Ergonomics
Vol. 49, No. 4, 15 March 2006, 329–343

Taylor & Francis
Taylor & Francis Group

Gait parameters as predictors of slip severity in younger and older adults

B. E. MOYER*, A. J. CHAMBERS, M. S. REDFERN and R. CHAM

Human Movement and Balance Laboratory, Department of Bioengineering, 749 Benedum Hall, University of Pittsburgh, Pittsburgh, PA, 15260 USA

This study investigated the association between slip severity and pre-slip gait characteristics of younger and older subjects. Sixteen younger and eleven older healthy adults walked onto an unexpectedly slippery surface. Slip severity was categorized as either hazardous or non-hazardous using a 1.0 ms peak slip velocity threshold. The results showed that hazardous slips were associated with greater step lengths (normalized by leg length) (SLR), larger and more rapidly changing foot–floor angles (FFA) at heel strike, and increased cadence across the two subject groups. Older subjects were found to walk with shorter SLR and with smaller and more slowly changing FFA at heel strike compared to younger subjects. However, both younger and older subjects experienced hazardous slips at the same rate. A logistic regression model relating SLR and cadence to slip severity predicted that increased SLR and decreased cadence would result in increased probability of hazardous slip ($R^2 = 0.45$, $\chi^2 = 15.30$, $p < 0.01$). A second logistic regression model relating FFA with slip severity predicted that increased FFA would result in increased probability of hazardous slip ($R^2 = 0.53$, $\chi^2 = 16.55$, $p < 0.01$). These results suggest that gait characteristics prior to foot contact play an important role in the severity of an ensuing slip. The finding that older adults experienced hazardous slips at the same rate as young adults even though their SLR and FFA are smaller suggests that age is also playing a role in other aspects of postural control that impact slip severity.

Keywords: Slips; Falls; Gait; Balance; Biomechanics; Ageing

1. Introduction

Slips were found to be the most frequent event leading to fall and overexertion-related injuries in the Swedish labour force (Courtney *et al.* 2001) and were the most common fall-initiating event for employees in the UK (Gao and Abeysekera 2004). The US National Health Interview Survey questionnaire administered by the National Center for

*Corresponding author. Email: bmoyer@pitt.edu

Ergonomics
ISSN 0014-0139 print/ISSN 1366-5847 online © 2006 Taylor & Francis
http://www.tandf.co.uk/journals
DOI: 10.1080/00140130500478553

Health Statistics in 1997 revealed that a clear majority (64%) of work-related falls were attributable to slipping, tripping or stumbling and indicated that 43% of occupational same-level fatal falls were most commonly triggered by a slip (Courtney *et al.* 2001). According to the Bureau of Labor Statistics (2003), nearly 30% (28.7%) of workers who sustained injuries from slips and/or falls missed 31 d of work or more. Further, 14% of accidental deaths in the workplace were reportedly caused by falls (Bureau of Labor Statistics 2004a). In addition to the risk of fall-related injuries and fatalities, slip recovery efforts have been shown to contribute to high rates of overexertion injuries (Courtney and Webster 2001). De Laet and Pols (2000) estimated that the annual direct cost of all fall-related occupational injuries in the US alone was approximately six billion dollars.

The risk of slip and fall accidents increases with age. A ten-fold increase in the incidence of falls was reported in the elderly (65 + years) compared to younger individuals (16–64 years) (Thomas and Brennan 2000) and Lloyd and Stevenson (1992) indicated that while slips and trips caused 32% of falls for young people, 67% of falls for the elderly were initiated by slips. Falls on the same level caused roughly 20% of all injuries to older workers as compared to around 10% for the general population with 'floor and ground surfaces' listed as the most common source of non-fatal injuries among workers in the 55 year and older age group (Personick and Windau 1995). In 2004, over one-third (39%) of the occupational fatal fall victims were 55 years and older (Bureau of Labor Statistics 2004a), more than double that age group's share of the work force (16%) (Bureau of Labor Statistics 2004b).

Just as the risk for slips and falls increases with age, so too does the severity of the outcome of these accidents. Falls are often listed among the leading causes of serious unintentional injuries, disability and death among older adults (King and Tinetti 1995, 1996, Rivara *et al.* 1997, Luukinen *et al.* 1999, De Laet and Pols 2000). Approximately 65% of all serious injuries (Injury Severity Score > 15) and 55% of deaths were attributed to falls for patients aged 65 years and over, compared to 11% and 7.5% in the younger population, respectively (Sterling *et al.* 2001). Fatality rates from falls showed a significant increase for workers as young as 45 to 54 years old (Agnew and Suruda 1993). Specifically, nearly half of the fatal falls in the US workforce occur in adults aged 45 years and older (Tinetti and Williams 1997). Additionally, Personick and Windau (1995) suggested that older workers are at a greater risk of non-fatal injuries resulting from slips, even those not resulting in falls, due to overexertion during recovery attempts.

There has been some disagreement in the literature regarding the characteristics of a recoverable slip. Perkins (1978) commented that longer slip distances (Sd) and slip velocities exceeding gait speed (GS) increased the likelihood for loss of balance. Perkins also characterized slips as full or 'macro-slips' if the slipping distance was greater than 10 cm. Leamon and Li (1990) used a 3 cm threshold to differentiate full or macro-slips from smaller slips. Strandberg and Lanshammar (1981) suggested that Sd of greater than 10 cm and slip velocities greater than 0.5 ms typically resulted in falls and reported a continuum of slip severity (mini-, midi- and maxi-slips) correlated to Sd and peak slip velocity (PSV). Research by Cham and Redfern (2002b) indicated that falls were typically associated with Sd greater than 10 cm and peak slip velocities greater than 0.8 ms. Other research results suggest that these velocity and distance thresholds may be too conservative; that is; individuals are able to avoid falls for slips with peak slip velocities far exceeding 1.0 ms (Brady *et al.* 2000), but still indicate that longer, faster slips are more likely to result in falls. Lockhart *et al.* (2003) reported slip severity thresholds of 1.44 and 1.07 ms for younger and older adults respectively walking on a motor-oil-contaminated surface. Regardless of whether a Sd or slip velocity threshold is chosen, it seems

reasonable to define slip severity based on one of these slip magnitude measures in that longer, faster slips have been associated with an increased risk of falls.

Why, given the same environmental conditions, are some slips unlikely to lead to falls ('non-hazardous slips (NH slips)', short slipping distance and slow slipping velocity), while other slips are much more likely to lead to falls ('hazardous slips (H slips)', greater slipping distances and faster slipping velocity)? Although there are clearly other contributors (environmental conditions, subject mindset, etc.), two general subjective factors (which are clearly not independent factors) likely contribute to slip severity are: (1) the state of the body and, perhaps more importantly, of the perturbed foot at slip initiation; (2) corrective reactions generated in response to slipping.

This paper focuses on the first group of factors, specifically walking speed, step length, foot angle at heel strike (HS), heel velocity and cadence, as these have previously been implicated as affecting PSV (Strandberg and Lanshammar 1981) and thus influencing fall potential (Brady *et al.* 2000, Smeesters *et al.* 2001, Cham *et al.* 2002, Marigold and Patla 2002). However, these variables have not previously been studied in a systematic way.

The goal of this research project was to investigate the relationship between slip severity and general gait characteristics, including initial conditions at HS onto an unexpectedly slippery floor. This relationship was evaluated for younger and older subjects. The underlying hypothesis of this study was that pre-slip parameters would differentiate H from NH slips classified using a peak slipping velocity threshold of 1 ms. Because these initial condition variables may be modified via training, a greater understanding of the impact of these variables on slip severity may help to reduce fall incidents precipitated by slips.

2. Methods

This study included 11 older individuals aged 55 to 67 years and 16 younger individuals aged 20 to 33 years (their details are shown in table 1). Written informed consent, approved by the University of Pittsburgh Institutional Review Board, was obtained prior to participation. Exclusion criteria included a clinically significant history of neurological, orthopaedic, cardiovascular or pulmonary abnormality as well as any other difficulties hindering normal gait. In addition, subjects were excluded if a clinical neurological examination revealed abnormalities that might affect balance.

Subjects walked along an 8.5 m long vinyl-tiled walkway. An eight M2-camera Vicon® (Vicon Peak–UK) 612 motion measurement system recorded three-dimensional motion data at a sampling rate of 120 Hz from 79 reflective markers placed on the body and shoes. Ground reaction forces were measured on two Bertec® (Bertec Corporation, OH, USA) type 4060a force plates embedded into the walkway. The surface of the left/leading foot force plate was extended such that its dimensions were 0.75×0.4 m. The forces were

Table 1. Subject details.

			Age (years)		Height (cm)		Weight (kg)	
	Female	Male	Mean	SD	Mean	SD	Mean	SD
Young	9	7	23.5	3.2	171.2	8.9	67.6	10.5
Old	7	4	60.9	4.0	166.2	8.1	78.2	10.9

recorded at a sampling rate of 1080 Hz and synchronized with the motion data. This paper describes a subset of the recorded data, including foot kinematics at HS and general gait biomechanical variables. Markers used in this analysis include those on the right and left hind foot segment (figure 1).

All participants wore the same brand/model of polyvinyl chloride hard-soled shoes. A harness system connected to an overhead trolley protected subjects from ground contact injuries. The harness caught the subject in the event of an irrecoverable balance loss, but did not impede walking or slipping.

Participants were all exposed to the same protocol. Prior to actual data collection, subjects were allowed to practise walking along the gait path while the starting position was adjusted such that the participant appropriately hit each force plate with one, and only one, foot (right foot on first plate, left foot on second plate). The lights were then dimmed to prevent the subject from discerning the potential application of the slippery contaminant on the floor and additional practice trials were conducted. Participants were instructed to walk as naturally as possible at a self-selected comfortable pace throughout the experiment.

Prior to each recorded trial, subjects walked to the start of the gait path, faced away from the walkway and listened to music via headphones for 1 min. The music was intended to disguise any audible hints of contaminant application. At the end of each 1-min waiting period, subjects were asked to turn around, to verify their set starting point, to focus on a target placed at eye-level on the far wall and to wait for a researcher to signal them to start the trial.

To ensure that participants walked as naturally as possible, they were informed that the first few trials would be non-slippery. Two or three dry trials were then collected ('baseline dry'), ensuring that appropriate foot contact was maintained. Then, without the participant's knowledge, a diluted glycerol solution (75% glycerol, 25% water) was applied to the left/leading foot force and another gait trial was conducted ('unexpected

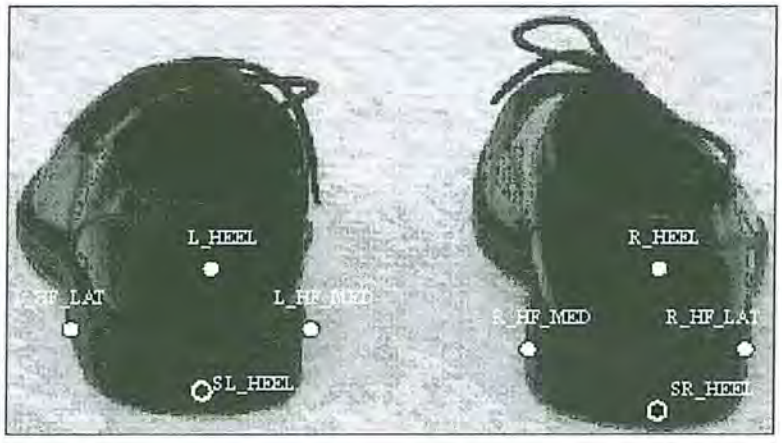

Figure 1. Reflective marker placement. Filled circles (L_HEEL, L_HF_LAT, L_HF_MED, R_HEEL, R_HF_LAT, and R_HF_MED) represent markers that remained on shoes during dynamic trials and hollow circles (SL_HEEL and SR_HEEL) represent markers removed after static trials and virtually recreated from other markers during dynamic trials.

slip'). The coefficients of friction of the shoe–floor interface were 0.53 and 0.03 for the dry and slippery surfaces, respectively, as measured with the English XL VIT Slipmeter® (according to standard ASTM F1679; American Society for Testing and Materials 1996).

Variables of interest were estimated from the force plate and marker data. HS and toe off were determined via analyses of changes in vertical ground reaction forces compared to no load levels. HS was identified as the first data point larger than the mean plus 1 SD as determined from a 1 s average unloaded measurement. This chosen point was accepted as HS if and only if the normal force remained larger than 1 SD and increased to 3 SD. HS determination was verified both by visual inspection of the normal force trace and through inspection of the heel marker vertical displacement. Toe off was determined using the same method but with the data reversed in time.

Kinematic variables were calculated from the marker data using a customized routine in Vicon BodyBuilder® (Oxford Metrics, Oxford, UK). A heel marker was not used during gait trials because it was easily knocked off by contact with the floor. Instead, a rigid-body analysis technique using static calibration markers was used. The location of a heel marker in the local frame of the hind foot segment was recorded along with all other markers during a standing calibration trial. This information was used to reconstruct the trajectory of the heel marker during walking without attaching a physical marker to the heel. The foot–floor angle (FFA) and its derivative (the rate of change of FFA at HS; FFAS) were estimated as the angle between the hind-foot segment and the floor. Other variables of interest, calculated using the heel marker (SL_HEEL, figure 1), were cadence (steps/min), vertical and horizontal (square root of the sum of the squares of back-to-front and side-to-side) velocity of the left heel at HS (V_VEL and H_VEL–ms), and step length normalized to leg length, i.e. 'step length ratio' (SLR–mm of left leg length). Sd (cm) describes the heel marker's travel distance along the floor from HS (Gronqvist *et al.* 2001) to a stable zero velocity. For H slips, Sd was determined by accruing the heel's travel distance from HS to the time when the subject either slipped beyond the contaminated force plate or he/she relied on the harness to regain balance as determined by visual inspection of the videos.

GS (ms) was defined as the average whole body centre of mass velocity along the direction of travel prior to slip initiation. The centre of mass was determined, using scaled anthropometry based on Chandler *et al.* (1975) and regression equations from Chaffin and Anderson (1991) to determine masses and centres of masses for the segments head, upper and lower arms, trunk, pelvis, thighs, shanks and feet. Segment locations and orientations were determined using at least three non-collinear reflective markers per segment.

Trial slip severity was categorized as either non-hazardous or hazardous using the peak velocity of the slipping heel virtual marker. Typical plots of the position and velocity of the left heel, as well as FFA, for both NH and H slip trials are illustrated in figure 2. At HS, horizontal heel velocity was often higher than the eventual peak slipping velocity (figure 2B); for that reason and to accommodate transients occurring at HS, PSV was identified as the local maximum horizontal heel velocity occurring after 50 ms from HS. H slips were defined as having a PSV greater than 1.0 ms. This PSV threshold was chosen to agree with slip velocities for larger slips as reported in previous studies (Strandberg 1983, Lockhart *et al.* 2003). PSV was chosen rather than Sd both to allow the inclusion of trials with indeterminate results (recoveries or falls) although, as illustrated in figure 3, an alternative Sd severity threshold of 10 cm would have generated approximately equivalent slip severity classification results.

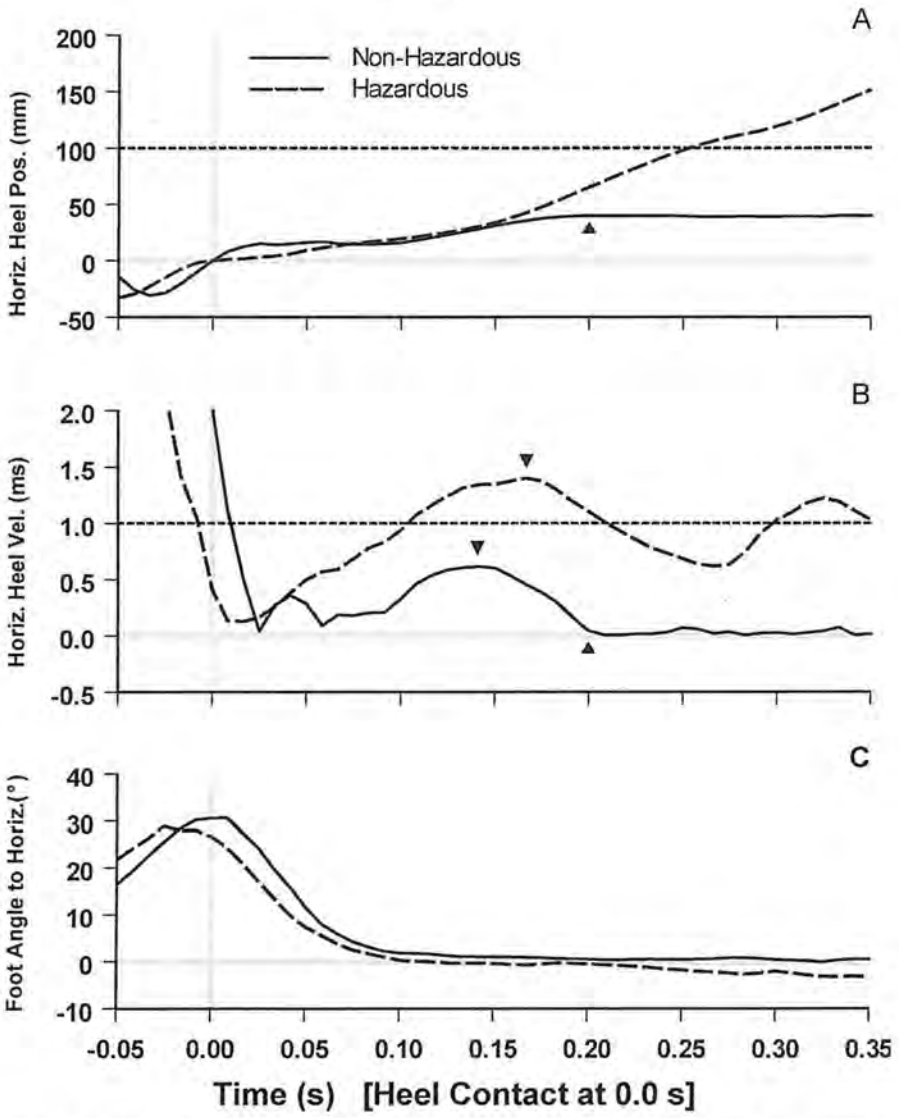

Figure 2. Typical plots for time dependent variables from two slip trials, hazardous and non-hazardous. Heel strike occurs at time 0. ▲ indicates slip distance locations; ▼ indicates peak slip velocity. — and – – – from the same non-hazardous/hazardous trials respectively. A) Horizontal position of the left heel, relative to heel strike location – positive values in the direction of travel. – – – illustrates a potential severity threshold for slip distance at 100 mm. B) Left heel horizontal velocity. – – – illustrates the severity threshold for peak slip velocity of 1 ms. C) Foot-floor angle.

3. Results

None of the slip events classified as non-hazardous based on the 1 ms PSV threshold resulted in falls (although some of the NH slips did elicit post-slip responses), while H slips resulted in recoveries, falls, slips completely off the force plate or harness-assisted

recoveries. Younger and older subjects experienced H slips at about the same rate: 64% (seven of 11) for older subjects and 69% (11 of 16) for younger subjects.

Many of the pre-slip baseline-dry gait characterization parameters were strongly correlated (magnitude of $r > 0.5$) as shown by the correlation coefficients summarizing the strength of the linear relationships between each pair of variables in table 2. PSV was highly correlated with Sd ($r = 0.89$ overall) both for younger ($r = 0.87$) and older subjects ($r = 0.98$) (figure 3). All trials categorized as hazardous, except one, also had a Sd greater than 100 mm. There was only weak correlation ($r < 0.3$, $p = 0.36$) between cadence and SLR for these experiments, suggesting that in this study cadence and step length were independently controlled. GS was strongly correlated with SLR and cadence ($r = 0.51$, $p < 0.01$ for each) and FFA at HS was also strongly correlated with SLR ($r = 0.67$, $p < 0.01$).

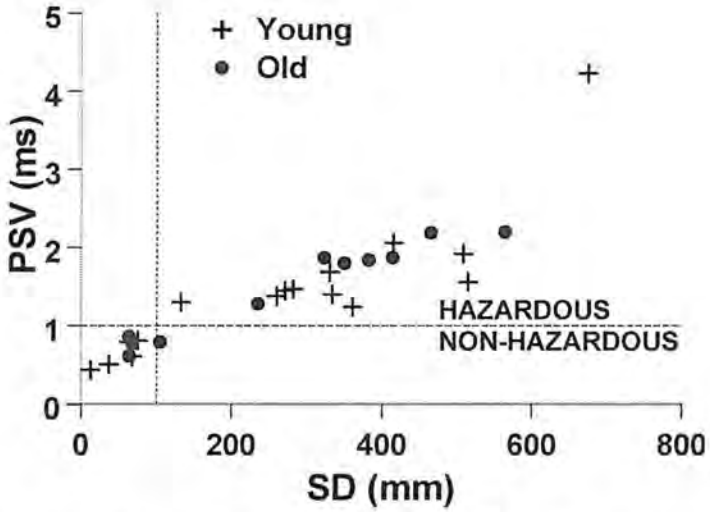

Figure 3. Relationship between peak slip velocity (PSV) and slip distance (SD). ¦ indicates a potential SD slip severity threshold of 100 mm proposed in the literature. – – illustrates the actual PSV slip severity threshold of 1.0 ms used for this report. Note similar results in categorization between the two criteria.

Table 2. Correlations among variables of interest.

PSV	0.89*	−0.32	0.49*	0.17	0.48*	−0.44*	−0.24	−0.47
	SD	−0.36	0.58*	0.32	0.45*	−0.46*	−0.08	−0.35
		CAD	−0.18	0.51*	−0.38*	0.13	0.50*	0.34*
			SLR	0.51*	0.67*	−0.70*	−0.26	−0.54
				GS	0.17	−0.43*	0.24*	−0.27
					FFA	−0.73*	−0.13	−0.54
						FFAS	0.33	0.68*
							H_VEL	0.29
								V_VEL

*Significant correlations ($p < 0.05$).
PSV = peak slip velocity; SD = slip distance; CAD = cadence; SLR = step length ratio; GS = gait speed; FFA = foot–floor angle; FFAS = rate of change of FFA at heel strike; H_VEL = horizontal velocity of the left heel at heel strike; V_VEL = vertical velocity of the left heel at heel strike.

Two-factor ANOVA were conducted to determine the associations between the pre-slip gait characterization parameters and the independent variables slip severity (hazardous or non-hazardous), age group and their interaction (table 3). Age did not have a significant effect on cadence, H_VEL, or V_VEL ($p=0.49$, 0.50 and 0.19 respectively). A trend for older subjects to walk more slowly (GS) than younger subjects did not reach statistical significance ($p=0.09$). Significant age effects were seen for SLR, FFA at HS, and FFAS at HS. Specifically, older subjects walked with shorter step lengths relative to their leg length (SLR) ($p=0.03$), with smaller FFA (closer to flat foot) at HS (FFA) ($p<0.01$), and with slower FFA rate of change (FFAS) at HS ($p=0.02$).

H_VEL and V_VEL were not found to be significantly related to slip severity ($p=0.34$ and $p=0.06$) although a trend linking higher vertical velocity to H slips is possible. Significance was found relating slip severity to cadence, SLR, FFA and FFAS ($p=0.03$, $p<0.01$, $p<0.01$, and $p<0.01$ respectively). Decreased cadence, longer SLR, higher FFA at HS and faster FFAS at HS occurred during H slips. There were no significant interaction effects of slip severity across age for any of the variables (all $p>0.2$). The relationships among these variables, age group, and slip severity are illustrated in figure 4.

A stepwise logistic regression analysis was performed in an attempt to relate common initial conditions and gait characteristics to slip severity (hazardous or non-hazardous) for younger and older subjects combined. The variables that were included initially were cadence, SLR, GS and age group (young/old). FFA was not included due to high correlations with the other variables. The stepwise regression found two variables (cadence ($p=0.05$) and SLR ($p=0.02$)) to be associated with slip severity. The overall model resulted in a $R^2=0.45$ with a likelihood $\chi^2=15.30$ ($p<0.01$). Parameters of the logistic regression model for SLR and cadence were 28.2 and -0.16, respectively. This model resulted in the probability plot shown in figure 5. Increasing SLR (longer steps) and decreasing cadence (slower steps/min) resulted in increasing probability of a H slip. Cadence and SLR were not highly correlated with each other ($r=-0.18$, $p=0.36$) and therefore supplied relatively independent contributions to the model. GS and age group were not good predictors of slip severity, either alone or in combination with the other variables.

An alternative logistic regression analysis was conducted using a single initial condition variable, FFA and age group, since FFA was well correlated with SLR, cadence and FFAS (table 2), all of which were statistically related to slip severity (table 3). This analysis showed a strong logistic relationship for FFA and no age group significance ($R^2=0.53$, $\chi^2=16.55$; $p<0.01$). The probability model is given in figure 6.

Table 3. Results of ANOVA (p values) for the variables of interest.

Variable	Age effect (Y/O)	Slip severity effect (H/NH)	Interaction effect (Y/O × H/NH)
CAD	0.49	0.03*	0.64
SLR	0.03*	<0.01*	0.46
GS	0.09	0.80	0.93
FFA	<0.01*	<0.01*	0.48
FFAS	0.021*	<0.01*	0.42
H_VEL	0.50	0.34	0.97
V_VEL	0.19	0.06	0.20

*Significant correlations ($p<0.05$).

Y/O = young/old; H/NH = hazardous/non-hazardous; CAD = cadence; SLR = step length ratio; GS = gait speed; FFA = foot–floor angle; FFAS = rate of change of FFA at heel strike; H_VEL = horizontal velocity of the left heel at heel strike; V_VEL = vertical velocity of the left heel at heel strike.

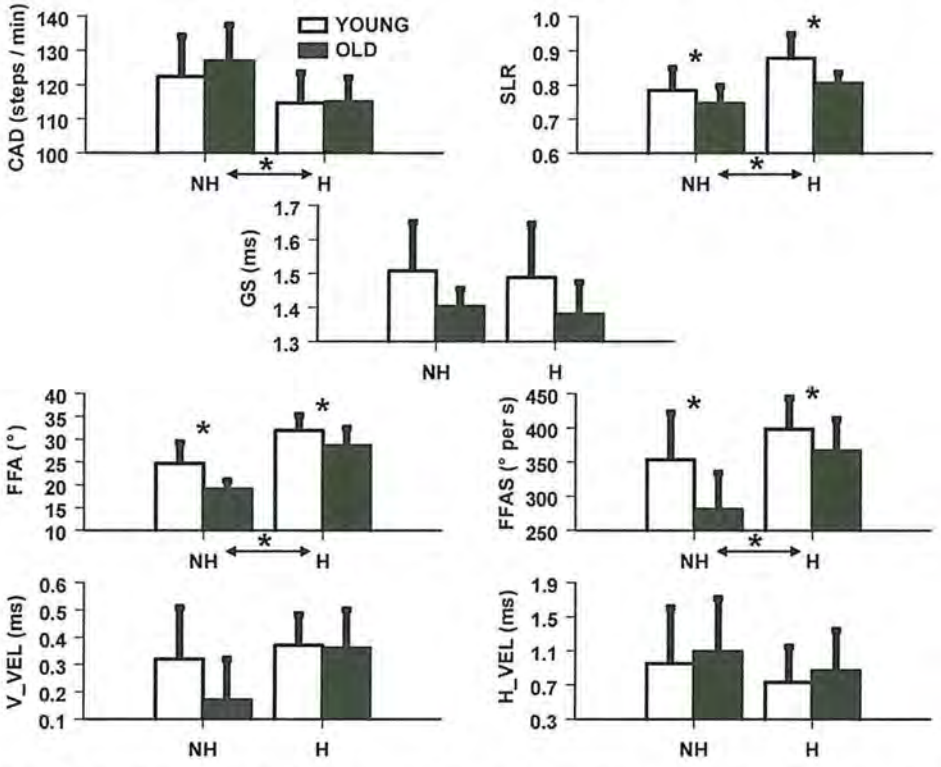

Figure 4. Relationships between age-group and variables of interest (slip type: non-hazardous (NH) and hazardous (H);). Positive foot-floor angle slope (FFAS) indicates decreasing foot-floor angle (FFA). Positive horizontal velocity (H_VEL) in direction of travel. Positive vertical velocity (V_VEL) into floor surface. *(significant difference ($p<0.05$). CAD = cadence; SLR – step length ratio; GS = gait speed.

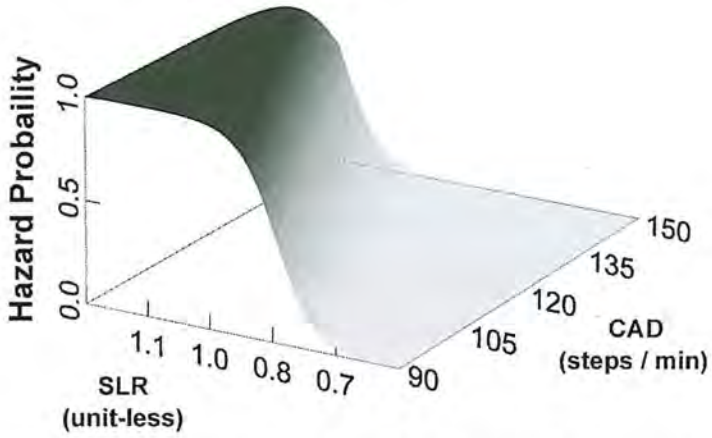

Figure 5. Probability of hazardous slip during first exposure to slippery environment based upon logistic model including step length ratio (SLR) and cadence (CAD).

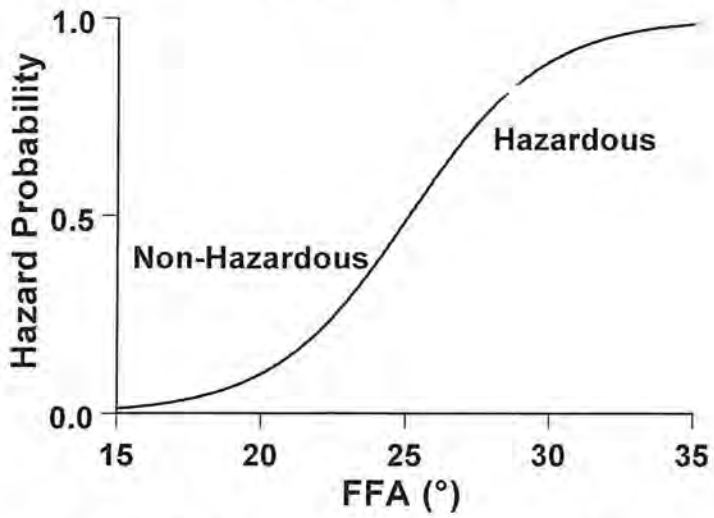

Figure 6. Logistic relationship between hazardous slip event and foot-floor angle (FFA) at heel strike.

Increasing FFA resulted in increasing probability of a H slip (logistic regression parameter of 0.43).

4. Discussion

The findings of this study suggest that initial conditions contribute to the severity of slips. In particular, cadence, normalized step length and the angle of the foot relative to the floor were found to be important. Decreased cadence, longer step lengths normalized to leg length, higher foot-floor angle at HS, and faster foot–floor angular velocity at HS were found during H slips. Older subjects were found to have gait that was generally less hazardous as characterized by smaller step length ratios, smaller FFA at HS and slower rates of change of the FFA at HS as compared to younger subjects, even though older subjects had equivalent numbers of H slips.

This research was based upon a classification of slips into two categories, hazardous and non-hazardous, rather than differentiating falls from recoveries. This has two major implications on the interpretation of the results. From a practical point of view, it avoids the issue of recovery efforts that are potentially assisted through reliance on the safety harness, slipping completely off the contaminated force plate or other indeterminate ground contact. From a theoretical point of view, the results must be interpreted differently from those based on a recovery/fall criterion. The hazardous criterion in the present study, based upon PSV, relies on biomechanical events that occur within 250 ms of heel contact, and thus does not capture the influences of a longer latency aspect of the postural control system in any recovery. Therefore, the focus is on the effects of initial conditions on slip severity independent of reactive postural responses during recovery efforts. Using a recovery/fall criterion, the results would be due to a mixture of initial condition factors and reactive postural control factors. This difference is important in the interpretation of the similarities and differences between the young and older subjects, which are discussed later.

H slips were associated with longer steps (SLR) compared to NH slips. This agrees with the previously reported relationship between step length and slip risk (Andres *et al.* 1992, Llewellyn and Nevola 1992, McVay and Redfern 1994, Myung and Smith 1997, Brady *et al.* 2000, Cham and Redfern 2002a, Lockhart *et al.* 2003). The effect of longer step length on slip severity may be due to increases in the ratio of required shear to normal force at HS for longer steps (Gronqvist *et al.* 2001, Cham and Redfern 2002a). Additionally, longer steps imply greater excursions of the foot with regard to the centre of mass, causing the foot to accelerate faster than it would for shorter steps and suggesting an increase in the magnitude of any required action needed to arrest a resulting sliding motion of the foot. Finally, taking long steps modifies the tension of lower extremity muscles (e.g. stretching the hamstrings), which may impact the ability to generate faster reflexive torque responses of appropriate magnitude in the face of external perturbations.

Increasing FFA at HS was a contributor to slip severity as well, a finding in support of previously published reports (Strandberg and Lanshammar 1981, Redfern and Bidanda 1992, Brady *et al.* 2000, Cham and Redfern 2002b, Chambers *et al.* 2003, Marigold *et al.* 2003). This finding may be due to a number of factors. First, decreased FFA at HS increases the shoe–floor contact area at landing. Also, foot-flat gait reduces the braking impulse at HS. Finally, decreased FFA, along with faster cadences and shorter step length ratios, impacts the dynamics of the centre of mass excursions, increasing the centre of mass to base of support safety margin, decreasing inertial loading on the foot at HS and thus reducing the frictional requirements needed to prevent a slip (Gronqvist *et al.* 2001).

GS did not appear to differentiate between H and NH slips. However, several researchers have previously reported that PSV exceeding GS increased the likelihood of falls (Perkins 1978, Strandberg and Lanshammar 1981, Gronqvist *et al.* 2001, You *et al.* 2001, Cham and Redfern 2002b, Lockhart *et al.* 2003). For the present study, subjects walked at self-selected GS ranging from 1.2 to 1.8 ms for both H and NH slips classified based on a PSV threshold of 1.0 ms. Thus, the range of speeds was not great and it is therefore understandable that a significant relationship between severity and GS was not found. Perhaps this relationship would be a more valuable differentiator of recoveries and falls.

While the correlation analysis confirmed a number of suspected relationships among gait variables, it also revealed interesting interactions that appear to be in disagreement with previously published literature. For example, in the present study cadence and SLR were not well correlated with each other ($r = -0.18$, $p = 0.36$), which is in contrast to significant positive correlations reported in the literature (i.e. Winter 1983). The lack of correlation is probably due to the limited range of GS induced by the self-paced constraint. Thus, within the self-paced limits, it appears that cadence and SLR are independently controlled. Some effects were similar to those reported in the gait literature (Brady *et al.* 2000) such as larger FFA (more vertical orientation of the foot) occurring as longer steps are taken ($r = 0.67$, $p < 0.01$) and a slower cadence is adopted ($r = -0.38$, $p = 0.048$).

H_VEL was not found to have a significant effect on slip severity. In contrast, other studies have shown that greater H_VEL results in a greater number of slips and falls (Winter 1991, Lockhart 1997, Brady *et al.* 2000, Lockhart *et al.* 2000). However, there tends to be variability in H_VEL during gait, with the heel slipping forward, backward or matching ground speed (Winter 1991). This variability is probably a function of the instructions given to the subject in the experiment and the subject's mindset (i.e. anticipation of the environmental conditions). Measurements of the coefficient of friction have been shown to be impacted by the velocity of the tests, with greater velocities resulting in lower coefficients of friction (see Chang *et al.* 2001 for a review); thus, one

would anticipate that H_VEL would have an effect on the available coefficient of friction with higher H_VEL more likely to result in H slips. However, the expectation that H_VEL would predict slip severity was not verified in the experiments.

Two logistic regression models were considered to predict slip hazardousness. The choice of predictor variables was based on three factors. First, the explanatory variables were general gait variables that are conventionally thought of as affecting slip potential and/or outcome. Second, significant differences in the predictor variables were found between H and NH slips. Third, independent variables included in the same model were only weakly correlated with each other. The first logistic model included cadence and SLR, both of which are widely used in gait research. These variables were also found to be predictive of slip severity and they were not strongly correlated with each other in this investigation ($r = -0.18$, $p = 0.36$); therefore, SLR and cadence were deemed to be good choices for the first logistic regression model (figure 5). The second model considered only FFA as an explanatory variable predicting slip hazardousness. Because FFA was correlated with both SLR and cadence, and because significant differences in FFA were found between H and NH slips, it seemed a reasonable choice to use FFA as a single predictor of slip severity (figure 6).

Age group was not found to be primarily associated with the classification of the slip. Thus, gait characteristics dominated the association with slip classification. However, even though younger and older subjects experienced H slips at about the same rate (64% (seven of 11) for older subjects and 69% (11 of 16) for younger subjects), older subjects appeared to adopt 'safer' gait styles, with shorter SLR, shallower FFA at HS and slower FFAS. Thus, there may be some influence of age that is counteracted by the changes in gait characteristics seen in older adults. Some possibilities include other unmeasured gait characteristics, psychophysical differences related to concern about slipping that could affect the mental set in this experiment, biomechanical differences, or possible reflexive response differences. In addition, the older subjects were (as a group) slightly heavier than the younger subjects (with increased BMI), which could be a covariate for future investigation. Deficiencies in reactive responses to slips have been cited as explanations for slips resulting in falls (Lockhart *et al.* 2000); however, as PSV occurs within the first 200 ms after HS, it is unlikely that non-reflexive responses would influence slip hazard as defined in this research. Further research is needed to understand the interplay among initial gait characteristics, postural control responses, H slips and ageing.

This study's results were limited by the relatively small number of slips analysed, one per subject, which was a necessity to avoid anticipation and learning effects (Cham and Redfern, 2002a). Although study participants were requested to walk naturally and were given ample unperturbed practice trials, it is not possible to determine the effect of the laboratory environment and experimental conditions on the subjects' responses to slips. Although no significant kinematic differences at HS were found between the slippery trial and preceding known dry trials, slip anticipation may have influenced all gait trials included in the testing session. Additionally, the older subject group was arguably not sufficiently old to impact general gait variables.

One of the potential long-term benefits of this study is its contribution to the understanding of the interplay among fundamental gait parameters, slip potential, and age. The 'human factors' involved in slipping are an important component that deserves increased attention. The results of this study suggest that H slip potential can be reduced by modifying specific gait parameters. This finding may influence training regimens to reduce H slips. Importantly, it appears that adjusting gait may be equally useful across the age groups tested here, although future research is needed to determine if the same

associations hold for very old adults. This research will also significantly contribute to definitions of important human factors that may some day be incorporated into new methods of slip resistance testing. There is general agreement within the slip testing community that increasing the 'biofidelity' of slip resistance testing will improve the test's ability to define useful slip measures towards preventing falls. Further understanding of the relation of human gait parameters to slip hazard could be useful in this regard. Finally, the concept of using H vs. NH slips instead of falls and recoveries could benefit future studies investigating interactions of floors and human locomotion. Other human slip studies may want to include this concept in defining the impact of floor condition, age, etc. on the potential for slip-related injuries, not only due to falls but also due to the larger responses required to recover from H slips.

Acknowledgements

This research was supported by NIOSH grant R03 OH007533. We are grateful to Joseph Furman, MD, PhD for the neurological screening of our subjects.

References

AGNEW, J. and SURUDA, A.J., 1993, Age and fatal work-related falls. *Human Factors*, **35**, 731–736.

AMERICAN SOCIETY FOR TESTING AND MATERIALS, 1996, *Annual Book of ASTM Standards, vol. 15.07: ASTM F1679–96 Standard Test Method for Using a Variable Incidence Tribometer (VIT)*. (West Conshohocken, PA: American Society for Testing and Materials).

ANDRES, R.O., O'CONNOR, D. and ENG, T., 1992, A practical synthesis of biomechanical results to prevent slips and falls in the workplace. In *Advances in Industrial Ergonomics and Safety IV*, S. Kumar (Ed.), pp. 1001–1006 (London: Taylor & Francis).

BRADY, R.A., PAVOL, M.J., OWINGS, T.M. and GRABINER, M.D., 2000, Foot displacement but not velocity predicts the outcome of a slip induced in young subjects while walking. *Journal of Biomechanics*, **33**, 803–808.

BUREAU OF LABOR STATISTICS, 2003, Lost-worktime injuries and illnesses: characteristics and resulting days away from work, 2003, United States Department of Labor 05–521. Available online at: http://www.bls.gov/news.release/pdf/osh2.pdf

BUREAU OF LABOR STATISTICS, 2004a, National census of fatal occupational injuries in 2004, United States Department of Labor 05–1598. Available online at: http://www.bls.gov/news.release/pdf/cfoi.pdf

BUREAU OF LABOR STATISTICS, 2004b, Annual averages – household data from the Current Population Survey, United States Department of Labor. Available online at: http://www.bls.gov/cps/cpsaat8.pdf

CHAFFIN, D.B. and ANDERSON, D.B., 1991, *Occupational Biomechanics*, 2nd ed. (New York: John Wiley and Sons).

CHAM, R., MOYER B.E. and REDFERN, M.S., 2002, Whole body biomechanics of responses to slips. In *Proceedings of the American Society of Biomechanics (ASB) in conjunction with the IVth World Congress of Biomechanics*, 4–9 August 2002, Calgary, Alberta, Canada, # 231, ID# 1044. Omnipress, 2002 (on CD-ROM).

CHAM, R. and REDFERN, M.S., 2002a, Changes in gait when anticipating slippery floors. *Gait Posture*, **15**, 159–171.

CHAM, R. and REDFERN, M.S., 2002b, Heel contact dynamics during slip events on level and inclined surfaces. *Safety Science*, **40**, 559–576.

CHAMBERS, A.J., MARGERUM, S., REDFERN, M.S. and CHAM, R., 2003, Kinematics of the foot during slips. *Occupational Ergonomics*, **3**, 225–233.

CHANDLER, R.F., CLAUSER, C.E., MCCONVILLE, J.T., REYNOLDS, H.M. and YOUNG, J.W., 1975, *Investigation of Inertial Properties of the Human Body*, DOT HS-801 430. (Washington, DC: U.S. Department of Transportation).

CHANG, W.R., GRÖNQVIST, R., LECLERCQ, S., MYUNG, R., MAKKONEN, L., STRANDBERG, L., BRUNGRABER, R.J., MATTKE, U. and THORPE, S., 2001, The role of friction in the measurement of slipperiness. Part 1: friction mechanisms and definition of test conditions. *Ergonomics*, **44**, 1217–1232.

COURTNEY, T.K., SOROCK, G.S., MANNING, D.P., COLLINS, J.W. and HOLBEIN-JENNY, M.A., 2001, Occupational slip, trip, and fall-related injuries – can the contribution of slipperiness be isolated? *Ergonomics*, **44**, 1118–1137.

COURTNEY, T.K. and WEBSTER, B.S., 2001, Antecedent factors and disabling occupational morbidity – insights from the new BLS data. *AIHAJ*, **62,** 622–632.

DE LAET, C.E. and POLS, H.A., 2000, Fractures in the elderly: epidemiology and demography. *Baillieres Best Practice and Research. Clinical Endocrinology and Metabolism* **14,** 171–179.

GAO, C. and ABEYSEKERA, J., 2004, A systems perspective of slip and fall accidents on icy and snowy surfaces. *Ergonomics*, **47,** 573–598.

GRONQVIST, R., ABEYSEKERA, J., GARD, G., HSIANG, S.M., LEAMON, T.B., NEWMAN, D.J., GIELO-PERCZAK, K., LOCKHART, T.E. and PAI, C.Y., 2001, Human-centered approaches in slipperiness measurement. *Ergonomics*, **44,** 1167–1199.

KING, M.B. and TINETTI, M.E., 1995, Falls in community-dwelling older persons. *Journal of the American Geriatrics Society*, **43,** 1146–1154.

KING, M.B. and TINETTI, M.E., 1996, A multifactorial approach to reducing injurious falls. *Clinics in Geriatric Medicine*, **12,** 745–759.

LEAMON, T.B. and LI, K.W., 1990, Microslip length and the perception of slipping. In *Twenty Third International Congress on Occupational Health*, Montreal, Canada, 22–28 September 1990, pp. 17–18.

LLEWELLYN, M.G.A. and NEVOLA, V.R., 1992, Strategies for walking on low-friction surfaces. In *Proceeding of the Fifth International Conference on Environmental Ergonomics*, Maastricht, The Netherlands, 22–28 September 1992, pp. 156–157.

LLOYD, D.G. and STEVENSON, M.G., 1992, Investigation of floor surface profile characteristics that will reduce the incidence of slips and falls. *Mechanical Engineering Transactions Institution of Engineers – Australia*, **ME17,** 99–105.

LOCKHART, T.E., 1997, The ability of elderly people to traverse slippery walking surfaces. In *Proceedings of the Human Factors and Ergonomics Society 41st Annual Meeting*, Albuquerque, NM, September 1997, pp.125–129.

LOCKHART, T.E., SMITH, J.L., WOLDSTAD, J.C. and LI, P., 2000, Effects of musculoskeletal and sensory degradation due to aging on the biomechanics of slips and falls. *Proceedings of the XIVth Triennial International Ergonomics Association Congress and 44th Meeting of the Human Factors and Ergonomics Society*, Volume 5, San Diego, 29 July–4 August 2000, pp. 83–86.

LOCKHART, T.E., WOLDSTAD, J.C. and SMITH, J.L., 2003, Effects of age-related gait changes on the biomechanics of slips and falls. *Ergonomics*, **46,** 1136–1160.

LUUKINEN, H., HERALA, M., KOSKI, K., KIVELA, S.L. and HONKANEN, R., 1999, Rapid increase of fall-related severe head injuries with age among older people: a population-based study. *Journal of the American Geriatrics Society*, **47,** 1451–1452.

MCVAY, E.J. and REDFERN, M.S., 1994, Rampway safety: foot forces as a function of rampway angle. *American Industrial Hygiene Association Journal*, **55,** 626–634.

MARIGOLD, D.S., BETHUNE, A.J. and PATLA, A.E., 2003, Role of the unperturbed limb and arms in the reactive recovery response to an unexpected slip during locomotion. *Journal of Neurophysiology*, **89,** 1727–1737.

MARIGOLD, D.S. and PATLA, A.E., 2002, Strategies for dynamic stability during locomotion on a slippery surface: effects of prior experience and knowledge. *Journal of Neurophysiology*, **88,** 339–353.

MYUNG, R. and SMITH, J.L., 1997, The effect of load carrying and floor contaminants on slip and fall parameters. *Ergonomics*, **40,** 235–246.

PERKINS, P.J., 1978, Measurement of slip between the shoe and ground during walking. In *ASTM-Special-Technical-Publication*, ASTM STP 649, pp. 71–87 (Philadelphia, PA: ASTM).

PERSONICK, M.E. and WINDAU, J.A., 1995, Characteristics of older workers' injuries. 891. (Washington, DC: U.S. Department of Labor, Bureau of Labor Statistics).

REDFERN, M.S. and BIDANDA, B., 1992, Effects of shoe angle, velocity, and vertical force on shoe/floor slip resistance. In *Advances in Industrial Ergonomics and Safety IV*, S. Kumar (Ed.) pp. 997–1000 (London: Taylor & Francis).

RIVARA, F.P., GROSSMAN, D.C. and CUMMINGS, P., 1997, Injury prevention. Second of two parts. *New England Journal of Medicine*, **337,** 613–618.

SMEESTERS, C., HAYES, W.C. and MCMAHON, T.A., 2001, Disturbance type and gait speed affect fall direction and impact location. *Journal of Biomechanics*, **34,** 309–317.

STERLING, D.A., O'CONNOR, J.A. and BONADIES, J., 2001, Geriatric falls: injury severity is high and disproportionate to mechanism. *Journal of Trauma*, **50,** 116–119.

STRANDBERG, L., 1983, On accident analysis and slip-resistance measurement. *Ergonomics*, **26,** 11–32.

STRANDBERG, L. and LANSHAMMAR, H., 1981, The dynamics of slipping accidents. *Journal of Occupational Accidents*, **3,** 153–162.

THOMAS, E.J. and BRENNAN, T.A., 2000, Incidence and types of preventable adverse events in elderly patients: population based review of medical records. *British Medical Journal*, **320**, 741–744.

TINETTI, M.E. and WILLIAMS, C.S., 1997, Falls, injuries due to falls, and the risk of admission to a nursing home. *New England Journal of Medicine*, **337**, 1279–1284.

WINTER, D.A., 1983, Biomechanical motor patterns in normal walking. *Journal of Motor Behavior*, **15**, 302–330.

WINTER, D.A., 1991, *The Biomechanics and Motor Control of Human Gait: Normal, Elderly, and Pathological*, 2nd ed. (Ontario: University of Waterloo Press).

YOU, J., CHOU, Y., LIN, C. and SU, F., 2001, Effect of slip on movement of body center of mass relative to base of support. *Clinical Biomechanics*, **16**, 167–173.