Effects of environmental and job-task factors on workers' gait characteristics on slippery surfaces

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Abstract. The objective of this study was to investigate the kinetic and kinematic aspects of slips associated with gait on a slippery surface under various environmental and job-task risk factors. Forty healthy industrial workers (age: 40.3 ± 14.9 years) participated in the study. Using a strain gauge type force platform and a video-based motion analysis system, kinetic and kinematic measurements of the subjects' foot movements were obtained. Of all gait trials, there were 1558 slips (60.9%). Slips were likely to occur when subjects were negotiating a turning path and an oily surface. Greater anterior-posterior center of pressure (CP) excursion and maximum required coefficient of friction (RCOF) were found for oily surfaces compared to dry surfaces. Subjects changed their gait patterns by shortening their stride length, slowing walking speed, and decreasing heel contact angle in the poorly lit and slippery environment. Significant correlations were found between slip occurrence and anterior-posterior CP excursion, mean RCOF, sliding distance and sliding velocity, but not the coefficient of friction (COF) of shoes. In addition to good housekeeping and proper selection of floor materials and safety shoes, slip and fall prevention should include proper workers' training in dealing with risk factors of slips and falls in the workplace.

Keywords: Slip, gait adaption, turning path, slip and fall prevention

1. Introduction

Accidents associated with slips and falls have been recognized as one of the major causes of injuries in workplace [3,4]. The US. National Safety Council estimated that occupational falls cause 250,000 to 300,000 injuries per year, and result in 1,200 to 1,600 deaths [20]. According to the 1996 National Census of Fatal Occupational Injuries conducted by the Bureau of Labor Statistics (BLS), the number of fatal work injuries fell to the lowest level in the five-year history of the Census of Labor [4]. However, fatalities from falls continued to rise, reaching a five-year high [4]. Falls are also one of the leading causes of non-fatal occupational injuries. In 1995, there were 343,929 nonfatal occupational falls that involved days away from work, which accounted for one-fifth of the total nonfatal injuries, based on the annual survey conducted by BLS [3]. It was estimated that lifetime costs associated with falls is $ 12.6 billion in the United States [24]. Falls have been found to be a significant contributor to lumbar spine injury, fracture of bones, and disability [10,17]. More often, the injury is a musculoskeletal strain

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Table 1
Demographic data

	Participants with kinetic data				Participants with kinematic data			
	Male (n = 20)		Female (n = 20)		Male (n = 5)		Female (n = 8)	
	mean	s.d.	mean	s.d.	mean	s.d.	mean	s.d.
Age (year)	41.0	14.9	39.5	14.9	49.4	11.8	54.1	3.6
Weight (kg)	84.6	12.5	75.9	18.6	84.3	12.5	73.0	19.7
Height (m)	1.75	0.05	1.61	0.06	1.72	0.05	1.63	0.06
Left foot length (cm)	27.2	0.88	24.7	1.00	27.5	0.86	24.9	0.70
Right foot length (cm)	27.3	0.84	24.7	1.07	27.4	0.98	24.9	0.82
Left foot width (cm)	10.1	0.47	9.3	0.52	10.2	0.42	9.3	0.49
Right foot width (cm)	10.0	0.51	8.8	2.13	10.0	0.38	9.2	0.47
Functional reach (cm)	76.0	3.4	69.4	4.5	75	5.6	70.5	4.8

injury, usually to the lower back, ankle, or knee [4]. As a result of these high frequencies of injuries and associated costs, the prevention of slips and falls is receiving an increasing amount of attention.

Biomechanical, tribological, epidemiological, psychological, and psychophysical studies on slips and falls have indicated that the causes of slips and falls in the workplaces are complex and many determining factors contribute to the mechanism of a slip [11,14,17,21]. Slips may arise from high shear forces at the feet as a result of the tasks being performed, conditions of poor illumination of the workplace, contaminated floor surface, poor slip-resistance of the shoe/floor interface, or poor perception of an impending fall and judgement of surface slipperiness [7,8]. Many industrial tasks require workers to maintain awkward postures, often resulting in muscle fatigue and propensity for loss of balance, which may give rise to a slip or fall accident.

To prevent slips and falls, previous studies have focused on the determination of RCOFs during gait and the development of slip resistance criteria [12,21]. The minimum RCOF to prevent any slipping was suggested to be 0.28 [21]. A minimum dynamic COF level of 0.20 was proposed to be "slip resistant" [12, 25]. However, these studies did not consider either the job-task factors (e.g., carrying a load, negotiating a curved path), nor environmental factors (e.g., poor lighting). Perturbations or external forces, such as carrying a weight in the hands or walking on a curved path, may increase the shear forces at the feet, thereby increasing the probability of slips. Further, lack of a worker-based database also limited the usefulness of the findings of previous studies. Thus, this study was undertaken to investigate the effects of environmental and job-task factors on slip occurrence and kinetics and kinematics associated with gait on a slippery surface. The effects of load carrying, shoe type, environmental lighting, surface slipperiness, and walking path on gait characteristics were examined.

2. Methods

2.1. Participant selection

Forty healthy worker subjects [mean age: 40.3 years ± 14.9 standard deviation (s.d.)] participated in this study. Kinetic data were collected from all forty subjects, while kinematic data were only collected for 13 subjects (mean age: 52.1 years ± 8.0 s.d.). Descriptive statistics for variables common to the subjects are provided in Table 1.

Subjects were recruited from local industries. These subjects represented a variety of occupations including radio operator, sales person, dock/receiving attendant, custodian, vehicle operator, plumber, health care worker, student, HVAC technician, clerical/secretary, store clerk, postal worker, laborer,

day care provider, and assembly line worker. This study was approved by the University of Cincinnati Human Research Committee and each subject was administered an informed consent statement before participating.

All study participants underwent a physical examination and medical history check-up. Subjects with a history of dizziness, tremor, alcoholism, vestibular disorders, neurological disorders, diabetic symptoms, cardiopulmonary disorders, and/or chronic back pain were excluded from this study.

2.2. Experimental conditions

There were five experimental conditions in the study – surface slipperiness, lighting, shoe type, weight carriage, and walking path. The experiment was blocked by the surface slipperiness conditions. Each subject underwent four testing sessions on four different days. During each session, there was only one surface condition, and two kinds of shoe conditions. Under each shoe condition, four test conditions were randomly selected from the total of eight combinations of light (good and poor), weight in hands (with and without), and paths (straight and turning). Each subject underwent 64 gait tests (32 tests replicated once). However, kinematic data were collected only for trials on a straight path from a sagittal view (Fig. 1). The various foot motions in negotiating a turning path, as performed in this study, cannot be captured by a two-dimensional kinematic analysis. The five experimental conditions are listed as the following:

Condition 1: Four levels of randomized slippery surfaces: dry, slightly, medium, and very oily surfaces.
Condition 2: Good (70 to 71 foot-candles) or poor (0.2 foot-candles) environmental lighting.
Condition 3: Subjects wore either new shoes provided by the laboratory or the subject's own old shoes (used shoes).
Condition 4: Subjects walked on a straight path or a turning path.
Condition 5: Subjects walked with a 5-pound weight in hand or with no weight.

2.3. Experimental procedures

2.3.1. Determination of shoe-surface slipperiness

The three levels of surface slipperiness used in this study were created by evenly applying glycerin on aluminum plates secured onto the force plate. The appropriate amount of lubricant needed to create the desired ranges of dynamic COF values had been determined by a series of pilot tests [7,8]. The particular shoe-lubricant-flooring combinations create three levels of slipperiness with dynamic COF values of 0.35, 0.18, and 0.11, representing slightly, medium, and very oily surfaces, respectively. This classification was based on Grönqvist's slip resistance criteria [12]. For COF values equal or greater than 0.30, a slip is unlikely to occur. For COF values of 0.15 to 0.19, a slip is possible, but often the loss of balance is recoverable. For COF values less than 0.14, a sudden slip will cause loss of balance. The dynamic COF values for used shoes and new shoes were also determined for the three levels of slipperiness. The relationship between shoe COF and subjective perception of slipperiness were reported elsewhere [8].

2.3.2. Gait test setup

A T-shaped walkway was used in the test as shown in Fig. 1. Subjects walked from point A and traveled (1) straight to points B and C or (2) to point B then turned left to point D. In both situations,
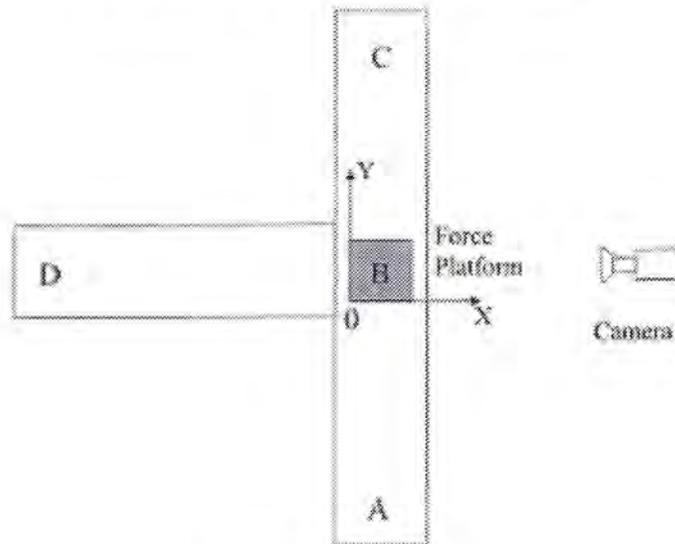
Fig. 1. Gait test setup.

the subjects were required to walk in a normal fashion, making certain that they stepped on the force platform (point B) with the right foot. Practice trials were performed at the beginning of the test sessions to ensure proper stepping. Trials with mis-stepping were repeated. Since walking on a slippery surface presented the risk of fall, a safety harness system with an overhead monorail attachment was used to ensure the safety of the subject in case of a fall. The lanyard of the harness was properly adjusted for the body dimensions of each subject, so that he/she would be protected but not restricted by the harness during walking.

In between each testing condition, the subject was asked to rub his/her shoes on special floor mats placed at points C and D. These rubber mats contained soapy water, which is good for cleaning the oil residue left on the shoe soles. The subjects then rubbed the shoes on an oil absorbing paper before the start of the subsequent trial.

2.3.3. Instrumentation

The kinematic measurements, which included incoming velocity, sliding distance, sliding velocity, heel contact angle and cycle time, were collected using a high frequency video camera (Pulnix camera: model TM-640) at 60 Hz. The camera focused solely on the foot that was in contact with the force plate to obtain a close-up observation of the foot-flooring interaction in the sagittal plane. The videos were then digitized to determine two-dimensional measurement of heel velocities and contact angle at heel strike in the sagittal plane using a video-graphic motion measurement system (Peak^{TM} Performance Technologies Inc., Englewood, CO).

The kinetic measurements, which included the forces and moments exerted on the force platform, were collected using a strain-gauge type force platform (Model OR6-5-1000, AMTI, Newton, MA) capable of measuring forces and moments in the three orthogonal directions. The details regarding the accuracy of the force plate are available in a previous study [2]. The force platform was placed flush with the floor and data were collected using Peak Performance Software (Peak Performance Technologies Inc.,

Englewood, CO) at 600 Hz. On the day of each testing session, the force platform calibration was checked to ensure that the measurement error of the plate was within the acceptable 2% range [2].

2.4. Description of dependent variables

2.4.1. Kinetic variables

Five numeric variables evaluated in this study included normal force, anterior-posterior (AP) and medial-lateral (ML) excursions of center of pressure (CP), maximum and mean RCOF. A categorical variable – slip – indicating if the subject slipped or not, was also recorded during the test session by a staff member.

Normal force is simply the vertical force (Fz) as a function of time applied to the floor surface during gait. The maximum and mean RCOF are defined as the maximum and mean ratio of shear force to normal force, respectively, while subjects stepped on the force plate. The shear force is the magnitude of the vector sum of forces in the x and y directions in the horizontal plane.

The CP excursion parameters are defined on the basis of the CP trace under the stance feet during gait. Figure 2 illustrates the trace of CP movement under the stance foot. The ML and AP excursion is the peak-to-peak range of CP displacement in the medial-lateral and anterior-posterior directions, respectively. These excursion parameters quantitate the extent of movement of the point of application of plantar force under the supporting feet. The movement of the CP under the stance foot is a time variant response to the momentary position of the whole body center of gravity (CG) with respect to the measure of dynamic stability performance during the gait. The cycle time in seconds is the time interval between heel strike and toe off.

2.4.2. Kinematic variables

A five-marker system, shown in Fig. 3, including markers placed on (1) heel, (2) 5th metatarsal point, (3) ankle, (4) plate near point, and (5) plate far point, was utilized for digitization and to calculate the gait variables, including contact angle, sliding distance, sliding velocity, incoming velocity and cycle time. A two-dimensional coordinate system was also defined as in Fig. 3 to facilitate the analysis.

The contact angle was defined as the tangent between the shoe sole and the flooring when the heel strike happens. The contact angle was obtained by calculating the angle between the lines joined by the shoe sole leading edge and the shoe sole trailing edge, and the plate near point and plate far point (Fig. 3).

The sliding distance of a slip was obtained by calculating the heel marker's displacement in the AP direction during a slip, as shown in Fig. 4. The displacement of the heel marker during a slip was determined by comparing the heel marker's coordinates in the AP direction at the beginning and the end of a slip.

Once the sliding distance had been measured, the average sliding velocity was then calculated from the sliding distance and the time elapsed during a slip. The elapsed time, which is the cycle time, was determined by the number of frames containing the slip and the video sampling frequency (60 Hz). The incoming velocity was determined by averaging the velocities of the last 10 frames immediately before the heel contact.

2.5. Data analysis strategy

A logistic regression model was used to test the effects of experimental conditions of shoe type, surface slipperiness, lighting, walking path (turn or curved vs. straight) and whether a weight was carried on slip occurrence. The kinetic outcomes of normal force, CP excursions in the AP and ML directions,
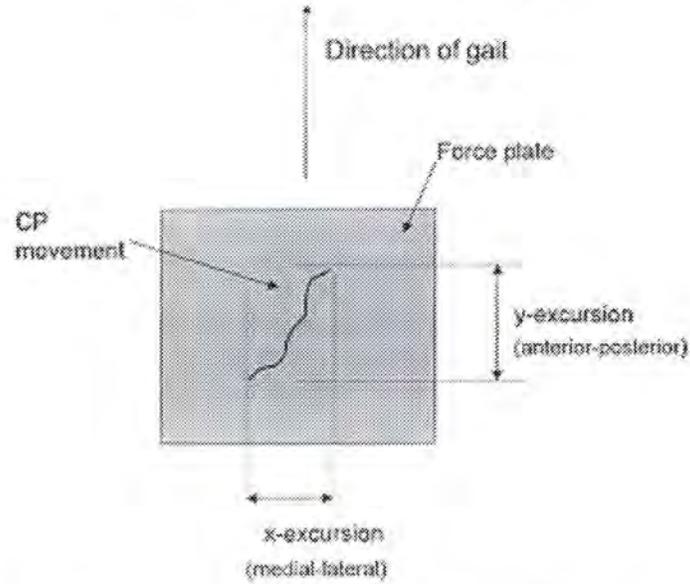
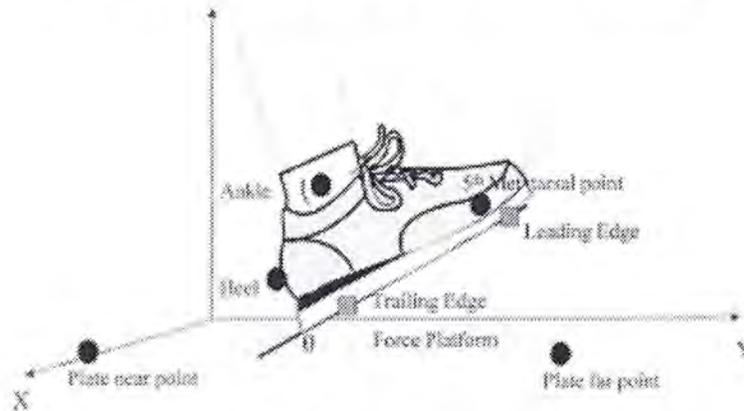Fig. 2. Illustration of anterior-posterior and medial-lateral excursions of CP.

Fig. 3. Illustration of 5-marker system and heel contact angle (θ): θ was determined by the angle between the lines joined by the shoe sole leading edge and the shoe sole trailing edge, and the plate near point and plate far point.

maximum RCOF, and mean RCOF were analyzed in both univariate and multivariable repeated measure analysis of covariance (MANCOVA). Kinematic measures of incoming velocity, heel contact angle, sliding distance, sliding velocity, and cycle time were analyzed in a separate MANCOVA model. The within-subject conditions analyzed for each variable were experimental conditions. The between-subject covariates of age, gender and height were used in the MANCOVA. An alpha-level of 0.05 was used in all tests of a null hypothesis. For any significant independent variables ($p < 0.05$), a posteriori comparisons were performed to further compare the levels of that experimental variable.

Pearson correlation analyses were carried out to determine if there are associations between number of
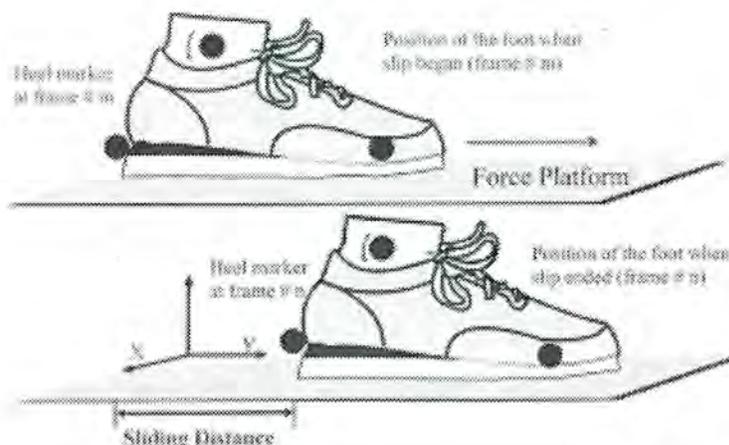
Fig. 4. Illustration of sliding distance: sliding distance was determined by the heel marker's displacement in x direction between the beginning (at time frame # m) and the end (at time frame # n) of a slip.

slips, COF of shoes and gait variables. In the analyses, the kinetic and kinematic variables were averaged across all experimental conditions.

3. Results

3.1. Slip occurrence during gait on slippery surfaces

In this study, the subject was considered to experience a slip if the subject's foot was sliding or the foot did not reach foot flat after heel strike. Video tapes were viewed if the investigators were unable to visually judge the slip occurrence during any of the trials. Of all the gait trials, there were 1558 slips (60.9%). Results from Logistic Regression Analyses indicated that slips were more likely to occur when negotiating a turning path compared to a straight path ($p < 0.01$). Slippery surfaces (slightly, medium, and oily surfaces) produced more slips than dry surfaces (all p values < 0.01). High frequencies of slip occurrence were associated with wearing new shoes (vs. used shoes, $p < 0.01$), and good lighting conditions (vs. poor lighting, $p < 0.04$). The effect of load carrying did not produce any significant effects on slip occurrence ($p > 0.05$).

3.2. Effect of risk factors on kinetic variables

Multivariate analyses of an overall effect on the kinetic outcomes were significant for all of the within-subject conditions except for whether a weight was carried ($p = 0.21$). Surface slipperiness was found to be significantly related to most kinetic outcomes, including AP excursion, ML excursion, and maximum RCOF (all $p < 0.01$). Table 2 presents the means and standard errors of kinetic variables for various testing conditions. Multiple comparisons indicated that the ML excursion on dry surfaces was significantly less than that on slightly, medium or very oily surfaces (all p values < 0.01). Similarly, smaller AP excursion was found for dry surfaces compared to slightly or medium or very oily surfaces (all three p values < 0.01). The maximum RCOF was smaller for dry surfaces than for any of the oily surfaces (all p values < 0.01).

Table 2
Means and standard deviations of kinetic variables for various risk factors

Risk factor		Normal Force (N)	AP excursion (cm)	ML excursion (cm)	Max. RCOF	Mean RCOF
Surface	Dry	753.3	25.6	11.8	0.196	0.029
		(235.2)	(6.1)	(8.8)	(0.200)	(0.029)
	Slightly	744.8	26.3	10.3	0.217	0.020
		(226.5)	(7.7)	(7.7)	(0.233)	(0.016)
	Medium	738.2	28.5	9.3	0.212	0.019
		(211.3)	(8.8)	(6.7)	(0.225)	(0.016)
	Very	718.9	28.9	10.2	0.203	0.019
		(223.2)	(9.5)	(7.4)	(0.228)	(0.024)
Shoe	New	736.7	27.6	10.3	0.206	0.021
		(220.8)	(7.7)	(7.5)	(0.216)	(0.018)
	Used	740.9	27.0	10.5	0.207	0.023
		(228.3)	(8.7)	(8.0)	(0.227)	(0.026)
Load	Without	729.4	27.2	10.3	0.204	0.022
		(219.9)	(8.1)	(7.7)	(0.220)	(0.025)
	With	748.2	27.4	10.5	0.209	0.022
		(228.7)	(8.4)	(7.7)	(0.224)	(0.019)
Path	Straight	748.5	27.9	5.5	0.112	0.019
		(227.1)	(6.4)	(4.2)	(0.221)	(0.016)
	Turn	729.1	26.7	15.3	0.301	0.024
		(221.5)	(9.7)	(7.2)	(0.178)	(0.027)
Light	Good	737.0	27.2	10.4	0.198	0.023
		(226.6)	(8.1)	(7.9)	(0.212)	(0.026)
	Poor	740.6	27.4	10.4	0.216	0.021
		(222.5)	(8.4)	(7.6)	(0.231)	(0.018)

The ambient lighting was significant in only the univariate test for mean RCOF ($p < 0.05$). Poor lighting conditions resulted in somewhat smaller mean RCOF with respect to good lighting ($p < 0.05$). The path traversed was found to be significant in five univariate tests except for AP excursion, in addition to the significant multivariate test noted above. Subjects traversing the turn had significantly smaller normal force, much greater excursions in the ML direction, and higher maximum and mean RCOF values, as compared to subjects walking along the straight path (all p values < 0.01).

The normal force was found to be affected in a univariate test of the differences due to carrying a weight ($p < 0.01$). Subjects carrying a weight tended to have greater normal forces, however, since this is the only univariate difference discovered for the effect of carrying a weight and the multivariate test for this experimental condition was not significant, it is likely to be due to chance. Furthermore, carrying a weight would be expected to increase the normal force since the added weight simply increased the downward force beyond the subject's own body weight associated normal force.

3.3. Effect of risk factors on kinematic variables

Results from MANCOVA indicated that the effect of surface slipperiness was highly significant on all five kinematic parameters ($p < 0.01$). The effect of environmental lighting was significant on incoming velocity ($p < 0.02$), heel contact angle ($p < 0.01$), and cycle time ($p < 0.01$) as indicated by the results of univariate analyses. Table 3 presents the means and standard errors of kinematic variables for various conditions. The incoming velocity and heel contact angle for good lighting conditions were significantly greater than those of poor lighting conditions (both p values < 0.01). Subjects walked more slowly in poor lighting conditions compared to good lighting conditions ($p < 0.01$) and thus resulted in longer cycle time ($p < 0.01$).

Table 3
Means and standard deviations of kinematic parameters for various risk factors

Risk factor		Sliding distance (m)	Sliding velocity (m/sec)	Heel contact angle (degree)	Incoming velocity (m/sec)	Cycle time (sec)
Surface	Slightly	0.009	0.04	12.73	0.98	0.757
		(1.003)	(1.012)	(1.48)	(0.14)	(0.152)
	Medium	0.019	0.09	11.92	1.06	0.722
		(1.001)	(1.026)	(1.94)	(0.22)	(0.154)
	Very	0.034	0.15	11.79	1.10	0.708
		(1.005)	(1.04)	(2.13)	(0.26)	(0.177)
Lighting	Good	0.02	0.09	12.38	1.09	0.716
		(1.0008)	(1.036)	(1.90)	(0.19)	(0.153)
	Poor	0.02	0.09	11.93	0.98	0.741
		(1.0016)	(1.020)	(1.57)	(0.19)	(0.171)

The very oily surfaces produced the greatest sliding distance (0.034 m) and velocity (0.15 m/sec), followed by the medium oily (0.019 m, 0.09 m/sec) and slightly oily surfaces (0.009 m, 0.04 m/sec, all p values < 0.03). Further, the mean heel contact angle of the slightly oily surface was found to be significantly larger than for other two oily surfaces (both p values < 0.03). The cycle time, defined by the time duration between heel strike and toe off, was the longest for slightly oily surfaces, which was significantly longer than the time for medium oily and very oily surfaces (p values < 0.0001).

The effect of shoe type was found to be significantly different in univariate comparisons involving cycle time ($p = 0.01$). Subjects walked slowly when they wore new shoes as indicated by significantly longer mean cycle times (0.75 second) as compared to used shoes (0.72 second, $p = 0.01$).

To further investigate the relationship between the sliding distance and surface slipperiness, the measured sliding distances were categorized into micro slip (< 3 cm), slip (between 3 and 10 cm), and slide ($>= 10$ cm). Using these categories, slip occurrence was categorized, and the percentage distribution discrepancy for each level of surface slipperiness is illustrated in Fig. 5. The sliding distances were found to be different for different levels of surface slipperiness. Although most of the slip occurrences fell into the category of micro slip across different levels of surface slipperiness, under very and medium slippery surfaces, higher percentages of slips and slides were observed than under the slightly slippery surface conditions.

3.4. Correlation analyses of gait variables with shoe COF and number of slips

Slip occurrence in the workplace has often been hypothesized to be related to the COF of the shoes, and slip-prevention efforts included the provision of work shoes with higher COFs. For this project, correlation analyses were undertaken to test for associations between slip occurrences and shoe COF. Results from Pearson correlation analyses indicated that no relationship existed between the number of slips and shoe COF ($r = -0.38$; $p = 0.19$). Table 4 presented the results of correlation analyses for kinetic variables. Two significant ($p < 0.05$) correlations were found for the total number of slips with the kinetic variables. A positive correlation with AP excursion ($r = 0.36$) and a positive correlation with mean RCOF ($r = 0.42$; $p < 0.05$) was found. The variable of shoe COF was not significantly correlated with any of the kinetic outcomes. Similar analyses conducted on the five kinematic variables showed significant positive correlations between the number of slips and the two kinematic variables of sliding distance ($r = 0.61$, $p < 0.03$) and sliding velocity (0.56, $p < 0.05$). These findings indicated that the larger the sliding distance and sliding velocity, the greater the number of slips observed.
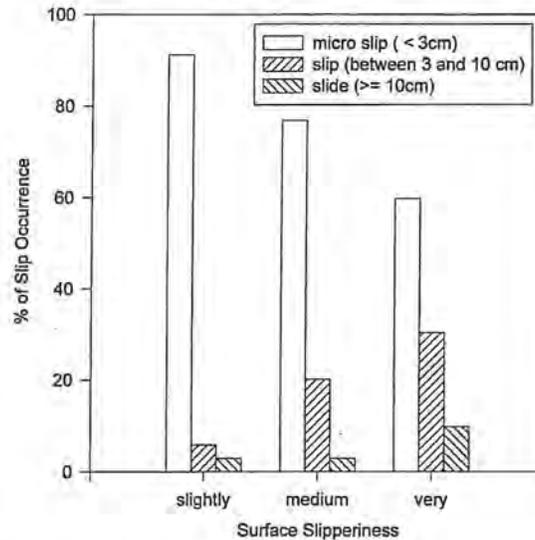
Fig. 5. Percentage of slip occurrence for various sliding distance and surface slipperiness conditions.

Table 4
Pearson correlation coefficients of kinetic and kinematic outcomes, shoe COF, and total number of slips

		Number of slips	Shoe COF
Kinetic variables	Normal Force	−0.16	0.11
	AP excursion	0.36*	−0.21
	ML excursion	−0.16	0.13
	Maximum RCOF	0.18	−0.05
	Mean RCOF	0.42*	−0.09
Kinematic variables	Incoming velocity	0.05	0.31
	Heel contact angle	−0.07	−0.25
	Sliding distance	0.61*	−0.015
	Sliding velocity	0.56*	0.15
	Cycle time	−0.02	−0.19

Any findings with $p < 0.05$ were considered statistically significant.

4. Discussions

4.1. Slip occurrence during gait tasks on slippery surfaces

This study provided an experimental design which investigated the effects of environmental and job-task risk factors on slip incidents and the dynamics of slip events. From a total of 2560 gait trials, about 60.9% of the trials produced observable slips. Significantly higher number of slips occurred on oily surfaces than dry surfaces as COFs of oily floors (0.35, 0.18, 0.11 for slightly, medium, and very oily respectively) were much smaller than dry floors (0.7). On an average, subjects slipped about 65%, 87%, and 91% of all trials performed on slightly, medium, and very oily surfaces, respectively. The slip occurrence for traversing a turning path (63.7%) was significantly greater than that for a straight path (56.3%). These findings indicate that traversing a turning path and walking on an oily surface appeared to be hazardous.

Previous research has documented that slips are most likely to occur at heel strike during locomotion [14,25]. When walking straight, there are decelerative horizontal forces at heel strike in the longitudinal direction and accelerative forces during propulsion, however, these force vectors are different when making a turn [9]. On turning a corner, horizontal forces in both longitudinal and transverse directions are increased at and after heel strike, and decreased during propulsion [9]. The increase in horizontal forces at heel strike would increase the friction demands required for walking safely without slipping, which might contribute to the high slip occurrence on a turning path at the most critical event of the gait cycle – heel strike. The increase in friction demands was observed in this study as the maximum and mean RCOF for turning path (Table 2). The friction demand variables were significantly greater than those of straight path ($p < 0.001$). An other explanation for more slip occurrences on a turning path is the high possibility of sideward slips. When walking straight, slips usually occur at heel strike with the subject falling backwards, or at toe-off with the subject falling forwards. In addition to these slips, sidewards slips of forefoot can also occur when negotiating a turning path [9,28].

Surprisingly, the number of slips was higher with new shoes than used shoes. This may be due to that subjects were familiar with their own used shoes, therefore it was easier to adapt to oily surfaces as they could adjust their movement strategies effectively when negotiating slippery surfaces. One other explanation is that the new shoe soles were not roughened prior to the experiment, thus they were relatively smooth compared to used shoes with certain degrees of roughness due to wear. More slips were also observed in good lighting conditions compared to poor lighting conditions. This may be attributable to the fact that subjects were very cautious in poor lighting conditions. They walked slowly when the light was dim and this was reflected in longer cycle time and slower incoming velocity compared to good lighting as observed in the experiment (Table 3).

4.2. Effect of risk factors on kinetic variables

Results from both multivariate and univariate analyses revealed significant effects of surface slipperiness and path. The normal force on a turning path was less than that observed on a straight path, while the cycle time of a turning path was longer than that of a straight path (Tables 2–3). This might be due to subjects walking more slowly on slippery surfaces, resulting in low normal ground reaction force, since force is related to walking speed. The AP excursions for medium and very oily surfaces was greater than that of slightly oily or dry surfaces, indicating smaller AP movement of CP for dry and slightly oily surfaces. Furthermore, AP excursion was found to have a significant positive correlation with the number of slip occurrences. The greater the AP excursion, the more slips occurred. Generally, most slips during gait are either forward or backward slips. The increase in AP excursion may, in itself, challenge the subject's stability by increasing the forward excursion of CG beyond the base of support provided by the stance foot.

Smaller maximum RCOF was required for dry surfaces than any of the oily surfaces, but there were no significant differences among the three levels of slippery surfaces in terms of number of slips. In other words, it can be simply stated that greater friction was required to walk on slippery surfaces safely without slipping. The non-differentiable outcomes among the three oily surfaces may be due to subjects' adaptions to slippery surfaces. After repeated exposures to slippery surfaces, subjects might change their gait patterns by shortening stride length, slowing walking speed, and prolonging double support stance phase of gait cycle. These gait changes minimize the shear forces exerted during heel strike, thereby decreasing the friction required for walking on slippery surfaces without slipping. According to results from correlation analyses, the maximum RCOF appeared to be a poor indicator for slips, rather, mean

RCOF had a positive correlation to the number of slips ($r = 0.42$). The mean RCOF was derived by averaging the RCOFs across the time period when the subject's foot was in contact with the force plate. Therefore, a consideration of the RCOF values over the entire stance period may be more important than just the maximum value. The analysis of friction gradients during the transition from static to kinetic may also help to better understand the risks of slipping [13].

The effect of load carrying did not show any significant differences in any of the kinetic variables except normal force. This might be due to the small load used in the experiment. Subjects were required to carry a light weight object (5 lb) that was carried symmetrically. The five-pound weight was lighter than most objects carried by workers at industrial or construction sites. Subjects can easily adjust their gait on a slippery surface when carrying a light object. The human body may become less stable as the weight and height of a load increases [9]. Carrying an object symmetrically might even increase postural stability, however, the chance of recovery is less likely if a slip occurs [15]. In a study of ramp safety, carrying a load was found to increase the ratio of shear to normal foot force when descending a ten-degree ramp, but not for level walking [5].

The effect of path was significant on all kinetic variables, except AP excursion. Gaits on a turning path were found to result in greater ML excursion, maximum RCOF and mean RCOF. As discussed earlier, more slips occurred on a turning path than on a straight path. Negotiating a turning or curved path during gait appear to be hazardous but rarely studied. In the real world, however, very few functional activities are exclusively linear. When turning a corner, the body's center of gravity shifted towards the inside of the curved path, decelerated in the longitudinal direction, and accelerated towards the new direction [9]. The shift in center of gravity sideways and the increase in horizontal forces at and after the heel strikes due to directional changes during gait imposed a perturbation of balance on the human body.

4.3. Effect of risk factors on kinematic variables

Results from the kinematic analysis indicate that there were behavioral changes associated with the slipperiness of the walking surfaces. The first obvious kinematic change was that subjects walked more slowly in a poorly lit condition. This finding of longer cycle time and smaller incoming velocity reflected the gait changes in adapting to the poorly lit environment (Table 3). Subjects also decreased the angle of shoe incidence with the floor when they could not see clearly in the poor lighting conditions, implying a cautious strategy.

The importance of visual inputs during gait are fairly obvious. In poor lighting conditions, subjects' proprioception and vestibular systems were challenged due to the lack of visual input. Under these circumstances, their gait was altered as indicated by the lower incoming velocity, longer cycle time, and smaller heel contact angle. However, no changes in incoming velocity were found due to the effect of different levels of surface slipperiness. One explanation for this phenomenon is that subjects were kept uninformed as far as the degree of surface slipperiness. Therefore, they were not aware of the existence of contaminants on the force plate or the degrees of slipperiness until their right foot hit the force plate. They were not able to adjust their walking speed accordingly a priori. However, subjects were able to alter their gait in a poor lighting condition prior to reaching the force plate. These findings suggest that subjects were able to adapt to walking on slippery surfaces if sufficient afferent inputs in terms of visual cues or proprioceptions were provided. Such findings have practical applications in safety training.

Some kinematic changes were found after subjects stepped on the force plate coated with different levels of contaminants. The heel contact angle on either medium or very oily surfaces was significantly smaller than that on the slightly oily surfaces. In other words, the foot angle of incidence decreased

on medium and very oily surfaces compared to slightly oily surfaces. This finding is consistent with previous research and represents one of the adaptions to walking on slippery surfaces [1].

Slips can be classified into micro slips, slips and slides with respect to slipping distance. The micro slip was defined as a sliding movement within a distance of three cm in the event of a slip and such micro slips were frequently undetected [16]. Slips and slides represent sliding movements of 3 to 10 cm, and greater than 10 cm, respectively [16]. In the current study, the mean sliding distance for very oily surfaces was 3.4 cm, which was significantly longer than that for slightly oily (0.9 cm) or medium oily surfaces (1.9 cm). The analysis of the slip occurrence showed that most slips were micro slips across all three levels of slipperiness. However, slightly oily surfaces had the highest percentages of micro slips, followed by medium oily and very oily surfaces (Fig. 5). On the contrary, very oily surfaces had the highest percentages of slips (with sliding distance between 3 and 10 cm) and slides (> 10 cm). The sliding velocity was the highest for very oily surfaces (0.15 cm/sec) compared to medium (0.09 m/sec) or slightly oily surfaces (0.04 m/sec). These findings are expected, as the design of the three levels of slipperiness was based on Grönqvist's classification of slips [12]. The dynamic COF for very oily surfaces of this study was 0.11, which may cause a sudden slip and loss of balance [12].

The correlation analyses of number of slips and COF values with kinematic variables indicate that slip occurrence was highly correlated with sliding distance ($r = 0.61$) and sliding velocity ($r = 0.56$). The greater the sliding distance and sliding velocity, the more slips occurred. As the sliding distance increased, slips were more likely to be detectable by subjects and loss of balance was often not recoverable. Micro slips with small sliding distances was often undetected and recoverable. These findings are consistent with previous studies which suggested that the displacement of the slipping foot and the velocity of the slipping foot are determinants of whether a slip will eventually result in a fall [21,25].

Previous studies have documented that human can adapt to walk continuously over slippery surfaces when the subject is aware that a slippery surface is being approached [1,6,21]. Workers should be instructed on how to modify their gait when walking over slippery surfaces that cannot be avoided in the workplace. The preventive strategies of walking on a slippery surface would be the decrease in stride length, walking speed, and the foot contact angle at heel strike.

Awareness of a potentially dangerous situation and appropriate modification of gait patterns may be one of the preventive strategies against falling as a result of slip. However, recognizing an impending danger of slipping, and the defensive adaption of engaging appropriate gait strategies, is not always possible. The number of slip occurrences was found to be positively correlated with sliding distance and velocity. Collectively, these results indicate that once a micro slip is initiated, reducing the sliding distance and velocity of the slipping foot may reduce the likelihood of a slip or fall incident. This may be achieved by better footwear and floor design to reduce slip displacement and velocity once a micro slip is initiated. In addition, proper training of workers cannot be neglected. The human body's nervous system can acquire an appropriate motor response after exposure to repeated trials of slipping [26,27]. Subjects who were cautious in assessing surface slipperiness prior to walking on a slippery surface had less postural instability during task performance [8]. These studies imply that workers may be trained to walk on slippery surfaces safely at the work place. However, the role of the human body itself in preventing slips is often overlooked since traditional slip and fall prevention programs emphasize the importance of providing floors and shoes with the best slip resistance characteristics.

5. Conclusions

Slip and fall prevention cannot be achieved through a single approach. It requires consistent and synergetic efforts through administrative control of good housekeeping, engineering control of proper

floor materials and safety shoes, as well as proper training of workers in dealing with risk factors of slips and falls at the work site. The conclusions reached by this study are:

1. The percentage of slip occurrence during locomotion on slippery surfaces was high (60.9%). Traversing a turning path appeared to be more hazardous than a straight path.

2. The physical characteristic of the shoe in terms of COF is not related to slip occurrence. Rather, the sliding distance, sliding velocity, CP movement of the stance feet, and mean RCOF are important factors associated with slip occurrence.

3. A training program is needed to instruct workers on how to modify their gaits when walking over slippery surfaces that cannot be avoided in the workplace. The preventive strategies for walking on a slippery surface would be a decrease in stride length, walking speed, and the foot contact angle at heel strike.

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