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Foot displacement but not velocity predicts the outcome of a slip induced in young subjects while walking

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Abstract

The purpose of the present study was to induce slips in healthy subjects as a means to determine if recovery from an induced slip is possible under conditions in which the displacements and velocities of the slipping foot exceed the generally accepted limits of 10 cm and 50 cm/s, respectively, and to determine if there are gait-related variables that predispose an individual to falling after a slip. Thirty-three young and barefoot adults, protected by an instrumented safety harness, were subjected to a single slipping trial following a series of unperturbed walking trials. The slip was induced when the bare foot contacted a vinyl sheet coated with mineral oil. Lower extremity kinematics were acquired using a video-based motion capture system. Fourteen and 12 subjects could be unambiguously categorized as having fallen or recovered, respectively. Four variables demonstrated significant between-group differences and two were used to compute the probability of the slip outcome using logistic regression. The variables were the displacement of the foot during the slip and the angle of the shank relative to the ground at the instant of ground contact just prior to the slip. Separate univariate logistic regressions using each variable were significant and correctly classified about 70% of the slip outcomes. The results demonstrated that previously published values for the displacement and velocity of the slipping foot, 10 cm and 50 cm/s, respectively, may not accurately represent the upper limits beyond which recovery is not possible. The results also demonstrated that heel-strike angle, reflective of stride length, exerts a significant influence on the outcome of a slip. © 2000 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Epidemiological studies confirm that slip-related injuries can be extremely serious. In particular, slip-related falls can be especially dangerous for older adults. Up to 25% of fall-related hip fractures in older adults result from slips (Cumming and Klineberg, 1994; Nyberg et al., 1996) and 66% of fall-related hip fractures occur on wet or slippery surfaces (Norton et al., 1997). Characterizing the biomechanical factors that determine the outcome of a slip may provide insight to the physiological variables that limit the ability to prevent a fall after a slip.

There are a small number of published biomechanical studies of slip-related falls. These studies suggest that the displacement of the slipping foot and the velocity of the slipping foot are determinants of whether an induced slip will result in a fall or whether dynamic stability can be restored (Perkins, 1978; Perkins and Wilson, 1983; Lanshammar and Strandberg, 1985; James, 1990). Based on the work of these authors, it seems to have been generally accepted that a fall will occur as a result of a slip if, during a slip, the displacement of the slipping foot exceeds 10 cm and if the peak velocity of the slipping foot exceeds 50 cm/s. However, qualitative observation and experience suggests that recovery of dynamic stability is possible if these boundaries are exceeded. The purpose of the present study was to induce slips in healthy young subjects and determine if subjects that recovered after the slip could be discriminated from those subjects who fell after the slip using selected lower extremity kinematics. Two experimental questions were asked: (1) is recovery from an induced slip possible under conditions in which the displacements and velocities of the slipping foot exceed 10 cm and 50 cm/s, respectively, and (2) are there

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gait-related variables that predispose an individual to falling as a result of a slip?

2. Methods

Thirty-three healthy volunteers subjects (21 men) were paid for participating in this institutionally approved study (age: 26.6 ± 3.9 years; height: 170.7 ± 7.9 cm; mass: 71.8 ± 13.8 kg). The purpose and general methods of the experiment were explained to the subjects, who provided written informed consent.

Subjects were placed in a safety harness (Pavol et al., 1999a, b) that was attached to an instrumented dynamic rope. The dynamic rope was secured to a sliding bracket on a steel rail mounted to the laboratory ceiling. The length of the dynamic rope was adjusted so that during a slip-related fall the subject's hands would not contact the floor. A strain gage load cell (Omega Engineering, Inc., Stamford, CT) at the top of the dynamic rope allowed the force applied to the rope to be recorded. The recorded force was sampled at 500 Hz. A second rope, attached to the sliding bracket, was pulled by an investigator, positioned beyond the gait path, to keep the dynamic rope just ahead of the subject while walking.

The barefoot subject walked on a carpeted walkway approximately 10 m long and 1 m wide. Subjects wore a hockey helmet with a plastic face mask during all trials. Opaque tape was applied to the face mask, thus blindfolding the subject during the trials. With practice (5–10 trials) most subjects could walk in a straight path. Some subjects required verbal directional cues to assist their walking in a straight path. Following the practice trials, subjects were warned that they would be slipped during a subsequent, but unspecified trial. The subjects were instructed to attempt to recover their balance and continue walking normally if they slipped. The subjects were instructed not to grab the dynamic rope if they slipped. All subjects complied with this instruction. About half of the subjects were instructed to walk at a self-selected comfortable pace. The other half of the subjects were instructed to walk at a self-selected quick pace. This was to provide a wider range of walking velocities.

The slip was induced by the bare foot contacting a slippery surface composed of a vinyl sheet that had been coated with mineral oil. The vinyl sheet was placed over a forceplate (AMTI, Newton, MA) approximately 4 m in front of the subjects' starting position. The maximum length of the vinyl surface was 90 cm and the width was 1 m. The maximum distance through which the subject's foot could slip along the vinyl sheet was dictated by the placement of the foot on the vinyl. The vinyl sheet was in place only during a single randomly selected trial in which a slip was induced. The subject was unaware of the specific step in the gait path during which the slip would occur. Sounds associated with preparation for the slip trial were masked by continuous loud music.

Lower extremity kinematics were acquired using a 6-camera video-based motion capture system operating at 60 Hz (Motion Analysis System, Santa Rosa, CA). Retro-reflective hemispherical markers were placed over the sacrum and bilaterally on the lateral femoral epicondyles, lateral malleoli, posterior calcaneii, and fifth metatarsal heads. The position data of the retro-reflective markers were filtered with a fourth-order, zero-lag, Butterworth filter (cutoff frequency = 9 Hz).

Slip onset was defined as the instant of heel-strike with the vinyl. For the first 12 subjects, for whom no force plate data were available, slip onset was manually determined using animations of the slip and the vertical position, forward velocity and forward acceleration of the heel marker. For the remaining subjects, data from the force plate, sampled at 500 Hz., was used to identify the instant of heel contact. The accuracy of the former method was validated by the trials using the force plate data. The end of the slip was manually determined and defined as the instant at which the heel marker of the slipping foot either came to a stop or was displaced vertically from the ground. The following sagittal plane kinematic variables were derived. Slip duration (s) was the difference between slip onset time and the end of slip. Slip displacement (cm) was the forward horizontal displacement of the heel marker of the slipping foot during the slip duration. The average and peak velocity of the slipping foot (cm/s) and peak acceleration of the slipping foot (cm/s^2) were computed for the slip duration. Velocity was derived from the smoothed position data using a finite differences algorithm. Acceleration was similarly derived from the smoothed velocity data. The average gait velocity (cm/s) for steps occurring within the calibrated volume but preceding the heel-strike of the slip onset and the instantaneous gait velocity at heel-strike (cm/s) were represented by the forward horizontal motion of the sacrum marker. The average forward horizontal velocity of the sacrum marker during the slip (cm/s) was determined. The heel strike angle (deg) was calculated as the angle formed between the shank and the floor at heel-strike just prior to the slip. The shank orientation was defined by the ankle and knee marker positions.

The signal from the safety harness load cell was used to assist classification of each slip outcome as a recovery, fall, or rope-assist using a previously described method (Pavol et al., 1999a, b). The signal from the safety harness load cell was low-pass filtered at 8 Hz using a fourth-order, zero-lag, Butterworth filter. The filtered signal was integrated for one second following the slip onset, and expressed as a percentage of the subject's body weight. Trials in which both feet left the ground or trials during which the peak force exerted on the load cell exceeded 50% of a subject's body weight were classified as falls.

The distribution of the subjects who exerted less than 50% of body weight on the rope exhibited two apparent modes separated by a distinct gap at 8% body weight × second. Based on this result, subjects having integrated forces of less than 8% body weight × second were classified as recoveries. Individuals whose peak rope force was less than 50% but whose integrated force following slip onset exceeded 8% body weight × second were classified as rope-assisted. Rope-assisted trials were excluded from further analyses.

The initial statistical analysis compared the group of subjects whose slip outcomes were classified as falls to those whose outcomes were classified as recoveries using independent t-tests with statistical significance at $p \leqslant 0.05$. The relationships between the dependent variables demonstrating significant between-group differences and the likelihood of falling or recovering from the slip were investigated using logistic regression. All statistical tests were performed using SPSS 7.0.

3. Results

Recovery from an induced slip was possible when the displacement of the slipping foot exceeded 10 cm. Of the subjects that fell ($n = 14$), all had displacement of the slipping foot greater than 27 cm (Table 1). However, of the subjects that recovered ($n = 12$), three subjects had slip displacements larger than 31.8 cm.

Recovery from an induced slip was possible when the velocity of the slipping foot exceeded 50 cm/s. Not surprisingly, the average velocity of the slipping foot was significantly larger in the subjects that fell ($p = 0.01$) compared to the subjects that recovered. However, on average, the subjects who recovered had average velocities of the slipping foot that were twice that of the 50 cm/s benchmark (Table 1).

The statistical analysis revealed that displacement, but not velocity, of the slipping foot slip was a determinant of whether the slip resulted in a fall. Four kinematic variables demonstrated significant between-group (fall vs. recovery) differences (Table 1). Not unexpectedly, some of these variables were strongly correlated (Table 2). The correlation between slip displacement and average velocity of the slipping foot was significant. However, slip displacement was not significantly correlated to the heel-strike angle. Therefore, slip displacement and heel-strike angle were selected for analyses using univariate logistic regression. The logistic regression performed using slip displacement was significant ($p = 0.002$) and cor-

Table 1
Subjects that fell after the slip and subjects who recovered after the slip differed to the greatest extent relative to kinematics of the slipping foot as opposed to pre-slip gait[a]

	Falls	Recoveries	p-value[b]
Slip duration (s)	0.28 ± 0.11 (0.15-0.55) $n = 14$	0.18 ± 0.11 (0.1 - 0.38) $n = 12$	0.03
Slip displacement (cm)	47.66 ± 17.49 (27.12-76.98) $n = 14$	22.37 ± 20.05 (2.27-65.99) $n = 12$	0.003
Average velocity of slipping foot (cm/s)	175.85 ± 42.58 (105.75-273.51) $n = 14$	116.44 ± 60.93 (22.66-209.65) $n = 12$	0.01
Peak velocity of slipping foot (cm/s)	239.44 ± 56.79 (181.51-385.30) $n = 13$	186.53 ± 86.05 (43.45-320.82) $n = 12$	> 0.05
Peak acceleration of slipping foot (cm/s^2)	2818.95 ± 913.30 (1484.18-4643.66) $n = 12$	2155.94 ± 1389.43 (− 420.48-3940.31) $n = 12$	> 0.05
Average gait velocity preceding heel-strike (cm/s)	135.76 ± 22.07 (96.36-172.70) $n = 14$	138.15 ± 32.87 (62.27-186.69) $n = 12$	> 0.05
Instantaneous gait velocity at heel-strike (cm/s)	158.69 ± 30.57 (107.79-209.35) $n = 13$	158.30 ± 37.39 (69.54-214.29) $n = 12$	> 0.05
Average forward velocity of the sacrum marker during slip (cm/s)	139.20 ± 24.19 (100.56-183.99) $n = 13$	149.42 ± 37.26 (70.64-210.01) $n = 12$	> 0.05
Heel-strike angle (degrees)	72.81 ± 4.88 (62.85-81.15) $n = 14$	76.72 ± 3.63 (70.75-81.95) $n = 12$	0.039

[a] Results of independent t-tests comparing subjects who fell and those who recovered following an induced slip. Values are given as mean ± standard deviation. Range of values is given in parentheses. The "n" value represents the number of subjects for which corresponding data were available.

[b] Results of independent t-tests.

Table 2
The pattern of significant correlation coefficients of the variables that demonstrated between-group differences resulted in the selection of heel-strike angle and slip displacement for further analysis

	Slip Displacement	Slip Duration	Average Slip Velocity	Heel-Strike Angle
Slip displacement	1.0			
Slip duration	0.80[a]	1.0		
Average slip velocity	0.70[a]	– 0.20	1.0	
Heel-strike angle	– 0.31	0.02	– 0.62[a]	1.0

[a] Denotes significance, $p < 0.05$.

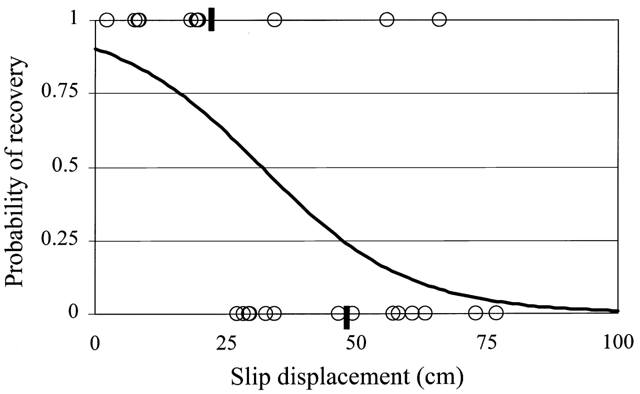

Fig. 1. The logistic regression in which the probability of recovering from an induced slip was predicted using the slip displacement, measured in cm correctly classified about 70% of the slip outcomes. The logistic equation, $\text{prob(recover)} = 1/(1 + e^{-(2.2327-(0.0702\cdot \text{slip displacement}))})$ was significant and correctly classified 73% of the subjects. Data points for individual subjects are plotted as open circles, with subjects who recovered and those who fell as a result of the slip shown on the upper and lower horizontal axes, respectively. The thick vertical lines on the upper and lower horizontal axes represent the mean values for each group.

rectly classified 73% of the subjects (10/14 falls and 9/12 recoveries, Fig. 1). A one standard deviation reduction in slip displacement (22.38 cm, $n = 26$) increased the odds of recovering from a slip by a factor of 4.8.

Heel-strike angle, reflective of the stride length, also was a significant determinant of whether the slip resulted in a fall. The univariate logistic regression performed using the heel-strike angle was significant ($p = 0.024$) and correctly classified 69% of the subjects (10/14 falls and 8/12 recoveries). An increase of heel-strike angle by one standard deviation (4.7°, $n = 26$) increased the odds of recovering from a slip by a factor of 2.91.

When tested in a multivariate model, slip displacement was found to be the singular determinant of whether the slip resulted in a fall. Based on the potential for a statistical interaction, a forward multiple logistic regression was performed using heel-strike angle, slip displacement and the heel-strike angle by slip displacement interaction. Heel-strike angle and the heel-strike angle by slip displacement interaction failed to meet the criterion for inclusion (i.e., a significant change in the log likelihood when adding the variables to the model). Therefore, the results of this multivariable analysis were identical that of the univariate logistic regression in which only slip displacement was considered (Fig. 1).

4. Discussion

We induced slips in healthy young subjects to determine if recovery from an induced slip is possible when the displacements and velocities of the slipping foot exceed 10 cm and 50 cm/s, respectively, and to determine if gait-related variables predispose an individual to falling as a result of a slip. We found that recovery from an induced slip is possible if the slipping foot has a displacement and velocity in excess of 10 cm and 50 cm/s, respectively. Therefore, these values do not accurately represent the upper limits for recovery.

The results also demonstrated that a small heel-strike angle, reflective of a long stride length, predisposed an individual to falling after the slip. Heel-strike angle and slip displacement were not strongly or significantly correlated to one another ($r = -0.31$, $p > 0.05$). The multiple variable logistic regression identified slip displacement as the more important of the two variables relative to predicting the probable slip outcome. Nevertheless, there is overlap of the slip displacement values of the subjects who recovered and the subjects who fell after the slip suggesting the influence of other variables that were not investigated (Fig. 1).

Slip displacement greater than 10 cm has previously been implicated as a factor contributing to slip-related falls (Perkins, 1978; Strandberg and Lanshammar, 1981). However, in the present study, 7 of 12 subjects who recovered had slip displacements larger than 18 cm. Furthermore, slip displacements as large as 31.8 cm. were predicted to be unlikely to result in a fall based on a probability level of 0.5 (Fig. 1). These findings suggest that 10 cm is too conservative an estimate for the maximum foot displacement during a slip from which recovery is possible.

Peak velocity of the slipping foot greater than 50 cm/s has also been associated with falls after a slip (Strandberg and Lanshammar, 1981). As a group, subjects who fell in the present study exhibited peak velocities nearly five times larger than this value. The peak velocity of the slipping foot of 10 of 12 subjects who recovered was greater than 100 cm/s and only a single subject had a peak velocity of the slipping foot of less than the 50 cm/s.

Between-study methodological differences may have contributed to these disparate findings. Subjects in Perkins (1978) and Strandberg and Lanshammar (1981) wore shoes and were fully aware of the slippery surface on which they were to step. In our study subjects were barefoot, prevented from actually seeing the slippery surface, and were unaware of its exact location. The studies of Perkins (1978) and Strandberg and Lanshammar (1981) used six and four subjects, respectively. The subjects were slipped at least 20 times (Perkins, 1978) and ranging from 7 to 62 times (Strandberg and Lanshammar, 1981; estimated from text). The present study had a much larger sample size but each subject was slipped only once. The extent to which subjects may have relied on the harness rope in Perkins (1978) and Strandberg and Lanshammar (1981) can not be determined. Indeed, the manner in which the term "fall" was defined in those studies can not be determined. We classified the slip outcome based on the force measured in the safety harness rope. These between-study methodological differences probably contributed to the different results. The different results point to the importance of further systematic study if the mechanisms of slip-related falls are to be better understood and if means to reduce the incidence of slip-related injuries are to be designed.

There is a public sentiment that slip-related falls and injuries are unavoidable (Leamon and Murphy, 1995) but the present study suggests that the incidence of slip-related falls can be diminished. Awareness of a potentially dangerous situation and appropriate modification of one's gait pattern clearly offers effective protection against falling as a result of a slip. Andres et al. (1992) reported that subjects negotiating a slippery surface reduced their stride length. This corresponds to an increased heel-strike angle and the present results demonstrate that this voluntary gait adjustment significantly increases the likelihood of recovery after a slip. However, whereas walking velocity is a key factor contributing to a fall after being tripped (Pavol et al., 1999b), the present data do not suggest the importance of walking velocity as a crucial gait variable to be modified. The 2% difference between the walking velocity of those subjects who fell and those who recovered was not significant and, we believe, not biomechanically important. However, the logistic regression revealed that taking shorter steps, that is, increasing the heel strike angle, increases the likelihood of recovering one's balance after a slip.

Recognizing an impending danger of slipping and engaging appropriate gait strategies is not always possible. Collectively, our results and the results of Perkins (1978) and Strandberg and Lanshammar (1981) indicate that once a slip is initiated, reducing the distance through which the slipping foot travels reduces the likelihood of falling. Is it is possible to affect slip displacement? Footwear may influence slip displacement and slip velocity under some conditions. The dimensions of the slippery surface can limit the slip displacement and slip velocity and the deceleration of the slipping foot caused by the increased surface frictional qualities marking the end of the slippery surface may actually assist recovery. However, the only available physiological mechanisms are reflexive, automatic, and voluntary processes. Reflexive muscle activation associated with slips can arise from visual, vestibular, and somatosensory inputs. Reflexive activation is effective in restoring postural control after a slip induced by having the foot displaced 10 cm and constant velocity of 40 cm/s. (Tang and Woollacott, 1998). Presently, it is unknown if the reflexive activation could effectively restore postural control under conditions having larger slip displacement and slip velocity. However, Tang et al. (1998) reported that the nervous system can acquire an appropriate motor response after exposure to repeated trials of slipping. The neuromechanical outcome of exposure to repeated trials of slipping seems worthy of further systematic investigation.

There are some experimental issues that may have influenced the outcome of the study and should be considered in other protocols that may develop. First, it is not possible to know how the laboratory slipping responses differed from those that occur in a non-laboratory environment. Aside from a video-monitoring study (Holliday et al., 1990), there are no publicly available biomechanical data from slip-related falls in the community. This represents a formidable obstacle. Second, the extent to which walking with obstructed vision may have affected the biomechanics of both the slip and the recovery effort is not known. However, we recognize that the alertness, or central set (Horak et al., 1989) of the subjects was likely increased during the experiment and that increased central set exerts a large influence on spinal reflexes (Beckley et al., 1991) and automatic motor responses (Horak et al., 1989). The decision to implement the method of obstructing vision was based on improving the element of surprise and avoiding the expected gait changes if the subjects could see the slippery surface. This experimental factor may be adequately addressed by reconsidering the mechanism used to induce the slips. Finally, it is possible that the safety harness may have affected the responses to the slips. However, we believe it is unlikely that subjects would incorporate an unfamiliar device (the harness) into their responses following the slip.

In summary, the sensitivity of correct categorization of recovery efforts following a slip induced in young healthy adults was about 70% using two variables. Prior to the slip, a small heel-strike angle is associated with falls after slipping. Thus short steps increase the likelihood of recovery after a slip. Once a slip is initiated, the variable that best describes the probable outcome is the slip displacement. This finding is somewhat consistent with those of other authors, although the differences in the size of the slip displacement identified as important to the outcome merit further study.

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