*	**Definition**
$AnklTorq_{HC}$	Ankle joint torque at heel contact
BOS	Base of support
COM	Body center of mass
FF	“Foot flat” type of trailing leg strategy
H	Hazardous slip (PSV > 1m/s)
HC	Heel contact
$HeelAcc_{HC}$	Horizontal heel acceleration at heel contact
$HeelVel_{HC}$,	Horizontal heel velocity at heel contact
$HipTorq_{HC}$	Hip joint torque at heel contact
KE	Knee extension strength data
KF	Knee flexion strength data
$KneeTorq_{HC}$	Knee joint torque at heel contact
MID	“Mid-flight” type of trailing leg strategy
MIN	“Minimum” type of trailing leg strategy
NH	Non hazardous slip (PSV > 1m/s)
O	Older age group
PSV	Peak slip velocity measured at the left heel
RCOF	Required coefficient of friction
RFD	Rate of force development
Step length ratio	Step length divided by leg length
TD	“Toe down” type of trailing leg strategy
TO	Toe off
Y	Young age group

3 Abstract

Slip and fall accidents are among the leading generators of injuries in the workplace, especially among older adults. The aging dynamics of the work force have motivated the long-term goal of this proposed study, that is to reduce slip-precipitated falls among older workers. Understanding the biomechanical reasons for the increased incidence of slip and fall accidents in older workers is required knowledge to achieve the long-term goal of this project.

The first set of results (related to Specific Aims 1 and 2) characterizes the trailing leg's biomechanical response to slips. Healthy participants divided into two age groups (20–33 years and 55–67 years) were asked to walk in two conditions: a known dry floor and a glycerol-contaminated floor expected to be dry, inducing an unexpected slip of the leading foot at heel contact. Four slip-related trailing leg response strategies were identified, ranging from a minimal disruption of the swing phase to a premature (~50 ms after toe off) interruption of the swing phase. Aging effects were minimal. The response of the leading/slipping leg preceded that of the trailing limb. The magnitude of the trailing leg's response was associated with that of the knee in the leading/slipping leg, suggesting interlimb coordination. The corrective moment at the knee of the trailing leg was also correlated with that measured at the hip in the same leg, suggesting intralimb coordination. The specific trailing leg's strategy used in a slip is partially determined by preslip walking patterns and early stance slip dynamics.

The second set of results (related to Specific Aim 3) confirms our previously reported findings associated with slippery floor warning. Specifically, when warned about the potential of encountering a slippery floor, both young and older adults increase cadence, which has been correlated with a lower risk of slipping and falling. As a result, the duration of the sub-phases of the gait cycle, e.g. single/double support, stance, stride, are all reduced when warned about the possibility of encountering a slippery floor. Gait speed was increased especially in the young group of subjects and this finding can be attributed to the increase in cadence. Step width was reduced when warned about slippery floors. This result is believed to be due to the increase in cadence as well. Finally, surprisingly,

The first goal of Specific Aim 4 was to investigate the relationship between lower extremity strength capabilities and slip severity. Reduced muscle strength has been 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 young and 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 shortly after heel contact onto the contaminated floor. Analyses revealed significantly greater left knee extension RTD and angular impulse in young males experiencing non-hazardous compared to participants who experience hazardous slips. Findings were not evident in older subjects, 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.

The second goal of Specific Aim 4 was to investigate the association between ability to integrate sensory information important for balance and slip severity. Decreased postural stability has also associated with aging and falls. The Sensory Organization Test (SOT) was administered and the amount and average velocity of body sway were calculated for each condition based on the center of pressure standard deviation (COP ST DEV) and path length (PATH LENGTH), respectively. COP ST

DEV and PATH LENGTH were each regressed on age group and hazardousness within condition. Significantly greater PATH LENGTH in Condition 4, in which somatosensation was rendered inaccurate, were evident in individuals experiencing hazardous compared to participants who experienced 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.

4 Highlights/Significant Findings

a) Four slip response strategies were identified for the trailing leg and these strategies were associated with the slip severity but also with normal gait characteristics. Additionally, interlimb coordination between the knee joint in the leading/slipping and trailing leg was found with scaling related to perturbation severity. Intralimb coordination between the hip and the knee was evident in the trailing leg.

b) The relationship between knee strength and slip severity was investigated in healthy young and older male and female participants. In young males, statistically significant gait-speed independent relationships were found between slip severity and knee extension peak torque and with knee flexion/extension rate of torque development (RTD). Specifically, slip severity in subjects with reduced knee extension peak torque and flexion/extension RTD values was greater than expected based on gait speed-based predictions of slip severity. No statistically significant associations were found between strength characteristics and gait speed-adjusted slip severity in the other three age/sex groups.

c) Subjects who experienced hazardous slips exhibited increased postural instability in Condition 4 of the Sensory Organization Test (SOT) compared to those experiencing non-hazardous slips. Condition 4 involves requires participant to stand on a moving floor providing inaccurate somatosensory information to the subject.

5 Translation of Findings

a) Prior research has focused on the important role of the stance/slipping leg. This project underlines the importance of the trailing leg in slip-initiated recovery attempts.

b) Knee strength, particularly extension strength (peak and explosive measures), is important in slip recovery efforts. 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 rate of torque development / RTD, collected from an isometric strength task can be successfully related to dynamic balance recovery tasks provided the time intervals used for the computation of strength measures are physiologically relevant to the postural task.

c) The ability to utilize somatosensory information to detect a slip may 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. Therefore, fall prevention programs may also consider including exercises or practice utilizing accurate somatosensory information to overcome distal perturbations such as slips. Another potential avenue of intervention is the development of shoes that increase the ability to sense a perturbation such as a slip.

6 Outcome/Relevance/Impact

This project provided a better understanding of the reasons for epidemiolgical findings suggesting increasing incidence of slip-initiated falls among older adults. By understanding the biomechanical reasons for such reports, the results of this study may have direct implications in 1) the development of more effective fall prevention and training programs aimed at reducing slip-precipitated falls among older adults and 2) the possible implementation of safety warning guidelines.

7 Scientific Report

7.1 Results related to Aim 1 and Aim 2

Aim 1: Investigate the relationship between slip severity (outcome falls/recovery or slipping velocity) and corrective reactions generated during slips.

Aim 2: Investigate the differences in recovery biomechanics between young (20-35 years old) and older (50-65 years) subjects.

In summary, trailing leg responses play an important role in the recovery from severe slips and thus in the prevention of falls initiated by slipping. The type of trailing leg response depends on the severity of the slipping perturbation and is coordinated with the leading/slipping leg. The results related to the overall pattern of the leading/slipping leg response confirm previously published results. In addition, we found that, in the leading leg, the knee response scales with the severity of the slip while the hip does not. The leading leg hip appears to be involved in keeping the torso upright. Finally, in general, age group effects were found not to be statistically significant. This finding may be partially due to the fact that research subjects recruited in this study were very healthy as a result of the thorough screening and/or that the older group of subjects was not old enough (IRB constraints related to the safety of the participants prevented the recruitment of subjects older than 65 years old). The details of the results are as follows:

1. <u>Classification of trailing leg responses observed during slipping</u>: Trailing leg responses to slips were categorized into four types of strategies termed minimum (MIN), foot-flat (FF), mid-flight (MID), and toe-down (TD). These four strategies were identified based on the dynamics of the trailing foot; specifically, flight distance, flight duration and orientation at touch down after the initiation of the slip. The dynamics of the trailing leg during the MIN strategy was similar to baseline walking on the non-slippery surface, with the trailing leg minimally deviating from the baseline trajectory during the slip (Figures 1a, 2). The swing phase of the trailing leg was interrupted in the three other strategies. Specifically, FF responses were typified by the entire shoe sole of the trailing foot contacting the ground either near or slightly behind the leading/slipping foot (Figures 1b, 2). For the MID strategy, the sole of the forefoot contacted the floor while the heel segment remained elevated (Figures 1c, 2). The MID strategy only occurred during severe slips (PSV > 1 m/s). Ground contact for the MID strategy occurred more quickly and more posteriorly with respect to the leading/slipping foot compared to the FF strategy. The TD responses were typified by the tip of the forefoot (as opposed to the sole) contacting the floor with the foot inclined substantially. The toe-down occurred immediately after trailing foot TO (Figures 1d, 2). This strategy occurred exclusively in severe slips (PSV > 1 m/s). The immediacy of foot contact in TD events caused the foot to contact the floor posterior to the slipping foot. All trailing leg strategies were found in both age groups.

   To confirm the association between slip severity and trailing leg strategy inferred in (1), PSV was regressed on strategy, age group and strategy x age group and only statistically significant strategy effects were revealed (p=0.0003, Figure 3). Post-hoc Student t-tests indicated that MIN patterns were associated with the least severe slips, followed by FF and MID strategies. TD responses were observed in the most severe slips.

(A) (B) (C) (D)

Figure 1: Snapshots of the trailing leg posture at ground contact after initiation of the slip. Four trailing strategies were identified during slipping, with (A), (B), (C) and (D) representing a MIN, FF, MID and TD response, respectively.

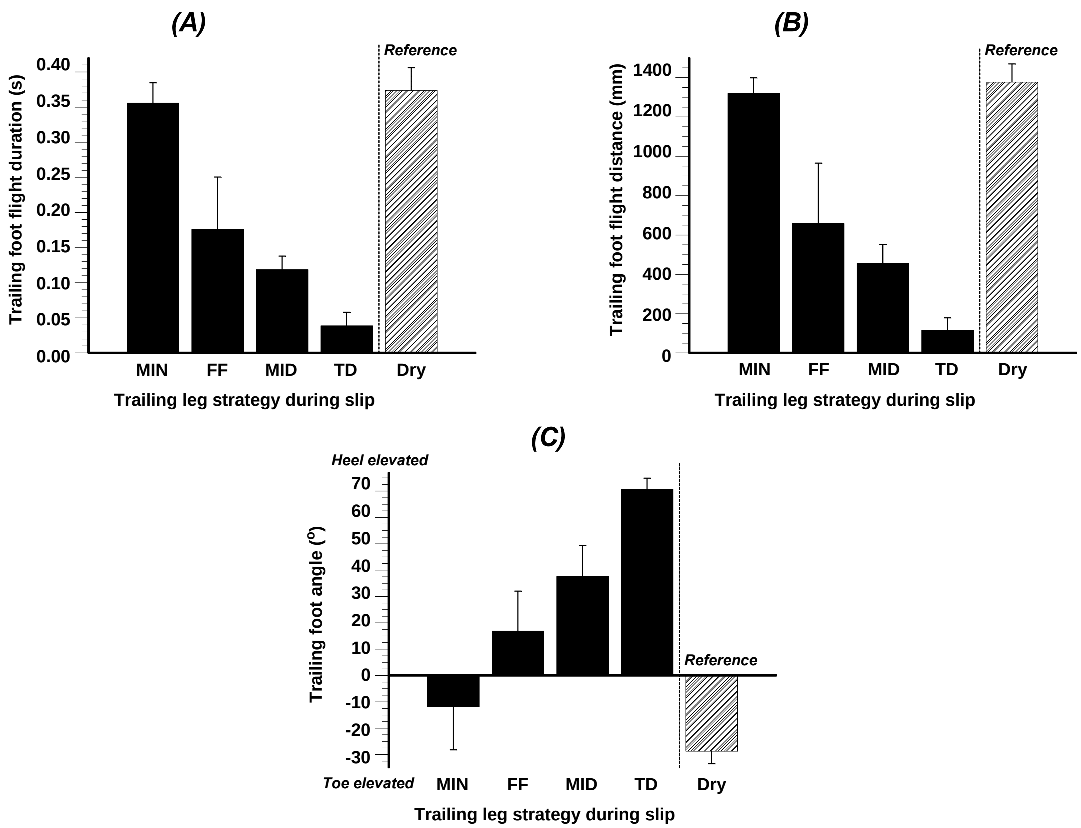

Figure 2: Quantitative characterization of trailing leg strategies using trailing foot flight duration (A) and distance (B) as well as foot contact angle (C). Statistical linear models regressing these variables on strategy (MIN, FF, MID and TD), age (younger/older) and the interaction of these variables revealed only strategy effects for all dependent parameters ($p<0.0001$). Post-hoc Student's t-tests revealed statistically significant differences in the three dependent parameters between all trailing leg strategies during slipping. Baseline dry data averaged across all subjects are included on the plots for comparison purposes. Error bars represent standard deviations.

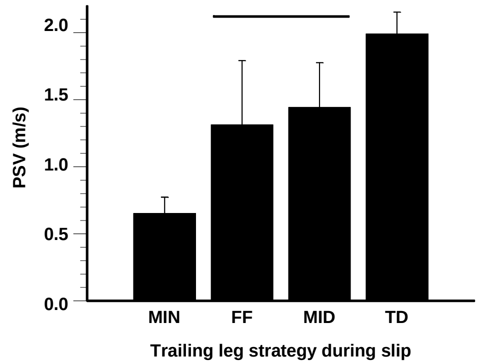

Figure 3: Relationship between PSV and trailing leg strategy. Linear models regressing PSV on strategy (MIN, FF, MID and TD), age group (younger/older) and the interaction of these variables revealed only strategy effects (p=0.0003). Post-hoc Student's t-tests revealed statistically significant differences in PSV between MIN, (FF/MID) and TD patterns. Error bars represent standard deviations.

2. Leading leg response and association with trailing leg strategy: Joint moments generated by the leading/slipping leg in response to the slip were found to be similar to previously published results. The primary corrective response produced by the leading/slipping leg consisted of a reduced extension moment at the knee, leading to a flexion moment for more extreme slips, followed by increased extensor activity at the hip. Knee moments were initiated 15-25% into stance and hip moments were initiated 25-30% into stance. A significant difference of about 50 ms occurred between the onsets of the knee and hip response (p<0.001) (onsets in sec are reported in Table 1). The correlation between the generation rate of the knee and hip corrective moment in the leading/slipping leg was not statistically significant (p=0.11, r=0.41), suggesting different muscle groups contributed to the response produced by these joints. Finally, to examine the scaling of the response magnitude with slip severity, the generation rate of the knee and hip corrective moments were regressed on PSV, age group and their interaction. Only knee response scaled with slip severity. Specifically, the generation rate of the corrective knee moment increased with slipping severity (p_{psv}=0.003).

Table 1: Mean±SD onset and moment generation rate of joint moment responses (Only trials with active moment response identified at specific joint of interest are included)

Joint →	**Leading Hip**		**Leading Knee**		**Trailing Hip**		**Trailing Knee**	
Parameter → **↓ Strategy**	***Onset (ms)***	***Rate (N.m/kg.s)***	***Onset (ms)***	***Rate** (N.m/kg.s)***	***Onset** (ms)***	***Rate* (N.m/kg.s)***	***Onset (ms)***	***Rate* (N.m/kg.s)***
MIN	----	----	142±----	^{A} 0.5±----	^{A} 206±29	^{A} 12.6±1.6	228±31	^{A} 8.8±2.8
FF	189±17	9.5±4.0	132±11	^{B} 6.0±1.7	^{A} 213±17	^{A} 21.2±7.6	218±16	^{B} 16.1±6.2
MID	173±26	8.7±7.2	127±9	^{B} 5.8±2.2	^{A} 205±14	^{B} 31.8±10.9	210±17	^{B} 19.2±5.3
TD	175±8	18.5±5.5	118±25	^{C} 10.5±3.2	^{B} 154±6	$^{A-B}$ 22.2±12.4	189±6	$^{A-B}$ 12.1±0.8

Statistical significant difference in this parameter was found between strategies (** p<0.01; * p<0.05). Subsequent findings of post-hoc students' t-tests are indicated with superscript letters, i.e. levels not connected by the same letter are significantly different (p < 0.05).

To further understand the coordination between the two legs, the corrective response of the leading/slipping leg was examined as a function of the type of trailing leg strategy. Corrective moments generated by the leading/slipping leg were identified in all TD/MID events, and in at least 50% of the FF responses. In contrast, a corrective leading leg moment response was identified in only one of the 7 MIN slips. The corrective moment onset and generation rate data were compared among the 4 types of trailing leg strategies. Only the leading/slipping leg moment rate at the knee was associated with strategy, with the smallest flexion rates noted in MIN events and the largest rates observed in the TD responses. No age group differences were found in either onset or moment rate.

3. Trailing leg response: Corrective knee and hip moments generated by the trailing leg were initiated after the onset of the leading/slipping leg response (Table 1). Specifically, an average delay of 20 ms and 80 ms was noted for the hip and knee, respectively ($p=0.005$ and $p<0.001$, respectively). The response of the trailing leg consisted of an extensor moment in the hip and a flexor moment in the knee initiated at about the same time, i.e. about 30% into stance (Table 1, Figure 4). Generation rates of the hip and knee corrective moment were correlated ($p<0.0001$, $r = 0.76$), suggesting the same muscle groups, e.g. hamstrings, contributed to the hip extension and knee flexion response in the trailing leg. Despite this statistically significant correlation, only the knee response was scaled with slip severity. Specifically, the generation rate of the corrective knee moment in the trailing leg increased with PSV, with more severe slips being associated with greater rates ($p = 0.03$). Aging did not impact the relationship between the trailing leg response and slip severity.

   Corrective moments generated by the trailing leg were identifiable in all TD, MIN and FF events. In contrast, a corrective hip and knee moment was not observed in 4 and 2 out of 7 MIN responses, respectively. The onset and generation rates of these corrective moments were significantly associated with trailing leg strategy. In general, generation rates were the smallest in MIN responses and increased in FF/MID events (Table 1). The increasing trend of the generation rates with trailing leg strategy (from MIN to MID) does not appear to continue in TD events (Table 1). This finding may suggest that subjects who experienced TD slips were perhaps not able to generate a sufficiently fast corrective response at the trailing leg. This last finding is despite an earlier onset time noted for the hip's corrective moment in the TD response compared to the other three types of trailing leg strategies (Table 1). As in the leading leg, the trailing leg's ankle joint appears to play a less important role than the knee and hip joints in severe slips (Figure 4). However, in MIN responses, an increase (relative to normal walking data) in plantarflexion moment was noted between HC of the leading/slipping leg and contralateral TO (Figure 4E). Finally, no age group differences were found in either the onset or generation rate of the corrective moments generated by the trailing leg.

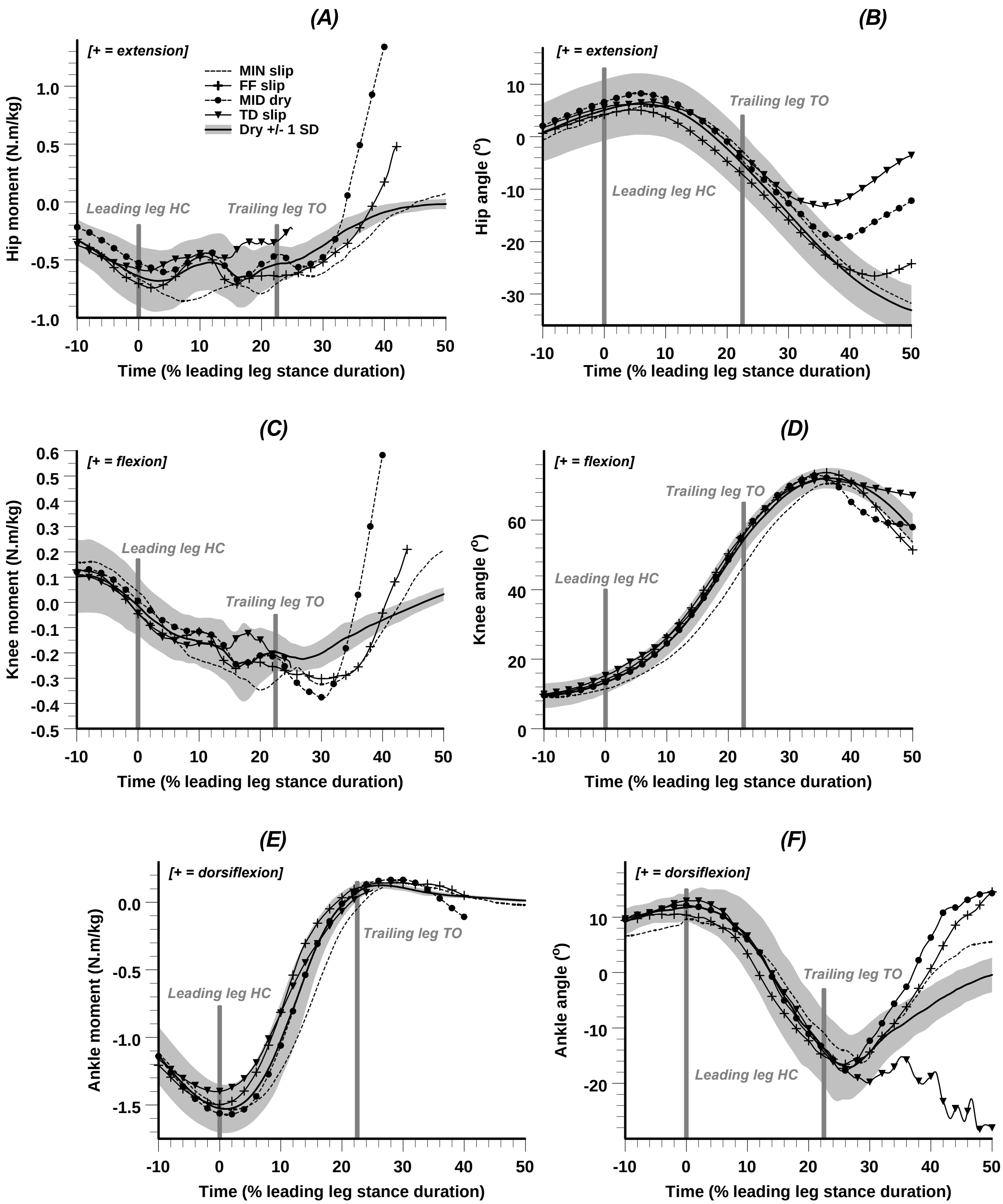

Figure 4: Hip, knee, and ankle sagittal joint moments (left) and angles (right) for the trailing leg. Time has been normalized to the leading leg stance duration from gait during normal walking (baseline conditions). Moment traces for slip trials terminate prior to 50% into stance as the trailing foot often contacted the floor outside the force platform area, causing inverse dynamics calculation difficulties. Joint angles are relative to upright standing posture and joint moments have been normalized to subject body mass.

4. Trailing strategy and normal gait characteristics: To determine if individuals with certain gait characteristics during normal walking are more prone to respond to a slip with a specific trailing leg strategy, the associations between trailing leg strategy and gait variables collected in the dry trial were examined. First, differences in general spatiotemporal gait characteristics between trailing leg strategies were investigated by regressing dependent variables of interest on strategy, age group and strategy x age group. The dependent variables considered in these analyses were step length normalized to leg length, cadence, foot-floor angle at HC, gait speed, and peak shear-to-normal ground reaction forces reflecting frictional requirements of slip-resistant gait. The results indicated that subjects experiencing a TD slip event required nearly 30% more friction to prevent a slip than other participants (Table 2, $p<0.05$).

   Bilateral joint moments and angles evaluated at TO of the trailing foot were compared among trailing leg strategies using a similar analysis as for the general spatiotemporal gait characteristics. The timing of contralateral TO was selected as all subjects were able to initiate swing phase. Thus, biomechanical variables evaluated at contralateral TO can serve as initial conditions for the swing phase. Also, this point in time is the last common gait cycle event that can be easily identified in all trailing leg strategies. The results suggest that subjects who normally walk with a reduced extension moment at the hip in the leading leg experienced a TD strategy when the floor was contaminated (Table 3, $p_{strategy}=0.008$). In general there were no statistical significant age effects ($p>0.05$). One exception is the ankle angle of the trailing leg at TO. Specifically, plantarflexion ankle angle of the trailing leg was about 35% smaller in older adults compared to their younger counterparts at TO (-10^o versus -17^o, $p_{age\ group}=0.03$). These findings were consistent both in the dry and slippery trials (only strategy effects are shown in Tables 3 and 4 as described next).

Table 2: Mean (SD) of general normal gait characteristics (baseline) stratified by trailing leg strategy

Gait variable → **↓ Strategy**	**Step length / leg length**	**Gait speed (m/s)**	**Cadence (steps/min)**	**Foot-floor angle at heel contact (^{o})**	**Peak required coefficient of friction***
MIN	0.80 (0.06)	1.46 (0.12)	120 (9)	25 (4)	^{A} 0.19 (0.03)
FF	0.80 (0.07)	1.46 (0.09)	121 (11)	27 (5)	^{A} 0.18 (0.02)
MID	0.83 (0.04)	1.41 (0.11)	116 (7)	30 (4)	^{A} 0.19 (0.02)
TD	0.82 (0.01)	1.32 (0.09)	110 (13)	30 (2)	^{B} 0.23 (0.04)

**** Statistical significant difference in this parameter was found between strategies. Subsequent findings of post-hoc students' t-tests are indicated with superscript letters, i.e. levels not connected by the same letter are significantly different (p < 0.05).***

5. Trailing leg strategy and biomechanical gait during slipping: To further understand the possible factors that determine the selection of a specific trailing leg strategy, the association between trailing leg strategy and biomechanical gait variables collected in the contaminated trial was examined. Specifically, bilateral sagittal-plane joint angles and moments evaluated at contralateral TO in the contaminated trial were regressed on trailing leg strategy, age group and their interaction. Trailing leg strategy was found to be associated with knee moment in the leading/slipping leg and hip extension in the trailing leg (Table 4). Specifically, subjects with MIN responses had the greatest knee extension moment in the leading leg, followed by FF/MID patterns. In contrast, in TD responses, the activity of the flexors in the knee of the leading leg dominated the extensors at contralateral TO, a finding that may be a potential contributor to body collapse in such events. Also, in the trailing leg, the hip flexion moment responsible for the swing phase is reduced in TD/MID slip patterns compared to MIN/FF responses (Table 4). Second, the leading leg knee angle at contralateral TO was associated with trailing leg strategy, with the least flexion noted in TD responses and the most flexion observed in MIN followed by MID/FF strategies (Table 4).

Table 3: Joint moments and joint angles evaluated at toe-off of the trailing leg during normal walking and stratified by trailing leg strategy during slip

	MIN	FF	MID	TD
Joint moments (N.m/kg)				
Leading leg				
Ankle moment *(+ = dorsiflexion)* **	0.00 (0.06) [B]	0.22 (0.11) [A]	0.17 (0.10) [A]	0.08 (0.08) [A-B]
Knee moment *(+ = flexion)*	-0.78 (0.23)	-0.74 (0.17)	-0.90 (0.23)	-0.91 (0.07)
Hip moment *(+ = extension)* **	0.55 (0.19) [A]	0.57 (0.18) [A]	0.56 (0.17) [A]	0.13 (0.06) [B]
Trailing leg				
Ankle moment *(+ = dorsiflexion)*	0.08 (0.04)	0.08 (0.08)	0.08 (0.04)	0.08 (0.05)
Knee moment *(+ = flexion)*	-0.21 (0.08)	-0.16 (0.11)	-0.18 (0.07)	-0.16 (0.06)
Hip moment *(+ = extension)*	-0.55 (0.13)	-0.55 (0.15)	-0.51 (0.15)	-0.44 (0.12)
Joint angles (^{o})				
Leading leg				
Ankle angle *(+ = dorsiflexion)*	-3.9 (2.3)	-7.5 (3.1)	-5.4 (2.8)	-5.1 (3.8)
Knee angle *(+ = flexion)* *	25.8 (4.8) [A]	19.6 (2.9) [B]	26.0 (4.8) [A]	23.9 (2.5) [A-B]
Hip angle *(+ = extension)*	-30.4 (2.6)	-29.3 (5.0)	-31.4 (6.2)	-29.3 (4.5)
Trailing leg				
Ankle angle *(+ = dorsiflexion)*	-13.6 (4.6)	-11.7 (7.8)	-15.4 (6.1)	-14.2 (7.3)
Knee angle *(+ = flexion)*	53.4 (4.2)	53.1 (5.4)	55.6 (4.1)	56.5 (4.5)
Hip angle *(+ = extension)*	-5.4 (4.3)	-5.2 (7.5)	-4.4 (6.0)	-4.9 (1.0)

Statistical significant difference in this parameter was found between strategies (** p<0.01; * p<0.05). Subsequent findings of post-hoc students' t-tests are indicated with superscript letters, i.e. levels not connected by the same letter are significantly different (p<0.05).

Table 4: Joint moments and joint angles evaluated at toe-off of the trailing leg during the slip and stratified by trailing leg strategy subsequently used in the same trial

	MIN	FF	MID	TD
Joint moments (N.m/kg)				
Leading leg				
Ankle moment *(+ = dorsiflexion)* **	0.01 (0.07) [B]	0.30 (0.08) [A]	0.27 (0.09) [A]	0.12 (0.04) [B]
Knee moment *(+ = flexion)* **	-0.48 (0.13) [C]	-0.30 (0.12) [B]	-0.24 (0.12) [B]	0.15 (0.02) [A]
Hip moment *(+ = extension)*	0.70 (0.32)	0.64 (0.19)	0.60 (0.21)	0.37 (0.09)
Trailing leg				
Ankle moment *(+ = dorsiflexion)*	0.09 (0.03)	0.10 (0.09)	0.07 (0.04)	0.05 (0.03)
Knee moment *(+ = flexion*	-0.25 (0.07)	-0.22 (0.16)	-0.20 (0.09)	-0.19 (0.04)
Hip moment *(+ = extension)* *	-0.65 (0.15) [B]	-0.60 (0.20) [B]	-0.46 (0.24) [A]	-0.33 (0.16) [A]
Joint angles (^{o})				
Leading leg				
Ankle angle *(+ = dorsiflexion)*	-7.5 (1.7)	-10.6 (3.6)	-10.5 (4.1)	-10.9 (6.8)
Knee angle *(+ = flexion)* **	22.2 (5.2) [A]	12.9 (3.7) [B]	14.6 (3.4) [B]	3.2 (0.5) [C]
Hip angle *(+ = extension)*	-29.2 (3.3)	-29.4 (4.9)	-30.9 (6.8)	-27.0 (5.0)
Trailing leg				
Ankle angle *(+ = dorsiflexion)*	-13.7 (4.5)	-12.3 (8.0)	-13.7 (6.5)	-15.1 (3.2)
Knee angle *(+ = flexion)*	53.2 (4.4)	53.2 (6.3)	56.2 (6.9)	58.0 (5.1)
Hip angle *(+ = extension)*	-6.2 (4.9)	-5.2 (7.5)	-4.7 (7.9)	-4.3 (1.8)

Statistical significant difference in this parameter was found between strategies (** p<0.01; * p<0.05). Subsequent findings of post-hoc students' t-tests are indicated with superscript letters, i.e. levels not connected by the same letter are significantly different (p<0.05).

7.2 Results related to Aim 3

Aim 3: Examine the impact of slippery surface warnings on slips and falls.

When warned about the potential of encountering a slippery floor,

1. Both young and older adults increase cadence. We have previously shown that a greater cadence is associated with a lower risk of slipping and falling, i.e. increasing cadence is an adaptive gait behavior that reduces the risk of slipping. As a result, the duration of the sub-phases of the gait cycle, e.g. single/double support, stance, stride, are all reduced when warned about the possibility of encountering a slippery floor.
2. Subjects did not change their step length. We have previously shown that walking with a shorter step length reduces the risk of initiating a slip.
3. Gait speed was increased especially in the young group of subjects as a result of the increase in cadence.
4. Step width was reduced. This result is believed to be due to the increase in cadence.

7.3 Results related to Aim 4

Specific aim 4: Investigate the impact of (a) postural stability (ability to integrate sensory information important for balance) and (b) lower extremity physical strength capabilities on slips and falls.

The results related to (a) have been processed. However, only a preliminary analysis (data for 10 subjects) has been completed. This very preliminary analysis suggests sensory information integration is not associated with slip severity or the risk for falls. We expect to complete the analysis of the entire set of data (all subjects) and write-up the results by 4/2007.

The analysis related to the lower extremity strength results, i.e. part (b), has been completed. the goal of this analysis was to investigate the relationship between knee flexion/extension (KF/KE) strength data (peak torque, rate of force development / RFD, and power) and slip severity in young and older adults. In summary, age group effects on strength data were statistically significant. Peak torque strength was not different between people who experienced hazardous slips and those who did not. However, young adults who experienced non-hazardous (NH) slips had significantly greater KE RFD values reported during strength testing than young adults experiencing hazardous (H) slips. Such finding was not found in older adults. For the power data, similar results as for the KE RFD were found. Further details are included below:

1. Peak torque for both KF and KE isometric strength data were regressed on age group (young/older), slip severity (H/NH) and the interaction of these factors. Only age group effects were significant, with young adults having higher peak torque values than older adults (Figure 5, Table 5).

Table 5: Significant Time Intervals for KF/KE Peak Torque, RFD, and Power. Significance ($p < 0.05$) are denoted by *.

		Age group	NH/H	Age group x NH/H
Peak torque	**KF**	*		
	KE	*		
RFD	**KF**	* 0-70 to 0-300 ms		* 0-80 to 0-300 ms
	KE	* 0-180 to 0-300 ms		* 0-130 to 0-300 ms
Power	**KF**	* 0-140 to 0-300 ms		* 0-160 to 0-300 ms
	KE	* 0-90 to 0-300 ms		

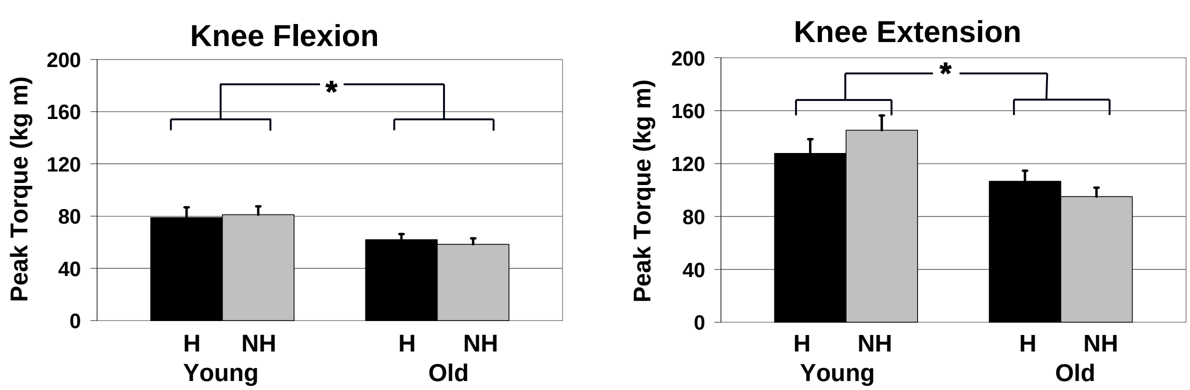

Figure 5: Isometric peak torque for KF (left) and KE (right). Significant age group effects are denoted by (*). Standard error bars shown.

2. RFD data were analyzed as peak torque data (analysis described in (1)). Young adults demonstrated significantly higher KF RFD values than older adults beginning with the time interval 0-70 ms and continuing to the 0-300 ms interval (Figures 6a, 7a, Table 5). Similarly, young adults exhibited significantly higher KE RFD values than older adults from the time interval 0-180 ms and continuing to 0-300 ms (Table 5). Significant NH/H x Y/O interaction effects were noted between the 0-80 ms and 0-300 ms time intervals. Post-hoc analysis revealed that the young adults who experienced NH slips had significantly higher KE RFD values reported during strength testing than both young adults experiencing H slips and older adults experiencing NH slips (Figures 6b). With a greater time interval, 0-130 ms continuing to 0-300 ms, significant interaction effects were also seen between the young adult group experiencing NH slips and the older adult group experiencing H slips (Figure 7b, Table 5). In general, young adults who experienced NH slips also demonstrated significantly greater KE RFD values.

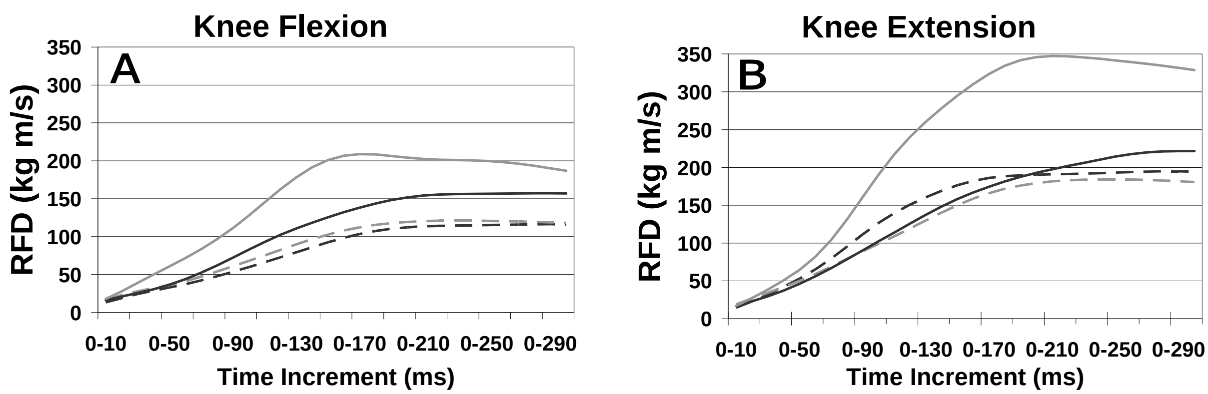

Figure 6: Average isometric KF RFD (A) and KE RFD (B) for each time increment. Solid lines denote KF RFD values for young subjects experiencing NH (gray) and H (black) slips. Dashed lines denote KF RFD values for older subjects experiencing NH (gray) and H (black) slips.

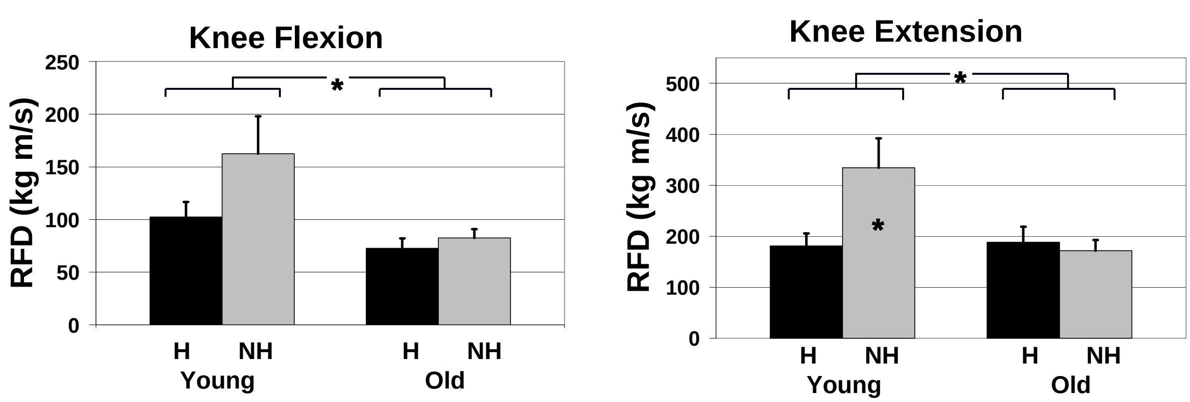

Figure 7: Average isometric KF RFD (left) at the 0-120 ms interval and KE RFD (right) at the 0-180 ms interval for NH (gray) and H (black) in both age groups (Y/O). Significant age (KF and KE) and interaction (KE) effects are denoted by (*). Standard error bars shown.

3. Power data were analyzed as peak torque data (analysis described in (1)). Young adults also recorded significantly higher KF and KE power values than older adults beginning with the time intervals 0-140 ms and 0-90 ms, respectively, and continuing to the 0-300 ms interval (Figures 8a and Table 5). Only KE power had significant NH/H x Y/O interaction effects beginning with the time interval 0-160 ms and continuing through to the 0-300 ms interval. Post-hoc analysis revealed young adults who experienced NH slips had significantly higher power values than the other three

groups: young adults experiencing H slips, older adults experiencing NH slips, and older adults experiencing H slips (Figures 8b and Table 5).

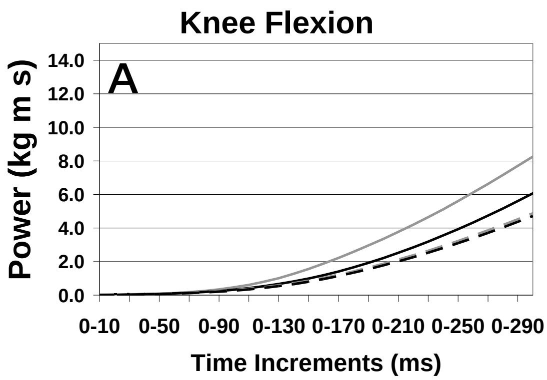

Figure 8: Average isometric KF (A) and KE (B) power values for each time increment. Solid areas denote power values for young subjects experiencing NH (gray) and H (black) slips. Diagonal lines denote power values for older subjects experiencing NH (gray) and H (black) slips.

7.4 Additional Results

7.4.1 Center of mass acceleration and slip outcome (recovery/fall)

The purpose of this analysis was to examine differences in COM angular acceleration at HC between slip-recovery and slip-fall outcomes in young and older adults. The results of this analysis demonstrate that angular acceleration at HC may be a predictor of the outcome of a slip. The details of the findings are as follows:

The body was modeled as a rigid body link of 15 segments and the body COM position was derived from the weighted average of the individual segments' COM. The Base of support (BOS) was determined as the projection of the heel marker onto the plane of the floor. The vector from the BOS to COM is projected into the sagittal plane and the angle from the resulting vector to vertical is θ (Figure 9).

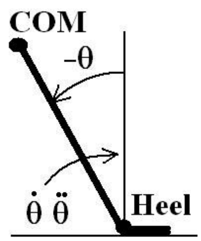

Figure 9: Inverted pendulum model used to determine angle (θ) and its derivatives

Subjects who fell during the slip had larger deviations in the profile of their angle, angular velocity and angular acceleration from baseline dry (Figure 10). Also, initial conditions at HC were different between fall and recovery events (Figure 10).

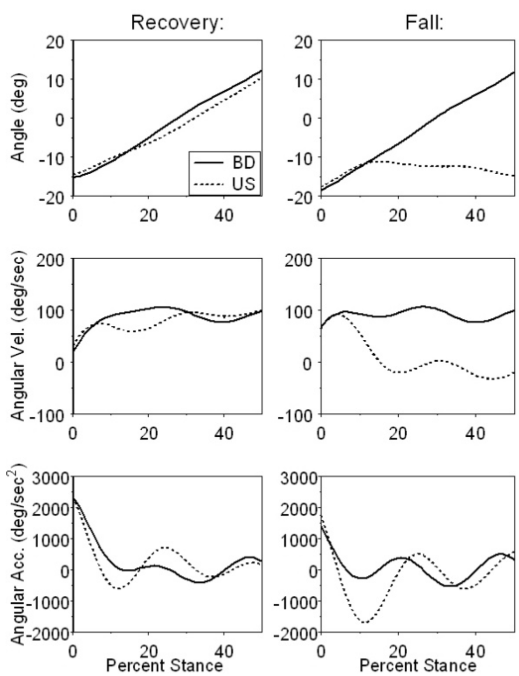

Figure 10: Typical angle, angular velocity, and angular acceleration. BD is baseline dry (solid) and US is unexpected slip (dashed). HC is 0% stance.

ANOVA was used to compare angular acceleration at HC between outcomes and age groups. An average 34% reduction in angular acceleration at HC was found in fallers compared to non-fallers ($p<0.05$) (Figure 9). Age group and its interaction with outcome were not significant effects. Thus, fall-recovery differences in angular acceleration at HC were similar in both age groups. "Thrust" push off force generated by the trailing leg produces forward and upward COM acceleration. This may be the underlying reason for the differences in angular acceleration at HC between recovery and fall outcomes, i.e. a potential predictor of slip and fall events is reduced push off thrust needed to move the COM over the BOS.

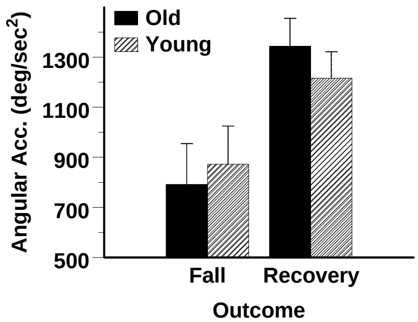

Figure 9: Angular acceleration stratified by age and outcome (SE bars)

7.4.2 Heel dynamics at heel contact contribute to slips and falls

In summary, anterior heel velocity and acceleration at heel contact were compared between slip-recovery and slip-fall outcomes. Recovery subjects contacted the floor with a greater heel deceleration and velocity than fall subjects. Also, knee torque alone explained most of the heel acceleration variability. No age effects were found. Thus, walking with a smaller knee flexion torque at heel contact will result in a reduced heel deceleration, a potential risk factor for slip-initiated falls. Further details related to these findings are included below.

1. Heel velocity and acceleration trajectories in the anterior-posterior direction during the dry conditions were consistent across subjects as reflected by the relatively small standard deviation magnitude (Figure 10). The horizontal heel dynamics are characterized by a rapid deceleration before, at, and soon after heel contact bringing the foot nearly to a stop by about 5% of stance time. The heel does not start to move again until later in the stance as the subject prepares for the unloading/swing phase. At heel contact, the ankle, knee and hip joints of the leading leg generate a plantarflexion, flexion and extension torque, respectively. Specifically, the mean (standard deviation) values for $AnklTorq_{HC}$, $KneeTorq_{HC}$ and $HipTorq_{HC}$ were 0.12 (0.05), 0.37 (0.09) and 0.47 (0.17) N.m/kg, respectively. No age group differences in joint torques at heel contact were found ($p>0.05$).

   There were no significant within-subject differences in gait speed, step length ratio, cadence, heel dynamics ($HeelVel_{HC}$, $HeelAcc_{HC}$) or joint torques ($AnklTorq_{HC}$, $KneeTorq_{HC}$, $HipTorq_{HC}$) between baseline and slippery conditions ($p>0.05$). These findings imply that subjects did not anticipate the slippery floor during the contaminated conditions. Thus, within-subject means of these variables were computed across conditions and used in subsequent analyses.

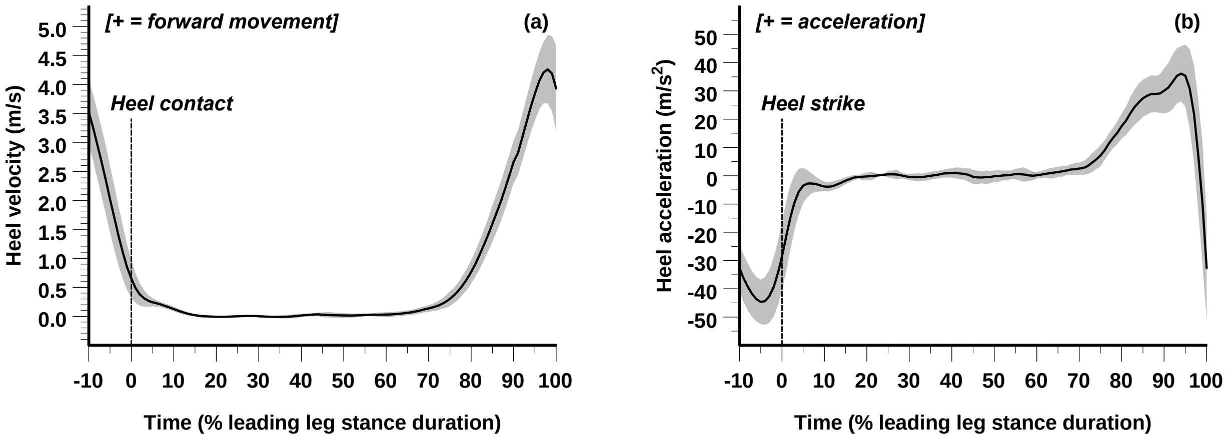

Figure 10: Average (black line) +/- 1 standard deviation (gray envelope) of anterior-posterior heel velocity (a) and acceleration (b) time series during baseline (known dry conditions). Time is normalized by stance time; with 0% representing heel contact and 100% is toe off. Heel contact was characterized initially by a forward moving heel with a large heel deceleration (negative heel acceleration) before, at and after heel contact. The foot has nearly stopped by about 5% stance

2. Heel Subjects classified as falls slipped with a greater anterior heel velocity and acceleration throughout the slip (Figure 11). Overall, older subjects experienced a greater rate of falls than younger participants, specifically 45% versus 31%. Statistical analyses regressing general gait variables of interest on age group, slip outcome and age group x slip outcome revealed significant differences only in cadence between recoveries and falls. Specifically, a faster cadence characterized the gait patterns of subjects who recovered from the slip compared to participants who fell ($p<0.05$). Only age group differences in step length ratio were statistically significant, with older adults taking shorter steps than their younger counterparts ($p<0.05$). Gait speed was similar between age groups and slip outcomes, i.e. about 1.4 m/s ($p>0.1$).

3. To test differences in heel contact dynamics between slip outcomes in young and older participants, a regression analysis was conducted with *age group*, *slip outcome* and their interaction used as predictors and with $HeelVel_{HC}$ and $HeelAcc_{HC}$ considered individually as dependent variables. This analysis revealed that subjects who recovered had a greater heel velocity and heel deceleration at heel contact than subjects who fell (Figure 12, $p<0.05$). The regression analyses reflected no statistically significant *age group* and *slip outcome x age group* effects. Finally, $HeelVel_{HC}$ and $HeelAcc_{HC}$ were found not to correlate with RCOF.

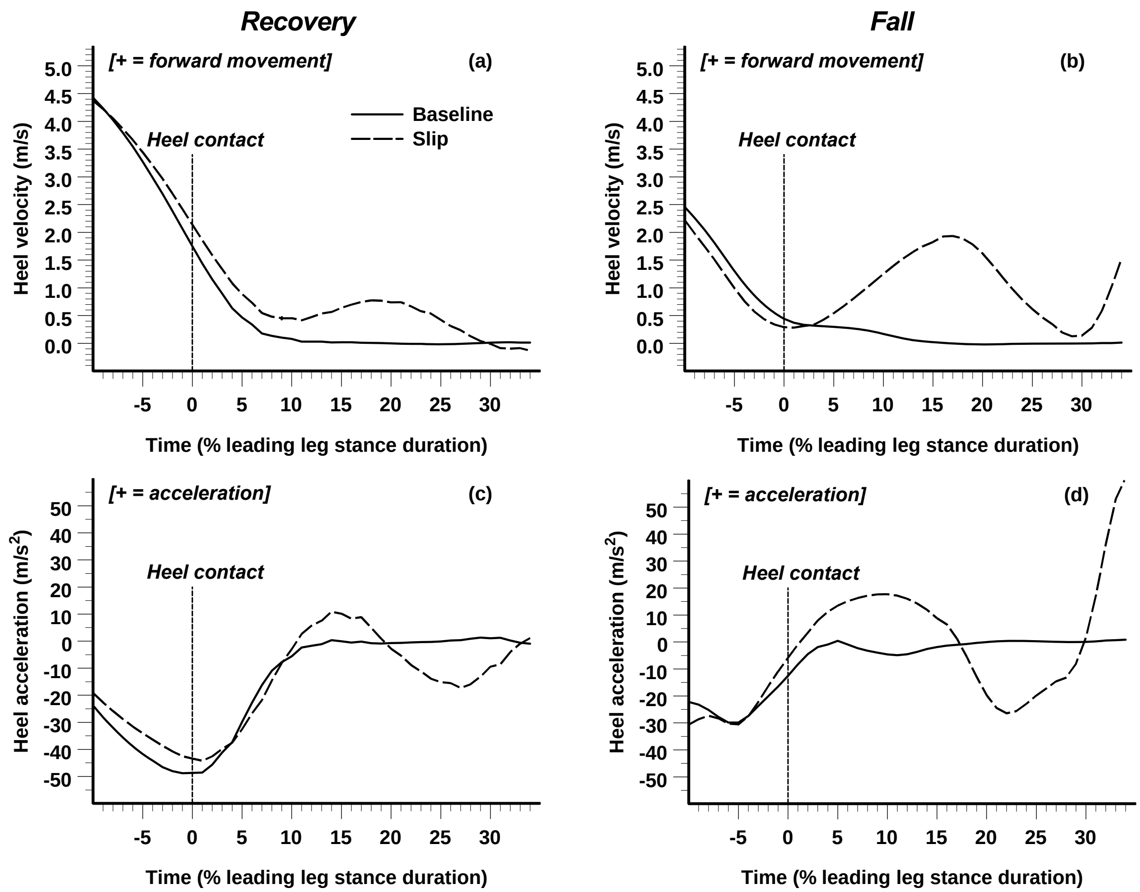

Figure 11: Typical time series plots for the anterior-posterior heel velocity (a-b) and acceleration (c-d) from two subjects, one that recovered (a-c) and one that fell (b-d) in the slippery condition. Data collected in the slippery condition (dashed line) and baseline trial (solid line) are represented for the same two subjects. Heel contact occurs at time 0. The recovery subject contacted the floor with a greater heel velocity and deceleration compared to the subject who fell. As expected, the perturbation is more severe in the slip-fall outcome compared to the recovery trial based on the increased peak slip velocity recorded in the fall trial.

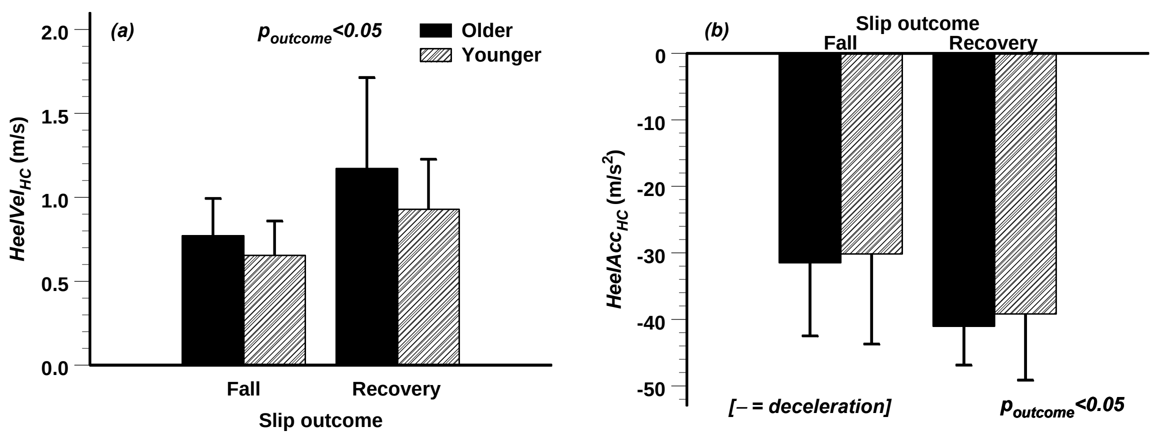

Figure 12: Average heel velocity (a) and acceleration (b) at heel contact stratified by slip outcome in older and younger participants. Subjects who recovered from the slip walked with a greater $HeelVel_{HC}$ and $HeelAccl_{HC}$ value than fallers ($p<0.05$), indicating that while their heel was moving faster, it was decelerating at a larger rate. No statistically significant age effects were found ($p>0.1$). Error bars reflect standard deviations.

4. All three joint torques at heel contact were found to strongly correlate with heel deceleration at heel contact (r~0.6-0.9, Table 6). Specifically, increasing ankle plantarflexion, knee flexion and hip extension moment resulted in greater heel deceleration at heel contact ($p<0.01$). Because ankle, knee and hip torques are interdependent, as shown by the Pearson correlation coefficients (Table 6), further regression analyses were conducted to determine the main joint contributor to heel deceleration at heel contact. Specifically, $HeelAcc_{HC}$ was regressed on $AnklTorq_{HC}$, $KneeTorq_{HC}$ and $HipTorq_{HC}$ both individually and simultaneously in different models and the behaviour of model R^2 was examined (Table 7). In order to determine driving determinants of heel contact heel acceleration, special attention was paid to the additional contribution of a specific joint torque to explaining $HeelAcc_{HC}$ variability above and beyond that explained by other joint torques (reflected by ΔR^2 between models in Table 7). Findings of this analysis indicate that a greater proportion of the variability in $HeelAcc_{HC}$ is explained by knee torque than by ankle or hip torques (Table 7). For example, 76% of the variability in $HeelAcc_{HC}$ is explained by $KneeTorq_{HC}$ alone, compared to 38 and 56% by $AnklTorq_{HC}$ and $HipTorq_{HC}$ alone, respectively. Furthermore, the added contribution to R2 by the combination of any two or all three joint torques explained no more than 1% of the variability in $HeelAcc_{HC}$ above and beyond the contribution by $KneeTorq_{HC}$ alone. In summary, knee kinetics are the main determinant of heel acceleration at heel contact, with increasing knee flexion torque being positively correlated with heel contact heel deceleration ($p<0.01$).

Table 6: Pearson correlation coefficients relating gait variables of interest. *(*p<0.05, **p<0.01)*

$HeelAcc_{HC}$	-0.71**	0.10	-0.48*	0.09	-0.62**	-0.62**	-0.87**	-0.75**
	$HeelVel_{HC}$	-0.24	0.20	-0.42*	0.69**	0.24	0.64**	0.76**
		RCOF	-0.31	0.18	-0.34	0.23	-0.09	-0.29
			Gait speed	0.31	0.65**	0.27	0.52**	0.55**
				Step length ratio	-0.15	0.11	-0.10	-0.25
					Cadence	-0.02	0.53**	0.81**
						$AnklTorq_{HC}$	0.72**	0.32
							$KneeTorq_{HC}$	0.83**
								$HipTorq_{HC}$

Table 7: R^2 values obtained by regressing $HeelAcc_{HC}$ on each joint torque individually and simultaneously. ΔR^2 between models can be computed to gain a better understanding of independent joint torque contributions to explaining the variability in heel contact heel deceleration. For example, ΔR^2 between Model 7 and Model 2 indicates that adding ankle and hip torque in the regression model explains only 1% of the variability in $HeelAcc_{HC}$ above and beyond contributions made by the knee torque.

Model 1 *$AnklTorq_{HC}$*	**Model 2** *$KneeTorq_{HC}$*	**Model 3** *$HipTorq_{HC}$*	**Model 4** *$AnklTorq_{HC}$ and $KneeTorq_{HC}$*	**Model 5** *$AnklTorq_{HC}$ and $HipTorq_{HC}$*	**Model 6** *$KneeTorq_{HC}$ and $HipTorq_{HC}$*	**Model 7** *$AnklTorq_{HC}$, $KneeTorq_{HC}$ and $HipTorq_{HC}$*
0.38	0.76	0.56	0.76	0.72	0.77	0.77

7.4.3 Upper extremity biomechanics during slipping

Previous research involving perturbed walking has to a large extent focused on lower extremity reactions, yet arm responses are often part of postural reactions to such perturbations. It is unclear if arms are used to aid in balance recovery or as protective strategy. This analysis was focused on arm responses to an unexpected slip. Specifically, the relationship between slip severity and shoulder biomechanics was examined. In summary, although arm responses were bilateral, only left (side of slipping foot) shoulder biomechanics, specifically moment generation rates and elevation angles were positively correlated with slip severity. The details of the results are as follows:

1. Kinematics: subjects experiencing a fall as a result of slipping raised their left arm more than subjects who recovered (Figure 13). No age effects were found.

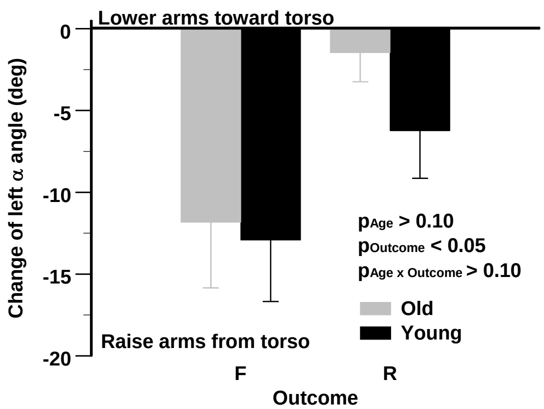

Figure 13: Change of left elevation angle (α). Subjects who fell (F) raised their left arm from the trunk more than those who recovered. Error bars are standard errors.

2. Kinetics: Overall, subjects who fell generated greater extensor moments in the left shoulder than those who recovered (Figure 14). Older subjects who fell tended to generate faster extension moments than young adults did, perhaps as a protective strategy to prepare in the event of a fall (Figure 14). Finally, older subjects who recovered generated a flexion moment at the left shoulder, implying the use of such strategy to recover balance in non-threatening perturbations.

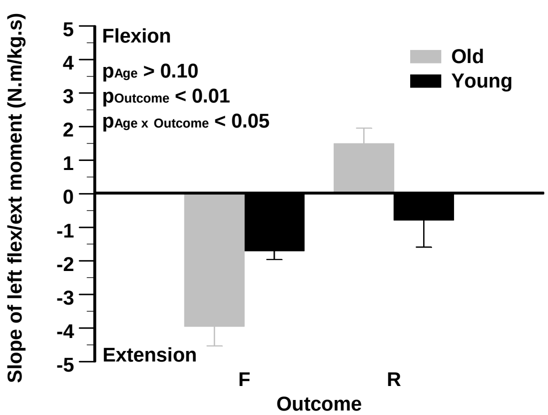

Figure 14: Left flexion moment generation rate stratified by age group and outcome. Fallers generated extensor moments in the left shoulder faster than those who recovered. Also, older subjects who recovered generated left flexion moments, while older subjects who fell generated increasing extension moments. Error bars are standard errors.

8 Publications

These publications include all research that was fully or partially supported / funded by this grant (R01 OH7592). Few of these manuscripts were also partially supported by a smaller slips/falls grant also funded by NIOSH (R03 OH007533). See detailed explanation in next section entitled "Inclusion of Gender and Minority Study Subjects".

8.1 Journal articles

- Moyer BE, Chambers AJ, Redfern MS, Cham R: [2006] Gait Parameters as Predictors of Slip Severity in Young and Older Adults. Ergonomics 49: 329–343, 2006. (Aim 2)
- Chambers AJ, Cham R: [2007] Slip-Related Muscle Activation Patterns of the Stance Leg During Gait. Gait and Posture 25: 565-572.
- Beschorner K, Cham R: [2008] Impact of Joint Torques on Heel Acceleration at Heel Contact, a Contributor to Slips and Falls. Ergonomics 51: 1799-1813. (Aim 1 and 2)
- Moyer BE, Redfern MS, Cham R: [2009] Biomechanics of Trailing Leg Response to Slipping - Evidence of Interlimb and Intralimb Coordination. Gait and Posture 29: 565–570. (Aim 1 and 2)
- Wyszomierski SA, chambers AJ, Cham R: [2009] Knee Strength Capabilities and Slip Severity. Journal of Applied Biomechanics, In press. (Aim 4)
- Beschorner K, Cham R: [2008] Impact of Joint torques on Heel acceleration at Heel Contact, a Contributor to Slips and Falls. Ergonomics 51: 1799-1813. (Aim 1 and 2)

8.2 Proceedings

- Chambers AJ, Cham R: "Anticipation of slippery floors: Muscle onsets and co-contraction of the stance leg," Proceedings of the American Society of Biomechanics (ASB) in conjunction with IVth World Congress of Biomechanics, Cleveland, Ohio, September 2005.
- Beschorner K, Cham R: "Center of mass acceleration and slip outcome," Proceedings of the American Society of Biomechanics (ASB), Blacksburg, Virginia, September 2006.
- Wyszomierski S, Chambers AJ, Cham R: "Knee strength and slip severity in young and older Adults," Proceedings of the American Society of Biomechanics (ASB), Blacksburg, Virginia, September 2006.
- Beschorner K, Cham R: "Heel acceleration at heel strike and slip outcome," Proceedings of the International Society of Posture and Gait Research (ISPGR), Burlington, Vermont, July 2007.
- Cham R, Moyer BE, Redfern MS: "Trailing leg postural strategies during slipping," Proceedings of the International Society of Posture and Gait Research (ISPGR), Burlington, Vermont, July 2007.
- Chambers AJ, Cham R: "The impact of anticipating slippery floors on spatial and temporal variability during gait," Proceedings of the International Society of Posture and Gait Research (ISPGR), Burlington, Vermont, July 2007.
- Cham R, "Swing phase interruption in a slip: active or passive response?," Proceedings of the American Society of Biomechanics (ASB), Stanford, California, August 2007.
- Cham R, Beschorner K, Redfern MS: "Whole body postural responses to slips," Podium presentation and published in the Proceedings of the International Conference on Slips, Trips, and Falls 2007: From Research to Practice, conference sponsored by the International Ergonomics Association (IEA), Hopkinton, Massachusetts, August 2007.
- Cham R, Sandrian PN: "Arm movements and slip severity," Proceedings of the Human Factors and Ergonomics Society (HFES), Baltimore, Maryland, October 2007.
- Beschorner K, Redfern MS, Sandrian PN, Cham R: "Do vestibular inputs trigger upper body responses during a slip?," Proceedings of the American Society of Biomechanics (ASB) in conjunction with the North American Congress on Biomechanics (NACOB), Ann Arbor, Michigan, August 2008.
- Moyer BE, Redfern MS, Cham R: [2008] "Bilateral lower extremity response to unexpected slips", National Occupational Injury Research Symposium (NOIRS), Pittsburgh, PA, October 2008.
- Timcho EA, Chambers AJ, Cham R: [2009] Recovery gait following an unexpected slip. Proceedings of the American Society of Biomechanics (ASB), State College, PA, August 2009.

8.3 Dissertation/Thesis

- Moyer BE: [2006] "Slip and fall risks: pre-slip gait contributions and post-slip response effects", Ph.D. Thesis, University of Pittsburgh.
- Beschorner KE: [2009] "Development of a computational model for shoe-contaminant-floor friction", Ph.D. Thesis, University of Pittsburgh.
- Chambers AJ: [2005] "Slip-related muscle activation patterns of the stance leg during gait", M.S. Thesis, University of Pittsburgh.
- Sandrian PN: [2006] "Arm movements during slipping", M.S. Thesis, University of Pittsburgh.
- Wyszomierski S [2008] "Role of strength and sensory integration in slipping", M.S. Thesis, University of Pittsburgh.

9 Inclusion of Gender and Minority Study Subjects

Two projects focused on slips and falls were funded by NIOSH as follows: (1) NIOSH 1 R03 OH007533, "Biomechanics of Human Reactions to Slip Events", Start date: 05/01/2002, End date: 04/30/2005 including one year no cost extension; and (2) NIOSH 1 R01 OH007592 "Biomechanics of Slips in Older Adults", Start date: 08/01/2002, End date: 07/31/2006 including one year no cost extension. The budget was significantly reduced in the R01 proposal because (1) there was some scientific overlap between the two projects and (2) the beginning/ending dates of the R03 proposal overlapped almost completely with the support period for the R01 project. Although no significant changes in the Aims were made as a result of this cut in the budget, data collected in the R03 project were (and will continue to be) used in the statistical analyses required in the R01 project when possible. Thus, because of the scientific overlap between the proposals, Table 8 below relates to the combined R03/R01 project.

Table 8: Subject distribution by ethnicity and race

	Sex/Gender		
Ethnic Category	**Females**	**Males**	**Total**
Hispanic or Latino	0	2	2
Not Hispanic or Latino	56	48	104
Unknown (individuals not reporting ethnicity)	4	7	11
Ethnic Category: Total of All Subjects	60	57	117
Racial Categories			
American Indian/Alaska Native	0	2	2
Asian	1	1	2
Native Hawaiian or Other Pacific Islander	0	0	0
Black or African American	5	2	7
White	49	41	90
More Than One Race	1	4	5
Unknown or Not Reported	4	7	11
Racial Categories: Total of All Subjects	60	57	117

10 Inclusion of Children

The research did not involve children subjects as the focus of the experiments were on falls in older adults.

11 Materials Available for Other Investigators

None.