Changes in gait when anticipating slippery floors

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Abstract

Falls precipitated by slipping are listed among the leading causes of injuries. The biomechanical analysis of such events is a necessary component of the slips/falls prevention research. One of the challenges of biomechanical studies is reproducing the unexpected nature of real-life slipping accidents. Thus, the goal of this study was to quantify changes in gait biomechanics when subjects anticipate slippery environments. Foot ground reaction forces and body dynamics of 16 subjects were recorded during level walking and descending ramps of varying frictional properties and inclination. 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 16–33% 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). Postural and temporal gait adaptations, which affected ground reaction forces, were used to achieve $RCOF_{peak}$ reductions. Statistically significant gait adaptations included reductions in stance duration (SD) and loading speed on the supporting foot, shorter normalized stride length (NSL), reduced foot-ramp angle and slower angular foot velocity at heel contact. As a result of these adaptations, anticipation of slippery surfaces led to significant changes in lower extremity joint moments, a reflection of overall muscle reactions. Thus, this study suggests that significant gait changes are made when there is a potential risk 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/falls. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Gait adaptations; Anticipation of slippery floors; Slips and falls biomechanics

1. Introduction

Falls are a major cause of 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 [1]. The US economic cost of falling accidents ranks second in the USA [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 [3] but also the severity of the injuries, with more than 25% of the workers sustaining falling injuries missing 31 days or more at work [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 [5]. The loss of balance leading to falls is often the result of slipping events [6]. The US National Health Interview Survey questionnaire of 1997 revealed a clear majority (64%) of the work-related falls attributed to slipping, tripping or stumbling. The 1992–1998 occupational same level fatal falls records providing narrative description of the incident indicated that slipping was the most common triggering event (43% of the cases). In 1998, slips, trips and falls accounted for 16.8% of all nonfatal occupational injuries involving days away from work and 11.9% of job-related deaths [4]. The incidence of slip accidents varies with geographical location and external environmental conditions. For example, it is particu-

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larly high among occupational populations (e.g. miners and mail deliverers) working outside during cold winter months [7,8]. In Sweden, Björnstig et al. found the cost of medical care inflicted by slipping accidents on ice and snow comparable with the cost of all traffic injuries in that same area [9].

Findings of biomechanical gait experiments have been used in an effort to understand human factors that cause slips/falls accidents and their complex interaction with environmental factors [10–14]. 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. One important example of the interaction between human and environmental factors is the increased risk of slipping as the frictional requirements of the task performed (walking, load carrying, pushing/pulling) exceed the available frictional capabilities of the shoe/floor interface, i.e. the measured coefficient of friction [12]. Thus, the frictional requirements of a particular task measured in slips/falls experiments are useful in setting thresholds of minimal friction needed to avoid a slip and determining whether an environment is 'slip-safe'. In addition, relevant gait variables generated from biomechanical slips/falls studies have been employed in the development of a new generation of slip resistance testers that measure the frictional properties of the shoe/floor interface by simulating foot movements during locomotion [15–17].

The use of biomechanical gait studies in slips/falls prevention research goes beyond measuring slip resistance and setting frictional thresholds to achieve slip-safe environments. Gait biomechanics partially determine the outcome of walking onto a contaminated floor and are reflection of the ability of the human neuromotor system to: (1) decrease slip potential in possibly dangerous environments (before a slip occurs); and (2) recover from a slip event by generating corrective reactions in an attempt to avoid a fall. The success of the human neuromotor system in achieving those goals will be affected by various factors such as anthropometry, strength, age, task (physical constraints) and cognitive/behavioral factors (mental stress, reaction time, attention, fear of falling). Thus, biomechanical studies are a valuable clinical tool to investigate the impact of each of those factors on the ability to decrease slip potential and recover balance after a slip event.

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. [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 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. The findings reported here (dry surfaces) are part of a larger study that investigated gait biomechanics on different surfaces of varying inclination and slipperiness (dry, wet, soap, oil).

2. Methods

2.1. Subjects

Sixteen healthy subjects (eight male, eight 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 normal locomotion.

2.2. Experimental set-up

A specially designed walkway was used to conduct these experiments [11]. 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°-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 ground reaction 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.

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 synchronize and collect force plate and motion data at 350 Hz. The OPTOTRAK system recorded 3-D whole body and foot motion by tracking LEDs attached to the subject with an accuracy better

than 1 mm. More specifically, the LEDs were attached to the left shoulder (acromion), hip (greater trochanter), knee (lateral femoral condyle), ankle (lateral malleolus) and shoe (three markers near the heel of the shoe and the fifth metatarsal level on the lateral side).

2.3. Experimental conditions and design

2.3.1. 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 (1) vinyl tile; (2) smooth painted plywood and (3) 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 slip 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.

2.3.2. Experimental design

A full factorial design was used such that each subject was tested on all 27 conditions (3 ramp angles × 3 floors × 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 ramp angles (the order of presentation of the ramp angles was randomized).

2.3.3. 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. Prior to each anticipation trial, the subject walked to the starting line of the walkway, faced away from the walkway, waited for about 1 min while listening to loud music, distracting him/her from any possible contaminant application on the floor. 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. Mistrials with subjects not fully contacting the force plate occurred in only 10% of the trials.

2.4. Data processing and analysis

Time was normalized to stance duration (SD), with 0% being heel contact (HC) and 100% representing toe-off the force plate. Ground reaction forces and body/foot motion data were used to calculate specific gait variables used as the dependent variables (Table 1). Shear (anterior–posterior along the ramp direction) and normal (perpendicular to the ramp direction) ground reaction forces were normalized to the subject's weight. The ratio of shear to normal ground reaction, (termed the required coefficient of friction (RCOF) [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 HC. Velocity information was calculated by numerically differentiating (using a two-time step differentiation routine) the position data provided by each LED. Velocity variables were the linear velocity of the heel along the ramp direction and the angular velocity of the foot as it rotated down onto the ramp floor. Both the linear heel velocity and angular foot velocity were evaluated at HC. In addition, maximum linear heel velocity in both rearward and forward directions recorded shortly after HC were also 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 HC to HC) and SD were considered in the analysis.

Due to the significantly different gait biomechanics on surfaces of varying inclination [11], the statistical analysis was conducted within each ramp angle condition. A within-subject repeated measures ANOVA of the effect of the independent variables (trial type, floor, trial type × floor) on each of the dependent variables (Table 1) was performed separately for each dependent variable. When the dependent variable was significantly affected by the trial type or floor type conditions, pairwise Tukey comparison tests were used to further investigate the differences in this dependent variable among the various trial and floor conditions. A significance level of $P \leq 0.01$ was used throughout the analysis except when otherwise specified.

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 anterior–posterior shear ground reaction force curve
$RCOF_{peak}$	Peak of the first phase of the required coefficient of friction (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 ($Norm_{Tpeak}$-$Shear_{Tpeak}$)
$RCOF_{Tpeak}$	Timing of $RCOF_{peak}$ in percent of stance
$AnklMom_{peak}$	Peak ankle dorsiflexion moment, i.e. peak of the first phase of the ankle moment curve
$KneeMom_{peak}$	Peak knee extension moment, i.e. peak of the first phase of the knee moment curve
$HipMom_{30}$	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
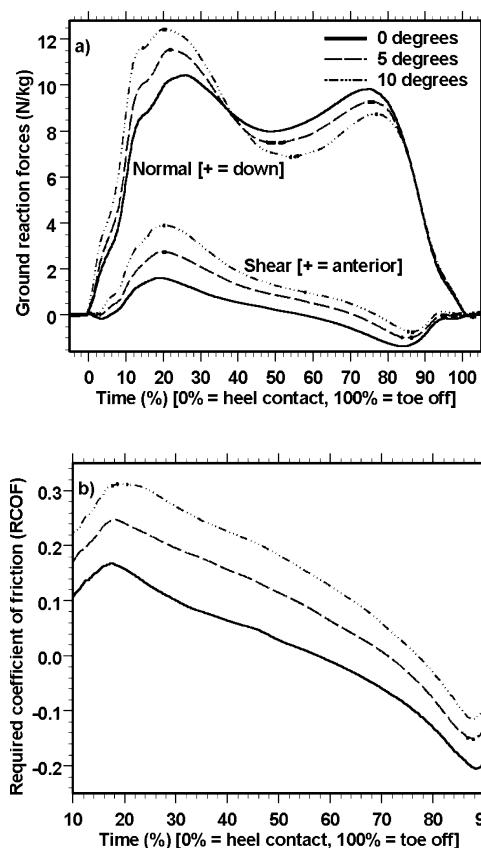
Fig. 1. Characteristic profile of ground reaction forces during gait on the vinyl tile floor (0°, 5°, 10°), averaged across all vinyl baseline trials, (a) Normal and anterior–posterior shear force (normalized to body weight); (b) required coefficient of friction, i.e. RCOF (shear/normal ratio) (in Fig. 1b, time is truncated to 10–90% to avoid 'instability' region when both shear and normal forces are near 0).

3. Results

3.1. 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 [11]. More specifically, increases in the ramp angle were associated with increases in ground reaction forces and RCOFs (Fig. 1). 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°.

Recorded kinematics showed that at the end of the swing phase, the heel rapidly decelerated (Fig. 2a–b and HeelAccx$_{HC}$ in Table 2) and, upon HC, a slight sliding motion of the heel occurred along the ramp surface. Different sliding patterns at or shortly after HC were observed. In general, the HC heel velocity was positive as noted in Fig. 2a and Table 2 (HeelVelx$_{HC}$), indicating a forward motion of the foot as it hit the floor. Then the heel slowed down rapidly 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 HC). After this rearward motion, the heel slid forward again with an average peak forward heel velocity of about 0.12–0.17 m/s (HeelVelx$_{forward}$ was recorded at about 4–5% into stance or 24–33 ms after HC and was greater on inclined surfaces) and finally came to a stop (at about 6–7% into stance or 40–50 ms after HC). However, there were also a significant number of trials where the velocity at HC was negative, i.e. foot moving in the rearward direction. In all cases, this rapid heel motion ended shortly after HC and the heel came to a complete stop. During this short heel motion time period after HC, 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 (Fig. 2c) and the shank proceeded in its forward rotation (Fig. 2d).

3.2. Anticipation effect on gait variables

In general, ground reaction forces 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 ground reaction forces variables (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 ground reaction forces variables (RCOF$_{peak}$, Shear$_{peak}$ and Norm$_{peak}$) were all significantly reduced by trial type (as shown by the positive differences from baseline values in Fig. 3). The anticipation trials produced peak RCOFs that were on average 16–33% lower than those collected during the baseline trials, with more pronounced reductions as ramp angle was increased (Fig. 3a). The peak RCOFs during recovery trials were greater than the anticipation trials, but did not return to the levels of the baseline (5–12% lower than baseline values). This trial type effect was found to

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

| Variable: mean (S.D.)	0°		5°		10°	
	Vinyl	Rough	Vinyl	Rough	Vinyl	Rough
Kinetic parameters						
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$_{HC}$ (degree per 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)
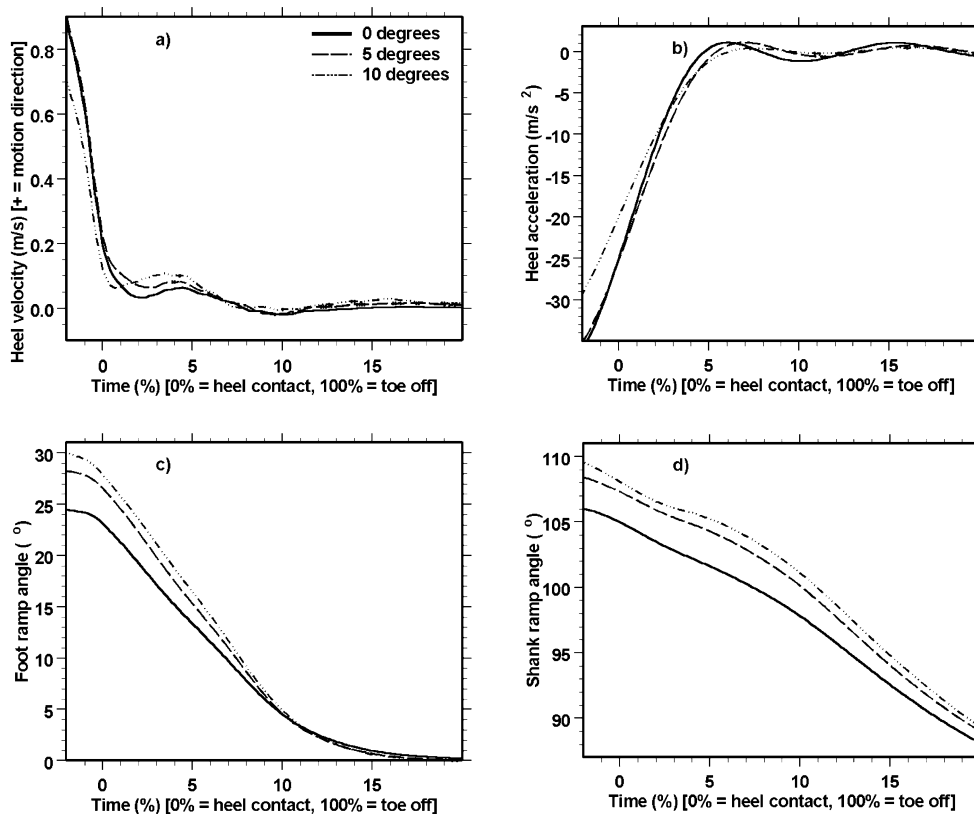
Fig. 2. Characteristic profile of the kinematic gait parameters (0°, 5°, 10°), averaged across all vinyl baseline trials, (a) heel velocity in the direction of motion; (b) heel acceleration in the direction of motion; (c) foot ramp angle and (d) shank ramp angle (time is truncated at 20% of stance for a more detailed view of heel contact dynamics).

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 with the baseline (17–40% difference) (Fig. 3b). The peak of the normal ground reaction forces was also reduced in the anticipation trials compared with the baselines (2–13%), but to a lesser extent than shear forces when comparing relative changes to baseline conditions (Fig. 3c and Table 2).

When walking down inclined surfaces, the NSL (Fig. 4a) and SD (Fig. 4b) were both reduced during anticipation trials. However, there was no significant trial type effect on these variables 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 3–6% when comparing the anticipation with baseline trials on inclined surfaces. Despite these small changes, pairwise Tukey 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°.

The ANOVA results showed no significant differences in $\mathrm{HeelVelx_{HC}}$ and $\mathrm{HeelAccx_{HC}}$ among trial types. However, shortly after HC, significant increases in the

peak rearward heel velocity ($\mathrm{HeelVelx_{rearward}}$) 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 Fig. 5a. Before coming to a stop, the heel slid forward with reduced peak forward velocities during anticipation trials (14–19% reduction in $\mathrm{HeelVelx_{forward}}$ from baseline characteristics for all ramp angles, Fig. 5b). No significant differences in $\mathrm{HeelVelx_{forward}}$ were detected between baseline and recovery conditions. Interestingly, during that short period of heel sliding after HC, anticipation of slippery surfaces led to significant increases in $\mathrm{HeelAccx_{peak}}$ (11, 29 and 40% for level walking, 5 and 10°, respectively) from magnitudes recorded during baseline trials (negative differences from baseline trials plotted in Fig. 5c). Differences in $\mathrm{HeelAccx_{peak}}$ between recovery and baseline trials were also significant, but lesser in amplitude (6–19% relative increases during recovery trials, as depicted in Fig. 5c). These increases in $\mathrm{HeelAccx_{peak}}$ are related to the greater $\mathrm{HeelVelx_{rearward}}$ values reported earlier during anticipation trials, the duration of the short heel sliding period after HC is comparable for all conditions, however, greater rearward peak velocities were recorded for an-

ticipation and recovery trials, thus leading to steeper $\Delta(\text{velocity}) - \Delta(\text{time})$ slopes or acceleration measures. In addition, decreases in FootAngVel_{HC} were recorded during anticipation trials (positive differences from baseline conditions plotted in Fig. 5d) 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.

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
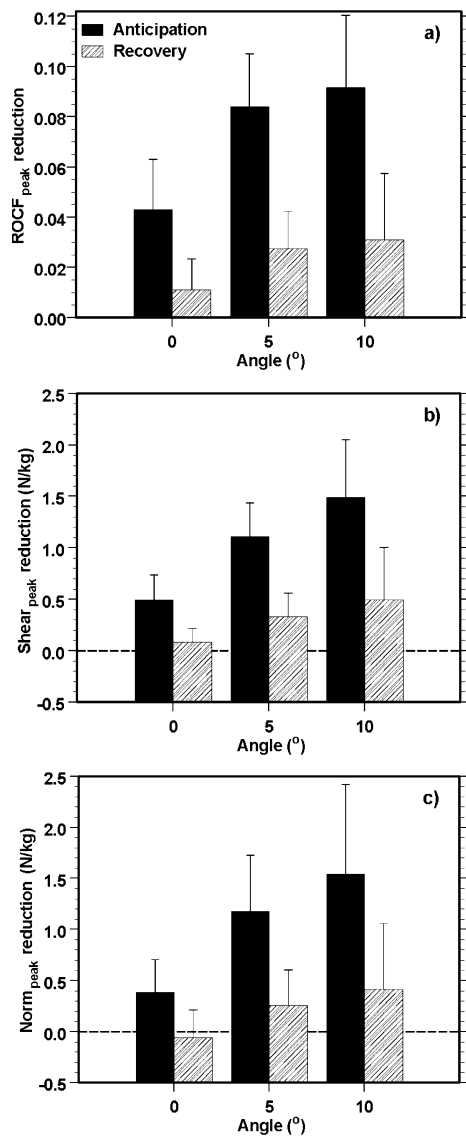

Fig. 3. Trial type effect on kinetic gait variables (data represent within-subject differences [baseline − anticipation/recovery] averaged across all subjects and flooring conditions), (a) peak required coefficient of friction; (b) peak anterior–posterior shear force and (c) peak normal force (dotted line indicates no-difference between baseline and anticipation/recovery trials).

conditions (positive differences plotted in Fig. 5e and f). The foot orientation with respect to the floor was the most affected variable between the two (11 and 27% decrease in FootAngl_{HC}). Less pronounced, but still statistically significant, reductions in the ShankAngl_{HC} were recorded (1–3%). 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 3–13% in the FootAngl_{HC}, and 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 with 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 pairwise Tukey 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 and normal ground reaction forces did not significantly change among trial types.

3.3. Floor type effect

Flooring condition had a small but statistically significant effect on the majority of the gait variables, while the interaction of the floor and trial type was not significant. The primary floor type influence on the kinetic variables was a higher RCOF_{peak} for the rough surface compared to the vinyl floor (0.01–0.04 overall difference) (Table 2 shows these differences for baseline values). This slight increase on rough floors was also true for the Shear_{peak} (0.1–0.4 N/kg increase), whereas the Norm_{peak} decreased on rough floors (0.1–0.4 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, recordings of the FootAngl_{HC} were greater on rough floors compared to the vinyl surfaces for seven
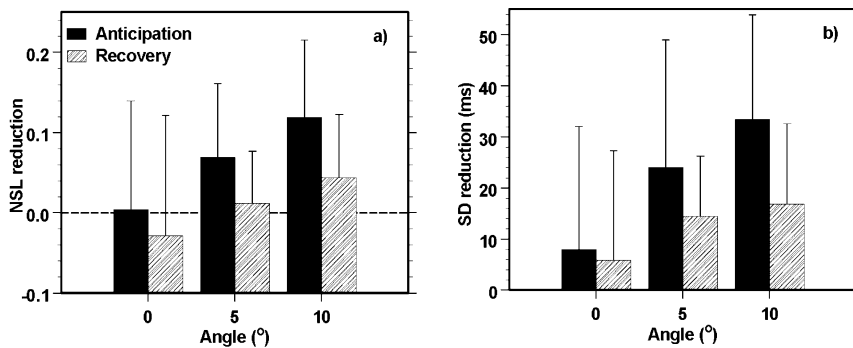
Fig. 4. Trial type effect on general gait variables (data represent within-subject differences [baseline − anticipation/recovery] averaged across all subjects and flooring conditions), (a) NSL; (b) SD (dotted line indicates no-difference between baseline and anticipation/recovery trials).

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 with 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.

3.4. 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 variables, HC dynamics and time characteristics of gait.

$RCOF_{peak}$ was significantly associated with slower loading rates ($Norm_{Tpeak}$ longer) and smaller foot-ramp angles at HC ($FootAngl_{HC}$) on all ramp angles (Table 3). The peak RCOF increased with increasing normalized stride length (NSL), longer stance duration (SD) and slower HC angular foot velocity ($FootAngVel_{HC}$), with a stronger effect of these variables as ramp angle was increased. Interestingly, longer SDs were associated with higher peak normal forces (r between 0.6 and 0.7) and reduced peak forward heel accelerations (r between 0.5 and 0.6), while slower loading rates generated lower

levels of shears (r between 0.5 and 0.6). Thus, subjects efficiently decreased their risk of slipping ($RCOF_{peak}$) by more slowly rotating the foot down onto the floor during HC, adopting shorter strides (length and duration), reducing foot contact angles and slowing the transfer of body weight to the supporting foot.

3.5. Joint moments

3.5.1. Baseline conditions

During most of the stance period (after the loading phase), moments generated at the ankle, knee and hip joints were biased towards plantarflexion, extension and flexion, respectively. Lower extremity joint moments were affected by ramp angle. Early in stance ($\sim 10\%$ 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 (Fig. 6a). 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 (Fig. 6c). The hip moment was affected by ramp angle mostly in the 20–40% time interval of stance (Fig. 6e). 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.

3.5.2. 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 (Fig. 6). Reductions in joint moments were more pronounced as ramp angle was increased (Fig. 7). More specifically, the mean baseline-anticipation difference in the peak dorsiflexion ankle moment decreased by 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 (Fig. 5e and f). During the recovery trials, joint moments were closer but still lower than baseline characteristics. Pairwise Tukey comparison tests indicated statistically significant ($P < 0.05$) differences in all three joint moment variables among all trial types except between baseline and recovery trials on horizontal surfaces ($P < 0.1$).

The same ANOVA uncovered a significant floor effect on joint moment variables 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 partic-
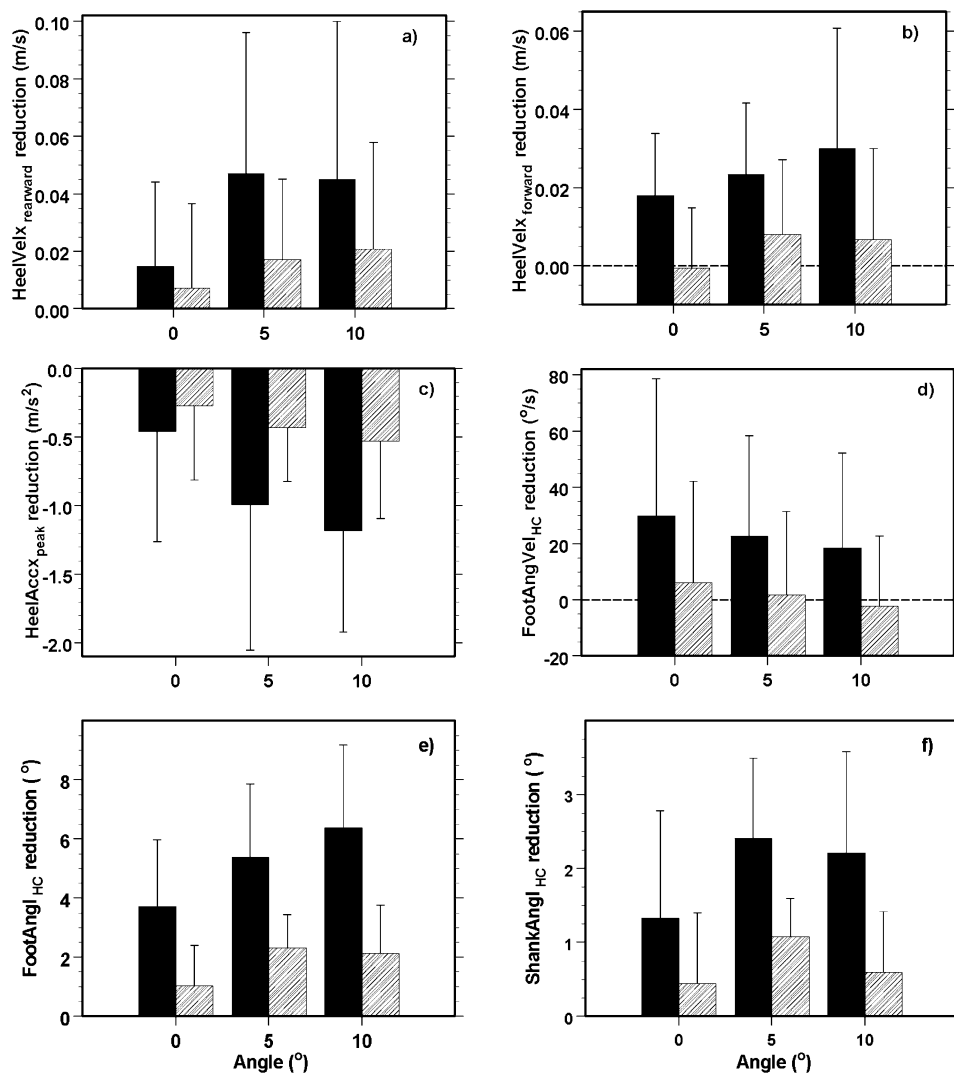

Fig. 5. Trial type effect on kinematic gait variables (data represent within-subject differences [baseline − anticipation/recovery] averaged across all subjects and flooring conditions), (a) peak rearward heel velocity; (b) peak forward heel velocity; (c) peak heel acceleration; (d) HC angular velocity of foot; (e) HC foot ramp angle and (f) HC shank ramp angle. (dotted line indicates no-difference between baseline and anticipation/recovery trials). Note, Heelvel$_{rearward}$ (negative) and HeelAcc$_{peak}$ (positive) increased with anticipation and recovery trials resulting in a positive and negative reduction in (a) and (c), respectively.

Table 3
Gait characteristics associated the peak RCOF[a]

Response = $RCOF_{peak}$ Independent variable → 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

[a] S indicates $P \leq 0.01$; NS indicates $P > 0.01$.

ular for the hip moment. The interaction (trial type × floor type) was not significant for the majority of the tests.

4. 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 with 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 [10–13,16,19,20]. 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 ground reaction 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 ground reaction 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 SD and loading speed on the supporting foot, shorter NSL, reduced foot-ramp angle and slower angular foot velocity at HC. 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 believed to be of practical relevance to the reduction in slip potential. This is evident in the extent of the frictional requirement 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. NSL and SD) 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 with 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 variables was significant but small, while the interaction of floor type and trial type was not statistically significant.

The baseline results reported here are comparable to findings of earlier studies. In particular, peak RCOFs were in close agreement with values reported by Redfern and Dipasquale [11] and Hanson et al. [12] on both horizontal and inclined surfaces, and by Perkins [10] and Strandberg and Lanshammar [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 [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 [11] and Winter [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 earlier 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) [11] and Winter (on level surfaces) [21]. The wide variation in HC heel velocity patterns observed among subjects was also reported by Strandberg and Lanshammar [13] with velocity magnitudes ranging from 0.14 to 0.68 m/s and associated with S.D. as large as 0.52 m/s, a finding that certainly agrees with the results of this study. A final example related to the HC foot orientation with respect to the floor published by Strandberg and Lanshammar [13] on horizontal surfaces (22.0 ± 5.3°), 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. [18] have reported similar gait adaptations than those reported here, including reduced foot angle and angular foot velocity at HC.

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.
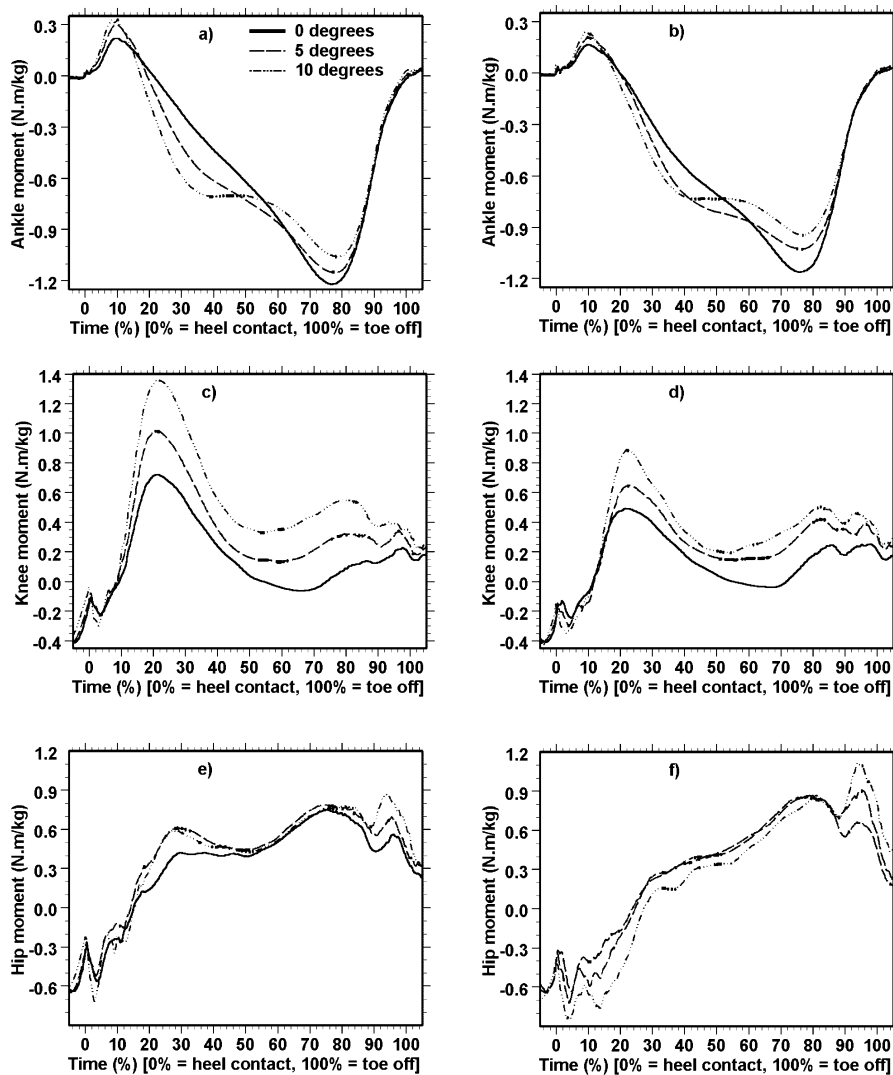

Fig. 6. Characteristic profile of lower extremity joint moments (normalized to body weight) during gait on the vinyl tile floor (0, 5, 10°), averaged across all baseline (left) and anticipation (right) trials, (a) ankle [+ = dorsiflexion], (b) knee [+ = extension], and (c) hip [+ = flexion].
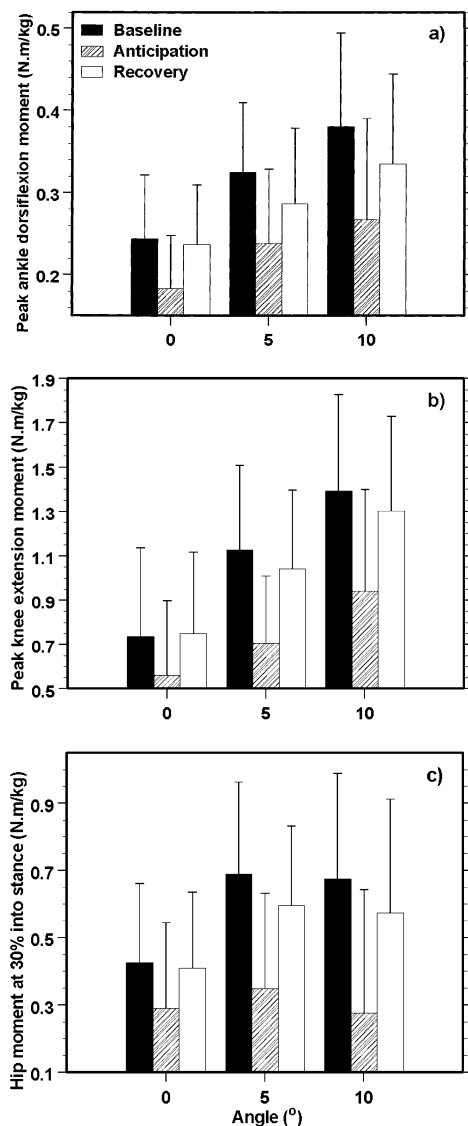
Fig. 7. Trial type effect on joint moments parameters (normalized to body weight) (0, 5, 10°), averaged across all subjects and floors, (a) peak ankle dorsiflexion moment; (b) peak extension knee moment and (c) hip moment evaluated at 30% into stance.

Finally, as a result of changes in ground reaction forces and postural adjustments during walking, anticipation of slippery surfaces affected lower extremity joint moments, a reflection of overall muscle reactions. 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 descrip-

tion 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 variables as input to slip resistance testers designed to reproduce foot motion. Finally, a potential safety implication of the findings of this paper is that proper safety warnings of slippery environments would result in similar gait changes as those associated with anticipation effects, thus decreasing slip potential.

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 with characteristics of baseline trials, during which subjects walked onto a known dry surface. The overall effect of these adaptations was a reduction in the $RCOF_{peak}$, thus humans have the ability to reduce slip potential on possibly contaminated floors. Findings related to the moment generated at the lower extremity joints suggested that the knee and hip appear to be used more than the ankle to control slip potential.

Acknowledgements

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