FINAL PERFORMANCE REPORT

PREDICTIVE MODELING OF SLIPS AND FALLS

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Principal Investigator

Rakié Cham, Ph.D.

Organization

Department of Bioengineering

749 Benedum Hall

University of Pittsburgh

Pittsburgh, PA 15213

Date

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1.0 ABSTRACT

Slip and fall accidents, caused by complex and interacting environmental and human factors, are a major ergonomic concern. In order to address the long-term goal of reducing slip/fall accidents, specific objectives were identified: 1) investigate changes in gait biomechanics when anticipating slippery environments, 2) describe foot dynamics during slip events, 3) compare center of pressure trajectory and joint biomechanics between no-slip and slip/fall events, 4) investigate gait biomechanics related to slips when carrying a load and 5) describe and possibly model the relationship among the probability of slip/fall, frictional requirements of walking and available friction. Ground reaction forces and sagittal plane body/foot motion dynamics of 16 subjects walking under various slippery and non-slippery environmental conditions were recorded at 350 Hz. Subjects were asked to walk as naturally as possible even without knowledge of the floor's contaminant condition. In spite of these instructions, subjects adopted postural and temporal gait changes when uncertain of the contaminant condition. These changes in gait patterns were associated with decreases (16 to 33%) in slip potential compared to recordings on known dry surfaces. During slipping experiments, corrective biomechanical reactions occurred from 25 to 45% of stance phase (about 190 - 350 ms after heel contact). These corrective reactions included increased flexion moment at the knee and extensor activity at the hip. The effects of this active knee/hip moment on body motion were reflected in the kinematics in an attempt to bring the foot back under the body and thus recover from a slip event. Load carrying experiments found decreased slip potential compared to free walking, with decreased required friction and more controlled heel contact dynamics. Logistic regression models proved to be useful in describing the relationship between the probability of falls and the difference between required and available friction (COF_{diff}). However, logistic regression functions of COF_{diff} alone did not provide a satisfactory fit of the probability of slip. The inaccurate assessment of the frictional characteristics of the shoe/floor interface is postulated to be the dominant reason for this unsatisfactory fit. This project revealed important biomechanical findings relevant to slips/falls prevention research. In addition, the research indicated that current slip resistance testing devices might be inadequate to predict slips.

2.0 SIGNIFICANT FINDINGS

2.1 Changes in Gait when Anticipating Slippery Surfaces

In spite of instructions to walk as naturally as possible, anticipation dry trials, during which subjects were uncertain of the contaminant condition (dry, water, soap or oil), produced peak required coefficient of friction ($RCOF_{peak}$) values that were on average 16 to 33% significantly lower than those collected onto known dry floors, thus reducing slip potential. $RCOF_{peak}$ reductions were achieved by adopting postural and temporal gait changes resulting in ground reaction forces decreases. Gait adaptations included reductions in stance duration and loading speed on the supporting foot, shorter normalized stride length, reduced foot-ramp angle and slower foot angular velocity at heel contact. As a result of these adaptations, anticipation of slippery surfaces led to significant reductions in lower extremity joint moments, thus decreasing the strength requirements of walking.

2.2 Foot Dynamics during Slip Events

Foot dynamics recorded on dry and oily floors were compared among no-slip (dry), slip-recovery and slip-fall events. For all trials, the foot rotated to foot-flat, even during slip and fall trials. Heel sliding patterns recorded upon and shortly after heel contact were similar for all conditions. Slip distances, sliding velocities and heel acceleration profiles varied across trials. During the fall trials, the slipping motion of the foot was found to decelerate around 200 to 300 ms into stance before accelerating again, eventually leading to the fall. This deceleration was believed to be an attempt by the subject to recover from the slip. Recovery attempts on inclined surfaces were less successful than on level floors. In general, the slip distance and peak forward sliding velocity associated with fall trials were greater than or equal to 10 cm and 0.8 m/s, respectively.

2.3 Center of Pressure (COP) and Joint Biomechanics during Slip Events

The onset of corrective actions taken by the body to recover from slips became evident at about 25% into stance and continued until about 45% into stance, i.e. on average between 190 and 350 ms after heel contact. These included increased flexion moment at the knee and extensor activity at the hip. By midstance, compensatory knee and hip reactive moments were recorded. The ankle, on the other hand, acted as a passive joint during fall trials, with the COP staying close to the heel/ankle indicating an incomplete body weight transfer to the supporting foot. Joint kinematics showed increased knee flexion, allowing subjects to rotate the shank forward in an attempt to bring the foot back near the body. Finally, only minimal changes in torso orientation were recorded during slip-recovery events. During slip-fall outcomes, the sliding foot eventually led to a loss of balance evident in the increasing rearward lean of the torso in the second half of the stance.

2.4 Load carrying Effect on Gait Biomechanics Relevant to Slips

The effect of carrying relatively light loads (2-handed method) on gait biomechanics relevant to slips/falls was examined on dry surfaces. Load carrying was associated with increases in the peak normal force and in the rate of the normal loading phase. Shear forces were not affected by load carrying. Changes in the ground reaction forces recorded during load carrying led to

reduced $RCOF_{peak}$ values, a parameter used to rate slip potential. This $RCOF_{peak}$ reduction is partly due to postural adaptations such as increased knee and hip flexion adopted during load carrying. Furthermore, load carrying was accompanied by slower heel contact heel velocity in the direction of motion and faster rearward heel movements at or shortly after heel contact. Finally, moments generated at the hip and knee joints were significantly biased towards the extensor and flexor direction, respectively.

2.5 Predictive Logistic Regression Modeling of Slips and Falls

Logistic regression models proved to be useful in describing the nature of the relationship between the probability of falls and the difference between biomechanical frictional requirements and available friction (COF_{diff}). However, logistic regression functions of COF_{diff} alone did not provide a satisfactory fit of the probability of slip ($r^2 < 0.50$). This poor performance of the model is believed to be due to the inaccurate assessment of the shoe/floor slip resistance by the two tribometers included in this study, especially for wet and soapy contaminant conditions. Thus, this modeling method is a potential tool to, not only evaluate the overall ability of tribometers to predict slips, but also identify specific environmental conditions under which slip resistance testers generate erroneous measurements.

3.0 USEFULNESS OF FINDINGS

3.1 Changes in Gait when Anticipating Slippery Surfaces

The results related to effects of slippery floors anticipation have at least two possible applied implications in future slip and fall experiments using human subjects. First, recruiting subjects for such experiments involves making them aware of the possibility of slipping; as a result of this expectation of potential floor contamination, subjects will walk "more carefully", thus modifying baseline gait characteristics to decrease slips/falls potentials; the extent of change in gait biomechanics will depend on the a-priori description of the study and specific instructions to the subject, thus emphasizing the need of being consistent throughout the trials. Second, reproducing the unexpected conditions often encountered in real life slips and falls incidents has proven to be very difficult, therefore the conclusions reported here underline the importance of being conservative when 1) applying research findings from human subjects slip and fall experiments to design criteria of "safe" floor-foot interfaces and 2) providing gait parameters as input to slip resistance testers designed to reproduce foot motion.

3.2 Foot Dynamics during slip events

This study described the details of heel/foot dynamics during no-slip (dry floors) and slip events, information that must be known to develop shoe/floor COF measurement systems that produce biomechanically relevant slip resistance measurements based on the faithful simulation of heel/foot movements. Research related to the prevention of slips and falls has indeed focused on an environmental factor, the frictional or slip-resistant properties of the shoe/floor interface, a risk factor that has been recognized to be a major predictor of slip events [3.1]. A wide variety of slip resistance testers are already being used in industry to rate slip potential (review chapter by Grönqvist [3.2]). Despite the fact that "friction" between two bodies (shoe/floor interface) seems to be a physical property, slip resistance measurements vary across devices. Recently developed slip resistance testers have attempted to simulate the velocities of the human foot during initial heel contact, hoping to obtain biomechanically relevant measures of slip resistance [3.3-3.5]. These devices do not yet fully simulate foot dynamics during actual slip events. The details of heel/foot dynamics during no-slip (dry floors) and slip events are thus needed as input parameters for these slip simulators. For example, an important parameter for the new generation of tribometers is the foot-floor angle. The "dangerous" forward sliding motion of the foot did not occur at heel contact but rather 60-80 ms after heel contact (on oily conditions), at which time subjects had time to rotate their foot to an almost foot-flat position.

In addition, the results of this study suggest that, although forward slipping is initiated shortly after heel contact, corrective reactions occurring later in the stance appear to be the primary factors affecting the outcome of recovery attempts following slip events. These complex motions at the shoe/floor interface during slipping should be taken into account for improving slip resistance measurement systems. More human subject testing such as was done in this study is needed to derive the temporal profiles of relevant gait variables to be used as input parameters for these slip simulators.

3.3 COP and Joint Biomechanics during Slip Events

The biomechanical analysis of responses elicited by slipping perturbations provided a better understanding of the complex relationship between gait and slip-precipitated falls. Gait analyses on contaminated surfaces revealed corrective actions generated by the body in attempt to recover from slips. The strength and control demands experienced by the musculoskeletal system during these corrective responses were reflected in the lower extremity joint moments, which were not investigated on slippery surfaces prior to this project. This study identified the specific actions taken by the body in attempt to arrest slip-precipitated falls. These actions recorded during slip events are different than those previously found using standing perturbations protocols during which ankle and hip moments dominate. The biomechanical analysis (magnitude and timing) of corrective responses is important to further understand the factors that affect the success of a recovery attempt.

3.4 Load carrying Effect on Gait Biomechanics Relevant to Slips

Epidemiological findings suggest that recovering from slip events is more challenging when performing load carrying tasks compared to unloaded conditions. For example, Anderson and Lagerlof [3.6] have reported that about 30% of load carrying-related injuries are related to slips/trips events. The first step in investigating the effect of load carrying on the success of slip-related recovery responses is understanding load-carrying effects on dry-surfaces. The findings related to load carrying effects underscore the dependence of gait biomechanics on the specific manual-handling task performed during locomotion. In general, the biomechanical characteristics of gait during load carrying were different than those recorded under unloaded conditions. This study identified different walking strategies when carrying a load. The adoption of these strategies may be related to attempts taken by subjects to increase stability, decrease strength and/or frictional requirements of walking tasks. Previous research has mostly examined carrying effects on gait biomechanics with carriage methods used in the military. However, the relationship between slip/fall biomechanics and the standard industrial symmetrical 2-handed posture has rarely been investigated.

3.5 Predictive Logistic Regression Modeling of Slips and Falls

Efforts directed towards the development of predictive logistic regression models to estimate the risk of slipping based on COF_{diff} (difference between required and available friction) resulted in various degrees of success depending on the environmental condition tested. The inaccurate assessment of the frictional characteristics of the environmental conditions is postulated to be the dominant reason for the model's inability to predict slips across all environmental/biomechanical conditions. Although, in these experiments, logistic regression models did not provide a satisfactory fit for the relationship between the probability of slip and COF_{diff}, they proved to be a potential method to evaluate the validity of slip resistance testers and predict falls. Furthermore, particular environmental conditions under which a specific tester (e.g. PSRT and Brungraber Mark II) generates erroneous slip resistance measurements can be identified using these regression models. Thus, the findings of this study based on the investigation of Hanson et al. [3.1] address the need of developing scientific means to validate slip resistance measures via the use of logistic regression models that relate the outcome of a walking trial to both gait biomechanics (required friction) and environmental factors (available friction).

In summary, the findings of this thesis revealed important biomechanical findings relevant to research aimed at preventing slips/falls accidents. These include 1) the ability of humans to reduce slip probability on potentially contaminated floors via postural and temporal gait adaptations, 2) the details of heel/foot dynamics during no-slip, slip-recovery and slip-fall events, 3) the specific corrective responses used by the body in an attempt to recover from slip accidents, 4) the postural and temporal gait adaptations associated with load carrying during locomotion on dry surfaces and 5) a potential method to compare the slip prediction capability of slip testers against actual slip probability provided by gait studies.

4.0 SCIENTIFIC REPORT I
CHANGES IN GAIT WHEN ANTICIPATING SLIPPERY FLOORS

4.1 Abstract

Unexpected slippery floors are often the cause of fall accidents. The unexpected nature of slipping accidents is challenging to reproduce during slip/fall biomechanical experiments. The first goal of this study was to quantify changes (if any) in gait biomechanics when subjects anticipate slippery environments. Foot ground reaction forces and body dynamics of 16 subjects walking on three flooring surfaces of varying frictional properties and inclination were recorded. Gait biomechanics were compared among three types of dry trials: 1) baseline (subjects knew the floor was dry), 2) anticipation (subjects were uncertain of the contaminant condition: dry, water, soap or oil) and 3) recovery trials recorded after a contaminated trial (subjects again knew the floor was dry). Subjects were asked to walk as naturally as possible throughout testing. Anticipation trials produced peak required coefficient of friction ($RCOF_{peak}$) values that were on average 16 to 33% significantly lower than those collected during baseline trials, thus reducing slip potential. During recovery trials, $RCOF_{peak}$ values did not return to baseline characteristics (5-12% lower). $RCOF_{peak}$ reductions were achieved by adopting postural and temporal gait changes resulting in ground reaction forces decreases. Gait adaptations included reductions in stance duration and loading speed on the supporting foot, shorter normalized stride length, reduced foot-ramp angle and slower foot angular velocity at heel contact. As a result of these adaptations, anticipation of slippery surfaces led to significant reductions in lower extremity joint moments, thus decreasing the strength requirements of walking. Thus, this study suggests that significant gait changes are made when there is a possibility of slipping even though subjects were asked to walk as naturally as possible. Insights are also gained into the adaptations that are used to reduce the potential of slips and falls.

4.2 Introduction

Injury investigations have often reported falling as being responsible for serious injuries and even deaths. More than 20% of injury-related emergency department visits have been attributed to falls, the single largest cause of such visits [4.1]. The US economic cost of all falling accidents ranks second [4.2]. The cost of falling injuries is also substantial among occupational populations for a number of reasons including the advancing age of the labor force [4.3] but also the severity of the injuries, with more than 20% of the workers sustaining falling injuries missing 31 days or more at work [4.4]. In a comparative study on analysis of injury mortality data across industrial countries, Fingerhut et al. frequently listed falling among the three leading generators of fatalities [4.5]. The loss of balance leading to falls is often the result of slipping events [4.6]. In 1996, slips, trips and falls accounted for 21% of all nonfatal occupational injuries [4.4]. The incidence of slip accidents varies with geographical location and external environmental conditions. For example, it is particularly high among occupational populations (e.g. miners and mail deliverers) working outside during cold winter months [4.7,4.8]. In Sweden, Björnstig et al. found the cost of medical care inflicted by slipping accidents on ice and snow comparable to the cost of all traffic injuries in that same area [4.9].

Causes of slips and falls are complex, including both human and environmental factors. Gait biomechanics and the health of the sensory and neuromuscular systems are included in human

factors. Among the most important environmental factors are the frictional and material properties of the shoes and floors. Slips and falls biomechanics partially determine the outcome of walking onto a contaminated floor. Indeed, findings of well-controlled gait experiments have been used in an effort to understand and ultimately reduce slip and fall accidents [4.10-4.14]. More specifically, such findings have been useful in the investigation of human responses to slippery floors, i.e., describing and understanding causes of slipping and the human reactions adopted in an attempt to avoid a fall after a slip has occurred. Relevant gait parameters generated from these studies have also been employed in the development of a new generation of slip resistance testers that measure the frictional properties of the shoe/floor interface. These new devices attempt to simulate foot movements during locomotion [4.15-4.17]. Finally, slips and falls experiments have attempted to determine whether a particular foot/floor interface can be considered a "slip-safe" environment [4.12].

A challenge in slip/fall biomechanical studies has been to reproduce the unexpected nature of real-life slipping accidents in laboratory settings. The effect of anticipating potentially slippery surfaces on gait biomechanics has not been investigated. Andres et al. [4.18] have compared the kinematic characteristics of steps prior to and onto a targeted known slippery area. However, the subjects knew the surface was slippery. Examining possible gait adaptations arising from anticipation effects will have implications on the findings of slip/fall experiments and provide insights on "control mechanisms" used to reduce slip and fall potentials.

The first goal of this study was to investigate whether subjects change gait biomechanics (on both level and inclined surfaces) when there is a possibility of a slippery environment. Specific changes in walking patterns (if any) adopted were quantified.

4.3 Methods

4.3.1 Subjects

Sixteen healthy subjects (8 male, 8 female) participated in this study with informed consent approved by the Institutional Review Board of the University of Pittsburgh. Their ages ranged from 19 to 30 years (mean 23 years, S.D. 4 years), mean weight from 62.6 to 82.4 kg (mean 68.7 kg, S.D. 6.8 kg) and height from 1.63 to 1.85 m (mean 1.73 m, S.D. 0.07 m). Exclusionary criteria included a history of neurological or orthopedic disease and any difficulties impeding walking up and down a ramp.

4.3.2 Experimental Set-Up

A specially designed ramp was used to conduct these experiments [4.11] (Figure 1). It consists of a ramp attached on one end to an electro-mechanical platform that can be raised or lowered to easily change ramp angle, and at the opposite end, this ramp is hinged to an extension of the walkway. This extension is the same height as the lowest level of the platform to attain a 0^{o}-walkway. The ramp is 1.8 m long and 1.0 m wide with a 1.4 m extension at the bottom. A force platform (Bertec, Inc.) is built into the ramp to record foot forces. This force plate is bolted to the superstructure of the ramp and positioned such that the subjects' left foot landed on the platform during the second or third step of descending the ramp. The top surface of the ramp is

made of 1.9 cm thick plywood that is bolted to the frame, but is easily removed to allow the relatively fast changing of flooring conditions.

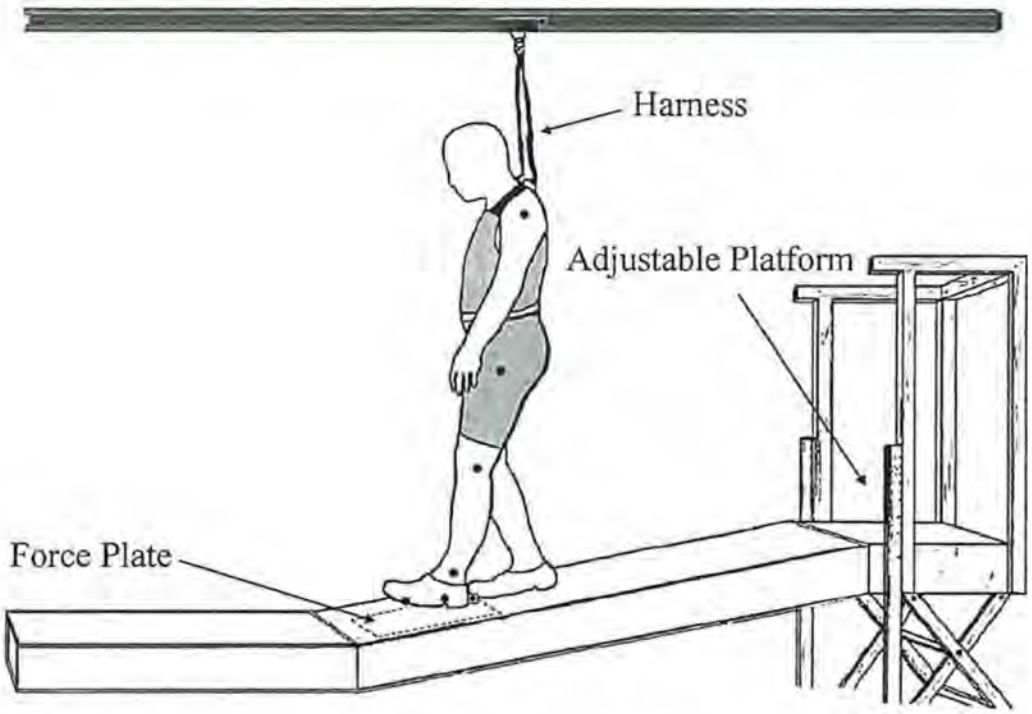

Figure 1 Experimental set-up. Ground reaction forces were collected from force plate embedded in the floor, while motion data information was derived by tracking seven LEDs placed on the left side of the body and shoe.

The data acquisition system consisted of the force plate, analog to digital (A/D) converter, PC computer and an OPTOTRAK 3020-motion measurement system. A graphical programming software (LABVIEW) was used to collect (sampling frequency of 350 Hz) and synchronize the force plate and motion data. The OPTOTRAK system recorded 3-D motion (with an accuracy of less than 1 mm) by tracking LEDs attached to the subject. Whole body motion and foot motion were recorded. More specifically, the LEDs were attached to the left shoulder (acromiom), hip (greater trochanter), knee (lateral femoral condyle), ankle (lateral malleolus) and shoe (3 markers near the heel of the shoe and fifth metatarsal).

4.3.3 Experimental Conditions

The primary independent variables included ramp angle, floor type and trial type. The three ramp angles used in this experiment were 0°, 5° and 10°. Subjects walked on vinyl tile, smooth painted plywood and a rough, silicate impregnated, painted plywood floors. The findings of three types of trials are reported here: baseline, anticipation (dry) and recovery. In the baseline

and recovery trials, subjects were certain that the floor was dry and therefore not slippery. The difference between these two types was that recovery trials occurred after a contaminated condition (wet, soap or oil), whereas baseline trials were collected at the beginning of a testing session before any slips occurred. In the anticipation trials, the subjects did not have a priori knowledge of the contaminant condition, but were told that there could be a contaminant. All subjects wore the same model of shoes with polyvinyl chloride (PVC) hard-soles for all trials.

4.3.4 Experimental Design

A full factorial design was used such that each subject was tested on all 27 conditions (3 ramp angles x 3 floors x 3 trial types). Subjects returned for a total of three visits, each time to be tested on a randomly chosen floor. The order of the conditions for each testing day was as follows: first, five baseline trials on each ramp angle were collected; then the ramp was set to the first angle at which the subject was to be tested; each of the three contaminated conditions (randomized) was "hidden" among one to three "anticipation dry" trials and followed by three "recovery" trials. This protocol was then repeated for the other two angles. The order of the presentation of the ramp angles was randomized.

4.3.5 Walking Protocol

First, an overview of the experiment (general goals, walking protocol, trial types, contaminants and variables recorded) was verbally described to the subject and informed consent obtained. LEDs were placed on the left side of the body and foot. After being equipped with the safety harness to prevent injury from falling should a slip occur, the subject was instructed to walk at a comfortable pace throughout the experiment and as naturally as possible even though there may be a slippery condition (the importance of these specific instructions was emphasized). Subjects were also reassured that they would be caught in a case of a slip. Each subject was first allowed to become familiar with the ramp set-up by walking across the force plate such that the left foot hits the force plate area. For the baseline trials, the subject walked to the top of the ramp, turned around and walked down the ramp. Foot forces and body/foot motion were collected while walking down the ramp only. Prior to each anticipation trial, the subject was asked to walk to the top of the ramp, and upon reaching the top, continue to face away from the ramp and wait for about 1 minute while listening to loud music. During this waiting period, a contaminant was applied to the surface of the force plate if required for that trial. (The lighting in the room was dimmed throughout the experiment so that subjects could not perceive the applied contaminant (if any).) At the end of the waiting period, the lights in the room were turned on and off, a signal for the subject to stop the music, turn around and walk down the ramp, while looking straight ahead at the wall on the opposite side of the room. Upon completing the trial, if the floor surface was contaminated, the subject was seated and the shoes/floor were either changed or cleaned. The trial was considered acceptable if the subject stepped on the force plate during the trial. Subjects stepped on the force plate in over 90% of the trials.

4.3.6 Data Processing

Time was normalized to stance duration, with 0% being heel contact and 100% representing toe-off the force plate. Foot forces and body/foot motion data were used to calculate specific

gait measures used as the dependent variables (Table 1). Shear (anterior-posterior) and normal ground reaction forces were normalized to the subject's weight. The ratio of shear to normal forces, (termed the required coefficient of friction (RCOF) [4.11]) was computed for each trial. In addition, ankle, knee and hip moments were derived. Kinematic variables in the sagittal plane included foot-ramp angle obtained from the heel and toe position data, and shank-ramp angle computed from the knee and ankle position data. These variables were evaluated at heel contact. Velocity information was calculated by numerically differentiating (using a 2-time step differentiation routine) the position data provided by each LED. Velocity variables were heel velocity in the direction of motion and foot angular velocity, both of which were evaluated at heel contact. In addition, maximum heel velocity in both rearward and forward directions recorded shortly after heel contact were considered. Position data were filtered (least square low pass filter with cutoff frequency of 12 Hz) only to derive acceleration variables used in lower extremity joint moments calculations. Finally, general gait variables such as normalized (to shank length) stride length (defined as the distance traveled in two steps from heel contact to heel contact) and stance duration were considered in the analysis.

4.3.7 Statistical Analysis

Due to the significantly different gait biomechanics on surfaces of varying inclinations [4.11], the statistical analysis was repeated within each ramp angle condition and for each dependent gait parameter listed in Table 1. A within-subject two-factor repeated measures design was used to investigate the effect of the trial type and floor condition (interaction effect of these two factors was included in the model) on specific dependent gait parameters (Table 1). Standard ANOVA methods and tests associated with repeated measures models were used to investigate the statistical significance of these factors. When the dependent variable was significantly affected by the trial type or floor condition, pairwise Tukey multiple comparison tests were used to further investigate differences among trial and floor types. A significance level of $p \leq 0.01$ was used throughout the analysis.

Table 1 Definitions/abbreviations of dependent estimated parameters

Kinetic Parameters
$Norm_{peak}$: peak of the first phase of the normal ground reaction force curve
$Shear_{peak}$: peak of the first phase of the shear ground reaction force curve
$RCOF_{peak}$: peak of the first phase of the RCOF curve
$Norm_{Tpeak}$: timing of $Norm_{peak}$ in percent of stance
$Shear_{Tpeak}$: timing of $Shear_{peak}$ in percent of stance
$Forc_{Tdiff}$: time difference between peaks of normal & shear ground reaction forces ($Norm_{Tpeak}$-$Shear_{Tpeak}$)
$RCOF_{Tpeak}$: timing of $RCOF_{peak}$ in percent of stance
$AnklTorq_{peak}$: peak ankle dorsiflexion moment, i.e. peak of the first phase of the ankle moment curve
$KneeTorq_{peak}$: peak knee extension moment, i.e. peak of the first phase of the knee moment curve
$HipTorq_{30}$: hip flexion moment evaluated at 30% into stance
Kinematic Parameters
NSL: normalized (to shank length) stride length
SD: stance duration
$HeelVelx_{HC}$: heel velocity in the direction of motion at HC
$HeelVelx_{rearward}$: peak rearward heel velocity in the direction of motion, recorded shortly after HC
$HeelVelx_{forward}$: peak forward heel velocity in the direction of motion, recorded shortly after HC
$HeelAccx_{HC}$: heel acceleration in the direction of motion at HC
$HeelAccx_{peak}$: peak heel acceleration in the direction of motion, recorded shortly after HC
$FootAngVel_{HC}$: foot angular velocity at HC
$FootAngl_{HC}$: foot-ramp angle at HC
$ShankAngl_{HC}$: shank-ramp angle at HC

4.4 Results

4.4.1 Baseline Data and Ramp Angle Effect

In order to investigate the anticipation effect of slippery surfaces on gait biomechanics, baseline normative values on horizontal and inclined vinyl surfaces were first recorded. As anticipated, the kinetics of locomotion in these baseline trials were affected by ramp angle [4.11]. More specifically, increases in the ramp angle were associated with increases in ground reaction forces and RCOFs (Figure 2). For level walking, the typical biphasic shear force reached a maximum of 1.8 N/kg and increased by about 60-70% and 125-135% on 5° and 10°, respectively ($Shear_{peak}$ in Table 2). The peak shear forces occurred at about 19% of stance for all ramp angles ($Shear_{Tpeak}$ in Table 2). Peak normal forces increased by nearly 1 N/kg ($Norm_{peak}$ in Table 2) and occurred earlier into stance as ramp angle was increased ($Norm_{Tpeak}$ in Table 2). The earlier occurrence of the peak normal force on inclined surfaces was also evident in the phase relationship of the ground reaction forces ($Forc_{Tdiff}$ in Table 2). As a result of changes in these force profiles, the peak RCOF ($RCOF_{peak}$ in Table 2), occurred about the same time ($RCOF_{Tpeak}$ in Table 2) as the peak shear force and increased from about 0.2 to 0.3 when changing the ramp angle from 0° to 10°.

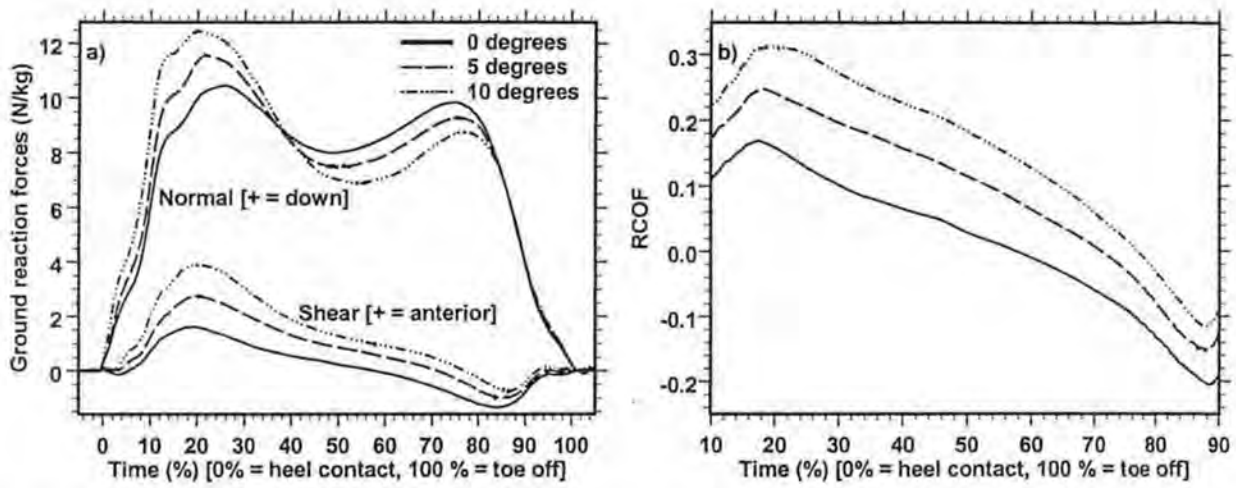

Figure 2 **Characteristic profile of ground reaction forces averaged across all baseline trials recorded on vinyl tile floors: (a) normal and shear ground reaction forces (normalized to body weight), (b) required coefficient of friction (RCOF = shear to normal force ratio). (In b, time is truncated to 10%-90% to avoid "instability" region when both shear and normal ground reaction forces are near 0.)**

Table 2 Baseline normative values of gait parameters on vinyl tile and rough floors

Variable mean (standard deviation)	0°		5°		10°	
Kinetic Parameters	**Vinyl**	**Rough**	**Vinyl**	**Rough**	**Vinyl**	**Rough**
$RCOF_{peak}$	0.18 (0.05)	0.19 (0.04)	0.26 (0.03)	0.28 (0.04)	0.32 (0.05)	0.34 (0.04)
$Norm_{peak}$ (N/kg)	10.92 (1.42)	10.73 (0.84)	12.15 (1.41)	11.90 (1.06)	13.33 (1.52)	13.06 (1.64)
$Shear_{peak}$ (N/kg)	1.77 (0.61)	1.80 (0.52)	2.94 (0.56)	3.03 (0.64)	4.06 (0.81)	4.23 (0.85)
$RCOF_{Tpeak}$ (%)	16.5 (2.4)	16.4 (2.8)	18.1 (3.6)	17.0 (2.8)	19.2 (4.6)	18.5 (4.1)
$Norm_{Tpeak}$ (%)	24.5 (5.2)	23.9 (4.7)	21.4 (4.3)	22.6 (4.3)	18.6 (5.4)	18.9 (5.6)
$Shear_{Tpeak}$ (%)	19.0 (3.1)	18.6 (3.0)	19.5 (2.6)	19.6 (3.5)	19.0 (4.6)	18.7 (4.6)
$Forc_{Tdiff}$ (%)	5.5 (3.8)	5.3 (4.2)	2.0 (3.6)	3.0 (3.1)	-0.4 (4.2)	0.2 (4.3)
Kinematic Parameters						
NSL	2.93 (0.38)	2.92 (0.39)	2.99 (0.41)	2.88 (0.41)	2.95 (0.40)	2.95 (0.42)
SD (ms)	781.7 (114.0)	792.8 (89.8)	716.5 (88.9)	730.3 (88.4)	666.6 (88.8)	677.1 (76.4)
$HeelVelx_{HC}$ (m/s)	0.19 (0.39)	0.15 (0.31)	0.25 (0.42)	0.10 (0.23)	0.13 (0.32)	0.01 (0.23)
$HeelVelx_{rearward}$ (m/s)	-0.11 (0.07)	-0.11 (0.07)	-0.09 (0.08)	-0.09 (0.06)	-0.09 (0.09)	-0.10 (0.10)
$HeelVelx_{forward}$ (m/s)	0.12 (0.04)	0.12 (0.04)	0.14 (0.05)	0.14 (0.05)	0.17 (0.08)	0.16 (0.05)
$HeelAccx_{HC}$ (m/s^2)	-24.86 (16.54)	-26.69 (13.72)	-26.69 (16.44)	-22.79 (11.0)	-21.35 (15.07)	-18.10 (10.62)
$HeelAccx_{peak}$ (m/s^2)	4.01 (2.34)	4.33 (2.25)	3.45 (2.18)	3.45 (1.62)	3.04 (1.98)	2.85 (1.70)
$FootAngVel_{HC}$ (°/s)	223.8 (98.4)	225.4 (77.9)	251.7 (111.9)	267.3 (79.2)	292.9 (86.9)	310.3 (79.8)
$FootAngl_{HC}$ (°)	23.5 (3.7)	24.1 (4.3)	26.4 (3.5)	26.4 (3.3)	26.9 (4.9)	27.6 (4.3)
$ShankAngl_{HC}$ (°)	105.3 (3.4)	105.6 (3.2)	107.2 (2.4)	106.8 (2.1)	107.8 (2.2)	107.7 (2.5)

Recorded kinematics showed that at the end of the swing phase, the heel rapidly decelerated (Figures 3a - 3b and $HeelAccx_{HC}$ in Table 2) and, upon heel contact, a slight sliding motion of the heel occurred along the ramp surface. Different sliding patterns at or shortly after heel contact were observed. In general, the heel contact heel velocity was positive as noted in Figure

3a and Table 2 ($HeelVelx_{HC}$), indicating a forward motion of the foot as it hit the floor. Then the heel rapidly slowed down and often even reversed direction with a mean peak rearward heel velocity of about -0.1 m/s ($HeelVelx_{rearward}$ reached at about 1-2% into stance or 6-12 ms after heel contact). After this rearward motion, the heel slid forward again with an average peak forward heel velocity of about 0.12 to 0.17 m/s ($HeelVelx_{forward}$ was recorded at about 4-5% into stance or 24-33 ms after heel contact and was greater on inclined surfaces) and finally came to a stop (at about 6-7% into stance or 40-50 ms after heel contact). However, there were also a significant number of trials where the velocity at heel contact was negative, i.e. foot moving in the rearward direction. In all cases, this rapid heel motion ended shortly after heel contact and the heel came to a complete stop. During this short heel motion time period after heel contact, average peak heel acceleration ($HeelAccx_{peak}$ in Table 2) values of about 3-4 m/s^2 were recorded. The foot rotated down on the floor rapidly during this period ($FootAngVel_{HC}$ in Table 2) to reach foot-flat position at about 15% into stance (Figure 3c) and the shank proceeded in its forward rotation (Figure 3d).

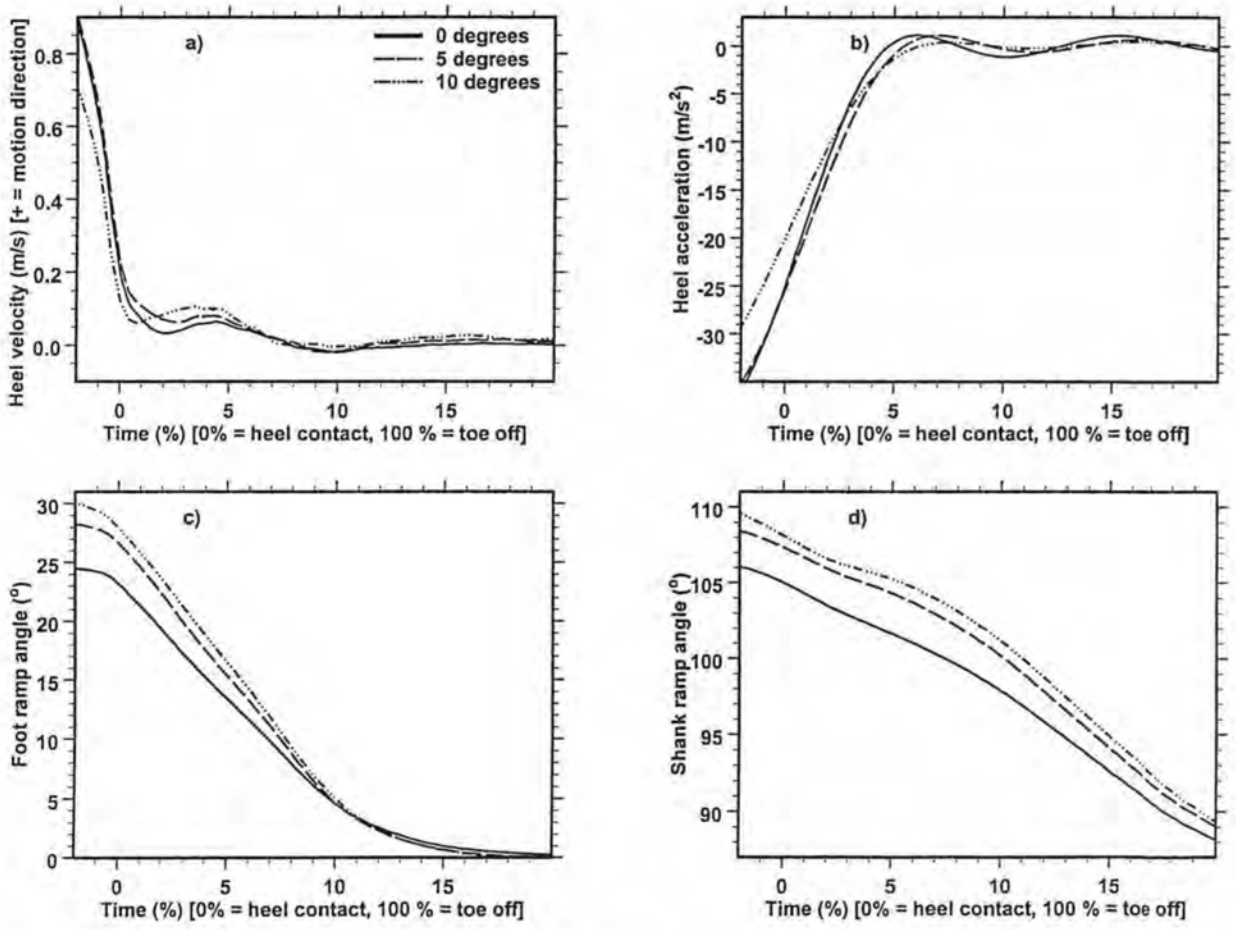

Figure 3 **Characteristic profile of selected kinematic gait variables averaged across all baseline trials recorded on vinyl floors: a) heel velocity in direction of motion, b) heel acceleration in direction of motion, c) foot ramp angle and d) shank ramp angle.**

4.4.2 Anticipation Effect on Gait Measures

In general, foot force and motion data profiles for the anticipation trials were similar in shape to those in the baseline trials. However, ANOVA revealed trial type significantly ($p \leq 0.01$) affected the magnitude and timing of gait, more specifically the foot forces values ($RCOF_{peak}$, $RCOF_{Tpeak}$, $Norm_{peak}$, $Norm_{Tpeak}$, $Shear_{peak}$, $Shear_{Tpeak}$), and lower extremity kinematics ($HeelVelx_{rearward}$, $HeelVelx_{forward}$, $HeelAccx_{peak}$, $FootAngVel_{HC}$, $FootAngl_{HC}$ and $ShankAngl_{HC}$). Other variables were significantly influenced by the trial type only on inclined floors ($p \leq 0.01$) but not when walking on horizontal surfaces (NSL and SD). Finally, $Forc_{Tdiff}$, $HeelVelx_{HC}$ and $HeelAccx_{HC}$ were not affected by trial type.

The foot force magnitude parameters ($RCOF_{peak}$, $Shear_{peak}$ and $Norm_{peak}$) were all significantly reduced during anticipation conditions (as shown by the positive differences from baseline values in Figure 4). The anticipation trials produced peak RCOFs that were on average 16 to 33% lower than those collected during the baseline trials, with more pronounced reductions as ramp angle was increased (Figure 4a). The peak RCOFs on the recovery trials were greater than the anticipation trials, but did not return to the levels of the baseline (5 to 12% lower than baseline values). This trial type effect was found to be significant for all three ramp angles. Similarly, significant differences in the peak shear forces were also found, with the anticipation trials having significantly lower shears compared to the baseline (17 to 40% difference) (Figure 4b). The peaks of the normal forces were also reduced in the anticipation trials compared to the baselines (2 to 13%), but to a lesser extent than shear forces when comparing relative changes to baseline conditions (Figure 4c and Table 2).

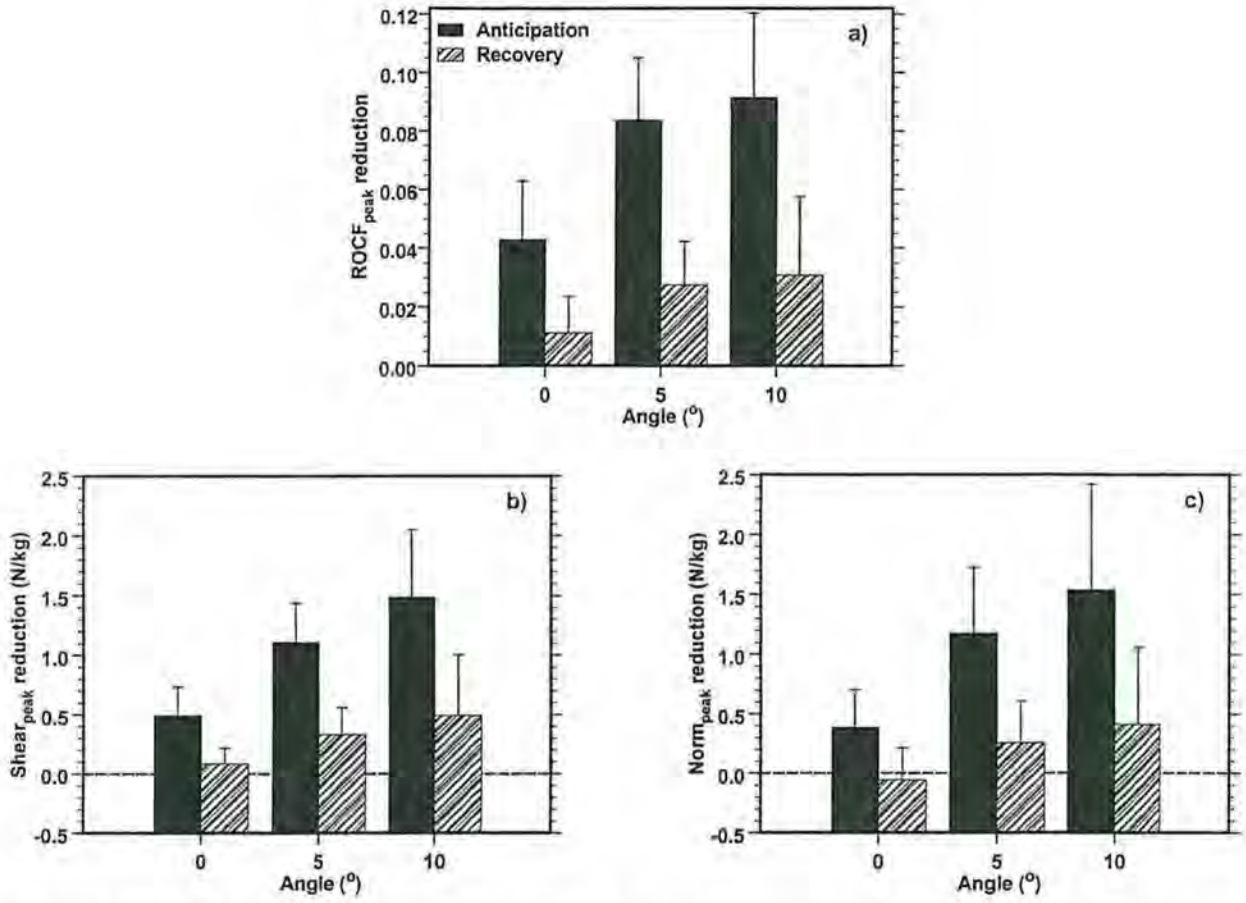

Figure 4 **Trial type effect on ground reaction forces variables: (a) peak RCOF, (b) peak shear ground reaction force, and (c) peak normal ground reaction force. Mean within-subject differences (baseline - anticipation/recovery) are plotted. (Dotted line indicates no-difference between baseline and anticipation/recovery trials).**

When walking down inclined surfaces, the NSL (Figure 5a) and SD (Figure 5b) were both reduced during the anticipation trials when anticipating slippery environments. However, there was no significant trail type effect on these parameters during the level surface (0°) condition. On the inclined surfaces, small decreases from baseline values in the NSL ranged from 2 to 4% for the anticipation trials. Similar findings were recorded for the SD, with significant decreases of 3 to 6% when comparing the anticipation to baseline trials on inclined surfaces. Despite these small changes, Tukey multiple comparison tests indicated significant differences in these variables among all trial type conditions (on 5° and 10°) except for the comparison in the NSL between recovery and baseline trials on 5°.

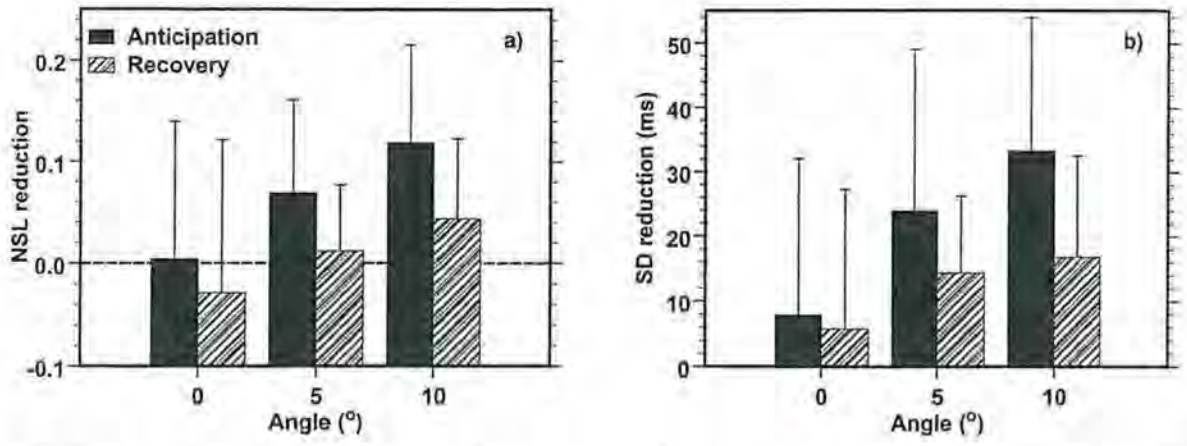

Figure 5 **Trial type effect on general gait variables: (a) normalized stride length (NSL), and (b) stance duration (SD). Mean within-subject differences (baseline - anticipation/recovery) are plotted. (Dotted line indicates no-difference between baseline and anticipation/recovery trials).**

The ANOVA results showed no significant differences in $HeelVelx_{HC}$ and $HeelAccx_{HC}$ among trial types. However, shortly after heel contact, significant increases in the peak rearward heel velocity ($HeelVelx_{rearward}$) were recorded during anticipation trials (10 and 50-55% increase from baseline values for level walking and inclined surfaces descent, respectively), and to a lesser degree during recovery trials (10-20% increase), as depicted in the positive differences plotted in Figure 6a. Before coming to a stop, the heel slid forward with reduced peak forward velocities during anticipation trials (14-19% reduction in $HeelVelx_{forward}$ from baseline characteristics for all ramp angles, Figure 6b). No significant differences in $HeelVelx_{forward}$ were detected between baseline and recovery conditions. Interestingly, during that short period of heel sliding after heel contact, anticipation of slippery surfaces led to significant increases in $HeelAccx_{peak}$ (11, 29 and 40% for level walking, 5° and 10° respectively) from magnitudes recorded during baseline trials (negative differences from baseline trials plotted in Figure 6c). Differences in $HeelAccx_{peak}$ between recovery and baseline trials were also significant, but lesser in amplitude (6-19% relative increases during recovery trials, as depicted in Figure 6c). These increases in $HeelAccx_{peak}$ are related to the greater $HeelVelx_{rearward}$ values reported earlier during anticipation trials: the duration of the short heel sliding period after heel contact is comparable for all conditions, however greater rearward peak velocities were recorded for anticipation and recovery trials, thus leading to steeper Δ(velocity)-Δ(time) slopes or acceleration measures. In addition, decreases in $FootAngVel_{HC}$ were recorded during anticipation trials (positive differences from baseline conditions plotted in Figure 6d) on all angles (decreases ranged from 0.5 to 23% with the smallest difference recorded on rough floors and the largest difference on vinyl tile surfaces). No significant differences in the $FootAngVel_{HC}$ were detected between the recovery and baseline trials.

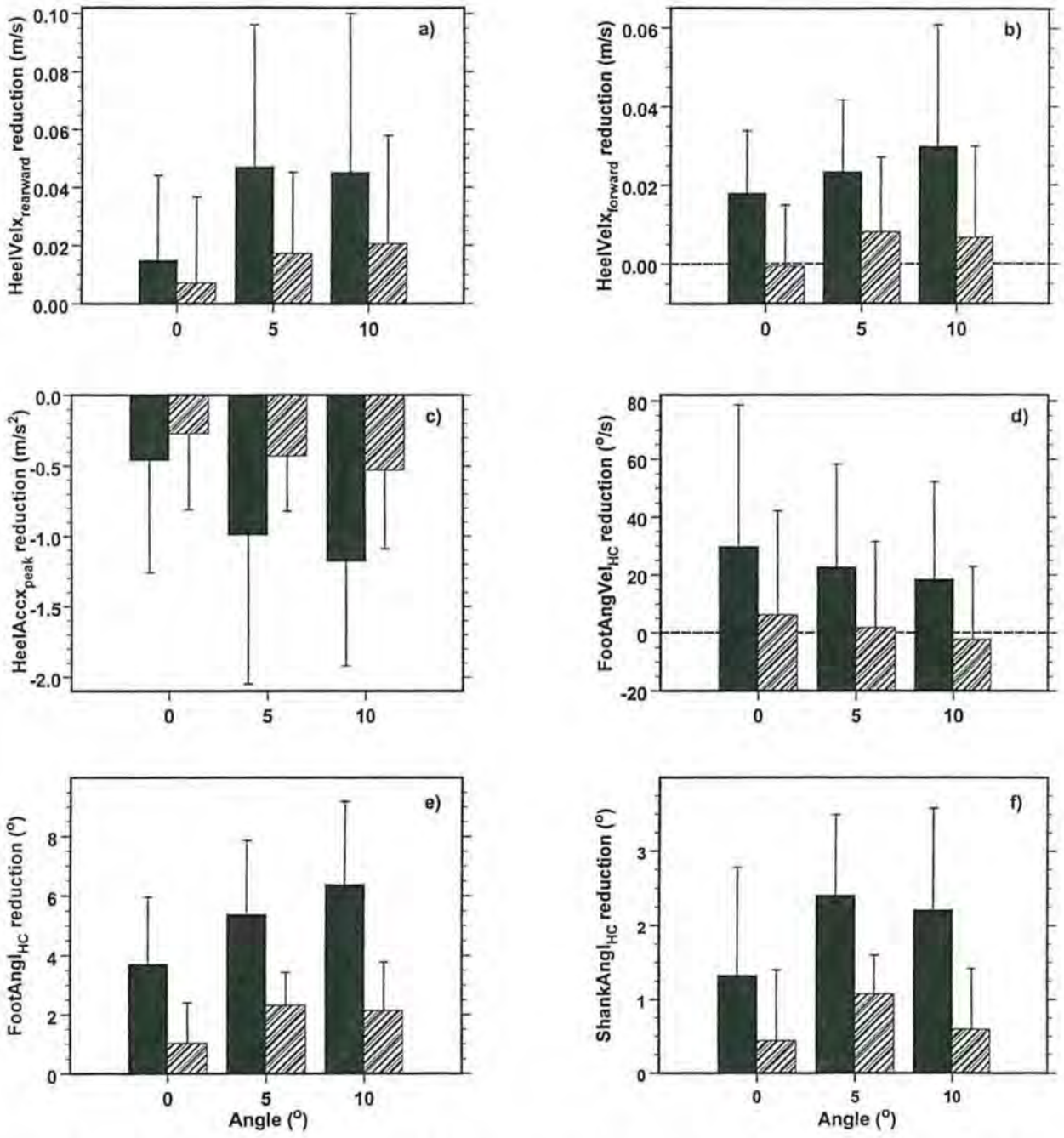

Figure 6 **Trial type effect on selected kinematic parameters: (a)/(b) peak rearward/forward heel velocity recorded shortly after heel contact, (c) peak heel acceleration recorded shortly after heel contact, (d) foot angular velocity at heel contact, (e) foot-floor angle at heel contact, and (f) shank-floor angle at heel contact. Mean within-subject differences (baseline - anticipation/recovery) are plotted. (Dotted line indicates no-difference between baseline and anticipation/recovery trials). Note, Heelvel$_{rearward}$ (negative) and HeelAcc$_{peak}$ (positive) increased with anticipation/recovery trials resulting in a positive negative reduction, respectively.**

The anticipation and recovery trials were characterized by a significant decrease in the $FootAngl_{HC}$ and $ShankAngl_{HC}$ from baseline values for all ramp angle conditions (positive differences plotted in Figures 6e and 6f). The foot orientation with respect to the floor was the most affected variable between the two (11 to 27% decrease in $FootAngl_{HC}$). Less pronounced, but still statistically significant, reductions in the $ShankAngl_{HC}$ were recorded (1 to 3%). Postural adaptations were also evident in the knee and hip flexion increases during early stance of anticipation trials. In the recovery trials, these gait variables were closer to baseline characteristics with a decrease of 3 to 13% in the $FootAngl_{HC}$, less than 2% in the $ShankAngl_{HC}$.

During the anticipation trials, the rate of loading on the supporting foot was significantly slower than for baseline trials. This is evident in the peak shear and peak normal force that were not recorded until 20-26% and 23-31% into stance for anticipation trials compared to 18-20% and 19-25% for baseline trials, respectively (i.e., higher $Shear_{Tpeak}$ and $Norm_{Tpeak}$ in the anticipation trials for all floor and ramp angle conditions). As a result, the peak RCOF also occurred later in the step for the anticipation trials ($RCOF_{Tpeak}$), with similar delays as the shear forces. The differences in these timing variables ($Shear_{Tpeak}$, $Norm_{Tpeak}$, $RCOF_{Tpeak}$) were not always significantly different when performing Tukey multiple comparison tests between recovery and baseline trials.

The trial type effect on the phase relationship between the normal and shear forces was investigated by examining the difference in timing between the peaks of the normal and shear forces among the trial type conditions. This variable ($Forc_{Tdiff}$) was not statistically different among trial types (all ramp angles), with less than 2% absolute differences with the baseline characteristics, indicating that the time relationship between the shear force and normal force did not significantly change among trial types.

4.4.3 Floor Type Effect

Flooring condition had a small but statistically significant effect on the majority of the gait measures, while the interaction of the floor and trial type was, in general, not significant. The primary floor type influence on the kinetic parameters was a higher $RCOF_{peak}$ for the rough surface compared to the vinyl floor (0.01 to 0.04 overall difference) (Table 2 shows these differences for baseline values). This slight increase on rough floors was also true for the $Shear_{peak}$ (0.1 to 0.4 N/kg increase), whereas the $Norm_{peak}$ decreased on rough floors (0.1 to 0.4 N/kg decrease) for the majority of baseline and recovery conditions but increased for the anticipation trials (less than 0.3 N/kg increase). Similarly, the kinematic variables were not greatly affected by the floor type, however, the changes were statistically significant. On average, subjects shortened their NSL when walking on rough floors compared to vinyl surfaces (less than 0.16 decrease), while increasing their SD by 10 to 35 ms. On average, recordings of the $FootAngl_{HC}$ were greater on rough floors compared to the vinyl surfaces for seven out of the nine (ramp angle, trial type) conditions. However, these variations in the foot orientation between the floor conditions were less than 2°. The findings related to the difference in the shank orientation between floors were less consistent across conditions and small in magnitude (less than 1°). $HeelVelx_{HC}$ was higher on vinyl surfaces compared to the rough floors (differences ranging from 0.04 to 0.23 m/s for baseline and recovery trials and 0.18 to 0.34 m/s for anticipation conditions), while the $FootAngVel_{HC}$ was greater on rough floors (differences with vinyl surfaces ranged from 1 to 17°/s for baseline trials and from 26 to 50°/s for anticipation

trials). In general, the floor effect on $HeelAccx_{HC}$, $HeelAccx_{peak}$, $HeelVelx_{rearward}$ and $HeelVelx_{forward}$ was not statistically significant.

4.4.4 How was a Reduction in the Peak RCOF Achieved

Given that the RCOF is an important variable in determining the potential for slips and falls, analyses were performed to investigate how the reduction of RCOF was achieved in the anticipation trials. In order to answer this question, a multivariate linear regression on the $RCOF_{peak}$ with the independent variables being NSL, SD, $FootAngVel_{HC}$, $FootAngl_{HC}$ and $Norm_{Tpeak}$ was repeated within each ramp angle condition. These variables were chosen for two reasons: 1) they significantly differed among trial types on one or more ramp angle conditions and 2) they describe general gait parameters, heel contact dynamics and time characteristics of gait.

$RCOF_{peak}$ was significantly associated with slower loading rates ($Norm_{Tpeak}$ longer) and smaller foot-ramp angles at heel contact ($FootAngl_{HC}$) on all ramp angles (Table 3). The peak RCOF increased with increasing normalized stride length (NSL), longer stance duration (SD) and slower heel contact foot angular velocity, with a stronger effect of these variables as ramp angle was increased. Interestingly, longer stance durations were associated with higher peak normal forces (*r* between 0.6 - 0.7) and reduced peak forward heel accelerations (*r* between 0.5 - 0.6), while slower loading rates generated lower levels of shears (r between 0.5 - 0.6). Thus, subjects efficiently decreased their risk of slipping ($RCOF_{peak}$) by more slowly rotating the foot down to the floor during heel contact, adopting shorter strides (length and duration), reducing foot contact angles and slowing the transfer of body weight to the supporting foot.

Table 3 Gait characteristics affecting $RCOF_{peak}$

Response = $RCOF_{peak}$ Independent → Ramp angle ↓	NSL	SD	$Footangvel_{HC}$	$Footangl_{HC}$	$Norm_{Tpeak}$
0°	NS	NS	NS (0.02)	S	S
5°	NS	NS	NS (0.06)	S	S
10°	S	S	S	S	S

S indicates $p \leq 0.01$; *NS* indicates $p > 0.01$

4.4.5 Joint Moments

Baseline trials: During most of the stance period (after the loading phase), moments generated at the ankle (plantarflexor), knee (extensor) and hip (flexor) joints were responsible for moving the body forward. Lower extremity joint moments were affected by ramp angle. Early in stance (~10% into stance), the peak dorsiflexion ankle moment during level walking was recorded at about 0.25 N.m/kg for baseline trials, and increased by 25-30% and 45-55% on 5°

and 10°, respectively. After this time, the plantarflexion moment of the ankle increased to reach a local maximum of 1.0-1.3 N.m/kg (lower peak on inclined surfaces) before rapidly decreasing and returning to baseline levels (Figure 7a). The knee was especially affected by ramp angle, with its maximum extension moment of 0.75 N.m/kg occurring later in the stance (21-24% into stance), increasing by 50-65% on 5° and almost doubling when descending the 10° ramp. After reaching this peak, the resulting knee moment decreased but stayed positive (extensor) during most of the stance with higher magnitudes on inclined surfaces (Figure 7c). The hip moment was affected by ramp angle mostly in the 20-40% time interval of stance (Figure 7e). Thus, it was evaluated at 30% into stance and found to increase on inclined surfaces (0.6-0.8 N.m/kg) from level walking characteristics (0.42 N.m/kg), with less pronounced differences (if any) between the 5° and 10° ramp angles.

Trial type effect: ANOVA confirmed that the changes in the ground reaction forces, kinematic and temporal characteristics of gait induced by the anticipation trials led to statistically significant ($p < 0.01$) decreases in the peak moments developed at the ankle and knee and in the hip moment evaluated at 30% into stance. Knee and hip moments were most affected by the trial type condition (Figure 7). Reductions in joint moments were more pronounced as ramp angle was increased (Figure 8). More specifically, the mean baseline-anticipation difference in the peak dorsiflexion ankle moment decreased about 27% during the anticipation conditions from baseline levels. The peak extension knee moment was associated with more significant differences between anticipation and baseline trials, leading to a relative reduction of 24% during level walking and about 35% when descending ramps. The anticipation conditions produced lower hip moment as well (evaluated of 30%) with relative reductions of 32, 49 and 59% on 0°, 5° and 10°, respectively. In addition to changes in its magnitude, the overall profile of the hip moment was somewhat modified during the anticipation trials (Figures 7e - 7f). During the recovery trials, joint moments were closer but still lower than baseline characteristics. Tukey multiple comparison tests indicated statistically significant ($p < 0.05$) differences in all three joint moment parameters among all trial types except between baseline and recovery trials on horizontal surfaces ($p < 0.1$).

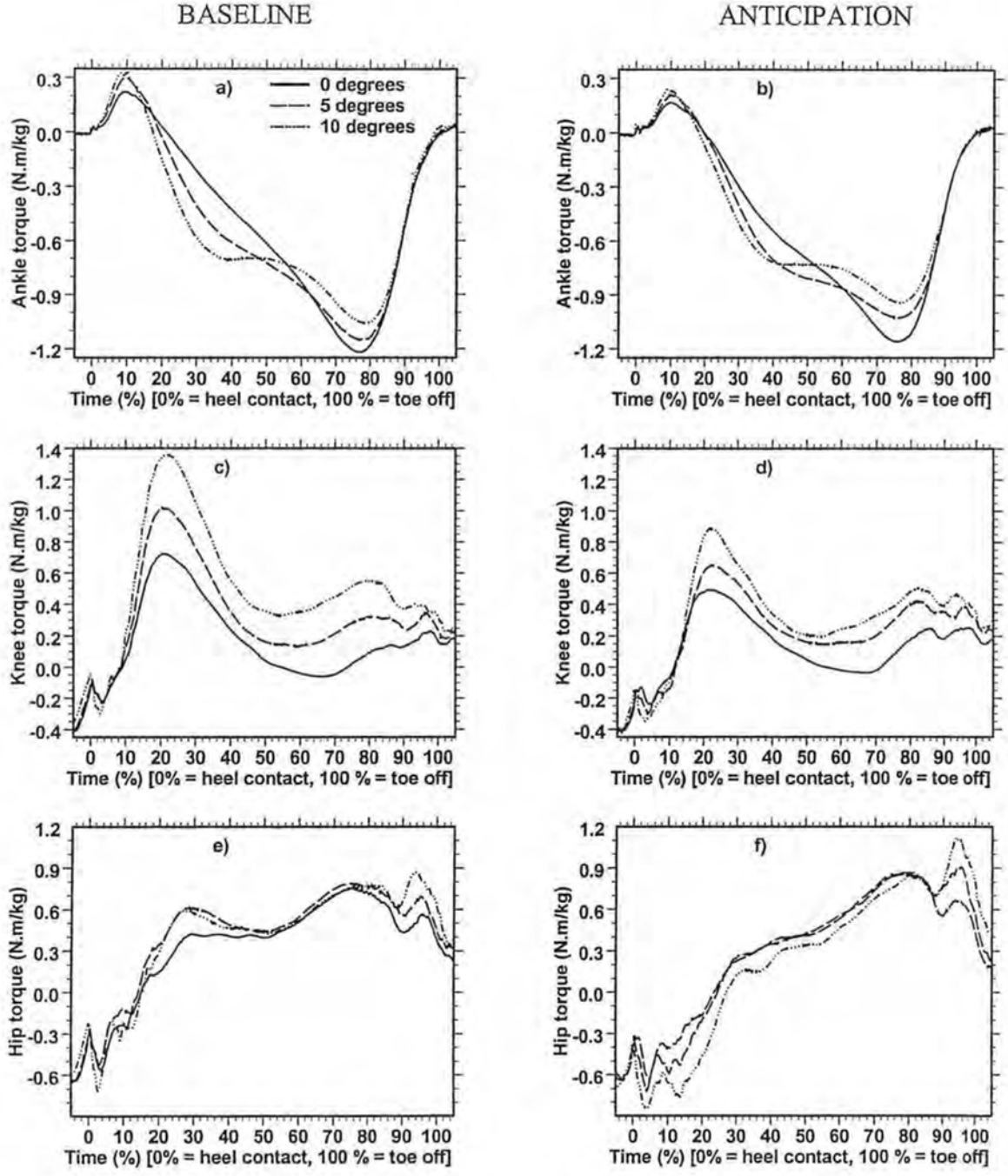

Figure 7 **Characteristic profile of joint torques (normalized to body weight) during gait on vinyl tile floors, averaged across all baseline (left) and anticipation (right) trials: (a)/(b) Ankle [+ = dorsiflexion], (c)/(d) Knee [+ = extension], and (e)/(f) Hip [+ = flexion].**

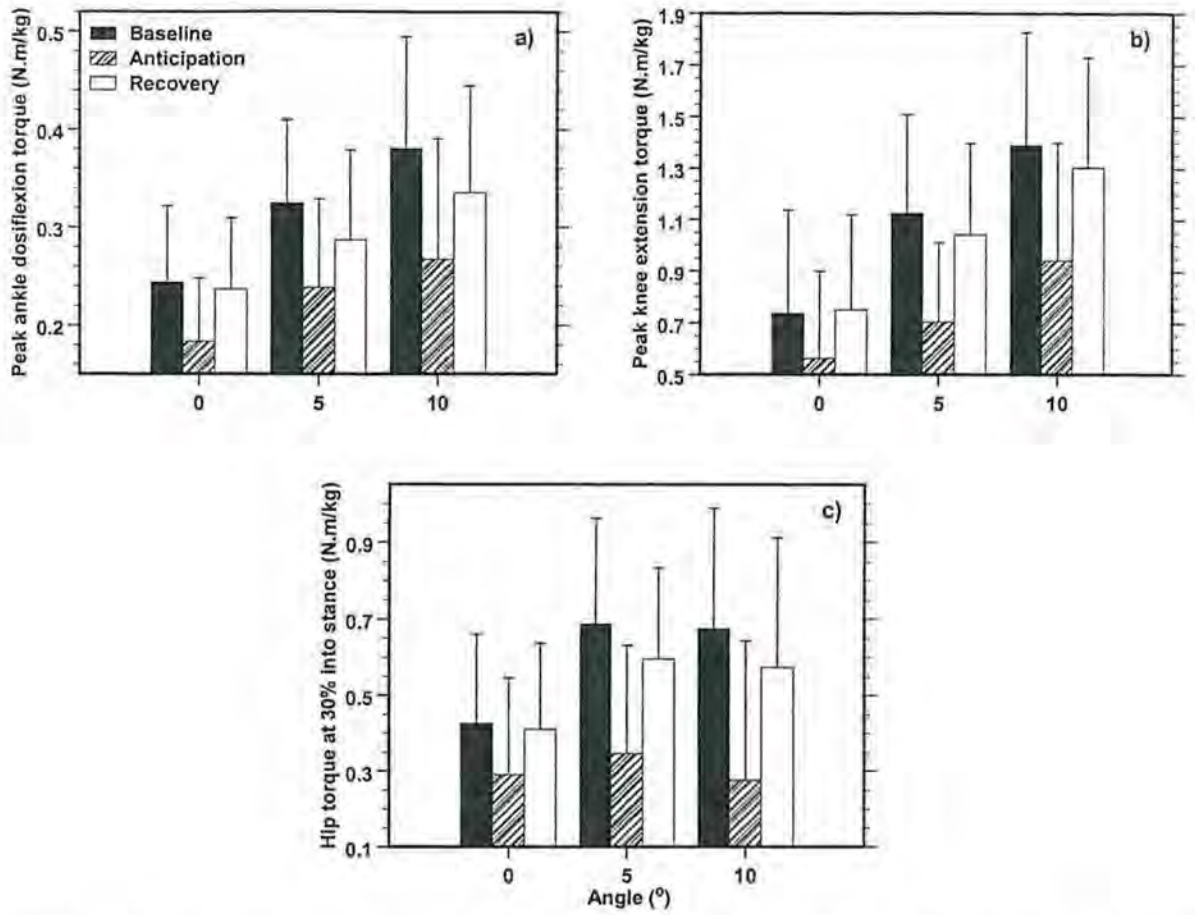

Figure 8 **Trial type effect on joint torque parameters (normalized to body weight): (a) peak ankle dorsiflexion torque, (b) peak extension knee torque and (c) hip torque evaluated at 30% into stance.**

The same ANOVA uncovered a significant floor effect on joint moment measures with, in general, slightly (but statistically significant) higher moments on rough floors compared to vinyl and smooth floors. Pairwise comparison tests indicated a number of negligible differences between the smooth and vinyl floors, in particular for the hip moment. The interaction (trial type x floor type) was not significant for the majority of the tests.

4.5 Discussion

The main finding of this study was that human adaptations to "potentially" slippery surfaces (anticipation trials) resulted in significant differences in gait biomechanics when compared to characteristics of baseline trials, during which subjects walked onto a known dry surface. The overall effect of these adaptations was a reduction in the peak RCOF, thus decreasing slip and fall potentials [4.10-4.13,4.16,4.19,4.20]. In addition, these adaptations led to significant reductions in joint moments. These two effects occurred despite instructions to the subjects to walk as normally as possible during both conditions.

Ultimately, the reaction forces at the shoe/floor interface are most important in determining the potential for slips and falls. The RCOF is believed to best reflect the aspects of the foot forces contribution to slip and fall potential. Thus, the method by which the RCOF is reduced is important in determining how individuals control slip potential. How was a decrease in the peak RCOF achieved by the subjects in these experiments? Reductions in the relative magnitude of both the shear forces and, to a lesser extent, the normal forces, resulted in the overall effect of a decrease in the peak RCOF. Another possible way of affecting the peak RCOF is to change the time relationship between the shear and normal forces. However, interestingly, the phase relationship between the profiles of the shear and normal ground reaction forces did not vary among trial types. Thus the magnitude of the foot force components appear to be adjusted and not the relative timing between the two. These magnitude changes in the kinetics of locomotion appear to occur due to temporal and kinematic gait adaptations including reductions in the stance duration and loading speed on the supporting foot, shorter normalized stride length, reduced foot-ramp angle and slower foot angular velocity at heel contact. Thus, expectation of a potentially slippery surface led to more "cautious" biomechanical gait patterns, which successfully resulted in a decrease of slip probability.

The overall statistical significance of anticipation effects is also believed to be of practical relevance to the reduction in slip potential. This is evident in the extent of the RCOF reduction during anticipation conditions. For example, an approximate 0.09 reduction in $RCOF_{peak}$ was recorded during the anticipation trials when descending the 10° ramp, resulting in an absolute $RCOF_{peak}$ value of about 0.23, which is comparable to baseline magnitudes observed when descending the 5° ramp. Thus, the consequences of biomechanical human reactions on slip potential during anticipation trials on the 10° ramp were equivalent to reducing the ramp angle by 5°. It is important to note however, that the practical significance of anticipation was varied across gait variables, with subtle changes in general gait variables (e.g. normalized stride length and stance duration) and more pronounced effects on postural responses (foot orientation), which are believed to be related to important consequences such as decreases in shear forces and thus reduction in slip potential.

The results of this study concerning the floor effect are consistent with the hypothesis that subjects were aware of the greater possibility of slipping on vinyl floors compared to rough floors, and therefore adapted their gait to achieve once again a reduction in the peak RCOF on the "more dangerous" surfaces. However, the possibility of a contaminated surface affected gait patterns more than floor type. In general, floor effect on gait measures was significant but small, while the interaction of floor type and trial type was not statistically significant.

The baseline results reported here are comparable with findings of earlier studies. In particular, peak RCOFs were in close agreement with values reported by Redfern and Dipasquale [4.11] and Hanson et al. [4.12] on both horizontal and inclined surfaces, and by Perkins [4.10] and Strandberg and Lanshammar [4.13] on level floors. Similarly, the timing and magnitude of peak ground reaction forces were in accordance with the same above-mentioned studies and results of baseline gait experiments conducted by Winter [4.21] on level surfaces. In general, the overall shape of the calculated joint moments were comparable and within the range of values reported by Redfern and Dipasquale [4.11] and Winter [4.21], although some differences were noted in the magnitudes. Potential reasons for these differences may include minor differences in marker

placement and other experimental factors such as specific instructions given to subjects. Despite these differences, the relative differences between the three trial types remain.

Baseline kinematic data were also comparable to previously published findings. For example, joint angles during walking on level and inclined surfaces agreed with results of Redfern and Dipasquale (on level and inclined surfaces) [4.11] and Winter (on level surfaces) [4.21]. The wide variation in heel contact heel velocity patterns observed among subjects was also reported by Strandberg and Lanshammar [4.13] with velocity magnitudes ranging from 0.14 and 0.68 m/s and associated with standard deviations as large as 0.52 m/s, a finding that certainly agrees with the results of this study. A final example related to the heel contact foot orientation with respect to the floor published by Strandberg and Lanshammar [4.13] on horizontal surfaces ($22.0^{\circ}\pm5.3^{\circ}$), which is also in agreement with values computed here. When comparing kinematic characteristics of steps prior to and onto a knowingly slippery area, Andres et al. [4.18] have reported similar gait adaptations than those reported here, including reduced foot angle and foot angular velocity at heel contact.

The findings of this study provide a better understanding of important aspects related to slips and falls biomechanics. First, humans have the ability to reduce slip probability on potentially contaminated floors. Second, in order to achieve this reduction, it appears that postural and temporal gait adaptations were adopted to decrease ground reaction forces, resulting in smaller RCOFs. Third, these adaptations did not lead to phase changes between the normal and shear foot floor forces. Finally, as a result of changes in foot forces and postural adjustments during walking, anticipation of slippery surfaces led to reductions in the lower extremity joint moments, thus decreasing not only slip potential (RCOF) but also the strength requirement of the walking task. In addition, the findings related to the moments at the lower extremity joints suggested that the knee and hip appear to be used more than the ankle to control slip potential.

The results of this study have at least two possible applied implications in future slip and fall experiments using human subjects. First, recruiting subjects for such experiments involves making them aware of the possibility of slipping; as a result of this expectation of potential floor contamination, subjects will walk "more carefully", thus modifying baseline gait characteristics to decrease slips/falls potentials; the extent of change in gait biomechanics will depend on the a-priori description of the study and specific instructions to the subject, thus emphasizing the need of being consistent throughout the trials. Second, reproducing the unexpected conditions often encountered in real life slips and falls incidents has proven to be very difficult, therefore the conclusions reported here underline the importance of being conservative when 1) applying research findings from human subjects slip and fall experiments to design criteria of "safe" floor-foot interfaces and 2) providing gait parameters as input to slip resistance testers designed to reproduce foot motion.

5.0 SCIENTIFIC REPORT II
HEEL CONTACT DYNAMICS DURING SLIP EVENTS

5.1 Abstract

This study describes heel contact dynamics during slip events, information that must be known to develop biomechanically relevant shoe/floor COF measurement systems. Sixteen subjects walked on a level, 5° and 10° ramp with 2 possible contaminants (dry, oil). Foot motion recorded at 350 Hz and compared among no-slip, slip-recovery and slip-fall events. For all trials, the foot rotated to foot-flat, even during slip and fall trials. Heel sliding patterns recorded upon and shortly after heel contact were similar for all conditions. Slip distances, sliding velocities and heel acceleration profiles varied across trials. During the fall trials, the slipping motion of the foot was found to decelerate around 200 to 300 ms into stance before accelerating again, eventually leading to the fall. This deceleration was believed to be an attempt by the subject to recover from the slip. Recovery attempts on inclined surfaces were less successful than on level floors. In general, the slip distance and peak forward sliding velocity associated with fall trials were greater than or equal to 10 cm and 0.8 m/s, respectively. These complex motions at the shoe/floor interface during slipping should be taken into account for improving slip resistance measurement systems.

5.2 Introduction

Slips and falls accidents raise particular ergonomic concerns. In 1996, 21% of all reported non-fatal work injuries (requiring days away from work) were attributed to slip, trip and fall accidents [5.1]. More than 20% of workers that sustain falling injuries miss 31 days at work or more [5.1]. In addition, falling accidents account for a substantial cost of the total medical care. Analyses of US workers compensation claims for the years 1989 and 1990 indicated a 24% contribution of fall-related injuries to the direct cost of all claims filed during this time period [5.2]. Knowledge regarding the specific contribution of slipping to falls-related injuries is sparse. However, available information suggests that falling is often initiated by slipping. For example, based on 1998 injury data analysis in Sweden, 55% and 23% of falls on the same level and to a lower level were attributed to slips, respectively [5.3]. Lloyd and Stevenson [5.4] reported that slips and trips cause 67% and 32% of falls sustained by the elderly and younger population, respectively. Up to 25% of fall-related hip fractures in older adults have resulted from slips [5.5], particularly on contaminated surfaces [5.6].

Causes of slips and falls are complex and involve both human and environmental factors. Research related to the prevention of slips and falls has focused on an environmental factor, the frictional or slip-resistant properties of the shoe/floor interface, a risk factor that has been recognized to be a major predictor of slip events [5.7]. A wide variety of slip resistance testers are already being used in industry to rate slip potential (review chapter by Grönqvist [5.8]). Despite the fact that "friction" between two bodies (shoe/floor interface) seems to be a physical property, slip resistance measurements vary across devices, particularly under contaminant conditions. Moreover, the lack of advanced scientific knowledge relating slip resistance measures to actual slips and falls incidence puts into question the utility, reliability and accuracy of such coefficient

of friction (COF) measurements. Recently developed slip resistance testers have attempted to simulate the velocities of the human foot during initial heel contact, hoping to obtain biomechanically relevant measures of slip resistance [5.9-5.11]. These devices do not yet fully simulate foot dynamics during actual slip events. More human subject testing under varying environmental and biomechanical conditions is needed to derive the temporal profiles of relevant gait variables to be used as input parameters for these slip simulators. In addition to getting us one step closer to the long-term goal of obtaining biomechanically relevant slip resistance measures for a given environment and thus predicting slip potential for a given environment, this information would also be useful in the design of safe industrial slip resistant shoe/floor interfaces.

Thus, the second goal of this study was to provide a quantitative description of heel and foot contact dynamics during slip events on oily surfaces of varying inclination. This information was compared to the foot dynamics on dry floors. An additional goal was to determine biomechanically relevant ranges of parameters needed for further development of slip resistance testers.

5.3 Methods

5.3.1 Subjects

Sixteen healthy young adults (19-30 years old), divided equally by gender, participated in this study. Their height ranged from 1.63 to 1.85 m (mean 1.73 m, S.D. 0.07 m) and mean weight from 62.6 to 82.4 kg (mean 68.7 kg, S.D. 6.8 kg). Exclusionary criteria included a history of neurological or orthopedic disease and any difficulties that would impede descending a ramp.

5.3.2 Experimental Set-Up

A ramp instrumented with a force plate (Bertec, Inc., model 4060A) was used [5.12]. The top surface of the ramp is made of vinyl tile over 1.9 cm thick plywood that is bolted to the frame. The force plate was positioned such that the subjects' left foot landed on the platform during the second or third step of descending the ramp. An Optotrak-3020 motion measurement system was used to accurately (accuracy $\leq$ 1 mm) record body movements. Seven Optotrak LEDs were attached to the left shoulder (acromiom), hip (greater trochanter), knee (lateral femoral condyle), ankle (lateral malleolus) and shoe (3 markers near the heel of the shoe and fifth metatarsal). Motion and foot forces were synchronized and recorded at 350 Hz. The data describing heel and foot dynamics are reported here. A harness system with an overhead trolley was used to catch the subject in case of a fall, without impeding his/her movements.

5.3.3 Experimental Conditions

The independent variables included three ramp angles (0°, 5°, 10°) and two contaminant conditions (dry, oil). For the oily condition, motor oil (10W-40) was uniformly applied across the entire surface of the vinyl tile floor sample that was fixed to the force plate (0.6 m x 0.4 m). The same polyvinyl chloride (PVC) hard-soled shoes were used for all trials. The frictional properties of the shoe-floor-contaminant conditions were assessed using the programmable slip

resistance tester (PSRT) described by Redfern and Bidanda [5.11]. The mean (S.D.) dynamic COF measurements for the dry and oily conditions were 1.41 (0.01) and 0.12 (0.01), respectively. In order to minimize possible cross-contamination, a clean floor sample and a clean pair of shoes were used after each oily condition.

5.3.4 Experimental Design

A full factorial repeated measures experimental design was used such that each subject was tested on all conditions. The ramp was set to the first angle at which the subject was to be tested. Subjects did not have a priori knowledge of the specific contaminant condition (dry or oil). In order to conceal the contaminant condition to the subject, each oily condition was mixed among a random number (1 to 3) of dry trials, during which the subject was unaware of the contaminant condition. This protocol was then repeated for the other two ramp angles. The order of the presentation of the ramp angles was randomized for each testing session.

5.3.5 Walking Protocol

First, informed consent approved by the Institutional Review Board of the University of Pittsburgh was obtained prior to any testing. Next, LEDs were placed on the left side of the subject's body and foot and subjects were then equipped with the safety harness. The subject was then allowed to practice walking down the ramp such that his/her foot hit the force plate. While practicing, he/she was instructed to look straight ahead at the wall and walk as naturally as possible at a comfortable pace throughout the experiment. The subject was instructed to walk to the top of the ramp, stop, continue to face away from the walkway and wait for about 1 minute while listening to loud music, during which time, a contaminant (dry or oil) was applied to the surface of the force plate. The lights in the room were dimmed so the subject could not see the applied contaminant (if any). At that moment, the subject turned and walked down the ramp, while motion and force plate data were recorded.

5.3.6 Data Processing

The description of heel and foot kinematics was focused on a 450 ms time interval (-100 ms to +350 ms, with heel contact time = 0). Heel contact time was determined based on force plate data. For each trial, the LEDs provided position data that were processed in the sagittal plane to derive kinematic variables describing the heel dynamics along the direction of motion and normal to the floor surface. These variables included heel position, linear heel velocity and linear heel acceleration. In addition, the information from the LED placed on the toe combined with the heel's position data was used to obtain the foot-floor angle and foot angular velocity. The heel linear velocity and foot angular velocity information was calculated by numerically differentiating (using a 2-time step differentiation routine) the heel position and foot-floor angle data, respectively. Position data was filtered (least square low pass filter of order 110 and actual cutoff frequency of 12 Hz) to derive acceleration variables.

The overall slip distance (SlipDist in Table 4), defined as the total heel movement that occurred along the floor between the time of heel contact and when the heel stopped moving ($Time_{HeelStop}$ in Table 4), was used to categorize the outcome of a walking trial into 3 possible

events: no-slip (slip distance < 1 cm, NS), slip-recovery (slip distance ≥ 1 cm but came to a stop, SR), and slip-fall (foot never stops, SF).

5.3.7 Statistical Analysis

Specific kinematic and timing parameters were derived and used as the dependent variable in a single-factor within-subject repeated measures design with the independent variable being the outcome of the trial (dry-NS, oily-SR and oily-SF). This statistical analysis was repeated within each ramp angle condition and for each dependent gait parameter listed in Table 4. Standard ANOVA methods associated with repeated measures models were used to investigate whether biomechanical gait parameters were significantly different among dry-NS, oily-SR and oily-SF trials. In addition, Tukey multiple pairwise comparison tests were conducted (when the F-test $p < 0.01$).

Table 4 Definitions/abbreviations of dependent estimated parameters

Abbreviation	Definition
Heel slip/travel distance parameters	
$Time_{HeelStop}$ (Dry-NS and Oil-SR only)	Time of end of heel's slipping motion, measured from heel contact
$Time_{EndRecAttempt}$ (Oil-SF only)	Time of end of recovery attempt, i.e. heel accelerates again leading to fall, measured from heel contact
SlipDist	Slip distance or overall heel movement (forward - rearward) between heel contact and $Time_{HeelStop}$ (Dry-NS and Oil-SR) or between heel contact and $Time_{EndRecAttempt}$ (Oil-SF)
TravDist	Travel distance or total distance (forward + rearward) traveled by the heel between heel contact and $Time_{HeelStop}$ (Dry-NS and Oil-SR) or between heel contact and $Time_{EndRecAttempt}$ (Oil-SF)
$TravDist_{rearward}$	Distance traveled by the heel in the rearward direction, recorded shortly after heel contact
Velocity parameters	
$HeelVelX_{HC}$, $HeelVelY_{HC}$	Linear heel velocity in the direction of motion ($HeelVelX_{HC}$) and normal to the floor surface ($HeelVelY_{HC}$), recorded at heel contact
$FootAngVel_{HC}$	Foot angular velocity at heel contact
MinHeelVelX	Minimum (typically in the rearward direction, i.e. negative) heel velocity recorded after heel contact (in the direction of motion)
$Time_{MinHeelVelX}$	Time of MinHeelVelX, measured from heel contact
$Time_{ForwSlip}$	Time of end of rearward slipping and start of forward slipping, measured from heel contact
MaxHeelVelX	Maximum forward heel velocity, recorded between heel contact and $Time_{HeelStop}$ (Dry-NS and Oil-SR) or between heel contact and $Time_{EndRecAttempt}$ (Oil-SF)
$Time_{MaxHeelVelX}$	Time of MaxHeelVelX, measured from heel contact
Heel acceleration parameters	
$HeelAccX_{HC}$, $HeelAccY_{HC}$	Linear heel acceleration in the direction of motion ($HeelAccX_{HC}$) and normal to the floor surface ($HeelAccY_{HC}$), recorded at heel contact
$HeelAccX_{peak}$	Peak forward heel acceleration, recorded shortly after heel contact (in the direction of motion)
Foot angle parameters	
$FootAngl_{HC}$	Foot-floor angle at heel contact
$FootAngl_{ForwSlip}$	Foot-floor angle at the time of forward slipping, i.e. at $Time_{ForwSlip}$
$Time_{FootFlat}$	Foot-flat time, measured from heel contact

5.4 Results

5.4.1 Outcome Distribution

A minimum 70 to a maximum of 80 dry trials per ramp angle condition were included in the analysis. For level walking on oily floors, 8 out of the16 trials were categorized as SRs, 4 were SFs and the last 4 were NS, i.e., overall slip distance was less than 1 cm (oily-NS trials were not further considered in the analysis). When descending the 5° oily ramp, 7 subjects slipped and recovered while 9 lost balance and fell. On the 10° oily ramp, recovering became more difficult: all trials resulted in falls.

5.4.2 Heel Sliding Patterns and Velocities Recorded Upon Heel Contact

5.4.2.1. Dry Conditions. Profiles of heel movements and velocities were similar for all ramp angle conditions. Typical position data indicated that at the end of the swing phase, the heel was moving in the forward direction and gently brought down onto the floor, at which time it came to a stop (Figure 9). A closer examination of the velocity information showed that at the end of the swing phase, the heel indeed rapidly decelerated, however, upon heel contact a slight sliding motion of the heel occurred along the ramp surface (Figure 10). In the majority of the dry trials, the heel contact heel velocity was positive as noted in Table 5 ($HeelVelX_{HC}$ decreasing on inclined surfaces), indicating a forward motion of the foot as it hit the floor. Then, the heel slid in the rearward direction, and slid forward again (forward slippage started between 15 and 30 ms after heel contact ($Time_{ForwSlip}$ in Table 5)) before coming to a stop between 40 and 60 ms after heel contact ($Time_{HeelStop}$ in Table 5). During this sliding motion of the heel, peak velocities in the rearward (MinHeelVelX in Table 5) and forward (MaxHeelVelX in Table 5) directions did not exceed 0.2 m/s and occurred typically within 5 to 20 ms and 25 to 40 ms after heel contact ($Time_{MinHeelVelX}$ and $Time_{MaxHeelVelX}$ in Table 5), respectively. These velocity peaks occurred sooner on inclined surfaces due to the shorter stance duration compared to walking on level surfaces. Thus, in general a forward-rearward-forward sliding pattern of the heel was observed upon heel contact (Figure 10). However, there were also a significant number of trials (20% and 50% of all dry trials for level walking and inclined surfaces, respectively) where the heel's velocity at heel contact was negative, i.e. the foot was moving in the rearward direction, especially on inclined surfaces. In these trials, the initial forward sliding phase of the heel was missing, and upon heel contact, the heel continued to slide in the rearward direction, then in the forward direction before coming to a stop. On dry conditions, the overall slip distance was on average less than 3 mm (SlipDist in Figure 11a), with a rearward travel distance of about the same magnitude ($TravDist_{rearward}$ in Figure 11b) and a typical total travel distance of 5 mm (TravDist in Figure 11c).

Table 5 Velocity related parameters [mean (SE)]

Angle (°) →	0			5			10	
Outcome → Variable ↓	Dry-NS	Oil-SR	Oil-SF	Dry-NS	Oil-SR	Oil-SF	Dry-NS	Oil-SF
$HeelVelX_{HC}$ (m/s)	0.44 (0.06)	1.01 (0.20)	0.62 (0.41)	0.29 (0.08)	0.37 (0.38)	0.35 (0.30)	0.12 (0.06)	0.54 (0.30)
MinHeelVelX (m/s)	-0.12 (0.01)	-0.27 (0.07)	-0.18 (0.16)	-0.13 (0.01)	-0.42 (0.10)	-0.40 (0.10)	-0.16 (0.01)	-0.35 (0.07)
$Time_{MinHeelVelX}$ (ms)	16.3 (1.2)	53.2 (5.3)	46.4 (6.5)	12.4 (1.4)	37.6 (10.3)	27.0 (6.3)	8.7 (1.1)	31.6 (6.8)
$Time_{ForwSlip}$ (ms)	27.6 (1.3)	78.9 (9.5)	65.7 (3.5)	21.8 (1.6)	61.6 (7.9)	72.4 (17.2)	18.7 (1.1)	54.3 (5.6)
MaxHeelVelX (m/s)	0.10 (0.01)	0.31 (0.06)	0.78 (0.16)	0.12 (0.01)	0.51 (0.07)	0.89 (0.15)	0.14 (0.01)	1.09 (0.11)
$Time_{MaxHeelVelX}$ (ms)	37.2 (1.2)	121.4 (12.4)	171.4 (28.7)	33.0 (1.7)	123.3 (15.0)	172.1 (28.4)	28.5 (1.2)	138.5 (13.0)
$Time_{HeelStop}$ (ms)	52.0 (1.2)	236.8 (30.3)		46.9 (1.9)	266.5 (36.8)		41.7 (1.3)	
$Time_{EndRecAttempt}$ (ms)			263.57 (24.53)			260.0 (29.4)		248.4 (15.7)

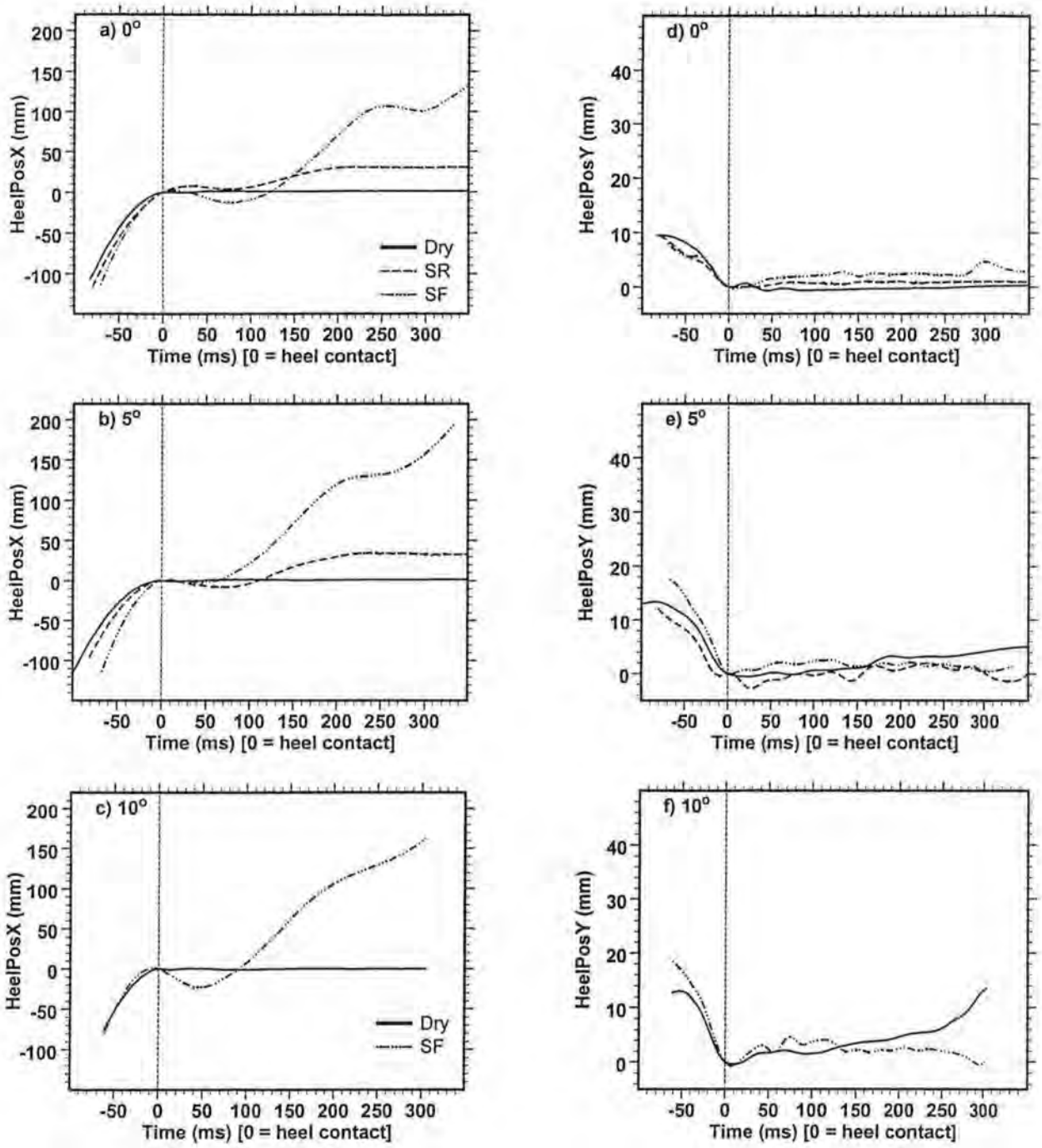

Figure 9 **Typical examples of heel position profiles recorded during dry (no-slip) and oily (slip-recovery and slip-fall) trials: (a) along the direction of motion during level walking, (b) along the direction of motion on the 5° ramp, (c) along the direction of motion on the 10° ramp, (d) normal to the floor surface during level walking, (e) normal to the floor surface on the 5° ramp, and (f) normal to the floor surface on the 10° ramp.**

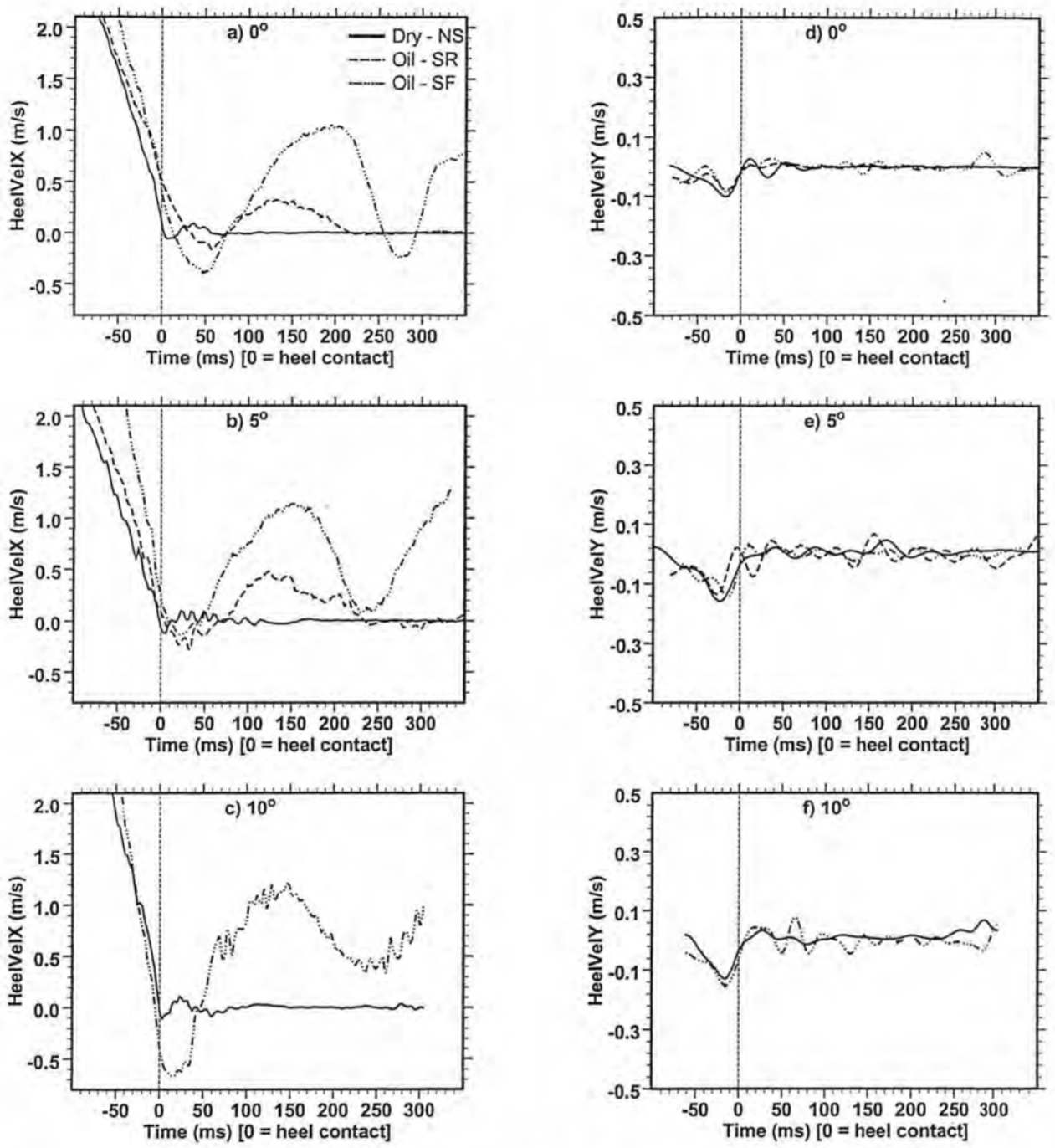

Figure 10 **Typical examples of linear heel velocity profiles recorded during dry (no-slip) and oily (slip-recovery and slip-fall) trials: (a) along the direction of motion during level walking, (b) along the direction of motion on the 5° ramp, (c) along the direction of motion on the 10° ramp, (d) normal to the floor surface during level walking, (e) normal to the floor surface on the 5° ramp, and (f) normal to the floor surface on the 10° ramp.**

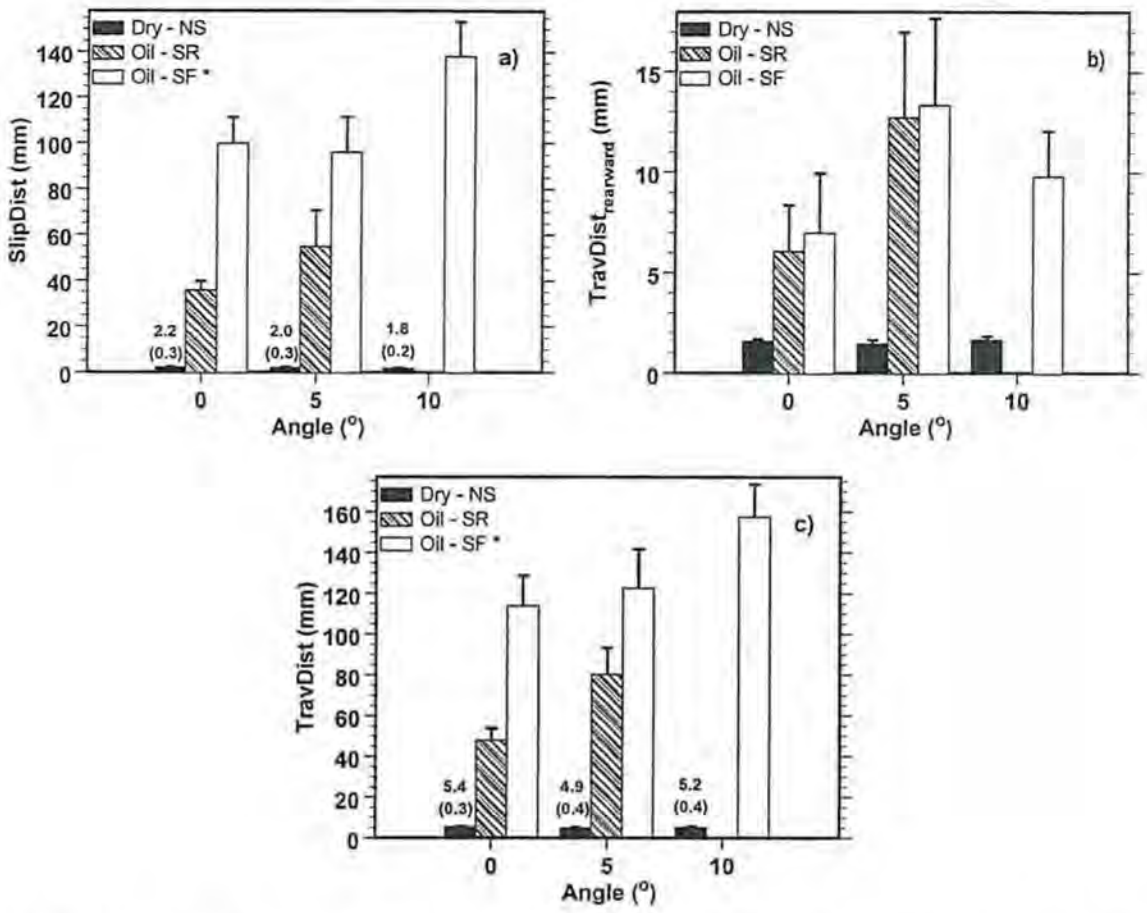

Figure 11 **Mean (SE) slip distance parameters recorded during dry (no-slip) and oily (slip-recovery and slip-fall) trials: (a) overall slip distance, (b) rearward travel distance, and (c) total travel distance. [For fall trials, SlipDist and TravDist recorded up to $Time_{EndRecAttempt}$. Subjects continued slipping after this time.]**

5.4.2.2. Oily Conditions (both Recoveries and Falls). Interestingly, on oily surfaces, similar forward-rearward-forward sliding patterns (Figures 9 and 10) were observed during slip events as for the dry conditions with, in general greater impact heel velocity and, as expected, significantly greater sliding distances and velocities in both directions, later occurrences of the peak velocities and longer times to recover in the SR trials. More specifically, heel contact heel velocity during slip events reached values of 1.0 m/s for level walking, while this difference in $HeelVelX_{HC}$ between dry and oily conditions became less pronounced on inclined surfaces ($HeelVelX_{HC}$ in Table 5). Slip trials were also characterized by significantly faster heel sliding movements in the rearward direction with peak velocities ranging from -0.2 to -0.4 m/s, especially on inclined surfaces (MinHeelVelX in Table 5). These peak rearward sliding velocities were recorded at about 30-55 ms ($Time_{MinHeelVelX}$ in Table 5) after heel contact. After sliding over 5 to 15 mm in the rearward direction ($TravDist_{rearward}$ in Figure 11b), the heel's forward slippage (last phase of the heel's sliding pattern) on oily conditions started, on average, between 50 to 80 ms after heel contact ($Time_{ForwSlip}$ in Table 5). $HeelVelX_{HC}$, MinHeelVelX,

$Time_{MinHeelVelX}$, $TravDist_{rearward}$ and $Time_{ForwSlip}$ values recorded during SR and SF outcomes were comparable.

5.4.2.3. Oily Conditions (Recoveries only). In these experiments, subjects were able to recover (SR) from mean peak forward sliding velocities of about 0.3 and 0.5 m/s (MaxHeelVelX in Table 5) and maximum recorded values of 0.74 and 0.80 m/s on 0° and 5°, respectively (trials "SR1" in Figures 12a and 12b). Typically, MaxHeelVelX occurred between 100 and 150 ms after heel contact ($Time_{MaxHeelVelX}$ in Table 5). Oily conditions produced mean SlipDist (and TravDist) values of about 4 (5) cm and 6 (8) cm on 0° and 5° (Figure 11), respectively. The maximum recorded slip distance (and corresponding travel distance) that subjects were able to recover from was about 6 (7) cm and 14 (15) cm during level walking and when descending the 5° ramp, respectively i.e., recovering from slip distances greater than 14 cm or sliding velocities above 0.7-0.8 m/s was unlikely. Typical heel position and velocity profiles during oily-SR trials (Figures 9 and 10) indicated recovery by about 200 to 250 ms and 250 to 300 ms after heel contact ($Time_{HeelStop}$ in Table 5) for level walking and when descending the 5° ramp, respectively. Occasionally, the heel did not stop slipping until after 300 ms into stance (as depicted in examples "SR2" of Figures 12a - 12b): the slipping motion occurred over a relatively longer period of time, thus resulting in slip distances greater than the 1 cm cutoff value. However, in these occasional trials, the heel was slipping relatively slowly, thus making recovery still possible.

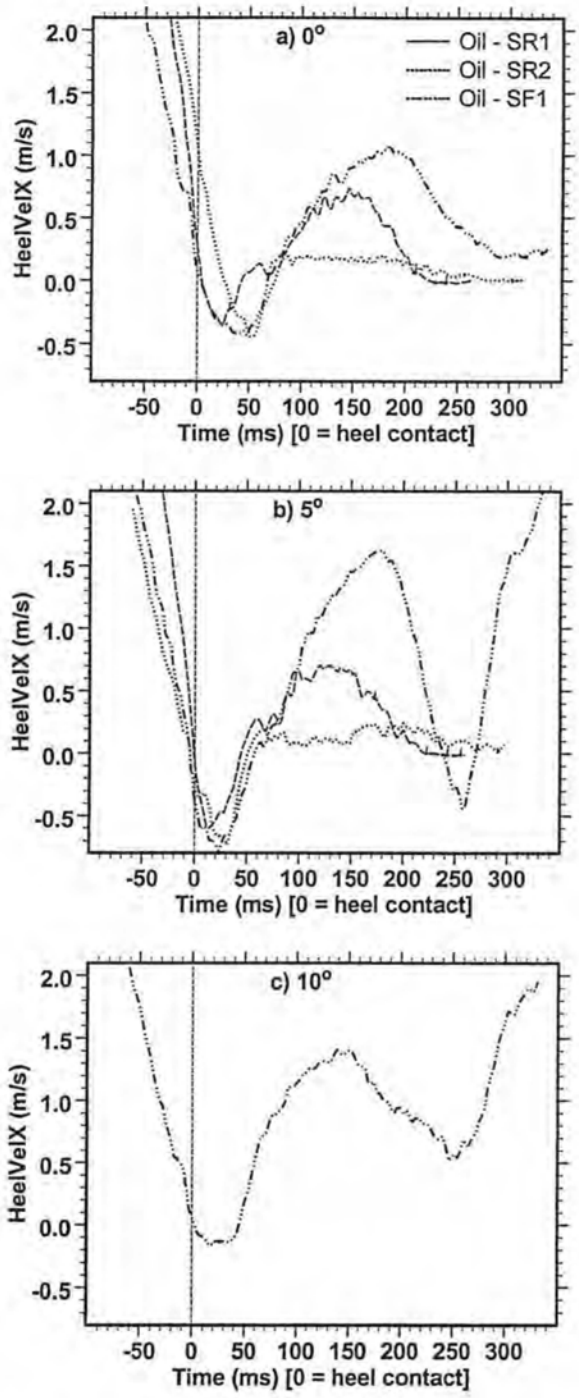

Figure 12 Other examples of heel velocity profiles along the direction of motion recorded on oily (slip-recovery and slip-fall) conditions: (a) during level walking, (b) on the 5° ramp, ad (c) on the 10° ramp.

5.4.2.4. Oily Conditions (Falls only). During the trials resulting in falls, subjects attempted to control the slipping motion of the foot. This reaction was evident as the subject was

able to slow down the heel's slipping movements, achieving a heel velocity local minimum recorded between 200 to 300 ms after heel contact (Figure 10). As ramp angle increased however, it became more difficult for subjects to reach low-level velocities (Figures 9 and 10). In one third of the fall trials on the 0° and 5° ramp, subjects were even able to reverse heel motion (negative HeelVelX values as depicted in the fall trials of Figures 10a and 12b) compared to only 15% when descending the 10° ramp. At the end of this recovery attempt ($Time_{EndRecAttempt}$ in Table 5), the foot accelerated again, eventually leading to a fall (Figures 9 and 10). Before the effects of this corrective reaction, mean peak forward sliding velocities of about 0.8 to 1.1 m/s (MaxHeelVelX (Table 5) increased on inclined surfaces) were typically recorded between 100 and 200 ms after heel contact ($Time_{MaxHeelVelX}$ in Table 5). As expected, the MaxHeelVelX values recorded during fall trials were the greatest among all outcomes and often exceeded normal walking velocity (1-2 m/s), as depicted in the examples of Figure 12. The mean overall slip distance (calculated only up to $Time_{EndRecAttempt}$ in the case of fall trials) was greater than 10-14 cm, with a corresponding total travel distance of 11-16 cm (SlipDist and TravDist in Figure 11).

5.4.3 Heel Acceleration

On the dry conditions, the overall profile of heel acceleration along the direction of motion (HeelAccX) and normal to the floor surface (HeelAccY) was similar across ramp angle conditions (Figure 13). On average, the absolute value of the heel's acceleration along the floor surface at heel contact ($HeelAccX_{HC}$ negative indicating deceleration) decreased from an average of -33.6 (SE 1.9) m/s^2 for level walking to -24.5 (SE 2.2) m/s^2 on the 10° ramp. In the direction normal to the floor surface, the heel dynamics were more controlled with mean heel contact heel acceleration ($HeelAccY_{HC}$) of only 5.2 (SE 0.3), 7.6 (SE 0.5) and 9.2 (SE 0.6) m/s^2 for level walking and when descending the 5° and 10° ramp angle, respectively. In general, there was no significant difference in $HeelAccX_{HC}$ and $HeelAccY_{HC}$ among outcomes. One exception is on the steepest ramp, on which oily trials produced significantly greater $HeelAccX_{HC}$ values (mean of 33.2 (SE 5.3) m/s^2) compared to dry conditions.

During the first 50 ms into stance on dry conditions, mean peak heel accelerations of about 4.5 to 5.0 (SE 0.3) m/s^2 (all ramp angles) were recorded the first 50 ms into stance ($HeelAccX_{peak}$). On oily conditions however, the mean $HeelAccx_{peak}$, recorded between 50 to 100 ms after heel contact, increased significantly to about 11.8 (SE 1.4), 16.0 (SE 1.6) and 24.1 (SE 2.9) m/s^2, reaching values as high as 20, 26 and 45 m/s^2 (fall cases) on level surfaces, 5° and 10° ramps, respectively (examples are shown in Figure 13).

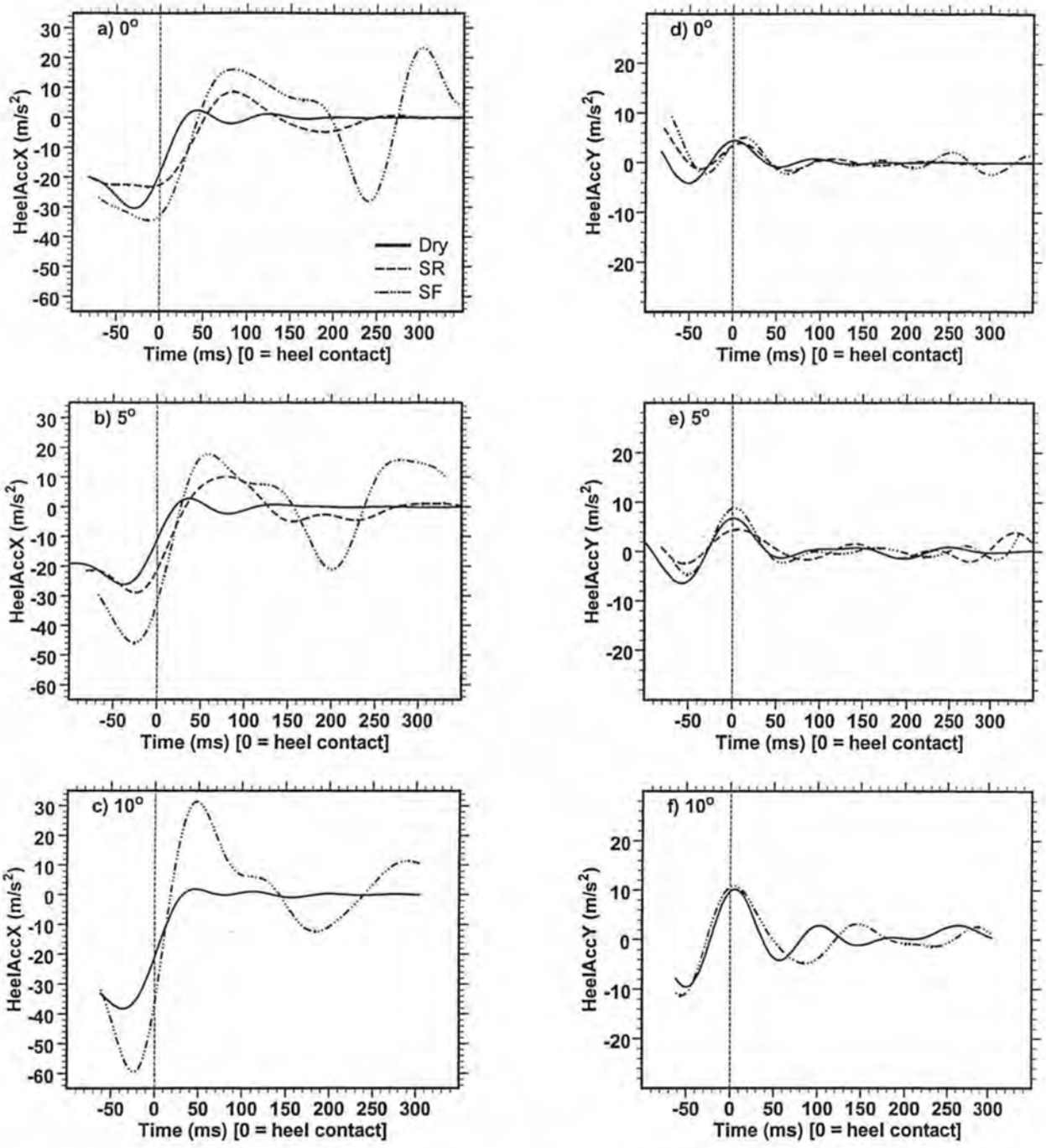

Figure 13 **Typical examples of linear heel acceleration profiles recorded during dry (no-slip) and oily (slip-recovery and slip-fall) trials: (a) along the direction of motion during level walking, (b) along the direction of motion on the 5° ramp, (c) along the direction of motion on the 10° ramp, (d) normal to the floor surface during level walking, (e) normal to the floor surface on the 5° ramp, and (f) normal to the floor surface on the 10° ramp.**

5.4.4 Foot Angle and Foot Angular Velocity

5.4.4.1. Dry Conditions. Foot-ramp angle profiles showed a continuous rotation of the foot from a mean heel contact angle near 20° ($FootAngl_{HC}$ in Table 6), reaching foot flat position 80 to 130 ms after heel contact ($Time_{FootFlat}$ in Table 6, with earlier occurrence on inclined surfaces) or 14-15% of stance time (all ramp angle conditions). At the time of the heel's forward slippage (i.e. $Time_{ForwSlip}$ = 15-30 ms in Table 5), the mean foot angle was about 12-16° ($FootAngl_{ForwSlip}$ in Table 6), thus not having reached foot flat position yet. Foot angular velocity at heel contact ($FootAngVel_{HC}$) increased on inclined surfaces, with mean values of 168°/s (SE 11.8°/s), 220°/s (SE 14.2°/s) and 269°/s (SE 12.4°/s) for level walking and when descending the 5° and 10° ramp, respectively.

Table 6 Foot angle related parameters [mean(SE)]

Angle (°) →	**0**			**5**			**10**	
Outcome → Variable ↓	**Dry-NS**	**Oil-SR**	**Oil-SF**	**Dry-NS**	**Oil-SR**	**Oil-SF**	**Dry-NS**	**Oil-SF**
$FootAngl_{HC}$ (°)	19.3 (0.1)	16.8 (1.5)	20.5 (0.9)	22.0 (0.7)	13.9 (2.4)	20.5 (2.4)	21.1 (0.7)	17.4 (1.7)
$FootAngl_{ForwSlip}$ (°)	12.6 (0.7)	1.5 (0.6)	2.2 (1.8)	16.2 (0.9)	1.3 (0.6)	6.0 (2.7)	15.8 (0.8)	4.3 (1.8)
$Time_{FootFlat}$ (ms)	121.9 (5.7)	118.6 (25.8)	91.4 (17.9)	109.1 (4.4)	86.1 (18.0)	110.8 (13.0)	90.2 (4.2)	90.5 (16.1)

5.4.4.2. Oily conditions. Subjects who recovered from slip events (0° and 5° ramp angle conditions) walked with smaller heel contact foot-floor angles than the values recorded on dry conditions, which were, in general, similar to those observed during falling trials ($FootAngl_{HC}$ in Table 6). Due to the increased time spent in the rearward sliding phase, the heel has almost reached foot flat position when it started slipping forward ($Time_{ForwSlip}$ = 50-80 ms on oily conditions), with foot angles ranging from 1° to 3° for level walking and 1° to 5° on inclined surfaces. As depicted in the examples of Figure 14 (level walking), subjects were able to rotate their foot flat onto the floor even in the fall cases. This is true for all ramp angle conditions. Finally, slip-recovery events were associated with slower foot angular velocities at heel contact ($FootAngVel_{HC}$), with relative reductions from the dry conditions ranging from 25-65% (more pronounced differences recorded for level walking).

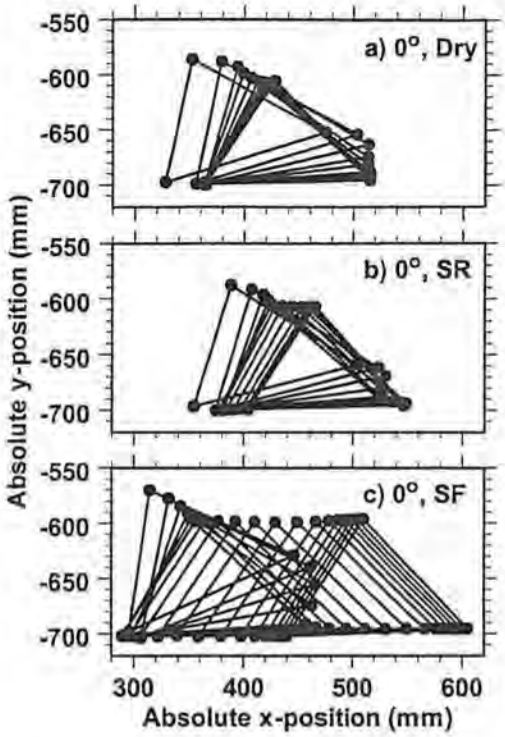

Figure 14 Typical example of stick figures representing foot dynamics on level walking [note that $\Delta t \sim 15$-20 ms (2^{nd} point is heel contact)].

5.5 Discussion

This study described in detail the heel's sliding motion recorded upon heel contact, including slip/travel distance and direction, timing, velocity and acceleration characteristics, which were then compared between dry and oily conditions during level walking and descent of inclined surfaces. In general, heel velocity at heel contact and peak acceleration recorded after heel contact along the floor surface were both greater during slip trials compared to dry conditions. On oily conditions (all ramp angles), the momentum generated during the swing phase and associated with the heel at heel contact and the longer duration of the rearward slipping phase enabled subjects to rotate their foot down onto the floor and achieve almost foot-flat position (even in the SF outcomes) prior to the "dangerous" forward slipping phase. Before loosing balance during the trials that resulted in falls, subjects attempted to control the slipping motion of the foot, sometimes even reversing heel motion before the heel accelerated again, eventually leading to a fall. This corrective reaction was more successful on level surfaces compared to inclined surfaces. In general, the overall slip distance and peak forward sliding velocity associated with fall trials were greater than or equal to 10 cm and 0.8 m/s, respectively. Finally, in these experiments, any attempted recovery from slip distances beyond 14 cm and peak forward sliding velocities above 0.7-0.8 m/s was not successful.

Interestingly, on oily surfaces, heel sliding patterns (e.g., biphasic shape of the heel's velocity profile) were similar to those recorded on dry conditions, however, as expected, they occurred

across greater slip distances and durations. This similarity in the heel contact dynamics between dry and oily conditions suggests that, during the first 100 to 150 ms, "learned" or "programmed" walking patterns of subjects coupled to the environmental conditions (lack of retarding frictional forces) led to the similar shape but more pronounced sliding patterns observed on the oily conditions compared to the dry conditions. Another interpretation of these findings is that corrective reactions to maintain balance did not occur prior to (at least) the first 100 to 150 ms into stance.

Humans usually adopt more cautious gait patterns to decrease slip potential when anticipating slippery surfaces, even when asked to walk as naturally as possible (Chapter 3). These gait adaptations include changes in heel contact dynamics such as a significant decrease in the foot-ramp angle and reduction in the foot angular velocity at heel contact when anticipating slippery surfaces. In the results presented here, special precautions in the protocol were taken to ensure that heel contact dynamics for both dry and contaminated surfaces were compared in the same setting: subjects did not know whether the surface was dry or oily. Therefore, the anticipation effect was a constant factor across all trials. In real-life slip incidents occur often unexpectedly and reproducing the unexpected nature of such slipping accidents in laboratory settings has proven to be difficult. Thus, findings reported here (and all other slip and fall investigations using human subjects) should be applied conservatively in the research directed towards the design criteria of "safe" shoe/floor interfaces and the development of slip resistance testers designed to reproduce foot movements during locomotion.

Previously published studies reported some parameters related to heel contact dynamics during slip events on level surfaces (inclined surfaces were not investigated). In general, the results reported here on level surfaces were in agreement with findings of earlier studies. For example, on dry conditions, the heel sliding motion recorded upon heel contact was also observed in previous investigations [5.13-5.14]. The description of typical slip events (sliding patterns and heel velocity profiles) seems consistent across these same studies, although specific magnitude and timing parameters of heel contact dynamics were not always reported. Strandberg and Lanshammar [5.14] reported a wide range of heel contact patterns, especially for the heel velocity, with velocity magnitudes ranging from 0.14 and 0.68 m/s and associated with standard deviations as large as 0.52 m/s. This wide range in heel contact strategies was also noticed across trials conducted in this study.

Another gait parameter that was the subject of previous investigations is the foot angle with respect to the floor. At heel contact, Strandberg and Lanshammar [5.14] published similar results (~ 21-22° (SD 5°)) to the ones computed here, which were, however, smaller than foot-floor angle values reported by Leamon and Son [5.15] (~30°). The timing of the forward slipping phase ($Time_{ForwSlip}$ here) was in accordance to findings of Perkins [5.13] and Strandberg and Lanshammar [5.14] (about 50-100 ms after heel contact). At that time, in this study, the foot was almost flat (mean $FootAngl_{ForwSlip}$ of 1 to 3°), while Strandberg and Lanshammar [5.14] reported a mean value of 5.5°, associated however with a standard deviation of 5.9°. Finally, in these experiments, all subjects were able to rotate their foot flat onto the floor even in the trials that resulted in fall outcomes. Perkins [5.13], on the other hand, discussed occasional fall trials (associated with large impact foot-ramp angles) during which the heel started forward slipping right at heel contact, did not slow down and the foot never reached foot flat position.

As expected, recovering from slip events becomes more challenging as slip distances and peak forward sliding velocity increase. All trials conducted by Perkins [5.13] and characterized by with slip distances greater than 10 to 15 cm resulted in falls, a result that was later confirmed by Strandberg and Lanshammar [5.14] who suggested that a slip is likely to result in a fall if the slip distance is in excess of 10 cm or the peak heel sliding velocity is greater than 0.5 m/s. In order to compare these values to findings of this study, the slip distance and peak forward sliding velocity distributions of the slip-recovery cases were more closely examined: 90% and 75% of all recovery trials (all ramp angles) were associated with a slip distance and a peak forward heel sliding velocity less than or equal to 9.4 cm and 0.5 m/s, respectively. Thus, the 10 cm slip distance and 0.5 m/s sliding velocity "limits" put forward by Perkins [5.13] and Strandberg and Lanshammar [5.14] are consistent with the characteristics of slip events recorded here. However, it is important to note that falls can also result from slip distances and sliding velocities below those levels. In fact, the data distribution of fall events indicated that 25% of the fall cases were characterized by slip distances less than or equal to 7.4 cm and sliding velocities below or equal to 0.55 m/s.

In conclusion, this study provided a detailed description of normal heel contact dynamics during locomotion on level and inclined vinyl flooring surfaces, which were then compared to those recorded on relatively slippery conditions. This information, valuable for the development of slip resistance testers, is however specific to the environmental conditions (material and frictional properties of the shoe/floor interface) and task performed by the subjects (e.g. pushing or load carrying). Thus, further research under a variety of conditions and activities is needed to obtain the complete biomechanically achievable range of gait parameters relevant to slips and falls. The recently developed slip resistance testers aim at reproducing heel velocity and foot orientation profiles during slip events. This study underlined the importance of other variables such as heel acceleration, which will improve slip resistance measures if incorporated in the heel dynamics of the robots. Finally, in addition to providing input parameters for these testers, the results of this investigation offer the potential of comparing the slip prediction capability of slip testers (using COF measures) against real slip events (for a given environmental condition).

6.0 SCIENTIFIC REPORT III
BIOMECHANICS OF SLIPS

6.1 Abstract

A substantial fraction of injuries in the workplace is attributed to slips and falls. Research efforts directed towards the prevention of slip-precipitated falls are challenged by the complex causes of such accidents, including environmental and human factors. In particular, biomechanical corrective responses to slip events have not been investigated yet. The third goal of this research was to quantitatively describe ground reaction forces and joint biomechanics (movements and moments) during actual slips, including strategies evoked by these perturbations to avoid a fall. Sixteen subjects walked onto a possibly oily vinyl tile floor, while ground reaction forces and body motion were recorded at 350 Hz. The onset of corrective actions taken by the body to recover from slips became evident at about 25% into stance and continued until about 45% into stance, i.e. on average between 190 and 350 ms after heel contact. These included increased flexion moment at the knee and extensor activity at the hip. By midstance, compensatory knee and hip reactive moments were recorded. The ankle, on the other hand, acted as a passive joint during fall trials. Joint kinematics showed increased knee flexion, allowing subjects to rotate the shank forward in an attempt to bring the foot back near the body. Finally, only minimal changes in torso orientation were recorded during slip-recovery events. During slip-fall outcomes, the sliding foot eventually led to a loss of balance evident in the increasing rearward lean of the torso in the second half of the stance. Thus, this study indicates that humans generate corrective reactions to slips. The timing and magnitude of the responses are critical to the success of arresting an impending fall.

6.2 Introduction

Falling is often listed among the leading causes of unintentional fatal injuries in industrial countries [6.1], and accounts for the largest fraction (20.6%) of injury-related emergency departments visits [6.2]. In the workplace, slips and falls raise particular ergonomic concerns. In 1996, 21% of all reported non-fatal work injuries were attributed to slip, trip and fall accidents [6.3]. Moreover, analyses of US workers compensation claims for the years 1989 and 1990 indicated a substantial 24% contribution of fall-related injuries to the direct cost of all claims filed during this time period [6.4]. Knowledge regarding the specific contribution of slipping to fall-related injuries is sparse. However, available information suggests that slipping is indeed often the underlying mechanism of equilibrium loss and ultimately falling. Lloyd and Stevenson [6.5] reported that slips and trips cause 67% and 32% of falls sustained by the elderly and younger population, respectively. Up to 25% of fall-related hip fractures in older adults have resulted from slips [6.6], particularly on wet and slippery surfaces [6.7].

Causes of slip events are complex and involve the interaction of human factors, such as gait biomechanics, and environmental factors including the frictional properties of the shoe/floor interface. Gait studies play an important role in the research directed towards the prevention of slip and fall accidents for two major reasons. First, in order to obtain biomechanically relevant slip resistance measures of the shoe/floor interface, researchers have recognized the necessity to develop tribometers that faithfully simulate heel and foot dynamics during actual slip events [6.8-6.10]. Second, biomechanics of human reactions to slippery surfaces partially determine the

outcome of a slipping perturbation and are therefore important in understanding the complex relationship between gait and falls. Prior studies have examined specific biomechanical parameters and their relevance to slip/fall potential. Such parameters include ground reaction forces, foot contact angle, heel velocity and stride length [6.11-6.20]. Redfern and Dipasquale [6.18] have also described lower extremity joint moments on both level and inclined dry surfaces. In order to avoid a slip accident on a contaminated surface, the body must generate a quick and effective response to re-establish balance and maintain an upright posture, while continuing with the locomotion task. The strength and control demands experienced by the musculoskeletal system during this corrective response are reflected in the joint moments (ankle, knee and hip). To our knowledge, such corrective responses (postural adjustment and moments) have not been investigated on real slippery surfaces. Instead, reactions to "simulated slip perturbations" or translation of the supporting surface [6.21-6.24] have been examined.

Thus, the third main goal of this research project was to provide a quantitative description of ground reaction forces and joint biomechanics (movements and moments) during slip and fall events on level surfaces, including a description of the corrective reactions elicited by these slipping perturbations.

6.3 Methods

6.3.1 Subjects

Sixteen healthy (no history of neurological or orthopedic disease) subjects divided equally by gender were voluntary recruited for these gait experiments. Their ages ranged from 19 to 30 years (mean 23 years, S.D. 4 years) and weight from 62.6 to 82.4 kg (mean 68.7 kg, S.D. 6.8 kg).

6.3.2 Experimental Set-Up

A force plate (Bertec, Inc, model 4060A) instrumented walkway built, as part of previous gait experiments [6.18], was used in this project. The floor's top surface is made of vinyl tile over 1.9 cm thick plywood. An Optotrak-3020 motion measurement system tracked LEDs (accuracy $\leq$ 1mm) attached to the left shoulder (acromiom), hip (greater trochanter), knee (lateral femoral condyle), ankle (lateral malleolus) and shoe (3 markers near the heel of the shoe and toe fifth metatarsal) of the subject. LABVIEW was used to synchronize and collect ground reaction forces and foot/body motion data at 350 Hz. A harness system with an overhead trolley caught the subject in case of a fall.

6.3.3 Experimental Conditions and Experimental Design

Two possible contaminant conditions (dry and oil) were used. For the oily condition, 10W-40 motor oil was applied such that there was a uniform application across the entire surface of a vinyl tile floor sample (0.6 m x 0.4 m) that was fixed to the force plate. The same polyvinylchloride (PVC) hard-soled shoes were worn for all trials. The frictional properties of the shoe-floor-contaminant conditions were measured using the Programmable Slip Resistance Tester developed by Redfern and Bidanda [6.10]. The mean (S.D.) dynamic COF measurements for the dry and oily conditions were 1.41 (0.01) and 0.12 (0.01), respectively. Each subject was tested on all conditions. In order to conceal the contaminant condition to the subject, the oily

condition was mixed among a random number (1 to 3) of dry trials, during which the subject was unaware of the contaminant condition.

6.3.4 Walking Protocol

First, informed consent approved by the Institutional Review Board of the University of Pittsburgh was obtained prior to any testing. After attaching the LEDs, subjects donned the harness and were instructed to walk as naturally as possible at a comfortable pace. Then, they were allowed to practice walking such that their left foot hit the force plate. Prior to each trial, the subject walked to the top of the ramp and, upon reaching the platform, continued to face away from the walkway and waited for about 1 minute while listening to loud music. During this waiting period, a contaminant was applied (if required) to the surface at the force plate. (The lights in the room were dimmed throughout experiment so that subjects could not perceive the applied contaminant.) At the end of the waiting period, the subject turned around and started walking while looking straight ahead at the wall on the opposite side of the room. Upon completing the trial, if the floor surface was contaminated, the shoes and floor sample were changed.

6.3.5 Data Processing

Ground reaction forces and motion data were processed to retrieve specific gait measures (Table 7). Shear (anterior-posterior) and normal ground reaction forces were normalized to the subject's body weight. The required coefficient of friction (RCOF) on dry surfaces or the achieved coefficient of friction (ACOF) on oily surfaces was calculated by dividing the shear ground reaction force by the normal ground reaction force for each trial [6.18]. Ankle, knee and hip moment were calculated based on ground reaction forces, body dynamics and body segmental properties derived using Plagenhoef's formulas [6.25] with general anthropometrical subject characteristics. Stance duration of dry trials was used to normalize time, with 0% being heel contact and 100% representing toe-off the force plate. The mean (S.D.) stance duration was 776 (108) ms.

Table 7 Definitions/abbreviations of dependent estimated parameters

Kinetic Parameters
Peak shear force ($Shear_{peak}$)
Time of peak shear force ($Shear_{Tpeak}$)
Timing of shear forces onset in ms from heel contact ($ShearOnset_T$)
Peak normal force ($Norm_{peak}$)
Time of peak normal force ($Norm_{Tpeak}$)
Peak shear-to-normal force ratio ($RCOF_{peak}$ on dry surfaces and ACOF on oily floors)
Time of peak RCOF/ACOF in percent of stance ($RCOF_{Tpeak}$/$ACOF_{Tpeak}$)
Ankle moment evaluated at 30% and 50% into stance ($AnklMom_{30}$, $AnklMom_{50}$,)
Knee moment evaluated at 30% and 50% into stance ($KneeMom_{30}$, $KneeMom_{50}$,)
Hip moment evaluated at 30% and 50% into stance ($HipMom_{30}$, $HipMom_{50}$,)
COP position relative to ankle, evaluated at 30% and 50% (COP_Ankl_{30}, COP_Ankl_{50})
Kinematic Parameters
Ankle angle evaluated at heel contact, 30% and 50% ($AnklAngl_{HC}$, $AnklAngl_{30}$, $AnklAngl_{50}$)
Knee angle evaluated at heel contact, 30% and 50% ($KneeAngl_{HC}$, $KneeAngl_{30}$, $KneeAngl_{50}$)
Torso-floor angle evaluated at heel contact, 30% and 50% ($TorsAngl_{HC}$, $TorsAngl_{30}$, $TorsAngl_{50}$)

Kinematic variables in the sagittal plane described lower extremity joint angles and torso orientation with respect to the floor. Position data were filtered (least square low pass filter of order 110 and actual cutoff frequency of 12 Hz) only to derive acceleration variables used in lower extremity joint moments calculations. Trials were categorized into no-slip (NS), slip-with-recovery (SR) and slip-and-fall (SF) by examining the slip distance of the heel. Based on the slip distance distribution recorded on dry surfaces, a cutoff value of 1 cm was chosen to differentiate SR from NS trials on oily surfaces. Two possible criteria were used to classify an outcome as a fall: 1) the subject lost balance and eventually sat in the harness or 2) it was determined, based on the heel's kinematic data, that the foot slid to the end of the force plate and never stopped. A total of 80 dry trials were included in the analysis. When walking on oily floors, 8 out of the16 trials were categorized as SRs, 4 were SFs and the last 4 were NS. (Oily-NS trials were not further considered in the analysis).

6.3.6 Statistical Analysis

Mean profiles and specific point-in-time values of kinetic and kinematic gait variables of interest were first established on dry surfaces prior to comparing gait biomechanics among different trial outcomes recorded on oily surfaces. Gait parameters were compared among outcomes by performing standard within-subject ANOVA tests associated with single-factor repeated measures designs with the dependent variable being the specific gait parameter (Table 7) and the independent variables including the outcome, i.e. dry-NS, oily-SR and oily-SF trials. When a p-value of less than 0.01 was found in the F-test of the ANOVAs, Tukey multiple pairwise comparison tests were used to further investigate differences in a dependent measure between outcomes.

6.4 Results

6.4.1 Ground Reaction Forces and RCOF/ACOF

6.4.1.1. Dry conditions. The typical biphasic shear ground reaction force reached its maximum of 1.2 N/kg at about 20% into stance ($Shear_{peak}$ and $Shear_{Tpeak}$ in Table 8), while the end of the loading phase marked by the first peak of the normal ground reaction force happened later in the stance ($Norm_{peak}$ and $Norm_{Tpeak}$ in Table 8, Figure 15a). As the non-supporting leg completed its swing phase and prepared for heel contact, the shear ground reaction force reversed direction to reach its minimum at about 80-85% into stance, and the second local maximum in the normal ground reaction force was recorded (Figure 15a). During the last 10-15% of stance (double-leg support) characterized by heel contact of the other foot, ground reaction forces under the rearward supporting foot returned to near-0 levels. As a result of these ground reaction force profiles, the peak RCOF occurred before the end of the loading phase ($RCOF_{peak}$ and $RCOF_{Tpeak}$ in Table 8), after which time, it closely followed the shape of the shears during most of the stance (Figure 15b).

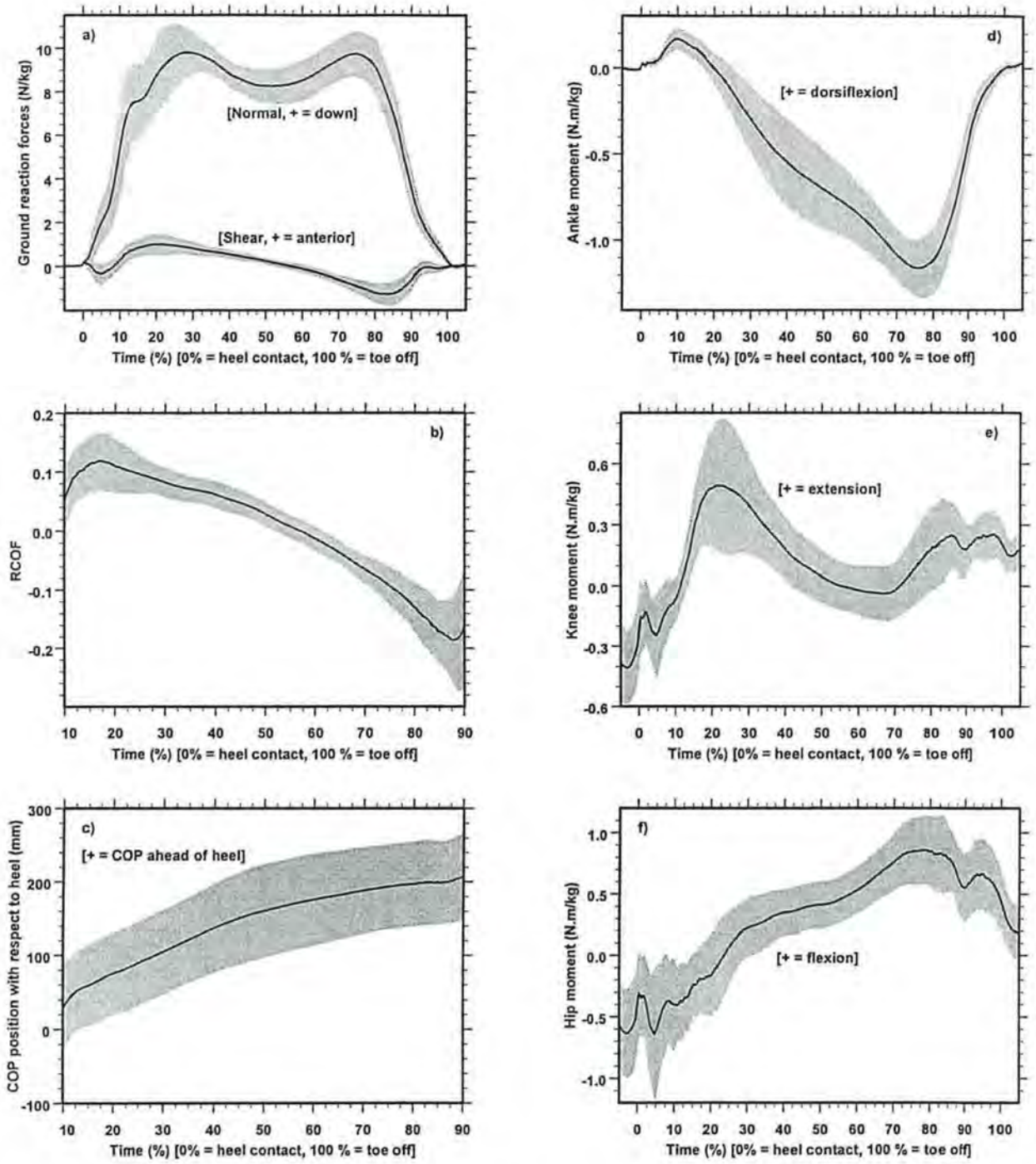

Figure 15 **Characteristic profile (mean ± 1 SD) of kinetic variables (dry conditions): (a) ground reaction forces (normalized to body weight), (b) RCOF (time truncated to 10%-90% to avoid "instability" region when both shear and normal ground reaction forces are near 0.), (c) center of pressure position with respect to heel, (d)-(f) ankle, knee and hip moment (normalized to body weight).**

Table 8 Mean (S.D.) of selected kinetic parameters (across all subjects) and statistical comparisons

Dependent Variable	Mean (SD)			Statistical Analysis p-value[1] / Tukey[2]
	Dry/NS	Oil/SR	Oil/SF	
$Shear_{peak}$ (N/kg)	1.19 (0.41)	0.93 (0.21)	0.97 (0.20)	< 0.01 / (Dry) - (SR & SF)
$Shear_{Tpeak}$ (%)	19.3 (5.2)	26.9 (2.9)	29.1 (3.9)	< 0.01 / (Dry) - (SR & SF)
$ShearOnset_T$ (ms)	5.6 (5.4)	84.0 (20.0)	77.9 (12.7)	< 0.01 / (Dry) - (SR & SF)
$Norm_{peak}$ (N/kg)	10.34 (1.22)	10.52 (1.74)	9.76 (0.72)	not significant
$Norm_{Tpeak}$ (%)	28.1 (5.9)	29.8 (4.2)	32.2 (3.8)	not significant
$RCOF_{peak}$ (dry) or $ACOF_{peak}$ (oil)	0.14 (0.04)	0.10 (0.02)	0.11 (0.02)	< 0.01 / (Dry) - (SR & SF)
$RCOF_{Tpeak}$ (dry) or $ACOF_{Tpeak}$ (oil)	15.7 (3.1)	21.4 (4.6)	23.2 (7.1)	< 0.01 / (Dry) - (SR & SF)
$AnklMom_{30}$ [+ = dorsiflexion] (N.m/kg)	-0.30 (0.19)	-0.16 (0.14)	0.10 (0.09)	< 0.01 / (Dry) - (SR) - (SF)
$AnklMom_{50}$ [+ = dorsiflexion] (N.m/kg)	-0.71 (0.23)	-0.57 (0.13)	0.06 (0.06)	< 0.01 / (Dry & SR) - (SF)
$KneeMom_{30}$ [+ = extension] (N.m/kg)	0.40 (0.24)	0.36 (0.37)	0.16 (0.19)	< 0.05 / not performed
$KneeMom_{50}$ [+ = extension] (N.m/kg)	0.05 (0.13)	0.20 (0.24)	1.05 (0.15)	< 0.01 / (Dry) - (SR) - (SF)
$HipMom_{30}$ [+ = flexion] (N.m/kg)	0.22 (0.24)	0.00 (0.34)	-0.06 (0.21)	< 0.01 / (Dry) - (SR & SF)
$HipMom_{50}$ [+ = flexion] (N.m/kg)	0.41 (0.19)	0.51 (0.28)	0.78 (0.01)	< 0.01 / (Dry & SR) - (SF)
COP_Heel_{30} (mm)	104 (19)	85 (18)	65 (12)	< 0.01 / (Dry) - (SR) - (SF)
COP_Heel_{50} (mm)	159 (31)	136 (23)	74 (8)	< 0.01 / (Dry & SR) - (SF)

[1] Results of the F-test (ANOVAs) investigating outcome differences.

[2] Results of Tukey multiple pairwise comparison tests, performed only when F-test showed p-value (associated with outcome factor) less than or equal to 0.01: outcomes with comparable characteristics are grouped within parenthesis.

6.4.1.2. Oily surfaces. Despite the varied profiles of ground reaction forces across subjects, a number of characteristics were identified during slip trials. The onset of the shear ground reaction force, determined by the time the force crossed the 0.2 N/kg level, was significantly delayed on oily surfaces ($ShearOnset_T$ in Table 8). The rearward peak in the shear ground reaction force usually recorded shortly after heel contact during locomotion on dry surfaces was non-existent during the majority of the oily trials (Figure 16b). In general, the peak magnitude of the shear ground reaction force was significantly reduced during slip events and occurred later in stance, however ANOVA tests on $Norm_{peak}$ and $Norm_{Tpeak}$ revealed comparable

values across outcomes ($Shear_{peak}$, $Shear_{Tpeak}$, $Norm_{peak}$ and $Norm_{Tpeak}$ in Table 8). As expected, the lack of shoe/floor friction during slip events prevented "normal" levels of shear to be generated, thus decreasing ACOF values compared to dry frictional requirements, findings confirmed with ANOVA tests ($RCOF_{peak}/ACOF_{peak}$ in Table 8). Due to the delay in $Shear_{Tpeak}$, the peak shear-to-normal force ratio occurred significantly later on oily floors ($RCOF_{Tpeak}/ACOF_{Tpeak}$ in Table 8). Finally, after a slip developed, a decrease in the shear ground reaction force (25-40% into stance, Figure 16b), sometimes even reversing direction was observed. This reduction is believed to be related to a corrective response or attempt of bringing the foot back near the body (decelerating slipping motion of the heel reported in Section 5). The extent of this decrease in the shears varied across slip trials.

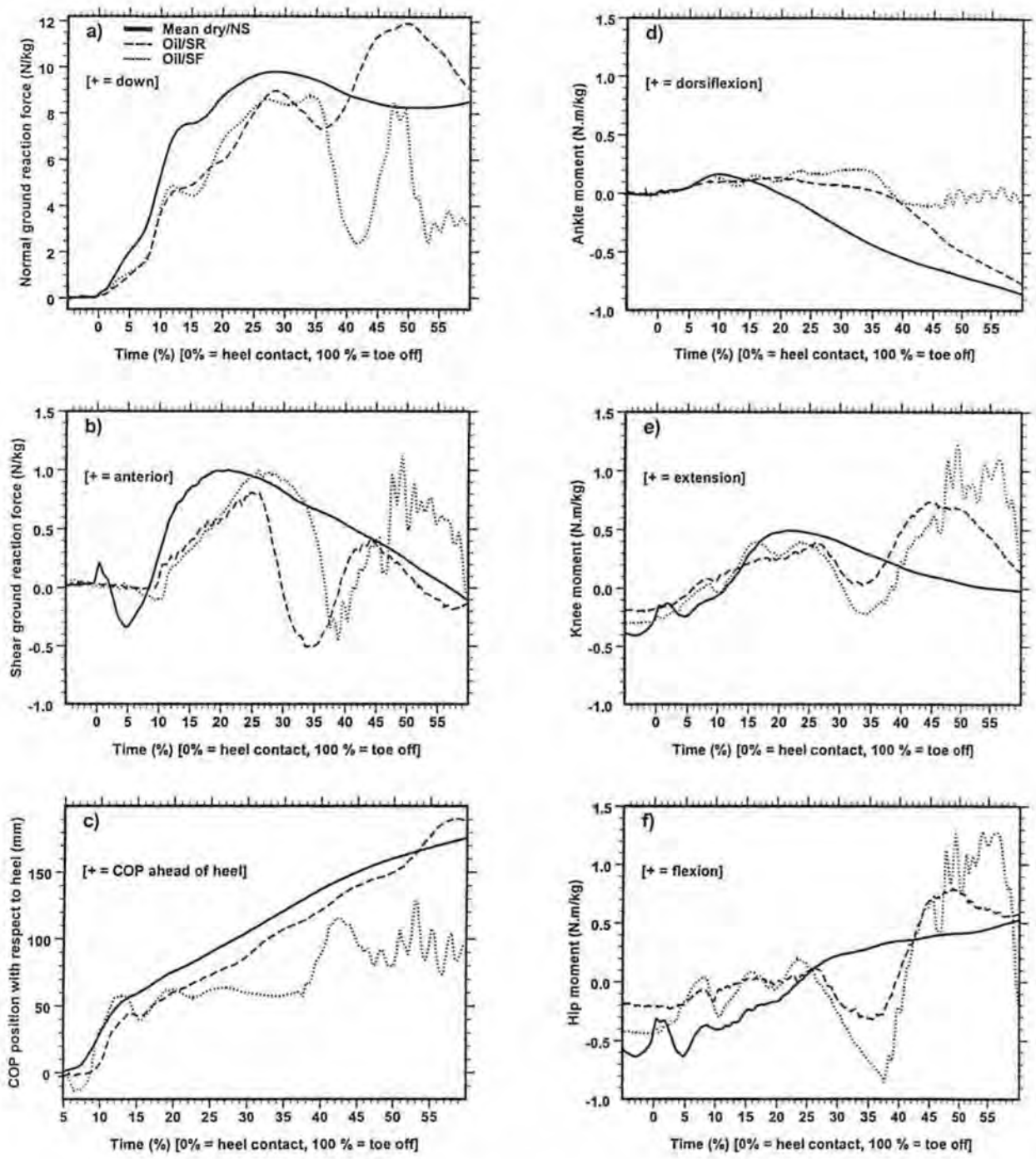

Figure 16 **Profile of kinetic variables on dry conditions (mean) compared to typical profiles during oil/SR and oil/SF events: (a) normal ground reaction force (normalized to body weight), (b) shear ground reaction force (normalized to body weight), (c) center of pressure position with respect to heel, (d)-(f) ankle, knee and hip moment (normalized to body weight).**

6.4.2 Center of Pressure (COP)

When walking on dry surfaces, the continuous forward transfer of body weight moved the COP in the same direction along the supporting foot (Figure 15c). During oil/SF trials, the swing phase of the non-supporting leg and the transfer of body weight over the base of support did not seem to be completed. This is evident in the shape of the normal ground reaction force (Figure 16a) and in the progression of the COP, which stayed close to the heel in fall cases (Figure 16c, COP_Heel_{30} and COP_Heel_{50} in Table 8). During oil/SR trials, the COP-heel distance along the floor was significantly reduced during the loading phase, however by midstance, COP_Heel_{50} values were comparable to dry conditions indicating signs of recovery (Figure 16c, COP_Heel_{30} and COP_Heel_{50} in Table 8).

6.4.3 Lower Extremity Joint Moments

6.4.3.1. Dry conditions. After the loading phase, muscle moments generated at the ankle, knee and hip joints revealed plantarflexor, extensor and flexor patterns during most of the stance, respectively (Figures 15d - 15f).

6.4.3.2. Oily surfaces. In general, the plantarflexion muscle moment generated at the ankle significantly decreased with the severity of the slip (Figure 16d, $AnklMom_{30}$ and $AnklMom_{50}$ in Table 8). In the most severe slips leading to fall outcomes, the ankle moment profile remained at very low levels throughout stance due to the COP's proximity to the ankle joint. By midstance, post-hoc tests revealed comparable values between dry and oil/SR trials, once again indicating signs of recovery ($AnklMom_{50}$ in Table 8).

The knee and hip moments appeared to be responsible for corrective reactions attempted between 25 and 45% into stance during slip events. A significant bias (compared to dry recordings) towards flexor patterns was observed at the knee during slip outcomes, especially during SFs (Figure 16e, $KneeMom_{30}$ in Table 8). By midstance, the majority of slip trials were associated with a compensatory reaction (extensor bias shown in Figure 16e and $KneeMom_{50}$ in Table 8). Since the ankle acted almost as a passive joint during SF events, the ground reaction forces, especially the shears (acting at a larger moment arm than the normal ground reaction force (COP close to ankle)), largely affected the profile of the knee moment. A significant extensor bias in the hip moment, more pronounced during trials resulting in falls, was recorded during slip events (Figure 16f). Tukey multiple comparison tests on $HipMom_{30}$ revealed significant differences among dry and SR/SF outcomes (Table 8). By midstance, just as for the knee moment, a compensatory reaction is evident in the motor patterns of the hip, with no significant differences between SR and dry trials ($HipMom_{50}$ in Table 8).

6.4.4 Joint Kinematics and Torso Orientation

6.4.4.1. Dry conditions. At heel contact, the ankle was slightly flexed but quickly reached its peak extension angle (around 10%, Figure 17a) as the foot rotated down on the floor, achieving flat position at about 15% into stance. Consequently, the continuous flexion of the ankle until about 80% into stance was attributed to the forward rotation of the shank. At that time, the preparation for toe-off phase started sending the ankle into extension.

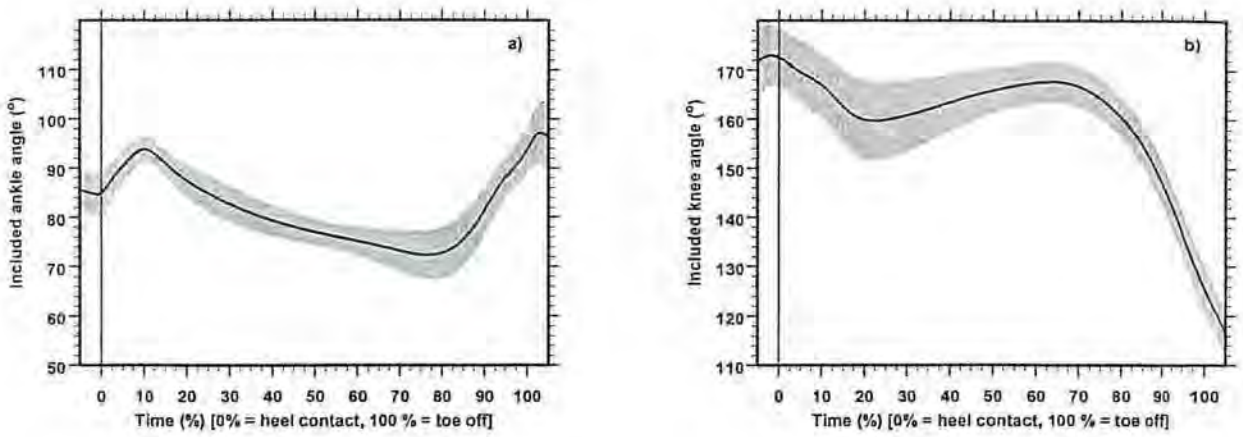

Figure 17 Characteristic profile (mean ± 1 SD) of postural variables (dry conditions): (a) included ankle angle, (b) included knee angle.

During the first 20-30% of stance (i.e., double support phase), individual analyses of the shank and upper leg orientation with respect to the floor showed that the slight flexion of the knee was mainly caused by the forward rotation of the shank (Figures 17b and 18). Then, as the body was moved forward over the base of support, the upper leg's forward rotation became the main factor responsible for the knee angle changes resulting in maximum knee extension at about 60-80% into stance (Figure 17b). During the last stance phase (> 60-80%) characterized by the movement of the body's CG past the single leg base of support, the knee went into flexion again as the subject prepared for heel contact of the swing leg and toe off of the supporting foot (Figure 17b). Finally, only small variations in torso orientation (few degrees) were recorded during stance (Figure 18).

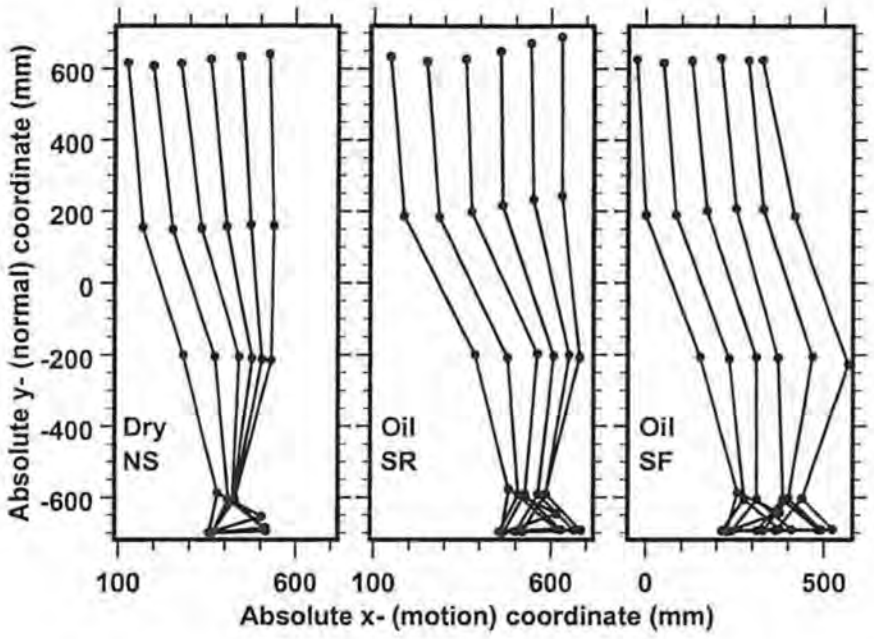

Figure 18 Typical stick figures representing body posture on dry conditions (NS) and oily surfaces (SR and SF events) at heel contact, 10%, 20%, 30%, 40% and 50% into stance

6.4.4.2. Oily surfaces. At heel contact, ankle angle was not significantly different among outcomes ($AnklAngl_{HC}$ in Table 9). At 30% into stance, as a consequence of the slipping motion of the heel (Section 5), the shank did not follow the sliding foot, but appeared slowed its forward rotation (Figure 18), sending the ankle into plantarflexion (Figure 19a). ANOVA tests confirmed significantly increased $AnklAngl_{30}$ values with increasing slip severity (Table 9). Another consequence of the slipping motion of the foot was the increase in knee extension recorded during fall outcomes (Figure 19b and $KneeAngl_{30}$ in Table 9).

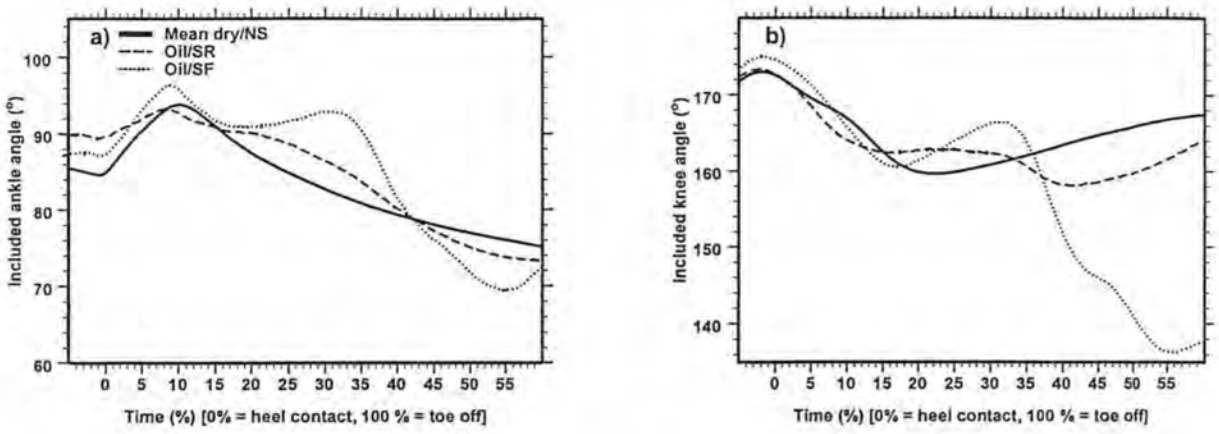

Figure 19 Profile of postural variables on dry conditions (mean) compared to typical profiles during oil/SR and oil/SF events: (a) included ankle angle, (b) included knee angle.

By 50% into stance, the included ankle angle profile during SR cases was similar to characteristics recorded on dry conditions (recovery has occurred), while in the SF cases, the differences in the included ankle angle indicated a slight over compensation with smaller $AnklAngl_{50}$ values (Figure 19a and $AnklAngl_{50}$ in Table 9). This complete or attempted recovery is reflected as a flexion reaction of the knee, especially evident in the fall cases with an average 20° smaller included knee angle compared to dry values (Figures 18, 19b and $KneeAngl_{50}$ in Table 9). A closer examination of the individual body segment orientation data indicated that knee flexion is achieved by a rearward orientation of the upper leg, coupled with the forward shank forward rotation (Figure 18). Finally, this knee flexion reaction was coincident and believed to be related to the recovery attempt of bringing the foot back under the body and stopping the heel's sliding motion. Interestingly, the trunk's orientation did not seem to be affected by the outcome until midstance when the subject lost balance in the fall cases (Figure 18), with the differences in torso orientation being significant only between SF and dry trials at 50% into stance ($TorsAngl_{HC}$, $TorsAngl_{30}$ and $TorsAngl_{50}$ in Table 9).

Table 9 Mean (SD) of selected kinematic parameters (across all subjects) and statistical comparisons

Dependent Variable	Mean (SD)			Statistical Analysis p-value[1] / Tukey[2]
	Dry/NS	Oil/SR	Oil/SF	
$AnklAngl_{HC}$ (°)	84.9 (3.8)	85.4 (2.7)	88.6 (4.8)	not significant
$AnklAngl_{30}$ (°)	82.7 (3.5)	83.8 (3.4)	90.9 (2.2)	< 0.01 / (Dry) - (SR) - (SF)
$AnklAngl_{50}$ (°)	76.9 (2.6)	76.2 (2.3)	74.8 (4.3)	< 0.05 / not performed
$KneeAngl_{HC}$ (°)	172.5 (5.8)	170.6 (6.84)	173.6 (3.2)	not significant
$KneeAngl_{30}$ (°)	160.9 (7.1)	160.7 (9.43)	165.9 (4.4)	< 0.01 / (Dry & SR) - (SF)
$KneeAngl_{50}$ (°)	165.9 (4.5)	163.8 (6.46)	146.4 (7.8)	< 0.01 / (Dry & SR) - (SF)
$TorsAngl_{HC}$ (°)	94.8 (3.2)	96.0 (3.9)	95.2 (5.2)	not significant
$TorsAngl_{30}$ (°)	93.4 (3.7)	94.9 (3.9)	94.7 (3.1)	not significant
$TorsAngl_{50}$ (°)	90.5 (3.5)	92.8 (3.4)	99.5 (3.6)	< 0.01 / (Dry & SR) - (SF)

[1] Results of the F-test (ANOVAs) investigating outcome differences.

[2] Results of Tukey multiple pairwise comparison tests, performed only when F-test showed p-value (associated with outcome factor) less than or equal to 0.01: outcomes with comparable characteristics are grouped within parenthesis.

6.5 Discussion

Biomechanically responses were found during slips with and without recovery. Increased flexion moment at the knee (at about 25-45% into stance) was shown to be the dominant reaction in an attempt to prevent falling. These moments are believed to be corrective actions taken by the body in an attempt to arrest a fall. Coincidently, the moment generated at the hip reflected a bias towards extensor activity. The ankle joint, on the other hand, acted as a passive joint during fall trials. This is due to the COP's proximity to the heel throughout stance in the fall cases, indicating an uncompleted full body weight transfer to the supporting foot. Corrective movements induced by these moments included knee flexion, allowing subjects to rotate the shank forward, thus restoring included ankle angle profiles and attempting to bring the foot back near the body. Finally, only minimal changes in torso orientation were recorded during slip-with-recovery events, while for slip-and-fall outcomes, the rearward orientation of the torso was not evident until the second half of stance.

The primary corrective response of knee-flexor and hip-extensor moments is not surprising. Winter [6.26] has reported such coordinated motor patterns between knee and hip muscles during normal walking on dry surfaces. Similarly, on slippery surfaces, well-controlled knee and hip moments are necessary for the safe forward progression of the body while maintaining an upright posture. Furthermore, these balance strategies are postulated to be the reasons for the minimal changes in torso orientation observed early in the stance during slipping perturbations.

Slipping perturbations elicited an ensemble of postural corrective reactions different than the set reported in response to active BOS translation applied during standing on flat support surfaces. The postural strategies used to generate these corrective movements can be partially identified with an analysis of the lower extremity joint moments. For example, Runge et al. [6.27] investigated ankle and hip moments in response to rearward BOS translation at speeds varying from 5 cm/s to 55 cm/s and found that 1) ankle strategy was present at all perturbation speeds and 2) ankle strategy was coupled with increased hip strategy at faster BOS translations. The presence of ankle reaction seems to be in contrast to findings of this study in which, after the occurrence of a severe slip, corrective reactions included mostly moments generated at the hip and knee with minimal (if any) ankle strategy. Another study by Horak and Nashner [6.28] examined the effect of the support surface's length (relative to foot length) on postural strategies during a given BOS translation. In this investigation, the authors reported that, on short support surfaces, hip strategy dominated the reactions with "generally unresponsive" ankle joints, while on normal length support surfaces, significant levels of ankle muscle work were observed. Thus, from this comparison across studies, it appears that subjects have the ability of adopting a wide spectrum of corrective strategies varying from pure ankle to pure hip reactions including complex combinations of lower extremity joint moments. Many factors could affect the type of corrective reactions used by the subjects including initial postural conditions at the onset of the perturbation and dynamics of the task performed during the perturbation (e.g. during locomotion, slips begin before body weight is fully transferred to the supporting foot). However, the importance of the knee in corrective responses in slips reported here is not found or underplayed in standing postural control studies.

Reaction time as measured by the occurrence of corrective moments generated at the knee and hip during slip events is comparable to the timing of responses reported by Runge et al. [6.29] during active rearward BOS translation. During the first 150 ms following the applied perturbation, Runge et al. [6.29] reported only passive joint movements resulting from the rearward translation of the BOS. However, active moments at the lower extremity joints became evident at about 150 to 200 ms after the applied perturbation. This is certainly in accordance to findings of this study conducted during slipping perturbations initiated at heel contact: the onset of corrective actions taken by the body to recover from slips was recorded at about 25% into stance and continued until about 45% into stance, i.e. on average between 190 and 350 ms after heel contact.

The results of this study suggest that heel contact might not be the only time during stance important to tribology research, recently focused on obtaining biomechanically relevant slip resistance measures by simulating heel and foot dynamics occurring at heel contact. Although forward slipping is certainly initiated shortly after heel contact (e.g. 60-80 ms on oily surfaces as reported in Section 5), corrective reactions occurring later in the stance appear to be the primary factors affecting the outcome of recovery attempts after the occurrence of a slip.

It is unclear whether active anterior translation of the base of support (BOS), used in recent investigations to simulate naturally occurring slip events [6.21-6.24], evoke similar motor muscle patterns, corrective movements and strategies comparable to those recorded during real slipping events. Although, intuitively, both types of perturbation are similar, i.e. the foot is suddenly moved in front of the body's COG, the full effects of these balance perturbations have not specifically been compared yet. Active anterior BOS translation experiments designed to

simulate slips can be divided into two major groups: 1) anterior translation of the supporting surface occurs while a subject is standing still (e.g. Hsaio and Robinovitch [6.21]), and 2) anterior translation of the supporting surface occurs during locomotion (e.g. Tang and colleagues [6.22-5.24]). In the first group, Hsaio and Robinovitch [6.21] acknowledged the lack of body dynamics simulation in their experiment, a factor that will obviously affect corrective reactions. In the investigations conducted by Tang and colleagues [6.22-6.24], the supporting surface is translated at a constant velocity of 40 cm/s. However, during real slip events, decreased friction of the shoe/floor interface was correlated with increasing heel acceleration recorded shortly after heel contact (Section 5). Thus, this aspect of heel dynamics was not taken into consideration in experiments performed with a BOS moving at a constant velocity. Another aspect differing between naturally occurring slip events and active anterior BOS translation relates to stability concerns. Pai and Iqbal [6.30] compared the region of stability of both scenarios using a computer simulation. (The region of stability was defined as the "feasible range of COM velocities that be reduced to zero with respect to the BOS while still allowing the COM to traverse within the BOS limits".) The authors have reported a substantial overlap between regions of stability of active anterior BOS translation and real slipping perturbations, however a significant difference in the shape of these regions was also discussed. Thus, using active anterior BOS translation to specifically reproduce heel and body dynamics during naturally occurring slip events has not been proven to be an accurate method yet.

In conclusion, the responses to slips found in this study suggest that the primary postural reaction includes knee flexion and hip extension of the sliding leg. This reaction occurs approximately 190 to 350 ms after heel contact. The success of this strategy will obviously depend on the magnitude and timing of these responses. This study identified postural strategies that are different than those previously found using standing perturbations protocols where ankle and hip moments dominate. This underscores the task specificity of postural reactions to maintain balance.

7.0 SCIENTIFIC REPORT IV
LOAD CARRYING AND GAIT AFFECTING SLIP POTENTIAL

7.1 Abstract

The complex human processes involved in balance maintenance and fall prevention during normal locomotion are further complicated by load carrying and/or in the presence of slippery floors. The fourth goal of this study was to investigate the effect of carrying loads (2-handed method) on gait biomechanics relevant to slips/falls. Ten subjects walked down surfaces of varying inclinations (0^{o}, 5^{o} and 10^{o}), while ground reaction forces and body/foot motion were recorded. Three load conditions (no load, 2.3 and 6.8 kg) were included. Load carrying was associated with increases in the peak normal force and in the rate of the normal loading phase. Shear forces were not affected by load carrying. Changes in the ground reaction forces recorded during load carrying led to reduced required coefficient of friction (RCOF) values, a parameter used to rate slip potential. This RCOF reduction is partly due to postural adaptations such as increased knee and hip flexion adopted during load carrying. Furthermore, load carrying was accompanied by slower heel contact heel velocity in the direction of motion and faster rearward heel movements at or shortly after heel contact. Finally, moments generated at the hip and knee joints were significantly biased towards the extensor and flexor direction, respectively.

7.2 Introduction

Walking necessitates the performance of a combination of complex human processes related to gait biomechanics, sensory information processing and neuromuscular mechanisms involved in maintaining postural balance and preventing falls. This goal is further complicated when performing manual handling tasks or/and in the presence of environmental hazards such as slippery floors. Over the years, lifting and holding loads have been shown to be potentially hazardous occupational tasks. Thus, much of the work in the prevention of manual handling-related injuries has been focused on the effect of load levels on stability parameters [7.1], musculoskeletal stresses particularly forces at the L5/S1 disk [7.2-7.4] and physiological strain parameters such as oxygen uptake and heart rate [5] while lifting and/or holding loads. Such studies have led to recommendations and legislation on safe load levels to lift based on based on epidemiological, physiological, psychophysical and biomechanical criteria (e.g. NIOSH, 1981, 1993). Load carrying on the other hand, which is part of the routine requirements of the job in many occupational settings, has less often been investigated. For load carrying, researchers have concentrated mostly on muscle activity patterns [7.6-7.10] and physiological strain parameters [7.9,7.11-7.13]. Information regarding load carrying effects on gait biomechanics and stability parameters is sparse.

Another serious ergonomic concern in industry is slips and falls accidents, which have been recognized to be a major cause of injuries and source of high economic costs in the US and a number of other industrialized countries. In the US, a total of 390,241 non-fatal work injuries (requiring days away from work) representing 21% of all reported cases were attributed to slips, trips and falls (STF) accidents (Bureau of Labor Statistics [7.14]). In Britain, STFs were ranked as the most frequent type of accidents causing major injuries, with STFs accidents on the same level and from height being responsible for 29.8% and 18.4% of all reported accidents in 1997/1998, respectively (Health and Safety Executive [7.15]). Similarly, the Swedish Information System

Occupational Injuries and Disease [7.16] attributed 22% of all occupational accidents to falls, once again the most numerous type of occupational accidents. Analyses of US workers compensation claims for the years 1989 and 1990 indicated a 24% contribution of fall-related injuries to the direct cost of all claims filed during this time period [7.17]. Based on the demographic trends of the US population including the advancing age of the labor force, Englander et al. [7.18] projected the total number of fall injuries and their cost to increase by 25.8% and 32.5% between 1995 and 2020, respectively.

Falls are often precipitated by slipping events, as recently reported by the Information System Occupational Injuries and Disease [7.16] in Sweden: slipping contributed to 55% and 23% of falls on the same level and to a lower level, respectively. Causes of slip/fall accidents are complex and multidimensional as they relate to environmental factors (e.g., floor slipperiness, lighting), human factors (e.g., gait biomechanics, postural control, aging, drug effects) and the interaction of these two types of risk factors (e.g. corrective reactions after the occurrence of a slip) (review of risk factors in Grönqvist [7.19]). Research focused on the prevention of slip/fall accidents has been directed towards the "accurate" and "reliable" measurement of slip resistance [7.20-7.22] and on gait biomechanics during slip events [7.23-7.26] or "simulated slip perturbations" i.e. translation of the supporting surface [7.27-7.31]. Findings of gait studies have been useful in determining the frictional and strength requirements of walking, and investigating biomechanical human reactions to slippery environments. Unfortunately this information is task-specific. Gait biomechanics have rarely been investigated during load carrying, despite the fact that the risk of injury from load carrying is dramatically increased when walking on slippery floors, possibly decreasing the chances of recovery compared to the unloaded conditions. In fact Anderson and Lagerlof [7.32] found that more than 30% of injuries occurring while load carrying had a slip or a trip as a contributing factor. Therefore, understanding load carrying effects on gait biomechanics relevant to slips and falls is the first step toward the long-term goal of preventing such accidents.

The majority of the small group of researchers that examined carrying effect on gait biomechanics have not considered the standard industrial symmetrical 2-handed load carrying posture, but instead have used back packs, front packs and doublepacks simulating carrying tasks mostly performed in the military [7.33-7.35]. The effect of load carrying on gait biomechanics and stability measures will depend not only on the load level but also on the load position and body posture used to handle the load. Thus, it is important to specifically investigate the effect of load carrying using the 2-handed symmetrical posture. Others have incorporated in their experiments the more common 2-handed method of handling a load, but their findings are limited to specific gait parameters such as stride length and heel velocity [7.36] or force plate data [7.37]. All of these gait experiments have been conducted only on horizontal surfaces, however tasks such as loading/unloading boxes from trucks using ramps for example are common in industry. In summary, there is a need for a greater understanding of workers' reactions to load carrying during normal locomotive tasks in both safe and slippery environments.

The primary fourth goal of this research is to investigate the effect of carrying relatively light loads (2-handed method) on gait biomechanics during normal locomotion on both horizontal and inclined surfaces that could influence slips and falls. Also, the changes in gait patterns (if any) adopted by subjects to alter slip potential while carrying load are identified. Finally, ankle, knee and hip moments will be compared between normal locomotion and load carrying. This study is

part of a larger project that investigated gait biomechanics on both slippery and non-slippery surfaces.

7.3 Methods

7.3.1 Subjects

Ten healthy adults (5 male, 5 female) between the ages of 19 and 30 years with no known history of orthopedic or neurological dysfunction participated in this study. Their weight varied from 63 to 81 kg (mean 68.7, S.D. 6.7) while body stature ranged from 1.64 to 1.88 m (mean 1.75, S.D 0.07) (Table 10).

Table 10 Subject anthropometry

Subject	Gender (M, F)	Age (years)	Body weight (kg)	Stature (m)
1	M	23	81.1	1.88
2	F	21	71.2	1.70
3	M	24	78.6	1.80
4	F	30	63.0	1.74
5	F	27	63.2	1.73
6	F	23	64.4	1.70
7	M	20	62.5	1.78
8	M	21	71.7	1.78
9	F	19	65.7	1.64
10	M	21	65.8	1.73
Mean		23	68.7	1.75
Standard deviation		3	6.7	0.07

7.3.2 Experimental Set-Up and Data Acquisition System

A ramp with a built-in force plate (details described in Redfern and Dipasquale [7.25] was used to conduct these gait experiments. The ramp is 1.8 m long and 1.0 m wide with a 1.4 m horizontal extension at the lower end. The top surface is made of 1.9 cm thick plywood covered with vinyl tile flooring. The force plate is bolted to the superstructure of the ramp and positioned such that the subjects' left foot landed on the platform during the second or third step of descending the ramp. An Optotrak-3020 motion measurement system was used to record body and foot movements, with LEDs placed on the subject's left shoulder (acromiom), hip (greater trochanter), knee (lateral femoral condyle), ankle (lateral malleolus) and shoe (3 markers near the heel of the shoe and toe fifth metatarsal). Motion and ground reaction forces were synchronized and sampled at 350 Hz.

A standard 42.5 cm (length) x 34.9 cm (width) x 26.7 cm (depth) plastic office file crate was used to hold the load, which was evenly distributed in the crate. Handle holes (16.5 x 7.0 cm) located midway on each side of the crate were used. For the load conditions, subjects were instructed to carry the loaded crate at about waist level, using the 2-handed symmetric posture without supporting the crate against the body (self-chosen horizontal distance of the crate from the torso). In general, the elbows were flexed slightly more than 90°.

7.3.3 Experimental Conditions

The nine experimental conditions included three ramp angles (0°, 5°, 10°) and three load conditions (no external load, 2.3 kg and 6.8 kg). The order of presentation of the load conditions was randomized. All subjects wore the same type and model of poly-vinyl-chloride (PVC) hard sole shoes.

7.3.4 Walking Protocol

After informed consent was given, subjects donned a safety harness and LEDs were attached. Specific instructions included walking as naturally as possible at a self-chosen speed while looking straight ahead at the opposite wall of the laboratory. Subjects were allowed to practice walking before data collection. Subjects were handed the appropriate load to carry (if any) prior to each trial. Kinematic and kinetic data were recorded as the subject walked across the force platform. A minimum of three to a maximum of five trials per (ramp angle, load) condition were collected.

7.3.5 Data Processing

For each trial, time was normalized to stance duration with 0% being heel contact and 100% representing toe-off the force plate. Shear (anterior-posterior) and normal ground reaction forces were normalized to the subject's weight. The ratio of shear to normal forces (also termed required coefficient of friction or RCOF [7.25] was calculated over time. In addition, the phase relationship between the shear and normal forces was quantified by the time difference between the peaks of the normal and shear forces. Kinematic variables (in the sagittal plane) were derived from position data provided by the LEDs, including foot-ramp angle, included joint angles (ankle, knee and hip), torso orientation (with respect to horizontal), heel velocity in the direction of motion and foot angular velocity. Velocity information was calculated by numerically differentiating (using a 2-time step differentiation routine) the position data. Sagittal plane joint moments generated at the hip, knee and ankle were computed using approximate lower extremity segmental properties defined by Plagenhoef [7.38]. These kinetic and kinematic variables were evaluated at specific time during stance (e.g. heel contact, 20% or time of peak values) and used as the dependent variables to be compared among load conditions (Table 11). Finally, general gait variables such as stride length (defined as the distance traveled by one foot from heel contact to heel contact) and stance duration were also considered in the analysis.

Table 11 Definitions/abbreviations of dependent estimated parameters

Kinetic Parameters
$Norm_{peak}$: peak of the first phase of the normal ground reaction force curve
$Shear_{peak}$: peak of the first phase of the anterior-posterior ground reaction force curve
$RCOF_{peak}$: peak of the first phase of the RCOF curve
$Norm_{Tpeak}$: timing of $Norm_{peak}$ in percent of stance
$Shear_{Tpeak}$: timing of $Shear_{peak}$ in percent of stance
$Forc_{Tdiff}$: time difference between peaks of normal and shear ground reaction forces, i.e. $Norm_{Tpeak}$ - $Shear_{Tpeak}$
$RCOF_{Tpeak}$: timing of $RCOF_{peak}$ in percent of stance
$AnklTorq_{peak}$: peak dorsiflexion ankle moment, i.e. peak of the first phase of the ankle moment curve
$KneeTorq_{peak}$: peak extension knee moment, i.e. peak of the first phase of the knee moment curve
$HipTorq_{30}$: hip moment evaluated at 30% into stance
Kinematic Parameters
NSL: normalized (to shank length) stride length
SD: stance duration
$HeelVelx_{HC}$: heel velocity in the direction of motion at heel contact
$HeelVelx_{rearward}$: peak rearward heel velocity (direction of motion), recorded shortly after heel contact
$FootAngVel_{HC}$: foot angular velocity at heel contact
$FootAngl_{HC}$: foot-ramp angle at heel contact
$AnklAngl_{HC}$ and $AnklAngl_{20}$: included ankle angle evaluated at heel contact and 20% into stance
$KneeAngl_{HC}$ and $KneeAngl_{20}$: included knee angle evaluated at heel contact and 20% into stance
$HipAngl_{HC}$ and $HipAngl_{20}$: included hip angle evaluated at heel contact and 20% into stance
$TorsAngl_{HC}$ and $TorsAngl_{20}$: torso angle with respect to horizontal evaluated at heel contact and 20% into stance

7.3.6 Statistical Analysis

All statistical analyses were repeated within each ramp angle condition. A single-factor repeated measures design was used for each dependent variable listed in Table 11, with the independent variable being the load level (no-carrying, 2.3 kg and 6.8 kg). Standard within-subject ANOVA tests associated with repeated measures models were performed to determine the statistical significance of the load level on gait biomechanics. Differences among load levels were further investigated (Tukey multiple pairwise comparisons tests) for all dependent variables for which the load effect was found significant, i.e. p-value associated with ANOVA F-test was less than or equal to 0.05).

7.4 Results

7.4.1 Overview

ANOVA findings revealed the significant effect of load carrying on more than half of the gait parameters on all ramp angles (Table 12). The kinetic variables included in these parameters were $RCOF_{peak}$, $Norm_{peak}$, $Forc_{Tdiff}$, $KneeTorq_{peak}$ and $HipTorq_{30}$. The kinematics affected by load carrying for all ramp angles were reflected in postural parameters ($KneeAngl_{HC}$, $TorsAngl_{HC}$, $AnklAngl_{20}$, $KneeAngl_{20}$, $Torsangl_{20}$), velocity variables ($HeelVelx_{HC}$, $HeelVelx_{rearward}$, $FootAngVel_{HC}$) and general timing gait characteristics (SD). Other variables were significantly affected by the load only on specific ramp angles (e.g., $Norm_{Tpeak}$, $AnklAngl_{HC}$, $HipAngl_{HC}$ and $HipAngl_{20}$). Finally, load carrying did not alter responses such as peak shear forces ($Shear_{peak}$) and normalized stride length (NSL).

Table 12 Statistical significance of load carrying effect on gait biomechanics

Dependent	0°	5°	10°
Kinetic Parameters			
$Norm_{peak}$	**	**	**
$Shear_{peak}$	NS	NS	NS
$RCOF_{peak}$	**	**	**
$Norm_{Tpeak}$	**	**	NS
$Shear_{Tpeak}$	*	NS	NS
$Forc_{Tdiff}$	**	**	*
$RCOF_{Tpeak}$	**	NS	**
$AnklTorq_{peak}$	**	NS	*
$KneeTorq_{peak}$	**	**	**
$HipTorq_{30}$	**	**	**
Kinematic Parameters			
NSL	NS	NS	NS
SD	**	**	**
$Heelvelx_{HC}$	**	**	**
$HeelVelx_{rearward}$	**	**	**
$FootAngVel_{HC}$	**	**	**
$FootAngl_{HC}$	**	NS	**
$AnklAngl_{HC}$	**	NS	NS
$KneeAngl_{HC}$	**	**	**
$HipAngl_{HC}$	NS	NS	*
$TorsoAngl_{HC}$	**	**	NS
$AnklAngl_{20}$	**	*	**
$KneeAngl_{20}$	**	**	**
$HipAngl_{20}$	NS	*	**
$TorsoAngl_{20}$	**	*	**

"**" indicates significant effect at $p \leq 0.01$, "*" $p \leq 0.05$, *"NS"* indicates $p > 0.05$

7.4.2 Ground Reaction Forces and RCOF

Normal ground reaction forces increased with load carrying, however, load carrying did not influence shear forces (Figures 20 and 21). More specifically, carrying a 2.3 kg and 6.8 kg load led to increases in the peak normal forces ranging from 4 to 8% and 7 to 15% from the no-load condition, respectively, with the smallest relative changes interestingly occurring on the 10° ramp angle (Figure 21b). Tukey multiple pairwise comparisons indicated significant differences in the $Norm_{peak}$ among the three load levels on all ramp angles except when testing the condition (2.3 kg, 10°) versus (6.8 kg, on 10°) (Figure 21b).

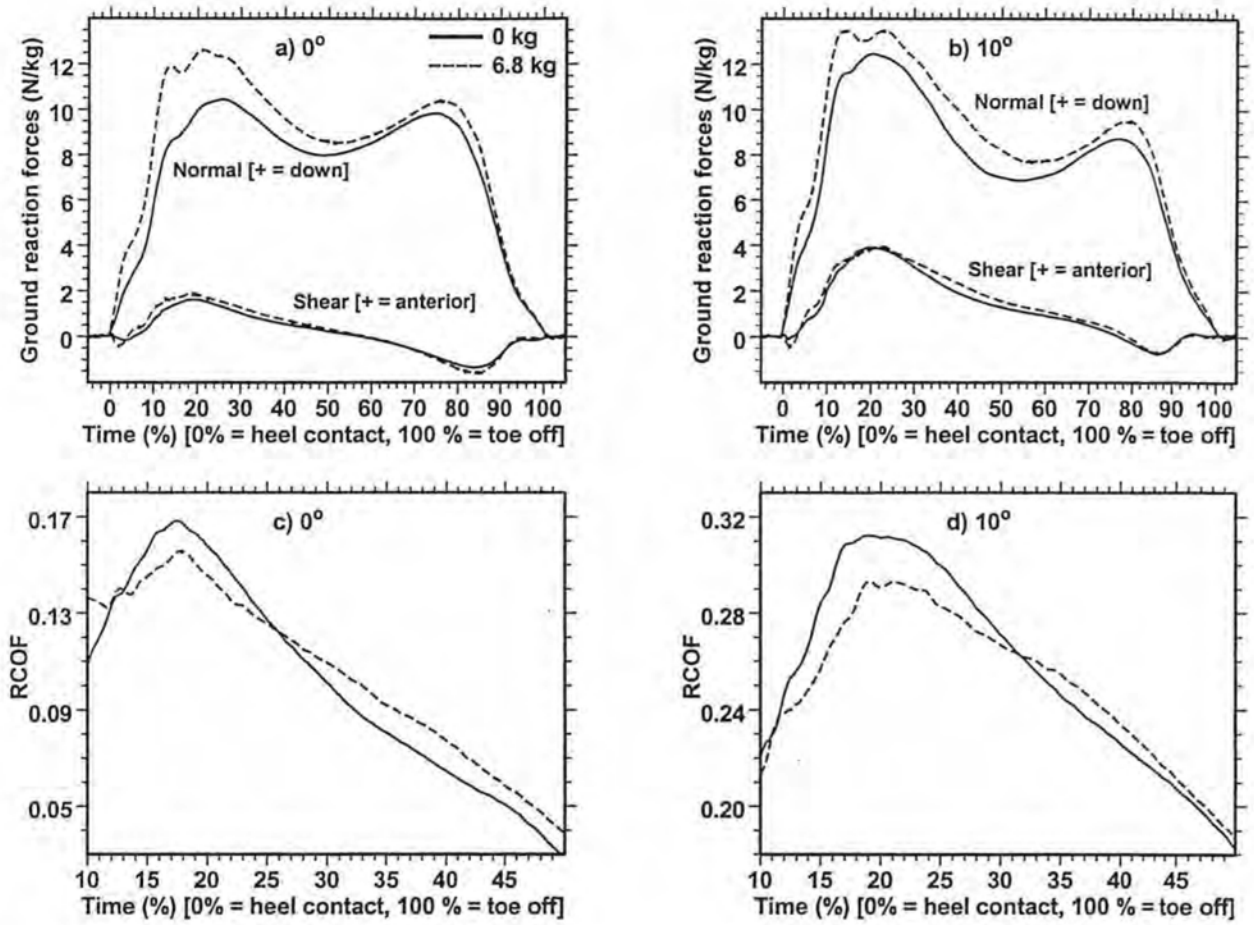

Figure 20 **Effect of carrying a 6.8 kg load on the mean profile of ground reaction forces and RCOF: (a)/(b) ground reaction forces (normalized to body weight) during level walking (a) and when descending the 10° ramp (b), (c)/(d) RCOF during level walking (c) and when descending the 10° ramp (d). [Note that in (c) and (d), time is truncated to 10%-50%).**

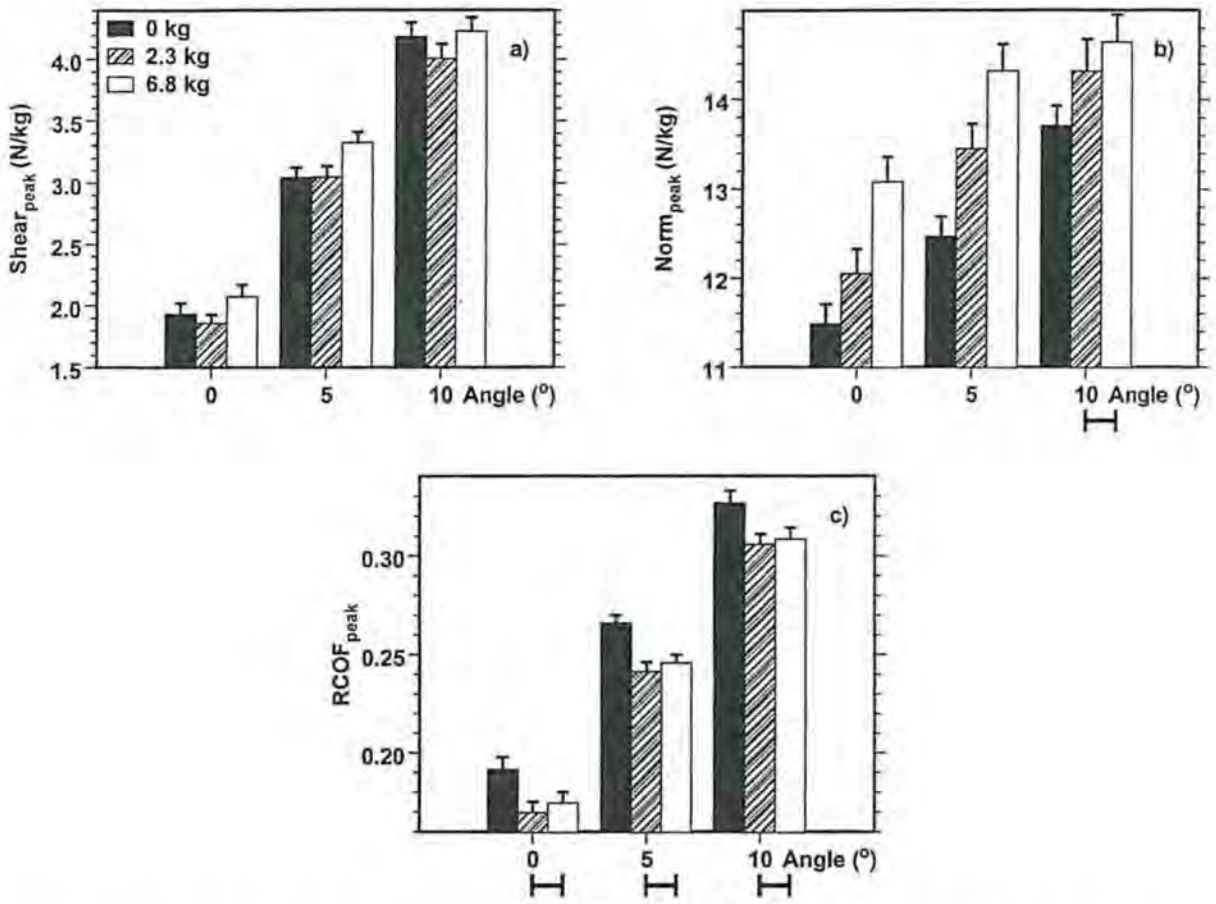

Figure 21 Effect of load carrying on peak ground reaction forces and RCOF: (a) peak shear ground reaction force, (b) peak normal ground reaction force, and (c) peak RCOF. Mean (SE bars) values are plotted. "*" indicates statistically significant differences (Tukey multiple pairwise comparison tests) among all load levels; Tukey multiple pairwise comparison tests were not performed if ANOVA tests showed no significant differences in dependent variable among load level conditions (e.g. Shear$_{peak}$).

In general, load carrying did not significantly affect the timing of the peak shear forces, except on 0° (less than 1% time difference as depicted in Figure 22a). On the other hand, maximum normal loading on the supporting foot occurred significantly earlier in stance when carrying a load for both level walking and while descending the 5° ramp (11 to 17% changes from the no-load condition) (Figure 22b). The same tendencies were recorded on 10°. This finding is also evident in Figures 20a-20b with the greater slope of the normal ground reaction force curve versus time during the first phase of the loaded gait. Faster normal loading led to changes in the phase relationship between the normal and shear forces, more specifically, the peak normal force occurred closer to the peak shear when load carrying (Figure 22c).

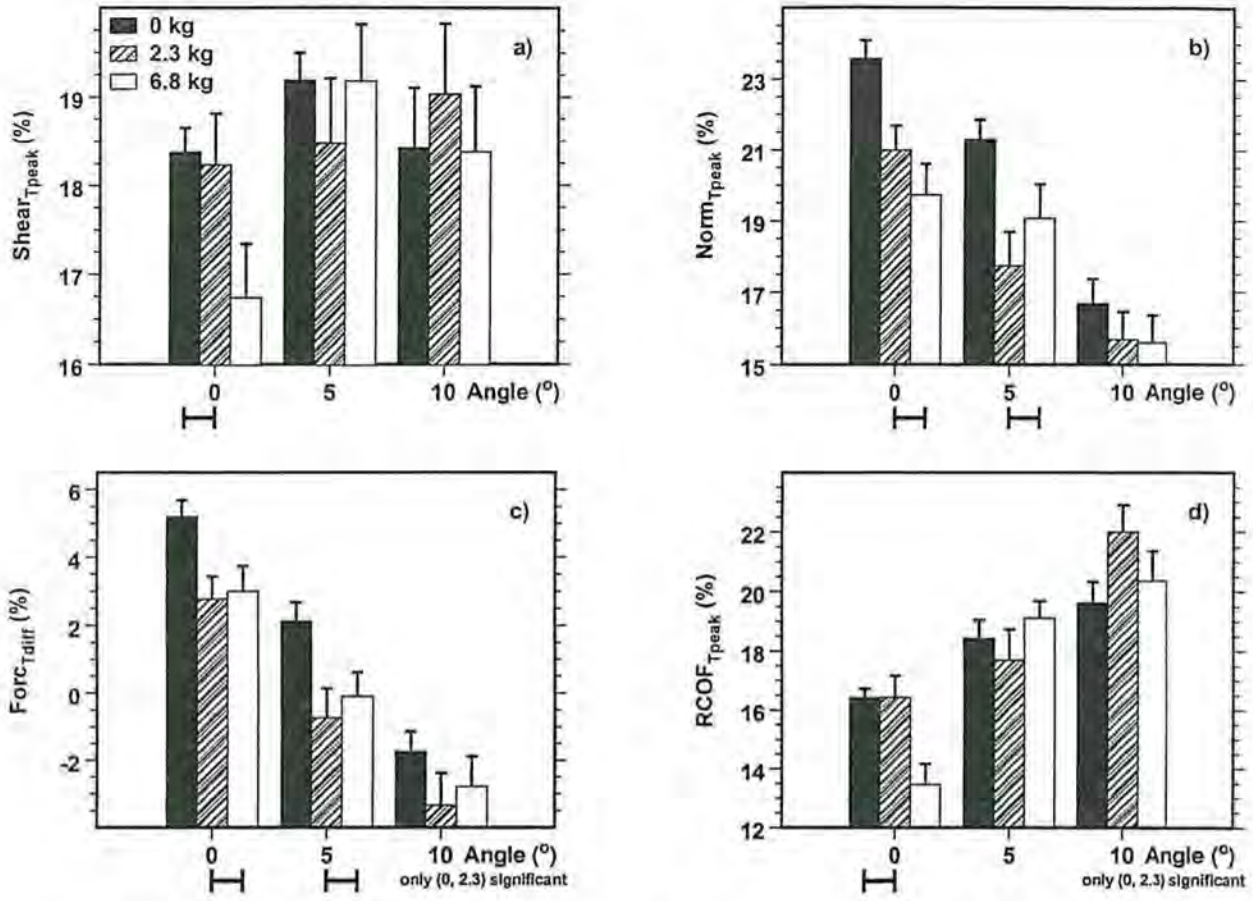

Figure 22 Effect of load carrying on timing parameters of ground reaction forces and RCOF: (a) timing of peak shear ground reaction force, (b) timing of peak normal ground reaction force, (c) time difference between peaks of normal and shear ground reaction forces, and (d) timing of peak RCOF. Mean (SE bars) values are plotted. Tukey multiple pairwise comparison tests were not performed if ANOVA tests showed no significant differences in dependent variable among load level conditions (e.g. Shear$_{Tpeak}$ on the 5° and 10° ramps).

As a result of the changes in the magnitude of the normal forces and phase between the normal and shear, the peak RCOF was also significantly affected by load carrying (Figures 20c, 20d), with a decrease of about 0.02 (on all ramp angles) when comparing loaded to unloaded conditions (Figure 21c). No significant differences were found between the 2.3 kg and 6.8 kg load levels. RCOF$_{Tpeak}$ (Figure 22d) followed the same general tendencies as Shear$_{Tpeak}$ (Figure 22a) among load levels, with the timing of the RCOF not being greatly affected by load carrying.

7.4.3 Kinematics

7.4.3.1. General Gait Variables. On average, subjects did not change normalized stride length (on any ramp angle) when carrying a load. In these experiments, mean stance duration was about 743, 698 and 649 ms for the control condition during level walking and when descending the 5^{o} and 10^{o} ramp, respectively. Small, but significant, decreases (2 to 8%) in the stance duration were recorded when subjects carried loads, with the greatest relative changes found during level walking and the smallest changes observed when walking down the 10^{o} ramp. Tukey multiple pairwise comparison tests indicated significant differences only between the control and load conditions, not between the different load levels.

7.4.3.2. Posture. The overall profile of the included lower extremity joint angles indicated that the ankle was the least affected joint and that increased knee and hip flexion were recorded during load carrying (Figure 23). At heel contact, differences in posture parameters among load levels were small and somewhat variable across ramp angles (Figures 24a, 24c, 24e, 24g and Table 12). However, by 20% into stance, these differences became, in general, more pronounced and consistent across ramp angles (Figures 24b, 24d, 24f, 24g and Table 12).

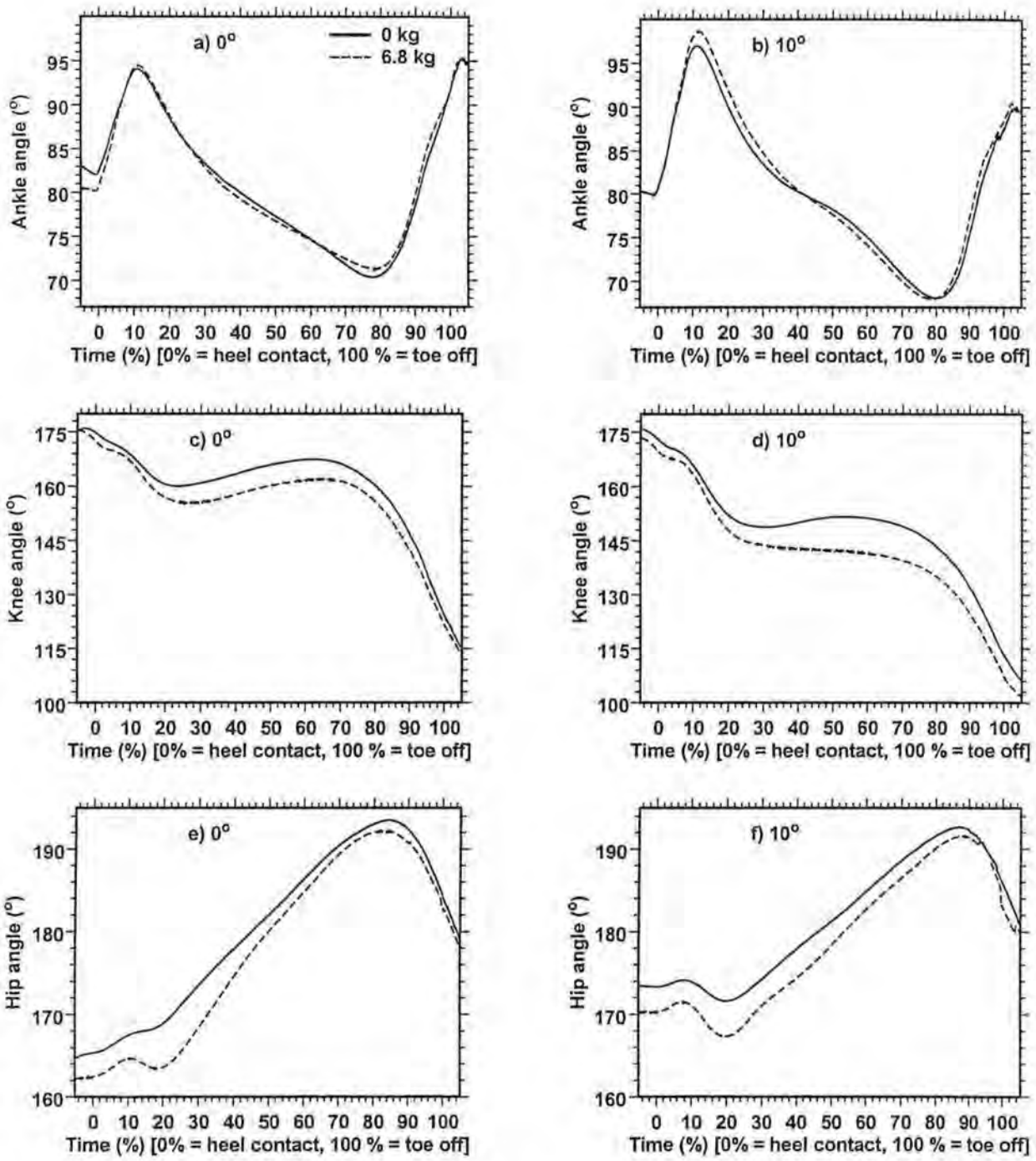

Figure 23 **Effect of carrying a 6.8 kg load on the mean profile of postural variables: (a)/(b) included ankle angle during level walking (a) and when descending the 10° ramp (b), (c)/(d) included knee angle during level walking (c) and when descending the 10° ramp (d), and (e)/(f) included hip angle during level walking (e) and when descending the 10° ramp (f).**

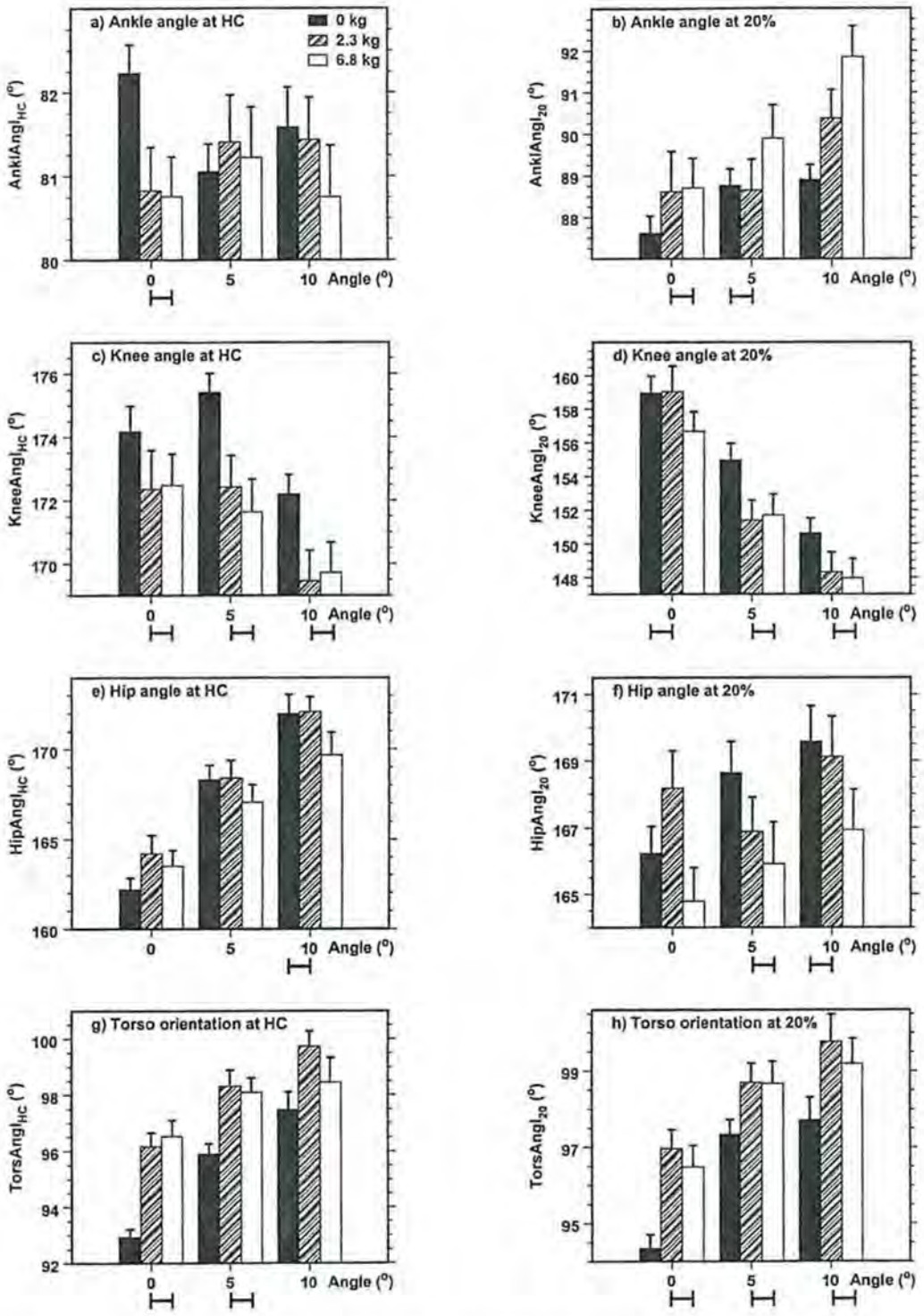

Figure 24 Load carrying effect on posture at heel contact (left) and 20% into stance (right): (a)/(b) included ankle angle, (c)/(d) included knee angle, (e)/(f) included hip angle, (g)/(h) torso-horizontal angle. Mean (SE bars) values are plotted. "*" indicates statistically significant differences (Tukey multiple pairwise comparison tests) among all load levels; Tukey multiple pairwise comparison tests were not performed if ANOVA tests showed no significant differences in dependent variable among load level conditions.

Foot-ramp angle at heel contact ($FootAngl_{HC}$) was significantly increased with load carrying for level walking and when descending the 10° ramp. Despite the statistical significance of these findings, the changes in foot orientation were small on these surfaces (less than 3°) and not significant at all on 5°. Similarly small but statistically significant changes in the shank-ramp angle at heel contact ($ShankAngl_{HC}$) were recorded only the 10° ramp, with an increase of less than 2° when carrying the 6.8 kg load. As expected, these small and inconsistent (across ramp angle conditions) changes in $FootAngl_{HC}$ and $ShankAngl_{HC}$ among load levels were also reflected in the findings of the included ankle angle, with small significant differences only between the control and loaded conditions during level walking ($AnklAngl_{HC}$ in Figure 24a, Table 12). By 20% into stance, the ankle joint was more extended during load carrying than the unloaded condition (significant differences on all ramp angles), especially when descending the 10° ramp (Figure 24b).

Carrying a load on all ramp angles resulted in increased knee flexion (significant decrease in $KneeAngl_{HC}$ and $KneeAngl_{20}$ in Figures 24c, 24d), bringing the body's center of gravity (COG) closer to the ground. This was done mostly by changing the upper leg's orientation with respect to the floor since, as previously mentioned, the shank's orientation did not significantly change among load levels (this was also verified independently: on average, the upper leg – ramp angle increased by 1 to 6° when carrying a load compared to the no-load condition). Once again, in general no significant differences in the included knee angle were detected between the two load levels.

In order to compensate for the weight of the load carried in front of the body, subjects extended the torso angle (Figures 24g, 24h) except at heel contact on the 10° ramp. These significant differences from the no-load condition ranged from about 1° to 4°. Despite these apparently small torso angle differences, it is important to note that the torso does not usually experience high changes in orientation and such numbers make a difference on gait biomechanics [7.39]. The largest differences in the torso orientation were recorded for level walking and were less pronounced (not significant) on the 10° ramp angle (Figures 24g, 24h).

Finally, at heel contact, the combination of greater knee flexion (or increasing upper leg angle with respect to the floor) and increasing backward torso lean resulted, in general, in non-significant differences in included hip angles among load levels, except on the 10° ramp where $HipAngl_{HC}$ was reduced when carrying the 6.8 kg load (Figure 24e). By 20% into stance, similar decreases in the included hip angle were observed when descending inclined surfaces (Figure 24f).

7.4.3.3. Velocity. The overall profile of the heel velocity in the direction of the support surface showed significantly slower forward velocity and often even backward heel movements when carrying a load (Figures 25a, 25b). These changes in heel dynamics were more pronounced as ramp angle was increased (Figure 25b). For level walking for example, similar heel contact heel velocities were recorded for both the no-load condition and the 2.3 kg load level (Figure 25c). However for the same load level on inclined surfaces, heel contact heel velocity dropped significantly from a forward velocity of 0.24 m/s (5°) and 0.10 m/s (10°) in the no-load condition to 0.08 m/s (5°) and -0.18 m/s (rearward heel movements on 10°). The decreases in heel contact heel velocity when carrying a 6.8 kg load were significant on all ramp angles. Tukey tests indicated no differences between the two load conditions on both 5° and 10°.

It is interesting to note that as the load level increased, subjects tended to generate more rearward heel movements at heel contact. After heel contact, rearward heel sliding was recorded in the majority of the trials (as depicted in the negative values of $HeelVelx_{rearward}$ plotted in Figure 25d). However, during load carrying, greater values of $HeelVelx_{rearward}$ were recorded (Figure 25d).

Load carrying was also associated with significant increases in the angular velocity of the foot at heel contact on all ramp angles. These increases ranged from 10% to 25% from the no-load condition (mean of 245, 280 and 323°/s for level walking, 5° and 10°, respectively), and are consistent with the fact that the loading phase occurred faster when carrying a load. There were no statistically significant differences in the foot angular velocity between the two load levels.

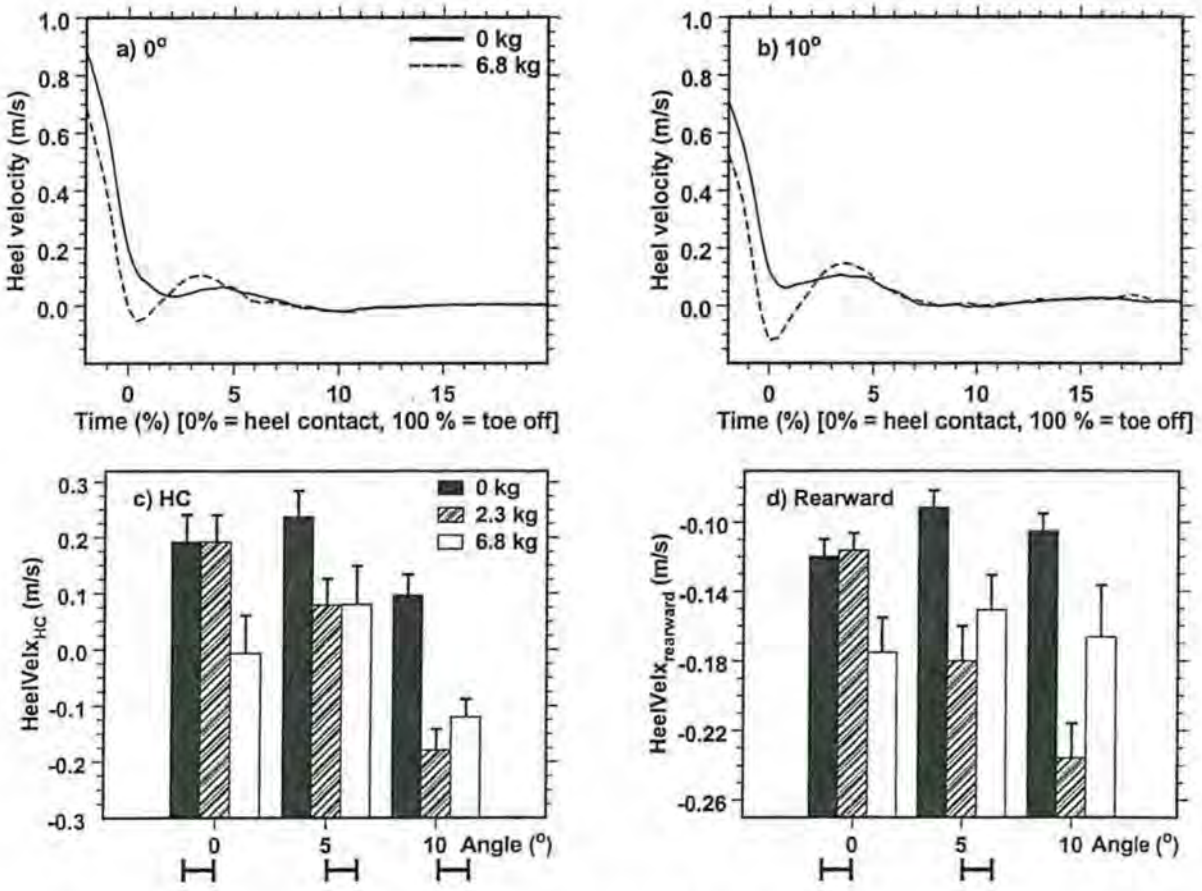

Figure 25 Effect of load carrying on heel velocity in the direction of motion: (a)/(b) mean profile of heel velocity during level walking (a) and when descending the 10° ramp (b), (c) average heel velocity evaluated at heel contact (SE bars), and (d) average minimum heel velocity recorded shortly after heel contact (SE bars). [Note that in (a) and (b), time is truncated to 20%).

7.4.4 Joint Moments

The gait modifications accompanied with load carrying were associated with changes in the relative shape (Figures 26 a-f) and magnitude (Figures 26 g-i) of the sagittal plane joint moments. The hip moment, which was consistently and significantly more biased towards the extensor direction with increasing load level, was the most affected among the 3 lower extremity joints: relative reductions from the control condition ranged from about 20 to 38% and from 67 to 90% for the 2.3 kg and 6.8 kg load, respectively (Figure 26i). Load carrying had similar significant but less pronounced effects on the peak knee extension moment that decreased by 10 to 30% from the no-load condition, i.e., biased towards the flexor direction (Figure 26h). Finally, the ANOVA tests revealed a less consistent (across ramp angles) but still significant load carrying effect (on 0° and 10°) on the peak dorsiflexion ankle moment with relative increases of 2 to 31% from the no-load condition (Figure 26g). After the loading phase was completed, the ankle had an increased plantarflexor pattern during load carrying (Figures 26a, 26d).

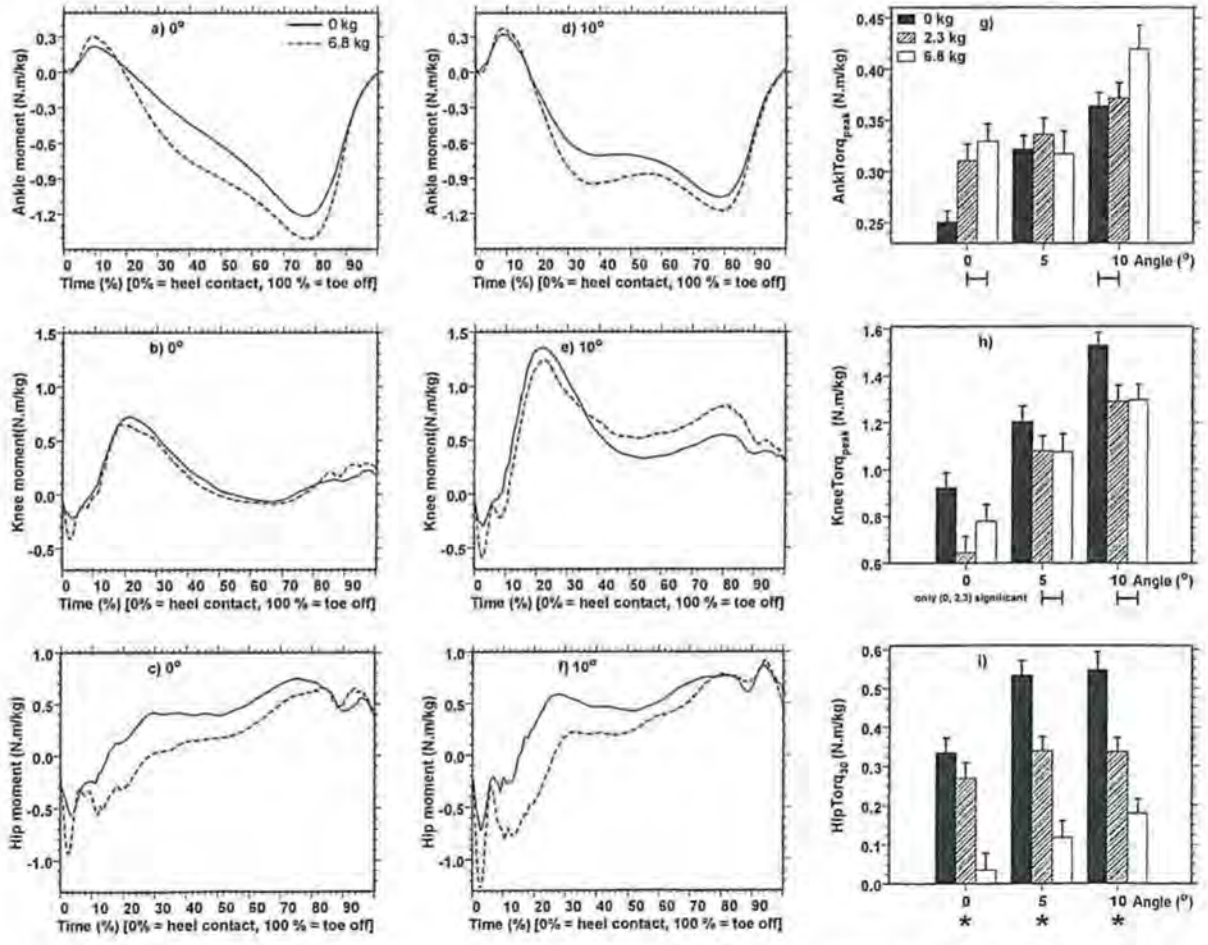

Figure 26 Effect of load carrying on lower extremity joint moments: (a)/(b)/(c) mean profile of ankle (a), knee (b) and hip (c) moment during level walking, (d)/(e)/(f) mean profile of ankle (d), knee (e) and hip (f) moment when descending the 10° ramp, (g) average peak ankle dorsiflexion moment (SE bars), (g) average peak knee extension moment (SE bars), and (i) average hip flexion moment evaluated at 30% into stance (SE bars).

7.5 Discussion

Carrying relatively light loads was associated with small but significant differences in gait biomechanics during both level walking and when descending ramps. In particular, load carrying was associated with increases in the peak normal force, but also interestingly, in the rate of the normal loading phase, thus changing the timing characteristics of the normal ground reaction force. In general, shear forces were not affected by load carrying. The findings related to the ground reaction force's timing resulted in the reduction of the time gap between the peak shear and normal ground reaction forces, which together with the decrease in the magnitude of the normal ground reaction forces, led to reduced $RCOF_{peak}$ values, an important parameter used to rate slip potential. This reduction in the RCOF was partly due to postural adaptations such as increased knee and hip flexion adopted during load carrying. Furthermore, load carrying was accompanied with more "controlled" heel contact dynamics such as slower heel velocity at heel contact and a significantly greater tendency of generating rearward heel movements at or shortly after heel contact. Finally, external moments generated at the hip moment and knee moment were significantly biased towards the extensor and flexor direction, respectively.

The paucity of data relating load carrying (using a symmetrical 2-handed posture) to gait biomechanics makes the comparison of findings across studies challenging. The method of carrying, load level and walking speed are all factors affecting gait parameters [7.33,7.34,7.37]. In addition, the load and body center of gravity location affect stability measures [7.1], which will undoubtedly be associated with postural adaptations. The reduction in the peak RCOF found during load carrying (in front of the body) has been previously qualitatively reported by Love and Bloswick [7.37]. Myung and Smith [7.36], who investigated a similar carrying posture as in this study, reported a significant decrease of stride length with increasing load levels, which ranged however from the no-load condition to 40% of body weight, a far greater load level than the ones investigated in this study. Kinoshita [7.33] and Martin and Nelson [7.34], on the other hand, investigated considerably heavier backpacks and doublepacks (up to 40% of body weight) and reported no statistically significant relationship between stride length and load level. However, Martin and Nelson [7.34] reported tendencies of subjects, especially female subjects, to decrease stride length with increasing load levels. Thus, the relationship between stride length and load levels is still the subject of some disagreement among researchers. Interestingly, Kinoshita [7.33]reported increased knee flexion via a reduction of the upper leg's vertical orientation while load carrying, a result that is in accordance to our conclusions. Another parameter was heel contact heel velocity. Myung and Smith [7.36] concluded that heel velocity at heel contact was not affected by load carrying levels on dry floors, a finding that apparently is in disagreement with our findings. However, it should be noted that at least two experimental/analysis procedures could be responsible for this apparent disagreement in the results: 1) in Myung and Smith [7.36], walking speed was fixed and 2) the resultant heel velocity (direction of motion and lateral direction) was considered not the individual component along the direction of motion as was done in this experiment.

The statistically significant load carrying effects on postural variables (knee and hip flexion, increased torso-horizontal angle), which are small in magnitude due possibly to the relatively light load levels, are believed to be of practical importance to slip potential reduction. The relevance of such postural adaptations is evident in their effects on ground reaction forces and thus on the RCOF and slip potential. More specifically, these postural adjustments during loaded

gait are speculated to be partly responsible for the increases in the normal forces and thus the reduction in the peak RCOF. The increase in the normal forces was also partly due to the addition of the load's static weight during the carrying conditions. For example, during level walking, an external load of 6.8 kg carried by a subject of average body mass 68.7 kg will produce an increase of about 1 N/kg in the amplitude of the normal forces. The recorded mean increase was about 1.6 N/kg. The difference between these two values may be attributed to changes in the orientation of the torso with respect to the floor: load carrying was associated with increases in torso angle, which in turn will produce a greater normal component of the ground reaction force. In addition, the earlier occurrence of the peak normal force during load carrying is certainly not due to the simple addition of an external load, but rather appeared to be possibly related to the observed increases in knee/hip flexion, which would indeed move the body closer to the base of support, thus allowing for a more rapid transfer of body weight to the supporting foot. Thus, it is believed that postural adaptations play an important role in the increase of the normal forces and therefore in slip prevention.

The reasons for postural adaptations during load carrying remain to be investigated. During static standing, Holbein and Redfern [7.1] confirmed the importance of the location of the COG of the body-load system on stability measures. For example, lowering the COG to the ground increased stability ranges. Similarly, during load carrying, subjects might have adopted postures that increased their stability. Another possible explanation for the postural adaptations recorded during load carrying is that postural adjustments facilitate such energy exchange. Kinoshita [7.33] has, for example, put forward the hypothesis that greater knee flexion is necessary "to allow in part the smooth transfer" of the body/load weight to the supporting limb, characterizing the "knee joint and the muscular system of the thigh" as a "shock absorber to reduce the impact force".

Load carrying significantly affected hip and knee moments. The moment generated at the hip has been referred to as a "balancing moment" and known to largely vary across subjects as it compensates for external "unbalancing" moments arising from, for example, walking patterns such as rearward/forward torso lean [7.39]. Load carrying introduces an additional unbalancing moment component: during level walking, a 6.8 kg load carried at a horizontal distance of 30 to 40 cm from the hip will result in a moment of about 20 to 27 N.m ($6.8 \times 9.81 \times 30 \times 10^{-2} = 20$ N.m) or 0.26 to 0.35 N.m/kg (if normalized to average body-load mass), "pulling" the torso in the direction of gravity. In order to maintain balance, an increased activity of the back/hip extensor muscles is necessary and evident in the bias of the hip moment towards the extensor direction recorded during load carrying (Figure 26). This bias is of the same order of magnitude as the unbalancing moment resulting from load carrying (roughly estimated). The flexor bias recorded for the knee moment can be attributed to the high correlation between hip and knee moments [7.39]. Thus, an extensor bias of the hip moment will be associated with a flexor bias of the knee moment (as found in this study). In conclusion, load carrying affected joint moments more than body posture (small but significant changes). Thus, the findings of this study seem to indicate that walking is so well controlled by balancing activities of the lower extremity joints that deviation from the normal unloaded body posture is largely prevented even when disturbed by relatively light load carrying.

8.0 SCIENTIFIC REPORT V
PREDICTIVE LOGISTIC REGRESSION MODELING OF SLIPS AND FALLS

8.1 Abstract

Occupational related slips and falls accidents are among the leading causes of severe injuries and deaths. Accurate assessment of the slip resistance of the shoe/floor interface is critical to determine slip and fall potentials. Unfortunately, slip resistance measurements from currently available tribometers do not agree with one another and there are no valid criteria to evaluate these devices. The fifth of this project was to use the biomechanical model put forward by Hanson et al. [8.1] in an attempt to evaluate the ability of two tribometers (PSRT and Brungraber Mark II) to predict slips. More specifically, this method used logistic regression modeling to predict the slips and/or falls based on the difference between the frictional requirements of walking (RCOF) and available friction (i.e. slip resistance). Sixteen subjects walked on level surfaces and ramps of varying inclination (5°, 10°), while ground reaction forces were collected at 350 Hz. This study varied slip resistance through changing the environmental conditions (floor-contaminant combinations), while increasing the walkway's ramp angle was chosen as a method to increase RCOF. Logistic regression models proved to be useful in describing the nature of the relationship between the probability of falls and the difference between biomechanical frictional requirements and available friction (COF_{diff}). However, logistic regression functions of COF_{diff} alone did not provide a satisfactory fit of the probability of slip ($r^2 < 0.50$). This poor performance of the model is believed to be due to the inaccurate assessment of the shoe/floor slip resistance by the two tribometers included in the study, especially for wet and soapy contaminant conditions.

8.2 Introduction

Falling accidents have often been listed among leading causes of serious non-fatal occupational injuries, generators of fatalities and sources of high economical costs [8.2-8.3]. Falls are in turn often the result of slipping. An estimated 55% of all reported falls in Sweden have been related to preceding slipping events [8.4]. Thus, reducing occupational slip-related accidents has been identified among long-term goals of governmental agencies such as NIOSH and many scientific investigations supported by industrial funding. Unfortunately, despite research efforts to achieve this goal, slips and falls continue to raise particular ergonomic concerns. The trends of these slip-induced injuries reported in epidemiological studies have been attributed to a multitude of complex environmental and human factors. Among the environmental factors are the properties of the shoe/floor interface (e.g. frictional and material properties), room lighting characteristics and floor contrast levels. Human factors on the other hand include gait biomechanics (e.g. corrective reactions during slips, anticipation), sensory and neuromuscular processes involved in the initiation and dynamic task of walking while maintaining an upright posture.

In an effort to control slip incidence, researchers have attempted to develop predictive models to estimate the risk of slipping. Very simple univariate model structures, i.e. based on single independent variable such as COF measurements obtained with slip testers or slip distance [8.5] as well as more elaborate models including neural network computational tools [8.6] have been developed. Other approaches have been comprehensive frictional models [8.7] and

multivariate slip-prediction models based on ratiometric and dimensionless independent variables [8.8]. Although these models are undoubtedly useful to understand the causes of slips and falls, their direct practical industrial applications (e.g. design of fall-safe walking surfaces and assessment of slipping risks) is less clear due to the difficulty of obtaining some of the necessary predictor variables for a specific environments and tasks to be performed. Hanson et al. [8.1] have recognized these limitations and used relatively simple logistic regression modeling to investigate the relationship between the probability of slips/falls and the difference between frictional requirements of walking (required coefficient of friction (termed RCOF) and measured slip resistance of shoe/floor interface (COF). This study provided a potential tool to 1) determine whether an environment is a slip-safe environment and 2) test the efficiency and validity of slip testing devices.

Strong scientific evidence needed to validate and standardize slip resistance measures is lacking. In spite of the fact that slip resistance seems to be a purely physical phenomenon, measurements from the different types of devices do not agree. However, in industry, measurements from these devices are the most widely and routinely used criteria for rating slip potential of various flooring conditions. The major problems associated with current COF measures are: i) slip resistance measures depend upon the tester used, ii) attempted COF safety guidelines associated with specific devices have been put forward based on consensus and not on actual data from slips and falls and iii) slip resistance measures do not take into consideration the biomechanical requirements for the task (e.g. walking on a ramp versus walking on a level floor). Thus, there is a need to develop a method and data set that can be used to evaluate the utility of testers currently available under various environmental and biomechanical conditions. Hanson et al. [8.1] attempted to meet these research needs by conducting a small human gait study on inclined and level surfaces of differing frictional properties. The study by Hanson and al. [8.1] is the basis of this investigation with increased number of subjects and environmental conditions.

The fifth goal of this research is to describe the relationship among the probability of slips/falls, the slip resistance (measured by two testers) and frictional requirements of the tasks performed by subjects. Logistic regression models, similar to those published in Hanson et al. [8.1], were developed to describe this relationship and used to evaluate the validity of slip resistance testers and their ability of predicting slips in specific environments.

8.3 Methods

8.3.1 Subjects

Sixteen healthy subjects voluntarily participated in this study. Exclusionary criteria included a history of neurological or orthopedic disease and any difficulties impeding walking down a ramp. The subjects' population was young with ages varying from 19 to 30 years old and divided equally by gender. Anthropometrical characteristics were not considered variables in this study.

8.3.2 Experimental Conditions

The independent variables were four contaminant conditions, three floor types and three ramp angles for a total of 36 experimental conditions. Contaminant and floor conditions varied

the environmental frictional properties of the shoe/floor interface, while ramp angle affected the biomechanical frictional requirements of the walking task. In addition to the dry conditions, three other contaminants were included in the study (wet, soap, oil). The detergent condition consisted of a solution of dish soap (Ajax) and water mixed to a ratio of three parts water to one part detergent. Motor oil (10W-40 Penzoil) was used for the oily condition. The contaminants were uniformly applied onto the floor sample attached to the force plate (0.6 m x 0.4 m). The same polyvinyl chloride (PVC) hard-soled shoes were used for all walking trials and slip resistance testing. In order to minimize possible cross-contamination, a clean floor sample and a clean pair of shoes were used after each oily trial, and special cleaning precautions were taken after each wet and soapy condition (all contaminated rough painted plywood floors were changed due to the longer time needed to clean them).

8.3.3 Slip Resistance Measurements

Coefficient of friction measurements of the shoe-floor-contaminant combinations were made with two devices: the Programmable Slip Resistance Tester (PSRT) of Redfern and Bidanda [8.9] and the Brungraber Mark II tester. The PSRT provides a measure of the dynamic coefficient of friction (DCOF). It applies a known vertical force on a robotic resin foot, which, under the influence of forward shear forces, slides a size 10 PVC shoe (used in the gait experiment) across a horizontal sample floor at a constant velocity. For this experiment, the PSRT was operating at a forward travel velocity of 3cm/s and a vertical force of 14.5 kg. The shear forces necessary to sustain the sliding motion of the robotic foot were recorded at a sampling frequency of 1000 Hz. The DCOF was then calculated by dividing those shear forces by the applied vertical force. Four trials per environmental condition were collected and the results were averaged.

The Brungraber Mark II tester, often used in industry to rate the slipperiness of a floor, is part of the articulated strut testers family, which measure the shoe/floor static coefficient of friction (SCOF). This tester consists of a weight mounted on the top end of an articulated arm and a sample of the PVC shoe sole (used in the gait experiments) is attached to the other end, the pivot point. The arm is dropped onto a sample floor at a known angle from the vertical. The specific angle at which the sole material slips is noted and directly related to the SCOF (trigonometrically). Thus, the vertical and horizontal forces are applied at the same time. Just as for the PSRT, four trials for each environmental condition were collected and the results were averaged.

8.3.4 Walkway Set-Up and Data Acquisition System

The same specially designed walkway used in Hanson et al. [8.1] and described in detail in Redfern and DiPasquale [8.10] was used to conduct these experiments. The walkway consisted of a ramp that can be easily raised or lowered on one side to vary ramp angle from 0° to 20°, and at the opposite end, the ramp is hinged to a horizontal extension. The ramp is 1.8 m long and 1.0 m wide with a 1.4 m extension at the bottom. The top surface of the ramp is made of 1.9 cm plywood covered with the appropriate flooring surface to be tested. A harness system with an overhead trolley is used to catch the subject and prevent injury should a fall occur.

Ground reaction forces during gait were recorded using a force plate (Bertec, Inc - Model 4060A) embedded into the rampway floor such that the subjects' left foot landed on the platform

during the second or third step of descending the ramp. An Optotrak-3020 motion measurement system was used to record body and foot movements, with LEDs placed on the subject's left shoulder (acromiom), hip (greater trochanter), knee (lateral femoral condyle), ankle (lateral malleolus) and shoe (three LEDs near the heel of the shoe and toe fifth metatarsal). Collection of ground reaction forces and three-dimensional body motion was synchronized and sampled at 350 Hz.

8.3.5 Experimental Design and Gait Protocol

A full factorial within-subject, repeated measures experimental design was used such that each subject was tested on all conditions. Subjects came back for 3 visits, each time to be tested on a randomly chosen flooring surface. The same walking protocol was used for each visit. The ramp was set to the first angle at which the subject was to be tested. In order to maintain constant changes in gait biomechanics due to anticipation of slippery surfaces, each contaminated condition (wet, soap or oil) was "hidden" or mixed among a random number (1 to 3) of dry trials, during which the subject did not know whether the surface was contaminated or not. Thus, throughout testing, subjects did not have a priori knowledge of the specific contaminant on the floor. The order of the contaminants was randomized. This protocol was then repeated for angles 2 and 3. The order of the presentation of the ramp angles was also randomized for each testing session.

Informed consent approved by the Institutional Review Board of the University of Pittsburgh was obtained prior to any testing. After attaching the LEDs, the subject donned the harness and was instructed to walk as naturally as possible at a comfortable pace. Then, he/she was allowed to practice walking such that his/her left foot hit the force plate. Prior to each trial, the subject walked to the top of the ramp and, upon reaching the platform, continued to face away from the walkway and waited for about 1 minute while listening to loud music. During this waiting period, a contaminant was applied (if required) to the surface at the force plate. (The lights in the room were dimmed so that subjects could not perceive the applied contaminant.) At the end of the waiting period, the subject turned around and started walking while looking straight ahead at the wall on the opposite side of the room.

8.3.6 Data Processing

Ground reaction forces measured from the force plate were used to retrieve the required coefficient of friction (RCOF) on dry surfaces. More specifically, the RCOF was calculated by dividing the anterior-posterior shear ground reaction force by the normal ground reaction force for each trial [8.1,8.10]. The peak RCOF ($RCOF_{peak}$) represented the frictional requirements for gait without slips.

The heel's motion data were processed in the sagittal plane to derive the overall slip distance of the foot, defined as the total heel movement that occurred along the floor between the time of heel contact and when the heel stopped moving. This slip distance was used to categorize the outcome of a contaminated walking trial into 3 possible events: no-slip (slip distance < 1 cm, NS), slip-with-recovery (slip distance ≥ 1 cm but heel came to a stop, SR), and slip-and-fall (heel never stopped or subject lost balance and sat in the harness, SF). This cutoff value of 1 cm was

chosen based on the slip distance distribution of dry trials in this experiment representing typical heel movements during normal walking.

8.3.7 Statistical Analysis

The data analyses conducted in this experiment were similar to those performed in Hanson et al. [8.1] with an increased number of environmental conditions and subjects. The relationship among the outcome of a trial, the measured slip resistance (COF) and the biomechanical frictional requirements ($RCOF_{peak}$) of the walking task was of primary interest. Ideally, if the available slip resistance was greater than the required friction, then no slip would occur. However, the transition in the data from no-slip to slip is not discrete. Therefore, this relationship was explored using a predictive logistic regression model based on the difference between the available and required coefficient of friction as the main predictor variable of slips and falls. More specifically, the probability of a slip or fall event was modeled by a logistic response function of the form (Figure 27):

$$probability(slip/fall) = \frac{\exp(\beta_o + \beta_1.COF_{diff})}{1+\exp(\beta_o + \beta_1.COF_{diff})}$$

where βo and β_1 are parameters of the model and $COF_{diff} = COF - RCOF_{peak}$. A COF_{diff} value was derived for each contaminated trial (wet, soap, oil), with the slip resistance (COF) being measured with a specific tester (PSRT or Brungraber Mark II) and a corresponding $RCOF_{peak}$ calculated during the dry trials preceding that contaminated trial.

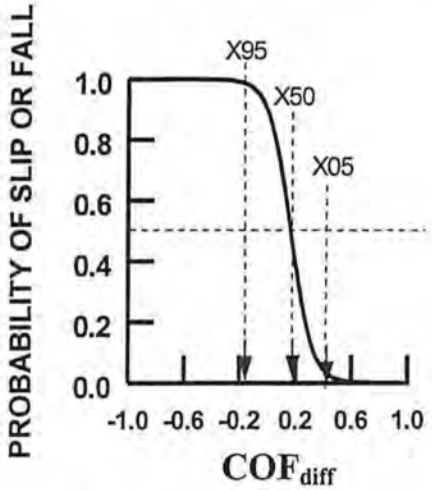

Figure 27 Example of logistic response function and description of measures proposed to evaluate the model's performance. X95, X50, and X05 are the values of COF_{diff} when the probability of a slip/fall is 95%, 50% and 5%, respectively.

Standard logistic regression diagnostic methods were used to examine the appropriateness of the fitted model. In particular, the log-likelihood of the reduced model was compared to the log-likelihood of the full model. Likelihood ratio tests were performed to determine the statistical significance of COF_{diff} on the probability of slip/fall for this simple one-factor logistic regression design. In addition, r^2-values were reported. Maximum likelihood point estimates and confidence intervals [upper 95% - lower 95%] of βo and β_1 were derived along with standard errors associated with each parameter.

In addition to standard goodness of fit measures, other performance indices specifically developed for this project were used to evaluate the ability of the fitted response to predict slips/falls. Figure 27 graphically depicts these performance indices. The first index is X50 and is defined as the value of COF_{diff} at which the estimated probability of a slip/fall event is 0.50. Another parameter is the accuracy of prediction (AOP), which is the range of COF_{diff} values between the 5^{th} and 95^{th} probability estimates. Thus, X50 measures how far COF measurements are shifted, while AOP measures the COF_{diff}'s range where most of the slips/falls occur. An ideal slip tester would have an X50 and AOP index equal to 0. A "poor" slip tester would have a large AOP. A tester with a non-zero X50 is not necessarily "poor", but the COF measurements must be biased i.e., the scale is shifted.

This statistical analysis was repeated for four data sets:

- PSRT tester used, probability of slip (recoveries and falls) considered
- PSRT tester used, probability of fall considered
- Brungraber Mark II tester used, probability of slip (recoveries and falls) considered
- Brungraber Mark II tester used, probability of fall considered

8.4 Results

8.4.1 Slip Resistance Measurements

The floor-contaminant conditions used in this experiment produced a wide range of slipperiness conditions with DCOF and SCOF measurements ranging from a maximum of about 1.4 and 0.8 on dry floors to a minimum of 0.08 and 0.03 recorded under oily conditions, respectively (Table 13). The PSRT and Brungraber Mark II devices provided different absolute slip resistance measures for the majority of the environmental conditions (Table 13). However, both testers indicated coefficient of friction recordings on vinyl tile and smooth painted plywood floors being more affected by the contaminant condition than those measured on rough painted plywood floors. For example, the DCOF and SCOF on dry conditions decreased by more than 50% when soap was applied to the vinyl tile and smooth painted plywood floors, compared to less than 25% on rough painted plywood floors. In general, the low standard deviations associated with the mean DCOF measurements and the majority of the SCOF recordings indicated repeatable measurements across the four trials recorded for each condition.

Table 13 Mean (SD) of dynamic coefficients of friction

Device →	PSRT[1]				Brungraber Mark II			
Contaminant → Floor ↓	Dry	Wet	Soap	Oil	Dry	Wet	Soap	Oil
Vinyl tile	1.41 (0.01)	1.25 (0.03)	0.62 (0.04)	0.12 (0.01)	0.70 (0.04)	0.48 (0.02)	0.22 (0.02)	0.03 (0.00)
Smooth	1.25 (0.01)	0.72 (0.03)	0.43 (0.01)	0.08 (0.01)	0.57 (0.03)	0.50 (0.03)	0.26 (0.02)	0.05 (0.00)
Rough	1.11 (0.02)	0.97 (0.01)	0.87 (0.02)	0.25 (0.02)	0.83 (0.09)	0.77 (0.06)	0.76 (0.03)	0.43 (0.03)

[1]PSRT operating at a velocity of 3 cm/s and a vertical load of 14.5 kg

8.4.2 Outcome Distribution

As expected, the outcome distribution of the number of slips or falls was affected by the floor-contaminant condition (Table 14). All falls occurred on oily conditions with the floor type being either vinyl tile or smooth painted plywood floors. As the ramp angle was increased, recovering from slip events on oily conditions became more challenging. The rough painted plywood floors appeared to be the most effective in preventing slips when contaminants were applied: only about 3% of the slip trials were recorded on the rough painted plywood floors.

Table 14 Number of no-slip (NS), slip-recovery (SR) and slip-fall (SF) trials recorded under contaminated conditions

Ramp Angle (°)	Floor	Contaminant	N_{total}	NS	SR	SF
0	vinyl	wet	16	15	1	0
		soap	16	14	2	0
		oil	16	4	8	4
	smooth	wet	16	15	1	0
		soap	16	13	3	0
		oil	16	9	4	3
	rough	wet	15	15	0	0
		soap	16	16	0	0
		oil	14	14	0	0
5	vinyl	wet	15	13	2	0
		soap	15	12	3	0
		oil	16	0	7	9
	smooth	wet	15	14	1	0
		soap	16	13	3	0
		oil	16	4	1	11
	rough	wet	15	15	0	0
		soap	14	13	1	0
		oil	15	14	1	0
10	vinyl	wet	15	15	0	0
		soap	15	12	3	0
		oil	15	0	0	15
	smooth	wet	16	14	2	0
		soap	16	13	3	0
		oil	16	2	3	11
	rough	wet	14	14	0	0
		soap	15	15	0	0
		oil	14	13	1	0

8.4.3 Dry Conditions - Ground Reaction Forces and RCOF

A total (across all subjects) of 200 to 220 dry trials per ramp angle condition were collected. As anticipated, the shape and magnitude of the ground reaction forces were affected by ramp angle including increases in the shears on inclined surfaces (Figure 28a). As a result of these changes in the ground reaction forces, the shear-to-normal force ratio profile or RCOF also varied with ramp angle (Figure 28b). The frictional requirements of walking were assessed on the dry surfaces, using the peak shear-to-normal force ratio or $RCOF_{peak}$ [8.1,8.10,8.11]. Increasing the ramp angle from 0° to 10° was associated with an approximate 70% $RCOF_{peak}$ increase (Figure 29).

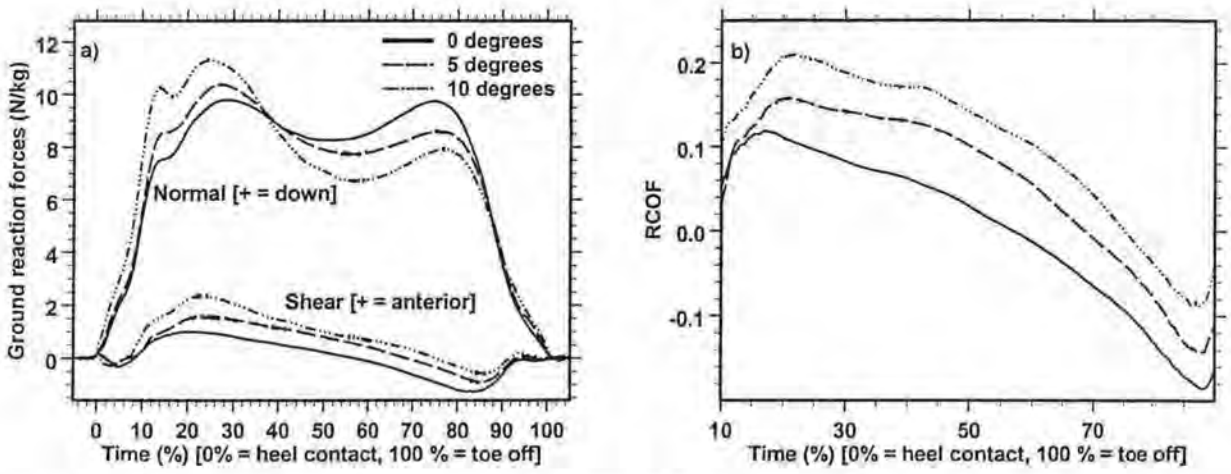

Figure 28 Characteristic profile of ground reaction forces averaged across dry trials recorded on vinyl tile floors: (a) normal and shear ground reaction forces (normalized to body weight), (b) required coefficient of friction (RCOF = shear to normal force ratio). (In b, time is truncated to 10%-90% to avoid "instability" region when both shear and normal ground reaction forces are near 0.)

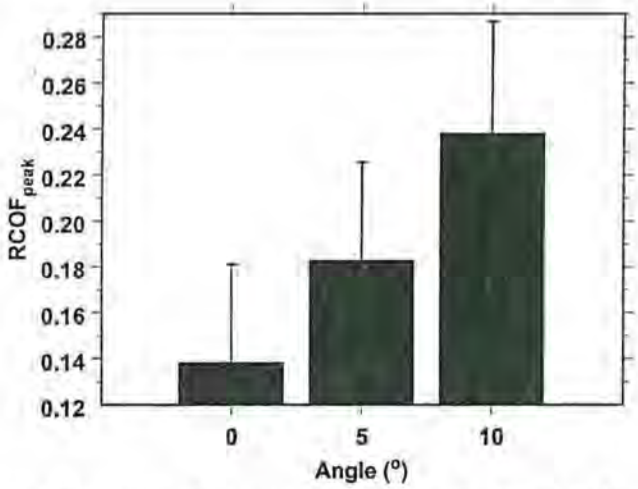

Figure 29 Effect of ramp angle on mean peak required coefficient of friction (SD bars)

8.4.4 Slip Probability and COFdiff

The difference between the available friction as measured by both slip resistance testers and the required friction, i.e. COF_{diff}, was compared to the probability of slips (both SR and SF) and probability of falls alone (SF) within each environmental condition. As suggested by Hanson et al. [8.1], the relationship between COF_{diff} and trial outcome was further investigated using a

logistic regression model. For an ideal relationship between COF_{diff} and slip/fall probability, negative values of COF_{diff} (i.e. less friction is available than required on dry surfaces) would theoretically be predictive of a slip and fall, while positive values (more friction is available than the requirement set by RCOF) would be associated with no slip/fall accidents. This ideal relationship assumes 1) slip resistance assessments are accurate and 2) the logistic regression model is an appropriate method to represent slip and fall data.

Increases in COF_{diff} certainly led to a decrease in the slip and fall probability (Figures 30 and 31). In addition, a slip or a fall probability greater than 0.5 was, in general, associated with negative COF_{diff} values. However, the relationship was not ideal: for a number of environmental conditions, slips still occurred even when COF_{diff} was positive (Figures 30a-b). These slips that occurred at positive COF_{diff} did not result in falls (Figures 31a-b).

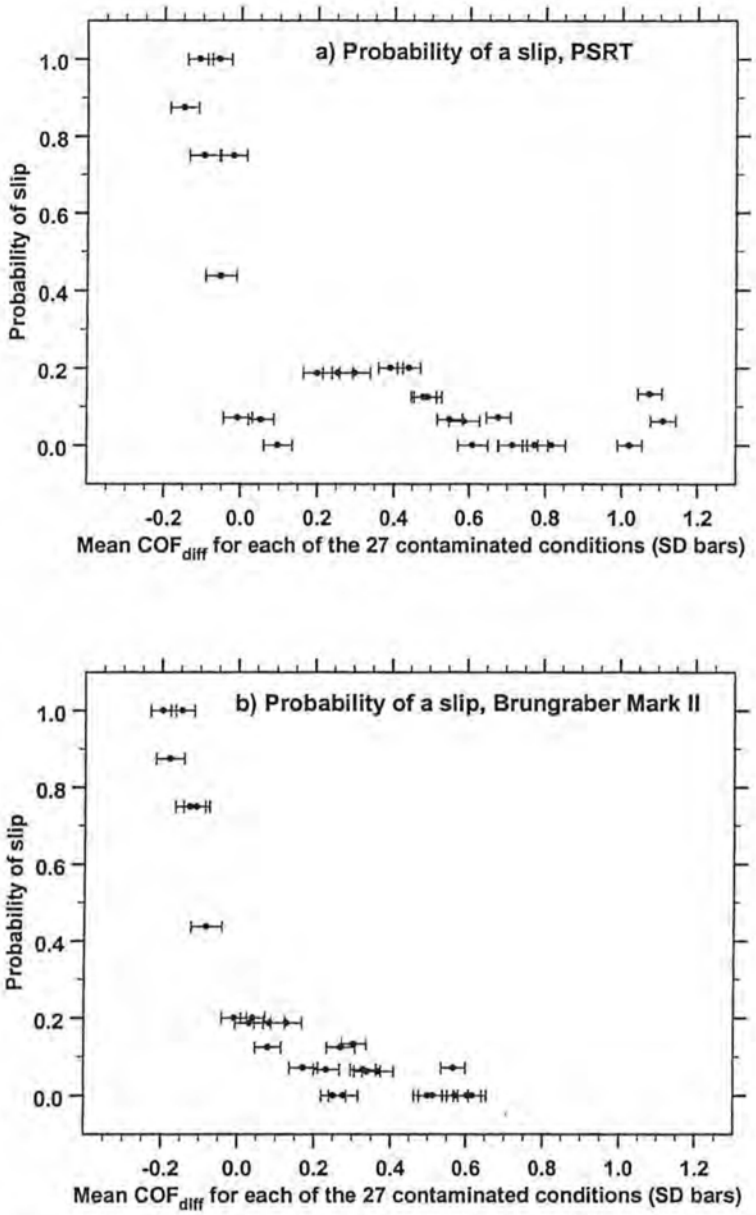

Figure 30 The probability of slips (both SR and SF) compared to COF_{diff}. The frictional properties of the shoe/floor interface were measured with (a) the PSRT and (b) the Brungraber Mark II device.

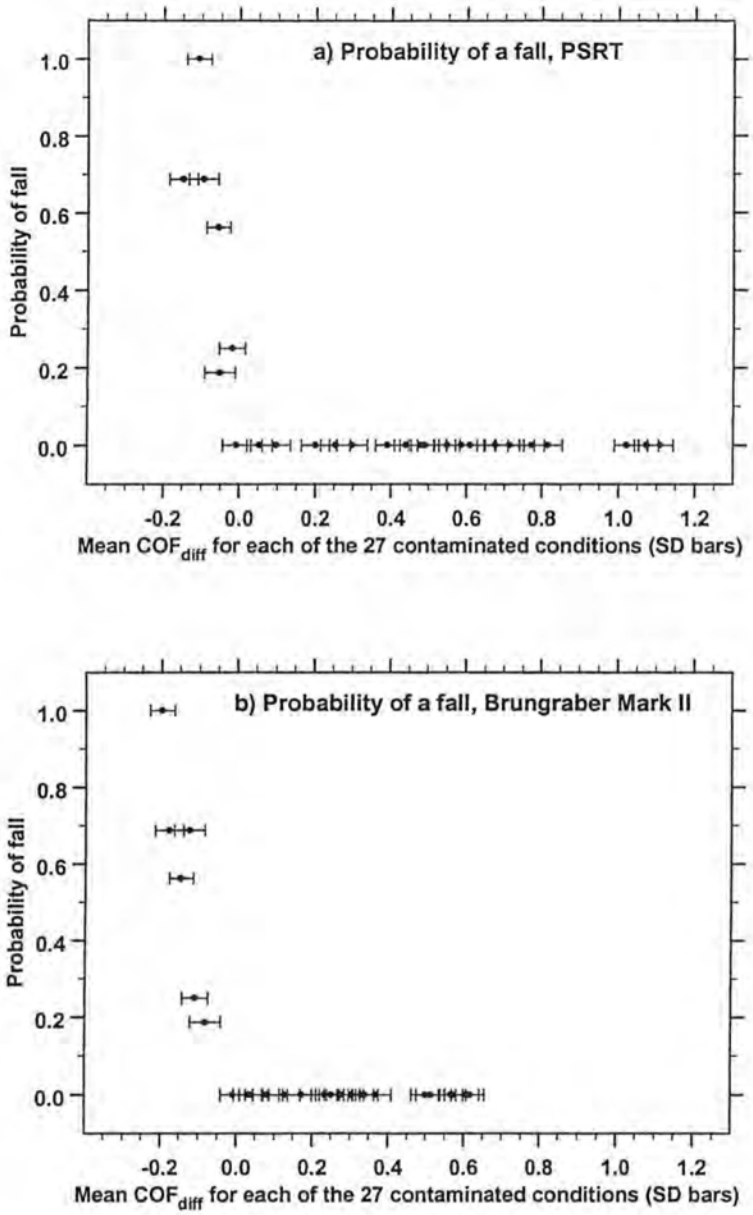

Figure 31 The probability of falls compared to COF_{diff}. The frictional properties of the shoe/floor interface were measured with (a) the PSRT and (b) the Brungraber Mark II device.

8.4.5 Logistic Regression Modeling

Next, logistic regression response functions were used to describe the relationship between COF_{diff} and the probability of slip. This relationship was found to be statistically significant as shown in the results of the likelihood ratio tests presented in Table 15 and the estimated confidence interval of β_1, which excluded 0 (Table 16). This finding was confirmed for all four data sets.

All slip events (both SR and SF trials): Despite the statistical significance of the COF_{diff} effect on the probability of slip, logistic regression curves did not capture well the overall characteristics of slip incidence (Figure 32). This was reflected in the low r^2 value (less than 0.5, Table 15), but also the relatively large AOP index (Table 16) of the model (true for both testers). Slip resistance measurements from the two testers led to significant differences in the resulting model's parameters (confidence interval estimates of β_1 in Table 16). The model resulting from COF-measurements using the Brungraber Mark II device performed better than the one using the PSRT slip resistance measurements (Figure 32). This improved performance is evident in the relative r^2 increase and the 50% reduction in the tightness of the logistic regression curve, i.e. AOP (Tables 3 and 4). The overall bias of the COF_{diff} recordings (X50 in Table 16) showed similar magnitude but opposite direction shifts between the two testers. Finally, the correct classification rate, based on a 0.5 cutoff probability, was comparable between the devices: the PSRT and Brungraber Mark II tester correctly predicted 71% and 73% of the slip events, respectively.

Only fall-events: In the case of severe slips that led to falls (oily conditions), logistic regression responses associated with the two testers were similar (Figure 33; r^2-value in Table 15; confidence interval estimates of β_1, X50 and AOP in Table 16). The analysis showed that logistic regression models provided a better fit to the fall events (i.e. extremely slippery conditions) compared to when all slip events were considered (Figures 32 and 33, Tables 3 and 4).

Table 15 Overall goodness of fitness measures of logistic regression models using COF_{diff}

Event →	Probability of Slip (slip-recovery & slip-fall)		Probability of Fall (only slip-fall)	
Device → Paramater ↓	PSRT	Brungraber Mark II	PSRT	Brungraber Mark II
log-likelihood (reduced model) = L(R)	-227.5	-227.5	-153.3	-153.3
log-likelihood (full model) = L(F)	-158.7	-130.3	-62.8	-56.5
Difference = L(F) - L(R)	68.8	97.2	90.5	96.8
$\chi^2 = 2.[L(F) - L(R)]$	137.6	194.3	181.0	193.6
p-value (likelihood ratio test)	< 0.0001	< 0.0001	< 0.0001	< 0.0001
r^2	0.30	0.43	0.59	0.63

Table 16 Specific parameters of logistic regression models and inverse prediction results

Event →	Probability of Slip (slip-recovery & slip-fall)		Probability of Fall (only slip-fall)	
Device → Paramater ↓	PSRT	Brungraber Mark II	PSRT	Brungraber Mark II
b_0 (SE) = point estimate of β_0	-0.10 (0.16)	0.36 (0.16)	1.80 (0.35)	3.49 (0.59)
b_1 (SE) = point estimate of β_1	4.87 (0.55)	10.02 (1.07)	22.85 (4.04)	26.12 (4.30)
[lower 95%; upper 95%] estimate of β_0	[-0.41; 0.21]	[0.06; 0.67]	[1.18; 2.55]	[2.48; 4.83]
[lower 95%; upper 95%] estimate of β_1	[3.86; 6.01]	[8.05; 12.27]	[15.76; 31.66]	[18.76; 35.74]
X50	0.02	-0.04	-0.08	-0.13
X05	-0.58	-0.33	-0.21	-0.25
X95	0.62	0.26	0.05	-0.02
AOP = X95 – X05	1.20	0.59	0.26	0.27

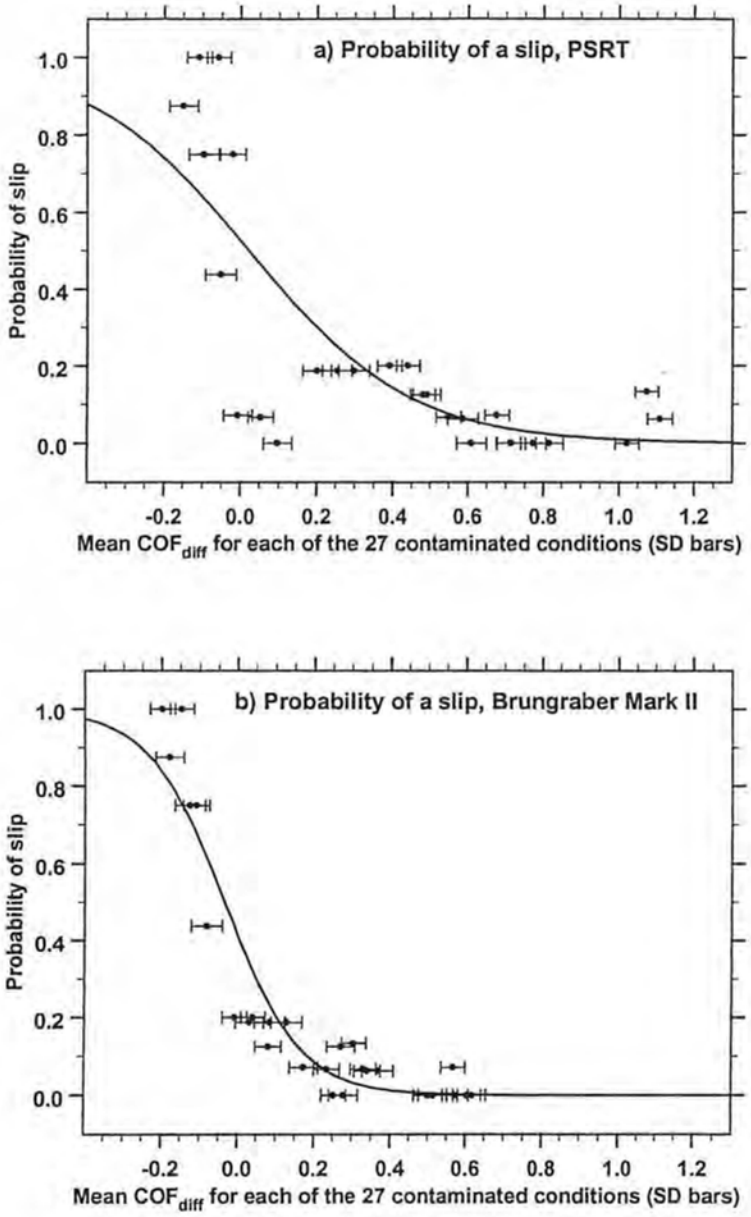

Figure 32 Logistic regression modeling of the relationship between the probability of slips (both SR and SF) and COF_{diff}. The frictional properties of the shoe/floor interface were measured with (a) the PSRT and (b) the Brungraber Mark II device.

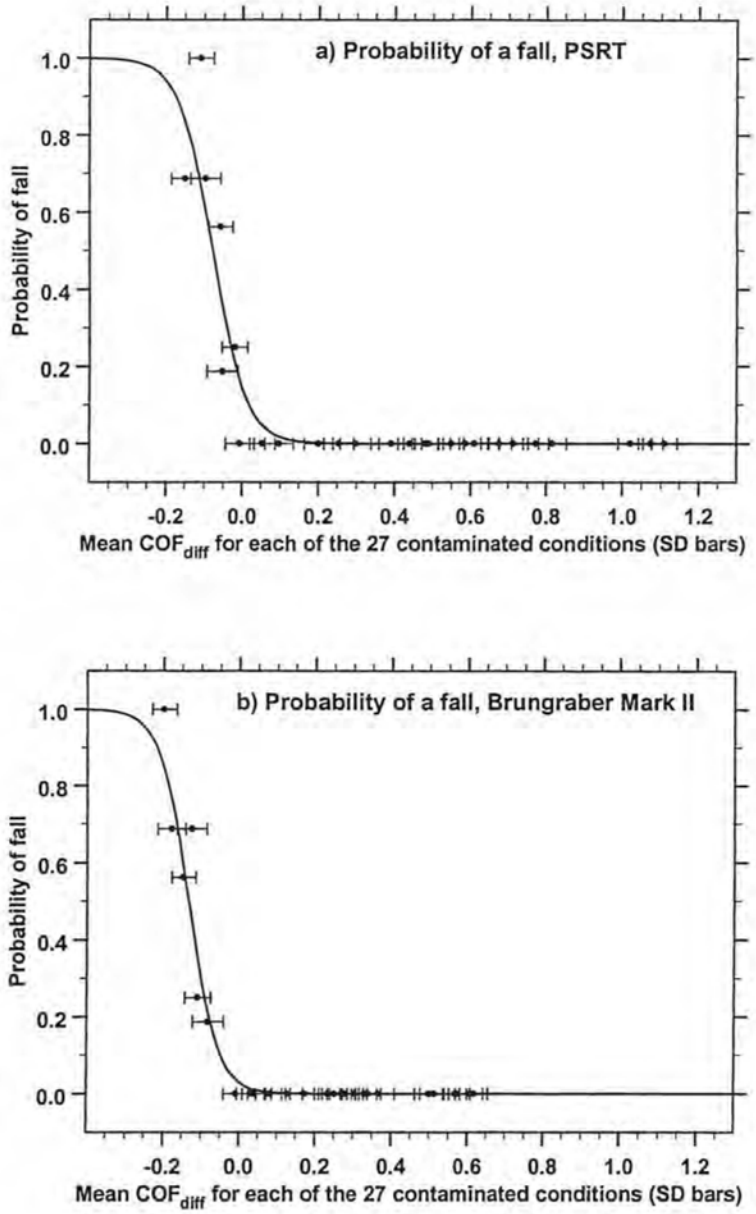

Figure 33 Logistic regression modeling of the relationship between the probability of falls and COF_{diff}. The frictional properties of the shoe/floor interface were measured with (a) the PSRT and (b) the Brungraber Mark II device.

COF ratio model: In addition to COF_{diff}, the effect of another explanatory variable was investigated:

$$COF_{ratio} = \frac{SCOF / DCOF}{RCOF_{peak}}$$

Using COF_{ratio} as a predictor variable of slip incidence could be useful. Ideally, a measure grater than 1.0 would indicate sufficient friction available and less than 1.0 inadequate friction. The statistical analysis was re-run with COF_{ratio} (Table 17). A comparison of these results with Table 15 revealed very similar findings whether COF_{diff} or COF_{ratio} was used. Thus, the COF_{ratio} analysis was not further explored.

Table 17 Overall goodness of fitness measures of logistic regression models using COF_{ratio}

Event →	Probability of Slip (slip-recovery & slip-fall)		Probability of Fall (only slip-fall)	
Device → Paramater ↓	PSRT	Brungraber Mark II	PSRT	Brungraber Mark II
log-likelihood (reduced model) = L(R)	-227.5	-227.5	-153.3	-153.3
log-likelihood (full model) = L(F)	-169.6	-140.6	-62.6	-57.5
Difference = L(F) - L(R)	57.9	86.9	90.7	95.8
$\chi^2 = 2.[L(F) - L(R)]$	115.8	173.8	181.4	191.6
p-value (likelihood ratio test)	< 0.0001	< 0.0001	< 0.0001	< 0.0001
r^2	0.25	0.38	0.59	0.63

Environmental conditions effect on the performance of the COF_{diff} model: The strength of the statistical correlation between the probability of slips and COF_{diff} was not uniform across all environmental conditions. The overall relatively weak correlation ($r^2 < 0.50$ and large AOP) may be attributed to the performance of the logistic regression model under specific contaminant/flooring conditions (Figure 34). The different contaminant conditions appeared to behave differently. For example, a closer examination of the COF_{diff} associated with each environmental condition revealed that, in general, wet and soapy conditions on vinyl tile and smooth painted plywood floors were clear examples of the exception to the hypothesized inverted *S* relationship between COF_{diff} and slip probability put forward by Hanson et al. [8.1] (Figure 34). However, a good performance of the model was obtained under extreme environmental conditions, i.e. very slippery (oily vinyl and smooth floors) and very slip-resistant conditions (rough floors). Finally, the use of slip resistance measurements from two different testers resulted in varying model performance across conditions (Figure 34a versus Figure 34b). More specifically, these differences were more pronounced on soapy and wet floors and kept to a minimum under oily conditions. Furthermore, when the PSRT was used to measure the frictional properties of the shoe/floor interface, the relationship between the probability of slip

and COF_{diff} appeared to be characterized by a greater variability for COF_{diff} values ranging from 0.2 to 0.6, i.e. soapy/wet conditions, compared to the rest of the COF_{diff} scale (Figure 34a). The extent of this variability was less pronounced with the use of the Brungraber Mark II tester (Figure 34b).

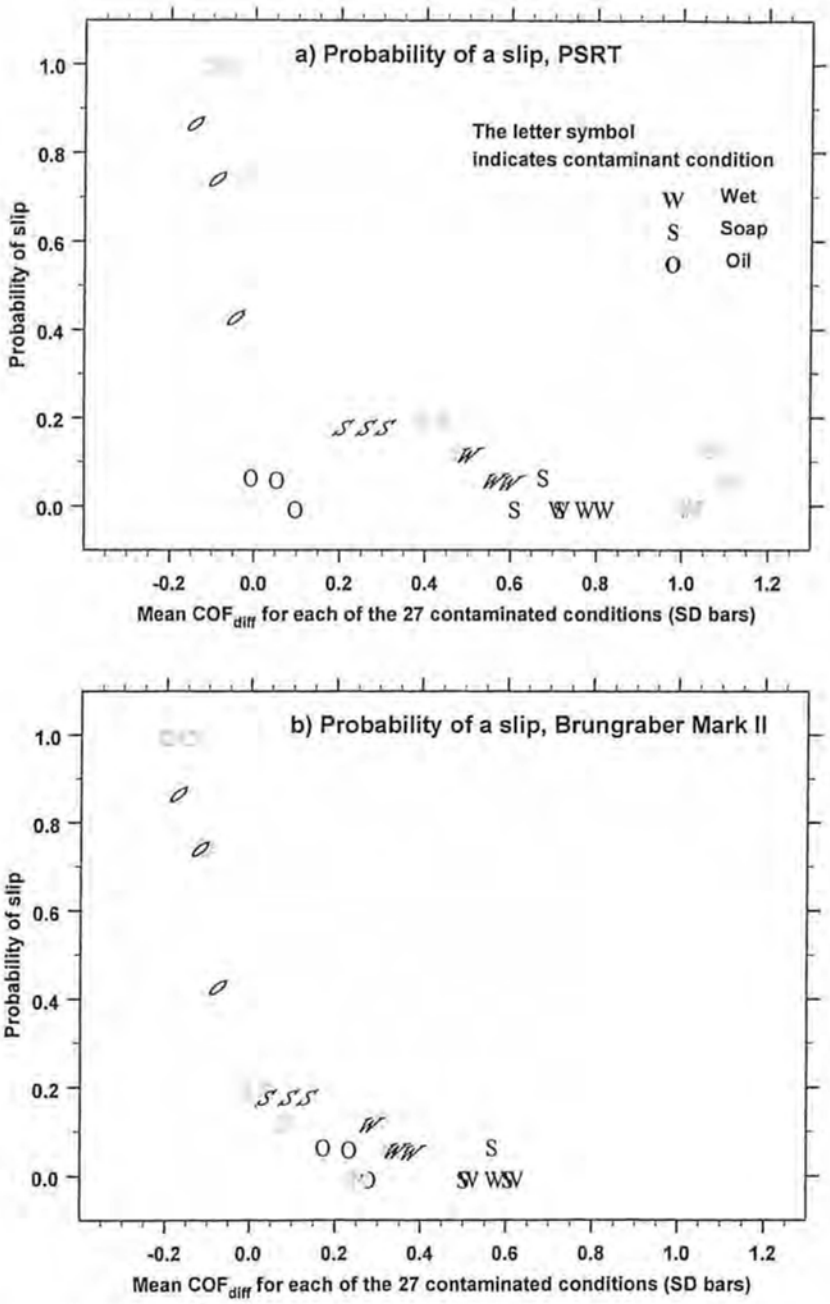

Figure 34 Effect of contaminant and flooring conditions on the relationship between the probability of slips and COF_{diff}. The frictional properties of the shoe/floor interface were measured with (a) the PSRT and (b) the Brungraber Mark II device. The font type and color of each data point is associated with a flooring condition: 1) gray and vinyl, 2) italic/black and smooth; 3) normal/black and rough.

8.5 Discussion

Logistic regression models proved to be useful in describing the nature of the relationship between the probability of falls and the difference between biomechanical frictional requirements and available friction (COF_{diff}). However, logistic regression functions of COF_{diff} alone did not provide a satisfactory fit of the probability of slip ($r^2 < 0.50$). Three possible factors are speculated to be the reasons of this high variability in the slip modeling: 1) the hypothesized probabilistic relationship between slip/fall probability and COF_{diff} is not appropriate to predict slips, 2) large RCOF variability within and across subjects and 3) inaccurate assessment of slip resistance measures (DCOF and SCOF). Based on previous research [8.1,8.10] and on the standard deviation bars associated with the $RCOF_{peak}$ in this experiment, the first two factors were concluded not to be probable reasons for this unsatisfactory fit. Thus, problems in slip measurement are believed to be the primary reason with the poor fit of the data.

There are numerous possible reasons for poor slip resistance performance. The forward velocity at which the PSRT was operating (3 cm/s) is believed to be too low (i.e. does not represent heel dynamics), thus overestimating the DCOF values, especially under contaminated conditions. This was also supported by the frictional characteristics of similar surfaces reported by Hanson et al. [8.1], also using the PSRT operating however at a forward velocity of 10 cm/s. For example, under wet-vinyl tile contaminant-floor conditions, a DCOF of 0.64 was recorded by Hanson et al. [8.1] compared to 1.25 here. While the shoe materials were different, it is believed that velocity played a significant role. The validity of the tractive properties of the shoe/floor interface measured with the Brungraber Mark II device can also be debated. A major limitation noticed during the slip resistance testing using this device was the adhesion of the PVC shoe sole on the following environments: vinyl and smooth painted plywood floors, dry and wet. Under these conditions, the horizontal shear forces must overcome these adhesive forces for the shoe sole to slip, a phenomenon that does not happen during normal walking. Thus, adhesion-related problems will result, once again, in the overestimation of SCOF readings. Flynn [8.12] reported similar adhesion-related problems and modified the surface of the floor sample by inserting groves and ridges in an attempt to reduce these effects. While these non-standardized preparation procedures may improve the accuracy of slip resistance readings, they also could modify the frictional characteristics of the shoe/floor interface due to the reduction in the contact area that occur with the insertion of groves and ridges.

The probability models proposed here for the PSRT device did not perform as well as the ones developed by Hanson et al. [8.1], who used the same tester. Many factors could have contributed to the differences in the overall model's performance between the two studies: 1) the tester's parameters of operation such vertical force and velocity effects (mentioned previously) were not the same, 2) the environmental (floor and contaminant) conditions were different and the accuracy of the DCOF measurements could vary across conditions, and 3) $RCOF_{peak}$ differences were noted between the two studies and are believed to result from the fact that, in Hanson et al. [8.1], the $RCOF_{peak}$ was computed during "baseline conditions", i.e. the subject was aware of the dry conditions, thus resulting in greater $RCOF_{peak}$ values (see section 3 on anticipation effects).

The testers used in this study may be effective in predicting slips/falls only in extreme conditions, i.e. under very slippery or slip-resistant shoe-floor interfaces with coefficient of friction measures being greater than 0.7 or less than 0.2. Indeed, specific non-extreme contaminant-floor conditions are believed to be among the contributing factors to the disagreement between the hypothesized probability of slips and falls (logistic regression model) and experimental findings. Thus, in spite of their overall poor performance, the logistic regression models were useful in identifying specific environmental conditions under which inaccurate coefficient of friction recordings were obtained using a particular tribometer.

8.6 Future Research

Further investigation is needed to verify that the estimation of the shoe/floor frictional characteristics is indeed the reason for the logistic regression model's inability to satisfactorily capture the relationship between slip incidence and COF_{diff}. First, the frictional properties of the shoe/floor interface used in this study need to be tested with other devices. A number of tribometers should be used to measure the tractive characteristics of the same shoe-floor-contaminant conditions used in this study. In addition to the Brungraber Mark II and PSRT devices, at least three other testers are suggested: 1) the Horizontal Pull Slip Meter, commonly used in industry, measures a SCOF by applying a horizontal force until a weighted sled begins to move; 2) the Ergodyne, otherwise known as English XL, is another articulated strut device that, unlike the Brungraber Mark II, is not gravity dependent but rather pneumatically actuated to produce a normal force; and 3) a portable test device recently developed by Grönqvist et al. [8.13]. Mean and reproducibility of slip resistance measurements should be compared among devices within each environmental condition by performing standard correlation analyses.

In addition to evaluating each testers' performance individually as was done here, differences in the ability of predicting slips among the five slip resistance testers could be analyzed simultaneously by including indicator variables representing the different devices in the logistic regression model (four dummy binary variables are needed to describe the five devices). Thus, in this two-factor analysis the COF_{diff} and device variables represent the independent variables, while the dependent variable is the outcome of the contaminated trial. Using this general model, the differences in the ability of predicting slips/falls among devices are revealed by simply performing multiple pairwise comparison Tukey tests between devices.

In summary, the primary goal of this ongoing project is to determine the relationship among measured slip resistance, $RCOF_{peak}$ and slip/fall events. The development of logistic regression models describing this relationship is believed to be a potential method to characterize slip resistance testers and their ability to predict slips and falls. The overall and specific characteristics of each tester under particular conditions should be examined individually and compared across devices. Performance indices should be used to evaluate the ability of each device in predicting slips and falls.

9.0 BIBLIOGRAPHY

Section 3.0

3.1 Hanson, J. P., Redfern, M. S., and Mazumdar, M., "Predicting Slips and Falls Considering Required and Available Friction," Ergonomics, Vol. 42, No. 12 (1999) pp. 1619-33.

3.2 Kumar, S., ed. Biomechanics in Ergonomics, "Slips and Falls, by Grönqvist, R." Taylor and Francis, 1999) pp. 351-75

3.3 Grönqvist, R., Roine, J., and Järvinen, E., "An Apparatus and a Method for Determining the Slip Resistance of Shoes and Floors by Simulation of Human Foot Motions," Ergonomics, Vol. 32, No. 8 (August 1989) pp. 979-95.

3.4 Slips, Stumbles, and Falls: Pedestrian Footwear and Surfaces, 1990, "Development of SATRA Slip Test and Tread Pattern Design Guidelines, by Wilson, M. P." (ASTM-Special-Technical-Publication. American society for testing and materials).

3.5 Redfern, M. S., and Bidanda, B., "Slip Resistance of the Shoe Floor Interface Under Biomechanically Relevant Conditions," Ergonomics, Vol. 37, No. 3 (March 1994) pp. 511-24.

3.6 Anderson, R., and Lagerlof, E., "Accident Data in the New Swedish Information System on Occupational Injuries," Ergonomics, Vol. 26, No. 1 (January 1983) pp. 33-42.

Section 4.0

4.1 McCaig, L. F., and Stussman, B. J., National Hospital Ambulatory Medical Care Survey: 1996 Emergency Department Summary (National Center for Health Statistics, 1997).

4.2 Rice, D. P., and MacKenzie, E. J., Cost of Injury in the US: A Report to Congress (Institute for Health and Aging, University of California and John Hopkins University Press, 1989).

4.3 Englander, F., Hodson, T. J., and Terregrossa, R. A., "Economic Dimensions of Slip and Fall Injuries," Journal of Forensic Sciences, Vol. 41, No. 5 (September 1996) pp. 733-46.

4.4 The United States Bureau of Labor Statistics (under the authority of the United States Department of Labor, 1996).

4.5 Fingerhut, L. A., Cox , C. S., and Warner, M., International Comparative Analysis of Injury Mortality - Findings From the ICE on Injury Statistics (National Center for Health Statistics, 1998).

4.6 Lloyd, D. G., and Stevenson, M. G., "Investigation of Floor Surface Profile Characteristics That Will Reduce the Incidence of Slips and Falls," Mechanical Engineering Transactions Institution of Engineers - Australia, Vol. ME17, No. 2 (September 1992) pp. 99-105.

4.7 Bell, J. L., Gardner, L. I., and Landsittel, D. P., "Slip and Fall-Related Injuries in Relation to Environmental Cold and Work Location in Above-Ground Coal Mining Operations," Americal Journal of Industrial Medicine, Vol. 38 (2000) pp. 40-48.

4.8 Bentley, T. A., and Haslam, R. A., "Slip, Trip and Fall Accidents Occurring During the Delivery of Mail," Ergonomics, Vol. 41, No. 12 (December 1998) pp. 1859-72.

4.9 Björnstig, U., Björnstig, J., and Dahlgren, A., "Slipping on Ice and Snow - Elderly Women and Young Men Are Typical Victims," Accident Analysis and Prevention, Vol. 29, No. 2 (1997) pp. 211-15.

4.10 Walkway Surfaces: Measurements of Slip Resistance, 1978, "Measurement of Slip Between the Shoe and Ground During Walking, by Perkins, P. J." (ASTM-Special-Technical-Publication. American society for testing and materials).

4.11 Redfern, M. S., and DiPasquale, J., "Biomechanics of Descending Ramps," Gait and Posture, Vol. 6, No. 2 (October 1997) pp. 119-25.

4.12 Hanson, J. P., Redfern, M. S., and Mazumdar, M., "Predicting Slips and Falls Considering Required and Available Friction," Ergonomics, Vol. 42, No. 12 (1999) pp. 1619-33.

4.13 Strandberg, L., and Lanshammar, H., "The Dynamics of Slipping Accidents," Journal of Occupational Accidents , Vol. 3 (1981) pp. 153-62.

4.14 Tang, P.-F., and Woollacott, M. H., "Inefficient Postural Responses to Unexpected Slips During Walking in Older Adults," Journals of Gerontology. Series A, Biological Sciences & Medical Sciences, Vol. 53, No. 6 (November 1998) pp. M471-M480.

4.15 Grönqvist, R., Roine, J., and Järvinen, E., "An Apparatus and a Method for Determining the Slip Resistance of Shoes and Floors by Simulation of Human Foot Motions," Ergonomics, Vol. 32, No. 8 (August 1989) pp. 979-95.

4.16 Redfern, M. S., and Bidanda, B., "Slip Resistance of the Shoe Floor Interface Under Biomechanically Relevant Conditions," Ergonomics, Vol. 37, No. 3 (March 1994) pp. 511-24.

4.17 Slips, Stumbles, and Falls: Pedestrian Footwear and Surfaces, 1990, "Development of SATRA Slip Test and Tread Pattern Design Guidelines, by Wilson, M. P."

(ASTM-Special-Technical-Publication. American society for testing and materials).

4.18 Advances in Industrial Ergonomics and Safety IV, 1992, "Practical Synthesis of Biomechanical Results to Prevent Slips and Falls in the Workplace, by Andres, R. O., O'Connor, D., and Eng, T.," pp. 1001-6.

4.19 Slips, Stumbles, and Falls: Pedestrian Footwear and Surfaces, 1990, "Slip Resistance Needs of the Mobility Disabled During Level and Grade Walking, by Buczek, F. L., Cavanagh, P. R., Kulakowski, B. T., and Pradhan, P." (ASTM-Special-Technical-Publication. American society for testing and materials).

4.20 Buczek, F. L., and Banks, S. A., "High-Resolution Force Plate Analysis of Utilized Slip Resistance in Human Walking," Journal of Testing and Evaluation, Vol. 24, No. 6 (November 1996) pp. 353-58.

4.21 Winter, David A, A.B.C. (Anatomy, Biomechanics and Control) of Balance During Standing and Walking Waterloo, Ontario: Waterloo Biomechanics, 1995).

Section 5.0

5.1 The United States Bureau of Labor Statistics (under the authority of the United States Department of Labor, 1996).

5.2 Leamon, T. B., and Murphy, P. L., "Occupational Slips and Falls: More Than a Trivial Problem," Ergonomics, Vol. 38, No. 3 (March 1995) pp. 487-98.

5.3 Information System om Arbetsskador (Sweden), translated to "Information System Occupational Injuries and Disease," (under the authority of the National Board of Occupational Safety and Health, 1998).

5.4 Lloyd, D. G., and Stevenson, M. G., "Investigation of Floor Surface Profile Characteristics That Will Reduce the Incidence of Slips and Falls," Mechanical Engineering Transactions Institution of Engineers - Australia, Vol. ME17, No. 2 (September 1992) pp. 99-105.

5.5 Cumming, R. G., and Klineberg, R. J., "Fall Frequency and Characteristics and the Risk of Hip Fractures," Journal of the American Geriatrics Society, Vol. 42, No. 7 (July 1994) pp. 774-78.

5.6 Norton, R., Campbell, A. J., Lee-Joe, T., Robinson, E., and Butler, M., "Circumstances of Falls Resulting in Hip Fractures Among Older People," Journal of the American Geriatrics Society, Vol. 45, No. 9 (September 1997) pp. 1108-12.

5.7 Hanson, J. P., Redfern, M. S., and Mazumdar, M., "Predicting Slips and Falls Considering Required and Available Friction," Ergonomics, Vol. 42, No. 12 (1999) pp. 1619-

33.

5.8 Kumar, S., ed. Biomechanics in Ergonomics, "Slips and Falls, by Grönqvist, R." Taylor and Francis, 1999) pp. 351-75.

5.9 Grönqvist, R., Roine, J., and Järvinen, E., "An Apparatus and a Method for Determining the Slip Resistance of Shoes and Floors by Simulation of Human Foot Motions," Ergonomics, Vol. 32, No. 8 (August 1989) pp. 979-95.

5.10 Slips, Stumbles, and Falls: Pedestrian Footwear and Surfaces, 1990, "Development of SATRA Slip Test and Tread Pattern Design Guidelines, by Wilson, M. P." (ASTM-Special-Technical-Publication. American society for testing and materials).

5.11 Redfern, M. S., and Bidanda, B., "Slip Resistance of the Shoe Floor Interface Under Biomechanically Relevant Conditions," Ergonomics, Vol. 37, No. 3 (March 1994) pp. 511-24.

5.12 Redfern, M. S., and DiPasquale, J., "Biomechanics of Descending Ramps," Gait and Posture, Vol. 6, No. 2 (October 1997) pp. 119-25.

5.13 Walkway Surfaces: Measurements of Slip Resistance, 1978, "Measurement of Slip Between the Shoe and Ground During Walking, by Perkins, P. J." (ASTM-Special-Technical-Publication. American society for testing and materials).

5.14 Strandberg, L., and Lanshammar, H., "The Dynamics of Slipping Accidents," Journal of Occupational Accidents , Vol. 3 (1981) pp. 153-62.

5.15 Advances in Industrial Ergonomics and Safety I, 1989, "The Natural History of a Microslip, by Leamon, T. B., and Son, D. H.," pp. 633-8.

Section 6.0

6.1 Fingerhut, L. A., Cox , C. S., and Warner, M., International Comparative Analysis of Injury Mortality - Findings From the ICE on Injury Statistics (National Center for Health Statistics, 1998).

6.2 McCaig, L. F., and Stussman, B. J., National Hospital Ambulatory Medical Care Survey: 1996 Emergency Department Summary (National Center for Health Statistics, 1997).

6.3 The United States Bureau of Labor Statistics (under the authority of the United States Department of Labor, 1996).

6.4 Leamon, T. B., and Murphy, P. L., "Occupational Slips and Falls: More Than a Trivial Problem," Ergonomics, Vol. 38, No. 3 (March 1995) pp. 487-98.

6.5 Lloyd, D. G., and Stevenson, M. G., "Investigation of Floor Surface Profile Characteristics That Will Reduce the Incidence of Slips and Falls," Mechanical Engineering Transactions Institution of Engineers - Australia, Vol. ME17, No. 2 (September 1992) pp. 99-105.

6.6 Cumming, R. G., and Klineberg, R. J., "Fall Frequency and Characteristics and the Risk of Hip Fractures," Journal of the American Geriatrics Society, Vol. 42, No. 7 (July 1994) pp. 774-78.

6.7 Norton, R., Campbell, A. J., Lee-Joe, T., Robinson, E., and Butler, M., "Circumstances of Falls Resulting in Hip Fractures Among Older People," Journal of the American Geriatrics Society, Vol. 45, No. 9 (September 1997) pp. 1108-12.

6.8 Grönqvist, R., Roine, J., and Järvinen, E., "An Apparatus and a Method for Determining the Slip Resistance of Shoes and Floors by Simulation of Human Foot Motions," Ergonomics, Vol. 32, No. 8 (August 1989) pp. 979-95.

6.9 Slips, Stumbles, and Falls: Pedestrian Footwear and Surfaces, 1990, "Development of SATRA Slip Test and Tread Pattern Design Guidelines, by Wilson, M. P." (ASTM-Special-Technical-Publication. American society for testing and materials).

6.10 Redfern, M. S., and Bidanda, B., "Slip Resistance of the Shoe Floor Interface Under Biomechanically Relevant Conditions," Ergonomics, Vol. 37, No. 3 (March 1994) pp. 511-24.

6.11 Slips, Stumbles, and Falls: Pedestrian Footwear and Surfaces, 1990, "Slip Resistance Needs of the Mobility Disabled During Level and Grade Walking, by Buczek, F. L., Cavanagh, P. R., Kulakowski, B. T., and Pradhan, P." (ASTM-Special-Technical-Publication. American society for testing and materials).

6.12 Buczek, F. L., and Banks, S. A., "High-Resolution Force Plate Analysis of Utilized Slip Resistance in Human Walking," Journal of Testing and Evaluation, Vol. 24, No. 6 (November 1996) pp. 353-58.

6.13 Hanson, J. P., Redfern, M. S., and Mazumdar, M., "Predicting Slips and Falls Considering Required and Available Friction," Ergonomics, Vol. 42, No. 12 (1999) pp. 1619-33.

6.14 Eighth International Congress of Biomechanics, July, 1981, "Horizontal Floor Reaction Forces and Heel Movements During the Initial Stance Phase, by Lanshammar, H., and Strandberg, L."

6.15 Winter, D. and others, ed. Biomechanics, "Assessment of Friction by Speed Measurement During Walking in a Closed Path, by Lanshammar, H., and Strandberg, L." Champaign, IL: Human kinetics publishers, 1985)

6.16 McVay, E. J., and Redfern, M. S., "Rampway Safety - Foot Forces As a Function of

Rampway Angle," American Industrial Hygiene Association Journal, Vol. 55, No. 7 (July 1994) pp. 626-34.

6.17 Perkins, P. J., and Wilson, M. P., "Slip Resistance of Shoes - New Developments," Ergonomics, Vol. 26, No. 1 (1983) pp. 73-82.

6.18 Redfern, M. S., and DiPasquale, J., "Biomechanics of Descending Ramps," Gait and Posture, Vol. 6, No. 2 (October 1997) pp. 119-25.

6.19 Proceedings of the Annual Conference of the Human Factors Association of Canada, 1988, "Measurement and Comparison of "Required" Versus "Available" Slip Resistance, by Rhoades, T. P., and Miller, J. M." (Human factors association of Canada).

6.20 Strandberg, L., and Lanshammar, H., "The Dynamics of Slipping Accidents," Journal of Occupational Accidents , Vol. 3 (1981) pp. 153-62.

6.21 Hsaio, E. T., and Robinovitch, S. N., "Common Protective Movements Govern Unexpected Falls From Standing Height.," Journal of Biomechanics, Vol. 31, No. 1 (1998) pp. 1-9.

6.22 Tang, P.-F., Woollacott, M. H., and Chong, R. K., "Control of Reactive Balance Adjustments in Perturbed Human Walking: Roles of Proximal and Distal Postural Muscle Activity," Experimental Brain Research, Vol. 119, No. 2 (March 1998) pp. 141-52.

6.23 Tang, P.-F., and Woollacott, M. H., "Inefficient Postural Responses to Unexpected Slips During Walking in Older Adults," Journals of Gerontology. Series A, Biological Sciences & Medical Sciences, Vol. 53, No. 6 (November 1998) pp. M471-M480.

6.24 Tang, P.-F., and Woollacott, M. H., "Phase-Dependent Modulation of Proximal and Distal Postural Responses to Slips in Young and Older Adults," Journals of Gerontology. Series A, Biological Sciences & Medical Sciences, Vol. 54, No. 2 (February 1999) pp. M89-M102.

6.25 Plagenhoef, S. C., "Anatomical Data for Analyzing Human Motion," Research Quarterly, Vol. 54 (1983) pp. 169-78.

6.26 Winter, David A, A.B.C. (Anatomy, Biomechanics and Control) of Balance During Standing and Walking Waterloo, Ontario: Waterloo Biomechanics, 1995).

6.27 Runge, C. F., Shupert, C. L., Horak, F. B., and Zajac, F. E., "Ankle and Hip Postural Strategies Defined by Joint Torques," Gait and Posture, Vol. 10, No. 2 (October 1999) pp. 161-70.

6.28 Horak, F. B., and Nashner, L. M., "Central Programming of Postural Movements: Adaptation to Altered Support-Surface Configurations," Journal of Neurophysiology, Vol. 55, No. 6 (June 1986) pp. 1369-81.

6.29 Runge, C. F., Shupert, C. L., Horak, F. B., and Zajac, F. E., "Role of Vestibular Information in Initiation of Rapid Postural Responses," Experimental Brain Research, Vol. 122, No. 4 (October 1998) pp. 403-12.

6.30 Pai, Y. C., and Iqbal, K., "Simulated Movement Termination for Balance Recovery: Can Movement Strategies Be Sought to Maintain Stability in the Presence of Slipping or Forced Sliding?," Journal of Biomechanics, Vol. 32, No. 8 (1999) pp. 779-86.

Section 7.0

7.1 Holbein, M. A., and Redfern, M. S., "Functional Stability Limits While Holding Loads in Various Positions," International Journal of Industrial Ergonomics, Vol. 19, No. 5 (May 1997) pp. 387-95.

7.2 Chaffin, D. B., "Biomechanical Modelling of the Low Back During Load Lifting," Ergonomics, Vol. 31, No. 5 (May 1988) pp. 685-97.

7.3 Marras, W. S., and Sommerich, C. M., "A Three-Dimensional Motion Model of Loads on the Lumbar Spine: I. Model Structure,", Vol. 33, No. 2 (1991) pp. 123-37.

7.4 Marras, W. S., and Sommerich, C. M., "A Three-Dimensional Motion Model of Loads on the Lumbar Spine: II. Validation," Human Factors, Vol. 33, No. 2 (1991) pp. 139-49.

7.5 Asfour, S. S., Tritar, M., and Genaidy, A. M., "Endurance Time and Physiological Responses to Prolonged Arm Lifting," Ergonomics, Vol. 34, No. 3 (March 1991) pp. 335-42.

7.6 Ghori, G. M., and Luckwill, R. G., "Responses of the Lower Limb to Load Carrying in Walking Man," European Journal of Applied Physiology & Occupational Physiology, Vol. 54, No. 2 (1985) pp. 145-50.

7.7 Neumann, D. A., and Cook, T. M., "Effect of Load and Carrying Position on the Electromyographic Activity of the Gluteus Medius Muscle During Walking," Physical Therapy, Vol. 65, No. 3 (March 1985) pp. 305-11.

7.8 Cook, T. M., and Neumann, D. A., "The Effects of Load Placement on the EMG Activity of the Low Back Muscles During Load Carrying by Men and Women," Ergonomics, Vol. 30, No. 10 (October 1987) pp. 1413-23.

7.9 Holewijn, M., "Physiological Strain Due to Load Carrying," European Journal of Applied Physiology & Occupational Physiology, Vol. 61, No. 3-4 (1990) pp. 237-45.

7.10 Neumann, D. A., Cook, T. M., Sholty, R. L., and Sobush, D. C., "An Electromyographic Analysis of Hip Abductor Muscle Activity When Subjects Are Carrying Loads in One or Both Hands," Physical Therapy, Vol. 72, No. 3 (March 1992) pp. 207-17.

7.11 Datta, S. R., Chatterjee, B. B., and Roy, B. N., "The Relationship Between Energy Expenditure and Pulse Rates With Body Weight and the Load Carried During Load Carrying on the Level," Ergonomics, Vol. 16, No. 4 (July 1973) pp. 507-13.

7.12 Bhambhani, Y., and Maikala, R., "Gender Differences During Treadmill Walking With Graded Loads: Biomechanical and Physiological Comparisons," European Journal of Applied Physiology, Vol. 81, No. 1-2 (January 2000) pp. 75-83.

7.13 Laursen, B., Ekner, D., Simonsen, E. B., Voigt, M., and Sjogaard, G., "Kinetics and Energetics During Uphill and Downhill Carrying of Different Weights," Applied Ergonomics, Vol. 31, No. 2 (April 2000) pp. 159-66.

7.14 The United States Bureau of Labor Statistics (under the authority of the United States Department of Labor, 1996).

7.15 Health and Safety Statistics (United Kingdom), (under the authority of Health and Safety Executive, 1998/1999).

7.16 Information System om Arbetsskador (Sweden), translated to "Information System Occupational Injuries and Disease," (under the authority of the National Board of Occupational Safety and Health, 1998).

7.17 Leamon, T. B., and Murphy, P. L., "Occupational Slips and Falls: More Than a Trivial Problem," Ergonomics, Vol. 38, No. 3 (March 1995) pp. 487-98.

7.18 Englander, F., Hodson, T. J., and Terregrossa, R. A., "Economic Dimensions of Slip and Fall Injuries," Journal of Forensic Sciences, Vol. 41, No. 5 (September 1996) pp. 733-46.

7.19 Kumar, S., ed. Biomechanics in Ergonomics, "Slips and Falls, by Grönqvist, R." Taylor and Francis, 1999) pp. 351-75

7.20 Grönqvist, R., Roine, J., and Järvinen, E., "An Apparatus and a Method for Determining the Slip Resistance of Shoes and Floors by Simulation of Human Foot Motions," Ergonomics, Vol. 32, No. 8 (August 1989) pp. 979-95.

7.21 Redfern, M. S., and Bidanda, B., "Slip Resistance of the Shoe Floor Interface Under Biomechanically Relevant Conditions," Ergonomics, Vol. 37, No. 3 (March 1994) pp. 511-24.

7.22 Slips, Stumbles, and Falls: Pedestrian Footwear and Surfaces, 1990, "Development of SATRA Slip Test and Tread Pattern Design Guidelines, by Wilson, M. P." (ASTM-Special-Technical-Publication. American society for testing and materials).

7.23 Perkins, P. J., and Wilson, M. P., "Slip Resistance of Shoes - New Developments," Ergonomics, Vol. 26, No. 1 (1983) pp. 73-82.

7.24 Strandberg, L., and Lanshammar, H., "The Dynamics of Slipping Accidents," Journal of Occupational Accidents , Vol. 3 (1981) pp. 153-62.

7.25 Redfern, M. S., and DiPasquale, J., "Biomechanics of Descending Ramps," Gait and Posture, Vol. 6, No. 2 (October 1997) pp. 119-25.

7.26 Hanson, J. P., Redfern, M. S., and Mazumdar, M., "Predicting Slips and Falls Considering Required and Available Friction," Ergonomics, Vol. 42, No. 12 (1999) pp. 1619-33.

7.27 Hsaio, E. T., and Robinovitch, S. N., "Common Protective Movements Govern Unexpected Falls From Standing Height.," Journal of Biomechanics, Vol. 31, No. 1 (1998) pp. 1-9.

7.28 Tang, P.-F., and Woollacott, M. H., "Inefficient Postural Responses to Unexpected Slips During Walking in Older Adults," Journals of Gerontology. Series A, Biological Sciences & Medical Sciences, Vol. 53, No. 6 (November 1998) pp. M471-M480.

7.29 Tang, P.-F., and Woollacott, M. H., "Phase-Dependent Modulation of Proximal and Distal Postural Responses to Slips in Young and Older Adults," Journals of Gerontology. Series A, Biological Sciences & Medical Sciences, Vol. 54, No. 2 (February 1999) pp. M89-M102.

7.30 Tang, P.-F., Woollacott, M. H., and Chong, R. K., "Control of Reactive Balance Adjustments in Perturbed Human Walking: Roles of Proximal and Distal Postural Muscle Activity," Experimental Brain Research, Vol. 119, No. 2 (March 1998) pp. 141-52.

7.31 Pai, Y. C., and Iqbal, K., "Simulated Movement Termination for Balance Recovery: Can Movement Strategies Be Sought to Maintain Stability in the Presence of Slipping or Forced Sliding?," Journal of Biomechanics, Vol. 32, No. 8 (1999) pp. 779-86.

7.32 Anderson, R., and Lagerlof, E., "Accident Data in the New Swedish Information System on Occupational Injuries," Ergonomics, Vol. 26, No. 1 (January 1983) pp. 33-42.

7.33 Kinoshita, H., "Effects of Different Loads and Carrying Systems on Selected Biomechanical Parameters Describing Walking Gait," Ergonomics, Vol. 28, No. 9 (1985) pp. 1347-62.

7.34 Martin, P. E., and Nelson, R. C., "The Effect of Carried Loads on the Walking Patterns of Men and Women," Ergonomics, Vol. 29, No. 10 (1986) pp. 1191-202.

7.35 Proceedings of the Human Factors Society 35th Annual Meeting, 1991, "Load Carrying and Slip Length, by Leamon, T. B., and Li, K. W." (Human factors society).

7.36 Myung, R., and Smith, J. L., "The Effect of Load Carrying and Floor Contaminants on Slip and Fall Parameters," Ergonomics, Vol. 40, No. 2 (February 1997) pp. 235-46.

7.37 Proceedings of the Annual Conference of the Human Factors Association of Canada, 1988, "Slips and Falls During Manual Handling Activities, by Love, A., and Bloswick, D." (Human factors association of Canada).

7.38 Plagenhoef, S. C., "Anatomical Data for Analyzing Human Motion," Research Quarterly, Vol. 54 (1983) pp. 169-78.

7.39 Winter, David A, A.B.C. (Anatomy, Biomechanics and Control) of Balance During Standing and Walking Waterloo, Ontario: Waterloo Biomechanics, 1995).

Section 8.0

8.1 Hanson, J. P., Redfern, M. S., and Mazumdar, M., "Predicting Slips and Falls Considering Required and Available Friction," Ergonomics, Vol. 42, No. 12 (1999) pp. 1619-33.

8.2 The United States Bureau of Labor Statistics (under the authority of the United States Department of Labor, 1996).

8.3 Leamon, T. B., and Murphy, P. L., "Occupational Slips and Falls: More Than a Trivial Problem," Ergonomics, Vol. 38, No. 3 (March 1995) pp. 487-98.

8.4 Information System om Arbetsskador (Sweden), translated to "Information System Occupational Injuries and Disease," (under the authority of the National Board of Occupational Safety and Health, 1998).

8.5 Brady, R. A., Pavol, M. J., Owings, T. M., and Grabiner, M. D., "Foot Displacement but Not Velocity Predicts the Outcome of a Slip Induced in Young Subjects While Walking," Journal of Biomechanics, Vol. 33 (2000) pp. 803-8.

8.6 Twomey, J. M., Smith, A. E., and Redfern, M. S., "A Predictive Model for Slip Resistance Using Artificial Neural Networks," IIE-Transactions, Vol. 27, No. 3 (June 1993) pp. 374-81.

8.7 Kumar, S., ed. Biomechanics in Ergonomics, "Slips and Falls, by Grönqvist, R." Taylor and Francis, 1999) pp. 351-75.

8.8 Proceedings of the 1995 Fourteenth Southern Biomedical Engineering Conference, 1995, "The Friction-Related Component of a Comprehensive Slip-Prediction Model.Part II: Use of Ratiometric Analysis and Thresholded Dimensionless Numbers, by Fendley, A. E., Marpet, M. I., and Medoff, H. P." (IEEE).

8.9 Redfern, M. S., and Bidanda, B., "Slip Resistance of the Shoe Floor Interface Under Biomechanically Relevant Conditions," Ergonomics, Vol. 37, No. 3 (March 1994) pp. 511-24.

8.10 Redfern, M. S., and DiPasquale, J., "Biomechanics of Descending Ramps," Gait and Posture, Vol. 6, No. 2 (October 1997) pp. 119-25.

8.11 Strandberg, L., and Lanshammar, H., "The Dynamics of Slipping Accidents," Journal of Occupational Accidents , Vol. 3 (1981) pp. 153-62.

8.12 National Occupational Injury Research Symposium (NOIRS), 2000, "Precision and Bias Testing of the English XL Variable Incidence Tribometer and the Brungraber Mark II Portable Inclinable Articulated Strut Tester, by Flynn, J. E., and Underwood, D. C." (Center for Disease Control and Prevention and National Insitute for Occupational Safety and Health).

8.13 Grönqvist, R., Hirvonen, M., and Rajamäki, E., "Development of a Portable Test Device for Assessing on-Site Floor Slipperiness: an Interim Report," Applied Ergonomics (2000).

10.0 PUBLICATIONS

10.1 Refereed Articles Under Review

Cham R, Redfern MS: "Changes in gait when anticipating slippery surfaces," submitted to *Gait and Posture.*

Cham R, Redfern MS: "Load carrying and gait affecting slip potential," submitted to *International Journal of Industrial Ergonomics.*

Cham R, Redfern MS: "Heel contact dynamics during slip events on level and inclined surfaces," submitted to *Safety Science.*

Cham R, Redfern MS: "Biomechanics of slips," submitted to *Journal of Biomechanics.*

10.2 Refereed Articles In Preparation

Redfern MS, Cham R, Mazumdar M: "Predictive modeling of slips and falls," to be submitted to *Ergonomics.*

Cham R, Redfern MS, Bertocci GE: "Computer simulation modeling of slip and fall dynamics," to be submitted to *Journal of Computer Methods in Biomechanics and Biomedical Engineering.*

10.3 Proceedings

Cham R, Musolino M, Redfern, MS: "Heel contact dynamics during slip events," *Proceedings of the International Ergonomics Association (IEA) and Human Factors and Ergonomics Society (HFES) Congress,* San Diego, California, vol. 4, pp. 514:517, July - August 2000.

Cham R, Redfern MS: "Slip potentials during load carrying," *Proceedings of the American Society of Biomechanics (ASB)*, Chicago, Illinois, pp. 77:78, July 2000.

10.4 Abstracts

Cham R, Redfern MS: "Adjustments in gait biomechanics on potentially slippery floors," *National Occupational Injury Research Symposium* (NOIRS) hosted by the National Institute for Occupational Safety and Health (NIOSH), October 2000.

Redfern MS, Cham R: "Slip potentials during load carrying," *National Occupational Injury Research Symposium* (NOIRS) hosted by the National Institute for Occupational Safety and Health (NIOSH), October 2000.

DEPARTMENT OF HEALTH AND HUMAN SERVICES

Public Health Service
Centers for Disease Control
and Prevention (CDC)

Memorandum

Date: May 9, 2001

From: Roy M. Fleming, Sc.D., Director, Research Grants Program RMF
Office of Extramural Programs, NIOSH, D30

Subject: Final Report Submitted for Entry into NTIS for Grant 5 R03 OH003621-02.

To: William D. Bennett
Data Systems Team, Information Resources Branch, EID, NIOSH, P03/C18

The attached final report has been received from the principal investigator on the subject NIOSH grant. If this document is forwarded to the National Technical Information Service, please let us know when a document number is known so that we can inform anyone who inquires about this final report.

Any publications that are included with this report are highlighted on the list below.

Attachment
cc: Sherri Diana, EID, P03/C13

List of Publications

L0026162 Cham R, Musolino M, Redfern MS: Heel Contact Dynamics during Slip Events. Proceedings of the Internationa Ergonomics Association (IEA) and Human Factors and Ergonomics Society (HFES) Congress, San Diego, California, Vol 4, pp. 514-517, July - August, 2000

Cham R, Redfern MS: Slip Potentials during Load Carrying. Proceedings of the American Society of Biomechanics (ASB), Chicago,Illinois, pp. 77-78, July 2000

Title: Predicitive Modeling of Slips and Falls
Investigator: Rakie Cham
Affiliation: University of Pittsburgh
City & State: Pittsburgh, PA
Telephone: (412) 647-7923
Award Number: 5 R03 OH003621-02
Start & End Date: 9/30/1998–9/29/2000
Total Project Cost: $68,621
Program Area: Not NORA
Key Words:

Abstract:
Slip and fall accidents, caused by complex and interacting environmental and human factors, are a major ergonomic concern. In order to address the long-term goal of reducing slip/fall accidents, specific objectives were identified: (1) investigate changes in gait biomechanics when anticipating slippery environments, (2) describe foot dynamics during slip events, (3) compare center of pressure trajectory and joint biomechanics between no-slip and slip/fall events, (4) investigate gait biomechanics related to slips when carrying a load and (5) describe and possibly model the relationship among the probability of slip/fall, frictional requirements of walking and available friction. Ground reaction forces and sagittal plane body/foot motion dynamics of 16 subjects walking under various slippery and non-slippery environmental conditions were recorded at 350 Hz. Subjects were asked to walk as naturally as possible even without knowledge of the floor's contaminant condition. In spite of these instructions, subjects adopted postural and temporal gait changes when uncertain of the contaminant condition. These changes in gait patterns were associated with decreases (16 to 33%) in slip potential compared to recordings on known dry surfaces. During slipping experiments, corrective biomechanical reactions occurred from 25 to 45% of stance phase (about 190 - 350 ms after heel contact). These corrective reactions included increased flexion moment at the knee and extensor activity at the hip. The effects of this active knee/hip moment on body motion were reflected in the kinematics in an attempt to bring the foot back under the body and thus recover from a slip event. Load carrying experiments found decreased slip potential compared to free walking, with decreased required friction and more controlled heel contact dynamics. Logistic regression models proved to be useful in describing the relationship between the probability of falls and the difference between required and available friction (COFdiff). However, logistic regression functions of COFdiff alone did not provide a satisfactory fit of the probability of slip. The inaccurate assessment of the frictional characteristics of the shoe/floor interface is postulated to be the dominant reason for this unsatisfactory fit. This project revealed important biomechanical findings relevant to slips/falls prevention research. In addition, the research indicated that current slip resistance testing devices might be inadequate to predict slips.

Publications
Cham R, Musolino M, Redfern MS: Heel Contact Dynamics during Slip Events. Proceedings of the Internationa Ergonomics Association (IEA) and Human Factors and

Ergonomics Society (HFES) Congress, San Diego, California, Vol 4, pp. 514-517, July - August, 2000

Cham R, Redfern MS: Slip Potentials during Load Carrying. Proceedings of the American Society of Biomechanics (ASB), Chicago,Illinois, pp. 77-78, July 2000