Published in final edited form as:
Gait Posture. 2008 October ; 28(3): 461–465. doi:10.1016/j.gaitpost.2008.02.008.

Modifiable performance domain risk-factors associated with slip-related falls

Karen L. Troy, **Stephanie J. Donovan**, **Jane R. Marone**, **Mary Lou Bareither**, and **Mark D. Grabiner**
Department of Kinesiology and Nutrition, University of Illinois at Chicago

Keywords
aging; falls; locomotion; slip

Introduction

Previous research has demonstrated that older adults can learn within one training session to avoid falling after a forward-directed trip [1,2] and slip [3]. This suggests that fall-prevention programs could benefit from emphasizing task-specific training. The effectiveness and efficiency of a task-specific approach might be beneficially influenced by the identification of the components of the recovery task that are most sensitive and accessible to intervention, and that are demonstrable mechanisms of falls.

Biomechanical investigation of responses following a slipping event has identified potentially important differences between individuals who have either fallen or recovered. The present study determined the extent to which performance-related factors contribute to slip-related falls and quantified the degree to which slip-related fall-risk could be decreased by improving these factors. Based on the published literature on slip-related falls we hypothesized that avoiding a fall after a slip would be dependent upon arresting the motion of the slipping foot [4,5] and rapidly lowering the non-slipping limb to the ground posterior to the trunk center of mass [6, 7]. Based on our previously published research on recovery from induced trips [1,8] we hypothesized that avoiding a fall after a slip would be dependent upon arresting the slip-related trunk extension motion.

Methods

Thirty-five healthy young adults (18 males, age 25±5 years, height 172±11 cm, mass 69.5±15.7 kg) and 21 independent, community-dwelling older adults (8 males, age 70.9±5.1 years, height 165.6±10.9 cm, mass 72.2±13.2 kg) participated in this study and provided written informed consent. The study was reviewed and approved by the Institutional Review Board (IRB2004-0131 and IRB2004-0523). Older adults were screened by a physician for exclusion

Corresponding author: Mark D. Grabiner, PhD, Professor and Head, Department of Kinesiology and Nutrition (MC 994), University of Illinois at Chicago, 1919 W. Taylor St. Room 650, Chicago, Illinois 60612, Tel: 312.996.2757, FAX: 312.996.9296, Email: grabiner@uic.edu.

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factors that included neurological (including vestibular/otolith), musculoskeletal, and cardiovascular disorders.

The motions of twenty-three passively reflecting markers placed over specific body landmarks [9] were tracked using an eight camera motion capture system operating at 60 Hz (Motion Analysis, Santa Rosa, CA). The markers were used to construct a 13-segment rigid body model from which whole body center of mass and joint kinematics were derived (OrthoTrak, Motion Analysis, Santa Rosa, CA).

Subjects were protected from a fall to the floor by a safety harness. In the event of a fall the harness comfortably arrested the fall and completely supported the subject while precluding contact between the hands or buttocks with the floor. The safety harness was instrumented with a load cell that revealed when the harness began supporting the subject.

Subjects wore their own comfortable walking shoes and walked at a self-selected speed along a designated path that included a 1.22 × 2.44 m × 0.63 cm Plexiglas sheet. Subjects first performed a number of control walking trials to establish a normal walking pattern without the safety harness, after which a second set of control trials was performed with the safety harness. The subjects knew that following the control trials they could be slipped during any trial. However, because the actual number of control trials was not specified the transition between control trials and trials during which they might be slipped was unknown. In addition, the subjects were unaware of how the slip would be induced. Based on our experience, only one slip was attempted for each subject [4,10].

Prior to the slipping trial the subject was distracted by an investigator who engaged him/her in conversation while pretending to adjust a reflective marker or the safety harness. Meanwhile, another investigator made the Plexiglas sheet slippery. For the young subjects this was accomplished with a thin film of mineral oil. For the older adults, the mineral oil was replaced with a thin film of water soluble lubricant that had been allowed to dry and that was rapidly and quietly activated with a mist of water. Both lubricants were similarly slippery. The static coefficient of friction was measured as 0.19±0.13 (depending on the footwear) and the dynamic coefficient of friction was approximately 90 percent smaller. A slip was initiated when the subject’s foot contacted the slippery surface.

The slip was considered bounded in time by the onset, defined as the instant of heel strike on the slippery surface, and recovery, defined as the time at which the recovery foot contacted the floor. The ability to arrest the trunk extension motion subsequent to the slipping event was represented by trunk angular velocity. Trunk extension was referenced to vertical and measured up to 133 ms after recovery (rec_{+133}), which represented the longest period across subjects following the slip onset for which the safety harness was unloaded.

The ability to arrest the sagittal and frontal plane motion of the slipping foot was characterized using the peak displacement, velocity and acceleration of the heel marker. In addition, at recovery, the anteriorly-directed velocity of the slipping foot was referenced to the anteriorly-directed velocity of the overall body center of mass [11].

The ability to rapidly lower the non-slipping limb to the ground, i.e., reaction time, was measured as the elapsed time between the slip onset and recovery. The ability to lower the non-slipping limb to the ground posterior to the center of mass (COM) was measured as sagittal plane recovery foot centroid relative to the center of mass.

A trial was categorized as a fall if, after the slip, the subject was completely and unambiguously supported by the harness. Trials during which subjects grabbed the safety harness rope were excluded from the analyses. Variables for which the between-group differences (young subjects who avoided falling versus older adults who fell) achieved significance using independent t-tests were entered in a stepwise discriminant analysis to determine the extent to which falls and recoveries could be correctly distinguished based on the selected variables. A logistic regression was used to characterize the extent to which slip-related fall-risk could be decreased based on the potential to improve these factors. This was determined by computing the change in the odds of a fall occurring after a slip given a physiologically-relevant (1 standard deviation) improvement in each independent variable. All statistics were performed using SPSS v. 12.0 and $p \leq 0.05$ was considered significant.

Results

Most of the older adults fell after the slip (18 of 21; 3 older adults avoided falling) whereas most of the young adults did not fall (30 of 35; 2 young subjects fell and 3 were excluded either because they noticed the slippery surface or grabbed the safety harness rope). The difference in fall incidence was not related to pre-slip walking velocity, the values of which did not differ significantly for older and younger adults (133±15 vs. 133±13 cm/s, respectively). The difference in fall incidence was also not related to the velocity of the slipping foot just prior to heel contact with the slippery surface (89.4±52.1 vs. 90.6±40.1 cm/s for older and younger adults, respectively); or immediately following heel contact with the slippery surface (137.4 ±71 vs. 122.6±59.2 cm/s for older and younger adults, respectively). Laterally- and backward-directed falls occurred with similar prevalence. Eight older adults fell primarily in the lateral direction and six fell primarily backwards. There were no adverse events during the course of the study.

The differences between the young and older adults were significant for seven of the independent variables. The older adults were less effective at arresting the motion of the slipping foot than the younger adults. The peak distance, velocity and acceleration of the slipping foot of older adults were 172% longer ($p<0.001$), 155% faster ($p<0.001$) and 151% larger ($p<0.001$) than that of the younger adults (Table 1). Furthermore, at the instant of recovery, the anteriorly- directed slipping foot velocity of the younger adults was slower than that of the COM. In contrast, the anteriorly-directed velocity of the slipping foot of older adults exceeded that of the COM ($p<0.001$).

The difference between young and older adults related to reaction time, i.e., the elapsed time between the slip onset and the instant at which the recovery foot contacted the ground, was not significant (age-related difference: 40 ms; $p=0.097$; Table 1). However, the older adults did placed their recovery foot on the ground more posteriorly to the COM than the young adults ($p=0.021$). The older adults also placed the recovery foot on the ground more laterally to the COM than the young adults ($p=0.005$). In light of the high incidence of laterally directed falls this variable was included in subsequent analysis.

The older adults were significantly less effective at arresting the trunk extension motion than the younger adults. At rec_{+133} the younger adults had not only arrested the trunk extension velocity but had reversed its direction. In contrast, at the instant of rec_{+133} the trunk of the older adults remained in extension ($p=0.05$).

Three of the seven independent variables for which the between-group differences achieved significance and entered into a stepwise discriminant analysis were selected in the final discriminant function. The variables were the anteriorly-directed velocity of the slipping foot relative to that of the COM, the laterally directed distance of the recovery foot placement relative to the COM, and the trunk extension velocity at rec_{+133}. The discriminant function was significant ($p<0.001$, Wilk's lamda = 0.35). The discriminant function correctly classified 93.8 percent of the recoveries of the young adults (28 of 30) and falls by older adults (17 of

18). A cross-validation in which each subject was classified using the discriminant function derived from all of the other subjects correctly classified 91.7% of the subjects.

Based on the Wald statistic, an indicator of the importance of a variable to the logistic model, the analysis revealed that both the slipping foot and the recovery foot contributed significantly and independently to the incidence of slip-related falls by the older adults. The logistic regression equation was:

[p]= 1/(1+exp(−1.932 + .037*[foot_COM_veloc] + 0.143*[lat_dist])) (Figure 1).

where "p" is the probability of recovery, "foot_COM_veloc" is the velocity of the slipping foot relative to the velocity of the COM at recovery (Wald=9.38; p=0.002), and "lat_dist" is the lateral placement of the recovery foot relative to the COM (Wald=4.90; p=0.027). The trunk extension velocity at rec_{+133} was not included in the final logistic regression (Wald=2.5; p=0.113).

The increase in the odds of a recovery was computed assuming that some form of intervention could decrease the velocity of the slipping foot relative to the velocity of the COM at recovery, and the lateral placement of the recovery foot relative to the COM of the older adults to zero (1.6 and 1.86 standard deviations, respectively). Reducing the velocity of the slipping foot relative to the body COM from 77.6 to 0.0 cm/s, would increase the odds of recovery by 16.6 percent. However, reducing the lateral distance of the recovery foot relative to the COM from 9.3 to 0.0 cm would increase the odds of recovery by 26.5 percent.

Discussion

The purpose of the present study was to determine how selected performance-related factors contribute to slip-related falls and to characterize the extent to which improvement of these factors could potentially decrease fall-risk due to a slip. The hypothesis that the ability to arrest the motion of the slipping foot would be associated with fall risk was supported. The hypothesis that the ability to rapidly lower the non-slipping limb to the ground posterior to the center of mass would be associated with fall risk was not supported. However, we serendipitously discovered that the ability to avoid a fall was associated with minimizing the lateral distance from the recovery foot to the vertical projection of the COM. Lastly, the hypothesis that the ability to arrest trunk extension after the slip would be associated with fall risk was not supported.

The results are consistent with previous research revealing the importance of limiting the distance through which the slipping foot travels [4] and previous research linking knee and hip flexor moments following slip onset with limited slipping foot motion [5]. In the present study, however, the slipping foot kinematics were less important than the extent to which the velocity of the slipping foot was smaller than the velocity of the COM at recovery [11]. The ability to assign a specific change in odds of a fall with a plausible improvement in this measure is clinically relevant. Because of its reliance on physiological factors such as reaction time, muscle strength/power, and multi-articular coordination, the velocity of the slipping foot relative to the velocity of the COM would seem to be malleable and directly accessible through intervention.

The results did not support the expectation that rapidly lowering the non-slipping foot to the ground may contribute to avoiding a fall. Although the reaction time did not differ between the older adults who fell and the younger adults who recovered, the faster slipping velocity of the older adults may have resulted in a greater likelihood of placing the recovery foot on the slippery surface. Because placement of the recovery foot did occur in many cases, the larger posterior distance from the recovery foot to the COM could not be translated into a successful recovery. The absence of friction, which allowed the continued forward motion of the recovery foot, precluded establishing a stable base of support from which adjustments to dynamic stability might have been initiated.

The significance of the lateral recovery foot placement relative to the COM was surprising insofar as it was not initially expected. However, this variable was associated with an approximately 60 percent larger influence on the odds of a slip-related fall than was the slipping foot-COM velocity relationship. Based on the apparent sensitivity of recovery to this variable we consider it to be of primal importance for a targeted intervention.

Although the expected differences between the trunk extension velocity of the older adults who fell and the younger adults who did not fall were significant, the ability to arrest the slip-induced trunk extension motion was not associated with the ability to avoid falling after a slip. The significant between-group differences were insufficient for inclusion in the final stepwise logistic regression function. It is possible that this variable may play a more prominent role under conditions in which the recovery foot is not placed on the slippery surface.

The results support previous observations that large backwards disturbances requiring stepping responses are more difficult to recover from than are large forward disturbances [12], especially for older adults. The 86% fall incidence by the older adults here was considerably higher than that of older adults following an induced trip [10], in which 36% fell. This tends to support the premise that the exercise/physical activity components of fall-prevention programs may be enhanced by considering the direction-related and disturbance-related specificity that can largely dictate feasible recovery solutions [13].

Our protocol involved a single slip which may be a limitation. However, considerable performance improvement occurs after a single trial in both young and older adults [1,14]. Thus, the element of surprise, considered crucial if a surrogate is to mimic the conditions associated with many, if not most slip-related falls in the community, is lost or considerably reduced after the first exposure. A second limitation of the present study is that the influence of upper extremity motion to the recovery response was not considered. Limited evidence suggests that the upper extremities may be helpful in recovering from a slip [6,15]. However, these protocols limited the slipping foot displacement and the extent to which a fall was possible. Thus, the contribution of the upper extremities to recovery from a slip, and whether young and older adults use the upper extremities similarly remain open, and important, questions. Lastly, the present study was limited to healthy and independently living older adults. However, older adults less physically robust than the present subjects would be expected to fare worse than the present subjects for whom the incidence of falls approached 90 percent.

The present work appears to be the first report of older adults subjected to unconstrained slips which were allowed to result in an approximated actual fall. Numerous studies have been reported in which older adults subjected to slips using translating platforms. These studies have documented control of head and trunk motion [16]; initial "fall" incidence and ability to adapt [17]; postural responses and corrective balance strategy [18]. However, slips induced with translating platform limit the slipping foot motion to that allowed by the platform, whereas slips induced with slippery surfaces result in significant medially- and laterally-directed slipping foot motion [19]. Thus, the extent to which findings from platform studies can be extended to the design and implementation of interventions is not known.

Older and younger adults have previously been subjected to slips on slippery surfaces in studies focused on the initial phase of the slip [20,21]. In these studies, the maximum slip distance analyzed was approximately 10 cm and subjects were allowed to descend up to 15 cm before engaging the safety harness. However, recovery from a slip is possible with slip distances as large as 32 cm [4] and in the present study one subject was able to avoid falling after their

COM descended 21.4 cm. The functional importance of these disparities is not known. However, 210 recognizing their potential importance may promote further discussion of and development of common criteria by which a laboratory falls, losses of balance, and stepping responses may be defined and distinguished.

In summary, given the premise that characterizing biomechanical mechanisms of locomotion-related falls can inform fall-prevention interventions, we compared the successful recoveries of young adults to the falls older adults following induced slips. The outcome of the induced slip was associated with two lower extremity performance variables: the ability to limit the slipping foot velocity relative to the COM velocity, and the lateral distance between the recovery foot placement and the COM. The strength of the relationship between these variables and the odds of falling, and the direct accessibility of the variables to intervention, strongly suggests that slip-related fall risk can be reduced. The relationship between fall-related hip fracture and exposure of the greater trochanter to impact motivates further study of mechanisms of the incidence of laterally-directed falls. The 27% decrease in the odds of a slip-related fall based on a realistically attainable improvement in the lateral placement of the recovery foot relative to the COM is a compelling rationale for further study.

Acknowledgement

Supported by the National institutes of Health, R01AG16778

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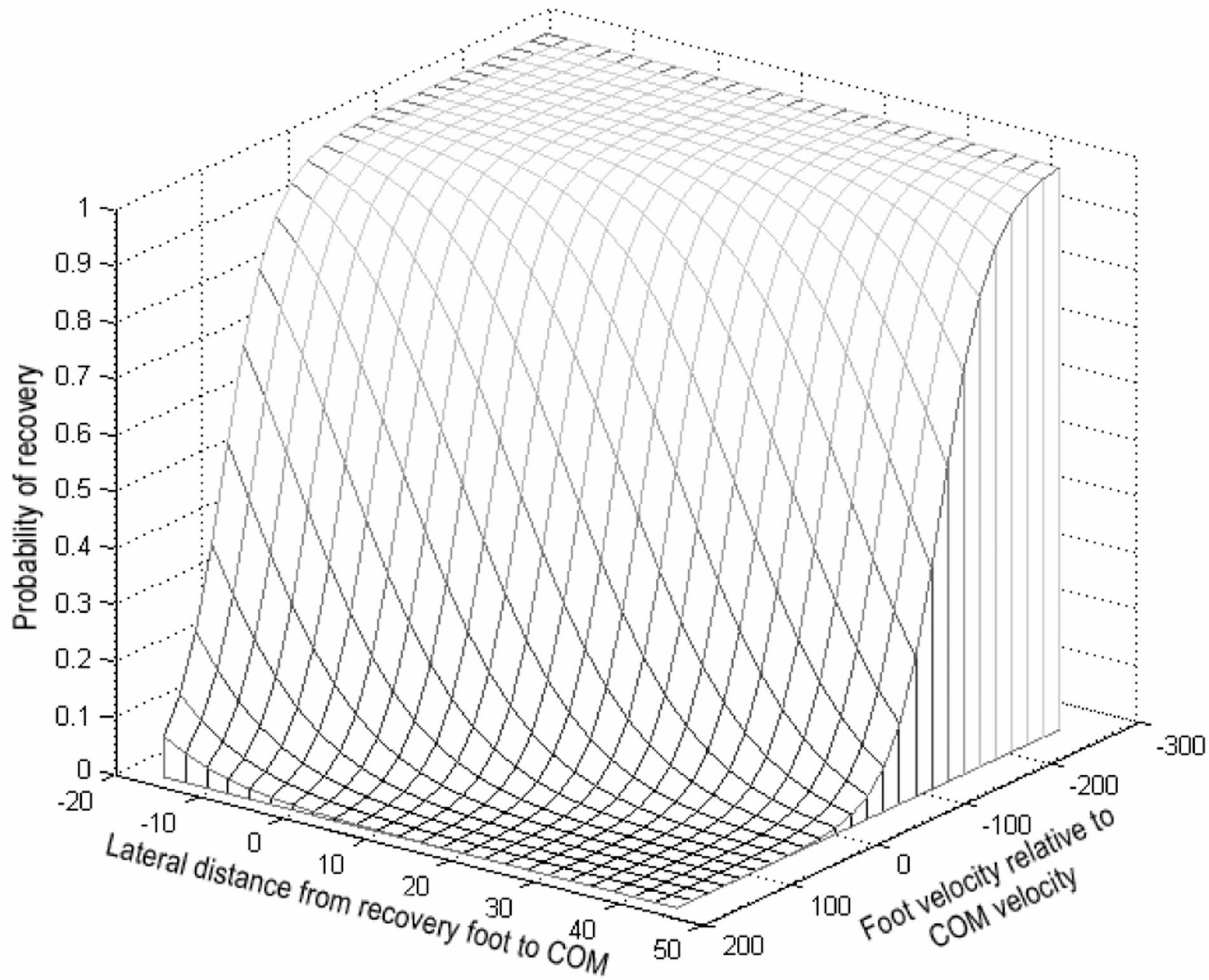

Figure 1.

Surface plot of the logistic regression function revealing the complex interaction between the two independent variables and the probability of recovery following an induced slip.

Table 1

Mean (SD) for young subjects who recovered versus old subjects who fell. 95% Confidence Interval values are for the difference between the two groups.

	young non-fallers (n=30)	old fallers (n=18)	95% CI
At slip initiation			
pre-slip walking velocity (cm/s)	133 (15)	133 (13)	−8.9 – 8.9
pre-slip heelstrike velocity (cm/s)	89.4 (52.1)	90.6 (40.1)	−29.3 – 31.7
post-slip heelstrike velocity (cm/s)	137.4 (71.0)	122.6 (59.2)	−58.3 – 28.6
During slip			
slip distance (cm)	19.6 (13.7)	39.8 (11.1)	12.6 – 27.9
peak slip velocity (cm/s)	139.5 (63.8)	236.5 (33.0)	68.7 – 125.2
peak slip acceleration (cm/s2)	1207.9 (702.0)	2074.7 (657.5)	455.1– 1278.4
At/after recovery			
trunk extension velocity at recovery+133 ms (deg/s)	−17.0 (112.4)	47.7 (104.1)	0.9 – 130.4
slip foot velocity relative to COM velocity (cm/s)*	−50.9 (77.7)	77.6 (48.6)	91.9 – 165.3
reaction time (s)	0.27 (0.06)	0.31 (0.17)	−0.10 – 0.02
posterior distance from recovery foot to COM (cm)	−2.3 (37.3)	20.2 (17.3)	5.7 – 39.6
lateral distance from recovery foot to COM (cm)*	0.7 (11.6)	9.3 (5.0)	3.7 – 13.5

* variable included in logistic regression function