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"Ergonomics of Task Performance on Slippery Surfaces"

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TABLE OF CONTENTS

	Page
Title Page	1
Table of Contents	2
List of Abbreviations	3
List of Figures	5
List of Tables	8
Significant Findings	12
Abstract	13
A. Specific Aims	14
B. Background and Significance	14
C. Static Postural Stability Evaluation During Task Performance on Slippery Surfaces	17
Summary of findings/implications: postural stability evaluation during static task performance on slippery surfaces	46
D. Dynamic Stability Evaluation During Task Performance on Slippery Surfaces	66
Summary of findings/implications: postural stability evaluation during dynamic task performance on slippery surfaces	93
References	128
List of current and possible future Publications	131
Acknowledgment	133
Appendices: A to G	

LIST OF ABBREVIATIONS

IPSB: Index of Proximity to Stability Boundary

SAR: Sway Area Ratio

WRTI: Weighted Residence Time Index

FSB: Functional Stability Boundary

TSB: Theoretical Stability Boundary

CP: Center of Pressure

CG: Center of Gravity

p: Minimum distance between the stabilogram and the FSB

R_{max}: Radial distance of the point on the FSB that is closest in proximity to the CP

A_t: Area of the envelop around the stabilogram

A_{sb}: Area of the FSB

α^i: Fraction of time spent in proximily zone i.

BOSA: Base of supporting area

PSOS: Perceived Sense of Slip or Fall

COF: Coefficient of friction

Fx: Horizontal force in the x-direction

Fy: Horizontal force in the y-direction

Fz: Vertical force

AP: Anterior-Posterior

ML: Medio-lateral

H/V or RCOF: Ratio of resultant horizontal force to vertical force or Required or Utilized coefficient of friction

$$RCOF = \frac{\sqrt{F_x^2 + F_y^2}}{F_z}$$

LIST OF FIGURES

C-1: Shoe COF Tester
C-2: Illustration of the three simulated tasks
C-3: Schematic of slip/gait study facility
C-4: Definition of CP excursions for Static Tasks
C-5: Illustration of the concept of CP based IPSB and stability boundary
C-6: Illustration of the concept of CG based IPSB and stability boundary
C-7: % of slip occurrence vs. RCOF/shoe COF for all tasks
C-8: % of slip occurrence vs. RCOF/shoe COF for reach task
C-9: % slip occurrence vs. Perceived sense of slip for all tasks
C-10: % slip occurrence vs. Perceived sense of slip for reach task
C-11: The relationship between subjective rating of slipperiness and the objective measure of slipperiness (COF)
C-12: Arithmetic mean pf perceived sense of slip (PSOS) for various tasks and surface Conditions
C-13: IPSB(CG) and IPSB(CP) vs. time for stationary tasks with new shoes under good lighting and dry surfaces
C-14: IPSB(CG) and IPSB(CP) vs. time for stationary tasks with new shoes under poor lighting and very oily surfaces
C-15: IPSB(CG) and IPSB(CP) vs. time for reach tasks with new shoes under good lighting and dry surfaces
C-16: IPSB(CG) and IPSB(CP) vs. time for reach tasks with new shoes under poor lighting and very oily surfaces

LIST OF FIGURES (continued)

D-1: Definition of Heel Contact Angle for gait tasks
D-2: Definition of Sliding Distance in a 1-dimensional plane for straight gait tasks
D-3: Approximated BOSA
D-4: Definition of the regions used to calculate the COG_H deviation distance
D-5: The projection of the acceleration vector of COG on horiontal plane and its components
D-6: Definition of slide distance and direction in a 2-dimensional plane for straight and turning gait tasks
D-7: % slip occurrence vs. $RCOF_{MAX}/COF_{SHOE}$ for walking on a turning path
D-8: % slip occurrence vs. $RCOF_{MAX}/COF_{SHOE}$ for walking on a straight path
D-9: % slip occurrence vs. $RCOF_{MAX}/COF_{SHOE}$ for all gait tasks
D-10: Mean values of anterior-posterior shear forces associated with dynamic task performance on various slippery surfaces
D-11: Mean values of medio-lateral shear forces associated with dynamic task performance on various slippery surfaces
D-12: Mean values of vertical force associated with dynamic task performance on various slippery surfaces
D-13: Mean values of cycle (dwell) time associated with dynamic task performance on various slippery surfaces
D-14: Mean values of anterior-posterior excursion of CP associated with dynamic task performance on various slippery surfaces
D-15: Mean values of medio-lateral excursion of CP associated with dynamic task performance on various slippery surfaces
D-16: Mean values of minimum utilized COF associated with dynamic task performance on various slippery surfaces
D-17: Mean values of maximum utilized COF associated with dynamic task performance on various slippery surfaces
D-18: Sliding distance distribution vs. Surface slipperiness during straight walk
D-19: % of slip incidents per each PSOS rating for all gait tasks
D-20: % of slip incidents per each PSOS rating for gait tasks on straight path without weight
D-21: % of slip incidents per each PSOS rating for gait tasks on turning path without weight
D-22: % of slip incidents per each PSOS rating for gait tasks on straight path with weight
D-23: % of slip incidents per each PSOS rating for gait tasks on turning path with weight
D-24: Set up of gait test and coordinate system
D-25: Data from one subject showing the relative position of COG_H and supporting feet when negotiating a turning path on a very slippery surface
D-26: Total utilized COF versus COF utilized by the centrifugal force (data of one trial)
D-27: Average COG_H deviation distance during single stance period
D-28: Average sliding distance while negotiating different paths on different surfaces
D-29: Average slide directions while walking on a very slippery surface
D-30: Average total utilized COF versus COF utilized by the centrifugal force
D-31: Average total utilized COF for different surfaces

D-32: Average COG horizontal velocities during single stance
D-33: Average turning radii of negotiating a turning path on dry and very slippery surfaces
D-34: Comaprison of the total utilized COF calculated from video data versus that from the force plate data.
D-35: The positions of CP and CG with respect to BOS.

LIST OF TABLES

C.1 : Summary of the Types of Surfaces and Lubricants for
Creating the Three Levels of Surface Slipperiness

C2: Anatomical landmarks for reflective marker placement

C.3.: Demographic Data (n = 40)

C.4 : Summary of Number of Slips and % of Slip Occurrence
for All Static Tasks in Various Range of RCOF / COF

C.5 : Summary of Number of Slips and % of Slip Occurrence
for the Reach Task in Various Range of RCOF / COF

C-6 : Summary of Number of Slips and % of Slip Occurrence
for All Static Tasks in Various Range of PSOS

C-7 : Summary of Number of Slips and % of Slip Occurrence
for the Reach Task in Various Range of PSOS

C-8 : Pearson Correlation Coefficients
(Residuals vs. Postural Sway and Instability Variables for All Static Tasks)

C-9 : Pearson Correlation Coefficients
(Residuals vs. Postural Sway and Instability Variables for Reach Task)

C-10 : Analyzing separately by static task but Combining all 6 Depenedent Measures of postural sway
(P values are shown)

C-11 : Analyzing for all Static Tasks combined but sperately for each measure of postural sway (P values are shown)

C-12 : Geometric Means and Standard Deviations for Static Balance Measurements, by Gender, Surface Condition, Shoe Worn, Lighting, Task Performed and by Surface and Shoe Worn

C-13 : Percentage Change from Baseline Observed for each Significant Factor

C.14 : Geometric means and standard deviations of postural instability variables
for various risk factors (n = 40)

C.15 : Estimated % Increases in Postural Sway and Instability Parameters
Due to Environmental and Job-Task Factors

C.16 : Summary of the ANCOVA of Maximum RCOF

C.17 : Geometric Means and Standard Deviations of Maximum
RCOF for Various Risk Factors

C.18 : Summary of the ANOVA of PSOS

C-19 : Arithmetic Means and Standard Errors of PSOS* for Various Risk Factors

C.20 : Summary of the Regression Coefficients for
PSOS on Postural Sway and Instability Variables

D.1 : Definition of the regions surrounding the supporting foot.

D.2 : P-values for the Multivariate and Univariate Tests of the Factors Used In the Models for Gait

D.3. : Means and Standard Deviations, by the Factors Used in the Models for the Gait Outcomes

D.4.: Correlation of Kinematic (Gait) Outcomes and the Slip Rating Scale Deviations, the COF and the Total Number of Slips

D.5. : Summary of the Multivariate ANOVA

D.6. : Summary of the Univariate ANOVA for the Incoming Velocity

D.7. : Summary of the Univariate ANOVA for the Heel Contact Angle

D.8. : Summary of the Univariate ANOVA for the Sliding Distance

D.9.: Summary of the Univariate ANOVA for the Sliding Velocity

D.10.: Geometric means and standard deviations of kinematic parameters for various risk factors

D.11.: All Gait Tasks (Also refer to the figure D-19)

D.12.: Gait tasks without weight in hand on a straight path (Also refer to the figure D-20)

D.13.: Gait tasks without weight in hand on a turning path (Also refer to the figure D-21)

D.14.: Gait tasks with weight in hand on a straight path (Also refer to the figure D-22)

D.15.: Gait tasks with weight in hand on a turning path (Also refer to the figure D-23)

D.16.: Analaysis of covariance p-values for gait Perceived Sense of Slip (PSOS) Scores

D.17: Gait test results of 10 subjects (Mean±std.err.)

D.18 : P-values from Univariate Analysis of Covariance

D.19 : Means and Standard Deviations for the Kinematic Data

D.20 : Pearson correlation coefficients and p values between kinematic variables, number of slips and

shoe COF

D.21.: Pearson Correlation Coefficients for mean and max values of OP, GQ and OG with slip occurrence

SIGNIFICANT FINDINGS

The data from 40 industrial subjects have been analyzed to quantitate postural stability characteristics during static and dynamic task performance on slippery surfaces under various combinations of environmental, personal and job-related factors. The effects of various risk factors on the static postural sway and instability variables were rank ordered. The type of task showed the most significant effect on postural sway as well as on postural instability variables. The Reach task as compared to the stationary task produced the largest postural sway and instability and the highest numbers of observed slips (70%). The number of slips were significantly correlated with 4 (SA, IPSB, SAR and WRTI) out of 5 postural sway/instability variables while the shoe COF did not show significant correlation with any of the postural sway/instability variables. Therefore, measurement of shoe COF alone (most of the commercial equipment available to assess the slip potential of a surface measure only the shoe COF not the variables which can quantitate postural instability) is not sufficient to quantitate slip/loss of stability potential during task performance on slippery surfaces. The effect of type of task (Stationary vs Bending vs Reach) and the environmental lighting had the largest and second largest effect on postural sway and instability, respectively. The gender,surface and shoe type had the third, fourth and fifth,respectively, largest effect on postural sway. Males showed significantly higher postural sway than those observed for the female. The explanation for the gender related finding is not clear.

In comparison to static tasks, the dynamic tasks performed on slippery surfaces produced about 36% more slips (24.2% of static tasks produced slips vs. 60% of dynamic tasks).In the present study, on the average all 40 subjects slipped about 65%, 87% and 91% of all trials on slightly, medium and very slippery surfaces, respectively. It is interesting to note that in the static tasks of reach, the total number of slips were much higher than those observed for dynamic tasks of gait (70.5% for reach task vs. 60% for all gait tasks). In other words, upper body dynamics of the reach task, while carried out in a stationary position, were producing sufficiently high horizontal shear forces as well as postural instability to create a significant numbers of slip incidents to occur. The largest and most general effects on these gait outcomes was found to be for surface slipperiness. Most of the gait variables responded to even a slight degree of slipperiness, so that much of the statistical difference exists between the dry surface and a surface of any slipperiness. The second most important variable was whether a turn was traversed or a straight path was followed. The path significantly affected three of the eight gait outcomes. The shoe worn (new vs. used) followed by the subjects' gender displayed the next largest effects. Both of these variables were found to be significant in two of eight univariate tests. Finally, light intensity is the remaining experimental condition which displayed a significant multivariate difference in terms of these outcomes and represents the smallest statistically reliable difference in these data. The remaining effects which were modeled, i.e., the effects of age, height and of carrying a weight, were not significant in the multivariate test nor consistently significant in univariate tests to suggest effects beyond those likely by chance. The shoe COF was a poor predictor of gait heel kinematics (as characterized by the variables of slide velocity and heel contact angle) and total number of slips experienced. Kinematic variables such as slide velocity and slide distance provide a better prediction of slip incidents, as well as postural instability while walking on slippery surfaces.

ABSTRACT

This study provided an experimental design which investigated the interaction between age, sex and other fall/postural instability risk factors such as surface slipperiness, shoe wear/tear, and lighting. In this study, postural instability, fall potential, slip incidents were quantitated during static and dynamic task performance by 40 industrial workers (21 to 60 years of age) on dry, slightly, medium and very slippery surfaces. The dynamic coefficient of friction (COF) values for dry, slightly, medium and very slippery surfaces were 0.67, 0.35, 0.18 and 0.11, respectively. The static and dynamic tasks peformed simulated conditions which occur in nonoccupational and occupational environments while standing or walking on a slippery surface. From these results, the effects of various risk factors on static and dynamic postural sway and instability were rank ordered. Based on objective measures of postural sway and instability, the type of task performed and environmental lighting had the, largest and the second largest, respectively, detrimental impact on postural stability, while performing tasks in a stationary position (i.e. static task). The gender,surface and shoe type had the third, fourth and fifth,respectively, largest effect on postural sway. For the dynamic task performance, the largest and the second largest detrimental impacts on workers' postural stability/sway were associated with surface slipperiness and the type of walking path negotiated (Straight vs. Turning path), respectively. The turning path caused a significantly higher postural instability than those observed for the gait task in a straight path. The shoe worn (new vs. used) followed by the subjects' gender displayed the next largest effects. Finally, light intensity was the remaining experimental condition which displayed a significant multivariate difference in terms of dynamic gait outcomes. For both static and dynamic tasks, the effects of age and height were not significant. The results from both static and dynamic tasks, implied that the slipping events are not dictated solely by the frictional properties of the shoe/floor interface. Body movements which modify the postural stability also contribute to the occurrence of a slip event. This implication is supported by the fact that the total number of slips were significantly correlated with measures of postural sway/instability but the shoe COF did not show any significant correlations. Workers who were cautious in assessing surface slipperiness had less postural instability during static task performance, as indicated by indices of postural instability. However, the current study did not address the issue of whether there is a learning trend in assessing surface slipperiness with repeated assessment. If the ability to assess surface slipperiness can be improved by training, then a training program can be developed to help minimize slip incidence while performing tasks on slippery surfaces. In addition, workers can also be instructed to avoid working on potentially hazardous surfaces without first carefully assessing the slip potential of working surface using the new and validated subjective scale developed in this study. The variables defined and tested in this study can be used to assess the degree of difficulty of a task and the fall/slip/instability risks associated with it. This study also provides a biomechanical basis for differentiating the utilized COF based on the dynamics of the task. Based on the prominent slide direction (due to slipping incident) during task performance in a turning path, it is important to redesign working shoes' sole tread to provide adequate COF in this direction.

A. Specific Aims

A1. To determine the relationship between subjective assessment of slipperiness and the objective measure of coefficient of friction under optimal environmental lighting, job-task, and shoe sole wear/tear conditions. Also, determine the age-associated influence on the above relationship.

A2. To determine the effect of non-optimal conditions of environmental lighting, job-task, shoe sole wear/tear and the subject's age on her/his ability to correctly assess the slipperiness of a surface and detrimentally influence one's task performance and safety.

A3. To determine the effect of environmental lighting, job-task, shoe sole wear/tear conditions, and age on the subject's ability to perform tasks (of daily living and occupational nature) requiring demands on her/his static (upright balance) and dynamic (gait) postural balance while her/his shoe sole surfaces are in contact with a slippery surface.

A4. To identify and quantitate postural balance variables relevant for assessing the fall potential associated with task performance on slippery surfaces under various combinations of environmental lighting, job-task, and shoe sole wear/tear conditions.

A5. To determine the characteristics of the required coefficient of friction values and body segment movement dynamics for performing tasks without slipping under various combinations of environmental lighting, job-task, and shoe sole wear/tear conditions.

A6. To determine the correlation between coefficient of friction demand during gait testing with that measured by a slip-testing device which utilizes some of the biomechanical variables collected during the gait test.

B. BACKGROUND AND SIGNIFICANCE

A significant fraction of accidents both in the workplace and in daily life is associated with slipping and/or tripping. An accident profile analysis of 3000 cases in the workplace by Cohen et al. (1) showed that the event that immediately led to injury was slips in about 50% of the cases. The next highest number of cases (14%) of injuries was related to trips. In another study of "underfoot first event" accidents sustained by 10,000 workers, Manning (2) found that 62% of accidents were related to foot slips and 17% of the accidents were related to tripping.

An accident profile study conducted at an automobile company by Manning (3) showed that slipping was the most frequent first event. It caused the largest number of days of lost work (1168 days) due to slipping out of a total of 1592 days lost due to all kinds of underfoot-related accidents (including slipping, tripping, ankle twisting, surface moved, etc.). Slipping also caused 732 restricted days out of a total of 1517 restricted days for all kinds of underfoot-related accidents. These types of underfoot "first events" have been the main contributor to falls at the same level.

In most industries, falls are the key cause of accidents in the workplace. Falls usually result in severe bodily damage, permanent disability, and even fatality (3). In 1988, falls were the third leading type of accident occurring in the workplace (4). The National Safety Council estimated that the number of injuries caused by occupational falls ranges between 250,000 and 300,000 per year. In 1987, falls at the job site were responsible for about 16.4% of occupational fatalities in the United States (5). Falls have been found to be a significant contributor in causing lumbar spine injury, fracture of bones, and disability (2,6).

There are two kinds of tasks (both performed as tasks of daily living and as part of an occupation) which can place the human body at risk of slipping and falling. These are dynamic tasks performed in a standing position and tasks performed while walking on a slippery surface. The effect of these two types of tasks on the potential of slipping and falling is discussed in the following and also formed the main focus of the present study.

There are a variety of dynamic tasks performed in a standing position which can place the human body 's ability to maintain upright balance at risk, such as bending down to pick up an object from floor level while standing on a slippery surface. From the viewpoint of biomechanics, these tasks cause the body's center of gravity (CG) to move out and reach closer to the stability boundary (described by the outer perimeter of the subject's feet) and, thereby, increase the probability of falling. Healthy subjects standing on a dry (non-oily) and firm surface can perform these tasks without much risk of falling. However, performance of such tasks on a slippery surface under non-optimal lighting will be more dangerous. An increase in postural sway brings the body's CG nearer to the subject's stability boundary and, thereby, increases the potential of postural instability. However, what is not known is how one's prior knowledge of (subjectively) degree of slippery surface affects her/his ability to perform a task without slipping and/or loss of balance. What is the coefficient of friction (COF) demanded for the performance of such tasks without slipping? How does shoe wear/tear affect COF demand while carrying out tasks on slippery surface? Are there age-related differences? These and other related issues were investigated in the present study.

While the above discussion addresses the issue of potential slipping during performance of dynamic tasks in a standing position on a slippery surface, it is well established that task performance during walking will place even more demand on the body's ability to maintain balance and slip-avoidance on a slippery surface.

In human gait, the body equilibrium is lost and gained from one step to another (7). During gait, the CG of the body ventures out of the basal support momentarily. The point of application of the foot would determine how the CG travels through space during gait. While walking on a slippery surface, CG may travel very close to one's stability boundary and cause a loss of dynamic balance. A slight perturbation or an external loading (like carrying a weight in one hand) may be enough to cause the CG to travel outside the basal support area and cause a fall. The point of application of force during weight acceptance in the gait cycle and the deviation of the center of pressure (CP) from the centerline would characterize the dynamic stability during gait. Such measures have been utilized in the past for the investigation of dynamic stability during walking (8).

There are two important periods in the gait cycle when potential slipping might occur. These are: 1) immediately after heel contact when only the back edge of the heel is in contact with the ground (subject falling backward); and 2) at the point of toe-off (subject falling forward) when only the front region of the shoe is in contact with the floor surface (9-11).

The minimum friction requirement during walking can be calculated with the use of the classic law of friction (7). Walking is safe when the COF [Friction Force(F_μ)/Normal Force] is greater than the ratio of the horizontal (F_H) and vertical (F_V) components applied to the floor (measured with a force platform). There are several studies wherein the data of minimum requirement of COF is given for normal walking. Generally, this range of COF is 0.15 to 0.30 (9-10,12). For COF values 0.20 and greater, a slip is not likely to occur. For 0.15 to 0.19, a slip is possible but the loss of balance is often recoverable while performing normal walking on a level surface with no task performance (11). The studies of Strandberg and Lanshammar[10] emphasized that the dynamic friction properties (and its rate of change) seem to be more important than static COF as, in their experiments, the heel was sliding at the point of heel strike even in the absence of a slippery surface.

The above criteria are for normal walking with shoes with no wear/tear and with no task performance. In the daily task performance and/or occupational environment, a person is likely to have shoes with worn-out heels and toes (front part of the sole) and might be performing some tasks such as carrying a small weight (such as small grocery bag or a box). As per Cavanagh's study (8) of old shoes, both heel and the front part of the shoe are significantly worn-out as a result of normal use. Therefore, it is reasonable to theorize that these worn-out regions of the shoe sole will not make proper contact (will reduce contact surface area)--causing mismatch of the ratio of F_H and F_V forces applied to the floor with the COF requirements of the shoe-lubricant-flooring. This mismatch may cause slipping or falling. Furthermore, task performance of carrying a small weight while walking on a slippery surface will further modify the F_H/F_V characteristics in relation to the shoe-lubricant-flooring COF. From a biomechanics standpoint, the F_H values at the foot will increase in proportion to the body mass plus the load in hand while walking in a straight line. However, walking and turning with a load in hand can increase the moment of inertia disproportionately (13). Under these circumstances, one can expect disproportionately larger transverse forces under the foot and, thereby, slips during the propulsive phase of walking and turning would be likely.

These two factors of shoe wear/tear and task of carrying a weight on a slippery surface can significantly influence the heel strike and toe-off phases of the gait which are known to be most susceptible to slipping. There are no worker-based data available to address these issues and also no safety criteria exists regarding minimum shoe-lubricant-flooring COF while wearing a worn-out shoe and carrying a weight on a slippery surface. The present study was designed to address some of these issues. Availability of such information will help guide workers/employers in developing criteria for shoe replacement (schedule) and maintenance.

Walking on a slippery surface with prior knowledge is found to be better than when the slipperiness of the surface is unknown. A sudden change in the frictional value of the walking surface is more detrimental as the person is unaware of the sudden loading on the locomotion system (14). During a heel strike on a surface with reduced friction, there may occur a micro-slip which is characterized by momentary slip at heel contact and then a grip (10). Such micro-slips act as a warning for one to modify one's gait pattern in order to regain balance and negotiate the slippery surface (14). Most falls associated with slip are preceded by a forward skid on heel (15) and, thus, it is essential to measure the heel velocity at this juncture with sufficient accuracy.

In occupational and daily life environments, individuals have to make judgements regarding the slipperiness of a surface before initiating a task. Generally, it is not practical and/or feasible to make objective measurement of COF of the shoe-lubricant-flooring immediately before the task performance. For all practical purposes, this judgement usually has to be made immediately and, therefore, is done in a subjective fashion. This judgement is primarily based on one's application of pressure and movement of the shoe's sole surface on the slippery surface in question. This shoe sole pressure/force information is compared with one's mental model of friction limit (16). It is not clear, however, how this and other factors affect the ability to correctly judge the slipperiness of a surface. Davis's (13) research indicates that vision and fatigue might affect correct subjective judgement of slipperiness. The importance of studying the psychophysics of equilibrium on slippery surface is critical as slipperiness is deceptive and it is not practical to develop special shoes with the highest COF for each type of surface.

Organization of Methods and Results/Discussion Sections

The results from the study is presented in two components: 1) Static Postural Stability Evaluation (Section C) 2) Dynamic Stability Evaluation during task performance (Section D). In the following, the methods and results/discussion are presented first for the Static Postural Stability Evaluation Section then the Dynamic Stability Evaluation Section is given. Some of the descriptions of methods section and the risk factors section are common to both Static and Dynamic Stability Sections. Most of the figures (the remaining figures are included in the body of the report) for the Static and Dynamic Task Evaluation sections are given at the end of their respective sections (see section C.11 and D.10 for the Static and Dynamic tasks, respectively).

METHODS

C. Static Postural Stability Evaluation

C.1. Worker-Subjects:

Forty worker subjects were recruited from local industries. These include service trades such as maintenance and janitorial, commercial food service workers, construction workers and plumbers/pipefitters. These subjects were stratified into two groups representing young and old age groups. The young and old age groups were composed of workers 21 to 30 and 51 to 60 years of age, respectively. The same subjects participated in both Static and Dynamic Postural Stability Evaluation components of the study. This study was approved by the University of Cincinnati Human Research Committee and each subject was given informed consent before participating. Subjects underwent a physical examination and medical history check-up. Subjects with the history of dizziness, tremor, alcoholism, vestibular disorders, neurological disorders, diabetic symptoms, cardiopulmonary disorders, and/or chronic back pain were excluded from this study. On each day of testing, a health questionnaire was filled out inquiring about (i) current health status, (ii) current medication use, (iii) consumption of caffeinated drinks in the 24 hour period prior to the tests, and (iv) major injuries to the head, neck, or back. These factors could influence the task performance. The health questionnaire is attached in Appendix A.

C.2. Study Design:

The study was carried out in two components: 1) Static Postural Stability Evaluation 2) Dynamic Stability Evaluation during task performance.

The Static Postural Stability Evaluation component was a multi-factor design where each of the four risk factors (independent variables) was investigated to see what contribution it makes to the outcomes (postural balance and required friction to perform the task safely) being measured. Each subject underwent a total of four balance test sessions on four different days consisting of 12 baselines and 48 possible treatment combinations among the four risk factors (shoe type, lighting, surface slipperiness, and task). The descriptions of various risk factors or treatment conditions are given in the following.

C.3. Risk Factors/Treatment Conditions (Independent Variables) for Static Tasks:

The four conditions are as follows:

Condition 1: good or poor environmental lighting. (See Section C.3.a. for details)
Condition2: dry, slightly, medium, or very oily surface. (See Section C.3.b. for details)
Condition 3: new shoes were provided by the laboratory, or subject's own used shoes. (See Section C.3.c. for details)
Condition 4: stationary, bending, or lateral reach task. (See Section C.3.d. for details)

Subjects underwent three baseline trials (stationary, bending, and lateral reach) under optimal environmental conditions (new shoes, good lighting, and dry surface) at the beginning of each test session. Next, 12 out of the 48 test trials were performed in each session. The order in which all 48 tests of 30 seconds each was randomized.

C.3.a. Work Environment Lighting (Condition 1): Availability of proper visual cues are critical for maintenance of postural balance. In a poorly lit area, visual cues will be inadequate for the maintenance of balance. In a work environment, lighting has been found to be one of the critical factors related to accidents due to falls. In this study, subjects were tested for postural balance under two extremely different lighting conditions, using illumination guidelines for rough to moderately precise work: (1) Acceptable, good lighting: 320 - 800 lux (30 - 74 foot candles) and (2) Unacceptable, poor lighting: < 20 lux (< 2 foot candles). A light meter was used for measuring the lighting condition (in lux). All subjects were presented with these same two conditions of lighting.

C.3.b. Determination of Shoe-Surface Slipperiness (Condition2)

The three levels of surface slipperiness used in this study were created by evenly spreading different amounts of lubricant on aluminum plates attached to the force plate. A series of pilot tests had been conducted to determine the appropriate amount and the type of lubricant needed for creating the particular shoe-lubricant-flooring combinations with three desirable ranges of dynamic COF values: $\geq$ 0.30, 0.15 - 0.19, and 0.05 to 0. 14. These three levels represent the slightly, medium, and very oily surfaces, respectively. For COF values of 0. 3 0 and greater, a slip is not likely to occur. For COF values of 0. 15 to 0. 19, a slip is possible, but the loss of balance is often recoverable. For COF values less than 0.14, a sudden slip will cause loss of balance (11).

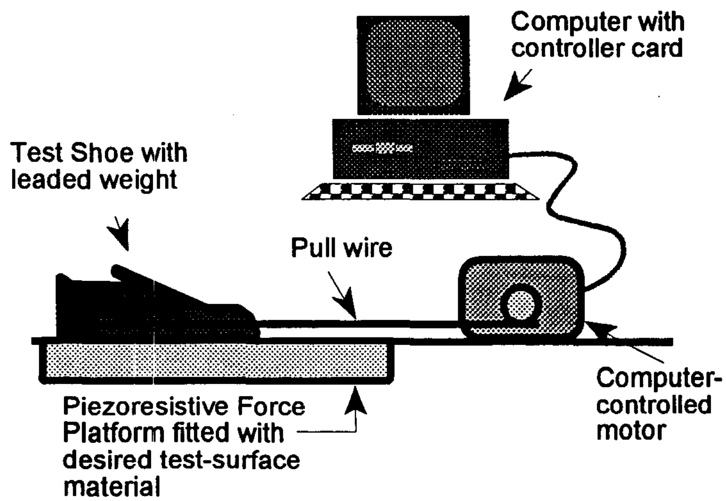


Figure: C-1: Shoe COF Tester

The dynamic COF values were measured by using a computer-controlled COF measurement device to exert a horizontal force on the shoe parallel to the force plate surface. The computer-controlled COF measurement device consisted of a controller, a stepper motor with a gear box, and a force platform with an aluminum plate attached to it (Figure C.1). Small lead balls were added into the shoe to create 58.5N vertical force. The shoe with lead balls inside it was then placed on an aluminum plate attached to a force platform. A stainless steel cable was used to connect the shoe to be tested to the spindle of the gear box attached to the micro stepping motor (Model S83-135, Parker Hannifin Corporation, Rohnert Park, CA). When the motor is activated, the spindle of the gear box turns, creating tension in the cable and causing the shoe to move. The micro stepping motor and the gear box were used to pull the shoe at a velocity of 20 cm/sec, which was suggested by Tisserand [16] to improve the accuracy and repeatability of measurements. The controller (Model NE34-005, Parker Hannifin Corporation, Rohnert Park, CA) was used to remove the "jerking" effect that a discrete step revolution would have on the aluminum plate during a test. As a result of the pilot test, three floor/contaminant combinations created for the present study representing slightly, medium, and very oily surfaces are shown in Table C.1.

Table C.1
Summary of the Types of Surfaces and Lubricants for
Creating the Three Levels of Surface Slipperiness

Surface	Lubricant	Amounts of Lubricant	Dynamic COF	Level of Slipperiness
Coarse Aluminum	Glycerin	1.6 ml	0.35	Slightly oily
Coarse Aluminum	Mineral oil	4.5 ml	0.18	Medium oily
Smooth Aluminum	Mineral oil	9 ml	0.11	Very oily

C.3.c. Determination of Shoe wear and hardness of sole (Condition 3):
The amount of shoe wear in old or used shoe was determined by evaluating the percentage of tread available for each used shoe. A shoe print was made for each used shoe by using an ink roller to spread ink evenly on the shoe sole, which was then pressed onto a piece of tracing paper. Each small area with-tread available was visually determined and marked. Using sigma Scan Tm Software (Jandel Scientific, Corta Madera, CA), the total area of the shoe and the area with tread still available were digitized. The percentage of tread available was then calculated.(19)

The hardness of each shoe was determined by using a type B hand held digital durometer (DuroTronit TM Model 1000, Shore Instrument, Freeport, NY) which conforms to ASTM D2240 standards published by the American Society for Testing Materials. This instrument has a high resolution LCD display and a precision stainless steel mainspring providing an indentor force to ± 0. 1% of full scale load. The hardness was determined by indentor penetration of the shoe sole material and displayed on a scale graduated equally from 0 to 100. The larger the number, the harder the material. Three measurements were taken at the center of the heel area for each shoe..The same procedures were used to measure the hardness of the center toe area. The mean of the six measurements was used for data analysis (19).

C.3.d. Static Postural Stability Tasks (Condition 4)
Each subject went through four test sessions on four different days to finish 48 postural stability tests and 12 baseline trials. At the beginning of each test session, subjects performed three simulated tasks (stationary, bending, and lateral reach) under optimal test conditions (good lighting, new shoes, dry surface) representing baseline. The 48 tests consist of all possible test treatment combinations among the independent variables of task, lighting, surface slipperiness, and shoe type. The protocol of each task is described as follows:

Task 1 - Standing Upright (Stationary Task) Subjects were required to stand quietly on the force platform with hands on the back (Figure C-2) for thirty seconds. The top surface of the platform had -the appropriate surface contamination as described before.

Task # 2 - Rapid Trunk Movement (Bending Task): For the first 12 seconds, the subject maintained upright posture on the force platform with hands on the back (Figure C-2). Next, the subject was given a command to bend her/his trunk about 90 degrees (with respect to vertical) in the sagittal plane. This posture was maintained for five seconds. Finally, the subject was asked to rapidly bring her/his trunk back to an upright position and stay for additional 13 seconds.
Task # 3 - Lateral Reach During Lifting (Reach Task): The subject stood upright on the force platform facing a table (T1) with adjustable height placed at a distance (D1) (Figure C-2). Another table (T2) was placed on subject's left side at a distance (D2). D1 and D2 distances were adjusted so that the subject can grasp a five-pound weight with two hands. The test protocol involved the subject first standing upright with hands at the back for four seconds; then, with a voice command, the subject was instructed to reach the front table (T1) and grab the weight with both hands and bring it to the lateral table (T2). This process was repeated for a total of four lifting cycles ending with the weight returned to its original place (T1). At the end of the lifting task, the subject brought her/his arm to the back and maintained upright position for the remaining period of the test.

C.4.. Final marker system for the study and experimental protocol: The final marker system used for human body motion analysis for this study is shown in Appendix-B and Table C.2.

C.5. Experimental Procedures
The sequence of events which takes place during a typical day of experiments is given in Appendix C. All tests were carried out in our specially designed Fall-Stability-Gait facility which was described in the previous year's progress report (Figure C-3).

On the day of the test, the force platform calibration is checked again to ensure that the measurement error of the plate is within the acceptable 2% range (20). The video-system also was calibrated (Appendix-D). The experimental test conditions (illumination levels, surface slipperiness level, and shoe type) and the postural sway and gait tests were *a priori* randomized by the statistician co-investigator. Two staff members attended the microcomputer which controls and collects data from the video, force plate and in-sole pressure measurement device. One staff member was responsible for the subject's compliance with the protocol, administration of Perceived Sense of Slip/Fall (PSOS) Scale after each of the tests, and also being present near the subject to prevent any injury from potential fall. All subjects wore a full body harness with lanyard attached to the overhead monorail for protection from any potential fall during the test. A fourth staff member was responsible for making proper changes needed for preparing the desired surface conditions, light control, shelving height control and holding the data cable to the in-sole pressure measurement device. He was also responsible for monitoring the camera placed to measure the heel slip profile. On three additional days gait testing were carried out (See Section D for details).On each test day the subject first performed the Slipperiness Evaluation Test described in Section C.5.a. After completion of this test each subject went through four test sessions on four different days to finish 48 postural stability tests and 12 baseline trials. At the beginning of each test session, subjects performed three simulated tasks (stationary, bending, and lateral reach) under optimal test conditions (good lighting, new shoes, dry surface) representing baseline. The 48 tests consist of all possible test treatment combinations among the independent variables of task, lighting, surface slipperiness, and shoe type. The protocol of each task is described in the Section C.3.d.

A short questionnaire-type rating scale (see Appendix-E) was administered immediately after each postural stability or gait test to determine the subjective perception of slip during task performance. This scale consists of four simple questions. The PSOS is determined by adding the scores from four answers. A high score implies a high subjective perception of slip and loss of balance.

In between each testing condition, shoes were carefully cleaned. The subject was asked to rub the shoes on oil absorbing paper after the trial. Then, the subject sat on a chair and set his feet on a foot stool with the shoe sole facing the experimenter. The experimenter used paper towels to wipe out all the oil residue left on the shoe sole. Alcohol pads were then used to clean the treads and the channels in between the treads thoroughly.

C.5.a. Slipperiness Evaluation Test

On the first day of the experiment, the subject underwent 12 slipperiness evaluation tests under different surface conditions (slightly, medium, and very oily) with used shoes or new shoes. This slipperiness evaluation test was designed to allow subjects to be exposed to the various surface conditions that they would encounter in the subsequent balance and gait tests. Each subject was asked to use his/her entire foot to move back and forth two times on an 8 inch x 20 inch area of the aluminum plate in the diagonal direction for approximately three seconds. Then the subject was asked to move his/her foot freely to assess slipperiness of the surface for approximately two seconds. An additional five seconds was used to rate the surface condition using the Subjective Slipperiness Rating Scale. The Subjective Slipperiness Rating Scale is the same as the one used by Swensen et al. (1992) to obtain the subject's evaluation of slipperiness. Immediately after each trial, subjects provided the rating by placing a vertical mark along a 3.5 inch horizontal scale representing 0 to 10 units. The ratings of 0, 5, and 10 represent very, medium, and not slippery, respectively [21]. This rating scale has been tested for reproducibility [19].

During this test Insole pressure distribution data were collected at a sampling rate of 60 Hz for five seconds using a F-Scan sensing device (See Appendix-F for details of the FSCAN System).

The COF values of each shoe/floor combination was determined on a different day after the subjective assessment of slipperiness tests were completed, representing the objective measurements. The method and instruments used for determining COF values is the same as the one used for creating the three desirable ranges of friction for the study, as described in section C.3.b. In this study, two pairs of new shoes were used by each subject. One pair of new shoes was used specifically for dry conditions. The other pair of new shoes, which are of the same size, model, and manufacturer, were used for oily conditions. The used shoes were borrowed from the subjects and they were kept in the laboratory until the COF testing was over. Shoes were cleaned carefully in between COF testing using paper towels and alcohol pads.

C.6. Instrumentation

C.6.a. Kinetic measurements

The kinetic measurements, which include the forces and moments exerted on the force platform, were collected using a piezoresistive force platform (Model OR-6-1000, Serial # 3371 manufactured by 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 Bhattacharya (1988). The force platform was placed flush with the floor. The signals from the plate went into an amplifier (AMTI, model SGA6). The signals coming out of the amplifier were then delivered to an IBM compatible 486 personal computer, using A/D board and Peak™ Performance Software (Peak Performance Technologies Inc., Englewood, CO) for data collection. The data collection frequency was set at 60 Hz for a duration of 30 seconds (1800 data points). After all the data were collected, they were processed to determine the variables of postural sway, postural instability, and RCOF.

C.6.b. Kinematics

The kinematic measurements, which include linear and angular displacement, velocity, and acceleration, were collected using a videographic motion measurement system (Peak™ Performance Technologies Inc., Englewood, CO). Four cameras (Pulnix cameras, model: TM-640) were installed for the videographic recording as shown in Appendix-D. An Infrared (IR) light source of 600 watts capacity was installed next to each camera in order to be able to record the marker movement in both good and poor lighting conditions. Twenty-four reflective markers were placed on subjects' anatomical landmarks (Table C.2. and Appendix-B) for use with the semi-automatic digitization for the determination of kinematic parameters.

The Peak Performance system was used for the digitization of three-dimensional spatial movement of the markers. Calibration of each test session was performed to ensure the accuracy of the digitization. After digitizing the video pictures, the whole body CG movement was determined. The data from the force plate and videographic system were synchronized with the help of an event synchronization system.

Table C.2
Anatomical landmarks for reflective marker placement

Marker	Anatomical Position	Marker Number
Right first MTP	Base of the 1st metatarsal of the right foot	1
Right fifth MTP	Base of the 5th metatarsal of the right foot	2
Right heel	Right calcaneus	3
Right ankle	Lateral malleolus of the right ankle	4
Right knee	Head of the fibula at the right knee	5
Right hip	Right upper femoral condyle	6
Right ASIS	Right anterior superior iliac spines	7
Left ASIS	Left anterior superior iliac spines	8
Back	Lumbar 3	9
Left hip	Left upper femoral condyle	10
Left knee	Head of the fibula at the left knee	11
Left ankle	Lateral malleolus of the left ankle	12
Left heel	Left calcaneus	13
Left first MTP	Base of the 1st metatarsal of the left foot	14
Left fifth MTP	Base of the 5th metatarsal of the left foot	15
Right wrist	Radial styloid at the right wrist	16
Right elbow	Lateral epicondyle of the right elbow	17
Right shoulder	Right acromion	18
Left shoulder	Left acromion	19
Left elbow	Lateral epicondyle of the left elbow	20
Left wrist	Radial styloid at the left wrist	21
Neck	Occipital bone	22
Right temple	Right temple	23
Left temple	Left temple	24

C.7.Dependent Variables:

C.7.a. Determination of Postural Sway and Instability

C.7.a.1. Objective Measures of Postural Sway: Sway area (SA) is the area of the projection of the body's CP on the xy plane due to sway, and sway length (SL) is the distance traveled by the CP. We have used these variables in many research studies in our laboratory (20,22-23). Sway Fy (RMS) [also known as F(AP)] and Sway Fx (RMS) [also known as F(ML)] are the root mean square values of the horizontal forces in the AP and ML directions respectively. The definition of Maximum Sway AP Excursion and Maximum Sway ML Excursion are given in the following (24). These definitions are also relevant for the variables used in the Dynamic balance evaluation section presented later in this report.

Excursion Parameters
The excursion parameters are defined on the basis of the lateral and medial deviation of the center of pressure (CP) trace under the feet during static task performance. Figure C-4 shows the trace of the movement of the CP under the feet. The medial lateral (ML) excursion is the net deviation of the CP in the ML direction. The anterior posterior (AP) excursion is quantitated by measuring the net deviation of the CP in the AP direction.

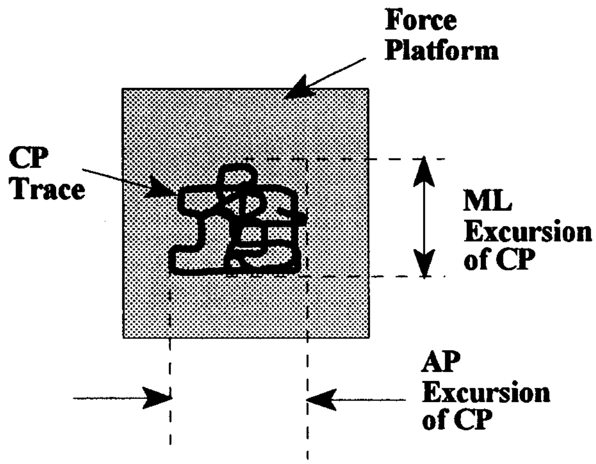


Figure C-4

The excursion parameters quantitate the extent of movement of the point of application of plantar force under the supporting feet. This movement of the CP under the foot is a time variant response to the momentary position of the whole-body center of gravity (CG) with respect to the basal supporting area provided by the feet. Thus, the excursion parameters provide an indirect measure of the dynamic stability performance during the posture.

C.7.a.2. Objective Measures of Postural Instability:
Three non-dimensional indices, which are similar to those described by Bagchee et al [25], were used to quantitatively determine the propensity of momentary loss of postural instability associated with a sway pattern formed by the CP with respect to the postural stability boundary (basal support area). However, in previous study, the propensity of postural instability was defined only using CP data, and the possibility that the CP travels outside the stability boundary was not considered. In the current study, the CP data from all forty subjects were used to determine the propensity of postural instability. The theoretical stability boundary (TSB), which is defined by the outer perimeter of the feet was used to determine CP based postural instability. The stability boundary used to determine CG based postural instability was used for dynamic tasks and are described in Section D. The three variables used to describe the propensity of postural instability are described as follows:

Index of Proximity to Stability Boundary (IPSB)
IPSB measures how close the body's CP or CG travels to a person's stability boundary, which is graphically shown in Figure C-5 and Figure C-6, respectively. The equation is as follows:

$$IPSB = \frac{p}{R_{\max}}$$

where,
p = the minimum distance between the stabilogram and the stability boundary.
R_{max} = the radial distance of the point on the stability boundary that is closest to the CP or CG movement ($\overline{OG}$ either in Figure C-5 or Figure C-6).

A lower value of IPSB indicates that the subject has a greater propensity of postural instability while performing a given task. A negative value of IPSB implies that subjects' CP or CG are outside of the stability boundary.

Weighted Residence Time Index (WRTI)

WRTI is the weighted measure of time that the subject's CP or CG lies in various proximity zones to the stability boundary. The proximity zones (200%, 180%, 160%, 140%, 120%, 100%, 80%, 60%, 40%, and 20% distances of the stability boundary from the center) are constructed by drawing concentric lines to the stability boundary at the predetermined distances. The greater the residence time in the outer proximity zones, the greater is the propensity of postural instability for a given task under specified intrinsic and extrinsic conditions. The equation for determining WRTI is shown in the following:

$$WRTI = K \frac{\sum e^i z_i}{}$$

where z_i = frequency count of zone *I*.
i = 3, 4, 5, 6, 7, 8, 9, 10.
K= e^{-4}

Stability Area Ratio (SAR)

SAR considers the spread of the stabilogram in comparison to the stability boundary, which is defined as:

$$SAR = \frac{A_S}{A_{SB}}$$

where A_S = the area of the envelope around the stabilogram.
A_{SB} = the area of the stability boundary.

Under ideal conditions of upright stability, a subject would produce zero sway area ($A_S = 0$), while poor stability would produce sway area close to or larger than that of the stability boundary. Therefore, the higher the SAR, the higher the propensity of postural instability.

C.7.a.3. Determination of Total Utilized COF or Required or Utilized Coefficient of Friction (RCOF or H/V :Objective Measure):

Maximum RCOF

The maximum RCOF is defined as the maximum ratio of shear force to normal force during the 30 second task performance. The shear force is the magnitude of the vector sum of shear forces in the medio-lateral (ML) and anterior -posterior (AP) directions (measured with the force platform). Mathematically,

$$RCOF = \frac{\sqrt{F_x^2 + F_y^2}}{F_z}$$

where Fx = horizontal force in ML direction.
Fy = horizontal force in AP direction.
Fz = normal (vertical) force.

Maximum Time Rate of Change in RCOF

The maximum time rate of change in RCOF is the maximum value of the first order derivative of RCOF with respect to time experienced by the subject during the trial. The formula is shown below:

$$\text{Maximum time rate of change in RCOF} = \frac{dRCOF}{dt}$$

where t = time in seconds.

C.7.b. Subjective Measures of Postural Instability:

Perceived Sense of Slip/Fall (PSOS): A short questionnaire-type rating scale was administered to determine the subjective perception of slip and/or potential fall of the subject during postural sway and gait tests. It consisted of simple questions which the subject had to answer immediately after each test. The results from this test were used to see how the subject's subjective perception correlates with the objective measures of postural stability as measured by the various postural sway parameters. A high score (max. score possible: 8; min. score possible: 0) implies a high subjective perception of slip or sway and/or fall. The questionnaire used for this study is given in Appendix E. The PSOS scale has been validated and tested in other studies conducted in our laboratories. (26-27)

C.8. Data Analysis Strategy for Static Postural Stability Evaluation during Task Performance on Slippery Surfaces

The CP data collected from forty subjects were processed for characterizing postural sway and postural instability. The statistical analyses were performed using the Statistical Analysis System (SAS) and the Biomedical Computer Programs (BMDP) package. All postural sway and postural instability parameters were transformed to their natural logarithm to achieve approximate normality of the statistical distributions.

This study involves a multi-factor design where each of the four factors (independent variables of lighting, task, shoe type, surface) was investigated to see what contribution it made to the outcomes being measured. Data collected on the nine parameters of sway (sway length, sway area, rms Fx, rms Fy, AP Excursion, ML Excursion) and instability (IPSB, SAR and WRTI) were analyzed by both univariate and multivariate repeated measure analyses of variance (ANOVA). Between-subject covariates include age and sex. Within-subject factors of the experimental conditions (surface, lighting, shoe type, and task) and the interactions between these experimental conditions, were tested in the model.All insignificant covariates were dropped and a final model was estimated and tested.

Repeated measure ANCOVA was performed to investigate the relationship between PSOS and each postural sway and instability variable. In these analyses, PSOS was treated as one of independent variable and postural sway and instability variables were taken as dependent variables. The regression of PSOS on each postural sway and instability variable was calculated.

C.9. RESULTS AND DISCUSSION

C.9.a. Static Postural Stability Evaluation during Task Performance on Slippery Surfaces

C.9.a.1. Demographic Data

Forty worker subjects [mean 41.0 years ± 14.9 standard deviation (s.d.)] participated in this study. Most of the subjects were maintenance workers recruited from the surrounding community. Half of the subjects are male. Descriptive statistics for variables common to the subjects are provided in Table C.3.

Table C.3.
Demographic Data (n = 40)

	Male (n = 20)		Female (n = 20)	
	mean	s.d.	mean	s.d.
Age (year)	41.0	14.9	39.5	14.9
Weight (kg)	84.6	12.5	75.9	18.6
Height (cm)	175.3	4.9	161.3	5.70
Left Foot Length (cm)	27.2	0.88	24.7	1.00
Right Foot Length (cm)	27.3	0.84	24.7	1.07
Left Foot Width (cm)	10.1	0.47	9.3	0.52
Right Foot Width (cm)	10.0	0.51	8.8	2.13
Foot Reaction Time (m. second)	43.6	6.8	42.6	5.6
Hand Reaction Time (m. second)	36.3	7.8	39.2	7.5
Theoretical Stability Boundary (cm^2)	729.2	37.3	608.5	39.3
Functional Reach (cm)	76.0	3.4	69.4	4.5

Male subjects appeared to be slightly heavier than the average American man (83.2 kg ± 15.1 s.d.), and their stature was larger than the average American man (174.5 cm ± 6.6 s.d.) [18]. Female subjects were heavier than the average American woman (66.4 kg ± 13.9 s.d.), and their stature was smaller than the average American woman (162.1 ± 6.0 s.d.) [18]. For this study, the average % of tread available of the of left and right foot used shoes were 78.6% (standard deviation = 17.8) and 77.9% (17.4), respectively. The average hardness values of the left and right foot used shoes were 36.9 (standard deviation = 6.9) and 36.4 (6.3), respectively.

C.9.a.2. Slip Occurrence during Static Task Performance (relevant to Specific Aim # A5)
In the current study, the subject was considered to be experiencing a slip whenever his/her foot moved outside the stability boundary defined by the outer perimeter of his/her feet. Among all test trials performed by 40 subjects, there were 464 slips (24.2%). 434 out of 464 slips (93.5 %) occurred during reach tasks.

Table C.4 and C.5 present the number of slips and % of slip occurrence in various ranges of RCOF / COF for the three tasks combined (stationary, bending, and reach) and the reach task only, respectively. Figures C.7 and C.8 graphically illustrate these data. The comparison of RCOF (= horizontal force / vertical force, i.e. H/V) and shoe COF values has been used to predict slips in previous research [13]. Theoretically, slip is expected to occur when RCOF is larger than shoe COF (i.e. RCOF / COF is greater than one).

Table C.4
Summary of Number of Slips and % of Slip Occurrence
for All Static Tasks in Various Range of RCOF / COF

Range of RCOF / COF	# of slips	# of trials	% of slip occurrence
0-0.1	38	727	5.2
0.1-0.2	52	355	14.6
0.2-0.3	64	219	29.2
0.3-0.4	62	183	33.9
0.4-0.5	64	131	48.9
0.5-0.6	53	99	53.5
0.6-0.7	26	40	65
0.7-0.8	20	29	69
0.8-0.9	16	28	57.1
0.9-1.0	19	26	73.1
1.0-1.1	7	11	63.6
1.1-1.2	11	17	64.7
1.2-1.3	6	12	50
1.3-1.5	5	12	41.7
1.5-1.7	5	10	50
1.7-2.1	5	10	50
2.1-2.5	8	11	72.7

Table C.5
Summary of Number of Slips and % of Slip Occurrence
for the Reach Task in Various Range of RCOF / COF

Range of RCOF / COF	# of slips	# of trials	% of slip occurrence
0-0.2	98	236	41.5
0.2-0.3	62	80	77.5
0.3-0.4	60	77	77.9
0.4-0.5	56	63	88.9
0.5-0.6	53	59	89.8
0.6-0.7	26	26	100
0.7-0.8	20	20	100
0.8-0.9	14	16	87.5
0.9-1.0	16	16	100
1.0-1.2	15	16	93.8
1.2-1.7	14	17	82.4
1.7-2.2	12	13	92.3

In the region in which no slip is expected, the % of slip occurrences for all three tasks combined increased as the ratio of RCOF / COF increased (Figure C-7). The % of slip occurrence reached a maximum (73.1%) when the ratio of RCOF / COF was about one, and then dropped to 41.7% in the RCOF / COF range of 1.3 to 1.5. After that, the % of slip occurrence started to increase again and reached 72.7% in the RCOF / COF range of 2.1-2.5.

The % of slip occurrence for reach tasks ranged from 41.5% to 100% in the entire range of RCOF / COF (0 to 2.2). In the region in which no slip is expected, the % of slip occurrence increased drastically and reached above 50% in the RCOF / COF range of 0.2 to 0.3 (Figure C-8). The % of slip occurrence reached 100% in the RCOF / COF range of 0.6 to 0.7 and remained in between 82.4% and 100% above these values.

To better understand if the subjects were able to perceive an impending slip during task performance, the number of slips and % of slip occurrence in various ranges of PSOS score for all tasks combined were compared. These data are summarized in Table C-6, and the data from the reach task only are shown in Table C-7, Figures C-9 and C-10 graphically illustrate the relationship of slips and the PSOS score. A higher score on the PSOS scale implies greater perceived sense of slip.

For all three tasks combined, the % of slip occurrence was only 4% in the PSOS range of 0 to 0.5. The % of slip occurrence increased with increasing PSOS and reached 100% in the range of 4.5 to 5.0 (Figure C-9).

For the reach task only, the % of slip occurrence increased as PSOS increased (Figure C-10). The % of slip occurrence reached 100% in the PSOS score range of 4.0 to 4.5 and stayed at 100% beyond this range.

Table C-6
Summary of Number of Slips and % of Slip Occurrence
for All Static Tasks in Various Range of PSOS

Range of PSOS	# of slips	# of trials	% of slip occurrence
0-0.5	46	1148	4.0
0.5-1.0	59	206	28.6
1.0-1.5	73	139	52.5
1.5-2.0	28	61	45.9
2.0-2.5	36	57	63.2
2.5-3.0	29	40	72.5
3.0-3.5	24	30	80.0
3.5-4.0	24	29	82.8
4.0-4.5	34	35	97.1
4.5-5.0	25	25	100
5.0-5.5	23	23	100
5.5-6.5	24	24	100
6.5-7.5	15	15	100
7.5-8.0	24	24	100

Table C-7
Summary of Number of Slips and % of Slip Occurrence
for the Reach Task in Various Range of PSOS

Range of PSOS	# of slips	# of trials	% of slip occurrence
0-0.5	39	162	24.1
0.5-1.0	56	83	67.5
1.0-1.5	69	84	82.1
1.5-2.0	25	33	75.8
2.0-2.5	33	38	86.8
2.5-3.0	26	27	96.2
3.0-3.5	21	23	91.3
3.5-4.0	22	23	95.7
4.0-4.5	32	32	100

4.5-5.0	25	25	100
5.0-5.5	23	23	100
5.5-6.5	24	24	100
6.5-7.5	15	15	100
7.5-8.0	24	24	100

C.9.a.3. Effect of Prior Knowledge of Surface Slipperiness on StaticTask Performance (relevant to specific aim # A1 and A2)
The subjects' ability to correctly assess the surface slipperiness was evaluated by comparing their subjective ratings of surface slipperiness with the COF values of the shoe/floor surface. Figure C-11 presents the scatter plot of the subjective rating versus the COF values. The COF values of new shoes were 0.35, 0.18, and 0.11 for slightly, medium, and very oily surfaces, respectively. There are three clusters in Figure C-11 at COF values of 0.11, 0.18, and 0.35 representing the COF values for new shoes.

Subjects used the 10 unit rating scale (21) to judge the slipperiness of various shoe / floor surfaces with COF values ranging from 0 to 0.35. Ideally, subjects would rate the most slippery surface (COF = 0.02) with the subjective slipperiness rating scale value of 0 and the least slippery surface (COF = 0.35) with the scale value of 10. The line, subjective rating = 30.3 x (COF-.02), was therefore drawn to represent this theoretical relationship between the subjective and objective measurements (Figure C-11). The theoretical residual (differences between each observation and the predicted value for each observation based on the theoretical relationship) was calculated to represent the discrepancies between the rating given by the subject and that value predicted by the theoretical relationship.

The subjective ratings of slipperiness, as deviated from their theoretical value, were analyzed by repeat measure analysis of covariance (ANCOVA). The ANCOVA model used the covariates of height, age, gender, available tread, shoe sole hardness and MRCPP5 (Maximum rate of peak pressure under the whole foot measured with the FSCAN sensor). The within-subject variables of foot, surface slipperiness and the interaction of these two factors also were investigated in this model. A strategy of backward elimination was followed to remove any insignificant ($p>0.05$) covariates and interaction.

The final model for the deviated slipperiness ratings included only the significant main effects of surface slipperiness, i.e., all covariates and the foot by surface slipperiness interaction were not significant. In this final model, slightly ($p<0.0001$) and medium ($p<0.03$) slippery surfaces were found to be judged less slippery than would be expected by the theoretical model based on the surface COF. The workers also judged the surface to be somewhat less slippery when using their left foot than when using their right foot; however this difference was not statistically significant ($p=0.25$).

To investigate if the subjects who were more "accurate" in assessing surface slipperiness (i.e. evidenced small residuals) would have less postural sway and instability during task performance, a correlation analysis was performed. Table C-8 contains the correlation coefficients between the residuals and the number of slips, postural sway variables, indices of postural instability and shoe COF for all three tasks combined.

Table C-8
Pearson Correlation Coefficients
(Residuals vs. Postural Sway and Instability Variables for All Static Tasks)

	Sway Length	Sway Area	IPSB**	SAR	WRTI	Number of Slips
Theoretical Residual	0.17 (p = 0.16)	0.20 (p = 0.13)	**-0.38*** **(p = 0.02)**	0.24 (p = 0.08)	**0.45*** **(p = 0.01)**	0.14 (p = 0.21)
Shoe COF	0.08 (0.61)	-0.2 (0.22)	0.24 (0.14)	-0.3 (0.06)	-0.3 (0.06)	**-0.39*** **(0.013)**
Number of Slips	0.24 (0.14)	**0.49*** **(0.0012)**	**-0.41*** **(0.0085)**	**0.53*** **(0.0004)**	**0.39*** **(0.012)**	1.00 (0.0)

Note: one-tailed tests were performed

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

** CP based IPSB were used for analysis. The stability boundary was calculated by digitizing the shoe print of each subject.

Table C-9
Pearson Correlation Coefficients
(Residuals vs. Postural Sway and Instability Variables for Reach Task)

	Sway Length	Sway Area	IPSB**	SAR	WRTI	Number of Slips
Theoretical Residual	0.10 (p = 0.28)	0.14 (p = 0.21)	**-0.32*** **(p = 0.045)**	0.17 (p = 0.16)	**0.43*** **(p = 0.01)**	0.11 (p = 0.27)

Note: one-tailed tests were performed

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

** CP based IPSB were used for analysis. The stability boundary was calculated by digitizing the shoe print of each subject.

There was a significant negative correlation between the residuals and IPSB and a positive association between the residuals and WRTI. The larger the residuals, the smaller the IPSB values or larger the WRTI implying greater postural instability. The same results were found for the reach task. The number of slip occurrences were significantly correlated with 4 out of 5 postural sway and instability variables. The shoe COF did not correlate with any of the postural sway and instability variables. Table C-9 contains the correlation coefficients between the residuals and the postural sway and instability variables for the reach task. IPSB and WRTI were the only two variables which were found to be significantly associated with these residuals.

In summary, the subjects always slipped when the PSOS rated by the subjects was beyond the "ceiling" value of 4.5. Subjects were able to perceive the instability, and this perception was reflected in their rating. This finding has practical implication in identifying tasks and workplace areas with potential for slips. A field survey can be conducted to investigate workers' PSOS under possible extrinsic and intrinsic risk factors using the PSOS scale. Prevention strategies can then be developed once the workers' PSOS score are close to the ceiling value. Workers who were cautious in assessing surface slipperiness had less postural instability during task performance, as indicated by IPSB and WRTI. However, the current study did not address the issue of whether there is a learning trend in assessing surface slipperiness with repeated assessment. If the ability to assess surface slipperiness can be improved by training, then a training program can be developed to help minimize slip incidence. In addition, workers can also be instructed to avoid working on potentially hazardous surfaces without first carefully assessing the working surface. The results from this study indicate that subjects were able to perceive the impending slips due to the change in job-task and surface slipperiness. The PSOS scale is reproducible, easy to use, and provides a simple way to evaluate the potential slip hazard in the workplace. Additional details can be found in the enclosed draft manuscript (34).

C.9.a.4. Repeated Measure ANOVA of Postural Sway and Instability Parameters (relevant to specific aim # A3 to A5)

For each of the three static tasks, a multivariate and univariate repeated measure analysis of variance (ANOVA) was performed to analyze all six postural sway (sway length, sway area, rms Fx, rms Fy, AP Excursion, ML Excursion) and three instability (CP based IPSB, SAR, WRTI) parameters.

<u>Summary of the Statistical Analyses of the Static Postural Task Data</u>. Table C-10 and C-11 shows the results of univariate (i.e., including all tasks but analyzed separately for each postural balance outcome) and multivariate (i.e., analyzed across all postural balance outcomes within each task) analyses of the postural balance data. The postural sway outcomes used in this analysis are sway area, length, RMS sway Fx or F(ML) (ML direction force), RMS sway Fy or F(AP) (AP direction force), and maximum excursion in the AP and ML directions. The between-subject covariates of age and gender were regressed on these outcomes; also, the within-subject factors of surface condition, shoe worn, light intensity, task performed and all possible interactions among these within-subject factors were tested for significance. Only those effects with at least one significant ($p<0.05$) result are shown in the Table C-10-11.

Age was found to effect only the RMS F_x ($p<0.03$). Older workers tended to have a slightly greater sway force in the x-direction. Since this finding for age is only marginally significant and was not demonstrated for any other univariate test or any multivariate test within a given task, it is likely a chance finding and was not pursued further. A number of significant effects due to gender were found. Gender was found to be a significant covariate of each task in each of the multivariate tests. Males were found to have significantly greater postural sway in terms of the area of sway, the RMS sway F_y, and the maximum excursion in both the AP and ML directions. Surface slipperiness was found to effect the Reach task, the RMS sway F_x, and the maximum excursion in the AP direction.

However, the effect of surface slipperiness on RMS sway F_x is moderated by a significant surface slipperiness by shoe worn interaction and the effect on excursion in the AP direction is marginally significant ($p<0.03$). For these main effects, very and medium slippery surfaces tended to increase postural sway relative to slightly slippery and dry surfaces. Shoe worn demonstrated a significant (multivariate) effect on the Bending tasks but no significant effects in any of the univariate models for the individual parameters of sway. However, as noted above, significant shoe worn by surface slipperiness interactions were found in these analyses. In addition to the RMS sway F_x, significant shoe by slipperiness interactions were detected for the Reach task and the RMS sway F_y. For both RMS sway outcomes, the combination of a slightly slippery surface and new shoes tended to produce greater sway than would be expected from either the surface condition or the shoe worn alone. These effects are only marginally significant ($p<0.04$ and $p<0.05$, respectively) but may be suggestive of different types of shoe designs to be worn on surfaces which are usually only slightly slippery . The lighting available was a highly significant predictor of sway, both for each of the three tasks and for all the individual sway parameters except RMS sway in the F_x and F_y directions. Sway was increased by poor lighting. Finally, the type of task performed had highly significant effects on each of the sway outcomes ($p<0.0001$ for all 6 balance parameters). Sway was greatest for the Reach task, second greatest for the Bending task and least for the Stationary task.

The geometric means and standard deviations for each of the balance outcomes classified by each of these significant factors is shown in Table C-12. In Table C-13, the relative percentage increase in sway as compared to the baseline (or least affected) category of these factors is shown. From these tables, it is also possible to rank the relative effects on balance of each of these factors. Task had the greatest effects on sway, with the Reach task increasing sway between 32.45% (for RMS sway F_y) and 2267.27% (for sway area) and the Bending task increasing sway between 5.96% (for RMS sway F_x) and 400.01% (for sway area), as compared to the Stationary task. Lighting had the second largest effects on sway. Where lighting significantly affected sway, poor light increased sway between 12.18% (for excursion in the ML direction) and 32.99% (for sway area) relative to good light. The third largest effects on balance were noted for gender. Males tended to sway between 11.68% (for excursion in the AP direction) and 26.97% (for sway area) greater than did females. The surface slipperiness and shoe worn combinations had the next smaller effects on sway. The combination of an old shoe on a very slippery surface increased RMS sway F_x by 7.08%, while the combination of a new shoe on a slightly slippery surface increased RMS sway F_x by 5.22% relative to a new shoe on a dry surface. The combination of a new shoe on a slightly slippery surface increased RMS sway F_y by 3.36% relative to an old shoe on a dry surface. Finally, the main effect of surface increased excursion in the AP direction between 4.25 and 4.79% (for very and medium slippery surfaces, respectively) relative to a dry surface. The surface slipperiness factor demonstrated the fewest and smallest effects (other than the main effect of shoe worn, which was not significant in any of the univariate models).

Table C-10: Analyzing separately by static task but Combining all 6 Dependent Measures of postural sway (P values are shown)

Independent Variable	Stationary Task	Bending Task	Reach Task
Age	0.21	0.10	0.82
Gender	0.007*	0.01*	0.005*
Surface	0.56	0.30	0.0001*
Shoe	0.88	0.01*	0.18
Lighting	0.0001*	0.0001*	0.01*
Surface*Shoe	0.90	0.19	0.04*

Table C-11: Analyzing for all Static Tasks combined but sperately for each measure of postural sway (P values are shown)

Independent Variable	SA	SL	RMS Sway Fx (ML)	RMS Sway Fy (AP)	Max. Sway AP excurs	Max.Sway ML excurs.
Age	0.90	0.38	0.03*	0.05	0.72	0.45
Gender	0.009*	0.33	0.08	0.006*	0.02*	0.009*
Surface	0.65	0.10	0.01*	0.62	0.03*	0.55
Shoe	0.98	0.17	0.78	0.41	0.41	0.69
Lighting	0.0001*	0.0001*	0.26	0.61	0.0001*	0.0001*
Task	0.0001*	0.0001*	0.0001*	0.0001*	0.0001*	0.0001*
Surface*Shoe	0.44	0.11	0.04*	0.05*	0.76	0.46

*Statistically significant at $p<0.05$.

Table C-12: Geometric Means and Standard Deviations for Static Balance Measurements, by Gender

	Area (cm^2)	Length (cm)	RMS F_X (ML)	RMS F_Y (AP)	AP Excursion (cm)	ML Excursion (cm)
Female	9.94	72.89	180.59	315.53	3.58	5.26
	(1.30)	(1.12)	(1.41)	(1.40)	(1.17)	(1.16)
Male	12.62	75.60	206.39	391.27	3.99	6.06
	(1.34)	(1.13)	(1.23)	(1.20)	(1.15)	(1.19)

Geometric Means and Standard Deviations for Balance Measurements, by Surface Condition

	Area	Length	RMS F_X	RMS F_Y	AP Excursion	ML Excursion
Very	11.31	75.21	197.37	350.49	3.84	5.70
Slippery	(1.38)	(1.13)	(1.33)	(1.33)	(1.18)	(1.22)
Medium	11.41	74.96	195.60	351.13	3.86	5.69
Slippery	(1.38)	(1.12)	(1.35)	(1.34)	(1.19)	(1.21)
Slightly	10.92	73.33	191.72	354.04	3.73	5.54
Slippery	(1.38)	(1.14)	(1.38)	(1.36)	(1.19)	(1.19)
Dry	11.15	73.48	187.82	349.88	3.69	5.64
	(1.36)	(1.13)	(1.33)	(1.33)	(1.17)	(1.19)

Geometric Means and Standard Deviations for Balance Measurements, by Shoe Worn

	Area	Length	RMS F_X	RMS F_Y	AP Excursion	ML Excursion
Old	11.22	73.84	192.90	350.21	3.77	5.66
	(1.36)	(1.13)	(1.33)	(1.33)	(1.18)	(1.18)
New	11.17	74.62	193.20	352.50	3.79	5.63
	(1.37)	(1.12)	(1.35)	(1.34)	(1.17)	(1.20)

Geometric Means and Standard Deviations for Balance Measurements, by Light Condition

	Area	Length	RMS F_X	RMS F_Y	AP Excursion	ML Excursion
Poor	12.91	80.60	194.30	350.70	4.14	5.98
	(1.34)	(1.14)	(1.32)	(1.33)	(1.17)	(1.18)
Good	9.71	68.34	191.82	352.04	3.45	5.33
	(1.37)	(1.12)	(1.35)	(1.34)	(1.17)	(1.20)

Geometric Means and Standard Deviations for Balance Measurements, by Task Performed

	Area	Length	RMS F_X	RMS F_Y	AP Excursion	ML Excursion
Reach	54.03	170.07	255.43	411.32	9.35	12.30
	(1.37)	(1.14)	(1.40)	(1.35)	(1.23)	(1.21)
Bending	11.41	67.23	172.79	339.65	3.44	6.34
	(1.35)	(1.17)	(1.32)	(1.33)	(1.21)	(1.18)
Stationry	2.28	35.81	163.06	310.55	1.68	2.31
	(1.60)	(1.18)	(1.32)	(1.33)	(1.25)	(1.35)

Table C-12 (Cont'd): Geometric Means and Standard Deviations for Balance Measurements, by Surface Condition and Shoe Worn

	Area (cm^2)	Length(cm)	RMS F_X (ML)	RMS $_Y$ (AP)	APExcursion (cm)	ML Excursion (cm)
Very Slippery / Old	11.53 (1.39)	75.10 (1.13)	200.94 (1.32)	350.59 (1.33)	3.83 (1.18)	5.80 (1.23)
Very Slippery / New	11.10 (1.43)	75.32 (1.14)	193.87 (1.34)	350.39 (1.34)	3.86 (1.21)	5.61 (1.24)
Medium Slippery / Old	11.54 (1.44)	74.80 (1.14)	196.97 (1.34)	353.75 (1.33)	3.86 (1.24)	5.72 (1.23)
Medium Slippery / New	11.28 (1.38)	75.12 (1.12)	194.09 (1.37)	348.26 (1.35)	3.87 (1.18)	5.66 (1.22)
Slightly Slippery / Old	10.83 (1.36)	72.23 (1.15)	186.32 (1.37)	347.03 (1.34)	3.70 (1.20)	5.58 (1.18)
Slightly Slippery / New	10.96 (1.46)	74.37 (1.15)	197.44 (1.43)	361.21 (1.39)	3.76 (1.22)	5.50 (1.25)
Dry / Old	11.01 (1.38)	73.41 (1.14)	187.98 (1.33)	349.48 (1.33)	3.68 (1.18)	5.56 (1.20)
Dry / New	11.29 (1.37)	73.56 (1.13)	187.65 (1.33)	350.29 (1.35)	3.69 (1.18)	5.71 (1.22)

Table C-13: Percentage Change from Baseline Observed for each Significant Factor

	Area	Length	RMS F_X (ML)	RMS F_Y (AP)	AP Excursion	ML Excursion
Gender:						
Male	26.97			24.00	11.68	15.15
Surface:			*	*		
Very Slippery					4.25	
Medium Slippery					4.79	
Slightly Slippery					1.21	
Lighting:						
Poor	32.99	17.94			19.85	12.18
Task:						
Reach	2267.27	374.98	56.64	32.45	456.44	433.17
Bending	400.01	87.76	5.96	9.37	104.43	174.80
Surface/ Shoe						
Very Slippery / Old			7.08	0.32		
Very Slippery / New			3.31	0.26		
Medium Slippery / Old			4.97	1.22		
Medium Slippery / New			3.43	-0.35		
Slightly Slippery / Old			-0.71	-0.70		
Slightly Slippery / New			5.22	3.36		
Dry / Old			0.17			
Dry / New				0.23		

* See significant Surface/Shoe interaction effects. (cm^2)

Summary of the Statistical Analysis of the Instability Outcomes :
The greatest postural instability (lowest IPSB and highest SAR and WRTI) was found to occur for the reach task. Results from a posteriori comparisons indicated that the mean of the reach task's postural instability were significantly different from those of the bending and stationary tasks (both p values = 0.0001). The mean IPSB and SAR indicated greater postural instability for poor lighting compared to good lighting, but this trend was not true for WRTI (Table C.14).

Table C.14
Geometric means and standard deviations of postural instability variables for various risk factors (n = 40)

STATIC TASK	IPSB**	SAR	WRTI
Stationary	0.770 (1.06)	0.004 (1.93)	0.009 (1.05)
Bending	0.643 (1.08)	0.017 (1.52)	0.013 (1.05)
Reach	0.262 (1.33)	0.082 (1.50)	0.225 (1.53)
LIGHTING			
Good	0.544 (1.26)	0.015 (4.34)	0.087 (1.33)
Poor	0.543 (1.24)	0.020 (3.48)	0.069 (1.26)
SURFACE			
Dry	0.589 (1.14)	0.017 (3.70)	0.029 (1.06)
Slightly	0.579 (1.17)	0.017 (3.76)	0.043 (1.14)
Medium	0.514 (1.20)	0.018 (4.15)	0.105 (1.35)
Very	0.500 (1.34)	0.018 (4.15)	0.139 (1.48)
SHOE			
New	0.506 (1.28)	0.017 (3.87)	0.147 (1.27)
Used	0.488 (1.36)	0.017 (4.00)	0.180 (1.43)

** CP based IPSB were used for analysis

Both IPSB and WRTI indicated that the postural instability of very oily surfaces was the greatest among the four surfaces, followed by medium oily, slightly oily, and dry surfaces. For IPSB and WRTI, the mean postural instability of very oily surfaces was significantly different from those of dry and slightly oily surface (all p values < 0.05), but not medium oily surfaces. Both IPSB and WRTI indicated that the postural instability of used shoes was greater than that of new shoes.

The % increase in the instability variables with respect to ideal conditions (stationary task, good lighting, dry surface, and new shoes) are presented in Table C.15.

In comparison to the stationary task, the % increase in the instability variables for the reach task was much higher than those of the bending task. The effect of poor lighting on IPSB was slight, with a 0.18% increase in postural instability. The very oily surface was only responsible for a 2.0% increase in SAR. However, its effect on WRTI was drastic with a 379.3% increase in postural instability. The % increases in IPSB and WRTI due to used shoes were minor, but the shoes used accounted for a 22.5% increase in WRTI. In this study, subjects wore either new shoes provided by the laboratory or their own used shoes during the experiment.

Table C.15
Estimated % Increases in Postural Sway and Instability Parameters
Due to Environmental and Job-Task Factors

Main Effects	IPSB**	SAR	WRTI
Static Task:			
Bending	-16.5	325.0	44.4
Reach	-66.0	1950.0	2400.0
Poor lighting	-0.18	33.3	-20.7
Surface:			
Slightly oily	-1.70	-1.5	48.2
Medium oily	-12.7	1.9	262.1
Very oily	-15.1	2.0	379.3
Used shoes	-3.6	0.02	22.5

** CP based IPSB were used

Based on Table C.15, postural instability for any combinations of the non-optimal conditions can be easily estimated after the subject's baseline (postural sway or instability under optimal conditions) is determined. The postural sway or instability is estimated by multiplying the baseline by each multiplier of the non-optimal condition. For example, if a worker performs reach tasks under poor lighting and very oily surfaces with used shoes, the estimated % increase in SAR can be calculated as:

Estimated sway area ratio = (Baseline) (1+1950%) (1+33.3%) (1+2.0%) (1+0.02%)

where (1+1950%): the multiplier for the reach task;

(1+33.3%): the multiplier for poor lighting;

(1+2.0%): the multiplier for a very oily surface;

(1+0.02%): the multiplier for used shoes.

C.9.a.5. Repeated Measure ANCOVA of RCOF and Maximum Time Rate of Change in RCOF (relevant to specific aim # A5)

Results from Analysis of Covariance (ANCOVA) showed a significant within-subject effect of task ($p = 0.0001$) on maximum RCOF (Table C.16). No main effect and no interactions were found to be significant for the variable of maximum time rate of change in RCOF.

Table C.16
Summary of the ANCOVA of Maximum RCOF

Source	DF	Mean Squares	F	Pr > F
Task	2	0.313	111.84	**0.0001***
Surface	3	0.0002	1.14	0.34
Shoe	1	0.00004	0.15	0.70
Light	1	0.00001	0.07	0.79
Task x Surface	6	0.0001	0.86	0.53
Task x Shoe	2	0.000002	0.01	0.99
Surface x Shoe	3	0.0001	0.44	0.72
Task x Light	2	0.0001	0.93	0.40
Surface x Light	3	0.0001	0.49	0.69
Shoe x Light	1	0.001	6.91	**0.01***

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

The speed of bending and lifting was treated as a time-varying covariate in the initial ANOVA Model. The mean values of speed were 1.03 second (± 0.10 sem) and 1.10 second (± 1.10 sem) for the motion of bending down and coming up, respectively. The mean lifting speed was 2.56 seconds (± 0.02 sem) for the reach task. Since the speed of bending and lifting turned out to be insignificant ($p > 0.05$), it was not included in the final reduced ANCOVA model.

A posteriori comparisons showed that the average of the maximum RCOF for the three tasks were significantly different from each other (all p values = 0.0001).The geometric mean and standard deviations of the maximum RCOF for the three tasks, for new and used shoes, and for the two lighting conditions are shown in Table C.17.

Table C.17
Geometric Means and Standard Deviations of Maximum
RCOF for Various Risk Factors

Static Task:		Geometric Mean	Geometric S.D.
	Stationary	0.016	0.17
	Bending	0.044	0.38
	Reach	0.058	0.24
Shoe x Light:			
New shoes	Good light	0.035	0.64
	Poor light	0.035	0.59
Used shoes	Good light	0.034	0.62
	Poor light	0.036	0.61

The average of the maximum RCOF for all three tasks was small, ranging from 0.016 to 0.058 (Table C.17). The average of the maximum RCOF for the reach task (0.058) was the largest amongst all three tasks. The bending task (0.044) had a smaller average maximum RCOF than did the reach task, but was greater than the stationary task (0.016). The average maximum RCOF for used shoes and poor lighting (0.036) was slightly greater than that of new shoes (0.35), but the average maximum RCOF for new shoes and good lighting (0.035) was slightly greater than that of used shoes (0.034).

C.9.a.6. Reproducibility Testing of the PSOS Scale

The reproducibility of the PSOS scale was tested using baseline data (data from optimal test conditions of good lighting, dry surfaces, and new shoes). A repeated measure ANOVA was performed to determine the effects of visit on PSOS score. No significant change ($p = 0.11$) in PSOS score due to different visits was found, indicating that no learning trend developed with repeated testing.

C.9.a.7. Repeated Measure ANOVA of the PSOS Variable (relevant to specific aim # A2)

The effects of Task, Surface, and Task x Surface were found to be highly significant on the PSOS score (all p values = 0.0001). The results from this ANOVA are shown in Table C.18. A posteriori comparisons revealed that the mean PSOS score of the reach task was significantly different from that of the stationary or bending tasks (both p values = 0.0001). However, the mean PSOS score for the bending task was not significantly different from that of the stationary task ($p > 0.05$). The mean PSOS score for all four levels of surface slipperiness were significantly different from each other (all p values = 0.0001).

Table C.18

Summary of the ANOVA of PSOS

Source	DF	Mean Squares	F	Pr > F
Task	2	105.1	124.4	**0.0001***
Surface	3	11.5	53.1	**0.0001***
Shoe	1	0.39	1.53	0.22
Light	1	0.53	2.79	0.10
Task x Surface	6	10.2	85.1	**0.0001***
Task x Shoe	2	0.12	1.16	0.32
Surface x Shoe	3	0.02	0.19	0.90
Task x Light	2	0.11	2.60	0.08
Surface x Light	3	0.06	0.93	0.43
Shoe x Light	1	0.01	0.21	0.65

* Any findings with p < 0.05 were considered statistically significant

Table C.19 presents the means and standard errors of the PSOS score for various tasks and surfaces. The mean PSOS score for the reach task was the greatest of the three tasks. This was also true when comparing the reach task to the other tasks for each surface. Among all four surfaces, the greatest mean PSOS score occurred for the very oily surface (1.24), followed by the medium oily (1.13), slightly oily (0.64), and dry surfaces (0.30). Figure C-12 illustrates the mean PSOS scores for the three tasks under various surface conditions. The mean PSOS scores for the stationary and bending tasks were about the same across all four surfaces, ranging from 0.19 to 0.28. The mean PSOS scores for the reach task were much higher than those found for bending and stationary tasks, ranging from 0.49 (dry) to 3.20 (very oily). For the reach task, there was a 553.1% increase in mean PSOS score noted to occur between the dry surface and the very oily surface.

Table C-19
Arithmetic Means and Standard Errors of PSOS* for Various Risk Factors

Static Task:		Mean	Standard Errors
	Stationary	0.21	0.021
	Bending	0.26	0.026
	Reach	2.01	0.087
Surface:			
	Dry	0.30	0.029
	Slightly oily	0.64	0.055
	Medium oily	1.13	0.087
	Very oily	1.24	0.092
Task x Surface:			
Stationary	Dry	0.22	0.044
	Slightly oily	0.19	0.040
	Medium oily	0.20	0.036
	Very oily	0.23	0.043
Bending	Dry	0.19	0.038
	Slightly oily	0.27	0.051
	Medium oily	0.28	0.053
	Very oily	0.28	0.063
Reach	Dry	0.49	0.063
	Slightly oily	1.45	0.131
	Medium oily	2.91	0.186
	Very oily	3.20	0.185

* Perception of slip is least for a minimum PSOS score of 0 and most for a maximum PSOS score of 8.

C.9.a.8. Relationship of PSOS with the Postural Sway and Instability Variables for Static Tasks

Repeated measure Analysis of Covariance (ANCOVA) was performed to investigate the relationship between PSOS score and each postural sway and instability variable after adjusting for age, gender, baseline, and test sequence. In this analyses, the PSOS score was treated as one of the covariates and the postural sway and instability variables were the dependent variables. The regression coefficients, correlation coefficients, and p values are summarized in Table C.20.

Table C.20
Summary of the Regression Coefficients for
PSOS on Postural Sway and Instability Variables

	DF	Mean Square	F	Correlation Coefficients	Regression Coefficients	Pr > F
Sway Length	1	0.11	1.03	0.07	0.013	0.32
Sway Area	1	2.04	3.00	0.11	0.055	0.09
IPSB**	1	1.36	12.8	-0.34	-0.045	**0.001***
SAR	1	2.35	2.96	0.13	0.059	0.09
WRTI	1	2.90	14.4	0.46	0.066	**0.0006***

* Any findings with $p < 0.05$ were considered statistically significant
** CP based IPSB were used for analysis

It was found that there were significant associations between PSOS and the postural instability variables of IPSB and WRTI. Marginally significant associations were found between PSOS and sway area ($p = 0.09$) and between PSOS and SAR ($p = 0.09$). The regression coefficient for PSOS on IPSB was -0.045, indicating that the higher the PSOS, the lower the IPSB. Lower IPSB implies greater postural instability, and higher PSOS indicates greater perception of slip. The regression coefficient for PSOS on WRTI was 0.066, which also indicated that there was a significant increase in postural instability (higher WRTI) with increasing PSOS score. The strongest correlation was found between PSOS and WRTI in which the correlation was 0.46.

SUMMARY OF FINDINGS/IMPLICATIONS: POSTURAL STABILITY EVALUATION DURING STATIC TASK PERFORMANCE ON SLIPPERY SURFACES

The results from the current study showed that slips did occur during task performance in the standing position on slippery surfaces even though such tasks are less dynamic than those performed during walking. The slip occurrence rate was high (70.5%) for the reach task due to the shift of center of gravity near or out of the base of support.

The effects of various risk factors on the static postural sway (Table C.10-11) and instability (Table C.14) variables were also rank ordered. The type of task showed the most significant effect on postural sway as well as on postural instability variables. The Reach task as compared to the stationary task produced the largest postural sway and instability. This finding was expected as during Reach task the body is voluntarily moving away from the center of the base of support causing postural sway and instability variables to increase in value. While the Reach task produced the expectedly highest values of sway and instability, it is interesting to note that during this task the slip occurrence was also the highest (70.5%). The body movement strategy associated with a reach task will tend to increase the horizontal shear forces under the feet causing the RCOF variable to increase implying a higher demand of shoe COF (Table C.16). If the shoe does not provide the desired COF then a slip must occur. A biomechanical analysis of a slip incident indicates that if the value of the ratio of resultant horizontal forces to vertical force (i.e. RCOF) during task performance is larger than the shoe/floor surface COF, the occurrence of a slip should be imminent. In other words, if the ratio of RCOF to shoe/floor COF is greater than 1 then a slip must occur. However, our study and others (9) have found that slip may occur at RCOF/COF values less than 1 (Figure C-7 and 8). **This finding suggests that the slip potential is not totally influenced by the shoe COF, rather body movement strategies could modify one's ability to keep one's center of mass within the stability boundary and prevent a slip.** In our study, the effect of body movement strategies on postural instability and postural sway is quantified by Sway Area (SA) and Sway Length (SL) and IPSB, WRTI and SAR, respectively. In Table C.8, it can be seen that number of slips were significantly correlated with 4 (SA, IPSB, SAR and WRTI) out of 5 postural sway/instability variables while the shoe COF did not show significant correlation with any of the postural sway/instability variables. Therefore, measurement of shoe COF alone (most of the commercial equipment available to assess the slip potential of a surface measure only the shoe COF not the variables which can quantitate postural instability) is not sufficient to quantitate slip/loss of stability potential during task performance on slippery surfaces (refers to specific aim #A6)..

The effect of type of task (Stationary vs Bending vs Reach) and the environmental lighting had the largest and second largest effect on postural sway and instability, respectively. The gender,surface and shoe type had the third, fourth and fifth,respectively, largest effect on postural sway. Males showed significantly higher postural sway than those observed for the female. The explanation for the gender related finding is not clear (relevant to specific aim # A2 to A5).

It is interesting to note that while significant postural sway effect levels (e.g AP Excursion) of surface slipperiness (Table C.13) was somewhat small (1.2% to 4.8% increase in AP Excursion for the slightly to very slippery surface conditions with respect to dry surface) the postural instability variables (WRTI and IPSB in Table C.15) showed a much larger range of increases (-1.7% to -15.1% and 48.2% to 379.3% for IPSB and WRTI, respectively). This demonstrates the sensitivity and superior ability of the IPSB and WRTI variables in quantifying postural instability during task performance on a slippery surface. Also, as per the responses of IPSB and WRTI variables (Table C.15) the used shoes produced much greater postural instability than that observed for the new shoes.

The subjects' ability to correctly assess the surface slipperiness was significantly correlated with objective measure of COF values of the shoe/floor surface (Figure C-11). In this study, none of the covariates (age, height, weight, under foot pressure, environmental lighting) significantly affected the relationship between the subjective slipperiness value and the COF values of the shoe/floor surface. (relevant to specific aim #A1).

The PSOS scale used to capture the subjective ability of the subject to rate the slip potential/loss of balance during task performance, was reproducible, easy to use, and provides a simple way to evaluate the potential slip hazard in the workplace. Subjects always slipped when the PSOS rated by the subjects was beyond the value of 4.5 out of a maximum score of 8 (figures C-9 and C-10). Subjects were able to perceive the instability, and this perception was reflected in their rating.

This finding has practical implication in identifying tasks and workplace areas with potential for slips. A field survey can be conducted to investigate workers' PSOS rating under possible extrinsic and intrinsic risk factors using the PSOS scale. Prevention strategies can then be developed to help prevent slip associated injuries.

Workers who were cautious in assessing surface slipperiness had less postural instability during task performance, as indicated by IPSB and WRTI responses (Figure C-11 and Tables C.8 and C.9; relevant to specific aim# A1 and A2). However, the current study did not address the issue of whether there is a learning trend in assessing surface slipperiness with repeated assessment. If the ability to assess surface slipperiness can be improved by training, then a training program can be developed to help minimize slip incidence while performing tasks on slippery surfaces. In addition, workers can also be instructed to avoid working on potentially hazardous surfaces without first carefully assessing the slip potential of working surface.

In day-to-day activities, the demand for friction changes continuously due to change in task and environmental conditions; therefore, in addition to having a shoe with a medium level of COF on most types of surfaces, there is a need to train workers (who are going to be exposed to slippery surfaces on a routine basis because of the nature of their work) as well as the "older" (>55 to 75 years old) workers (who are at a higher risk of falling than the younger group; see ref# 36) regarding proper use of body segment movement strategies while working on a slippery surface. **While such ideas of training (on slippery surfaces) seem reasonable based on our current experimental study and theorized by others (35), there is no scientific data available regarding their validity. Several questions still need to be answered before such an approach can be pursued further. These are: 1) Can repeated exposure to a known slippery surface improve the subject's ability to correctly (increase in correlation between subjective score of slipperiness and objective measure of COF) judge the slipperiness of a surface? 2) Can repeated exposure to a known slippery surface improve task performance and slip-avoidance while working on that surface? The fourth year (which was not funded) of the originally proposed project had experiments designed to address these issues but were eliminated. Availability of answers to the above questions in a future project will help in developing guidelines for worker training to avoid slips and falls while working on slippery surfaces.**

C.10. Pilot Study: The Relationship between Center of Pressure and Center of Gravity during Static Task Performance

A pilot descriptive study was carried out to determine the relationship between whole body CG and CP during task performance on slippery surfaces.

Biomechanically speaking, potential loss of balance should be calculated using the subject's center of gravity (CG) movement pattern information with respect to subject's base of support especially for dynamic tasks. On the other hand, postural instability is traditionally evaluated by measuring the CP of the body with respect to base of support (25). While the CG based data provides a biomechanically sound assessment of loss of balance, this variable is based on the concept that the entire body weight is concentrated at one point (not necessarily inside the body) and the subject has no conscious "feeling" about the motion of the CG with respect to his/her base of support. On the other hand, CP is a point under the feet of the subjects through which the resultant force passes during task performance. As the task dynamics changes, the magnitude of the resultant force and its point of application underneath feet also change. This movement of point (also known as the Center of Pressure or CP) of application of resultant force is actually "felt" by the subject as a concentrated pressure point under the sole of his/her feet. In the biomechanics literature, it is suggested that CP serves as the control signal for the body to move its CG appropriately (via movement of appropriate body segments to contain its CG within its base of support) with respect to its base of support so that a fall is prevented. In other words, subjects sense the direction of movement of postural instability via CP and then appropriate muscular contractions cause the whole body' CG to bring close to the base of support to avoid a fall incident. Experimentally, CG measurement requires tedious kinematic video based data and a spatial whole body model with assumptions of body segment mass distributions. Therefore, for practical studies in the field, the collection of kinematic video data may pose some experimental problems. On the other hand, the CP measurement can be done very accurately, reliably and relatively easily (without any assumptions) and this measurement is something which subject actually "feels" as a pressure point underneath his/her feet thereby may allow him/her to develop body movement strategies to avoid an impending fall. Recent studies by Hassan et. al. (38-39) have carefully addressed this issue and provided sufficient justification for using CP instead of CG for static tasks. In the current study a preliminary analysis was carried out to compare the CP and CG motion patterns during task performance and their relationship to slip events.

The postural instability variable of IPSB described in the previous sections is calculated based on the body's CP movement. In this section, the IPSB was also determined using the whole body CG movement, which was obtained after digitizing the twenty-four reflective markers placed on the subjects' anatomical landmarks. The stability boundary was determined based on the area enclosed by the six markers placed on the subject's shoes. The mean IPSB from six subjects are presented in this section to illustrate the change in CG based IPSB [IPSB(CG)] versus time for two tasks under two extreme lighting and surface conditions. The corresponding CP based IPSB [IPSB(CP)] are also presented for comparison. These four test conditions are listed in the following:

Test	Task	Shoe	Lighting	Surface
Condition 1	Stationary	New	Good	Dry
Condition 2	Stationary	New	Poor	Very oily
Condition 3	Reach	New	Good	Dry
Condition 4	Reach	New	Poor	Very Oily

Five events were defined for reach tasks in this analysis. They are:

Event #1: started reaching.

Event #2: reached a five-pound weight placed on the front table at the distance of 1.2 x subjects' functional reach.

Event #2s: slip began.

Event #3: the five-pound weight was moved to a side table located on subjects' left side.

Event #4: the five-pound weight was moved back to the front table.

Figure C-13 and C-14 illustrate the mean IPSB(CG) and mean IPSB(CP) versus time for test conditions 1 and 2. Since the six subjects simply stood upright during the stationary task, the trends for both types of IPSB were quite similar. For test condition 1 and 2, IPSB(CG) was consistently greater than IPSB(CP). IPSB(CG) ranged from 0.76 to 0.80, and IPSB(CP) ranged from 0.68 to 0.72. The larger the IPSB, the greater the propensity of postural instability.

Figure C-15 presents the IPSB data for test condition 3. It was found that IPSB(CG) decreased as soon as the subject started to reach for the five pound weight and it dropped to 0.05 when the subject reached the weight at event #2. The IPSB(CG) increased to 0.66 at event #3 and then decreased again until the five pound weight was brought back to the front table (event #4). No slips were observed for any of the six subjects under test condition 3. The IPSB(CP) was greater than IPSB(CG) for most of the time. The lowest value of IPSB(CP) occurred just before the five-pound weight was moved back to the front table (event #4).

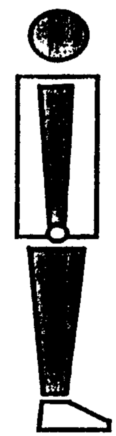
For test condition 4 (Figure C-16), the mean IPSB(CG) of event #2 (0.247) and #4 (0.291) were greater than those of test conditions 3. All six subjects slipped between event #2 and #3, when they moved the five-pound weight from the front table to the side table. IPSB(CG) decreased drastically from 0.40 to -0.26 immediately after the subjects slipped. Negative IPSB implies that the subjects' CG was out of the stability boundary. For IPSB(CP), there was a decreasing trend between event #2s and event #3, but the IPSB(CP) for event #3 was well above 0 (the limit of the stability boundary). The IPSB(CP) for test condition 4 was greater than IPSB(CG) for most of the time. The lowest value of IPSB(CP) (0.33) occurred at event #4, when the five-pound weight was moved back to the front table.

In general, during static task performance without slipping incident, the CP and CG motion patterns are comparable. However, the CP motion pattern does not follow the motion pattern of the CG near the slip-event (Figure C-16).

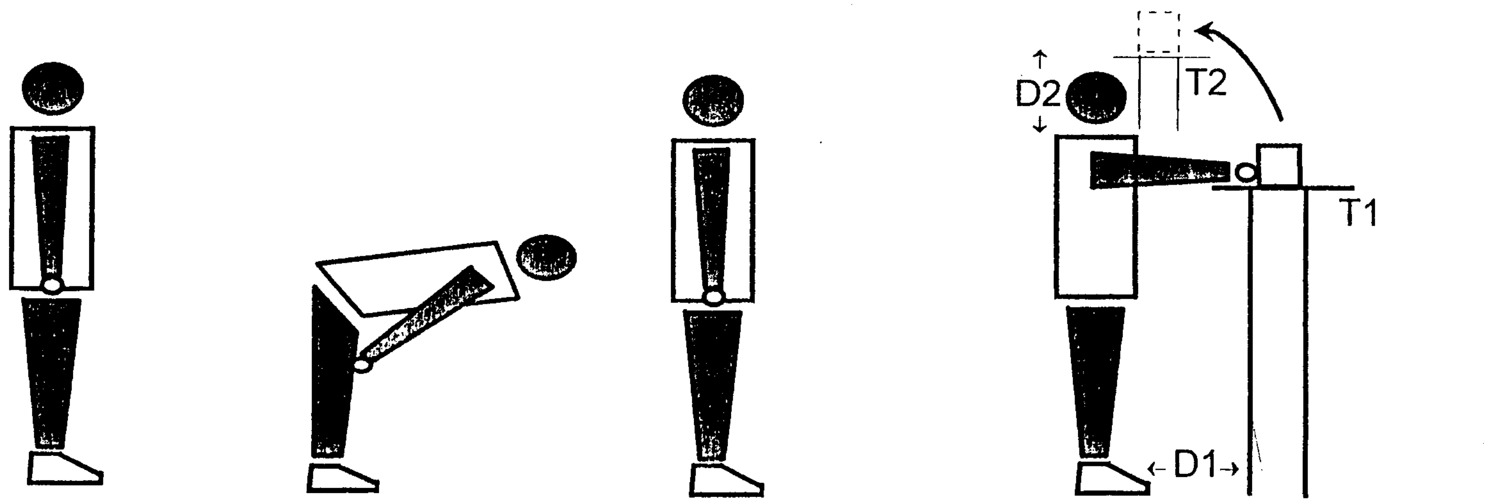
C.11. Figures for the Static Task Performance Evaluation Section:

Figure C-2

Illustration of the Three Simulated Tasks

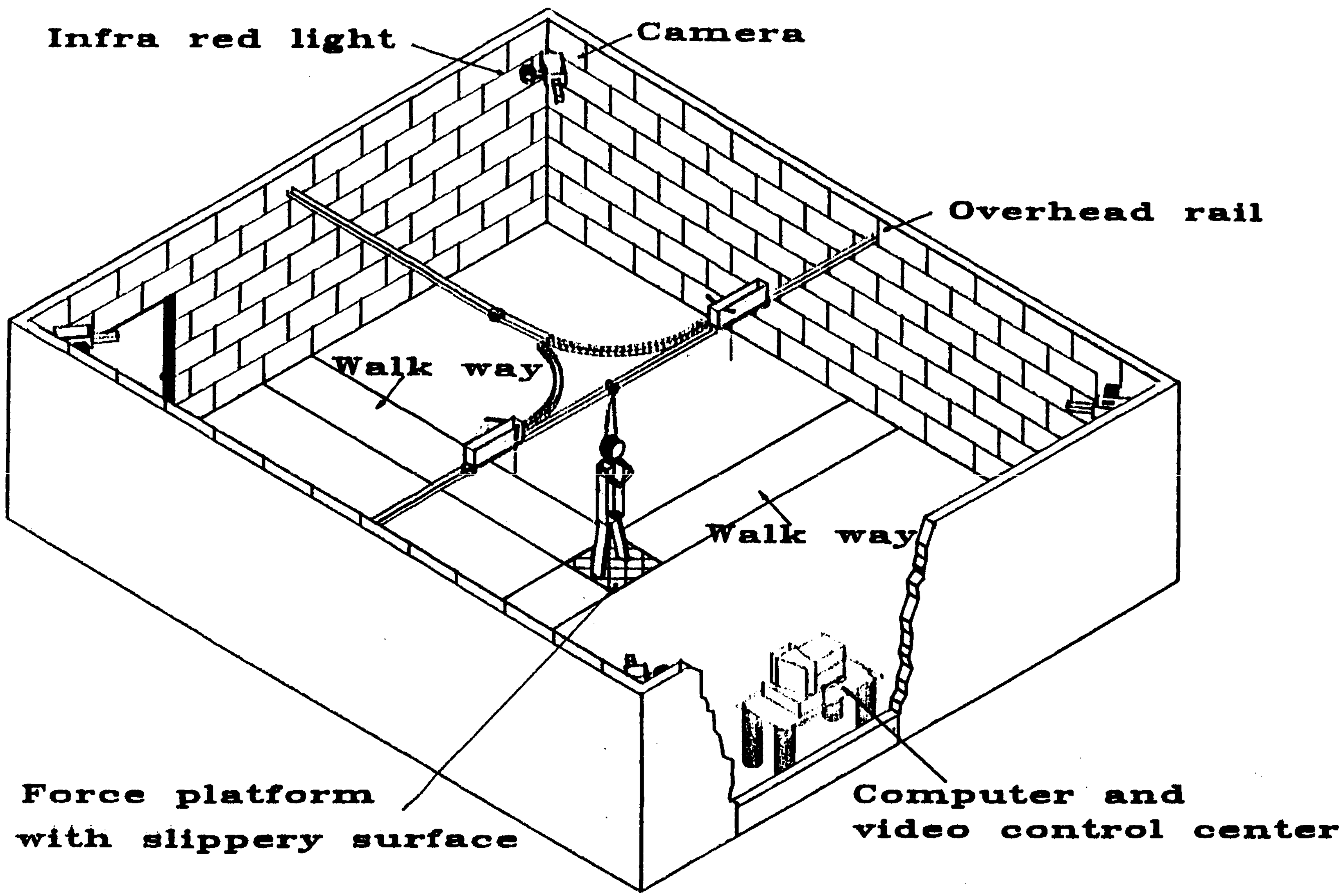


(1) STANDING UPRIGHT



(2) RAPID TRUNK MOVEMENT

(3) LATERAL REACH



SCHEMATIC OF SLIP/GAIT STUDY FACILITY

Figure C-3

Figure C-5
Illustration of the Concept of
CP Based IPSB and Stability Boundary

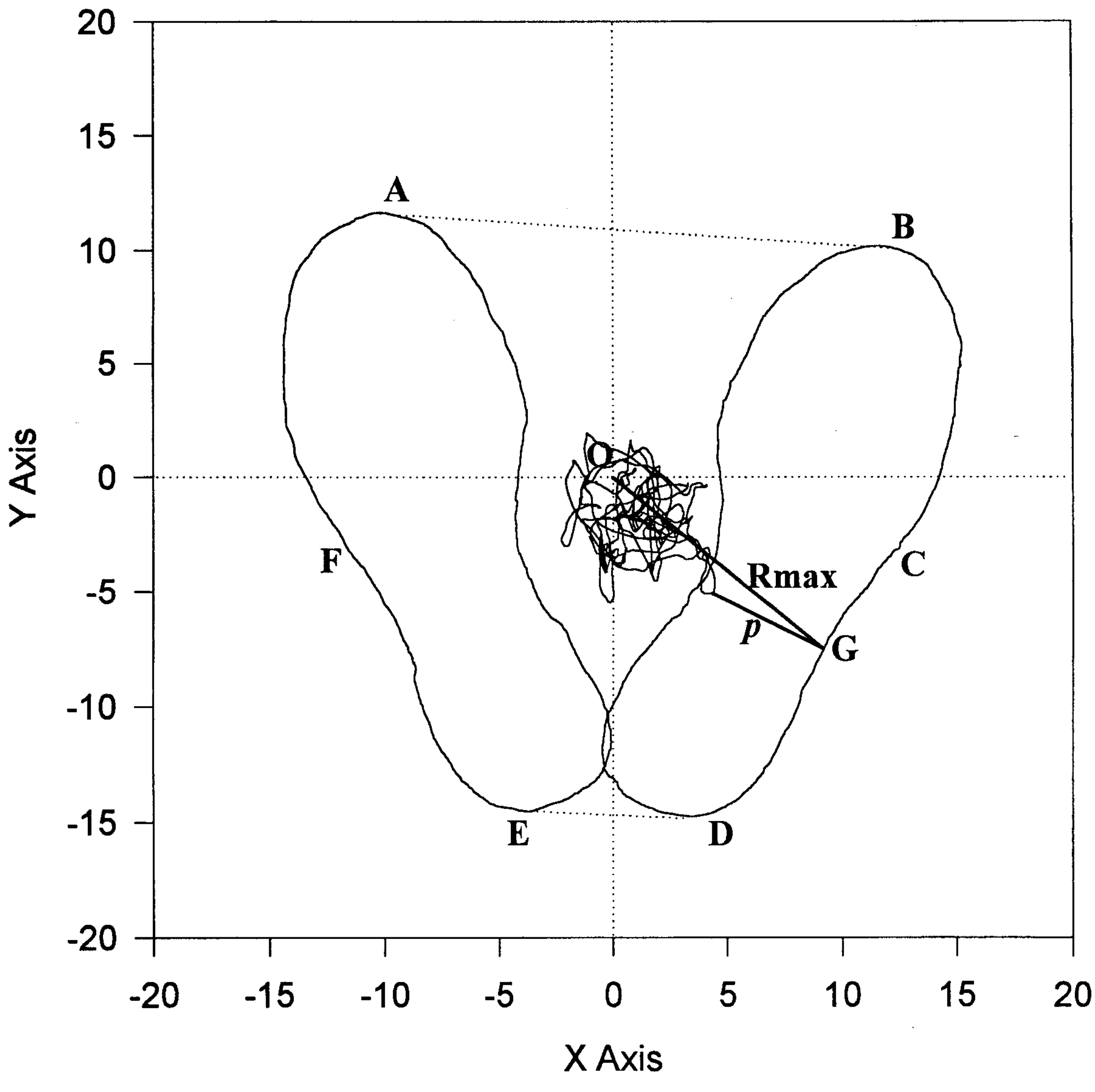
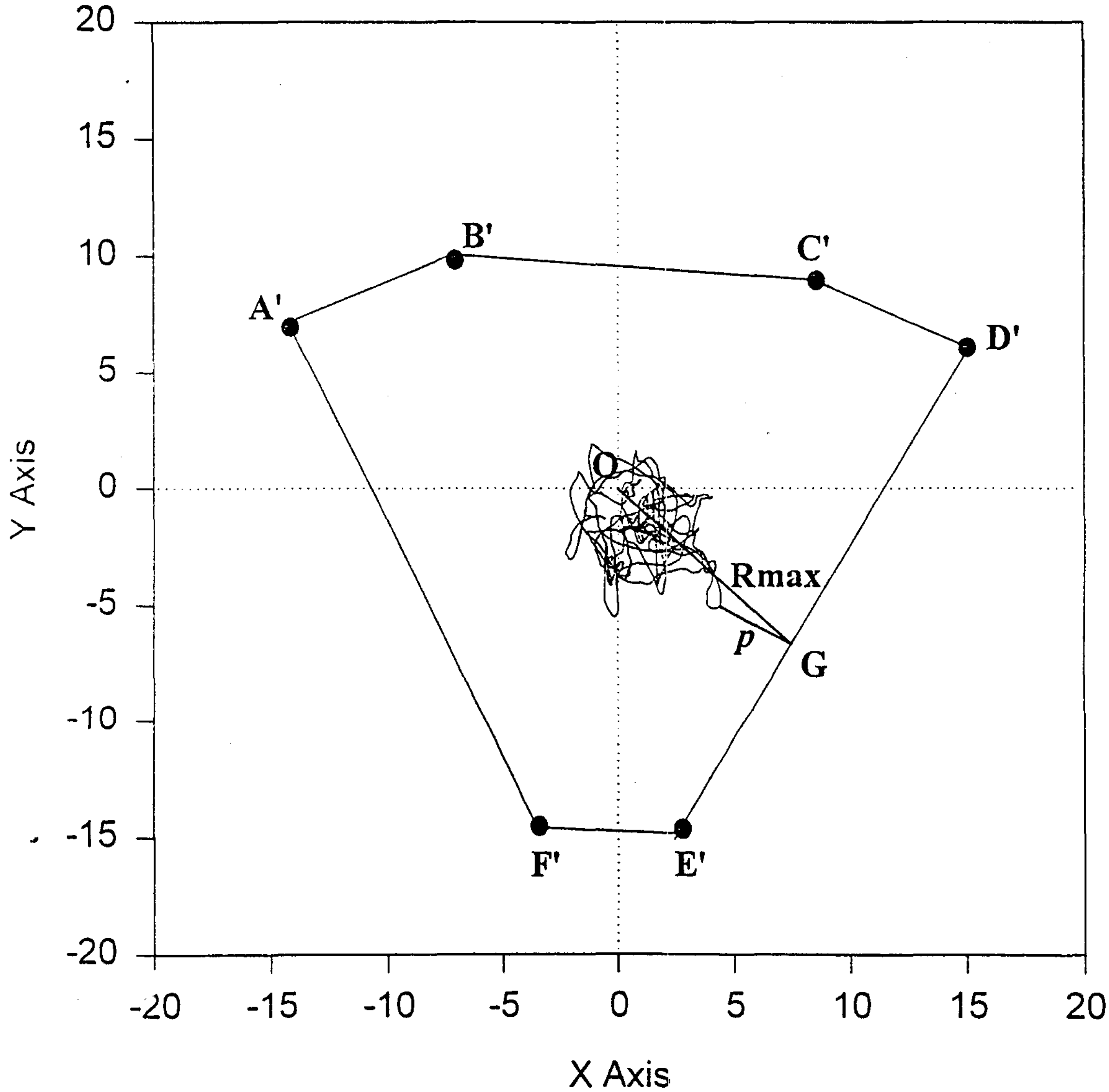


Figure C-6

Illustration of the Concept of CG Based IPSB and Stability Boundary



A': 5th MTP of left foot
B': 1st MTP of left foot
F': left heel

C': 1st MTP of right foot
D': 5th MTP of right foot
E': right heel

Figure C-7

% of Slip Occurrence vs. RCOF / COF for All Tasks

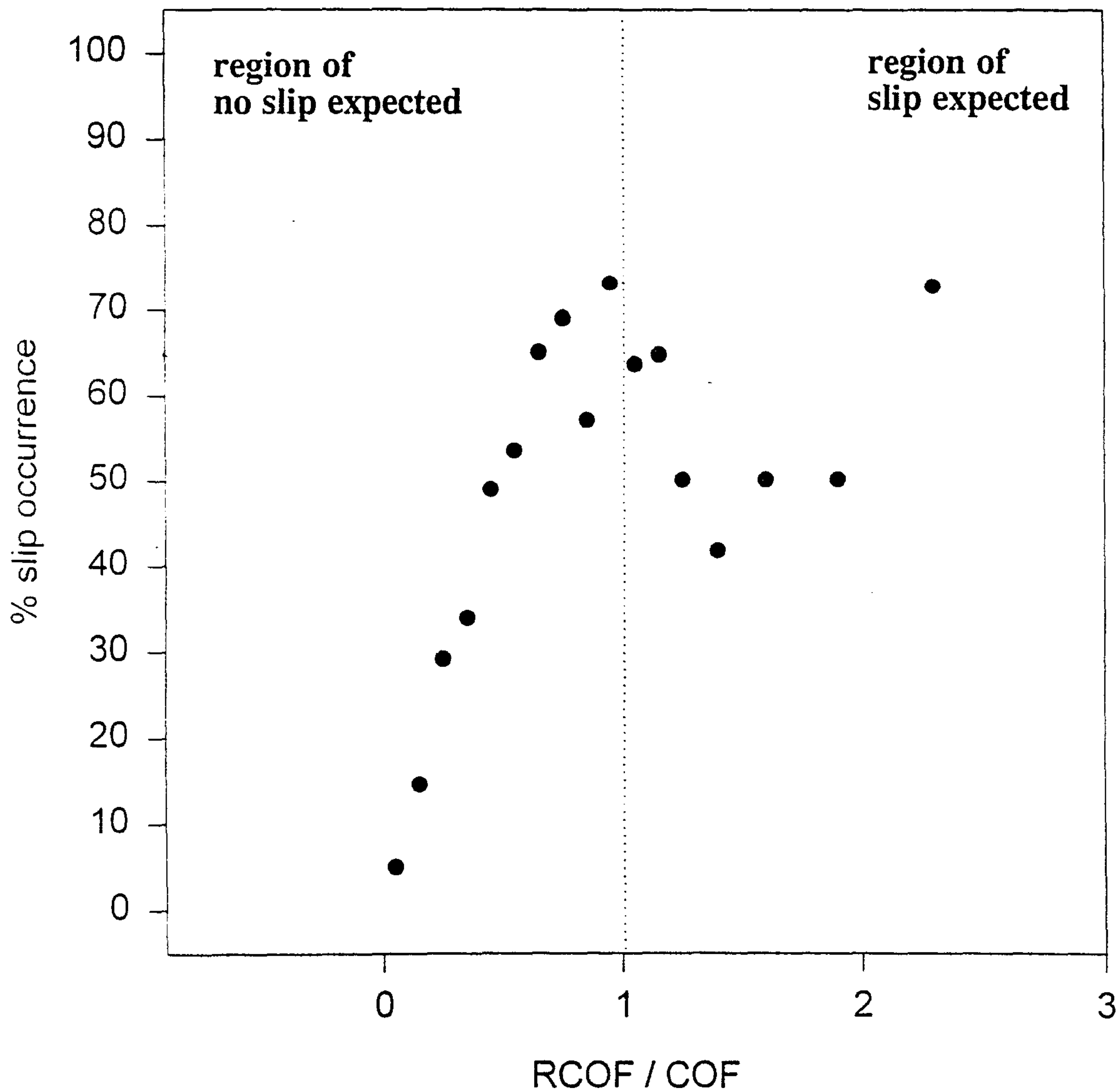


Figure C-8

% Slip Occurrence vs. RCOF / COF for Reach Tasks

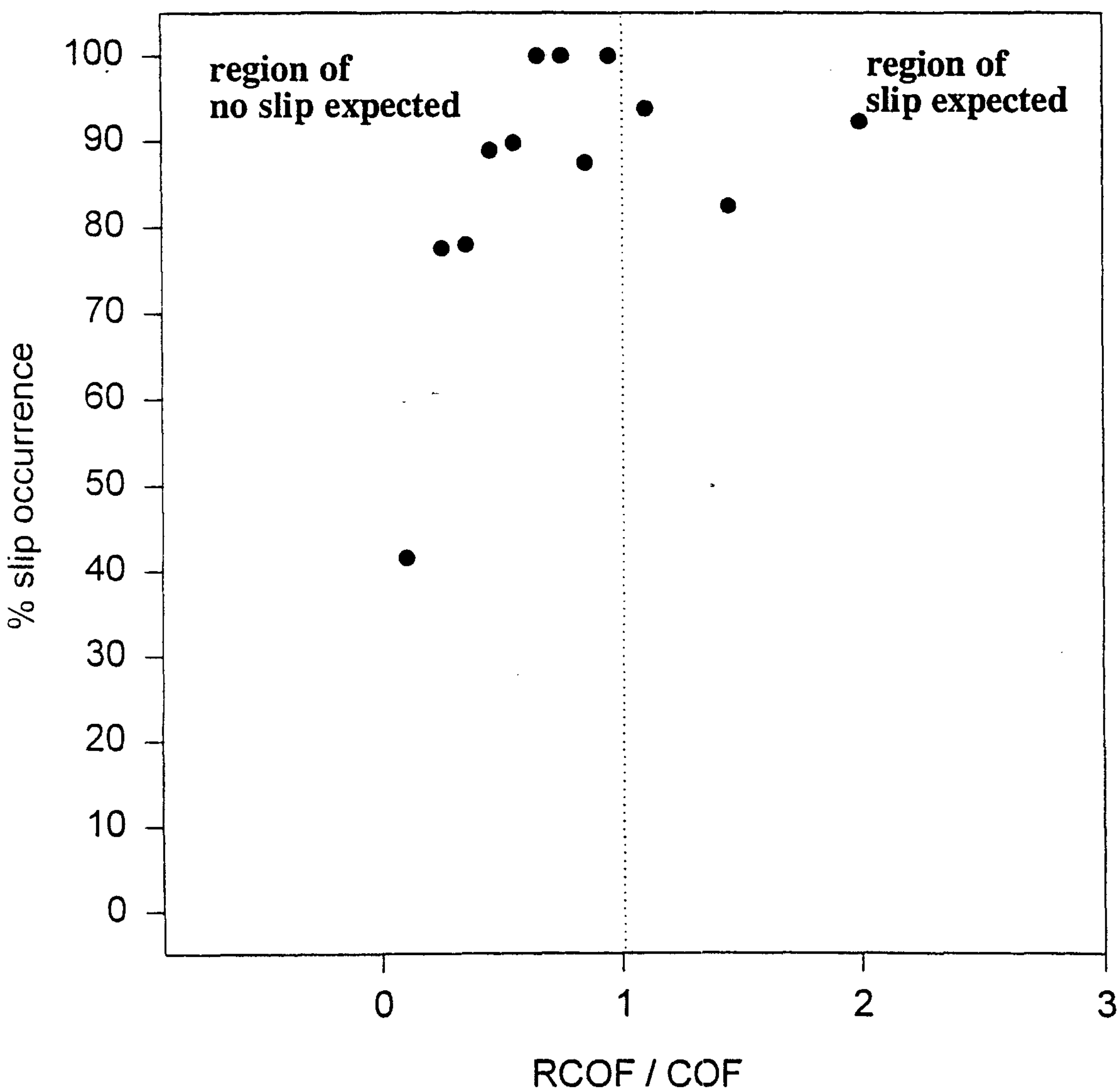


Figure C-9
% Slip Occurrence vs. Perceived Sense of Slip for All Tasks

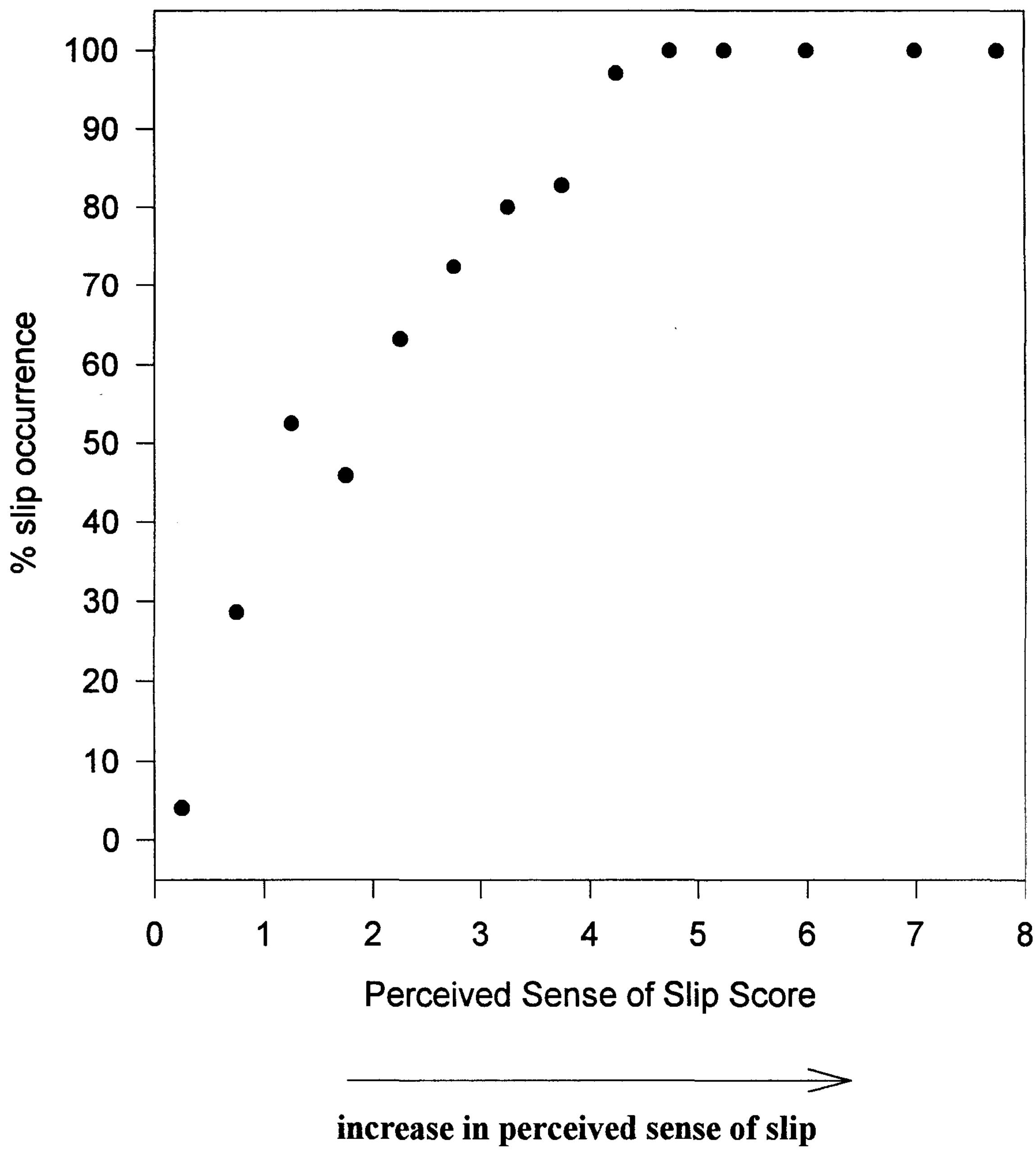
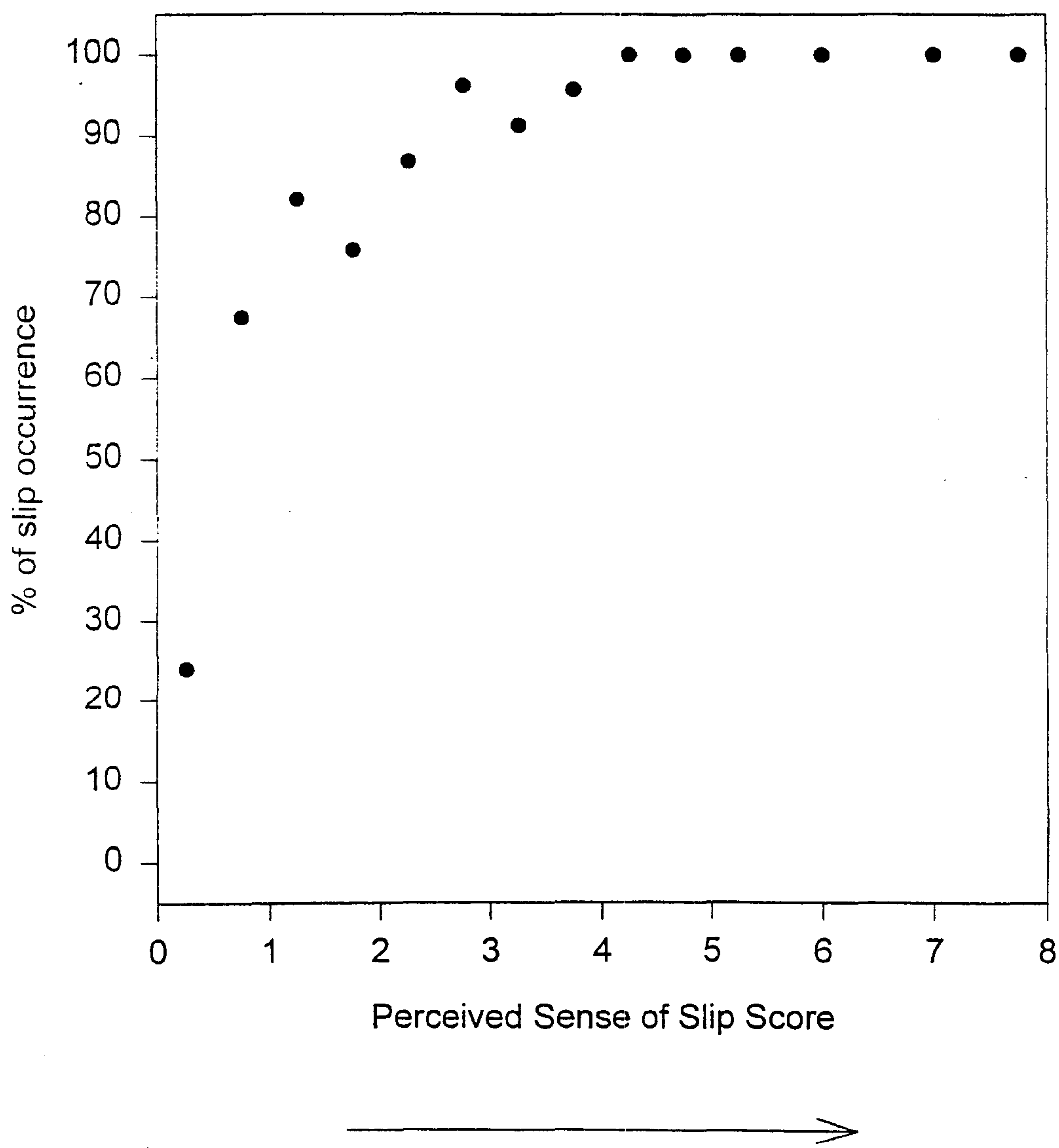


Figure C-10

% of Slip Occurrence vs. Perceived Sense of Slip for Reach Tasks



increase in perceived sense of slip

Figure C-11
The relationship between subjective rating of slipperiness and the objective measure of slipperiness (COF)

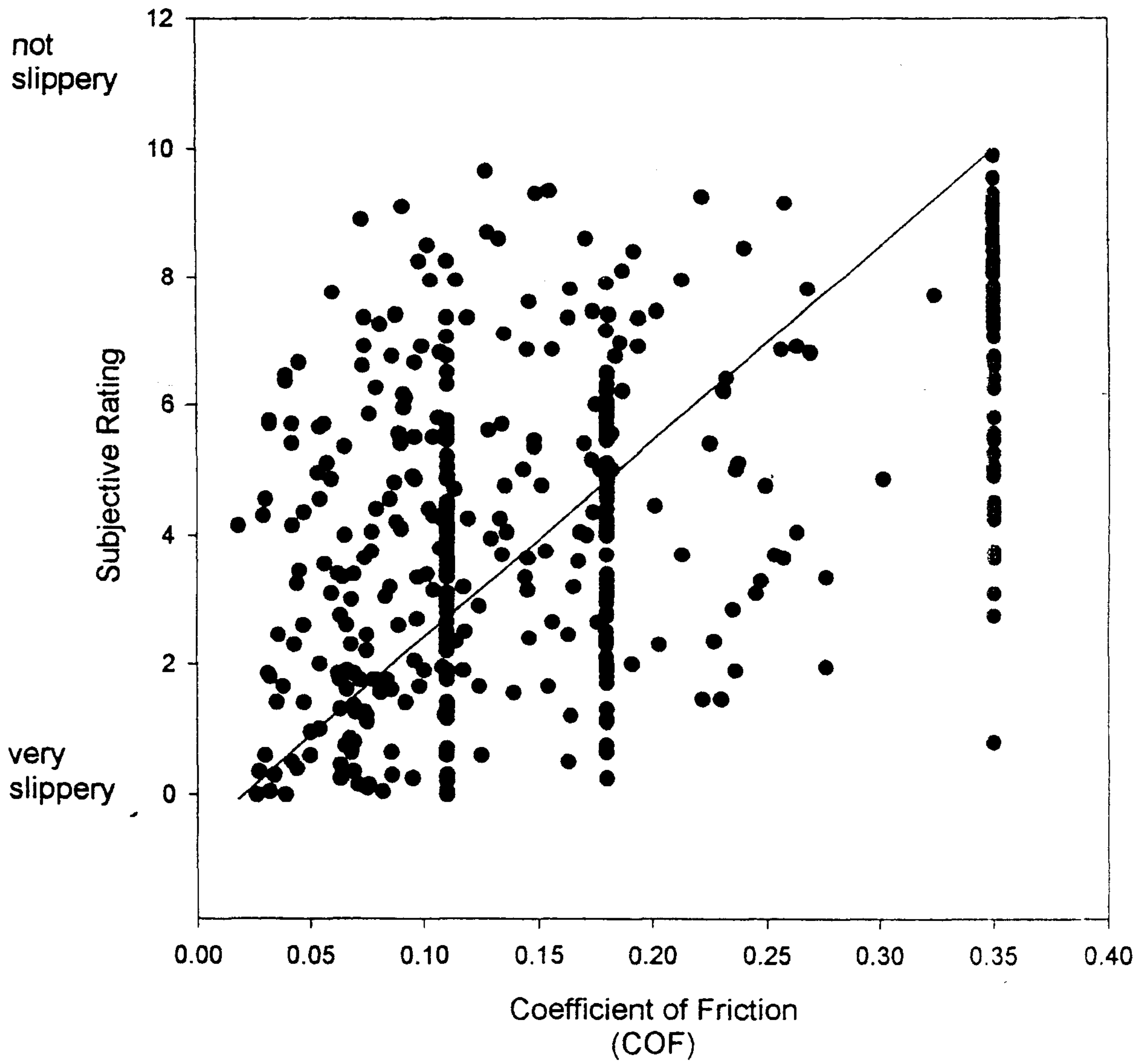


Figure C-12

Arithmetic Mean of Perceived Sense of Slip for Various Task and Surface Conditions

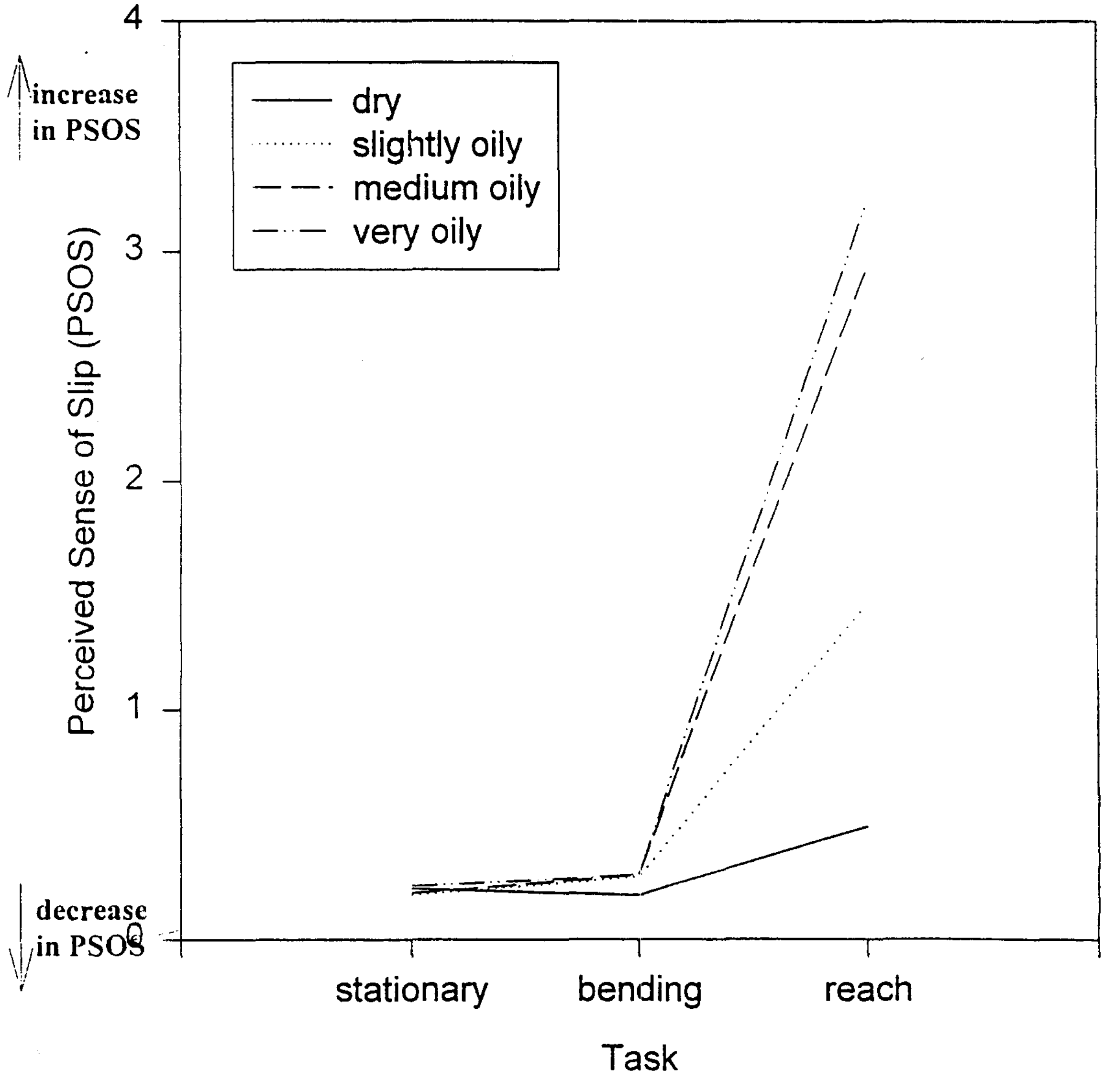


Figure C-13
IPSB (CG) and IPSB (CP) vs. Time for the Stationary Task with New Shoes, Good Lighting and a Dry Surfaces

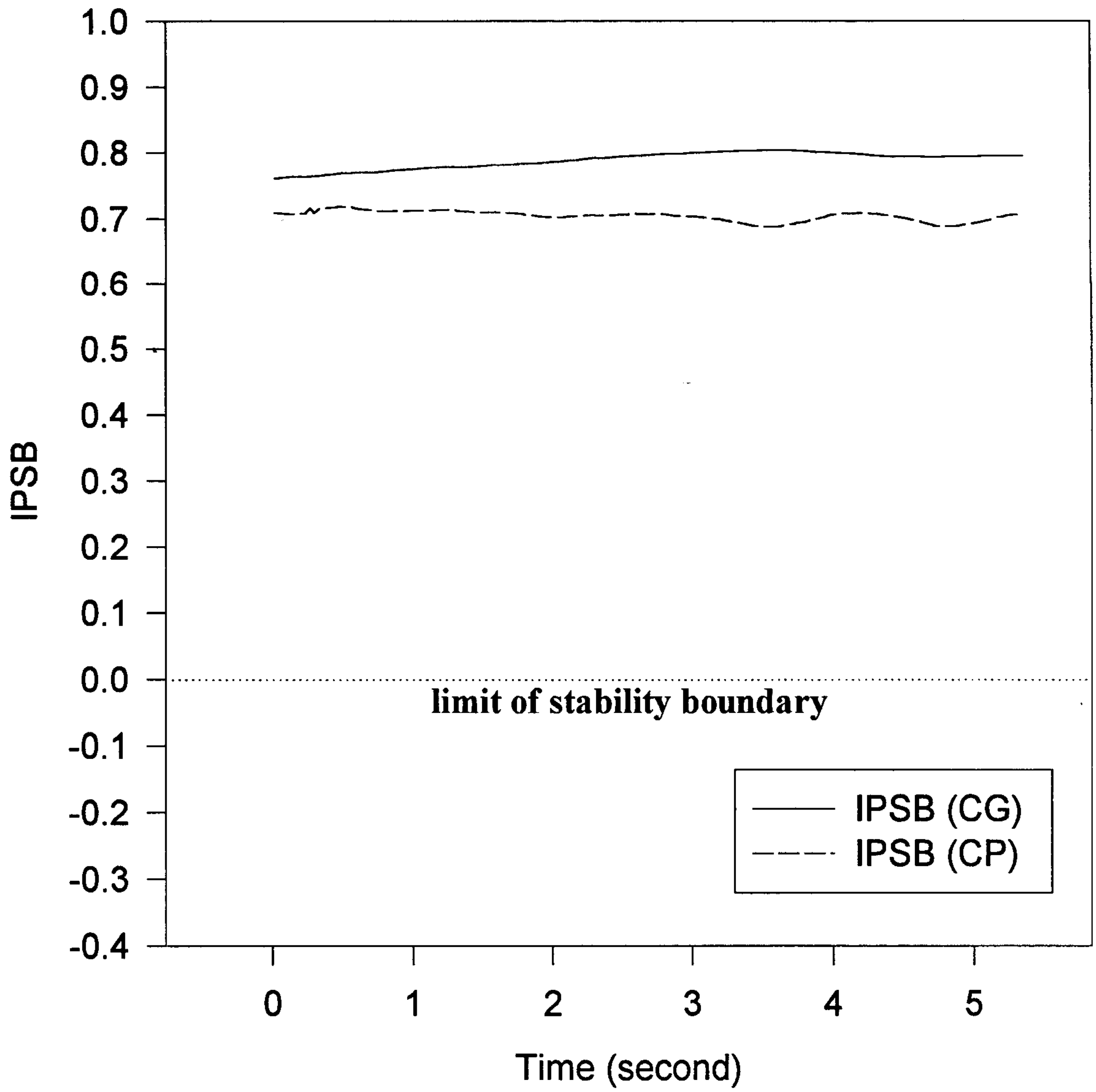


Figure C-14
IPSB (CG) and IPSB (CP) vs. Time for the Stationary Task with New Shoes, Poor Lighting and a Very Oily Surface

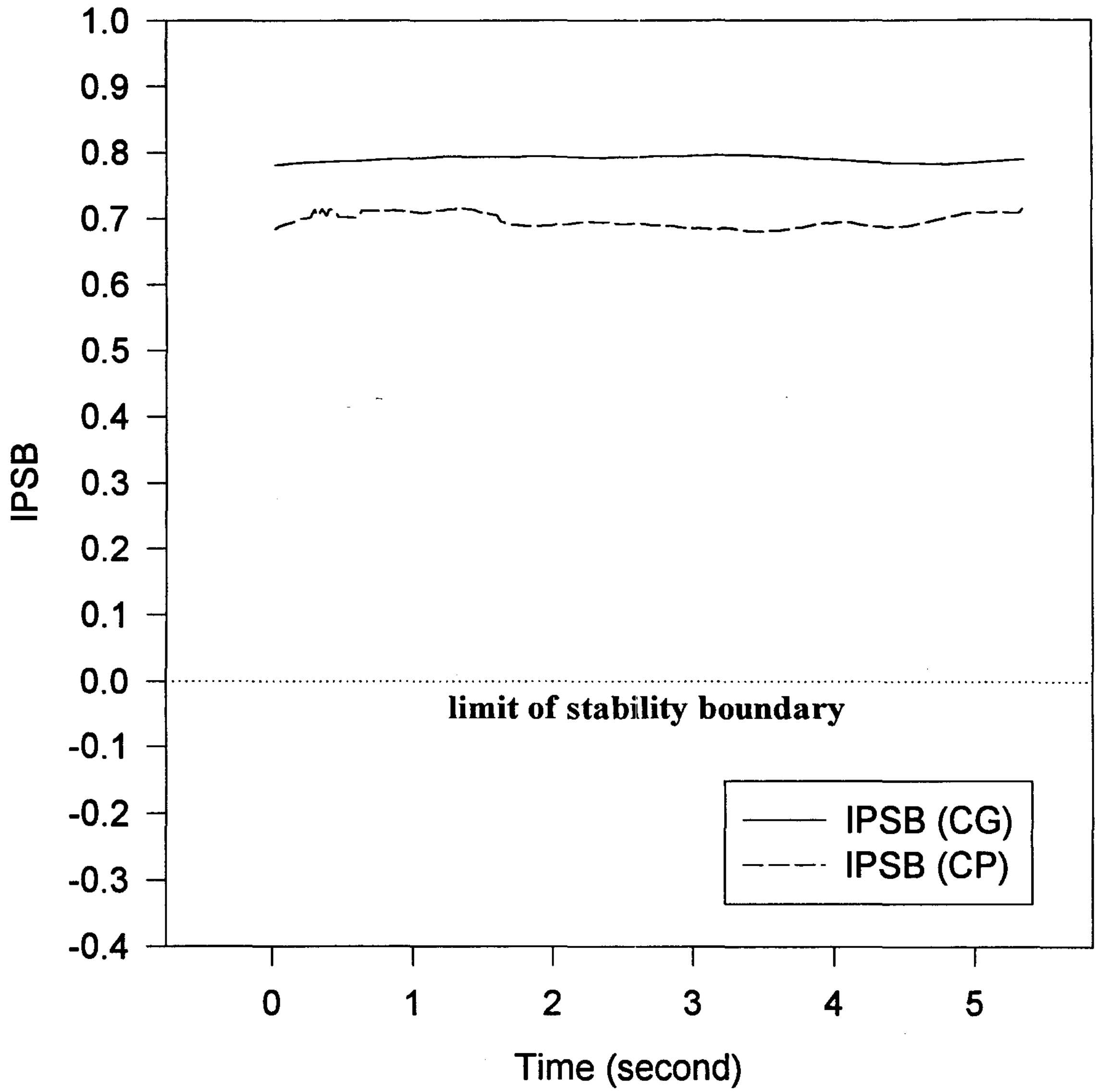
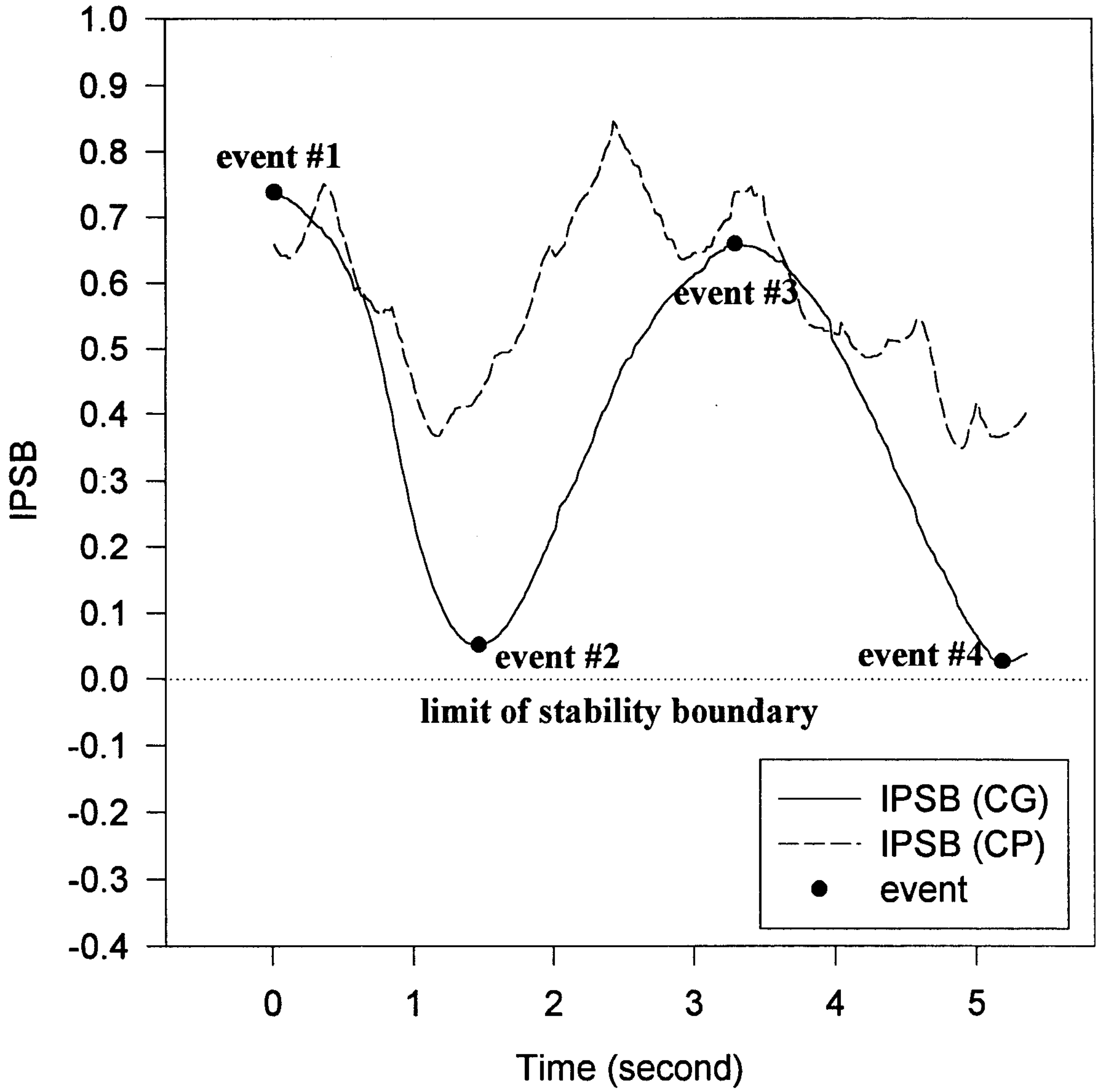


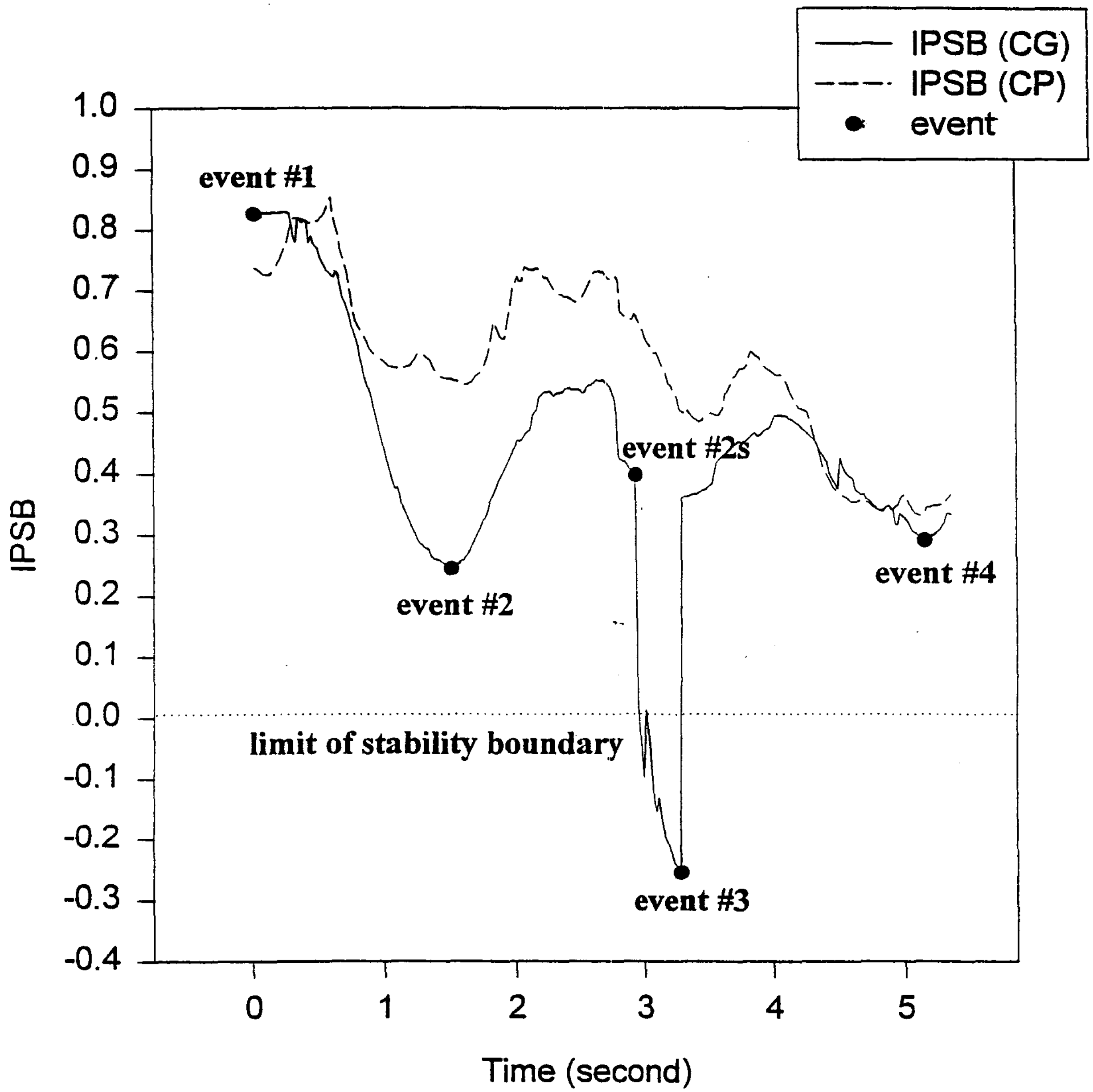
Figure C-15
IPSB (CG) and IPSB (CP) vs. Time for the Reach Task with New Shoes, Good Lighting and a Dry Surface



event #1: started reaching
event #2: reached a 5-lb weight placed on the front table
event #3: the 5-lb weight was moved to a side table located on subjects' left
event #4: the 5-lb weight was moved back to the front table

Figure C-16

IPSB (CG) and IPSB (CP) vs. Time for Reach Tasks with New Shoes under Poor Lighting and Very Oily Surfaces



event #1: started reaching
event #2: reached a 5-lb weight placed on the front table
event #2s: slip began
event #3: the 5-lb weight was moved to a side table located on subjects' left
event #4: the 5-lb weight was moved back to the front table

D. Dynamic Stability Evaluation during Task Performance on Slippery Surfaces
(Note: See Section D.10 for all the figures relevant to Section D)

D.1. Study Design:
The Dynamic Stability Evaluation component used the risk factors described below. It was organized in a one- half incomplete block design (Appendix-G). For the dynamic tests, the ordering of treatment combinations were randomized.

Risk factors/Treatment Conditions (Independent Variables) for Dynamic Tasks:

Condition 1: new shoes were provided by the laboratory, or subject's own used shoes.
Condition 2: good or poor environmental lighting.
Condition 3: dry, slightly, medium, or very oily surface.
Condition 4: walk on straight path or turning path
Condition 5: walk with a weight or with no weight

D.2. Instrumentation:
The instruments used for the Dynamic Task evaluation (gait) part of the study were the same as those used in the Static Task evaluation part.(For details refer to the Instrumentation section of the Static Task evaluation part of this report).

D.3. Marker system for the study

The marker system used for human body motion analysis for this study is shown in Appendix-B and Table C.2. The sequence of events which took place during a typical day of experiments is given in Appendix C. All testing sessions were carried out in our specially designed Fall-Stability-Gait facility (Figure C-3).

D.4. Experimental Procedure for Dynamic Stability Evaluation during Task Performance on Slippery Surfaces

The gait protocol was blocked by the surface conditions. During each test day (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 turn). Each test condition has one repetition. So under each surface and shoe condition there were eight trials. The ordering of the test conditions were randomized. A typical test session took about 3.5 hours. Each subject underwent 32 gait tests (replicated once=64 total gait tests), as explained above.

On the day of the test, the force platform calibration was checked again to ensure that the measurement error of the plate was within the acceptable 2% range (as per our previous published studies). The video-system was calibrated as explained in Appendix-D. The experimental test conditions (illumination levels, surface slipperiness level, and shoe type) and the postural sway gait tests were *a priori* randomized by the statistician co-investigator. Two investigators attended the microcomputer which controls and collects data from the video, force plate and in-sole pressure measurement device. One staff member was responsible for subject's compliance with the protocol, administration of Perceived Sense of Fall Scale after each of the tests, and was also present near the subject to prevent any injury from potential fall. All subjects wore a full body harness with lanyard attached to the overhead monorail for protection from any potential fall during the test. A fourth staff member was responsible for making proper changes needed for preparing the desired surface conditions, light control, and preparing the subject's hand-held weight. He was also responsible for monitoring the camera placed to measure the heel slip profile.

All the data collected were stored on computer mass media storage disks and duplicated for data safety. The stored data were later analyzed with our custom developed software. The video data was digitized to yield the coordinates of body segment movement, which were then used to calculate the indices of postural instability. Separate datasets were formed to store all the major anthropometric and somatotypic data, along with the questionnaire data, and the recorded slip incidences. In a separate experimental setup, the coefficient of friction values were calculated and entered into a database. The datasets were then uploaded to the mainframe for statistical analysis.

D. 5. Dependent Variables

D.5.a. Objective measures of Gait/Friction Variables and kinematics of Heel Strike: Measurement of micro-slips is essential to understanding the phenomena of slip on a lubricated surface. A squeeze-film is formed at the point of contact of the heel. Sliding velocity and the dynamic COF gradient are the two most important characteristics that can be measured to quantitate micro-slip (11,14). As velocities of gait are calculated by differentiation of displacement data, a fairly high rate of data collection (sampling rate) is necessary to reduce the generated noise in the differentiated data (15). For this reason, a single high-frequency video recorder/camera would have been most appropriate (250/500 Hz). However, because of budget cut (by the Study Section) at the beginning of the project, we had to estimate the sliding velocity and distance with an extra regular 60 Hz camera (5th Camera) focused solely at the shoes of the worker during the gait tests to obtain a clear picture of the beginning and ending of the slip incidents. Two-dimensional measurement of heel velocities and contact angle at heel strike in the sagittal plane were measured using this camera.

A five-marker system, shown in Figure D-1, including heel (1), 5th metatarsal point (2), ankle (3), plate near point (4) and plate far point (5) markers, was utilized for digitization and to calculate the gait/friction variables, like contact angle, sliding distance and sliding velocity. A two-dimensional coordinate system was defined as in Figure D-1 to facilitate the analysis. A two-dimensional project was built (in the Peak Analysis Software) to define the spatial model for the analysis. In addition, a series of events were defined to pinpoint the critical movements during a slip. The dependent gait/friction variables were defined in the 2-D project to perform the automatic calculations and analysis in the later processing of data.

The contact angle θ was defined as the tangent between the shoe sole and the flooring when the heel strike event occurs. The contact angle θ 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, (Figure D-1) separately.

Digitization Procedure

I. Contact Angle: The procedure involved in obtaining the contact angle can be summarized in the following steps: 1. Identification of video frame where the heel strike happened. 2. Digitizing the following markers or physical points: plate near point, plate far point, shoe sole leading edge and shoe trailing edge. 3. Determining the coordinates of the above four points. 4. Marking this video frame at the event of heel strike. 5. The contact angle was then calculated by the analysis software.

II. Sliding Distance and Velocity: The sliding distance L of a slip, was obtained by calculating the heel marker's (1) displacement in X direction during a slip, as shown in Figure D-2. The displacement of the heel marker during a slip was determined by comparing the heel marker's coordinates at the beginning and the end of a slip.

Once the sliding distance was calculated, the sliding velocity was then calculated from the sliding distance and the elapsed time during a slip. The elapsed time was determined by the number of frames containing the slip and video sampling frequency.

The procedure for sliding distance and sliding velocity can be summarized as follows: 1. Search and locate the video frame where the slip started and mark it as the event of "slip begin". 2. Digitize all the markers. 3. Search and locate the video frame where the slip ended and mark it as the event of "slip end". 4. Digitize all the markers. 5. The displacement, velocity of the heel marker were calculated automatically by the analysis software.

Summary of Objective measures of Gait/Friction Variables: The dependent variables, defined in accordance with Grönqvist, (11) Strandberg, (15) and Chaffin, (14) are as follows.

(a) Contact angle: This is the angle between the shoe sole and the flooring. The descent of the feet determines how the squeeze film would react (drainage time) (28). A kinematic variable measured with the Peak Motion Analysis System.

(b) Sliding velocity: This is the relative sliding velocity between the shoe sole and the flooring surface in the sagittal plane. (10). A kinematic variable measured with the Peak Motion Analysis System.

© Normal force: This is simply the vertical force (Fz) as a function of time applied to the floor surface during gait. The dynamic frictional force is dependent on this normal force and on the COF of the surface. A kinetic variable measured with the AMTI force platform system.

(d) Ratio of resultant horizontal shear force (Fx and Fy) to normal force (this ratio is known as dynamic required COF): The significance of this measurement is that it indicates where, in the walking step, slip is most likely to occur. A kinetic variable calculated with Fx, Fy and Fz measured with the AMTI force platform system.

(e) Rate of change of dynamic required COF: A sudden change in the value of COF is one of the major factors causing slip. Hence, measurement of this quantity would indicate the position during the step at which the largest COF gradient occurred. A kinetic variable calculated with the variable obtained in item # (d).

(f) Position of the first contact point of the shoe and the length through which CP travels before reaching the midline (expressed as percent of foot length): This would indicate the pattern of stepping on the slippery surface by different individuals under various combinations of factors (such as lighting, shoe wear, surface COF, and loading). A kinematic variable calculated from digitized video data obtained with the Peak Motion Analysis System.

(g) Cycle Time or Dwell Time (sec): The time interval between heel strike and toe off.

D.5.b. Objective Measures of Slip/Loss balance or fall Potential During Walking

Indices of fall potential during Walking

The distance from the projection of the center of gravity on the horizontal plane (COG_H) to the base of the supporting area (BOSA), the slide distance, slide direction, and the utilized COF were used as indices to assess the potential of fall when negotiating different paths on surfaces of different slipperiness (33). The turning radius and COF utilized by the centrifugal force were used to describe the kinematic properties of negotiating a curved path. The initiation of slip may begin at heel contact, but whether or not the subject will recover from a slip is usually determined by his/her ability to utilize his body segment movement strategies to modify the whole body COG with respect to the BOSA so that a recovery is accomplished from such a slip [10]. In previous studies [11], it has been shown that slips with slide distances exceeding 10 cm usually result in an unrecoverable loss of balance. Thus, a slip event at the heel contact may not provide sufficient information about the risk of an ensuing fall. The variables mentioned above were used to assess the kinematic characteristics of COG with respect to BOSA during single stance on a slippery surface.

<u>D.5.b.1. COG Deviation Distance</u>

When performing static tasks, the center of pressure (CP) is generally used to estimate the projection of the COG on the horizontal plane [29]. However, when performing dynamic tasks such as gait, the COG will move out of BOSA. The CP always resides within BOSA, thus using CP to estimate COG movement is not valid [30].

Three reflective markers were attached to the shoes in this marker system. They represented the following anatomic landmarks: roots of the 1st Metatarsal and 5th Metatarsal and the calcaneus (Fig. D-3). The triangle formed by connecting these three markers was used to approximate the perimeter of BOSA during single stance. The surrounding area of the approximated BOSA is divided into six regions to facilitate the calculation of COG deviation distance (Fig. D-4). These regions are defined in Table D.1.

Table D.1-- Definition of the regions surrounding the supporting foot.

region 1	area enclosed by lines passing through point *a* and perpendicular to *ab* and *ac*
region 2	area enclosed by line *ab* and the lines perpendicular to *ab* and passing through points *a* and *b*
region 3	area enclosed by lines passing through point *b* and perpendicular to *ab* and *bc*
region 4	area enclosed by line *bc* and the lines perpendicular to *bc* and passing through points *b* and *c*

region 5	area enclosed by lines passing through point *c* and perpendicular to *bc* and *ca*
region 6	area enclosed by line *ca* and the lines perpendicular to *ca* and passing through points *c* and *a*
region 7	area within the triangle *abc* (I. e. BOSA)

The COG deviation distance was defined as the distance from the COG_H to the BOSA. This distance was calculated depending upon which region the COG_H projection was in during the test (Fig. D-4).

(a) If the COG_H was in region 1, 3 or 5, this distance was calculated as the distance of COG_H (x_c, z_c) to marker *a*, *b* or *c*, respectively.
(b) If COG_H fell in region 2, 4 or 6, the distance was calculated as the distance from COG_H to line *ab*, *bc* or *ac*, respectively.
© If the COG_H fell within the basal supporting area (region 7), COG deviation distance was equal to zero.

D.5.b.2. Total Utilized or Required COF

From the kinematic data during single stance, the utilized external forces were calculated using Newton's second law of motion: $F=m*a$, where F is the reaction force, and m is the mass of the subject, a is the acceleration of COG. The total utilized COF during gait is defined as:

$$COF_{uti.} = \frac{F_h}{F_v} \quad (1)$$

where F_h and F_v are the resultant horizontal and vertical reaction forces, respectively, calculated from the video data. During single stance, the reaction force acting on the supporting foot is equal to the subject's body mass times the acceleration of COG. The total utilized COFs calculated using the force plate data were used to compare the COF values from the video data.

D.5.b.3. Turning Radius and COF Utilized by the Centrifugal Forces

The turning radius is an important variable describing a gait pattern when turning on a slippery surface. It affects the angular momentum generated by the human body during turning around a vertical axis. The radius of the trajectory of COG_H when walking along a turning path can be calculated by Equation (2) [31]:

$$R = \frac{(\dot{x}^2 + \dot{z}^2)^{\frac{3}{2}}}{\dot{x}\ddot{z} - \ddot{x}\dot{z}} \quad (2)$$

where R is the radius of the projection of the trajectory of COG on the horizontal plane when turning. $\dot{x}$, $\dot{z}$, $\ddot{x}$, $\ddot{z}$ are the first and second derivatives of the x and z coordinates of the COG_H respectively.

Pilot data of a subject walking along a path turning to the left suggested that the trajectory of the subject's COG_H can be approximated by a curve, as shown in Fig. D-5.

From the point of view of mechanics, kinematic and kinetic vectors can be resolved into two or three orthogonal directions. Thus, the projection of the COG acceleration vector on the horizontal plane can be resolved into x and z directions of the laboratory coordinate system (a_{COG_X}, a_{COG_Z}) as well as the radial and tangential directions of the COG_H trajectory (a_r, a_τ), as shown in Fig. D-5. For this application, the horizontal acceleration component of COG and reaction force utilized to accomplish the turning task were resolved into radial and tangential directions:

$$F_r = m*a_r \tag{3}$$

$$F_\tau = m*a_\tau \tag{4}$$

where a_r and a_τ are the horizontal acceleration components of the COG in the radial and tangential directions, respectively.

The assumption that the tangential force F_τ is very small during the turning period and negligible as compared to the radial direction force F_r was evaluated in this study. If this assumption is valid, then, the radial reaction force alone can be used to estimate the total utilized COF. The relationship between the utilized COF and gait parameters such as walking speed and turning radius can be evaluated on the basis of this assumption.

As per Fig. D-5, the horizontal and vertical resultant forces and total utilized COF can also be calculated as:

$$F_h = m*\sqrt{a_\tau^2 + a_r^2} \tag{5}$$

$$F_v = m*(a_{COG_y} + 9.81) \tag{6}$$

$$COF_{uti.} = \frac{F_h}{F_v} = \frac{m*\sqrt{a_\tau^2 + a_r^2}}{m*(a_{COF_y} + 9.81)} \tag{7}$$

It can be seen from equation (7), that the total utilized COF consists of two parts: the COF utilized by the centrifugal force $COF_{cent.}$ (due to a_r) and the COF utilized by the tangential force $COF_{tang.}$ (due to a_τ). The contribution of each component of the utilized COF to the total utilized COF to perform a turning movement can be estimated separately:

$$COF_{cent.} = \frac{F_r}{F_v} = \frac{m*a_r}{m*(a_{COG_Y} + 9.81)} \tag{8}$$

$$COF_{tang.} = \frac{F_\tau}{F_v} = \frac{m * a_\tau}{m * (a_{COG_Y} + 9.81)} \qquad (9)$$

where

$$COF_{uti.} = \sqrt{COF^2_{cent.} + COF^2_{tang.}} \qquad (10)$$

The COF values in the above were calculated from kinematic data during single stance.

D.5.b.4. Slide Distance during a Slip Incident

Pilot tests showed that the distance from COG_H to the supporting base increased as the supporting foot slid. This indicates that the potential of a fall is related to the slide distance. In this study, the slide distance was defined as the total displacement of the geometric center of the supporting foot during slipping as shown in Fig. D-6. In the figure, (x_o, z_o) and (x'_o, z'_o) are the coordinates of the geometric centers of the slipping foot during two video pictures. The total slide distance d_{slide} was defined as the distance between the geometric centers of the foot at the beginning position (x_o, z_o) and ending position (x'_o, z'_o) of the slip period.

D.5.b.5. Slide Direction during Slip Incidence

The purpose of calculating the slide direction was to find the direction in which the shoe sole did not provide enough COF for the turning task. The slide direction was defined by the angle α formed by two lines as shown in Fig. D-6: the first line passes through the calcaneus and the middle point between the markers of the roots of 1st and 5th Metatarsal, the second line passes through the geometric centers of the supporting foot at any two video pictures during the slip period. This angle α was calculated using equation (11) [31]:

$$\alpha = \arctan \frac{k_1 - K_2}{1 + k_1 * k_2} \qquad (11)$$

where k_1 and k_2 are the slopes of the two lines mentioned above.

In summary, the following loss of balance variables during single stance were used for analysis:

1. $\overline{COF}$: Average COF utilized during single stance when negotiating different paths on surfaces of different slippery conditions;
2. $\bar{d}_{dev.}$: Average COG deviation during single stance when negotiating different paths on surfaces of different slippery conditions;
3. $\bar{R}$: Average radius of COG_H trajectory on the horizontal plane when turning on surfaces of different slippery conditions;
4. $\bar{\alpha}$: Average slide direction when slipping;
5. $\bar{d}_{slide}$: Average slide distance;
6. $\overline{V_H}$: Average horizontal velocity of COG;
7. $\overline{COF}_{cent.}$: Average COF calculated from the centrifugal force.

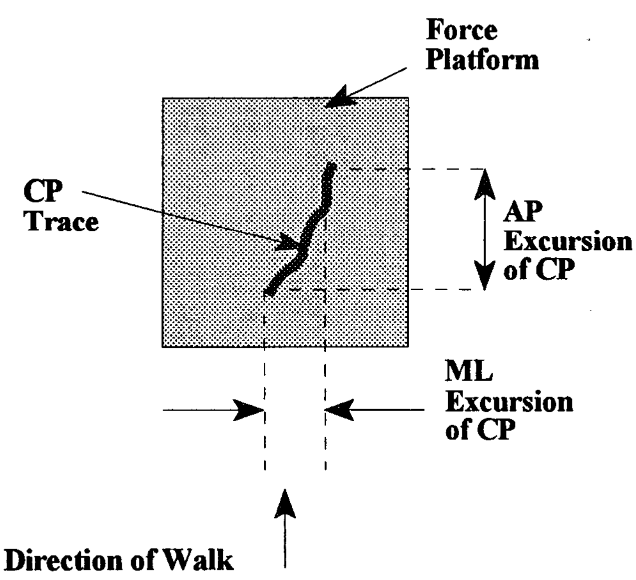
D.5.c. Excursion Parameters
The excursion parameters are defined on the basis of the lateral and medial deviation of the center of pressure (CP) trace under the feet during gait. The figure below shows the trace of the movement of the CP under the stance foot. The medial lateral (ML) excursion is the net deviation of the CP in the ML direction. The anterior posterior (AP) excursion is quantitated by measuring the net deviation of the CP in the AP direction.

The excursion parameters quantitate the extent of movement of the point of application of plantar force under the supporting feet. This 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 basal supporting area provided by the stance foot. Thus, the excursion parameters provide an indirect measure of the dynamic stability performance during the gait.

D.5.d. Slip Occurrence during Gait Evaluation: In this study, the subject was considered to be experiencing a slip whenever a foot sliding movement was observed during each trial. This information was recorded as an slip incident.

D.5.e. Subjective Measures of Postural Instability:

Perceived Sense of Slip/Fall (PSOS): A short questionnaire-type rating scale was administered at the end of each trial to determine the subjective perception of slip and/or potential fall of the subject during postural gait tests. The details of this test is explained in the Static balance evaluation section (C.7.b.).



D.6. RESULTS AND DISCUSSION OF DYNAMIC BALANCE DURING TASK PERFORMANCE

D.6.a. Relationship between Slip Occurrence and frictional properties of walking surface and required COF during Gait Tests (relevant to specific aim # A5)

From a total of 2569 gait trials about 60% of the trials produced observable slipping during task performance on slippery surfaces of varying degrees of slipperiness (COF range: .35 to .11). Among all trials (1569) which produced slipping, about 54% of slipping events occurred during turning motion (combined with and without weight in hand) and 46% were associated with straight walking (combined with and without weight in hand). The turning task with weight in hand produced somewhat (27%) more events of slipping than those observed during walking straight with a weight (23%).

The percentage of slip occurrences versus the ratio of maximum RCOF to the shoe COF for walking turn trials is shown in Figure D-7. It illustrates how the percentage of slip occurrences increase as the ratio of maximum of RCOF to the shoe COF rises. According to the result, when this ratio exceeds one (i.e. the required COF is greater than the shoe COF), a slip is more likely to occur. It ranges from 70.69% to 100% when the ratio is greater than one, as opposed to 0% to 64%, when the ratio is less than or equal to one.

The same analysis was also performed to investigate the walking straight trials, and the result is shown in Figure D-8. It illustrates the relationship between the percentage of slip occurrences and the ratio of maximum RCOF to the shoe COF in those walking straight trials. The combined response of walking straight and walking turn trials, is shown in Figure D-9.

D.6.b. Gait Kinetics (relates to specific aim # A3)
Data from 2558 trials from 40 subjects were used in this analysis and an univariate analysis of variance was performed on each of the kinetic variables.

Analyses of Gait Outcomes. The gait outcomes of force (Fx, Fy and Fz) exerted in the three orthogonal directions (labeled X, Y and Z), cycle time or dwell time, excursion in the X (AP) and Y (ML) directions and the minimum and maximum H/V ratios (=RCOF equation in Section C.7.a.3) were analyzed in a multivariate repeat measure analysis of covariance (MANCOVA). The within-subject conditions analyzed for each gait outcome were the shoe worn, surface slipperiness, light intensity, path (turn v. straight) and whether a weight was carried. The between-subject covariates of age, gender and height were also used in the MANCOVA. An alpha-level of 0.05 was used in all tests of a null hypothesis.

The results of the MANCOVA are shown in Table D.2. The tests for an overall (multivariate) effect on the gait outcomes were significant for all of the within-subject conditions except for whether a weight was carried (p=0.21) and was significant for gender but not for age (p=0.30) or height (p=0.74). The tests of hypothesis for height are not shown in this table, (none of them were statistically significant). Age was significantly related only to excursion in the y-direction (ML direction), with excursion increasing with age. Since the multivariate test was not significant and this is the only univariate test to be found significant, it likely is a chance finding. In addition to the significant overall difference found for males and females, gender was found to have significant effects in the univariate tests involving excursion in the x-direction (AP direction) and maximum H/V. Males were found to have significantly greater excursion in the x-direction and a higher maximum H/V relative to females (see Table D.3.). The shoe worn was found to be significantly different in univariate comparisons involving cycle or dwell time and maximum H/V. New shoes had a longer cycle time but a lower maximum H/V, as compared to used shoes (Table D.3.).

Slipperiness of surface was found to be significantly related to all eight gait outcomes. However, the relationship between surface slipperiness and gait was not always found to be a simple monotonic one. For the three force outcomes, the largest value was found for the dry surface, but the smallest for the slightly slippery surface, with the medium and very slippery surface's means between these two extremes (Table D.3 and figures D-10 to D-17).

The ambient light was found to be significant in only the univariate test for cycle time, which was somewhat greater for the subjects while walking in poor light, with respect to good light (Table D.3.). The path traversed was found to be significant in three univariate tests of hypotheses, in addition to the significant multivariate test noted above. Subjects traversing the turn had longer cycle times, much greater excursions in the y-direction, and higher minimum H/V values, as compared to subjects walking along the straight path (Table D.3.). Finally, only the minimum H/V was found to be affected in a univariate test of the differences due to carrying a weight. Subjects carrying a weight tended to have a slightly higher minimum H/V (Table D.3.); 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.

Table D.2: P-values for the Multivariate and Univariate Tests of the Factors Used In the Models for Gait

	Multivariate	F_x(AP)	F_y(ML)	F_z	Cycle Time	$Excursion_x$	$Excursion_y$	Min. H/V	Max. H/V
Age	0.30	0.60	0.62	0.62	0.27	0.85	**0.01**	0.79	0.40
Gender	**0.005**	0.09	0.10	0.10	0.29	**0.0001**	0.72	0.61	**0.02**
Shoe	**0.0001**	0.23	0.41	0.43	**0.001**	0.18	0.42	0.26	**0.006**
Surface	**0.0001**	**0.01**	**0.008**	**0.008**	**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**
Light	**0.005**	0.11	0.06	0.08	**0.0001**	0.39	0.60	0.10	0.24
Path	**0.0001**	0.85	0.48	0.50	**0.0001**	0.17	**0.0001**	**0.004**	0.08
Weight	0.21	0.10	0.08	0.10	0.16	0.80	0.18	**0.01**	0.34

Table D.3.: Means and Standard Deviations, by the Factors Used in the Models for the Gait Outcomes

Means and Standard Deviations for the Gait Outcomes, by Gender

	F_x	F_y	F_z	Cycle Time	$Excursion_x$	$Excursion_y$	Min. H/V	Max. H/V
Female	6.97	7.82	30.98	0.72	24.77	10.56	0.022	0.27
	(29.30)	(31.27)	(122.00)	(0.15)	(6.31)	(6.95)	(0.016)	(0.13)
Male	17.47	18.30	71.74	0.76	29.99	10.32	0.021	0.32
	(45.88)	(47.64)	(185.20)	(0.13)	(7.52)	(7.37)	(0.015)	(0.29)

Means and Standard Deviations for the Gait Outcomes, by Shoe Worn

	F_x	F_y	F_z	Cycle Time	$Excursion_x$	$Excursion_y$	Min. H/V	Max. H/V
Old	11.26	12.34	48.65	0.73	27.10	10.54	0.022	0.31
	(36.69)	(38.48)	(151.55)	(0.15)	(7.64)	(7.34)	(0.016)	(0.16)
New	13.18	13.79	54.06	0.75	27.66	10.34	0.021	0.28
	(40.88)	(42.68)	(164.42)	(0.14)	(7.17)	(6.98)	(0.015)	(0.27)

Means and Standard Deviations for the Gait Outcomes, by Surface Slipperiness

	F_x	F_y	F_z	Cycle Time	$Excursion_x$	$Excursion_y$	Min. H/V	Max. H/V
Dry	22.98	24.71	97.12	0.77	25.62	11.92	0.028	0.40
	(54.98)	(57.40)	(224.57)	(0.11)	(5.82)	(8.54)	(0.019)	(0.13)
Slightly Slippery	7.20	7.66	29.77	0.75	26.38	10.35	0.020	0.28
	(27.30)	(28.70)	(109.90)	(0.14)	(6.88)	(7.13)	(0.012)	(0.13)

Medium Slippery	10.64 (34.86)	11.24 (36.44)	44.70 (142.63)	0.72 (0.15)	28.54 (7.97)	9.27 (5.97)	0.019 (0.013)	0.25 (0.11)
Very Slippery	8.12 (30.16)	8.70 (31.47)	34.05 (120.63)	0.71 (0.16)	28.95 (8.21)	10.23 (6.54)	0.018 (0.015)	0.27 (0.37)

Means and Standard Deviations for the Gait Outcomes, by Lighting Intensity

	F_x(AP)	F_y(ML)	F_z	Cycle Time	$Excursion_x$	$Excursion_y$	Min. H/V	Max. H/V
Poor	11.15 (36.92)	11.71 (38.39)	46.36 (150.04)	0.75 (0.15)	27.46 (7.48)	10.40 (6.99)	0.021 (0.015)	0.30 (0.27)
Good	13.28 (40.65)	14.42 (42.72)	56.35 (165.68)	0.73 (0.13)	27.30 (7.35)	10.49 (7.33)	0.022 (0.016)	0.29 (0.16)

Means and Standard Deviations for the Gait Outcomes, by Path Traversed

	F_x	F_y	F_z	Cycle Time	$Excursion_x$	$Excursion_y$	Min. H/V	Max. H/V
Turn	12.07 (38.46)	12.48 (39.87)	49.19 (154.74)	0.77 (0.16)	26.77 (8.89)	15.44 (6.23)	0.023 (0.018)	0.31 (0.28)
Straight	12.36 (39.22)	13.65 (41.36)	53.49 (161.38)	0.71 (0.11)	27.99 (5.50)	5.45 (3.74)	0.019 (0.012)	0.29 (0.15)

Means and Standard Deviations for the Gait Outcomes, by Weight Carried

	F_x	F_y	F_z	Cycle Time	$Excursion_x$	$Excursion_y$	Min. H/V	Max. H/V
Weight Carried	13.72 (42.76)	14.68 (44.06)	57.00 (170.10)	0.74 (0.14)	27.41 (7.53)	10.56 (7.17)	0.022 (0.015)	0.30 (0.28)
No Weight Carried	10.72 (34.41)	11.44 (36.80)	45.68 (144.90)	0.74 (0.14)	27.35 (7.30)	10.32 (7.16)	0.020 (0.016)	0.29 (0.15)

Table D.3A: Overall Means and Standard Deviations for the Gait Outcomes using all subjects' measurements

F_x	F_y	F_z	Cycle Time	$Excursion_x$	$Excursion_y$	Min. HV	Max. HV
12.22 (38.83)	13.06 (40.61)	51.34 (158.05)	0.74 (0.14)	27.38 (7.41)	10.44 (7.16)	0.021 (0.016)	0.30 (0.22)

These effects of risk factors as presented in Table D.3 on the gait outcomes are additive. In general, combined effects of multiple risk factors on any gait variable (in Table D.3) can be calculated relative to the overall mean of the gait variable of interest as follows:

Estimated value of gait variable of interest= OMGV+ [Sum of MRF- n*OMGV] ------ (A)

Where OMGV= Overall Mean of Gait Variable of interest from Table D.3A
n= number of risk factors to be considered
MRF= Mean value of gait variable of interest for a particular risk factor from Table D.3

For example, the combined effects of gender, shoe and surface on the maximum H/V may be calculated relative to the overall mean of this outcome of 0.30 (Table D.3A): A female walking with new shoes on a very slippery surface would have an estimated maximum H/V of 0.30 - 0.08 (=0.03+0.02+0.03) = 0.22, since these three factors diminish the maximum H/V by approximately 0.03 [=0.30-0.27 i.e. Overall Mean Max H/V (from Table D.3A)- Mean Max.H/V for Female (from Table D.3)], 0.02 (=0.30-0.28) and 0.03 (=0.30-0.27), respectively (see Table D3 and D.3A).

That is, the estimated value of Max H/V = 0.3 + [(.27+.28+.27)- 3x0.30]
=0.22

D.6.c. <u>**Correlations with Kinetic (Gait) Variables (relates to Specific Aim # A.6.)**</u>. In the literature, slip prediction at the workplace is generally thought to be related to the COF of the shoe and commercially available COF testing devices measure either static COF or dynamic COF. In order to test the shoe COF's ability to predict events of slips and/or postural instability during dynamic task performance, a correlational analysis was carried out. The deviation in the subject's slip rating scale scores from the theoretical line (Figure C-11) based on the coefficient of friction (COF), the COF, and the total number of slips were correlated with the kinetic variables from gait trials. For the correlations with the slip rating score deviations and the total number of slips, the kinematic variables were averaged across all conditions; for the correlations with the COF, only gait data collected for used shoes were used, and were averaged across all other experimental conditions. The only significant ($p<0.05$) correlations occurred for the total number of slips, which were significantly and positively correlated with excursion in the x-direction ($r=0.36$) and the Minimum H/V ratio ($r=0.42$). The deviation scores and the shoe COF values were not significantly correlated with any of the gait outcomes (Table D.4.).

Table D.4.. Correlation of Kinematic (Gait) Outcomes and the Slip Rating Scale Deviations, the COF and the Total Number of Slips

	F_x(AP)	F_y(ML)	F_z	Cycle Time	$Excursion_x$	$Excursion_y$	Maximum H/V	Minimum H/V
Slip Rating Score Deviation	0.22	0.21	0.22	-0.03	0.26	-0.16	0.27	0.08
COF (Used shoes only)	0.08	0.11	0.11	-0.02	-0.21	0.13	-0.05	-0.09
Total number of slips	-0.15	-0.16	-0.16	-0.19	**0.36***	-0.16	0.18	**0.42***

* Statistically significant at $p<0.05$

D.6.d. Repeated Measure ANOVA of Kinematic Parameters of Gait Heel Strike

Because of the use of a 60 Hz video camera (purchase of the high speed camera was disallowed by the Study Section), there were only 13 subjects with digitizable 5th camera video data for straight walk trials available for analysis. Furthermore, because dry surface condition was found to have no slip occurrence from the pilot trials, they were excluded from the analysis. Therefore, a total of 299 trials from 13 subjects were digitized. A mean imputation procedure were carried out in order to analyze the data by a repeated measure analysis of variance procedure.

The incoming velocity, heel contact angle, sliding distance, and sliding velocity were the kinematic variables measured in this study. A multivariate repeated measure analysis of variance (ANOVA), and four univariate ANOVA were performed to analyze all four kinematic parameters simultaneously. Table D.5. through Table D.9. summarize the results of the multivariate and univariate analyses.

Table D.5.
Summary of the Multivariate ANOVA

Source	DF	Mean Square	F Value	Pr > F
Surface	**2**	**1.30**	**10.41**	**0.0006**
Shoe	1	0.019	0.21	0.6538
Light	1	0.0001	0.00	0.96
Load	1	0.0008	0.02	0.8991
Surface x Shoe	2	0.083	1.92	0.1682
Surface x Light	2	0.021	0.56	0.5769
Shoe x light	1	0.00015	0.00	0.9471
Surface x Weight	2	0.0061	0.17	0.8483

Light x Weight	1	0.00007	0.00	0.9853
Shoe x Weight	1	0.0081	0.20	0.6643

Table D.6. Summary of the Univariate ANOVA for the Incoming Velocity

Source	DF	Mean Square	F value	Pr > F
Surface	2	0.483	2.03	0.1532
Shoe	1	0.129	0.57	0.4653
Light	**1**	**2.018**	**16.96**	**0.0014**
Weight	1	0.119	0.56	0.4177
Surface x Shoe	**2**	**0.298**	**3.76**	**0.0381**
Surface x Light	2	0.093	0.90	0.4197
Shoe x Light	1	0.202	1.45	0.2510
Surface x Weight	2	0.076	0.57	0.5725
Shoe x Weight	1	0.002	0.02	0.8998
Light x Weight	1	0.046	0.11	0.7426

Table D.7. Summary of the Univariate ANOVA for the Heel Contact Angle

Source	DF	Mean Square	F value	Pr > F
Surface	**2**	**54.424**	**3.80**	**0.0369**
Shoe	1	3.031	0.28	0.6051
Light	**1**	**32.065**	**5.06**	**0.0441**
Weight	1	0.056	0.04	0.8527
Surface x Shoe	2	4.977	1.52	0.2393
Surface x Light	2	0.640	0.18	0.8349
Shoe x Light	1	2.233	0.90	0.3613
Surface x Weight	2	0.847	0.17	0.8481
Shoe x Weight	1	6.984	1.49	0.2546
Light x Weight	1	25.195	1.22	0.2906

Table D.8. Summary of the Univariate ANOVA for the Sliding Distance

Source	DF	Mean Square	F value	Pr > F
Surface	**2**	**0.138**	**9.23**	**0.0011**
Shoe	1	0.044	2.54	0.1367
Light	1	0.00003	0.006	0.9474
Weight	1	0.00008	0.01	0.9178
Surface x Shoe	2	0.0065	1.19	0.3201
Surface x Light	2	0.0024	0.50	0.6129
Shoe x Light	1	0.001	0.19	0.6719
Surface x Weight	2	0.0016	0.36	0.7035
Shoe x Weight	1	0.0007	0.02	0.9042
Light x Weight	1	0.00004	0.00	0.9701

Table D.9. Summary of the Univariate ANOVA for the Sliding Velocity

Source	DF	Mean Square	F value	Pr > F
Surface	**2**	**1.540**	**10.07**	**0.0007**
Shoe	1	0.0003	0.00	0.9576
Light	1	0.0004	0.016	0.9403
Weight	1	0.0024	0.04	0.8460
Surface x Shoe	2	0.148	2.52	0.1019
Surface x Light	2	0.029	0.60	0.5549
Shoe x Light	1	0.0002	0.01	0.9426
Surface x Weight	2	0.0095	0.19	0.8316
Shoe x Weight	1	0.0141	0.27	0.6142
Light x Weight	1	0.0003	0.00	0.9694

From the results of the multivariate ANOVA, the effect of surface slipperiness was found to be highly significant on all four kinematic parameters (p=0.0006). The main effect of environmental lighting was significant on incoming velocity (p=0.014), and heel contact angle (p=0.0044). The effect of shoe wear / tear was found to significantly interact with surface on the incoming velocity parameter (p=0.0381). The main effect of load carriage was found to be insignificant on all kinematic parameters.

The geometric means and standard deviations errors of kinematic parameters for these significant risk factors are presented in Table D.10.

Table D.10. geometric means and standard deviations of kinematic parameters for various risk factors

Risk Factor	Kinematic Parameters: Geometric Mean and Geometric S.D.			
Surface	Incoming Velocity (m/sec)	Heel Contact Angle (degree)	Sliding Distance (m)	Sliding Velocity (m/sec)
Slightly	0.98 (0.14)	12.73 (1.48)	0.009 (0.003)	0.04 (0.012)
Medium	1.06 (0.22)	11.92 (1.94)	0.019 (0.001)	0.09 (0.026)
Very	1.10 (0.26)	11.79 (2.13)	0.034 (0.005)	0.15 (0.04)
Lighting				
Good	1.09 (0.19)	12.38 (1.90)	0.02 (0.0008)	0.09 (0.036)
Poor	0.98 (0.19)	11.93 (1.57)	0.02 (0.0016)	0.09 (0.020)

The mean sliding distance of very oily surfaces was the greatest (0.034 m) among the three surfaces, followed by the medium oily (0.019 m) and slightly oily surfaces (0.009 m). The mean sliding velocity for very oily surfaces was the highest among the three surfaces (0.15 m/sec), followed by the medium oily (0.09 m/sec) and slightly oily surface (0.04 m/sec). However, the mean heel contact angle of the very oily surfaces was found to be the smallest among the three surfaces (11.79). The heel contact angle of the slightly oily surfaces was found to be the greatest (12.73), followed by the medium oily surfaces (11.92). The mean incoming velocity was found to be greater under good lighting (1.09 m/sec) condition than poor lighting condition (0.98 m/sec).

To further investigate the relationship between the sliding distance and the surface slipperiness, the measured sliding distances were categoried into three types of "slip events", i.e., micro slip (< 3cm), slip (between 3 and 10 cm), and slide (>=10 cm). Using these strata, each slip occurrence was categoried. The percentage distribution of "slip event" type for each level of surface slipperiness is illustrated in Figure D-18.

From Figure D-18, the sliding distance characteristics are found to be different for different levels of surface slipperiness. Most of the slip occurrences fell into the category of micro slip across different surface slipperiness, however, under "very" and "medium" slippery surfaces, higher percentages of slip and slide were observed than those under the "slightly" slippery surface.

D.6.e. Relationship between slip occurrence and subjective measure of slip/loss of balance during dynamic task performance on slippery surface

The mean (SEM) value of the PSOS score for all gait trials (2569) was 1.67 (0.04). On the average each subject slipped during 61% of all trials (each subject performed 64 trials). The mean (SEM) PSOS scores for the gait (dynamic) tasks performed on dry, slightly, medium and very slippery surfaces were 0.12 (0.017), 1.45 (0.076), 2.22 (0.088) and 2.87 (0.095), respectively. Each subject performed 16 trials each for dry, slightly, medium and very slippery surfaces. Only two out of 40 subjects were observed to slip on the average 6.25% of all trials (each subject performed 16 trials on dry surface) performed on the dry surface. On the average all 40 subjects slipped about 65%, 87% and 91% of all trials performed on slightly, medium and very slippery surfaces, respectively.

The mean (SEM) PSOS scores for the gait (dynamic) tasks performed without weight on a straight path, with a weight on a straight path, without weight on a turning path and with a weight on a turning path were 1.15 (0.07), 1.2 (0.07), 2.11 (0.09) and 2.24 (0.096), respectively. Each subject performed 16 trials or tasks consisting of : without weight on a straight path, with a weight on a straight path, without weight on a turning path and with a weight on a turning path . On the average all 40 subjects slipped about 56%, 57%, 66% and 66% of all tasks (or trials) performed without weight on a straight path, with a weight on a straight path, without weight on a turning path and with a weight on a turning path, respectively.

Table D.11.: All Gait Tasks (Also refer to the figure D-19)

PSOS Score	# of trials	% of all trials (total trials=2569)	Total number of slips	% of all slip occurrence
0	1065	41.5	188	17.7
0.5	282	11	227	80.5
1	180	7	149	82.8
1.5	137	5.3	127	92.7
2	170	6.6	147	86.5
2.5	96	3.7	94	97.9
3	73	2.8	73	100.0
3.5	86	3.3	84	97.7
4	112	4.4	112	100.0
4.5	79	3.1	79	100.0

5	45	1.8	45	100.0
5.5	34	1.3	34	100.0
6	66	2.6	66	100.0
6.5	39	1.5	39	100.0
7	23	0.9	23	100.0
7.5	15	0.6	15	100.0
8	67	2.6	67	100.0

NOTE: For example, the data in row one means that out of 2569 trials in 1065 trials subjects gave a PSOS score of 0. Similarly, the data in row 5 means that out of 2569 trials in 170 trials subjects gave a PSOS score of 2.

Table D.12.: Gait tasks without weight in hand on a straight path (Also refer to the figure D-20)

PSOS Score	# of trials	% of all trials (total trials=640)	Total number of slips	% of all slip occurrence
0	327	51.1	73	22.3
0.5	85	13.3	72	84.7
1	35	5.5	30	85.7
1.5	28	4.4	26	92.9
2	33	5.2	28	84.8
2.5	30	4.7	29	96.7
3	16	2.5	16	100.0
3.5	13	2	13	100.0
4	28	4.4	28	100.0
4.5	9	1.4	9	100.0
5	7	1.1	7	100.0
5.5	4	0.6	4	100.0
6	5	0.8	5	100.0
6.5	8	1.3	8	100.0
7	5	0.8	5	100.0

7.5	4	0.6	4	100.0
8	3	0.5	3	100.0

Table D.13.:Gait tasks without weight in hand on a turning path (Also refer to the figure D-21)

PSOS Score	# of trials	% of all trials (total trials=639)	Total number of slips	% of all slip occurrence
0	221	34.6	33	14.9
0.5	58	9.1	47	81.0
1	40	6.3	32	80.0
1.5	35	5.5	32	91.4
2	48	7.5	41	85.4
2.5	31	4.9	31	100.0
3	26	4.1	26	100.0
3.5	25	3.9	24	96.0
4	30	4.7	30	100.0
4.5	26	4.1	26	100.0
5	11	1.7	11	100.0
5.5	10	1.6	10	100.0
6	27	4.2	27	100.0
6.5	14	2.2	14	100.0
7	7	1.1	7	100.0
7.5	6	0.9	6	100.0
8	24	3.8	24	100.0

Table D.14.: Gait tasks with weight in hand on a straight path (Also refer to the figure D-22)

PSOS Score	# of trials	% of all trials (total trials=645)	Total number of slips	% of all slip occurrence
0	300	46.5	55	18.3
0.5	87	13.5	70	80.5
1	60	9.3	49	81.7
1.5	32	5	30	93.8
2	45	7	40	88.9
2.5	13	2	12	92.3
3	16	2.5	16	100.0
3.5	19	2.9	19	100.0
4	21	3.3	21	100.0
4.5	15	2.3	15	100.0
5	6	0.9	6	100.0
5.5	5	0.8	5	100.0
6	10	1.6	10	100.0
6.5	4	0.6	4	100.0
7	1	0.2	1	100.0
7.5	2	0.3	2	100.0
8	9	1.4	9	100.0

Table D.15.: Gait tasks with weight in hand on a turning path (Also refer to the figure D-23)

PSOS Score	# of trials	% of all trials (total trials=645)	Total number of slips	% of all slip occurrence
0	217	33.6	27	12.4
0.5	52	8.1	38	73.1
1	45	7	38	84.4
1.5	42	6.5	39	92.9
2	44	6.8	38	86.4
2.5	22	3.4	22	100.0
3	15	2.3	15	100.0
3.5	29	4.5	27	96.6
4	33	5.1	33	100.0
4.5	29	4.5	29	100.0
5	21	3.3	21	100.0
5.5	15	2.3	15	100.0
6	24	3.7	24	100.0
6.5	13	2	13	100.0
7	10	1.6	10	100.0
7.5	3	0.5	3	100.0
8	31	4.8	31	100.0

D.6. f. Effect of risk factors on subjective measure of slip/loss of balance

The Perceived Sense of Slip (PSOS) data collected for the gait trials on 40 subjects were analyzed by separate analysis of covariance (ANCOVA) models depending on whether the subject traversed a straight or turning path. The covariates of age, gender , shoe hardness, available shoe tread and height were initially entered into each ANCOVA model. The main effects of the within-subject conditions of shoe worn, surface condition and weight carried (yes vs. no) were calculated, as were the two-way and three-way interactions among these factors. A strategy of backward elimination of insignificant ($p>0.05$) covariates and within-subject interactions was followed.

The p-values from the final models for the PSOS data are shown in Table D.16.. For the ANCOVA of data collected from subjects traversing a straight path, gender, height, shoe worn, surface and the shoe worn by surface interaction were all found to be significant. Females were found to rate straight path surfaces less slippery than males. Taller subjects were found to rate straight path surfaces less slippery than shorter subjects. The significant shoe worn by surface condition interaction suggested that used shoes were rated to perform particularly poorly on very oily surfaces as compared to new shoes, and also somewhat more poorly on slightly and medium oily surfaces as compared to new shoes. On dry surfaces while traversing a straight path, subjects perceived little difference between new and old shoes.

For the analysis of data collected from subjects navigating the turning path, a significant Available Shoe Tread correlation with the PSOS scores was found, in addition to significant main effects for the surface traversed and the weight carried.

Table D.16.: Analysis of covariance p-values for gait Perceived Sense of Slip (PSOS) Scores

Risk Factors	Straight Path	Turning Path
Available Shoe Tread		**0.03**
Gender	**0.03**	
Height	**0.03**	
Shoe Type (Used/New)	**0.0006**	Not tested
Surface	**0.0001**	**0.0001**
Weight Carried	0.27	**0.02**
Shoe * Surface	**0.0002**	Not tested

D.7. Measurement of Slip/Loss balance or fall Potential During Walking on a Turning Path(33)

Data from ten workers from the present study were used as part of this study. A brief description of the test setup and the protocol is repeated here for clarity. A T-shaped walkway was used in the gait test as shown in Fig. D-24. The subjects started walking from point A and traveled (1) straight to point B and C or (2) to point B and then turned left to point D. The subjects were required to walk in a normal fashion, making certain that they stepped in the middle of the force platform (point B) with the right foot. They were instructed not to target the force platform when walking. Ample practice trials were performed at the beginning of the session to ensure proper stepping. Trials with misstepping were repeated. The origin of the fixed laboratory coordinate system was placed at one corner of the force platform with the x-axis pointed from A to C, the y-axis pointed up perpendicular to the plane of force plate, and the z-axis pointed to the right, as shown in Fig. D-24.

An aluminum plate was placed on the top of the force platform. Dry and very slippery conditions were simulated, the latter by evenly coating the plate with 9 ml *Walgreen* ™[1] mineral oil (Section C.3.b.). Subjects wore Red Wings work shoes during the gait test. The COFs of shoe-floor interface were measured independently using a specialized setup. The average dynamic COFs for dry and very slippery surfaces were 0.67 and 0.11, respectively.

A commercial safety harness system, with overhead rail attachment, was employed to ensure safety of the subject in case of a fall. Subjects wore a safety harness during all gait trials. The length of the harness was adjusted for each subject, so that the subject could be protected but not pulled by the harness during walking.

Retro reflective foam markers were attached to the subject's body symmetrically about the sagittal plane at 24 anatomical landmarks for 3-D kinematic data collection. These anatomical landmarks 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 fifth metatarsal of the feet, and the calcaneus. The video data for each of these landmarks were acquired at 60 Hz using a 4-camera system (*PEAk* ™ *Performance Technologies Inc.*). After digitizing the video pictures, the 3-D coordinates of each body marker were calculated using *PEAK* software. The coordinate data were smoothed using optimal Butterworth filter and interpolated to provide the marker coordinates used in further analysis. Using a 12-segment model (head, trunk, lower arms, upper arms, upper legs, lower legs, and feet segments) and anthropometric data [32], the whole body center of gravity (COG) was calculated. Kinetic data were sampled at 600 Hz from the force platform (*AMTI* model # OR6-5-1000) during the gait test. The force data were collected in synchronization with the kinematic data.

Fig. D-25 shows an example of the use of the kinematic analysis strategy. It can be seen from the figure that during turning, the COG_H deviated considerably from the supporting foot. The deviation distance increases as the supporting foot slides (subject slipped in this trial), implying an increasing potential for loss of balance. The events marked on the trajectory of the COG_H in Fig. D-25 are: Left Heel Contact (LHC); Right Toe Off (RTO); Right Heel Contact (RHC); Begin to Slip (SLIP); and Left Toe Off (LTO). In this trial, the COG_H fell completely out of the BOSA during the single stance period of the right foot on the slippery surface [frame # 63 (LTO) to # 84 (LHC)]. Data from the same subject walking in a straight path on a dry surface showed that the COG_H falls within the BOSA most of the time during right single stance. Therefore, the potential of loss of balance is much lower compared to that of walking on a very slippery surface along a turning path.

Fig. D-26 shows the total utilized COF and COF calculated from the centrifugal force $COF_{cent.}$ for one subject. It can be seen that the centrifugal force contributed significantly to the total utilized COF. This result validated the assumption that the tangential force is much smaller than the centrifugal force.

The mean ± std.err. values of the loss of balance variables during right foot single stance period from 10 subjects are shown in Figures D-27 to D-33. Table D.17 lists the mean ± std.err. of the utilized COF, average walking velocity, and total slide distance in a complete gait cycle (from left heel contact

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[1]Walgreen Co., Deerfield, IL.

to next left heel contact) for 10 subjects. The average COG deviation distance for all subjects negotiating a turning path was greater than that of negotiating a straight path. When walking on a very slippery surface, a longer slide distance was observed when negotiating a curved path as compared to that of a straight path. The mean slide direction ± std.err. are 52.7 ±5.1 degrees for a turning path and 60.8 ±5.2 degrees for a straight path. On the average, $COF_{cent.}$ constituted about 80% of the total utilized COF.

Table D.17: Gait test results of 10 subjects.
(Mean±std.err.)

Surface Condition	Dry		Very Slippery	
Path	Straight	Turn	Straight	Turn
utilized COF	0.11±0.02	0.15±0.010	0.19±0.074	0.13±0.020
average horizontal velocity (m/s)	1.14±0.09	0.92±0.04	1.20±0.09	0.93±0.06
total slide distance (m)	0.009±0.009	0.009±0.008	0.126±0.040	0.281±0.056

Statistical analysis using a t-test showed that when negotiating a curved path on a dry surface, the average utilized COF is significantly greater than that of a straight path ($p< 0.05$). However, the utilized COF did not change significantly with paths when walking on very slippery surfaces. This is because the utilized COF for both paths exceeded the maximum available COF of the shoe-floor interface. The very slippery surface caused all the subjects to slip irrespective of the path.

The average horizontal velocity during single stance when walking on the very slippery surface was significantly higher than that on the dry surface ($P<0.05$). This was because the very slippery surface failed to provide enough braking force. The horizontal velocity was lower when negotiating a turning path on both surfaces ($p<0.05$) implying a slower gait while turning (Fig. D-32).

The average turning radii of 10 subjects negotiating a turning path was significantly greater on a slippery surfaces than on a dry surface ($p<0.05$). This is because the COF between the shoe and the floor was insufficient so that the subjects slipped and they were observed negotiating a larger curved path. This result validates the assumption that when turning on a surface of insufficient COF, gait patterns change or are modified even though this is not intended. From the viewpoint of biomechanics, the utilized reaction force when turning is proportional to the reciprocal of the turning radius. Thus, for safety considerations, people should avoid a sharp turn when the COF supplied by the shoe-floor interface is insufficient.

From Fig. D-34, it can be seen that the average COF calculated from kinematic data was higher than that calculated from the force plate data. This is because the calculation of the reaction force from kinematic data requires the displacement data to be differentiated twice. This process may exacerbate any error. The patterns of the COF calculated from the two methods (kinetic and kinematic) were similar and they were significantly correlated ($p<0.05$). Using kinematic data to calculate COF may be an alternative solution when a force plate is not feasible to use. Other variables derived from the kinematic data (such as those presented in this study) can provide more detailed information in assessing the risks associated with a slip and fall.

Since the COF utilized by the centrifugal force constituted about 80% of the total utilized COF, workers can be trained to modify their gait pattern to reduce the COF utilized in situations where floor-shoe interface may be unable to provide a sufficient COF. When walking on slippery surfaces, most subjects slid in the mediolateral (ML) direction (52-60 degrees) which implies that the available COF in this direction was insufficient. A pilot COF test did show that the COF in the ML direction was smaller than that of anterior-posterior (AP) direction for most of the working shoes investigated.

D.8. Effect of risk factors on objective measures of slip/loss of balance for the worst and the best test conditions:

Digitized gait data from 14 subjects were available for an analysis comparing the extreme conditions (i.e., traversing a very slippery surface in dim light while carrying a weight vs. traversing a dry surface in good light with no weight). The measured gait variables which were compared include: Slide Angle, Utilized COF, Horizontal Velocity, Sliding Distance, and Deviation Distance. All of the gait variables except Slide Angle were transformed to their natural logarithm in order to achieve approximate normality of the statistical distributions. An analysis of covariance (ANCOVA) was performed using age, gender and height as covariates and Condition (Extremely Good and Extremely Poor), Path (Straight vs. Turn) and these two factors' interaction as conditions of the gait experiment. Insignificant ($p>0.05$) covariates and the interaction were removed individually from each gait variables' ANCOVA model.

The resulting p-values obtained from the ANCOVA are shown in Table D.18. The means for each condition of the study and for gender are shown in Table D.19 Age was found to be significant only for the variables of slide angle and horizontal velocity. Older subjects tended to have a smaller slide angle and a larger horizontal velocity than younger subjects. Males and females differed only in terms of the slide angle: females exhibited a much smaller angle of slide than did males. Height was a significant covariate only of the utilized COF variable. Taller subjects tended to utilize less total COF. The condition of the experiment was significant as a main effect only for sliding distance. For both this variable and the deviation distance, however, a significant Condition*Path interaction was found. The interactions suggested that the turn path produced a somewhat larger sliding and deviation distance when paired with the worst condition than when paired with the best condition, as compared to the sliding or deviation distance while walking on the straight path. The path traversed was found to be significant for two gait outcomes independent of interaction: the utilized COF and the horizontal velocity. The straight path required less COF to be utilized and induced greater horizontal velocity. Utilized COF was significantly predicted by shoe sole hardness for old shoes ($r=0.79$, $p<0.001$) under the Extremely Poor condition. No other correlations between shoe hardness and tread availability with these gait variables were found to be statistically significant.

ANCOVA models were also calculated for the gait variables of COF required by centrifugal force and turning radius. Both of these variables were transformed to their natural logarithm to produce statistical distributions which were approximately normal. These gait variables are only observed for the turn path, so only the single factor of Condition (Extremely Good vs. Extremely Poor) could be included in these ANCOVA's. The same covariates of age, gender and height were initially included in these models; however, none of these covariates were found to be significant and were removed.

The condition of the experiment was not found to be a significant factor for either the COF required by centrifugal force (p=0.75) or the turning radius (p=0.29).

Table D.18: P-values from Univariate Analysis of Covariance

Risk Factors	Slide angle	ln(Utilized COF)	ln(Horiz. Velocity)	ln(Slide distance)	ln(CG Deviation distance)
Age	**0.006***		**0.03***		
Gender	**0.03***				
Height		**0.04***			
Test Conditions	0.16	0.69	0.17	**0.0001***	0.19
Path	0.26	**0.04***	**0.0001***	0.06	**0.0001***
Test Cond* Path				**0.0007***	**0.03***

* Statistically significant

Table D.19 Means and Standard Deviations for the Kinematic Data

For all test conditions measured on all subjects:

All Subjects' Measurements	Slide Angle	Utilized COF	Horizontal Velocity	Slide Distance	CG Deviation Distance
	82.53 (26.53)	1.25 (2.49)	1.02 (1.33)	0.013 (4.65)	0.11 (1.58)

By gender:

Gender	Slide Angle	Utilized COF	Horizontal Velocity	Slide Distance	CG Deviation Distance
Female	75.82 (24.37)	1.35 (2.57)	1.00 (1.36)	0.011 (4.73)	0.11 (1.63)
Male	90.00 (27.29)	1.14 (2.43)	1.04 (1.31)	0.015 (4.62)	0.12 (1.52)

By test condition:

Test condition	Slide Angle	Utilized COF	Horizontal Velocity	Slide Distance	CG Deviation Distance
Best	85.81 (19.62)	1.31 (2.57)	0.98 (1.30)	0.004 (2.10)	0.11 (1.40)
Worst	79.13 (32.23)	1.18 (2.45)	1.06 (1.36)	0.039 (3.71)	0.12 (1.75)

By path:

Path	Slide Angle	Utilized COF	Horizontal Velocity	Slide Distance	CG Deviation Distance
Straight	77.74 (29.20)	0.97 (2.64)	1.19 (1.23)	0.010 (3.10)	0.08 (1.42)
Turn	86.82 (23.58)	1.56 (2.25)	0.89 (1.33)	0.016 (6.17)	0.14 (1.48)

By test condition and path:

Test Condition / Path	Slide Angle	Utilized COF	Horizontal Velocity	Slide Distance	CG Deviation Distance
Best / Straight	80.33 (20.17)	1.13 (2.62)	1.20 (1.22)	0.005 (1.84)	0.09 (1.31)

Best / Turn	90.55 (18.48)	1.50 (2.56)	0.82 (1.19)	0.003 (2.24)	0.12 (1.37)
Worst /Straight	75.14 (36.80)	0.83 (2.97)	1.18 (1.24)	0.019 (3.30)	0.08 (1.53)
Worst / Turn	82.83 (28.21)	1.62 (1.98)	0.96 (1.42)	0.078 (2.80)	0.17 (1.49)

Note: Arithmetic means and standard deviations were calculated for the slide angle data. All other tabled results for the utilized COF, horizontal velocity, slide distance and the CG deviation distance are geometric means and standard deviations.

The digitized kinematic gait indices were also correlated with whether a slip was observed during the gait trial and the shoe's dynamic COF for the best and the worst cases. Only these variables' correlations with the sliding distance ($r=0.73$ for slips and $r=-0.72$ for shoe's dynamic COF, $p<0.05$) were statistically significant. Occurrence of a slip was also statistically related to the dynamic COF ($r=-0.97$, $p < 0.05$). One reason why these correlations are not uniformly strong for all the remaining gait kinematic indices (slide angle, utilized COF, horizontal velocity, and deviation distance), is that the slip variable represents a dichotomy (i.e. occurrence or no occurrence of a slip event).

SUMMARY OF FINDINGS/IMPLICATIONS: POSTURAL STABILITY EVALUATION DURING DYNAMIC TASK PERFORMANCE ON SLIPPERY SURFACES

In comparison to static tasks (Section C.9.a.2), the dynamic task performed on slippery surfaces produced about 36% more slips (24.2% of static tasks produced slips vs. 60% of dynamic tasks). This was expected, as the dynamic tasks (in comparison to static tasks) produce much larger horizontal shear forces which require a relatively higher value of shoe/floor COF to avoid a slip incident to occur. It is interesting to note that in the static tasks of reach, the total number of slips were much higher than those observed for dynamic tasks of gait (70.5% for reach task vs. 60% for all gait tasks). In other words, upper body dynamics of the reach task, while carried out in a stationary position, were producing sufficiently high horizontal shear forces as well as postural instability to create a significant numbers of slip incidents to occur.

The turning path had a higher mean H/V (Min H/V and Max) requirement than did the straight path walk, implying that the potential of slip was higher in the former case (Table D.3). In the current study the actual slip events associated with turning motion were higher (54% of all slipping events) than those observed for walking in a straight path (46% of all slipping events). The use of old shoes produced higher mean (Max and Min) H/V requirements (Table D.3) than did new shoes, implying the potential of slip in the case of old shoes if sufficient amount of shoe/floor COF is not made available. Similar to the findings from the static task performance on slippery surfaces, it can be seen that even when the ratio of max.H/V to shoe COF is less than 1, slip events are not uncommon for walking both the straight and turning paths (Figure D-7 and D-8). This finding, like in the case of static task, implies that even during dynamic task performance, the slipping events are not dictated solely by the frictional properties of the shoe/floor interface. Body movements which modify the dynamic postural stability (as characterized by variables such as excursion in AP and ML directions) also contribute to the occurrence of a slip event. This implication is supported by the fact that the total number of slips were significantly correlated with both anterior-posterior excursion variable as well as the Min. H/V variable (Table D.4). However, the shoe COF did not show any significant correlations with measures of dynamic postural stability during the performance of dynamic tasks (Table D.4; which is relevant to specific aim # A5).

During dynamic task performance, changes in all gait kinetic variables were significantly affected by the surface slipperiness (Table D.2). The primary differences in the three force variables appeared to be in comparing dry with a surface of any degree of slipperiness. The relationship for cycle time and the two excursion values with surface slipperiness was of a more monotonic character. The longest cycle time was observed for the dry surface, and decreased through each of the degrees of slipperiness; excursion in the x-direction (AP direction) increased monotonicly from a minimum observed on the dry surface to a maximum observed for the very slippery surface; and excursion in the y-direction (ML direction) decreased from a maximum on the dry surface to a minimum on the medium slippery surface, then increased somewhat for the very slippery surface (Table D.3.). Once again, the largest difference for the excursion variables appeared to be between the dry surface and a surface with some degree of slipperiness. The minimum H/V decreased monotonicly from a maximum on a dry surface to a minimum on a very slippery surface; maximum H/V decreased from the largest mean values on the dry surface to the smallest mean values observed for the medium slippery surface, then increased slightly for the very slippery surface. As for the force and excursion variables, much of the difference encountered between surfaces in terms of the H/V variables appeared to be accounted for by comparing dry vs. a surface with any degree of slipperiness. This implies that in a dynamic task performance on a slippery surface, the potential of slip is relatively high (i.e. >50% slip occurrence to take place) for slightly, medium and very slippery surfaces. In the present study, on the average all 40 subjects slipped about 65%, 87% and 91% of all trials on slightly, medium and very slippery surfaces, respectively (Figures D-7 to D-9 and Section D.6.e.).

From these results, the potency of the within- and between- effects on gait may be rank-ordered. The largest and most general effects on these gait outcomes was found to be for surface slipperiness (Table D.2). As noted above, most of these variables responded to even a slight degree of slipperiness, so that much of the statistical difference exists between the dry surface and a surface of any slipperiness. The second most important variable was whether a turn was traversed or a straight path was followed. The path significantly affected three of the eight gait outcomes (Table D.2). The shoe worn (new vs. used) followed by the subjects' gender displayed the next largest effects. Both of these variables were found to be significant in two of eight univariate tests. Finally, light intensity is the remaining experimental condition which displayed a significant multivariate difference in terms of these outcomes and represents the smallest statistically reliable difference in these data. The remaining effects which were modeled, i.e., the effects of age, height and of carrying a weight, were not significant in the multivariate test nor consistently significant in univariate tests to suggest effects beyond those likely by chance.

Pearson correlations were calculated among all the kinematic variables (Table D.20). The correlation coefficient (r) between the sliding velocity and the incoming velocity was 0.56 ($p<0.05$), implying that as the subjects' incoming velocity increased the sliding velocity during slip also increased. This is possible because an increase in incoming velocity will increase the momentum with which the foot will strike the slippery surface, thereby causing the sliding velocity to increase as well. The highest negative correlation was between heel contact angle and the incoming velocity ($r=-.77$, $p<0.002$). The negative correlation implies that as the subjects approached the force plate with increasing incoming velocity, their heel contact angle became smaller. The use of a smaller heel contact angle at a higher incoming velocity is indicative of a cautious body movement strategy to avoid sudden slip during a heel strike (Figure D-18). The cautious body movement strategy was also implied during walking in poor light as the incoming velocity and the heel contact angle of foot were significantly lower for the poor light condition compared to that observed for the good lighting condition. (Table D.6, D.7 and D.10).

Pearson correlations were also calculated between shoe COF, the total number of slips and all the kinematic gait variables (Table D.20). The shoe COF did not show significant correlations with any of the kinematic variables or the total number of slips. On the other hand, 2 out of 5 kinematic variables showed statistically significant correlations with total number of slips. The significant correlations were found between sliding distance ($r=0.61$, $p<0.03$) and sliding velocity with total number of slips ($r=0.56$, $p< 0.05$). [It is to be noted that the sliding velocity and the sliding distance variables are highly correlated with each other ($r=0.92$, $p=0.0001$)]. In other words, shoe COF is a poor predictor of gait heel kinematics (as characterized by the variables of slide velocity and heel contact angle) and total number of slips experienced. Kinematic variables such as slide velocity and slide distance provide a better prediction of slip incidents, as well as postural instability while walking on slippery surfaces (Figure D-18). This implies that avoidance of slipping incidents while walking on a slippery surface in a poorly lit environment, requires to have slower incoming velocity (before hitting the slippery surface) and smaller heel contact angle and not necessarily on shoe with high COF properties (relevant to specific aim # A5).

Table D.20: Pearson correlation coefficients and p values between kinematic variables, number of slips and shoe COF

Variable	# of slips	Incoming Velocity	Heet Contact Angle	Sliding Distance	Sliding Velocity	Shoe COF
# of slips		0.05 (p=0.86)	-0.07(0.8)	**0.61(0.028)***	**0.56(0.048)***	-0.38(0.19)
Incoming Velocity			**-0.77(0.002)**	0.38(0.2)	0.56(0.048)	0.31(0.3)
Heet Contact Angle				-0.25(0.41)	-0.44(0.13)	-0.25(0.4)
Sliding Distance					**0.92(0.0001)**	-0.015(0.96)
Sliding Velocity						0.15(0.63)

For dynamic tasks of walking in a turning path with or without weight in hand, the subjects always slipped when the subject's PSOS score was 4 or greater. However, walking (with or without weight in hand) in a straight path always caused a slipping incident when the subject's PSOS score was 3 or greater. Greater shoe tread on used shoes tended to lessen the PSOS for subjects traversing a turning path. A very slippery surface led to a significantly larger PSOS, as compared to all other surfaces. This implies that subjects were able to correctly judge the degree of slipperiness. Medium and slightly slippery surfaces tended to be rated more slippery than dry surfaces, although not different from each other. The inability to differentiate between medium and slightly slipperiness could be lack of sensitivity of the PSOS scale used. Carrying a weight led to a significantly greater rating for PSOS, as compared to not carrying a weight while navigating a turning path. This finding provides support to the PSOS scale design, which is to capture the combined effect of slipping and loss of balance during task performance.

Negotiating a curved path on a slippery surface is much more difficult than negotiating a straight path. This is true for both dry and slippery surfaces, as indicated by the COG_H deviation distance and foot slide distance measured in this study (Fig. D-27 and D-28). The variables defined in this study can be used to assess the degree of difficulty of a task and the risks associated with it. This study also provides a biomechanical basis for differentiating the utilized COF based on the dynamics of the task. When negotiating a curved path, the walking velocity was found to be significantly reduced, and the turning radius was observed to increase to compensate for the insufficient COF provided by the shoe-floor interface in the lateral direction. Based on the prominent slide direction for most of the subjects (Fig.D-29), it is important to redesign working shoes' sole tread to provide adequate COF in this direction. Results from this study also would be useful in providing guidelines for redesigning work surface, work practices, and shoes that are consistent with the task requirements.

D.9. Pilot Study: The Relationship between Center of Pressure and Center of Gravity during Dynamic Task Performance

This preliminary analysis was carried out to determine the relationship between the CG and CP motion patterns during the single stance phase of the dynamic (gait) task performance on slippery surface. The purpose was to investigate if CP based data (instead of CG) can be used to approximate the potential loss of balance associated with task performance on a slippery surface. The secondary aim was to qualitatively test the hypothesis that CP motion serves as a signal to the brain to move the whole body CG in a direction consistent with preventing a condition of loss of balance. The single stance phase was assumed to be quasi-static.

The data from 21 subjects were used. Five out of 21 subjects performed, 1 trials each under the "best" and the "worst" walking conditions giving a total of 10 data files. One half (8 subjects) of the remaining subjects performed the best walking condition trial. The second half (8 more subjects) of the remaining subects performed the worst walking condition trial. Therefore, total number of data files obtained from 21 subjects were 26. In the best walking condition, the subjects were required to walk straight and step on the middle of a dry force platform with the right foot in a normal fashion; in the worst walking condition, the subjects were instructed to walk straight and try to step on the middle of a very slippery force platform with the right foot, carrying 5 pounds of a weight with the right hand, in a poor lighting environment. Three variables were calculated during the single stance phase of gait. They are described as follows:

GQ: the distance between the whole body center of gravity (CG) and the center of the base of the support of both feet (Q).
OG: the distance between CG and the center of the base of support of the right foot.
OP: the distance between center of pressure (CP) and the center of the base of support of the right foot.

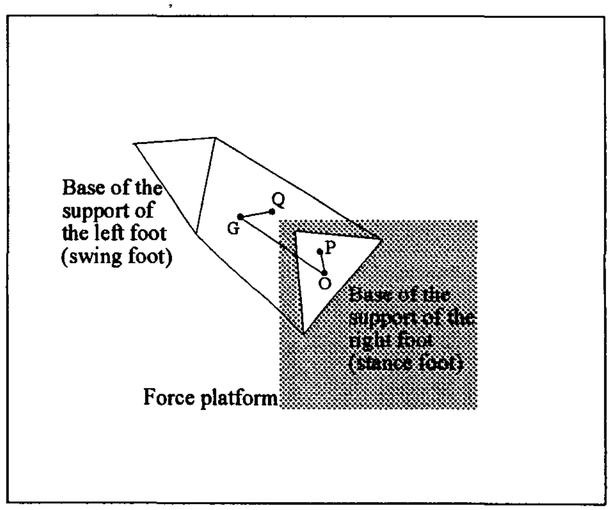


Figure D-35:The positions of CP and CG with respect to BOS.

The time series CP data during the single stance phase were obtained using a force platform. The time series CG data (synchronized with CP data) were calculated and acquired from digitized data for each trial. A slip was counted if the subject was observed to slip during the single stance phase. There was no slip occurrence in the best walking condition; however, 5 slips out of 13 trials occurred in the worst walking condition.Correlation analysis for mean values of OP, GQ and OG with slip occurrence was performed and shown in Table D. 21. The correlation analysis indicates that in the worst walking condition there is a significant negative correlation (r= -0.67, p=0.01) between OG maximum and slip occurrence. Also, a significant positive correlation (r= 0.6, p=0.03) between OP mean and slip occurrence is observed in the worst walking condition. Moreover, all trials for the best and worst walking conditions combined, significant positive correlation coefficients for OP mean with slip occurrence and OP maximum with slip occurrence are also found (Table D.21). The correlation data suggest that during the single stance phase the greater the OP value, the more likelihood of slip. Greater distance between the center of right foot and the CP suggests increase in postural instability which in turn may elicit body movement strategy to bring the CG closer to the base of support of right foot. In the present study, a negative correlation between OG and slip occurrence was found suggesting that the subjects tend to decrease the left step length and bring the CG nearer to the base of support of the right foot when a slip occurs which is indicative of body's natural reaction to protect it from falling. The minimum OG was observed approximately in the middle of the single stance phase for the best walking condition, implying that CG was closest to the center of the base of support of the stance foot. It supports the finding of MacKinn's study that body balance is ensured by the CG passing medial to the support foot during the single stance phase (37).

Table D.21. Pearson Correlation Coefficients for mean and max values of OP, GQ and OG with slip occurrence

	The Worst Walking Condition					
	OP mean	GQ mean	OG mean	OP max	GQ max	OG max
Slip Occurrence	0.60	-0.26	-0.35	0.54	0.25	-0.68
P value	0.03*	0.39	0.24	0.05*	0.40	0.01*
	The Best and the Worst Walking Conditions					
	OP mean	GQ mean	OG mean	OP max	GQ max	OG max
Slip Occurrence	0.60	-0.14	-0.22	0.60	0.14	-0.31
P value	0.001*	0.50	0.29	0.001*	0.48	0.13

* any finding with P<0.05 were considered statistically significant

D.10. Figures for the Section D

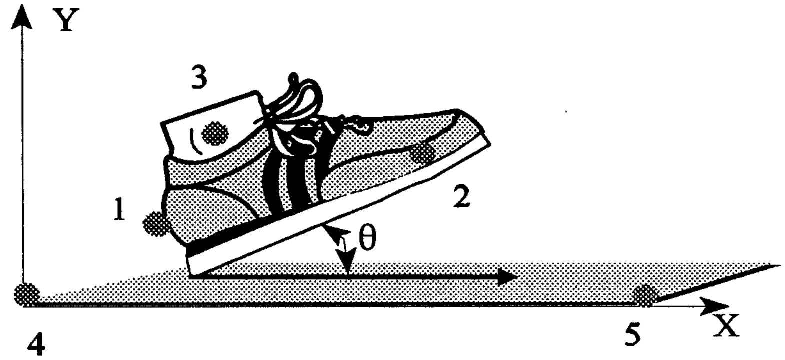


Figure D-1:
Definition of Heel Contact Angle for gait tasks

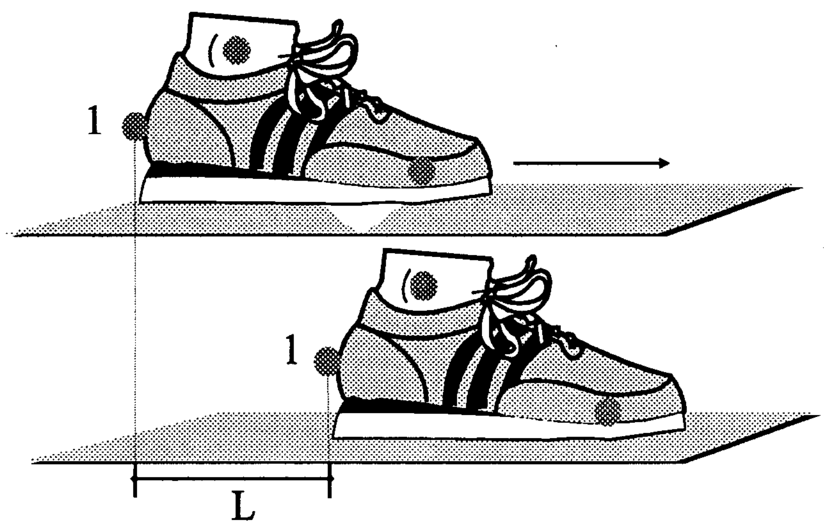


Figure D-2:
Definition of Sliding Distance in a 1-dimensional plane for straight gait tasks

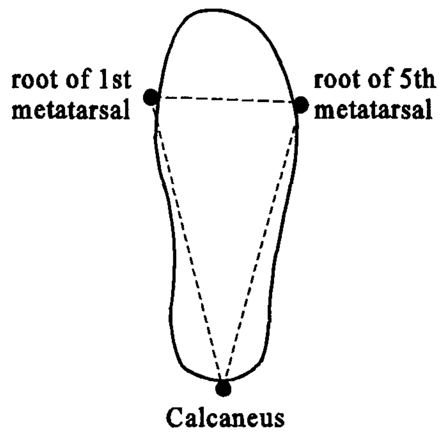


Figure D-3: Approximated BOSA

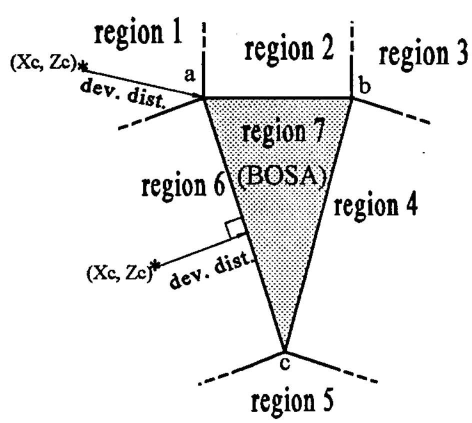


Figure D-4: Definition of the regions used to calculate the COG_H deviation distance

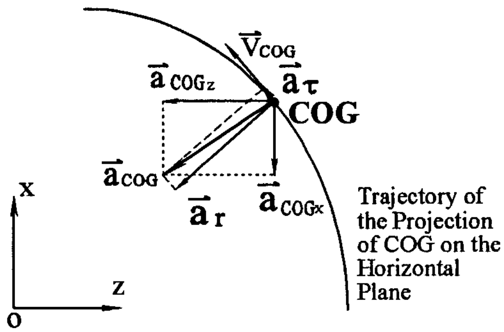


Figure D-5
The projection of the acceleration vector of COG on horiontal plane and its components

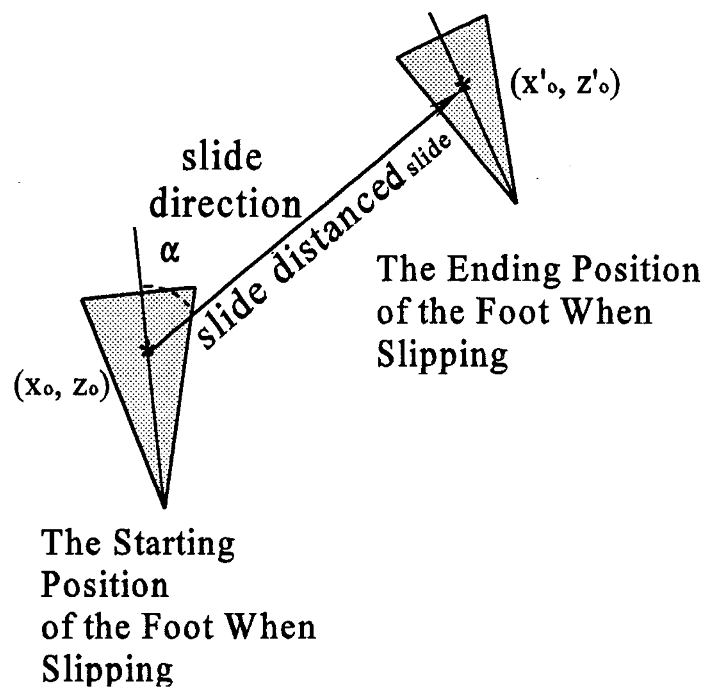


Figure D-6
Definition of slide distance and direction in a 2-dimensional plane for straight and turning gait tasks

Figure D-7
% SLIP OCCURRENCE VS. $RCOF_{MAX}$ / COF_{SHOE}
FOR WALKING ON A TURNING PATH

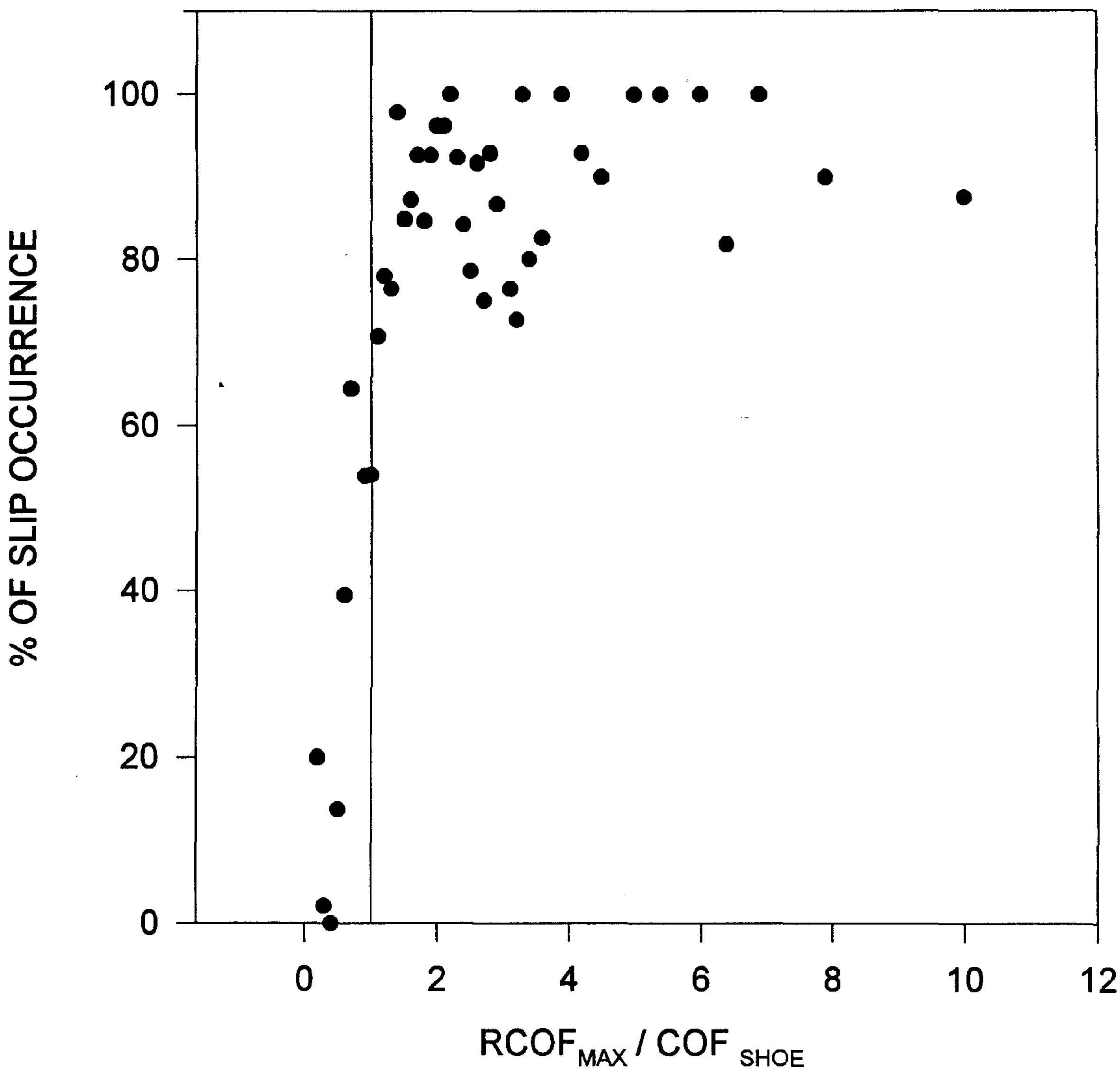


Figure D-8
% SLIP OCCURRENCE VS. $RCOF_{MAX}$ / COF_{SHOE}
FOR WALKING ON STRAIGHT PATH

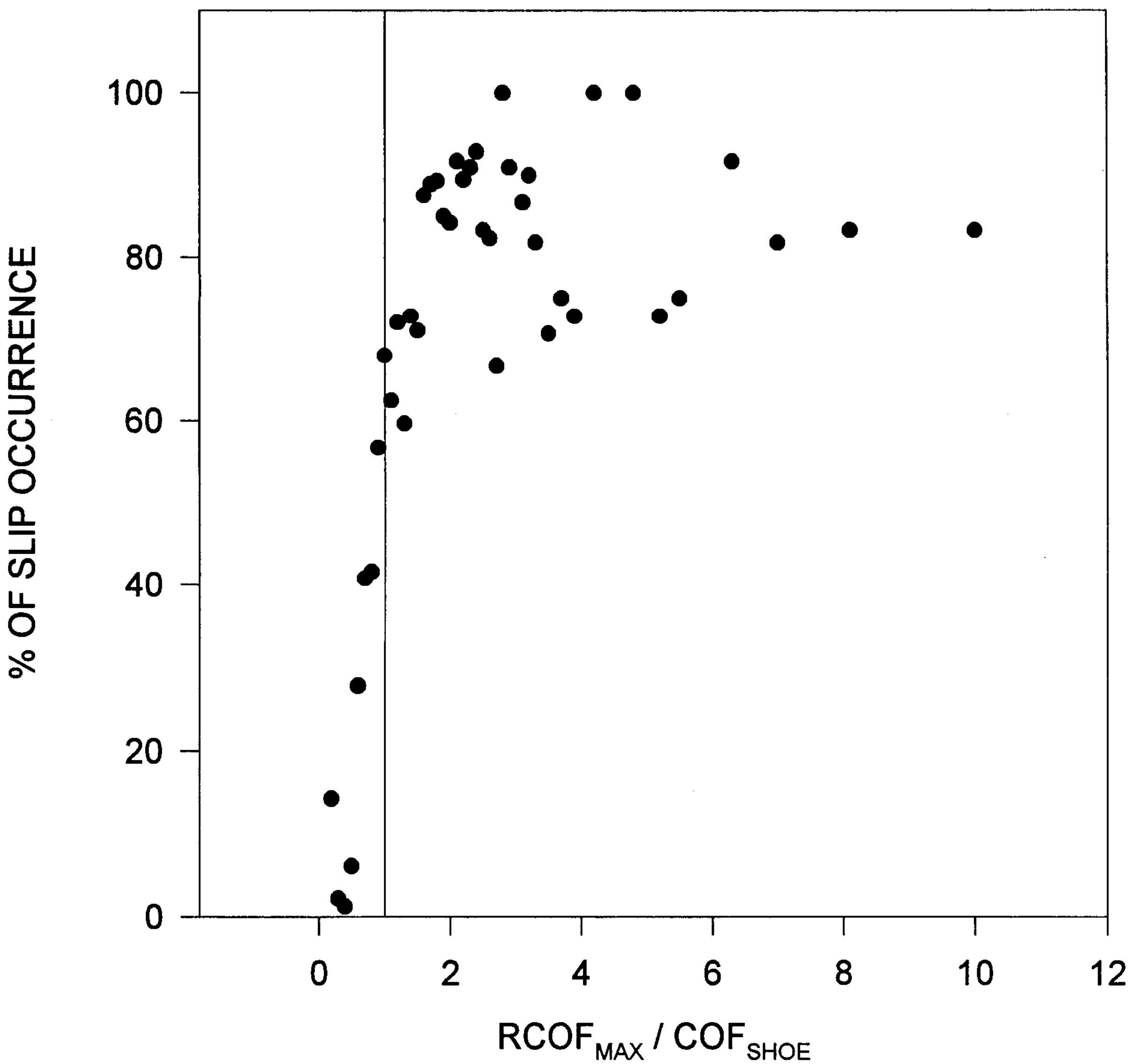


Figure D-9
%OF SLIP OCCURRENCE VS. ROCF$_{MAX}$/COF$_{SHOE}$
FOR ALL GAIT TRIALS

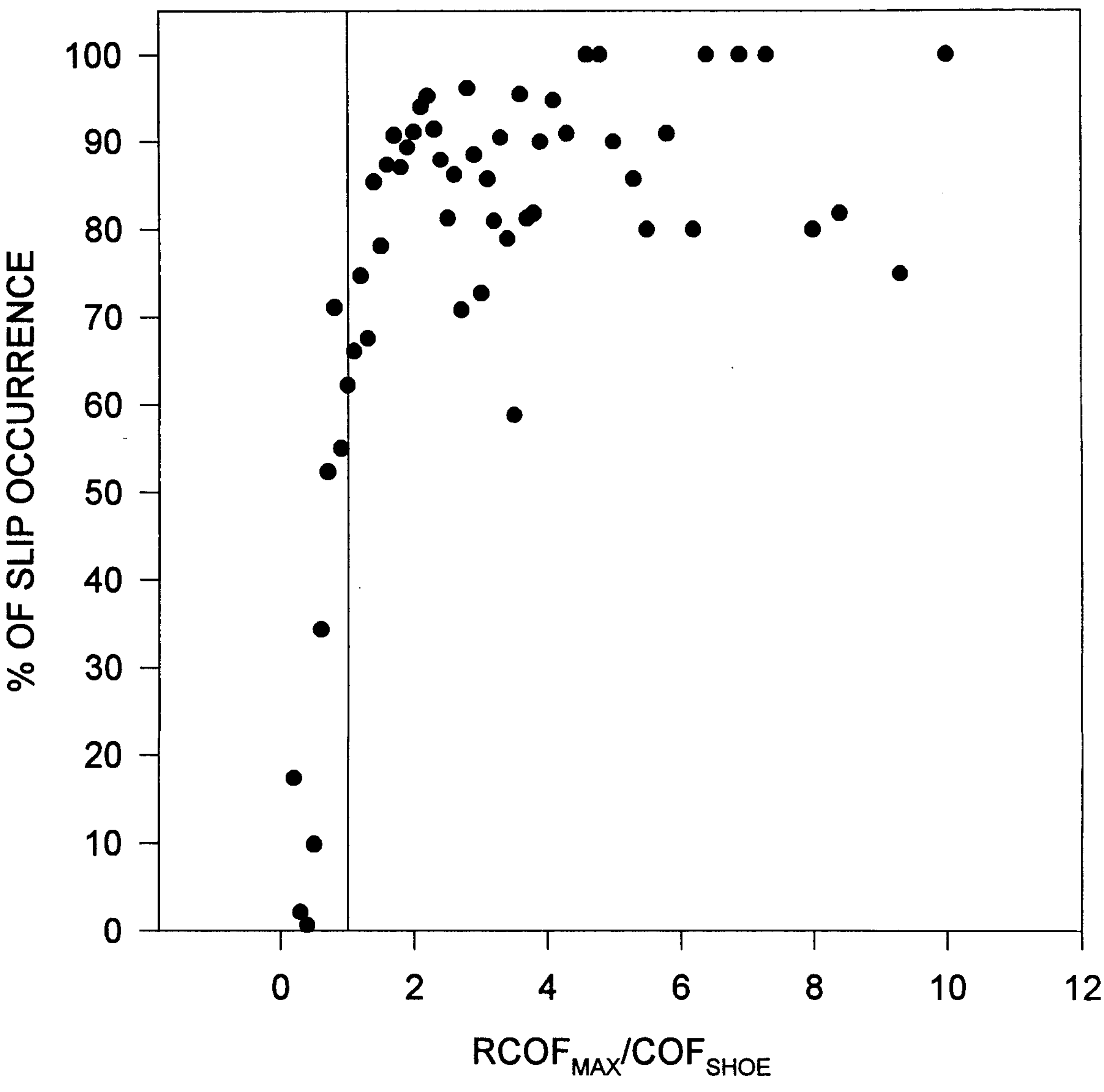


Figure D-10

Mean values of anterior-posterior shear forces associated with dynamic task performance on various slippery surfaces

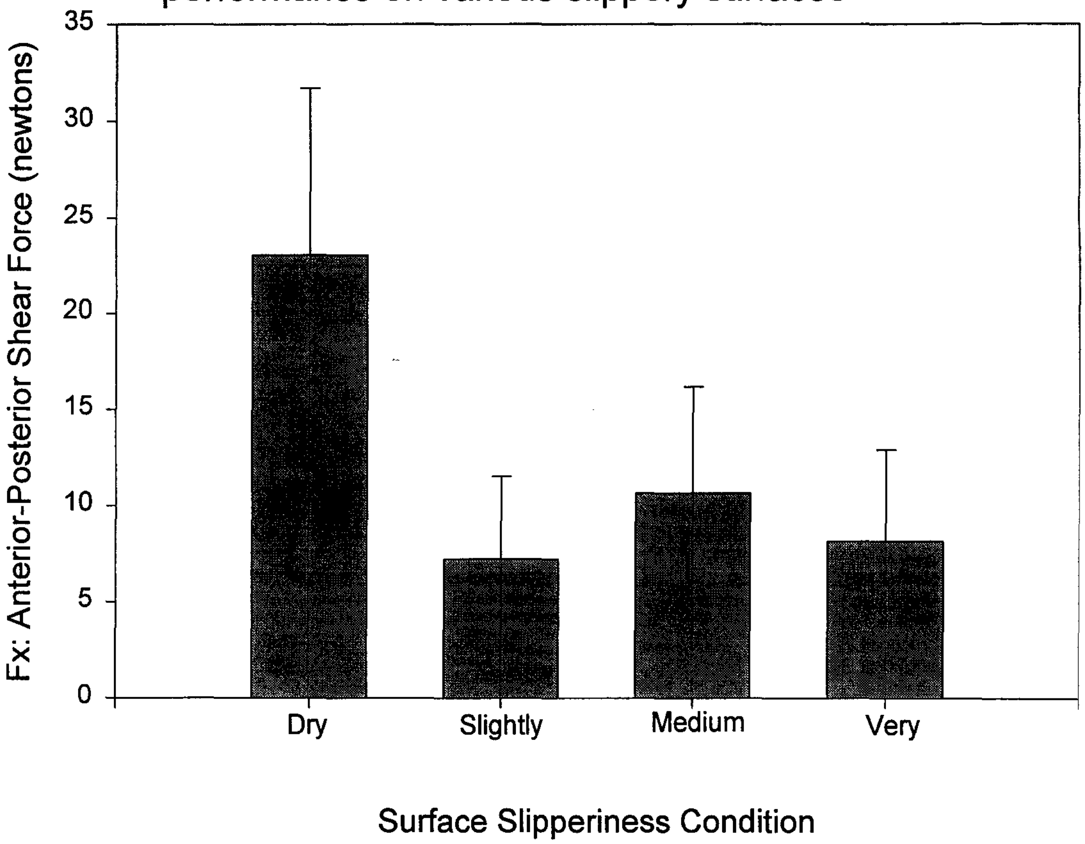


Figure D-11
Mean values of medio-lateral shear forces associated with dynamic task performance on various slippery surfaces

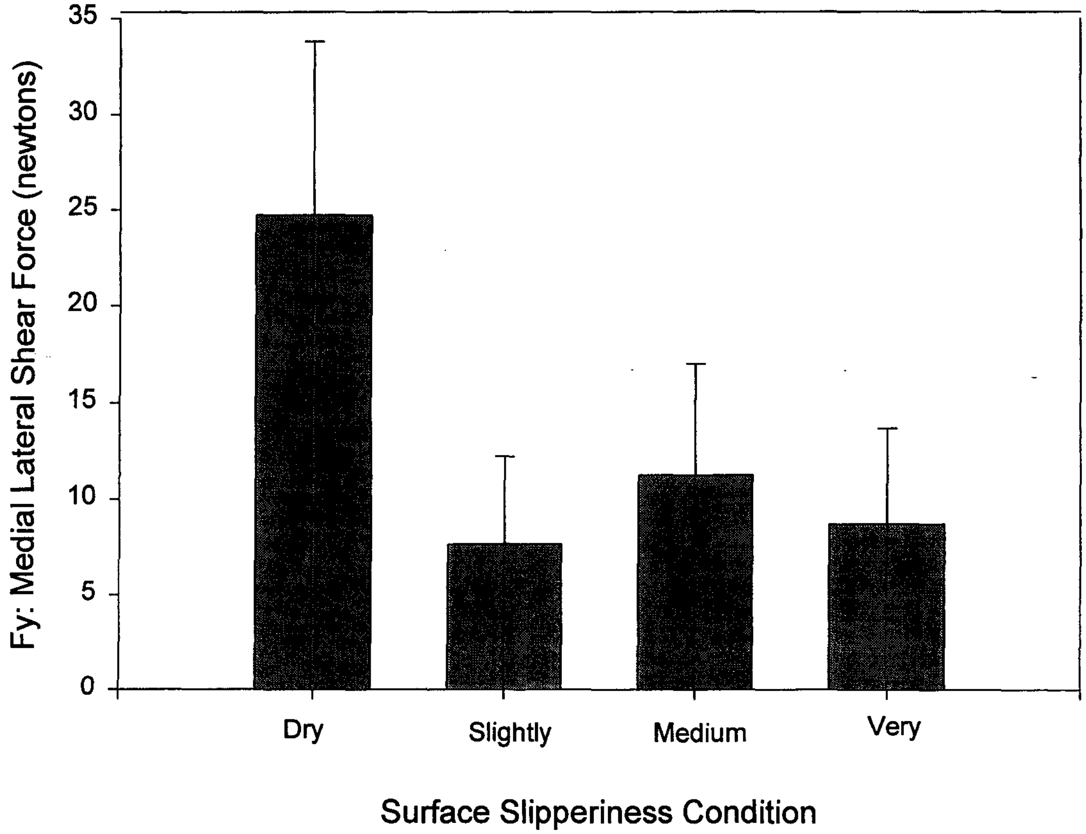


Figure D-12
Mean values of vertical force associated with dynamic task performance on various slippery surfaces

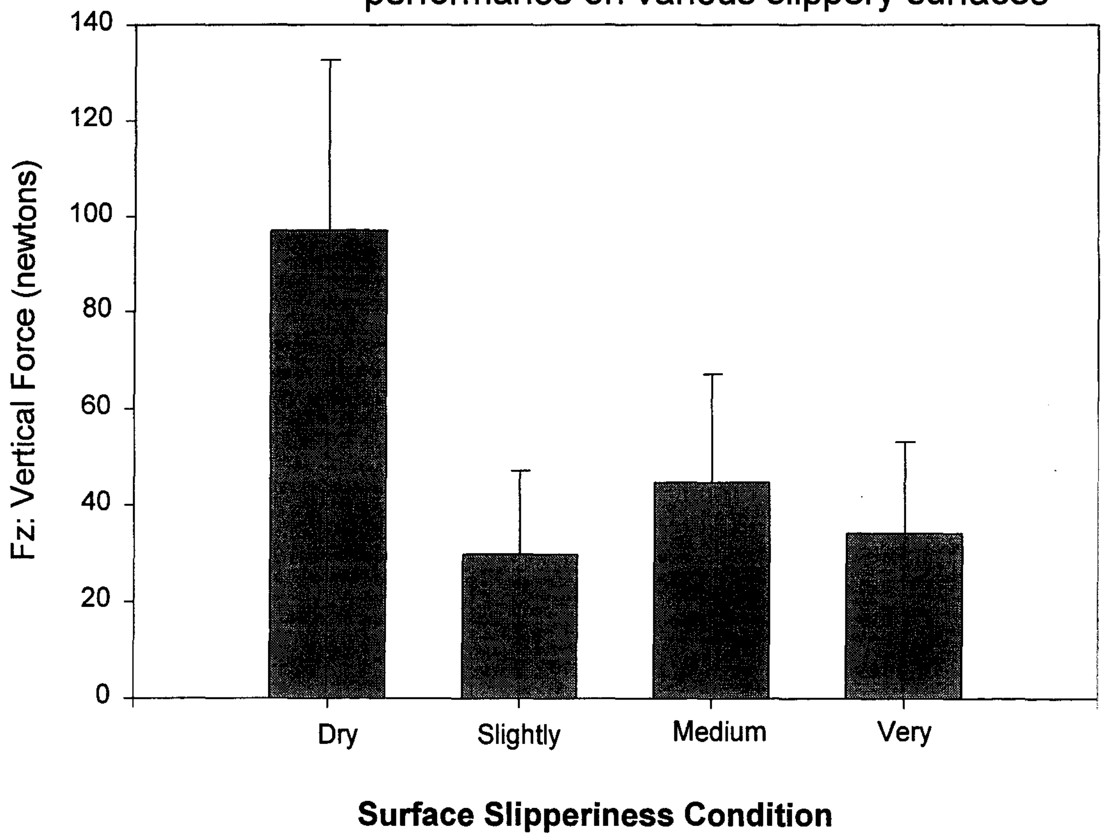


Figure D-13
Mean values of cycle (dwell) time associated with dynamic task performance on various slippery surfaces

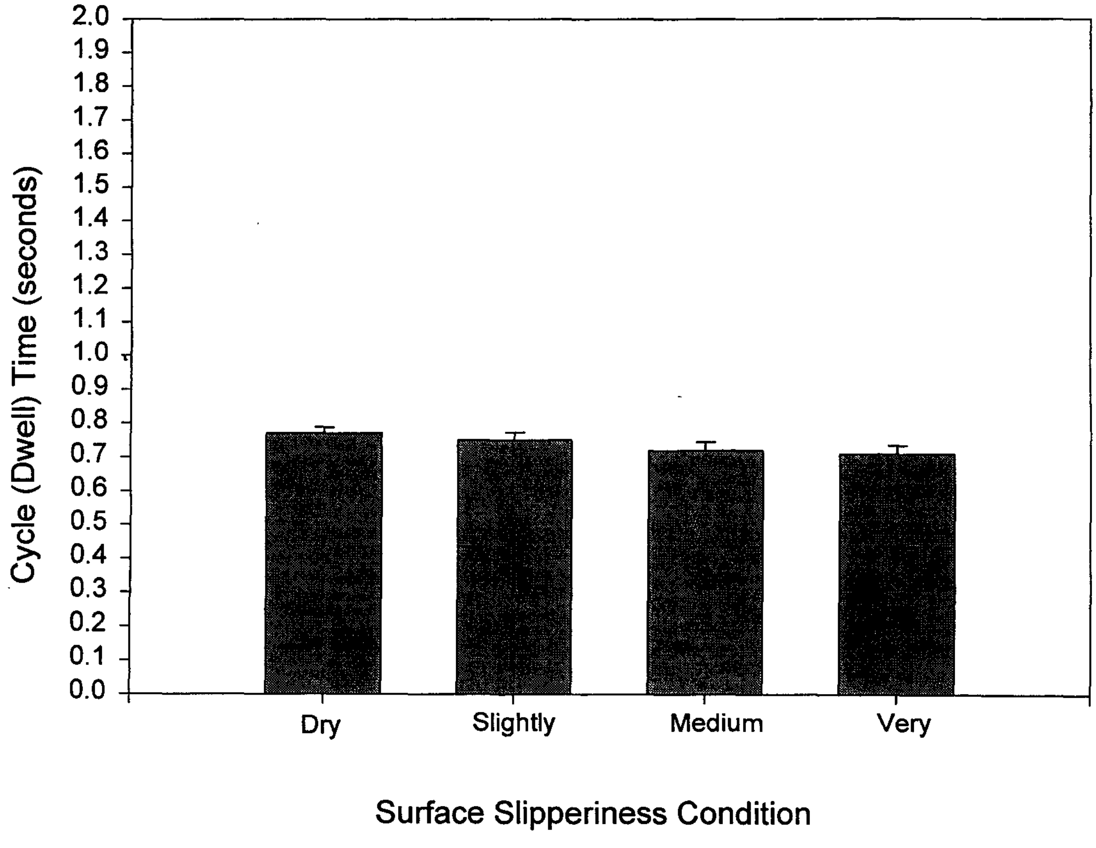


Figure D-14

Mean values of anterior-posterior excursion of CP associated with dynamic task performance on various slippery surfaces

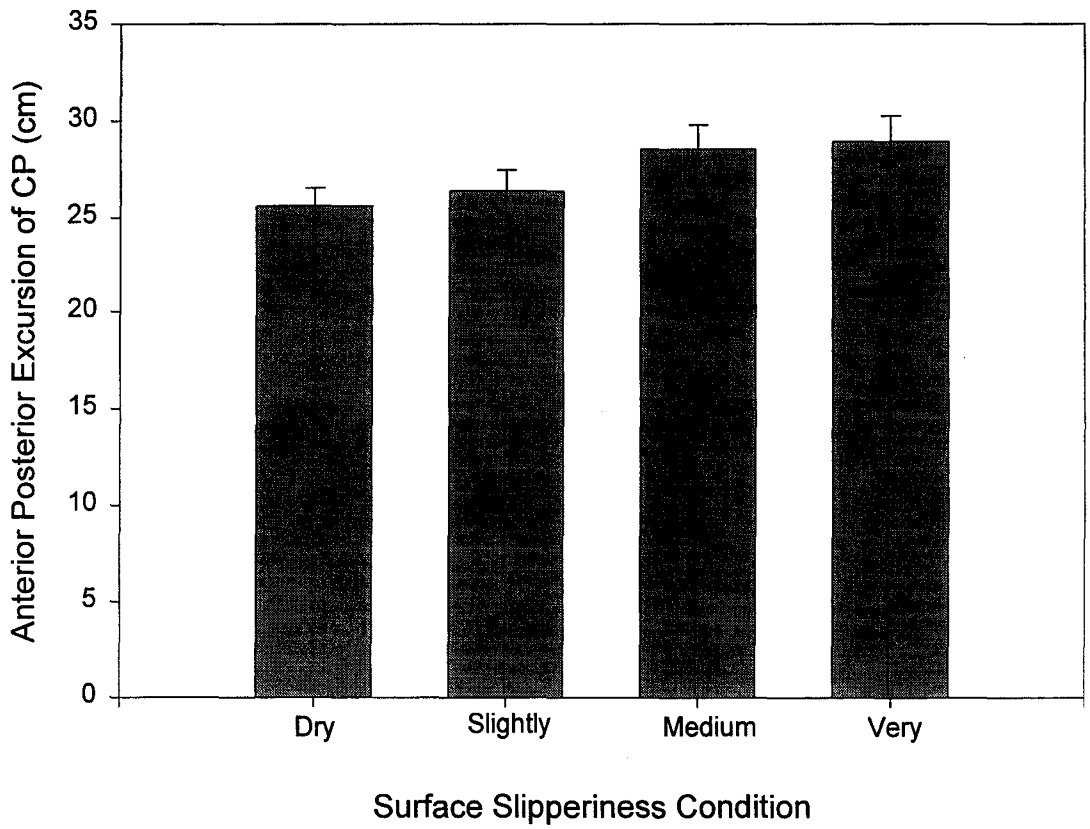


Figure D-15

Mean values of medio-lateral excursion of CP associated with dynamic task performance on various slippery surfaces

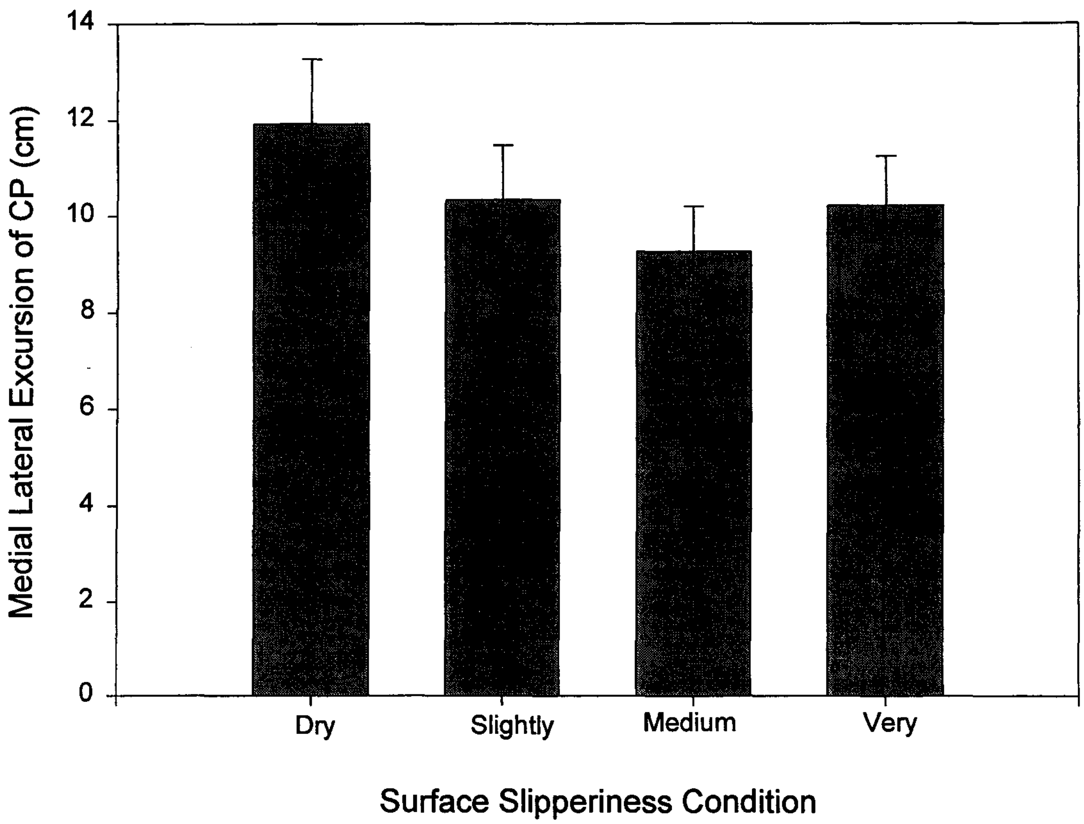


Figure D-16
Mean values of minimum utilized COF associated with dynamic task performance on various slippery surfaces

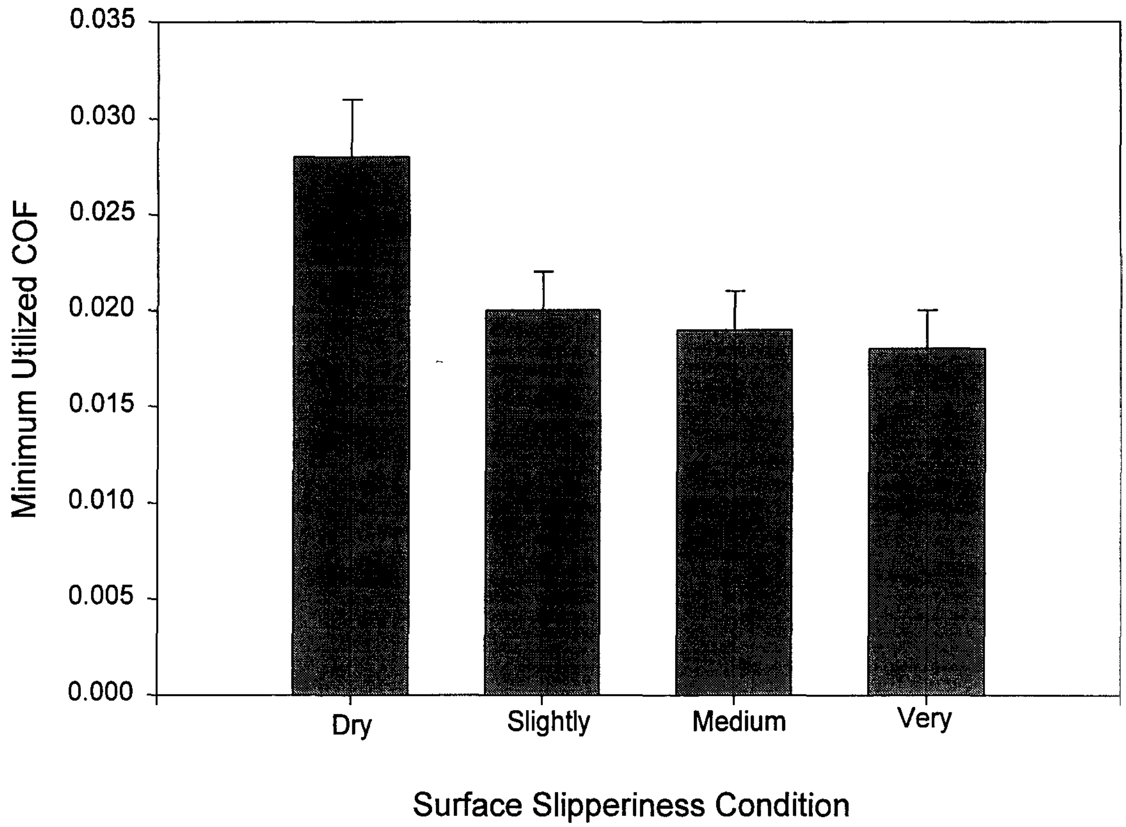


Figure D-17

Mean values of maximum utilized COF associated with dynamic task performance on various slippery surfaces

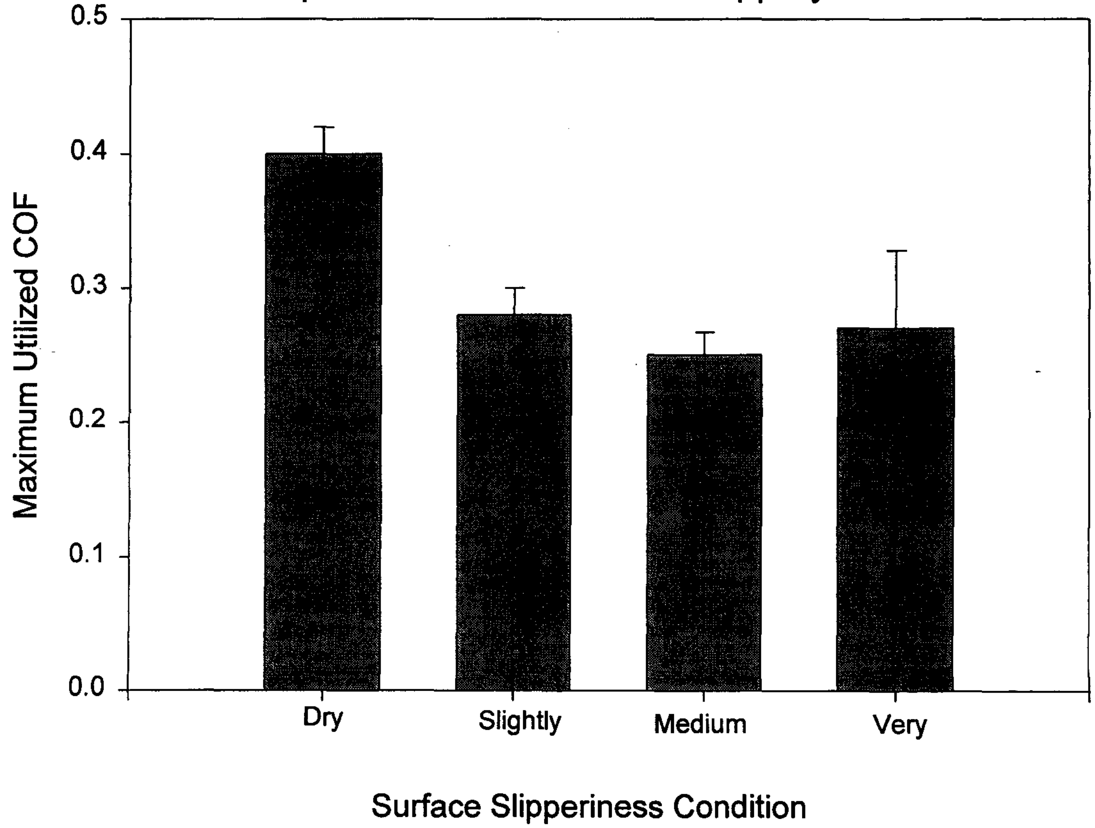


Figure D-18
Sliding Distance Distribution vs. Surface Slipperiness during Straight Walk

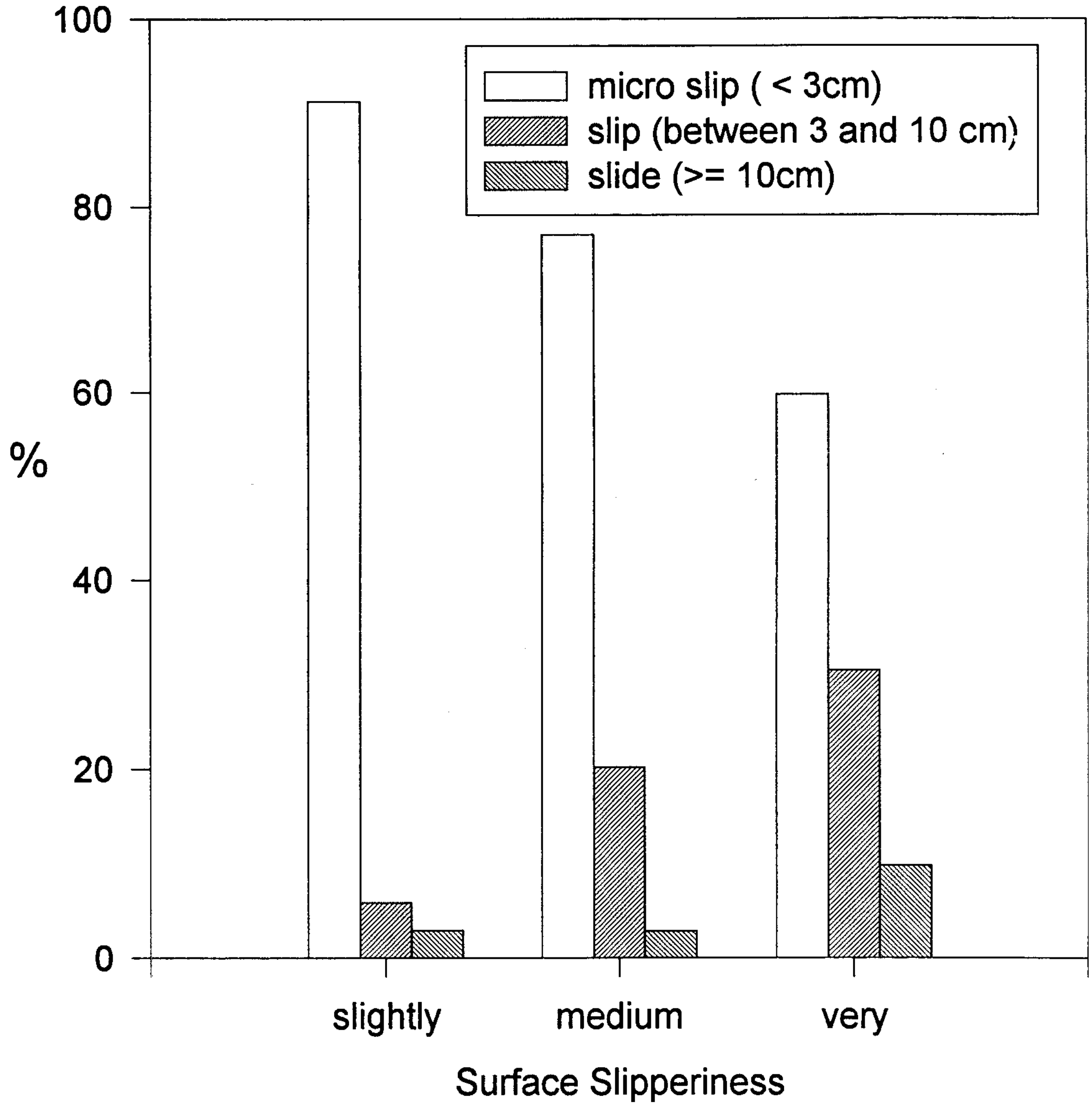


Figure D-19:
% of slip incidents per each PSOS rating for all gait tasks

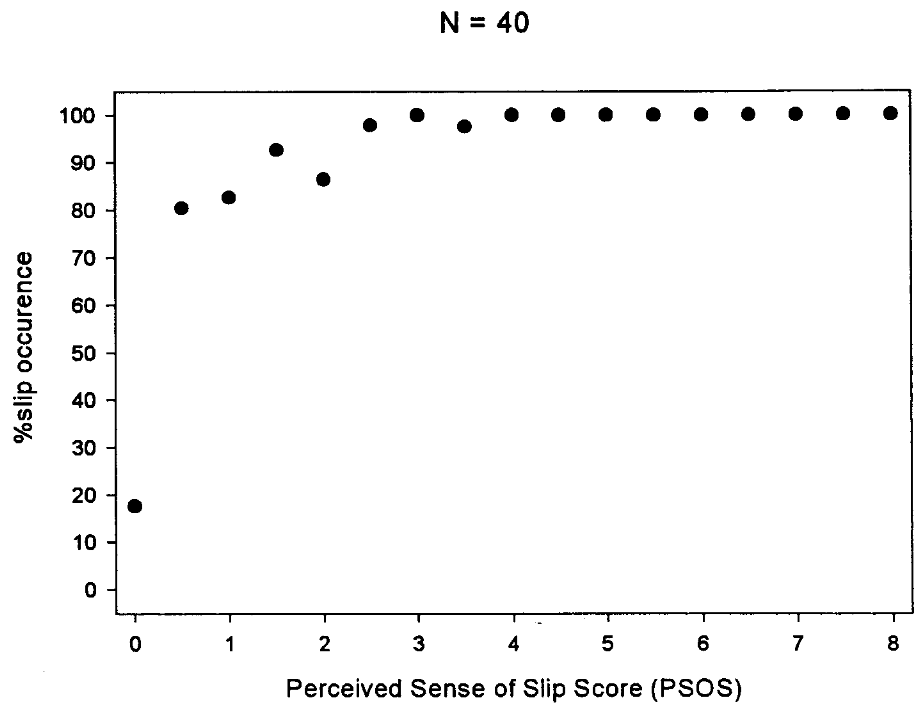


Figure D-20:

% of slip incidents per each PSOS rating for gait tasks on straight path without weight

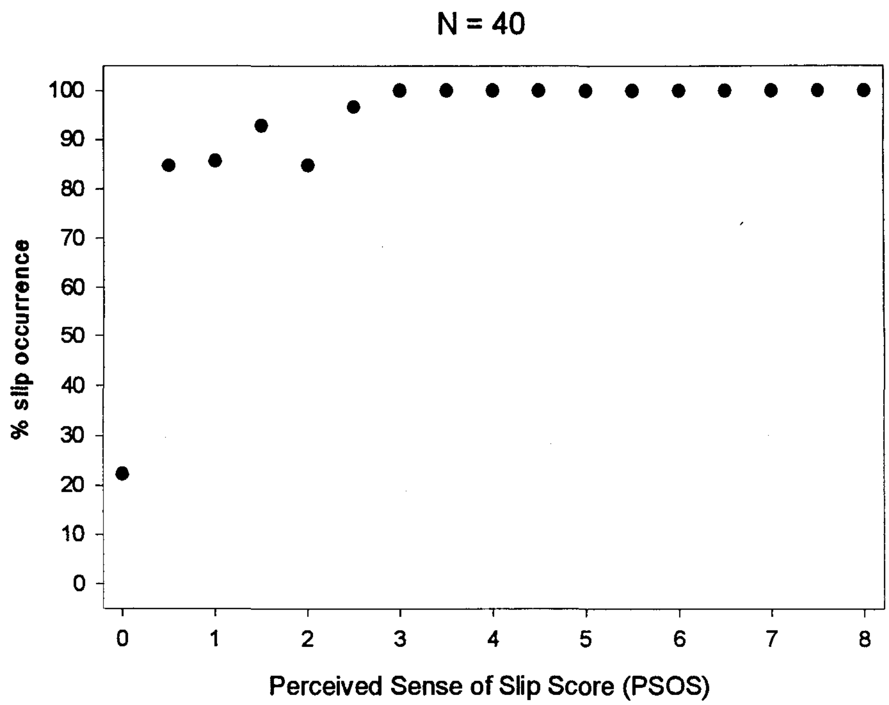


Figure D-21:
% of slip incidents per each PSOS rating for gait tasks on turning path without weight

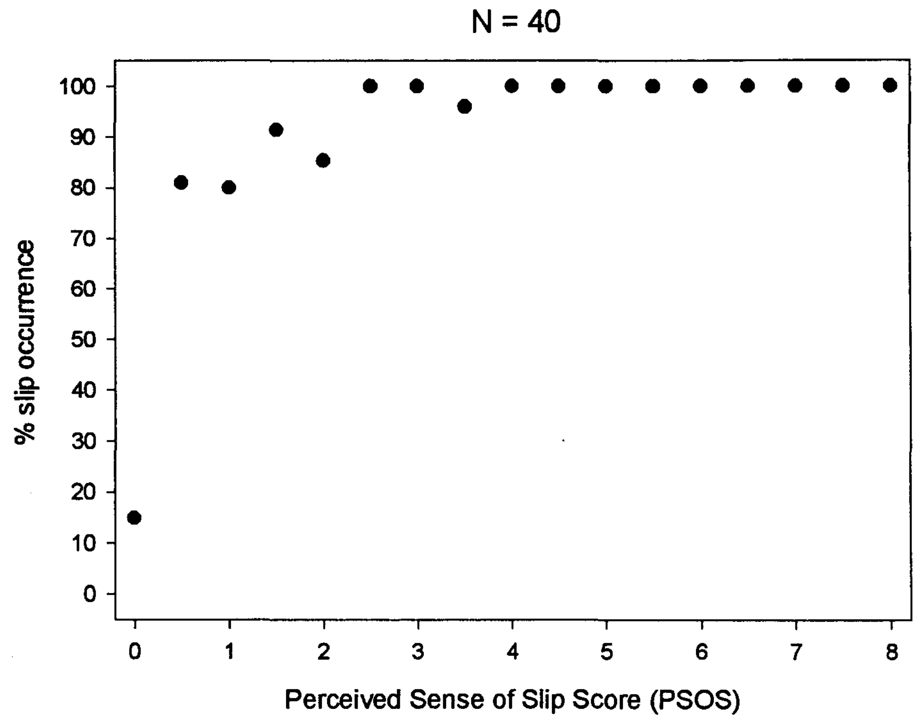


Figure D-22:
% of slip incidents per each PSOS rating for gait tasks on straight path with weight

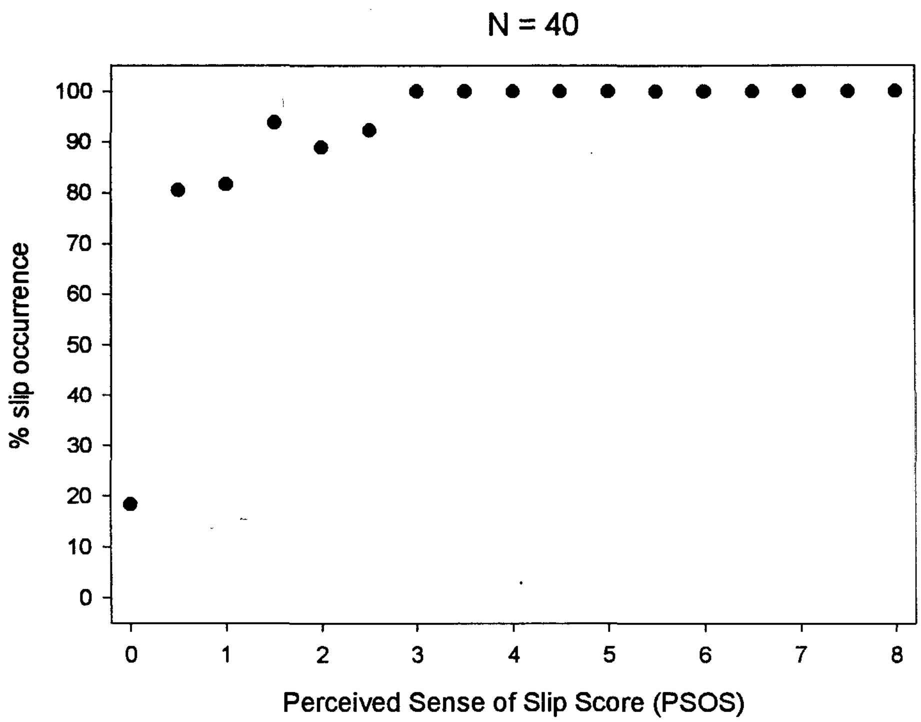
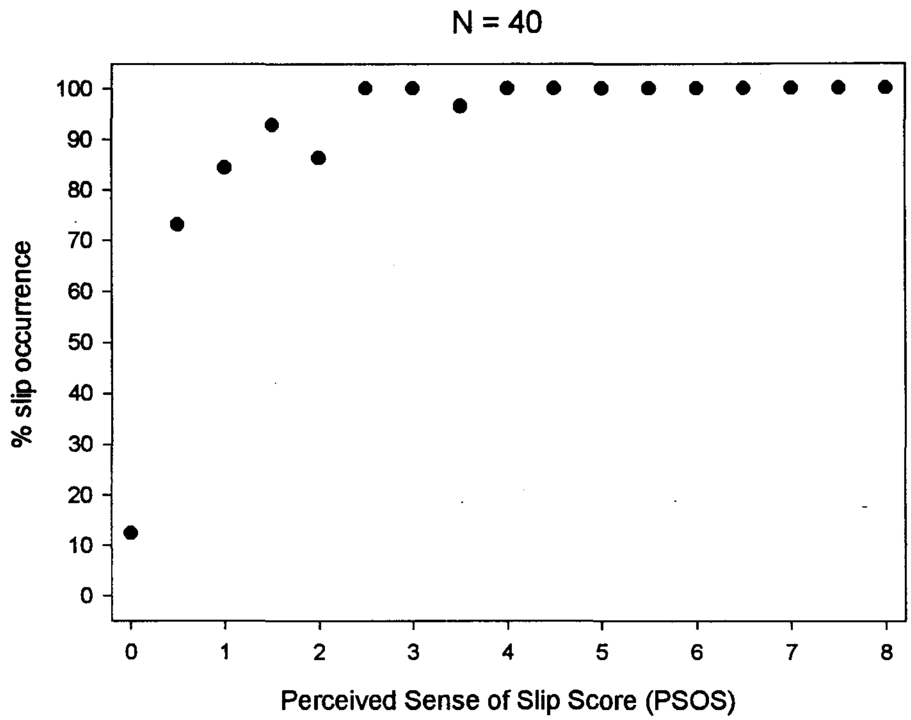


Figure D-23:
% of slip incidents per each PSOS rating for gait tasks on turning path with weight



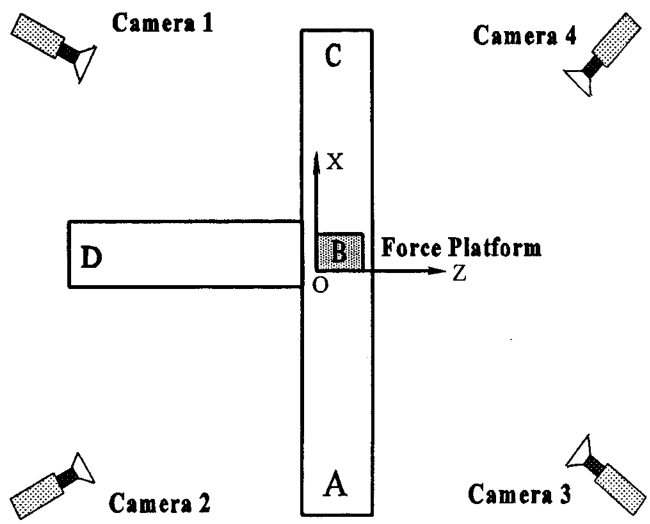


Figure D-24: Set up of gait test and coordinate system

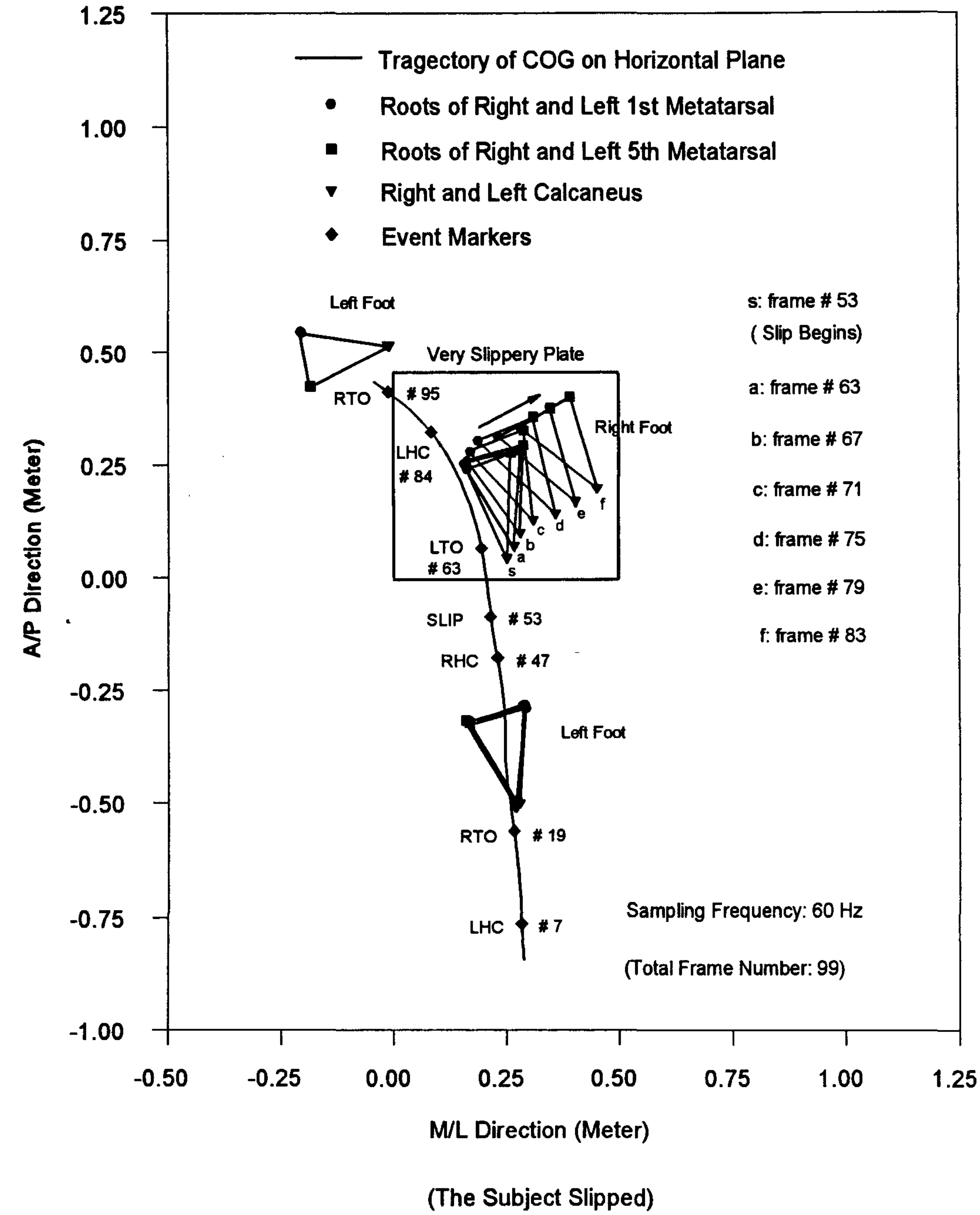


Figure D-25
Data from one subject showing the relative position of COG_H and supporting feet when negotiating a turning path on a very slippery surface

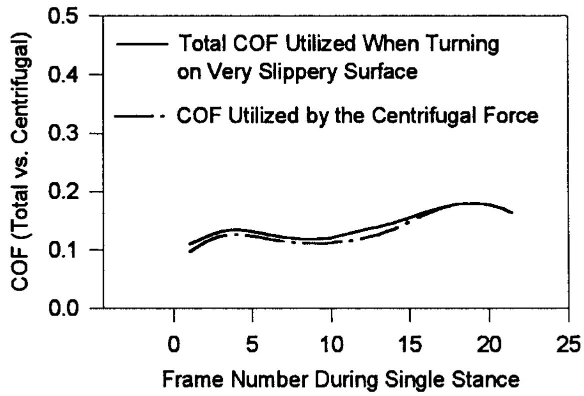


Figure D-26:
Total utilized COF versus COF utilized by the centrifugal force (data of one trial)

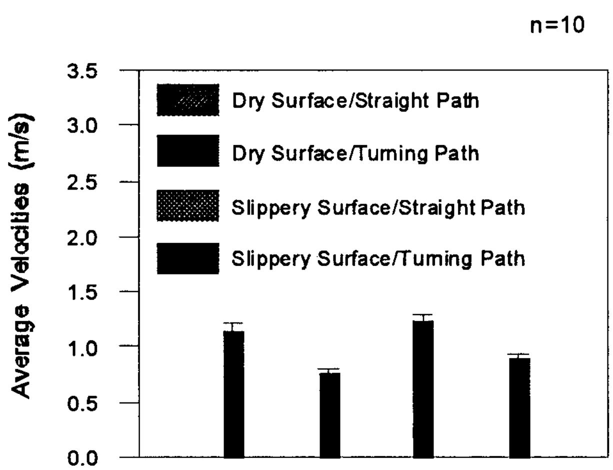


Figure D-32
Average COG horizontal velocities during single stance

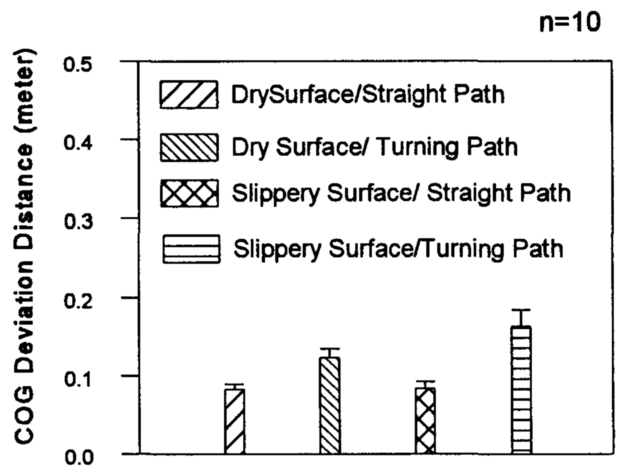


Figure D-27

Average COG_H deviation distance during single stance period

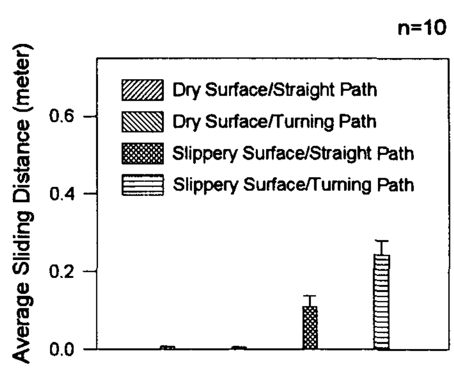
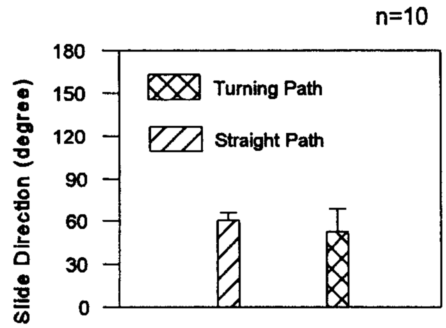
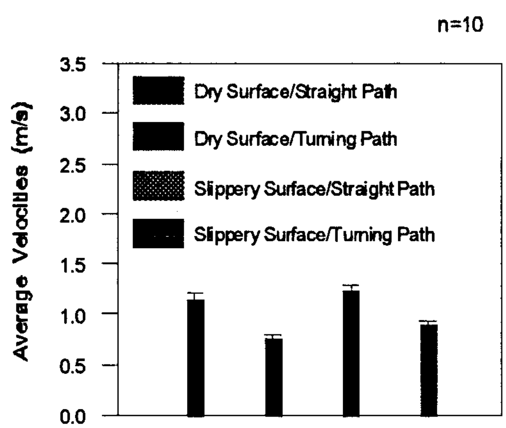


Figure D-28

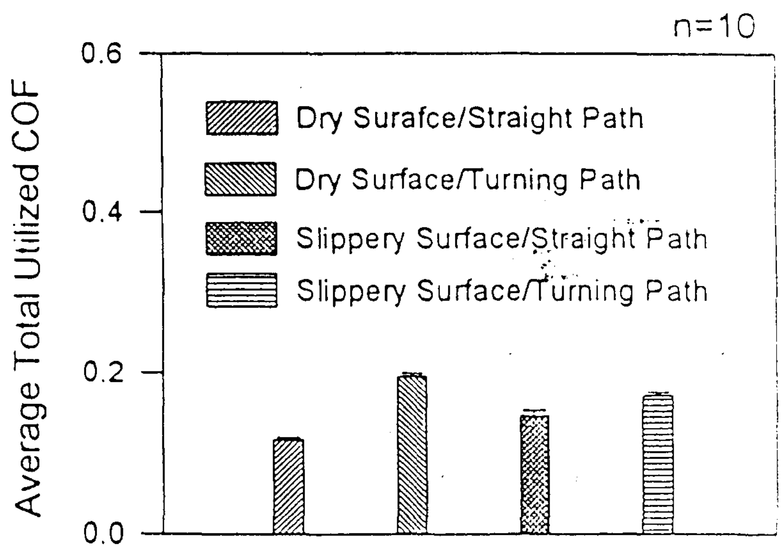
Average sliding distance while negotiating different paths on different surfaces



D-29: Average slide directions while walking on a very slippery surface



D-30: Average total utilized COF versus COF utilized by the centrifugal force



Average total utilized COF.

Figure D-31
Average total utilized COF for different surfaces

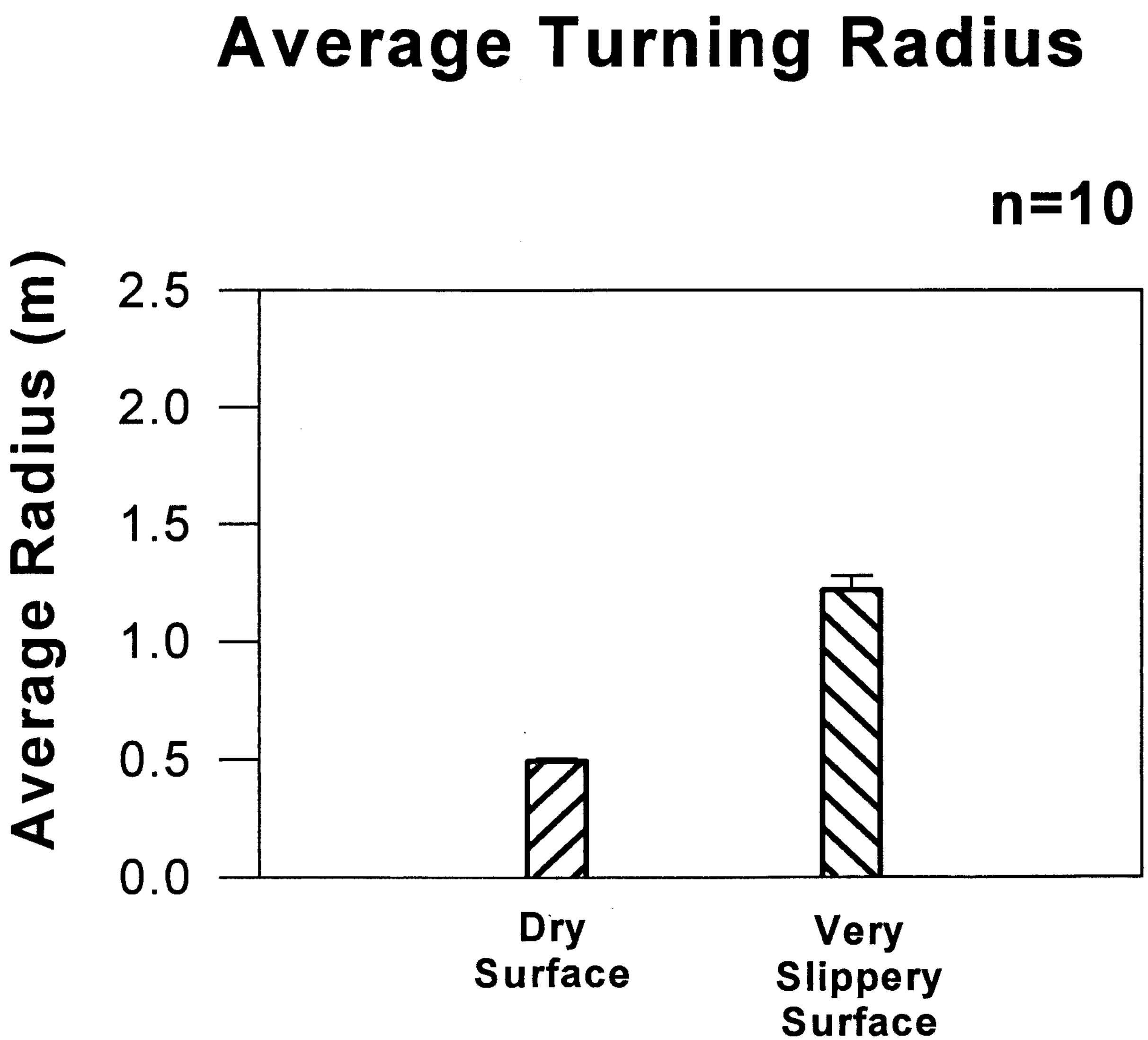


Figure D-33: Average turning radii of negotiating a turning path on dry and slippery surfaces

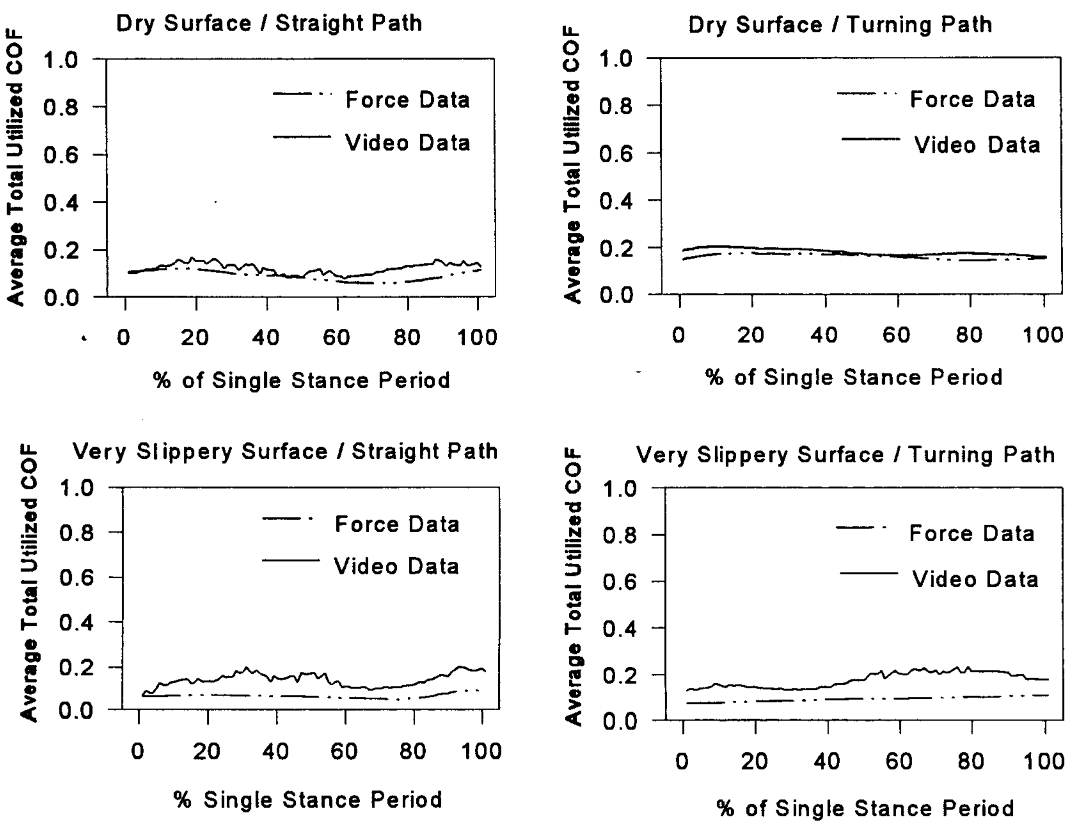


Figure D-34
Comaprison of the total utilized COF calculated from video data versus that from the force plate data.

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LIST OF CURRENT AND POSSIBLE FUTURE PUBLICATIONS

Current Publications

Wang B., Bhattacharya, A., Bagchee, A., and Wang, W., "Kinematic Methods for quantitating loss of balance while negotiating a curved path on a slippery surface" **J. Of Testing and Evaluation** Vol. 25, No.1, January 1997, pp 135-142.

Shiow-yi Chiou, Bhattacharya, A and Succop, P.A, "Effect of workers' shoe wear on objective and subjective assessment of slipperiness. **American Industrial Hygiene Journal** 57: 825-831, 1996.

Current Conference Abstract:

Lai, C. Bhattacharya A. and Chiou S., "Objective and subjective assessment of floor slipperiness with worn-out workshoes" Presented at the American Industrial Hygiene Association Conference, Washington D.C., May 18-24, 1996.

Chiou, S. Bhattacharya A. and Succop, P.A. "Evaluation of workers' postural stability on slippery surfaces during task performance" Presented at the American Industrial Hygiene Association Conference, Washington D.C., May 18-24, 1996.

Wang B., Bhattacharya, A., Bagchee, A., and Wang, W., "Kinematic Methods for quantitating loss of balance while negotiating a curved path on a slippery surface" Presented at the International Symposium on Slip Resistance: The Interaction of Man, Footwear and Walking Surfaces" National Institute of Standards and Technology, Gaithersburg, MD, October 30-31, 1995.

Unpublished Thesis/Dissertation:

Shiow-yi Chiou, "Effect of Worker's Shoe Wear/Tear on Coefficient of Friction", MS thesis, Department of Environmental Health, University of Cincinnati College of Medicine, Cincinnati, OH, 1994.

Shiow-yi Chiou, "Assessment of postural instability during semi-dynamic task performance on slippery surface" PhD dissertation in the Department of Environmental Health, University of Cincinnati College of Medicine, Cincinnati, OH, 1996.

Wang Bingshi, "Kinematic methods for quantitating loss of balance while negotiating a curved path on slippery surface" PhD dissertation in the Department of Mechanical, Industrial and Nuclear Engineering, University of Cincinnati College of Engineering, Cincinnati, OH, 1996.

Future

Shiowyi Sharon Chiou, Bhattacharya, A, and Succop, P.A., " Evaluation of workers' perceived sense of alip and effect of prior knowledge of slipperiness during task performance on slippery surfaces" (manuscript in preparation).

Lai, C. F, "Effects of environmental lighting, shoe wear/tear and load carriage on slip-resistance of the shoe-floor interface" PhD dissertation in prepartion.

Lu Ming-Lun, "The relationship between body center of gravity and center of pressure movement patterns during task performance" MS thesis in preparation.

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Appendix A

SLIP STUDY - SESSION INTERVIEW

NAME:__________ SUB ID:_____ DATE:________ SESSION#:_____

1. Asleep:_____ Woke:_____ #hrs slept: _____

2. Sleep uninterrupted: 1=yes 2=no 3=unknown _____

3. Time ate last:_____ #hrs since last meal _____

4. Caffeine last 12 hours: 1=yes 2=no 3=unknown _____

   type: 1=coffee 2=tea 3=soda 4=cocoa 5=combo 6=none _____

   amount: enter # ounces _____

5. # cigarettes smoked in last 12 hours: _____

   time last cigarette: _____

6. Sick in the last week: _____
   hx_____
7. Any recent surgery including dental: _____
   hx_____
8. Ear infection since last visit: _____
   hx_____
9. Currently taking any meds (last 24 hrs): _____
   hx_____
10. Injuries to head neck or back since last visit: _____
    hx_____
11. Have you fallen on the job since last visit: _____
    hx_____
12. In the last 24 hours, strenuous activity: _____
    hx_____
13. Stressful events at home or job in last 24 hrs: _____
    hx_____
14. Alcohol consumption in the last 48 hours: _____

    type: 1=beer 2=liquor 3=wine 4=none _____

    amount consumed: enter # ounces _____

15. Recreational drugs ingested in the last 24 hours: _____

    type: 1=marijuana 2=cocaine 3=narcot. 4=other 5=none _____

    freq./amount in last 24 hours _____

16. Did you work in the last 12 hours: _____

    # hours worked _____
    type work_____
17. Have you changed shifts in the last week: _____

    last shift worked _____

    current shift _____

18. BP_____ Pulse:_____

APPENDIX B

FINAL MARKER SYSTEM FOR HUMAN BODY ANALYSIS

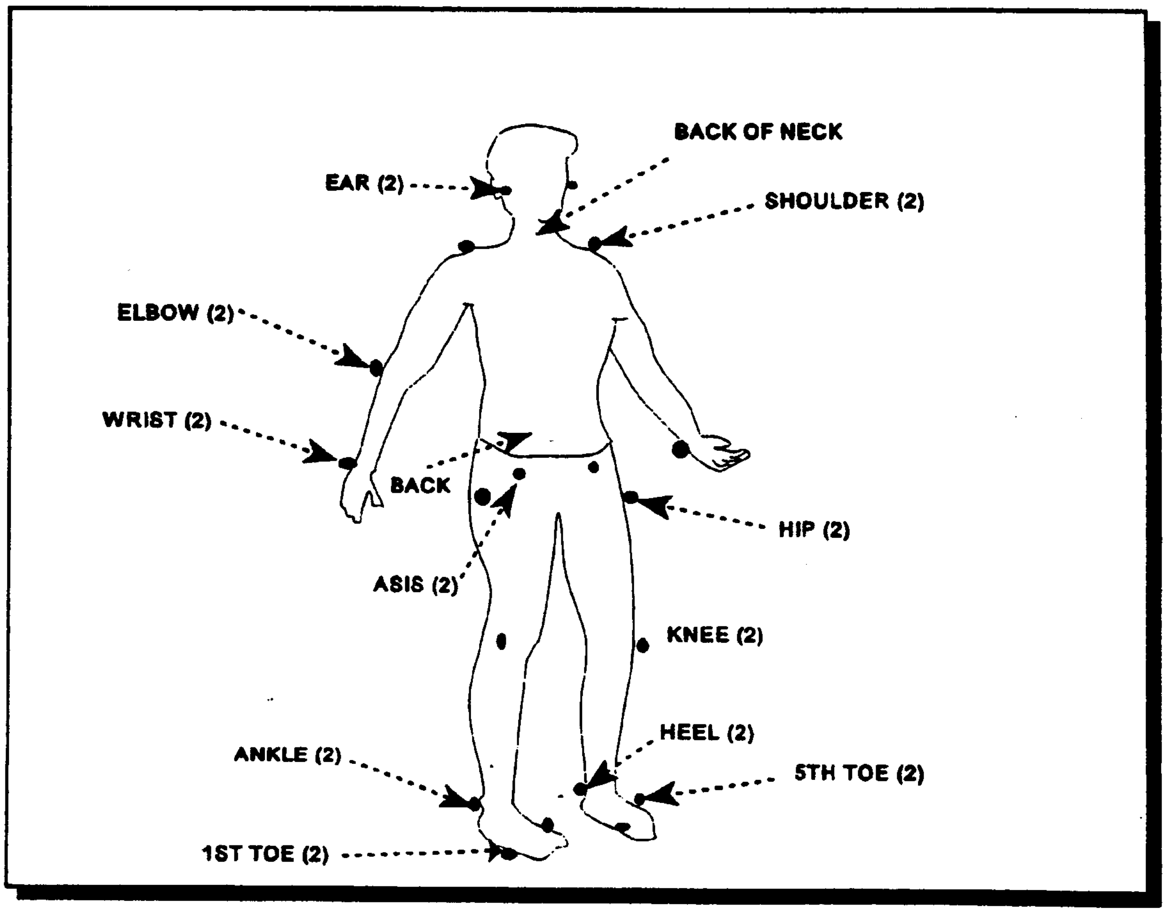


Figure B-1

APPENDIX C

SLIP STUDY CHECKLIST - SEQUENCE OF EVENTS

Subject Related:
- session forms with ID and files names
- testing attire including shirt, shorts, wrist bands
- Blood pressure equipment
- Heart Rate Monitor
- Shoes old & new
- safety harness
- Hair clamps
- F-Scan equipment (sensors trimmed and in shoes, & belt)
- Peak Markers & tape

Equipment SET-UP

Peak System

- Check the force plate connection: cable to amplifier, and amplifier to peak system
- Check cables from video camera: each camera has two output cables one is for video data output and another one is for genlock (camera one does not have genlock). These cables should be connected with the Black Box properly.
- Check the power connection for each set of camera: power for camera and power for IR light.
- Turn on the power for peak system: computer, VCRs, and the Black Box.
- Turn on the sync code.
- Put couple of markers on the force plate, and turn on the power for camera and IR light and check picture from all cameras.
- If the camera is pointed at wrong area, or not focused properly, or the picture is not light enough because the aperture changed position, readjust the camera.
- Adjust the camera until whole body of the subject when he/she stands on the plate, one step before, and one step after the plate is visible. The camera should create a sharp contrast between the reflective markers and the background.
- To calibrate the system use the 17-marker frame. After the calibration frame is set, check the level meter and the picture from all cameras. Be sure all the 17 markers can be seen from all cameras.
- Select four video tapes (be sure they have enough length left) and put them into the VCRs.
- Balance the force plate amplifier.
- Let the VCRs recording for about 3 minutes, then begin to record a trial. Every time the VCRs are turned off or the system is shut down, let the VCRs record for about 3 minutes before recording a trial. When recording calibration data, be sure all the operators and the subject are out of the view of cameras.

-Before collect a trial check all markers on the subject and the test condition.

Appendix-D

Four Camera Videographic System:

This system is designed by Peak Performance Inc. and consists of four 60 Hz cameras which allow measurement of body joint movements in three dimension.

Figure 1 shows the orientation of the cameras with respect to the pathway for gait testing.

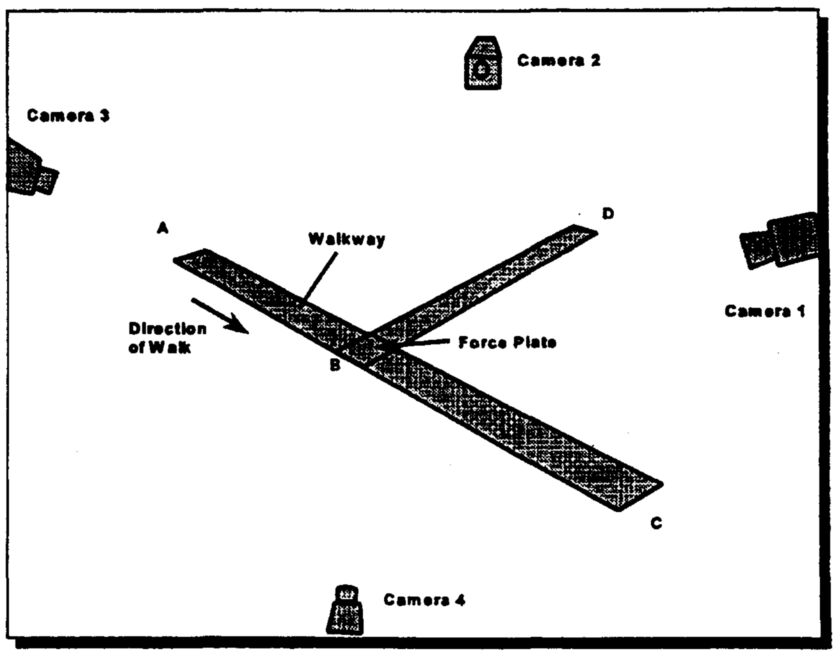


Figure 1

Each subject walks a T-shped walkway shown in Figure 2. An AMTI force plate (model OR6-6) is placed, flushed with the walkway floor, in the middle of the walkway at B. The distances AB, BC, and BD are approximately 8 feet in length, allowing adequate walk-up and follow-through distances for the subjects. An overhead track and pulley system provides a safety harness along the full length of the pathway. The subject either walks in a straight line from A through B or takes a left turn on the plate and walks along ABD.

The signals from the AMTI force platform are fed into the AMTI amplifier and then into the Analog Sampling Unit (ASU) of the Peak. The analog signals are captured using a Data Translation 2821 A/D board installed in a 486/33 pc desktop computer. Calibration of the system is performed by using the weight of the subject prior to the data collection. Electronic balancing of the channels is done by tweaking the corresponding channel pods on the AMTI amplifier. The baselines are read by the computer prior to each data collection, and the output is converted to real-world units before storing the data. The Peak Analog Sampling Module provides several options relating to the force platform data collection. These include (1) Sampling frequency; (2) Pre-trigger sample time or number of samples; (3) Post-trigger sample time or number of samples; (4) Channel number providing the trigger value; (5) Trigger threshold.

The frequency of data collection needs to be a multiple of 60 frames/sec from the video data. The collection frequency used in our setup is 60 Hz. The pre-trigger and post-trigger collection time have been set at 0.3 and 3.0 seconds, respectively.

The Peak system consists of four video cameras (as discussed above), synchronization unit, and four super video recorders (Panasonic model 1960). Three cameras are electronically hooked up to be slaves to a master camera through genlock system. A SMPTE code is generated in the synchronization unit and is superimposed on each of the four camera views, that are then recorded on the four recorders. Retro-reflective markers are then placed on anatomical positions of the body to be visible in the video recording. To enhance the marker visibility, especially in poor light conditions (< 0.2 footcandles), an infrared light source (250 watts) is attached next to each of the four cameras. Specially designed lens systems, that have higher sensitivity to IR light, allow the markers to appear brightly contrasted from the background allowing them to be tracked by the software.

An external pulse can be used to trigger the data collection. In our setup, the external sync signal is provided by the FSCAN pressure sensor device setup computer. The external sync signal burns a mark on each of the video views. During digitization, these synchronization marks can be used to time-match the video data with the FSCAN data. A schematic layout of the Peak/FSCAN system is shown in figure 2.

Calibration of Peak System:

Spatial calibration of the camera system is required whenever the camera view is adjusted or altered (focusing, panning, and zooming). The calibration of the Peak video system is performed by using a framework of spherical markers provided with the system. The spatial placement of the 17 makers on this frame are accurately known. Video data from the four camera views of this calibration frame is collected for several seconds. Each of the four views of the 17 markers is then digitized. A linear transformation matrix is formed by the program that combines the four camera views to calculate the three-dimensional coordinates of any given marker. Using the remaining markers (those not used in the matrix calculation), the error in detection of the marker positions is then performed, and the results are printed out by the program. If the error percent is greater than 1.0%, the calibration process is repeated until the desired level of accuracy is achieved.

Data Collection

Data collection involves several independent steps, as described below:

Camera setup: The camera views are adjusted to ensure optimized field of view during the time interval of data collection. The data collection is performed for approximately 3.0 seconds, starting at the penultimate step of the subject stepping on the plate. Proper focussing is necessary to ensure clear video pictures, that are critical for automatic digitization process.

Calibration: The calibration frame is then assembled and placed in the middle of the space in which digitization will be performed. The frame sits on a tripod provided with level meters to ensure that the x-z plane is horizontal. Several minutes of video data is then collected to complete the calibration process.

Datasheet preparation: A datasheet with the proper sequence of tasks is prepared with corresponding filenames. The filename is coded to include the subject ID, conditions of the task, visit number, and sequence.

Subject preparation: The subject is given a brief understanding of the experimental tasks. S/he is then provided with brief clothing fitted with velcro patches for marker placement to be worn during the testing. Twenty four markers are then placed on the body at anatomical positions, as shown in figure B-1 in Appendix B.

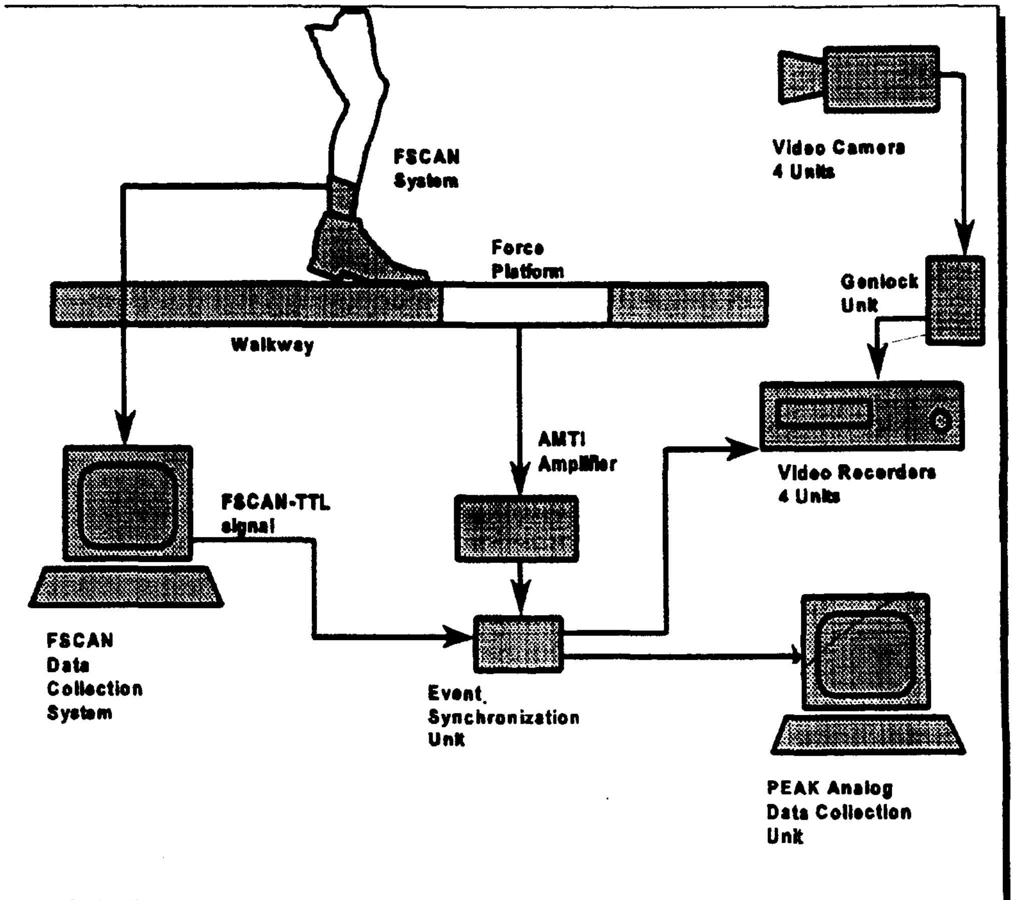


Figure 2

This system can track three dimensional coordinates of passively illuminated markers placed on the body joint. As our study protocol requires testing in both bright light and poor light the Peak system is designed to work under both lighting conditions. Under poor lighting conditions, the markers are illuminated with specially designed infrared lights. The entire system has been properly installed, tested and validated in our laboratory. Several of our staff members and P.I. have been trained in the use of this device by the Peak's factory technician. Because of the specialized nature of this equipment, it requires training by the factory personnel. This system is designed to synchronize data from all four cameras, insole pressure measurement device and the force platform. The synchronization process required several pilot testings and development of specialized software to accomodate the special requirements of our project's need. These synchonization activities were carried out by our staff with input from the hardware company.

SETTINGS

VCR's 1-4
Audio Rec Level: R, at least 3dB
Normal
OSD: On
MONO: Off
DIGITAL TRACKING: On
S-VHS: On
MTS: MTS
TAPE SELECT: ~T120
SIMUL: Off
INPUT SELECT: Line 1

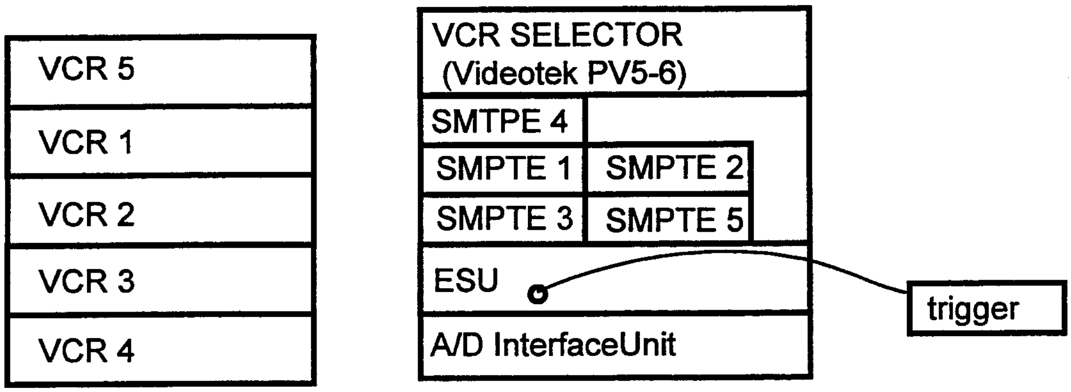
VCR 5
Audio Rec Level: R, at least 3dB
TAPE REMAIN: Norm
AUDIO REC: Manual
SPEED: SP
MPX FILTER: On
INPUT SELECT: Line 1

SMPTE UNIT 1
POWER: On
MODE: Gen
DATA: TC
V-pos
V-size
H-pos
H-size
(V-pos, V-size, H-pos, H-size:) operator can adjust

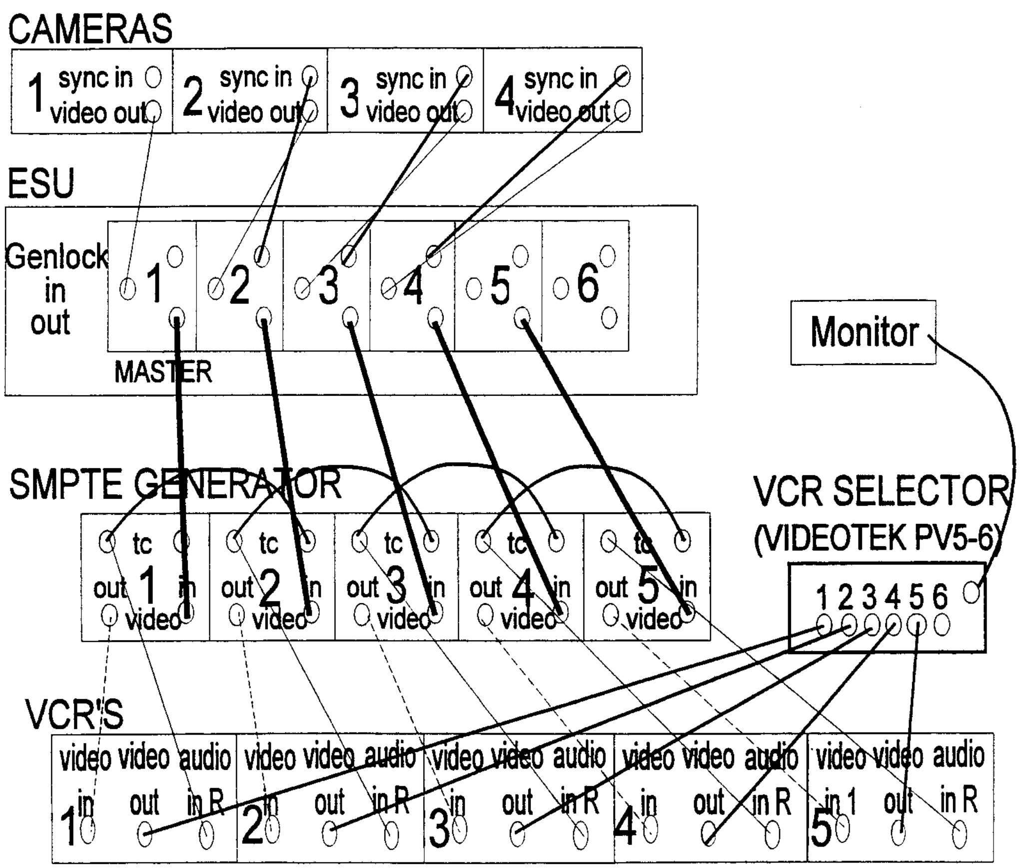
SMPTE UNITS 2-5
same except MODE: RDR

ESU
Video event indicator: operator can adjust color and vertical and horizontal position.

Front View



Back View



APPENDIX-E
Perceived Sense of Slip and/or Fall (PSOS)

1. How much did you feel yourself slip (i.e. loss of foot traction)?

a little		some		a lot
- 0 -	-0.5-	- 1 -	-1.5-	-2-

2. Did you have any difficulty in maintaining balance (how much did you or your muscles compensate for your movement)?

a little		some		a lot
- 0 -	-0.5-	- 1 -	-1.5-	-2-

3. Did you feel at any time that you would slip?

a little		some		a lot
- 0 -	-0.5-	- 1 -	-1.5-	-2-

4. What would you say was the overall difficulty of this task?

a little		some		a lot
- 0 -	-0.5-	- 1 -	-1.5-	-2-

APPENDIX- F

FSCAN system

The FSCAN system consists of: (1) pressure-sensitive insole sensors, (2) a light-weighted transducer units which are strapped to the subject's legs into which the sensors fit, (3) a coaxial cable which connects the transducer to the computer, and (4) software for data collection and analysis. The testing protocol of insole pressure distribution data collection using FSCAN system is presented in sequence as follows:

Sensor Preparation: A pair of new sensors are trimmed carefully according to the subject's shoe size. Sensors are trimmed slightly smaller than her/his actual shoe size to avoid causing any wrinkles while the subject is wearing them inside the shoes. All subjects wear the same type of socks provided by the laboratory.

Once the subject wears the sensors and they are connected with transducers, the conditions of the sensors are carefully checked by examining the FSCAN data collection windows on the computer monitor. A red dead spot or dead row which would not show any pressure (color) changes as the subject moves her/his feet around indicates that sensors were not properly placed inside the shoes. Under this circumstances, sensors have to be taken out from the subject's shoes and adjusted until the dead spots or rows disappear. If it fails to adjust the sensors, then new sensors have to be used.

Pre-Calibration: Before any data are collected, calibration of the sensors has to be done to ensure accurate pressure reading with the FSCAN system. The sensor on each foot is calibrated separately according to the subject's body weight. Each sensor is calibrated by asking the subject to stand on the foot corresponding to the sensor not being calibrated. Then, have the subject reverse feet so the subject is standing only on the foot of the sensor being calibrated. After approximately two seconds, press *ENTER* as directed by the computer monitor. Same steps are repeated for calibrating the other sensor.

Validation of the Calibration: The accuracy of the calibration can be checked immediately after the calibration is done by making and reviewing a recording. The subject is asked to walk in place slowly with one foot on the floor at a time. The calibration of the sensors can be verified by examining the graph of force changes versus time. If the difference between peak forces reached on each foot is 10% or less, the calibration is acceptable.

Determination of the Pressure Frame encompassed by the feet: In order to determine the actual area of the sensors that are under pressure (which is also the outline of the footprint) a recording is made before the data collection on subjective assessment of slipperiness begins. Subject is asked to lean forward by standing on her/his toe area and then lean backwards by standing on heel area according to the command of the experimenter. The leaning forward and backward movements are repeated several times until the five second data collection period is over. A special software developed by our laboratory can plot the outer perimeter of the pressure profiles depicting the outlines of the subject's feet. These footprint outlines are needed for future analysis.

Post Calibration: At the end of the experiment day, a post calibration is performed using the same procedures as used for validation of calibration described in the previous paragraph.

FSCAN CHECKLIST

- Sensors are trimmed properly according to subject's shoe size. Place the sensor in each shoe.
- Attach the cuff units to the velcro ankle bands. The velcro ankle bands are used to hold the cuff units in position at the subject's ankles.
-Connect the sensor to each cuff unit.The dial on the front of the cuff unit is used to open the unit for sensor insertion and to lock the sensor tab in place.
-Connect the cuff units with the interface board of the computer by using cables.
-Use the waist belt to hold the cables above the ground and out of the subject's way.
-Activate the FSCAN software. Two pressure display windows should show up and the pressure window status indicator, which appear to the bottom of each window, should indicate "Sensor OK".
-Click on the COM (comment) button which appears to the left of each window to type in subject's information such as ID, name, weight, and height.
-Click on OPTIONS in the menu bar. Click on CHANGE UNITS in the pull-down. Choose **P=kPa** and **F=Newton**.
-Click on OPTIONS. Click on SET RECORDING PARAMETERS in the pull-down. Check the following parameters:

Frequency (frames/sec): 60
Duration (sec): 4
√ External Sync: COM1

(make sure that the external sync:com1 is checked "√")
-Click on CALIBRATION in the menu bar. Click the FORCE CALIBRATION in the pull-down menu.
-In the highlighted field of the force calibration window, type the subject's weight. Since we choose "newton" as the force unit, the weight should be converted into newton. (newton = weight in kg x 9.8)
-Have the subject **raise his/her left foot** and prepare to click on the OK button.Then, have the subject stand on both feet and click OK.
-Have the subject **raise his/her right foot** and prepare to click on the button. Then, have the subject stand on both feet and click OK.14. Click on FILE in the menu bar. Save the calibration files.
-Now, you are ready to collect data. Press F2 to start data recording.
-Click on FILE in the menu bar. Save the recording after each trial.
-Click on WINDOWS in the menu bar. Click the REAL TIME before next data collection.
-Repeat steps 15-17 until the whole experiment is over.

APPENDIX G

Experiment design of Gait Test

Dry Surface		Slightly Oily Surface		Medium Oily Surface		Very Slippery	
New Shoe	Radomly Pick up 4 Combinations from the Total of 8 Combinations of : Light (Good, Poor); Weight in Hands (Yes, No); Path (Straight, Turn).	New Shoe	Radomly Pick up 4 Combinations from the Total of 8 Combinations of : Light (Good, Poor); Weight in Hands (Yes, No); Path (Straight, Turn).	New Shoe	Radomly Pick up 4 Combinations from the Total of 8 Combinations of : Light (Good, Poor); Weight in Hands (Yes, No); Path (Straight, Turn).	New Shoe	Radomly Pick up 4 Combinations from the Total of 8 Combinations of : Light (Good, Poor); Weight in Hands (Yes, No); Path (Straight, Turn).
Old Shoe	Radomly Pick up 4 Combinations from the Total of 8 Combinations of : Light (Good, Poor); Weight in Hands (Yes, No); Path (Straight, Turn).	Old Shoe	Radomly Pick up 4 Combinations from the Total of 8 Combinations of : Light (Good, Poor); Weight in Hands (Yes, No); Path (Straight, Turn).	Old Shoe	Radomly Pick up 4 Combinations from the Total of 8 Combinations of : Light (Good, Poor); Weight in Hands (Yes, No); Path (Straight, Turn).	Old Shoe	Radomly Pick up 4 Combinations from the Total of 8 Combinations of : Light (Good, Poor); Weight in Hands (Yes, No); Path (Straight, Turn).

The experiment is blocked by the surface conditions. Each test day (session) there is only one surface condition, and two kinds of shoe conditions. Under each shoe condition, four test conditions are radomly selected from the total of eight combinations of light, weight in hands, and paths. Each test condition has one repetition. So under each surface and shoe condition there are eight trials. The test conditions and repetition order are radomized during test.