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Falls resulting from a laboratory-induced slip occur at a higher rate among individuals who are obese

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Falls due to slipping are a serious concern, with slipping estimated to cause 40–50% of all fall-related injuries. Epidemiological data indicates that older and obese adults experience more falls than young, non-obese individuals. An increasingly heavier and older U.S. population and workforce may be exacerbating the problem of slip-induced falls. The purpose of this study was to investigate the effects of obesity and age on slip severity and rate of falling resulting from laboratory-induced slips. Four groups of participants (young obese, young non-obese, older obese, older non-obese) were slipped while walking at a self-selected, slightly hurried pace. Slip severity (slip distance, slip duration, mean slip speed and peak slip speed) and slip outcome (fall or recovery) were compared between groups. Obese individuals experienced 22% faster slips than non-obese individuals in terms of mean slip speed ($p=0.022$). Obesity did not affect slip distance, slip duration or peak slip speed. Obese individuals also exhibited a higher rate of falls; 32% of obese individuals fell compared to 10% of non-obese ($p=0.005$). Obese individuals were more than eight times more likely to experience a fall than non-obese individuals when adjusting for age, gender and gait speed. No age effects were found for slip severity or slip outcome. These results, along with epidemiological data reporting higher fall rates among the obese, indicate that obesity may be a significant risk factor for experiencing slip-induced falls. Slip severity thresholds were also reported that may have value in developing controls for fall prevention.

1. Introduction

Occupational falls and fall-related injuries are a major source of mortality, morbidity, and medical expense. In 2011, falls accounted for 553 occupational fatalities and 22% of injuries requiring days away from work in the U.S. (Stephen and Janocha, 2013). The annual cost of occupational fall-related injuries is estimated to be $5.7 billion in the United States alone (Yoon and Lockhart, 2006). Slipping causes an estimated 40–50% of all fall-related injuries (Courtney et al., 2001). For example, slips caused 85% of falls to the floor and 30% of falls to a lower floor during construction of the Denver International Airport between 1989 and 1994 (Lipscomb et al., 2006).

The problem of occupational slip-related falls may be exacerbated by the high prevalence of obesity. In the 1960s, only 13% of the U.S. population was considered obese based upon body mass index, or BMI (Wang and Beydoun, 2007). During 2011–2012, 69% of the population was estimated to be overweight ($25<\text{BMI}<30\ \text{kg/m}^2$) or obese ($\text{BMI}\geq 30\ \text{kg/m}^2$) and 35% was estimated to be obese (Ogden et al., 2012). All-cause fall rates are higher among obese individuals (Fjeldstad et al., 2008; Himes and Reynolds, 2012; Patino et al., 2010). These higher fall rates could be due, in part, to an impaired ability to maintain balance after slipping, secondary to the adverse biomechanical and physiological effects of obesity (Madigan et al., 2014). For example, muscle strength relative to body weight is lower among obese compared to non-obese individuals (Lerner et al., 2014), and could reduce net muscle moments and movement capabilities when trying to maintain balance after slipping. Trunk segment inertia is higher among obese individuals (Matrangola et al., 2008), which would increase the trunk's kinetic energy during walking and require additional joint work to attenuate when attempting to maintain balance after slipping. Lastly, plantar sensitivity is degraded among obese individuals (Wu and Madigan, 2014), and could contribute to delayed slip onset detection.These factors associated with obesity would lead to longer and faster slips that require higher net muscle moments to maintain balance.

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The problem of slip-related falls in the workplace could also be exacerbated by more adults are continuing to work later in life (Toossi et al., 2013), because fall rate increase with age (Tromp et al., 2001). Moreover, individuals who are obese *and* older would seem to be at a particularly elevated risk for falling due to the combination of risk factors associated with obesity and aging. However, the combined effects of obesity and age on slips and falls have not been investigated. Zhang et al. (2014) reported older adults who were obese were 2.5 times more likely to fall while walking following a simulated slip using a sliding platform (Zhang et al., 2014). This study provides evidence that obese older adults are less able to maintain balance after a large postural perturbation while walking compared to non-obese older adults. Given differences in slipping foot kinematics between slips on a sliding platform and slips on a low-friction surface (Troy and Grabiner, 2006), it is unclear how results from this prior study generalize to slips on a low-friction surface that are more common outside of the laboratory setting.

The purpose of this study was to investigate the effects of obesity and age on slip severity and the rate of falling after a laboratory-induced slip. Slip severity was quantified using slipping foot kinematics, and was operationalized by slip duration, slip distance, peak slip speed, and mean slip speed. These measures were selected based upon their use in other slip studies and their association with fall outcome after slipping (Brady et al., 2000; Lockhart et al., 2003; Troy and Grabiner, 2006; Yang et al., 2009). Three hypotheses were tested: (1) obese adults would experience more severe (i.e. longer in duration, farther in distance, and faster in speed) slips than non-obese adults; (2) obese adults would fall at a higher rate after slipping; (3) an obesity $\times$ age interaction would exist, in which the effects of obesity on slip severity and rate of falling would be magnified among older than younger adults. These hypotheses were based upon the potential for previously reported biomechanical and physiological factors impairing the ability to maintain balance after slipping (Madigan et al., 2014). Any effects of obesity or age on slip severity or rate of falls can be used to help identify workers at an increased risk of falling from a slip, and potentially guide subsequent investigations aimed at developing fall prevention strategies.

2. Methods

Seventy-two adults completed the study and were categorized into one of two age groups and one of two obesity groups. Participants included 26 young (18–29 years) non-obese (BMI 17.7–24.9 kg/m^2); 25 young obese (BMI 29.1–40.4 kg/m^2); 10 older (50–66 years) non-obese (BMI 19.5–26.3 kg/m^2); and 11 older obese (BMI 30.1–45.1 kg/m^2) individuals. Participants were recruited from the university and local community using electronic announcements, community flyers, and newspaper advertisements. All participants were screened using a medical questionnaire to exclude individuals with self-reported musculoskeletal or neurological disorders that could affect their gait or balance. Participants aged 65 and older, as well as one 60-year-old participant based upon responses to the medical questionnaire, were also required to pass a medical evaluation administered by a physician. This evaluation excluded participants with any neurological, cardiac, respiratory, ontological, or musculoskeletal disorders, and required a minimum bone density of the femoral neck of 0.65 g/cm^2 as assessed by DXA (General Electric, Lunar Digital Prodigy Advance, Madison, WI). The university Institutional Review Board approved this study, and informed consent was obtained from all participants prior to participation.

The experiment involved one experimental session during which participants were exposed to an unexpected slip while walking on a level walkway. Participants were asked to look straight ahead and walk at a self-selected, yet purposeful (slightly hurried), speed along a 10-meter walkway covered in vinyl tile. Initially, participants performed five to 10 walking trials to acclimate to the lab environment, and to establish a starting position so that the dominant foot (preferred foot to kick a ball) naturally and consistently landed on a force platform integrated in the middle of the walkway. Participants were then informed that a slip or trip may or may not occur during any subsequent walk down the walkway, and that if slipped or tripped, they should attempt to maintain their balance and continue walking. All participants wore shoes with polyvinylchloride soles to prevent any frictional differences between participants at the shoe-floor interface. To prevent impact with the floor in the event of an impending fall, participants wore a safety harness connected with a lanyard to a track above the walkway. The length of the lanyard was adjusted so that a participant's hands could not touch the floor and their knees would be 15 cm from the floor when kneeling.

To divert attention from walking and the possibility of a slip or trip, participants watched television (one positioned at each end of the walkway) and listened to the audio through wireless headphones while walking. For approximately 1–2 min between consecutive trials, participants stood at the end of the walkway, with their backs to the walkway, and watched the television until instructed to turn around and begin the next trial. This time interval allowed the investigators to prepare for the next trial. After a minimum of 10 acceptable walking trials (with proper foot placement on the force platform and walking/sacrum marker speed not fluctuating by more than ± 0.1 m/s between trials), a foam paint roller was used to apply a uniform layer of vegetable oil (50 mL) to the entire surface of the force platform (0.9 m $\times$ 0.9 m) while the participant faced away from the walkway. The next walking trial then continued using the same procedure as earlier trials. A slip occurred when the dominant foot contacted the contaminated surface, and all participants were successfully slipped on the first attempt. The lights in the lab were dimmed throughout testing to reduce any glare/visual cue created by the slip contaminant.

During walking and slipping trials, the three-dimensional position of 28 reflective markers were sampled at 100 Hz using a Vicon motion capture system with six T10 cameras (Vicon Motion Systems, Centennial, CO) and low-pass filtered at 7 Hz (second-order, zero-phase-lag Butterworth filter). Reflective markers were placed at anatomical landmarks based on a modified Helen Hayes marker set (Kadaba et al., 1990). Ground reaction forces under the slipping foot, and the force applied to the harness, were sampled at 1000 Hz using a 6-degree of freedom force platform (Bertec Corporation, Columbus, OH) and a uniaxial load cell (Cooper Instruments and Systems, Warrenton, VA), respectively. Both were low-pass filtered at 20 Hz (second-order, zero-phase-lag Butterworth filter).

Six dependent variables were obtained from each slip trial using custom-written code in Matlab 2013a (The Mathworks Inc., Natick, MA): gait speed, gait step length, slip duration, slip distance, peak slip speed, and mean slip speed. Gait speed was calculated as the forward speed of a marker on the sacrum for 2–3 steps preceding slip onset (Brady et al., 2000). Slip severity parameters were calculated by first identifying two events: slip onset and slip end (Brady et al., 2000; Redfern et al., 2001; Strandberg and Lanshammar, 1981). Slip onset was defined as heel contact onto the contaminated surface using force data collected from the force platform (Brady et al., 2000). The slip end was defined as the time when either: (1) the slipping foot slipped entirely off the edge of the force platform, (2) the heel came to a stop, or (3) the heel displaced vertically from the force platform (Brady et al., 2000; Cham and Redfern, 2001). Slip distance was calculated as the total distance traveled from slip onset to slip end, and slip duration was calculated as the time from slip onset to slip end. Peak slip speed was calculated as the maximum speed of the heel marker during the slip (Brady et al., 2000) using a finite difference algorithm.

Slip outcome (fall or recovery) was determined using forces collected from the harness load cell and methods described elsewhere (Brady et al., 2000). Slip outcome was classified as: (1) *recovery* if the peak harness load was $< 30\%$ body weight (BW) and the integrated harness load was $< 8\%$ BW $\times$ second; (2) *fall* if the peak harness load was $\geq 50\%$ BW; (3) *harness-assisted* otherwise. Harness-assisted trials were excluded from further analysis due to their ambiguous outcome had participants not been wearing the harness. Slip severity thresholds that correctly separated the highest percentage of falls and recoveries were determined by iteration.

Differences in gait speed and gait step length between obesity groups and between age groups were investigated using separate two-way analyses of variance. The interaction effect (obesity $\times$ age) was not statistically significant for gait speed ($p=0.166$) and gait step length ($p=0.147$), and was subsequently removed from both analyses. The four slip severity measures (slip duration, slip distance, peak slip speed, and mean slip speed) were analyzed using separate three-way analyses of covariance with independent variables of obesity group, age group, and gender, and with gait speed as a covariate. All three-way and two-way interaction effects were initially included in the analysis. Iterative backwards elimination was then used to remove non-significant three-way and two-way interactions until the final model included only main effects and significant interactions. Following this procedure, no interactions remained in the final models for any of the dependent variables. Slip outcome was analyzed using a logistic regression model with independent variables of obesity group, age group, gender, and gait speed. An obesity group $\times$ age group was initially included, but subsequently removed because it was not statistically significant. Gait speed and gait step length were normalized by body height prior to statistical analysis, but reported in units of meters and meters/second for utility. Statistical analyses were performed using JMP 10 (SAS Institute Inc., Cary, NC) with a significance level of $p \leq 0.05$.

3. Results

Gait speed and gait step length were not affected by obesity group (speed $p=0.486$, step length $p=0.886$) or age group (speed $p=0.245$, step length $p=0.593$; Table 1). One of four slip severity measures was affected by obesity group (Table 1). Mean slip speed was 22% higher ($p=0.022$) among obese participants, but slip duration ($p=0.974$), slip distance ($p=0.121$), and peak slip speed ($p=0.065$) were not affected by obesity group. Age group did not affect slip severity measures, including slip duration ($p=0.112$), slip distance ($p=0.933$), peak slip speed ($p=0.591$), and mean slip speed ($p=0.543$; Table 1). Gait speed affected three of four slip severity measures. Slip distance ($p=0.005$), peak slip speed ($p<0.001$), and mean slip speed ($p<0.001$) increased as gait speed increased, but gait speed did not affect slip duration ($p=0.148$).

Slip outcome differed between obesity groups ($p=0.005$; Fig. 1) in that 10 out of 31 (32%) obese participants fell after slipping compared to 3 out of 30 (10%) non-obese participants. The odds ratio for obesity group indicated that obese participants were 8.24 [95% C.I.: 1.81, 57.10] times more likely to fall than non-obese participants when adjusting for age group, gender, and gait speed. Slip outcome was not affected by age group ($p=0.937$) or gender ($p=0.395$; Table 2). However, a fall was more likely as gait speed increased ($p=0.003$), with an odds ratio of 1.08 [95% C.I.: 1.02, 1.14] for a 1 cm/s increase in gait speed when adjusted for obesity group, age group, and gender.

Inspection of the data revealed that falls were associated with more severe slips. Falls were associated with longer slip distances, but the slip distance for some recovery trials surpassed slip distances resulting in falls (Figs. 2 and 3). Similarly, falls were associated with slips that were longer in duration, and faster in speed, but the duration and speed of some recovery trials surpassed some resulting in falls (Fig. 3). As such, there were no slip severity thresholds that separated all falls from all recoveries. Participants who fell tended to experience more severe slips. In general, the majority of falls occurred with slip distances beyond 50 cm, slip durations longer than 0.3 s, peak slip velocities above 2.5 m/s, and mean slip velocities over 1.0 m/s. More specifically, a slip distance of 56.5 cm separated 85.4% of recoveries from 86.7% of falls, a slip duration of 0.35 s separated 54.2% of recoveries from 86.7% of falls, a peak slip speed of 2.57 m/s separated 91.7% of recoveries from 80.0% of falls, and a mean slip speed of 1.19 m/s separated 79.2% of recoveries from 86.7% of falls (Fig. 3).

4. Discussion

The purpose of this study was to investigate the effects of obesity and age on slip severity and the rate of falling after a laboratory-induced slip. Our first hypothesis was that obese adults would experience more severe slips than non-obese adults. This hypothesis was accepted because mean slip speed was higher among obese adults. Additionally, a post-hoc power analysis indicated peak slip speed would have be statistically significant with only four more participants added to each group (assuming the same standard errors and structural results as the current sample). This relatively small number of additional participants perhaps suggests a greater emphasis on the results than the lack of statistical significance would indicate. It is interesting to note that the range of slip severity parameters for falls and recoveries found here agreed well with those reported by Brady et al., despite experimental differences including the use of mineral oil to slip young adults age 26.6 ± 3.9 years who were walking barefoot.

Slip severity was related to slip outcome in that more falls resulted from more severe slips (Fig. 3). However, there were exceptions to this trend. For example, falls occurred after slip distances as short as 35.4 cm, and recoveries occurred after slip distances as long as 72.2 cm. Previously reported slip severity thresholds suggested falls would likely occur when slip distance exceeded 10 cm and peak slipping speed exceeded 50 cm/s (Cham and Redfern, 2002b; Perkins, 1978; Strandberg and Lanshammar, 1981). These previously reported thresholds were substantially smaller than those reported here (slip distance = 56.5 cm and peak slipping speed = 2.57 m/s). The large discrepancies between these studies may be attributed to methodological differences such as these prior studies employing multiple slips, and more recent work documenting a reduction in slip severity with repeated exposure to slipping (Siegmund et al., 2006). These thresholds for slip distance and peak slip speed have potential value in preventing falls from slips. Smooth flooring can be desirable for esthetics or ease of cleaning. Smooth flooring, however, is typically associated with a higher likelihood of slipping in the presence of a liquid contaminant. Using the slip severity thresholds identified here, smooth flooring could be designed to include high friction markings or boundaries that would arrest a slip. As long as these markings or boundaries were designed to limit any slip below the threshold identified here, they may help prevent falls after slipping. This potential engineering control would need to be confirmed experimentally through future research.

Our second hypothesis was that obese adults would fall at a higher rate after slipping. This hypothesis was accepted because obese adults were over eight times more likely to fall after slipping compared to non-obese adults after adjusting for age group, gender, and speed. Several underlying neuromuscular alterations associated with obesity (Madigan et al., 2014) could have contributed to the higher fall rate and less favorable trip recovery measures with obesity. First, obesity is associated with increased trunk mass (Corbeil et al., 2001; Matrangola et al., 2008), which would increase the mechanical demands necessary to arrest trunk motion when attempting to maintain balance after slipping. Second, obesity is associated with reduced lower extremity strength relative to body mass (Capodaglio et al., 2009; Wearing et al., 2006), which would seem to compromise the capacity to enact a quick and effective stepping response necessary to maintain balance after slipping. Third, sensory deficits could contribute to a delayed response and more severe slip (Wu and Madigan, 2014).

Our third hypothesis was that an obesity × age interaction would exist whereby the effects of obesity on slip severity and rate

Table 1
Gait and slip severity measures (mean ± standard deviation).

	Gait measures		Slip severity measures			
	Gait speed (m/s)	Step length (m)	Slip duration (s)	Slip distance (cm)	Peak slip Speed (m/s)	Mean slip Speed (m/s)
Obese	1.26 ± 0.14	0.70 ± 0.07	0.34 ± 0.12	40.2 ± 28.3	1.83 ± 1.03	1.01 ± 0.60*
Non-obese	1.29 ± 0.16	0.70 ± 0.06	0.35 ± 0.11	34.4 ± 22.3	1.58 ± 0.82	0.83 ± 0.47*
Older	1.31 ± 0.16	0.69 ± 0.07	0.30 ± 0.09	35.0 ± 25.8	1.60 ± 0.92	0.97 ± 0.61
Young	1.27 ± 0.15	0.71 ± 0.06	0.36 ± 0.12	38.0 ± 25.5	1.74 ± 0.94	0.91 ± 0.53
Male	1.28 ± 0.13	0.72 ± 0.05	0.31 ± 0.09	29.5 ± 21.7	1.50 ± 0.85	0.81 ± 0.48
Female	1.27 ± 0.17	0.68 ± 0.07	0.37 ± 0.13	44.1 ± 26.7	1.89 ± 0.97	1.01 ± 0.58

* indicates statistical difference ($p \leq 0.05$) between obesity groups. Slip distance, peak slip speed, and mean slip speed all showed a significant increase with gait speed.

of falling would be magnified among older adults compared to young adults. This hypothesis was rejected because no obesity group × age group interactions existed for any slip severity measures, or fall rate. Moreover, no age group differences in fall rate and slip severity were found. These results differ from previous studies that report older adults experienced higher fall rates and faster/farther slips following laboratory-induced slips (Lockhart et al., 2003). Regarding fall rate, Troy et al. (2008) reported that 18 out of 21 (86%) older adults (mean age 71 years) fell, and 2 out of 32 (6%) young adults (mean age 25 years) fell. Lockhart et al. (2003) reported that 7 out of 14 (50%) older adults (mean age 76 years) fell, and 2 out of 14 (14%) young adults (mean age of 23 years) fell. Regarding slip severity, Troy el al. (2008) reported slip distance was 39.8 cm among older fallers and 19.6 cm among young non-fallers, while peak slip velocity was 2.37 m/s among older fallers and 1.40 m/s among young non-fallers. Lockhart et al. (2003) reported initial slip distance was 2.2 cm among older adults and 1.1 cm among young adults, while sliding heel speed was 0.76 m/s among older adults and 0.47 m/s among young adults. Unfortunately, a direct comparison of slip severity parameters between these prior studies and the current study is difficult due to differences in how slip severity parameters were calculated and summarized. In particular, Troy et al. only reported slip severity measures of older fallers and young non-fallers. Lockhart et al. calculated sliding heel speed as the mean speed from slip onset to peak sliding heel speed, initial slip distance as distance from slip onset to peak heel horizontal acceleration, and a fall having occurred when sliding heel speed exceeded the whole-body center of mass speed during the slip. Additionally, older adults in these previous two studies had mean ages of 71 and 76 years, whereas older adults in the present study had a mean age of 58 years. This likely contributed to the differences in age-related effects between the studies.

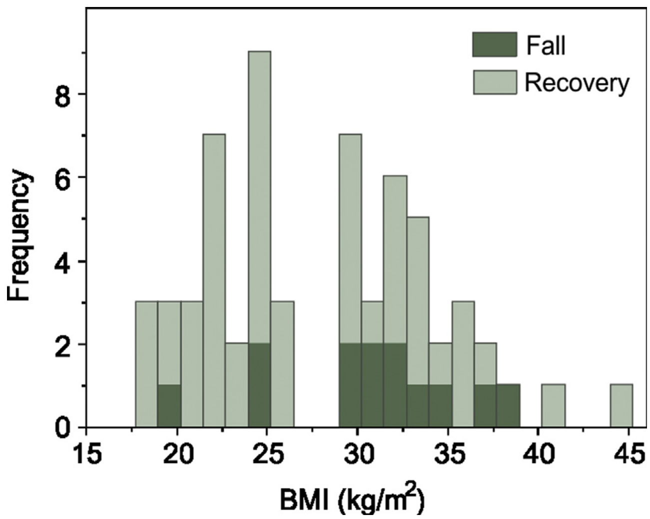

Fig. 1. The distribution of falls and recoveries across BMI shows a higher number of falls among the obese group.

Table 2
Slip outcomes among groups.

	Fall	Recovery	Harness-assisted	Total
Total	13	48	11	72
Obese	10*	21	5	36
Non-obese	3*	27	6	36
Older	3	12	6	21
Young	10	36	5	51
Male	4	24	5	33
Female	9	24	6	39

Logistic regression model to predict probability of a fall:
logit = −10.21 − 0.96OB_GRP − 0.30AGE_GRP − 0.01GEN + 11.17SP.
where: AGE_GRP = −1 for young and 1 for older;
OB_GRP = −1 for obese and 1 for non-obese; GEN = −1 for males and 1 for females; SP = speed in %BH/s; Probability of fall = $1/(1+e^{-\text{logit}})$. Probability of fall = $1/(1+e^{-\text{logit}})$.
Using a cutoff score of 0.5: Model Sensitivity = 25%.
Model Specificity = 94%.

* indicates statistical difference ($p \le 0.05$) between obesity groups.

Another factor influencing fall outcome was gait speed. Faster gait speed was associated with more severe slips and more falls. These results with respect to fall rate do not agree with prior work. Two previous studies used mineral oil (Brady et al., 2000) or a water-detergent mixture (Hu and Qu, 2013) to slip participants walking at a self-selected speed. Brady et al. reported no effect of gait speed on slip outcome, and Hu and Qu found no difference in walking speed between falls and successful recoveries. Other studies have reproduced slips with sliding platforms, and reported faster gait speeds to improve stability and reduced rate of falling (Bhatt et al., 2005; Espy et al., 2010). As such, the influence of gait speed on slip outcome remains an open question.

Several limitations were present in this study. First, participants were warned of a possible slip, so anticipation effects may have existed (Cham and Redfern, 2002a; Heiden et al., 2006; Horak and Nashner, 1986). Second, the age range of our older participants was

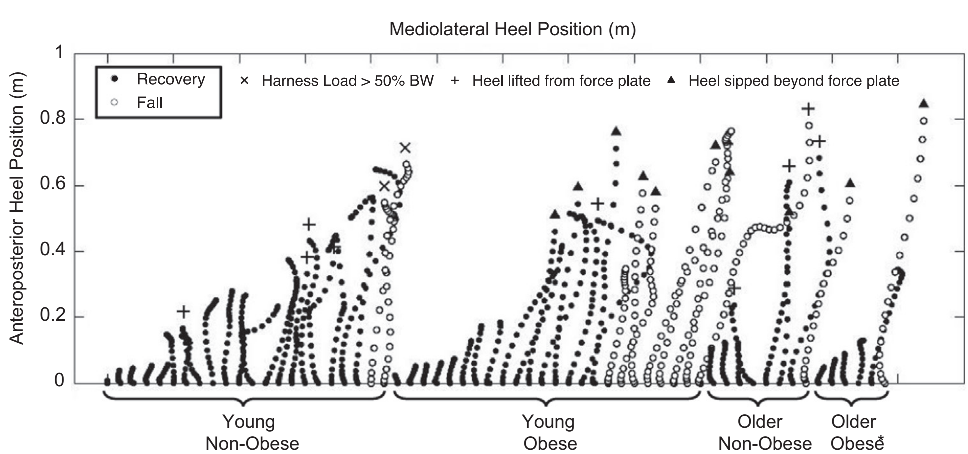

Fig. 2. Sliding heel trajectories for all slips classified as recoveries or falls, organized based on slip distance and age/BMI group. Each data point represents the sliding heel position from slip onset to slip end, separated by 20 ms intervals. Slips ended when the sliding heel came to a stop, unless otherwise indicated.

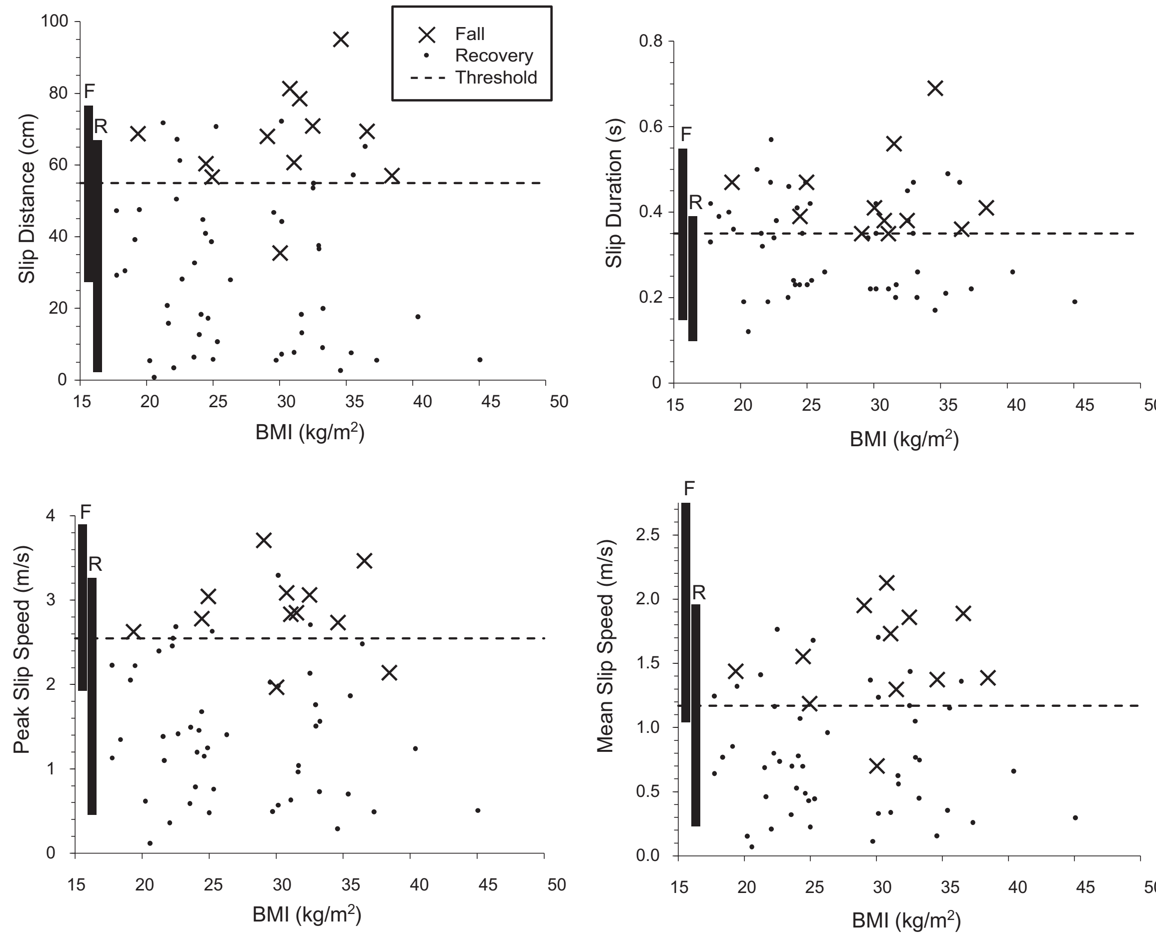

Fig. 3. Slip severity parameters from all slip trials were plotted as a function of subject BMI. Most falls occurred among the obese group, and falls were associated with more severe slips. Dashed slip severity threshold lines separated most falls from most recoveries. Vertical bars on the left of each subplot illustrate the range of slip severity parameters for falls (F) and recoveries (R) resulting from a laboratory-induced slip as reported by Brady et al. (2000).

50–66 years, and was chosen to correspond with the final years of the traditional working age. As such, our results with respect to age may not generalize to adults over the age of 65. Third, the end of slip for several participants occurred when the foot slipped up to (and over) the edge of the force platform. As such, it was unclear as to how far these participants would have slipped had the force platform been extended further on the walkway. Fourth, it is unclear if slip severity and fall rates are dependent upon the contaminant and shoe sole material employed. Any such dependence would potentially influence the ability to generalize parameter values between slipping studies and outside of the laboratory. Fifth, while a multivariate approach could potentially identify a group of slip severity parameters that better predict slip outcome than any single slip severity parameter, the univariate approach employed here was chosen as a pragmatic approach in that any engineering controls resulting from this work may only limit a single slip severity parameters. Sixth, our choice of slip severity parameters was not exhaustive, and others not investigated here (e.g. slip acceleration) may be influenced by obesity or age, and/or have value in designing engineering controls.

5. Conclusions

Obesity increased slip speed and fall rate after a laboratory-induced slip. These results suggest that the higher fall rate reported among obese individuals may be due, at least in part, to a reduced ability to maintain balance after slipping. Slip severity thresholds that separated the majority of falls from recoveries were also reported. These threshold values may have practical value in preventing falls from slips by incorporating friction markings or boundaries to limit slip distance to values lower than when falls occurred. This application would need to be confirmed experimentally.

Conflict of interest statement

The authors have no conflicts of interest to disclose.

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