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Predicting slips and falls considering required and available friction

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This study investigated the relationship among measurements of friction, the biomechanics of gait, and actual slip and fall events. The goal was to develop a method for estimating the probability of slips and falls based on measurements of available friction and required friction. Five subjects wearing safety harnesses walked down a ramp at various angles with either a tile or carpeted surface under dry, wet or soapy conditions. Ramp angles of 0°, 10° and 20° were used to vary the shear and normal foot force requirements. The dynamic coefficient of friction (DCOF) of shoe, floor surface and contaminant interfaces was measured. Required friction was assessed by examining the foot forces during walking trials when no slips occurred. Slips with recoveries and slips resulting in falls were recorded and categorized using a force plate and high-speed video camera. These data were then incorporated into a logistic regression to model the probability of a slip or fall event occurring based on the difference between the COF required by the foot forces generated and the measured DCOF. The results showed that the number of slip and fall events increased as the difference between the required COF and the measured DCOF increased. The logistic regression model fit the data well, resulting in an estimate of the probability of a slip or fall event based on the difference between the measured and required friction. This type of model could be used in the future to evaluate slip resistance measurement devices under various environments and assist in the design of safer work environments.

1. Introduction

Falls are a major cause of injuries at work, in public places and at home. Falls are estimated to cause 17% of all occupationally related injuries, and 18% of injuries in the public sector in the USA (NSC 1991, Leamon and Murphy 1995). Falls account for one in five injuries, including 33% of hospitalized injured persons and 20% of those non-hospitalized (Rice *et al.* 1989). Lifetime costs associated with falls in the USA have been estimated at $12.6 billion (Runge, *et al.* 1993). Substantial numbers of serious injuries due to falls are also found in other countries. In the UK, ~20 % (40 000) of all occupational injuries are reportedly due to slips and falls (Manning 1988, Thomas 1991). In Finland, occupational slips and falls have been reported mainly in manufacturing (34%), construction (28%) and transportation (21%) (Gronqvist and Roine 1993).

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Causes of falls are complex involving environmental and human factors. Environmental factors include characteristics of walking surfaces, shoes, contaminants, elevations, steepness of an incline, lighting and even floor compliance. Human factors include sensory capabilities, biomechanics, neuromuscular control and information processing. In most cases, falls occur from an inability of the individual to adapt to the environmental conditions. For example, increasing the slipperiness of a floor surface (i.e. from dry to oily) would create a high risk of slip and fall if the biomechanics of gait were not altered. Foot forces normally generated during gait require friction to counteract the shear forces to prevent slip. When the available friction at the shoe – floor interface cannot meet the biomechanical requirements, a slip becomes imminent, possibly resulting in injury.

The dominant environmental factor in falls is believed to be the slip resistance of the shoe – floor interface (Strandberg and Lanshammer 1981, Cohen and Compton 1982, Redfern and Bloswick 1997). Low frictional characteristics of the shoe – floor interface can cause a loss of traction resulting in a slip and ultimately a fall. Injury can also result from a slip without a fall. Often when slip occurs stability is recovered; yet injury can still result from striking an object or from a muscular strain (Manning and Shannon 1981, Troup *et al.* 1981, Anderson and Langerhof 1983). Injuries of this type are usually not reported as related to a slip; thus, the number of injuries caused by slips with recovery is undoubtedly underestimated.

Much of the work in the prevention of slips and falls has focused on the measurement of the 'tractive' or slip-resistant properties of flooring and shoes. Current slip resistance evaluation methods measure either the static or dynamic coefficient of friction of the shoe – floor interface under various contaminant conditions such as wet, oily, detergent, etc. Numerous devices have been developed to measure static coefficient of friction (SCOF). Some of these devices have been tested for usability and reliability (Andres and Chaffin 1985, Kulakowski *et al.* 1989). While these SCOF measures are routinely used in making evaluations regarding the safety of flooring (Pater 1985), validity of these measures under all conditions is questionable (Strandberg 1983). Also, measurements of SCOF vary greatly across devices, particularly under contaminant conditions (English 1990). Dynamic COF (DCOF) measures are believed by some to be equally, if not more, relevant to slips and falls (Perkins and Wilson 1983 Strandberg 1983, Redfern 1988). These DCOFs can vary greatly from SCOFs under the same shoe – floor – contaminant conditions. A number of DCOF measurement devices has been developed, including the horizontal pull slip meter (English 1990), dynamic sled tester (Redfern *et al.* 1990), the tortus (Andres and Chaffin 1985), the SATRA slip tester (Wilson 1990), the programmable slip resistance tester (PSRT) (Redfern and Bidanda, 1994), and the Finnish tester (Gronqvist *et al.* 1989). DCOF measurements can also vary across devices depending upon the shoe – floor – contaminant conditions tested.

Since COF measures vary across the many devices in use, there is currently no way to assess the utility of any device in predicting slips and falls. Thus, the choice of slip resistance testing device for use in evaluating the shoe – floor environment is subjective. The purpose of this study was to develop a method to evaluate the relationship between slip resistance measurements and actual slips and falls. This was accomplished in the laboratory by changing the biomechanical requirements through varying ramp angles and changing the slip resistance of the environment through the application of contaminants. In addition, predictive models of slips and falls based on the slip resistance measurement and the biomechanical requirements of walking were developed.

2. Methods

2.1. *Subject population*

Five healthy male adults (age 26 – 38 years) with no musculoskeletal, neurological or gait abnormalities participated in the study. Exclusionary criteria were a history of dizziness, vestibular disorders, neurological disorders, a history of low back pain, or any orthopaedic abnormalities of the lower extremities. Informed consent was obtained prior to participation.

2.2. *Apparatus*

Dynamic COF measurements were made using the programmable slip resistance tester (PSRT) described by Redfern and Bidanda (1994). This computer-controlled device records horizontal and vertical forces, while the shoe assembly moves across the surface being studied. The shoe is applied to the floor at a heel of angle of 5° with respect to the floor. The floor was always level (without inclination) when tested. The dynamic COF (DCOF) is calculated as the ratio between the measured horizontal force and the known vertical force.

For the gait experiment, a specially designed ramp was constructed in the Human Movement and Balance Laboratory, University of Pittsburgh. (figure 1). The ramp consisted of a walkway attached via a hinge to an electromechanical platform that could be raised or lowered automatically to easily change ramp angle. The ramp was also secured at the lower end to a level walkway. The ramp was 1.8 m long and 1.0 m wide with a 1.4 m extension at the bottom. A force platform (Bertec, Inc.) was integrated into the ramp to record foot forces. This force plate was bolted to the superstructure of the ramp. The exposed surface of the force plate was covered with a piece of removable 1.25 cm plywood. Thus, floor surfaces were easily changed between the trials. The floor surface placed on the force plate was level with the surface of the ramp.

The data acquisition system consisted of the force plate, analogue to digital (A/D) converter, computer, a NAC high-speed video camera and a video synchronization unit. Force plate data were collected at 240 Hz using an A/D converter connected to the computer. The high-speed video camera was used to record two-dimensional, sagittal plane movements of the subject during the trials at 120 Hz. The camera was focused on the space above the surface of the force plate to record movements of the foot striking the force plate. Small light reflective markers were placed on the heel and toe of the shoe, fifth metatarsal and malleolus (ankle) to capture movement of the foot.

2.3. *Experimental design and protocol*

The independent variables of this experiment were floor type, contaminant and ramp angle. The two floors used were a non-waxed vinyl composite tile (VCT) and a low-loop carpet. Contaminant conditions included dry, wet, and soap solution. Ramp angles used in the gait experiment were 0°, 10° and 20°. One type of shoe was used in the study, made of a closed-cell, blown PVC sole with a smooth PVC heel. A variety of sizes was available to fit the subjects and the same shoes were worn by the subjects throughout the study.

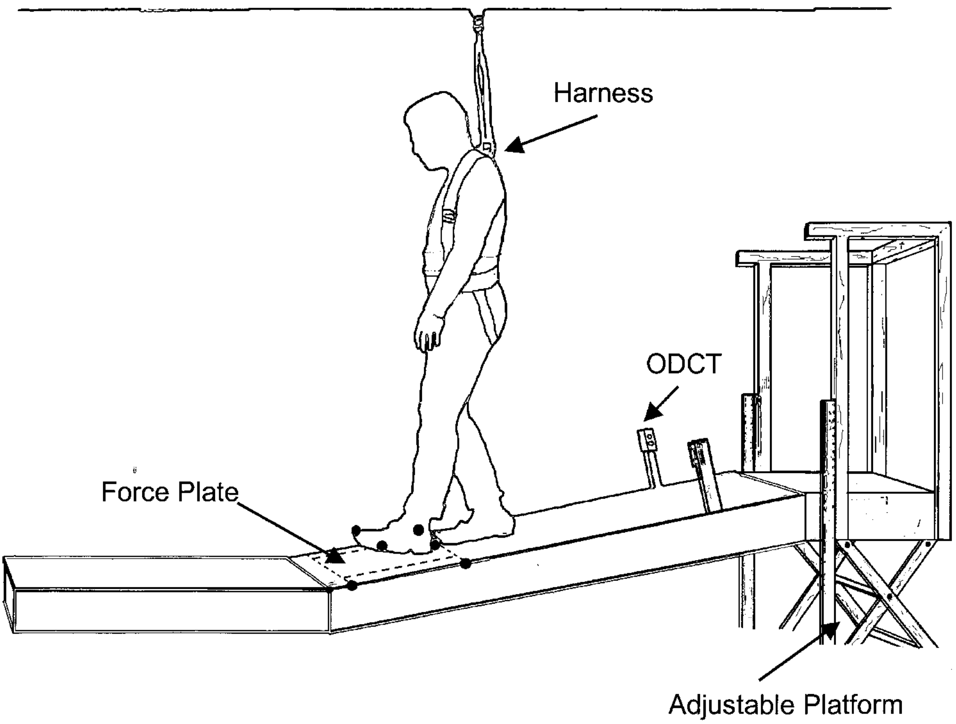

Figure 1. Diagram of the instrumented ramp with adjustable platform used to set the ramp angle, the optical data collection trigger (ODCT), force plate embedded in the ramp and specialized harness system to prevent injury due to falls. A high-speed video camera was focused on the area surrounding the force plate to capture motion of the markers on the foot.

2.3.1. *Slip resistance measurements*: DCOF measurements of the shoe, floor and contaminant combinations used in the inclined ramp studies were made prior to the gait experiments using the PSRT, as prescribed by Redfern and Bidanda (1994). Ten trials were conducted for each combination of floor, shoe and contaminant condition, and the results were averaged. DCOF measurements were made using 20 lbf vertical force on the shoe and a forward travel velocity of 10 cm/s for ~10 cm. The shear forces were sampled at 120 Hz and divided by the 20 lbf vertical force. All shoes were modified to simulate normal wear by sanding off the superficial tread pattern ($<$ 1.0 mm deep). The tread was sanded prior to both the ramp and DCOF trials and no further modification was done between the experiments. Surface contaminants were applied during the testing to emulate realistic spill conditions. Wet conditions were created by applying a film of water across the heel travel path while avoiding puddling. Soapy conditions were modelled by applying a 1 : 1 solution of household dish soap and water. Every attempt was made to create a uniform coating of contaminant on the VCT and the carpet. To create a film on the carpet, more liquid was required compared with the VCT.

2.3.2. *Gait experiment*: Three ramp angles (0°, 10°, 20°) and three contaminant conditions (dry, wet, soapy) were included in the gait study. Three trials for all combinations of ramp angle and contaminant condition were employed. Dry trials were conducted first followed by wet, then soapy trials. This prevented residual contamination during subsequent trials. The surfaces were initially prepared in the same manner as in the DCOF study. Additional fluid was applied after each trial to ensure that the shoe and surface conditions remained consistent between the ramp and DCOF studies.

Subjects were placed in a specially designed harness used to catch the subject when a fall occurred such that the subject did not strike the floor. They were instructed to walk down the ramp at a comfortable pace and focus their eyes on a target on the far wall ~5 m away. Prior to the experiment, each subject was also told that some of the surfaces may be slippery and that slips and falls were likely. They were also told that the experimenter would ask after each trial whether the subject subjectively felt 'no slip', 'slip and recovery' or 'slip and fall'. Subjects were instructed to define a trial as a 'slip and fall' if they required support from the safety harness or slid to the end of the force plate. No additional definitions nor descriptions of the categories were provided. The subject's perception was recorded following each trial and no attempt was made by the experimenter to question or influence the subject's response.

2.4. *Data processing and analysis*

Foot force data were processed to determine shear and normal forces during each trial. The shear forces were recorded for the antero-posterior direction. Heel contact time was defined as the time when the normal force >40 N, which is between 4 and 6% of the subject's weight. Heel contact occurs a brief time before our definition. The ratio between shear and normal forces was calculated to estimate the utilized COF during a trial. The video images were viewed, then digitized using Peak5 (Peak Performance, Inc., Golden, CO, USA) digitizing software. The software calculated the position of the reflective markers on the toe, heel and upper and lower force plate points into coordinates in the sagittal plane. Video data were analysed to determine the length of slip that occurred along the floor during a trial, specifically at the heel. Trials were categorized as slips with falls if any of the following conditions were met: (1) the digitized video clearly showed the subject's foot sliding down the ramp until being lifted off as the subject sat in the safety harness; (2) the digitized video heel position along the surface of the floor never stopped (also indicated by the velocity having never reached zero); or (3) the foot never reaching foot flat (determined by the angle of contact) before the subject hit the end of the force plate.

3. Results

The DCOF measurements of the shoe–floor–contaminant conditions made by the PSRT spanned a large range from 1.43 to 0.16 (table 1). Dry condition values were greatest while the soapy conditions created the smallest values, indicating that contaminant condition had more influence on the DCOF than the floor surface material. The measures were highly repeatable as indicated by the low SDs in table 1.

Slip and fall events during the gait trials were recorded from the subject's perception (table 2) and from the measured force and video data (table 3). No slips nor falls occurred for the dry conditions. Some slips with recovery and one fall occurred for the wet condition on the tile floor as the ramp angle was increased. Numerous slips with recovery and falls occurred with the soapy contaminant, with all subjects falling on all three repeated trials on the 20° ramp angle for VCT. Only one trial for one subject was categorized as a measured fall but not perceived as one. This occurred on carpet under soapy conditions at a 10° ramp angle. Differences between measured and perceived slip and recoveries were found in seven trials across three subjects with four occurring on the carpeted surface and three occurring on the tile surface.

The foot forces collected during the *dry* condition trials were processed to calculate the 'required' COF (RCOF). The foot forces during the dry trials showed increased shear forces as ramp angle was increased (figure 2). RCOFs were

Table 1. DCOF measurements of experimental floor conditions.

	Dry		Wet		Soapy	
	DCOF	SD	DCOF	SD	DCOF	SD
VCT	1.12	0.13	0.64	0.03	0.16	0.01
Carpet	1.43	0.08	0.80	0.01	0.46	0.03

Table 2. Number of perceived slips and falls during ramp gait trials.

		VCT				Carpet			
		No slip	Slip and recovery	Fall	Total slips	No slip	Slip and recovery	Fall	Total slips
Dry	0°	15	0	0	0	15	0	0	0
	10°	15	0	0	0	15	0	0	0
	20°	15	0	0	0	15	0	0	0
Wet	0°	15	0	0	0	15	0	0	0
	10°	14	1	0	1	15	0	0	0
	20°	6	8	1	9	13	2	0	2
Soapy	0°	3	8	4	12	15	0	0	0
	10°	0	4	11	15	11	4	0	4
	20°	0	0	15	15	3	9	3	12

Table 3. Number of measured slips and falls during ramp gait trials.

		VCT				Carpet			
		No slip	Slip and recovery	Fall	Total slips	No slip	Slip and recovery	Fall	Total slips
Dry	0°	15	0	0	0	15	0	0	0
	10°	15	0	0	0	15	0	0	0
	20°	15	0	0	0	15	0	0	0
Wet	0°	15	0	0	0	15	0	0	0
	10°	14	1	0	1	15	0	0	0
	20°	4	10	1	11	11	4	0	4
Soapy	0°	2	9	4	13	15	0	0	0
	10°	0	4	11	15	10	4	1	5
	20°	0	0	15	15	1	11	3	14

calculated for the force data over time by dividing the shear forces by the normal forces (figure 3). The peaks of the RCOF curves in the first half of the step, between

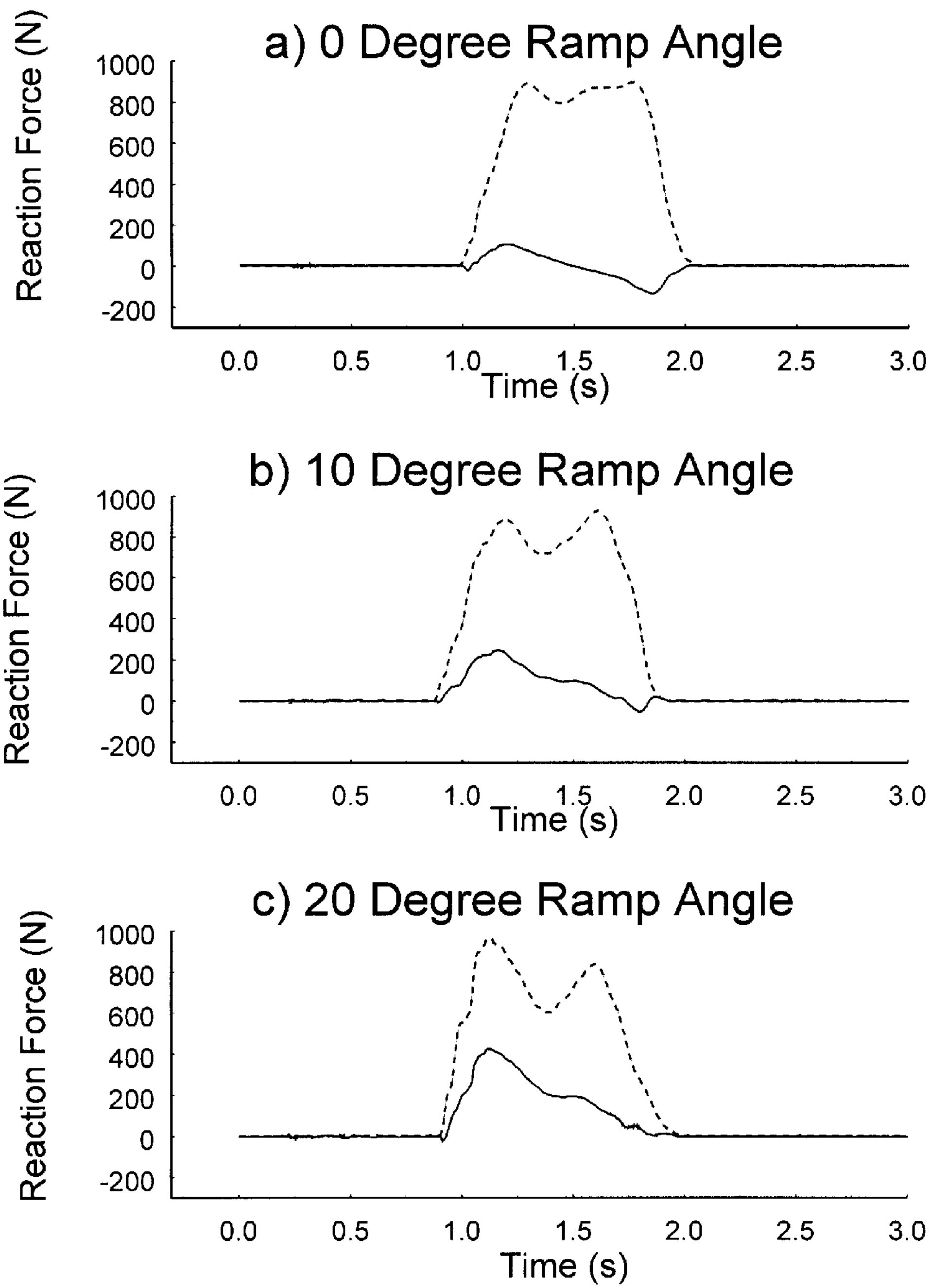

Figure 2. Representative foot forces for one subject during the dry condition on vinyl tile at the three ramp angles: (a) 0°, (b) 10° and (c) 20°. Shear forces are solid lines; normal forces in the antero-posterior direction are dashed lines.

heel contact and mid stance, for each trial were identified and recorded (table 4). Peak RCOFs for the dry conditions represent a baseline of the frictional requirements in normal walking for each ramp angle. Peak RCOFs for the VCT and carpet were similar (maximum 4% difference). Shear and normal foot forces for the other contaminant conditions when slips occurred were also used to calculate 'achievable' COFs (ACOF) (table 5). These measurements were defined as

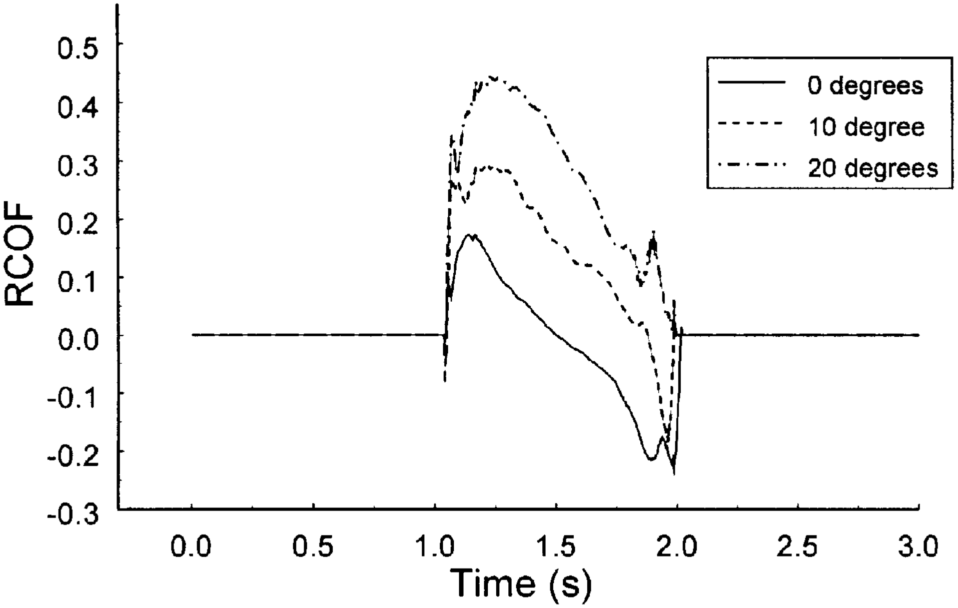

Figure 3. Required COFs calculated from the foot forces shown in figure 2.

Table 4. Peak required COF for walking on dry surfaces at the three ramp angles averaged across subjects.

Angle	VCT	Carpet
0°	0.182 (0.061)	0.190 (0.044)
10°	0.328 (0.031)	0.329 (0.042)
20°	0.455 (0.034)	0.444 (0.022)

SD are in parenthesis.

Table 5. Peak achievable COFs for walking on the surfaces with contaminants (wet and soapy) at the three ramp angles averaged across subjects when slips occurred.

	Wet			Soapy		
Angle	VCT	Carpet	Average	VCT	Carpet	Average
0°	0.150	0.179	0.165	0.114	0.135	0.125
10°	0.276	0.328	0.302	0.153	0.232	0.193
20°	0.416	0.446	0.431	0.223	0.339	0.281

'achievable' rather than 'required' COF because subjects slipped during these trials. ACOFs were lower for the 'fall' trials compared with the 'slip and recovery' trials (figure 4). Also, RCOFs for the 'no-slip' dry trials were higher than ACOFs for either 'falls' or 'slips with recovery'. This relationship was seen to hold across all ramp angles.

To relate the frictional requirements to actual slips and falls, the number of slips with recovery and falls were plotted as a function of the difference between the measured friction (DCOF) of the shoe–floor condition and the required friction (peak RCOF during the dry conditions) (figure 5). The combinations of floors and contaminants provided varying levels of DCOF. The three ramp angles provided different levels of required friction. This difference was expressed as: $COF_{diff} = DCOF - RCOF_{dry}$, where DCOF is the measured COF for the floor–contaminant conditions during the trial and $RCOF_{dry}$ is the peak RCOF recorded by the force plate during the dry trials. For each floor–contaminant condition a total of 15 trials was performed (three trials for each of the five subjects) resulting in each point in figure 5 representing a specific number of slips or falls between 0 and 15. Negative values of COF_{diff} indicate that the DCOF is less than the RCOF, so less friction is available than required on the dry surface and slipping would be ideally anticipated. Positive values indicate that the measured DCOF is larger that the COF required, therefore slipping would not be expected. Note that at when $COF_{diff} = 0$ some falls occurred, some slips and recoveries occurred, and some trials occurred without incident. When $COF_{diff} < -0.2$ nearly every trial resulted in a fall; and at $COF_{diff} > 0.4$ no slips or falls occurred. There appears to be a distribution of the slip and

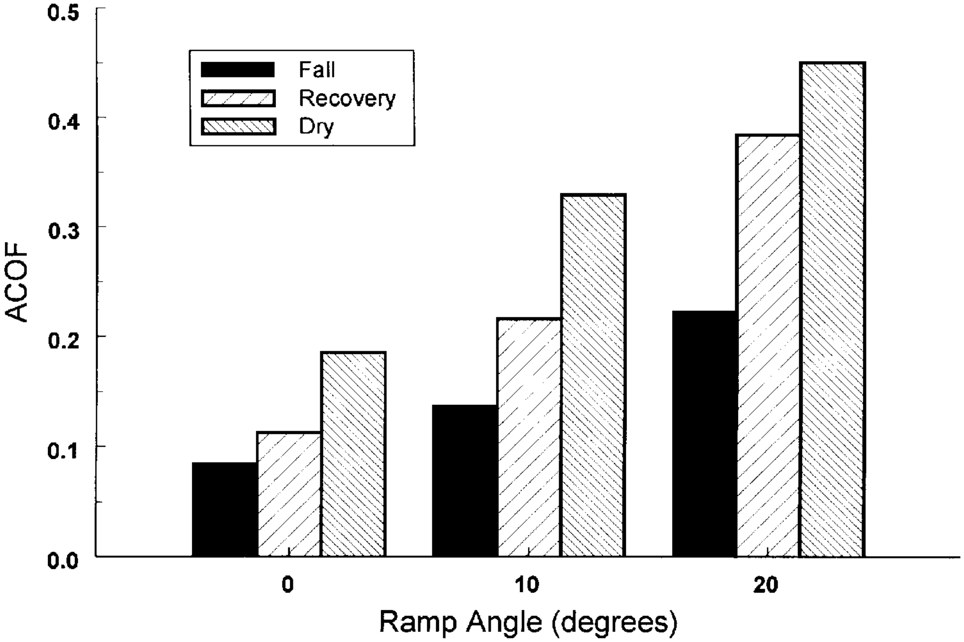

Figure 4. Peak values of the 'achievable' COF for the gait trials when falls and slips with recoveries occurred. Peak RCOFs for the dry conditions where no slips occurred are also shown for comparison.

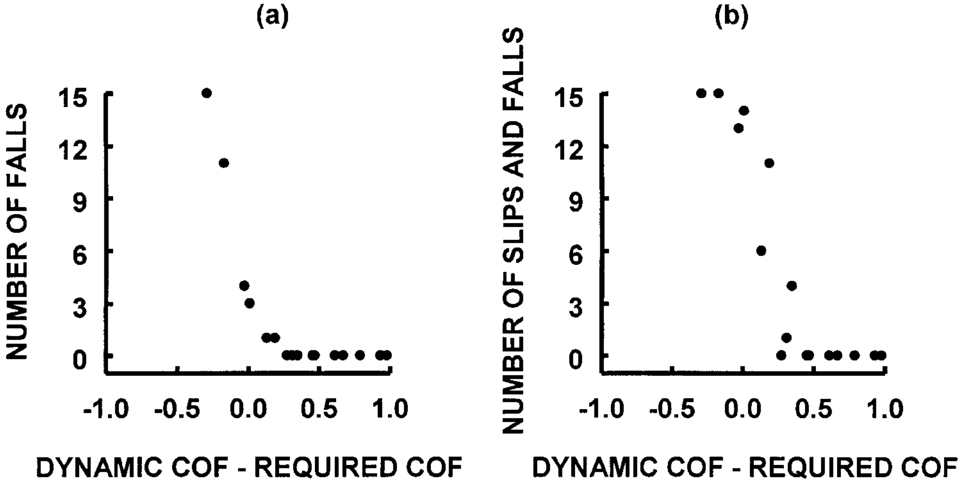

Figure 5. Number of slip and fall events that occurred as a function of the difference between the measured and required COF. Each point represents a specific combination of floor, contaminant and ramp angle. (a) Fall events only and (b) both slips with recovery and fall events are included.

recoveries that represents a transition between falls and walking when falls do not occur, centred near $\mathrm{COF}_{\mathrm{diff}} = 0$.

A logistic regression model was used to relate the observed slip and fall events to the $\mathrm{COF}_{\mathrm{diff}}$. This model is used in statistical analysis to model the relationship between a binary variable (corresponding in our case to occurrence and non-occurrence of a slip and fall event) to a set of explanatory variables. The model uses the explanatory variables to predict the probability that the response variable takes on a given value: y is the probability of a slip or fall event; x is $\mathrm{COF}_{\mathrm{diff}}$, the logistic regression model is as follows:

$$y = \frac{e^{(\beta_0 + \beta_1 x)}}{(1 + e^{\beta_0 + \beta_1 x})},$$

where β_0 and β_1 are parameters. They were estimated from the data using the LOGISTIC procedure of SAS. The regression is asymptotic to 0 on the lower tail (where RCOF is much greater than DCOF) and 1.0 on the upper tail (where DCOF is much greater than RCOF). The analysis showed that the logistic model provided a good fit to our data. The results of the fit are shown in figure 6 with the estimated parameters given in table 6. The probabilities shown in figure 6 are estimated from the number of occurrences (figure 5) out of the total number of trails ($n = 15$). As seen in table 3, there were $3 \times 3 \times 2 = 18$ factorial combinations of floor types, contaminants and ramp angles, and 15 observations per each combination resulting in a total of 270 data points.

The probability of a slip or fall was estimated based on the logistic regression model. Table 7 shows the estimated $\mathrm{COF}_{\mathrm{diff}}$ corresponding to specific probabilities of slips or falls at the $p = 0.50$, 0.95 and 0.99 levels. For example, a $\mathrm{COF}_{\mathrm{diff}} = -0.08$ corresponds to a p (no fall event) $= 0.50$, indicating that the trials have a $p = 0.50$ for resulting in a fall when the RCOF is 0.08 larger than the DCOF.

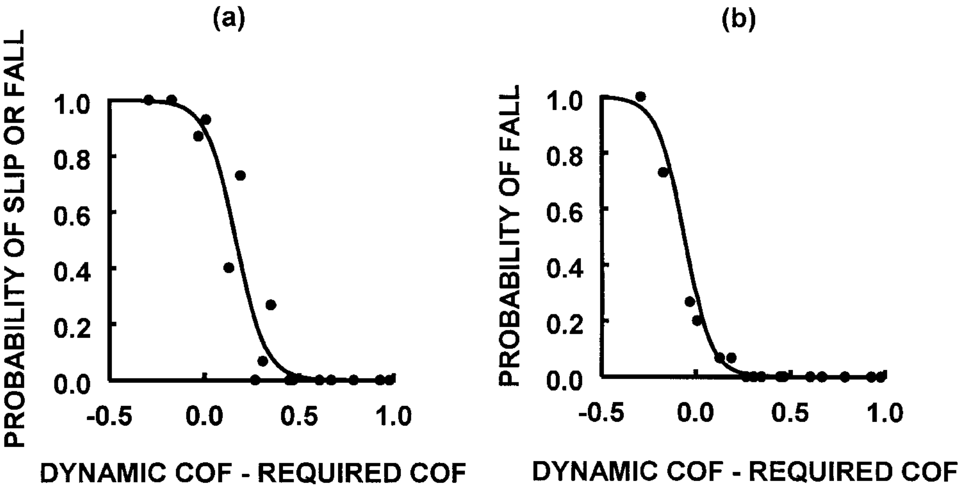

Figure 6. Results of the logistic regression model comparing the difference between the measured dynamic COF and the peak-required COF to the predicted probability of (a) a slip or fall event and (b) only fall events.

Table 6. Logistic regression results for measured slip events using COF_{diff}.

	Fall events only	Slip or fall events
B(0)[1]	1.17	− 2.10
B(0) SE	0.34	0.43
B(1)[2]	14.09	12.87
B(1) SE	2.52	1.88
Concordant[3]	96.6%	96.1%
Discordant[4]	1.6%	2.6%
Tied[5]	1.8%	1.3%

[1] B(0), point estimate of B_0.
[2] B(1), point estimate of B_1.
[3–5] For explanations, refer to *Logistic Regression Examples Using SAS System.*

Table 7. Logistic regression prediction of COF_{diff} for specific probabilities.

	DCOF-RCOF	
Probability	No fall	No slip
0.50	− 0.08	0.16
0.95	0.12	0.39
0.99	0.24	0.52

4. Discussion

The results show a relationship among measured friction, frictional requirements during walking, and slips and falls. Combinations of contaminant and floor were varied resulting in a variety of slipperiness measurements. Gait trials under these conditions for the three ramp angles produced responses ranging from no slip, to slips with recovery, to slips resulting in falls. A logistic regression model was used to relate the frictional measurements to actual slip and fall events. The probability of the occurrence of slips and falls was modelled using the difference between the peak RCOF and the measured DCOF as an independent variable.

Ideally, when the frictional requirements of walking exceed the frictional capabilities of the environment, a slip and fall should occur. In this study, the frictional requirements were quantified by the peak RCOF during dry trials in which no slips or falls occurred. Peak RCOFs have been used to describe the biomechanical requirements of walking on various surfaces (Buzec 1990, McVay and Redfern 1994, Redfern and Di Pasquale 1997) and performing pushing and pulling tasks (Redfern and Andres 1984). The assumption in the past has been that if the measured friction is lower than the peak RCOF (i.e. $COF_{diff} < 0$), then a fall should result. However, as was seen in this study, the relationship between slips and falls and COF_{diff} is not totally deterministic. There is range where no slips occur when the COF_{diff} is sufficiently high, and there is also a range where slips and falls always occur when the COF_{diff} is sufficiently low. Between these two extremes exists a range where slips and/or falls sometimes occur. To quantify the occurrence of slips and falls in this region, the notion of probability of slips and falls is introduced. The logistic regression model used in this study attempted to model the probability of slips and falls in this range of COF_{diff}. The concept of probability of falls is important in the design of environments to prevent slips. Environments need to be designed such that the probability of slip and fall is extremely low, for which the $COF_{diff} > 0$. This will be determined not only by the shoe, floor and contaminant exposures, but also the types of movements required.

The probability model proposed here is specific for the programmable slip resistance tester developed by Redfern and Bidanda (1994). However, the same protocol could be used to evaluate any slip resistance testing device. Each device could be evaluated with the same biomechanical data collected. Thus, comparisons of the predictability of slips and falls for each device could be performed. This comparison could be extremely useful. For example, a static $COF > 0.5$ is often cited as safe. However, different static devices can produce different COF measures depending on the shoe, floor and contaminant. It is possible that tests with one device could produce high COF measures leading to a conclusion that a certain environment is safe, while COF measures with a different device could be much lower leading to the conclusion that the same environment is hazardous. Comparisons among devices using data directly linked to slips and falls may help resolve this problem. However, it must be recognized that there may not be any one best slip resistance tester. Some slip testing devices may be better than others under specific conditions. For example, one device may be good at predicting slips and falls on wet surfaces, but be poor for oily conditions. Thus, evaluations of slip testing devices using actual gait studies need to be reported and interpreted for the set of specific conditions tested.

Slip testing devices could be evaluated using COF_{diff} data and examining the resulting logistic relationship. The bias of the tester could be defined as the COF_{diff} at which the probability of a fall is 0.50. The accuracy of prediction (AOP) could be defined as the range of COF_{diff} between the 5th and 95th probability estimates. Thus, the bias measures how far from the ideal of $COF_{diff} = 0$ the device is shifted, while AOP measures how wide the range of COF_{diff} is where falls occur. An ideal slip tester would have a Bias = 0 and an AOP = 0. A 'poor' slip tester would have a large AOP. Obviously, the AOP will never be zero since differences in the biomechanics of gait among subjects in the experiments (and real life) contribute to the width of the AOP. In addition, a tester with a significant bias is not necessarily 'poor', but the measurements must be interpreted on a different scale than a tester with a different bias. The PSRT used in this study resulted in a bias for falls of − 0.08 and an AOP = 0.40.

One point of interest is how the results of this study compare with the consensus safety standards currently used. The values for the PSRT in this study can be most appropriately compared with the standards for DCOF measures given by Ballance *et al.* (1985) based on the British Standards Institute (1977) that state a DCOF = 0.40 is the cut-off for a safe environment. This guideline is generally understood to be for walking on level surfaces. The peak RCOF for level walking was found in this study and others (Harper *et al.* 1967, McVay and Redfern 1994, Redfern and Di Pasquale 1997) to be ~0.18. At a DCOF = 0.40, the COF_{diff} for walking would be 0.22. In examining the distribution given by the logistic regression, a $COF_{diff} = 0.22$ equates to a probability 0.97 of no fall occurring and a probability 0.67 of no slip or fall occurring. Thus, the measurements by the PSRT under the conditions tested appear to reasonably follow the BSI guidelines in preventing falls. However, the probability of slips with recovery occurring may be too low. Questions regarding which value (falls or slips with recovery) to use are not clear and warrant further research.

A ramp was utilized during the gait trials to vary the biomechanical requirements beyond that of level walking. As ramp angle is increased the frictional requirements increase as the tangent of the angle (Redfern and Di Pasquale 1997). Varying the frictional requirements by changing the ramp angle creates a greater range of differences between the RCOF and the measured COF compared with varying the environmental factors alone. A broad range of COF_{diff} measures is needed to determine the risk of slips and falls from no slips to a condition where slips and falls always occur.

A secondary finding in this study was the comparison of measured slips and falls with perceived slips and falls. Perception of slipperiness and slips is of practical importance. Individuals are highly capable of evaluating relative slipperiness of a shoe – floor – contaminant interface (Swensen *et al.* 1992, Myung *et al.* 1993, Chiou *et al.* 1996). In this study, subjects were also found to be able to perceive when slips actually occurred in all but five cases. When subjects were incorrect, they did not perceive a slip when video recordings confirmed a slip had taken place. Thus, subjective errors occur in not noticing a slip when it occurred rather than incorrectly perceiving a slip that did not occur.

Some assumptions were made in this study that could lead to potential sources of error. First, it was assumed that the subjects' gait was consistent for all trials. Subjects were asked to walk normally (i.e. as if there were no contaminants on the surfaces) during all trials, but there may have been some subtle changes in gait between conditions. The subjects knew that there was a possibility of a slippery condition, and so could have slightly modified his/her gait. Every attempt was made to minimize this effect through having the subjects look at a point across the laboratory and not at the surface. In addition, subjects were reminded throughout the experiment to walk normally. An inspection of the data indicated that the subjects did walk consistently throughout the experiment. Foot forces were repeatable for the dry conditions and no differences in foot forces were found between floor surface conditions. However, there may have been changes across contaminant conditions that could affect the results. No obvious differences in the kinematics of the subjects were detected during the experiment. A second assumption was independence of the trials. Trials were blocked by floor to minimize the number of floor changes required. In addition, contaminant sequence was always dry, wet then soapy to minimize possible cross-contamination of the floor surfaces. Any order effects on the results would be confounded with the independent variable effects. Finally, the subjects in this study were limited to young, healthy adults. The results could be different for older adults or those with disabilities.

In summary, the results of this study indicate that the relationship between the frictional requirements of walking and measured friction of the shoe – floor – contaminant interface can be utilized to predict slips and falls. This relationship can be modelled as a logistic regression between the COF_{diff} and the probability of an event occurring. This approach can be used to evaluate the efficacy of slip resistance testers in predicting slip and falls. In addition the data can also be used to assist in the design of flooring systems for different environments to prevent slips and falls.

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