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Effects of walking environments on the objective and subjective gait measures during dynamic task performance

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Abstract. The objectives of this study were to evaluate the use of the center-of-gravity-based and center-of-pressure-based gait measures associated with loss of balance as well as the use of perceived sense of postural sway and instability (PSPSI) for the prediction of slip occurrence during dynamic task performance. The objective gait measures were determined by a multi-camera body motion analysis system and a strain gauge force platform. Twenty six trials performed by 21 subjects were collected for two walking environments in a laboratory-based experimental set-up. Two environments included the best (walking straight on a dry surface in good lighting) and the worst (walking straight on a slippery surface with a 2.3 Kg weight in the hand in poor lighting). Among the gait measures used in the study, it was found that the maximum distance between the center of pressure and the center of the base of support (OPmax) and the slide distance were the significant predictors of slip occurrence. An increase in the OPmax or slide distance indicates an increased likelihood of slip occurrence. The walking environment was found to have a significant effect on the PSPSI scale. It appears that the subjects were able to distinguish the difference in the walking environment but unable to perceive the potential hazards related to slips/falls during dynamic task performance. A comparison between the OPmax and slide distance (objective measures) and the PSPSI scale (subjective measure) can be used to predict a mismatch between the subjective perception of slip potential and the actual risk of slipping during task performance on a slippery surface.

Keywords: Perceived sense of postural sway and instability, gait measure, posture, balance

1. Introduction

Accidents related to slips and falls have been recognized as a primary risk factor of injuries in the workplace, especially in the construction industry. In 1991, according to the National Safety Council, approximately 12,400 Americans were killed as a result of falls in the workplace. Also, falls were the third leading cause (17%) of occupational injury resulting in disability [9]. In 1996, the number of fatal falls accounted for 11 percent of the total fatal injuries [15]. In 1988, Manning et al. [8] reported that approximately 2.9 million (62%) occupational accidents were caused by slipping and 0.8 million (17%) by tripping in the United Kingdom. Also, studies have shown that 50% of falls are immediately preceded

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by a slip [3]. Therefore, the maintenance of balance during walking or dynamic task performance is critical in many industrial settings. Understanding the control of postural balance on a slippery surface plays a key role in preventing falls that result in serious injury or mortality in the workplace.

Biomechanically, postural stability is provided by controlling body movements that maintain the whole body center of gravity (CG) within the base of support (BOS). The displacements of the CG and the center of pressure (CP) with respect to the BOS are useful predictors of postural stability [5, 6]. The measurement of the CP has been reported to be a reliable and fast method to quantify postural instability [2]. However, the measurement of CG requires a time-consuming digitizing procedure using filming technology [19]. Previous studies have shown that the locations of the CG and the CP are approximately the same during the static or semi-static posture [1,2,5,7,19]. Therefore, the measurement of the CP has been used to evaluate the postural stability during static or semi-dynamic task performance.

In this study, new gait measures related to postural instability during dynamic task performance were introduced and evaluated. The first objective of this study was to evaluate the use of the CP-based or CG-based gait measures for the prediction of slips in different walking environments.

During dynamic task performance, the motion of the CG with respect to the BOS cannot be perceived by a person. On the other hand, the movement of the CP is perceived by pressure receptors under the soles of an individual's feet, causing appropriate muscular contractions to maintain the CG within the BOS. The ability to perceive a slip/fall is crucial to maintain balance in many industries. Subjective ratings for slipperiness in a variety of climbing and walking conditions were studied and compared with the coefficient of friction (COF) [14]. In addition, Chiou [4] has reported that the rating of the subjective perceived sense of postural sway and instability (PSPSI) during static task performance is a simple and sensitive method to evaluate the potential for loss of balance in the workplace. However, it is not clear that the PSPSI can also be used to evaluate postural instability during dynamic task performance. The second objective of the study was to evaluate the use of the PSPSI scale for the prediction of slip/fall during dynamic task performance and its association with the objective gait measures for the prediction of slips.

2. Method

2.1. Subjects

Twenty one healthy industrial workers (9 males and 12 females) were screened by a physician to assure that at the time of testing these subjects did not have any neurological or musculoskeletal diseases, or other disorders which may affect their balance or gait. The subjects were 21 to 59 years old (mean ± standard deviation = 39.9 ± 15.7 years), 149 to 182 cm in height (166.6 ± 9.7 cm) and 57.4 to 124.6 kg in weight (87.2 ± 18.9 kg). The weight/height ratio ranged between 0.4 to 0.84.

2.2. Experimental conditions and procedures

As shown in Fig. 1, a straight walkway with a commercial force platform (AMTI, model OR6-5-1000) was used for gait testing under two environmental conditions-the best (A) and the worst (B) conditions. Prior to the test, environmental lighting was also measured using a light meter (Super Scientific, model 840021). The lighting/illumination was measured at subject's eye level at five places along the walkway. These five places were: (1) the starting point of walking, (2) the first step of a gait cycle, (3) in the middle of the force platform, (4) the last step of the gait cycle and (5) the end of the walking. In the

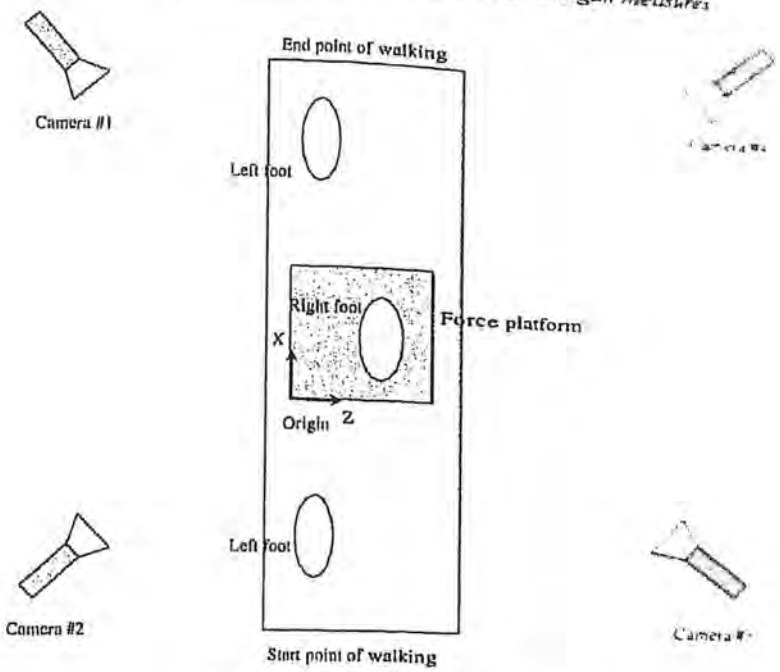

Fig. 1. Gait test laboratory set-up.

best condition, the subjects walked straight and stepped in the middle of a dry force platform with the right foot in a normal fashion in good ambient lighting (685.73 ± 132.99 lux); in the worst condition, the subjects walked straight and stepped in the middle of a very slippery force platform with the right foot, carrying a 2.3 kg weight in the right hand in poor ambient lighting (0.97 ± 0.22 lux). Due to the demanding nature of the test conditions, having a subject perform all the tests in one session is not practical. A balanced incomplete block design was used for the study to save time for each session. Therefore, not all subjects performed all gait trials in both conditions A and B. Only 5 of them did both, for a total of 10 trials. Eight of the remaining 16 subjects performed the gait trial in condition A and the other 8 performed it in condition B. Therefore, a total of 26 trials (13 in the condition A; 13 in the condition B) were collected on 21 subjects. Each trial was assigned to the subjects in a random order and was considered to be independent for the purpose of statistical analysis. Prior to the test, several practice trials were performed by each subject to ensure proper stepping. A commercial safety harness with an overhead rail attachment was worn by all subjects to prevent falls during the test. The length of the harness was adjusted according to each subject's height, so that the subject was protected but not pulled by the harness during walking.

2.3. Instrumentation and data acquisition

A motion analysis system (Peak5 Performance Technology Inc., 3D Module Version 5.3) was used to assess body movements (kinematic data) during the gait test. Twenty-four reflective markers were placed on the subject in order to capture the subject's body motion during gait. The locations of these

markers on the subject were recorded by 4 cameras around the testing room, as shown in Fig. 1. The locations of the markers recorded by the cameras were digitized to a computer file that provided the three dimensional coordinates (X,Y, and Z) with respect to the origin for each of markers.

To calculate the whole body CG coordinates, the human body was considered a system of 12 rigid segments including head, trunk, right and left lower arms, right and left upper arms, right and left upper legs, right and left lower legs, and right and left feet [18]. The locations of the markers for the 12 rigid segment system were: temples, neck, shoulders, lateral epicondyle of the elbows, radial styloid at the wrists, back, anterior superior iliac spines, hips (upper femoral condyle), heads of the fibula at the knees, lateral malleolus of the ankles, roots of the first and the fifth metatarsal of the feet, and the calcaneus. Based upon the marker system and the anthropometric data [18], displacements of the body segments and the CG coordinates were calculated using Peak5 Performance software. In this study, kinetic and kinematic data were obtained during the single stance phase of the gait test.

Digitized kinematic data were collected during the period of the left heel striking the ground to the left heel striking the ground again (a whole gait cycle). Seven gait events were recorded during the whole gait cycle. They included: (1) signal of synchronization with force-plate data occurs, (2) right heel contacts the ground (RHC), (3) left toe lifts off the ground (LTO), (4) slip begins, (5) slip ends, (6) left heel contacts the ground (LHC), (7) right toe lifts off the ground (RTO). The ground reaction forces and moments (kinetic data) during the period when the subject's right foot stood on the force platform were also recorded using a force platform. The force platform and the videotaping instruments were synchronized so that the kinetic and kinematic data were collected simultaneously. To compare the kinetic data with kinematic data, only the data obtained during the single stance phase (from event 3 to event 6) were utilized.

Dynamic utilized coefficient of friction (COF) values were calculated from the force platform using a custom software (All rights reserved by the University of Cincinnati, 1996). It was calculated as the ratio of the horizontal force to vertical force, both obtained from a force platform.

Before the trial, an aluminum plate was placed on top of the force platform. A very slippery walking condition was simulated by means of coating the plate with 8 ml Walgreens^{TM} mineral oil [17]. The aluminum plate was completely cleaned with detergent after each slippery walking condition trial ended and re-coated with oil for the following slippery condition trial. Red Wings^{TM} work shoes (model MAXUM 02160 for males and 02051 for females) were worn during the test. The dynamic COF of the shoe-floor interface was measured for each subject before the test. The dynamic COF measurement and procedure are described in one of our previous publications [17]. The average dynamic COF of the shoe-floor interface for the best and the worst walking conditions were approximately 0.67 and 0.11, respectively [17].

2.4. Calculations of objective gait measures associated with loss of balance

The primary goal during human walking is to maintain the projection of the CG onto the horizontal plane of the supporting feet. Therefore, the study focused on the changes in the gait variables in the horizontal plane.

In Wang's study, a few new kinematic variables were introduced to investigate loss of balance while walking along a turning path [17]. It was found that the slide distance of the supporting foot and the dynamic COF of the walking surface are significantly associated with potential falls. Two of the variables (slide distance and horizontal velocity of the CG), studied by Wang, were used again in the present study to investigate their contributions to a potential fall in different walking environments [17]. Three other

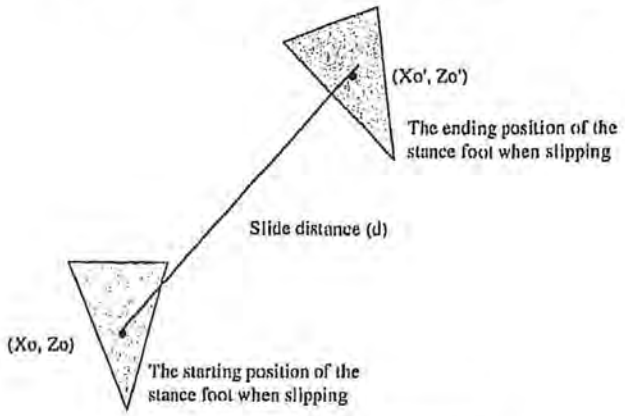

Fig. 2. Definition of the slide distance (d).

new gait measures were introduced in the present study to assist in utilizing the measures of the CG and CP to evaluate potential loss of balance while walking in two different walking environments. The definitions of these gait measures are described below.

Average slide distance (d): the slide distance was defined as the total displacement of the geometric center of the supporting foot during slipping as shown in Fig. 2. (X_0, Z_0) and (X_0', Z_0') are the coordinates of the geometric centers of the stance foot at the starting point and the ending point of slipping, respectively. In addition, Vcg is the average horizontal velocity of the CG; as shown in Fig. 3, OG is the distance between the CG and the geometric center of the BOS of the stance foot (area of ABC); OP is the distance between the CP (denoted as P in Fig. 3) and the geometric center (O) of the BOS of the stance foot; QG is the distance between the CG (denoted as G in Fig. 3) and the geometric center (Q) of the area of BCDEF. The area of BCDEF is considered to be the dynamic base of support (DBOS) of the two feet. Illustrated definitions of the OG, QG and OP are presented in Fig. 3. A slip was considered to have occurred when it began and ended during the single stance phase. In addition, the ratio of the maximum value of the utilized dynamic COF to the dynamic COF of shoe-floor interaction, denoted as the $COF_{utilized}/COF_{shoe}$, was calculated as another objective gait measure.

2.5. Observed slip occurrence during trials

Slip occurrence was observed and recorded by the tester during the single stance phase of the trial and confirmed by the digitizer during kinematic data digitizing. If a slip was observed, it was recorded as 1; otherwise 0, i.e., no slip occurrence.

2.6. Perceived sense of postural sway and instability (PSPSI)

To evaluate the workers' PSPSI during dynamic task performance, a short questionnaire that contained 4 questions was administered immediately after each test. The questionnaire was developed and evaluated in Chiou's study [3]. The PSPSI scale was used to determine its application for the evaluation of potential slips/falls during dynamic task performance. The sum of the 4 answers (each question has a scale of 0 to 2 with increments of 0.5) was defined as the subjective rating of PSPSI. The maximum rating of 8 represents the greatest PSPSI and implies that the subject perceives the maximum overall postural instability during task performance.

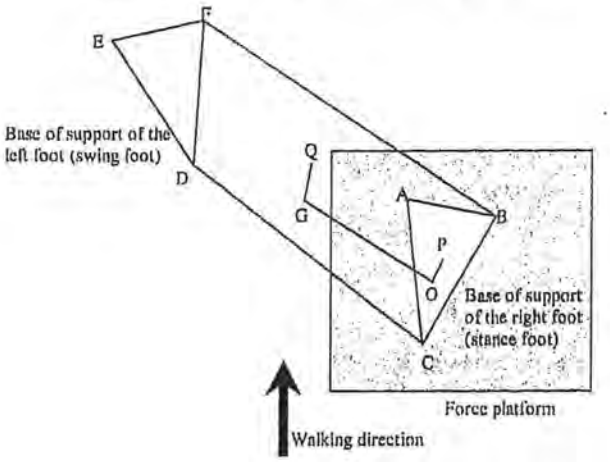

Fig. 3. Illustrated definitions of the OG, QG, and OP.

2.7. Statistical analysis

The statistical analyses were performed using the Statistical Analysis System (SAS) for the Personal Computer [10]. The purpose of the analyses was to determine the statistical relationship among the objective gait measures associated with observed slip occurrence in two walking environments. The linear correlation between the gait measures and observed slip occurrence was examined. Student's t-test was performed to test the difference in gait measures between two walking environments. A logistic regression model with backward elimination of insignificant between-subject covariates was used to investigate the relationship between the observed slip occurrence and the gait measures, including the OPmax, the average slide distance, and the $COF_{utilized}/COF_{shoe}$ for the two walking environments. The logistic regression analysis was performed for each gait measure and the PSPSI scale separately with the same covariates including walking condition, age, sex and weight/height ratio. Each gait measure was forced in each separate model. Insignificant covariates were removed from the final model. In addition, the subjective PSPSI scale was also included as one of the independent variables in a separate regression model. An analysis of covariance (ANCOVA) was used to determine the effects of gait measures and walking environments on the PSPSI scale. The same between-subject covariates as those in the logistic regression model were included in the ANCOVA.

3. Results

3.1. Results for the slip occurrence and objective gait measures

Data from recording of slip occurrence showed that none of the subjects slipped in the best walking environment. However, all the subjects slipped in the worst walking environment. Results from correlation analyses showed that the OPmax and the slide distance were significantly correlated ($r = 0.44$, $p < 0.02$). Figures 4 to 7 present the descriptive statistics for the gait measures, including average slide distance, average horizontal velocity of the CG, maximum and mean values of the OG, QG and

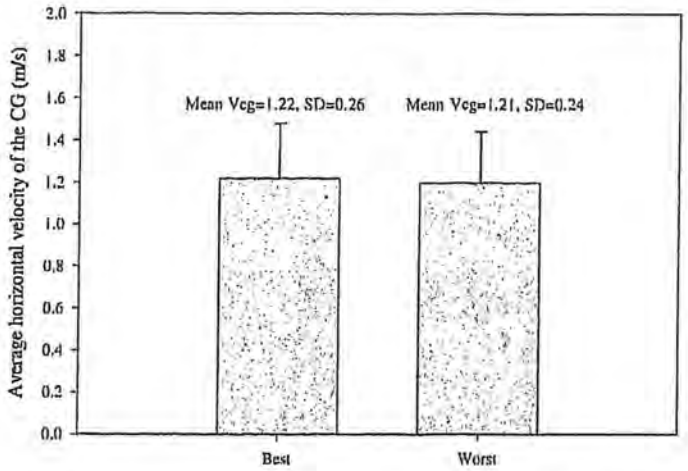

Fig. 4. Average and standard deviation (SD) of the horizontal velocity of the CG during the single stance phase in two walking environments.

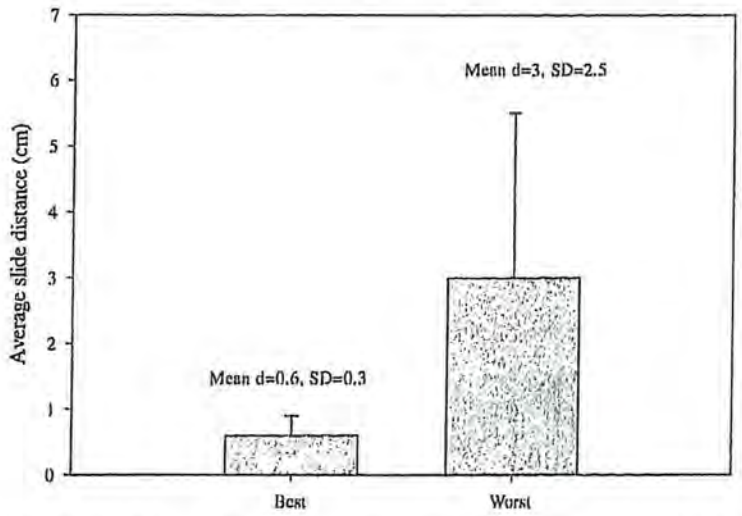

Fig. 5. Average and SD of the slide distance during the single stance phase in two walking environments ($t = 3.39$, $P < 0.01$).

OP in two walking environments. The mean values of the OG, QG, OP, the average horizontal velocity, and the average slide distance for each trial were obtained by averaging these gait measures across the duration of the single stance phase. Also, the maximum values of the OG, QG and OP for each trial were determined among all the OG, QG and OP values measured during the single stance phase.

Mean average horizontal velocities of the CG for the best and worst walking environments were 1.22 and 1.21 m/s, respectively (Fig. 4). It appears, that on the average, the subjects did not change their walking speed while walking on either surface. Although slip occurrence was not observed by the tester

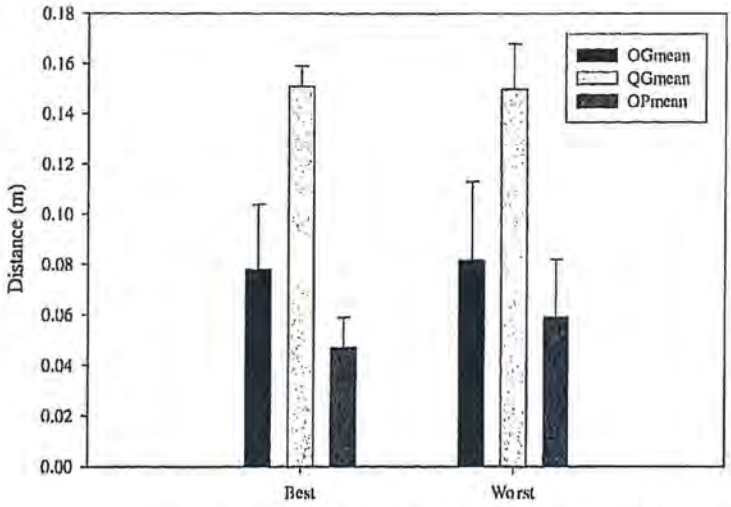

Fig. 6. Average and SD of the mean values of the QG, OG, and OP during the single stance phase in two walking environments.

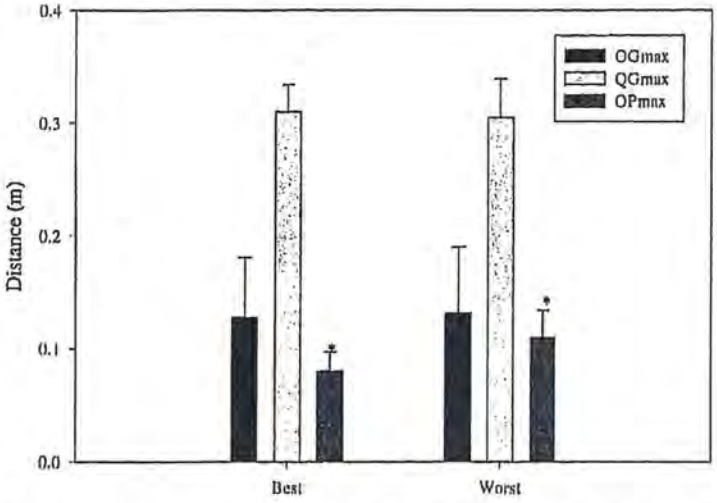

Fig. 7. Average and SD of the maximum values of the QG, OG, and OP during the single stance phase in two walking environments (*OPmax significantly different, $t = -3.68$, $P < 0.01$).

in the best walking environment, the kinematic data showed that in the best walking environment, the subjects actually slipped an average distance of 0.6 cm (i.e., slide distance = 0.6 cm). The average slide distances in the worst walking environment was 3 cm (see Fig. 5). The t-test showed that the average slide distance in the best walking environment was significantly less than that in the worst walking environment ($t = -3.39$, $p < 0.01$). As shown in Figs 6 and 7, OG mean, QG mean, OG maximum and QG maximum values do not appear to be different in the two walking environments. Both OP mean

(0.059 m) and OP maximum (0.11 m) in the worst environment, however, are greater than those (OP mean = 0.047 m, OP maximum = 0.08 m) in the best one. T-tests comparing these means showed a significant difference ($t = -3.68$, $p < 0.01$) only between the OP maximum values calculated for the two walking environments.

3.2. Logistic regression analysis for predicting slip occurrence from the objective gait measures and the subjective PSPSI scale

Among the gait measures, only the OPmax and the slide distance were found to be significant in the final logistic regression model ($p < 0.01$ and $p < 0.05$ respectively). Results also showed that the PSPSI scale is not significant for the prediction of slip occurrence. Although the PSPSI scale was significantly correlated with slip occurrence as a linear correlation ($r = 0.73$, $P < 0.01$), it was not a significant variable in the logistic model (which is a non-linear regression model). Figure 8 shows the predicted probability of the slip occurrence over the observed range of the OPmax and the slide distance. The logistic regression equations fitting the OPmax and the slide distance are also shown in Fig. 8. The probability of slip occurrence was calculated for different OPmax or slide distance values by solving the logistic regression equations. As shown in Fig. 8, the probability of slip occurrence increases as the OPmax or the slide distance value increases. It rises dramatically after the OPmax reaches approximately 0.08 m. If the OPmax exceeds 0.12 m, the probability of slip occurrence increases to approximately 90%. However, if the slide distance exceeds 2 cm, the probability of the slip occurrence increases almost to 90%.

3.3. Correlations between observed slip occurrence, the PSPSI scale and the objective gait measures

Table 1 shows the significant results from an analysis of the correlations between the observed slip occurrence and slide distance, OPmax and $COF_{utilized}/COF_{shoe}$, and PSPSI scale. The Vcg and other covariates, including, sex and weight/height ratio, were found to be not significantly correlated with the observed slip occurrence, whereas, the slide distance, the OPmax, the $COF_{utilized}/COF_{shoe}$ and the PSPSI scale were found to be significantly correlated with observed slip occurrence. Among the objective gait measures and the subjective measure, the PSPSI scale had the highest Pearson correlation coefficient ($r = 0.73$, $p < 0.01$). Table 2 shows the significant correlations between the PSPSI scale and the gait measures. Among the gait measures, the slide distance and the OPmax were found to be significantly but moderately correlated with the PSPSI scale ($r = 0.51$, $p < 0.01$, and $r = 0.47$, $p < 0.02$, respectively).

3.4. Effect of gait measures and walking environment on PSPSI scale

Only one subject provided a PSPSI scale rating of 0.5 in the best walking environment. The rest of the subjects provided a rating of 0, meaning they did not perceive postural instability in the best walking environment. For the worst walking environment, the PSPSI score ranged from 0.5 to 8, with a mean value of 3.85, compared to 0.04 for the best walking environment. Results from ANCOVA showed that the gait measures did not have any significant effect on the PSPSI scale ($p < 0.99$, $p < 0.47$, $p < 0.3$, for the OPmax, slide distance, and $COF_{utilized}/COF_{shoe}$, respectively). Walking environment was found to have a significant effect on the PSPSI ($p < 0.01$). The results suggest that the changes in the gait measures do not significantly reflect the changes in the PSPSI scale.

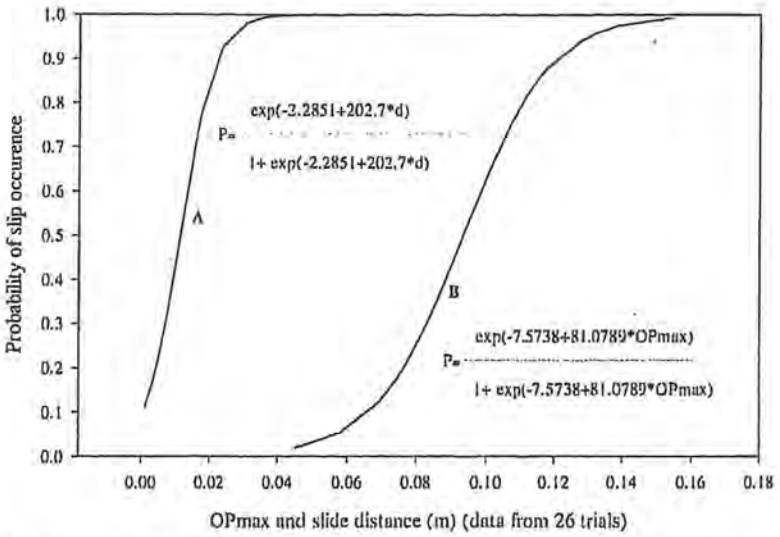

Fig. 8. Probability of observed slip occurrence vs. slide distance (curve A) and OPmax (curve B). Logistic regression equations for curves A and B are presented in the graph.

Table 1
Pearson correlation coefficients for slip occurrence with the objective gait measures

	Slide distance	OPmax	$COF_{utilized}/COF_{shoe}$	PSPSI Scale
Slip Occurrence	0.57	0.59	0.72	0.73
P value	0.01*	0.01*	0.01*	0.01*

*Any findings with $p < 0.05$ were considered to be statistically significant. Age, sex, weight/height and Veg were not significantly correlated with slip occurrence.

4. Discussion

In the present study, the average horizontal velocities of the CG, which reflects the whole body movement or walking speed, demonstrated that the subjects did not change their walking speeds when walking in the best and the worst walking environments. This suggests that when only one foot steps on a slippery surface in a dark environment, the speed of the whole body movement in horizontal plane does not change, compared to that in the best walking environment. However, Winter [18] has reported that when a person notices an existing potential hazard, such as a slippery surface, he/she will usually change gait pattern by decreasing stride length or walking speed. In the present study, the subjects practiced walking on the pathway a few times before performing a gait test. They may have known that the walking surface outside the force platform was safe and therefore did not need to decrease their walking speed when stepping onto the slippery force platform in a dark environment. Walking ability is a highly compensated task that can be fully or partially compensated by other control mechanisms [16]. Two modes of controlling body locomotion have been proposed [12]: reactivity and pro-activity. The reactive mode may be used more frequently when unexpectedly encountering a slippery surface. The study subjects used the proactive mode to anticipate potential hazards to walking and modify their movement in order to minimize the effects of these hazards. Therefore, it seems that when walking repeatedly

Table 2
Pearson correlation coefficients for the PSPSI scale with the objective gait measures

	Slide distance	OPmax	$COF_{utilized}/COF_{shoe}$
PSPSI Scale	0.51	0.47	0.39
P value	0.01*	0.02*	0.05

*Any findings with $p < 0.05$ were considered to be statistically significant. Other gait measures were not significantly correlated with the PSPSI scale.

on the same pathway and being aware of the slippery surface, visual input probably does not play an important role in balance control.

Among the gait measures, the slide distance and the OPmax showed a significant difference in the two walking environments. The significant difference in the OPmax showed that in the worst walking environment the CP deviated from the center of the BOS more than it did in the best walking environment. This indicates that the OP maximum may be a better variable than the OG or the QG for evaluating potential hazards in different walking environments. In addition, the slide distance measured in the worst walking environment was significantly greater than that found in the best, indicating that the slide distance is also an important variable for evaluating potential walking hazards.

The correlations of slip occurrence with the gait measures suggested that the greater the OPmax, the more likely the subject is to slip. In other words, as the maximum distance between the CP and the center of the BOS increases, the likelihood of slip increases. The slide distance also had a similar correlation with slip occurrence as did the OPmax. The $COF_{utilized}/COF_{shoe}$ and the PSPSI scale had a higher positive correlation coefficient ($r = 0.73$) with slip occurrence than the OPmax ($r = 0.59$) and slide distance ($r = 0.57$). However, in the logistic regression model, the PSPSI scale and the $COF_{utilized}/COF_{shoe}$ were not found to be significant predictors for slip occurrence. This implies the PSPSI scale and the $COF_{utilized}/COF_{shoe}$ may be correlated with the observed slip occurrence but not sensitive to detect the changes in COF that cause the subject to slip. The slide distance and the OPmax were found to be the significant predictors for observed slip occurrence ($P < 0.02$ for OPmax and $p < 0.04$ for slide distance). As shown in Fig. 8, the regression curve for slide distance is more sensitive for the prediction of slip occurrence than that for the OPmax because of the larger slope of the regression curve for the slide distance than that for the OPmax. The slide distance always continuously increased as a slip occurred. However, during the single stance phase, the CP can move forward without a slip occurrence or without changing the center of the BOS of the stance foot. In other words, the OPmax may increase without a slip occurrence. As a result, the regression curve for the OPmax on the slip occurrence is less sensitive than that for the slide distance.

Strandberg [13] found that if the slide distance exceeded 10 cm, the subjects usually experienced a fall. In addition, the sliding motions were often unnoticed by the subjects and occurred even without lubricant. In the present study, the mean slide distance in the worst walking environment was 3 cm (ranged between 0.13 and 7.76 cm). This range in the slide distance may be insufficient to cause a fall according to Strandberg's study. In addition, in the present study, the subjects were protected from falls during a trial with a safety harness. Therefore, fall-related incidences were not recorded and examined in the present study. However, even this range of the slide distances in the worst walking environment may pose a potential fall risk. Based upon the observations from the videotapes, slips occurred at the RHC, during the single stance phase, and at the RTO in the worst walking environment. In Strandberg's [13] study, falls resulted from "skids" that occurred shortly after heel strike. The sliding motion just before the toe-off, however, never resulted in a fall. Similar observations were made in this study.

The OP is determined by the BOS and the CP, which is derived from the forces under the foot. Slips that occur during gait are related to forces generated under the feet and the frictional properties of the shoe-floor interface. A slip occurs when the shear forces at the shoe-floor interface exceed the dynamic frictional forces between the shoe and the floor. This maybe why the OPmax, related to the CP measurement, is a better predictor for slip occurrence than the OG and the QG, which were not found to be significant.

The changes in these two gait measures (OPmax and slide distance) may provide a way to evaluate the risk factors associated with slips during dynamic task performance. Wang [17] has indicated that the slide direction while walking on a slippery surface is an important variable associated with slips. The slide direction and the direction of the OP when a slip occurs should be investigated in future study.

Non-significant correlations between slip occurrence and between-subjects variables including age, gender, and weight/height ratio showed that the cause of slipping may be independent of these covariates. According to Strandberg's [13] findings, slide distance was expected to be highly correlated with slip occurrence. Results from the present study showed a significant and fairly strong correlation ($r = 0.57$, $p = 0.01$). This correlation may have been attenuated by the fact that the slide distance was determined from kinematic data and the slip occurrence was recorded by the tester and confirmed from videotapes. Errors may occur while recording a slip occurrence and while digitizing markers in videotapes. In addition, the methodology of calculating the slide distance in the study was different from that used in Strandberg's [13]. The slide distance in his study was calculated after heel-strike, whereas the slide distance in the present study was calculated during single stance phase after heel strike. The discrepancy in the methodology between two studies may explain why the slide distance used in the present study was moderately correlated with the slip occurrence.

Theoretically, if the $COF_{utilized}/COF_{shoe}$ is greater than 1, a slip occurrence is expected. In the worst walking environment, $COF_{utilized}/COF_{shoe}$ ratio that did not exceed 1 still caused a slip. This may be due to the fact that slip occurrence during the single stance phase was subjectively observed and recorded by the testers. It was sometimes difficult to distinguish between the slip occurrence and the toe push-off during a trial or on the videotape. Slip occurrence is a complex process. Not only the frictional properties of the shoe-floor interface may cause a slip, but also the whole body movement with respect to the stance foot may play an important role [20]. In addition, a person's muscular strength and the coordination for maintaining balance on a slippery surface are also important.

Results from ANCOVA showed that only the walking environment was found to have a significant effect on the PSPSI scale. The slide distance, the $COF_{utilized}/COF_{shoe}$, and the OPmax, significantly correlated with the slip occurrence, did not have significant effects on the PSPSI scale. This means the subjects were able to identify the difference in walking environments but unable to distinguish the changes in the gait measures associated with slips. This may be due to the fact that in the worst walking environment (dark, slippery, holding a light weight in the hand), the postural control primarily relies on the vestibular system and proprioceptive input from the feet. These two control systems are weaker than the visual system, although the visual system can be compensated by the other two systems in many cases [16]. Chiou [4] reported that the PSPSI scale was an appropriate subjective measure for evaluating potential for loss of balance associated with static or semi-dynamic task performance. However, results from this study showed that the PSPSI scale seemed unable to reflect the potential hazard for slips in a walking environment without visual input. The PSPSI is a subject's overall perception to slips/falls. During walking, the perception for slips/falls may be affected by muscular activity, body orientation and psychological factors. In addition, with the small sample size, the results of the study may not provide sufficient evidence to show that the PSPSI scale is an appropriate tool for prediction of a potential

slip occurrence during dynamic task performance. Furthermore, with such a limited scale of 8 (with an increment of 0.5), the PSPSI scale may not be sensitive enough to reflect the changes in the gait measures. How humans perceive slipping or unstable walking in different walking environments is not well understood and may require further study to develop a more sensitive subjective measure which could be used as a supplement to the objective gait measures.

5. Conclusions

In summary, the conclusions drawn in the study are as follows:

1. The slide distance, the OPmax, the $COF_{utilized}/COF_{shoe}$ and the PSPSI scale were found to be significantly and moderately correlated with slip occurrence. Among all the gait measures used in the study, it was found that the OPmax and the slide distance were the significant predictors of slip occurrence while performing a dynamic task. An increase in the OPmax or slide distance indicates an increased likelihood of slip occurrence.
2. The PSPSI scale seemed unable to capture the changes in the gait measures that are associated with loss of balance. The walking environment was found to have a significant effect on the PSPSI scale. This implies that the subjects were able to distinguish the difference in walking environments but unable to perceive the potential hazards for slips/falls while performing a dynamic task.
3. Due to a mismatch between subjective perception of slip potential and the actual risk of slipping, the workers' safety is jeopardized during task performance on slippery surfaces. There are many jobs such as delivery, postal service, construction and shipyard where environmental conditions dictate the nature of the frictional properties of the workplace, which are beyond the control of the workers. Under these circumstances, there is a need to develop training program for workers to learn to correctly judge the slipperiness of the surface and how to perform task on that surface without compromising upright balance. The OPmax, slide distance and PSPSI scale can be used to predict a mismatch (slip occurrence predicted by OPmax or slide distance vs. PSPSI scale) between subjective perception of slip potential and the actual risk of slipping during task performance on slippery surfaces.

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