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Heel contact dynamics during slip events on level and inclined surfaces

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Abstract

This study describes heel contact dynamics during slip events, information that must be known to develop biomechanically relevant shoe-floor coefficient of friction measurement systems. Sixteen subjects walked on a level, 5 and 10° ramp with two possible contaminants (dry, oil). Foot motion was 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 approximately 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. © 2002 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Slip and fall 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 (Bureau of Labor Statistics, 1996). More than 20% of

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workers that sustain falling injuries miss 31 days at work or more (BLS, 1996). In addition, falling accidents account for a substantial cost of the total medical care. Analyses of USA 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 (Leamon and Murphy, 1995). 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 (Courtney et al., 2001).

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 (Hanson et al., 1999). A wide variety of slip resistance testers are already being used in industry to rate slip potential (review chapter of Grönqvist, 1999). 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 (HC), hoping to obtain biomechanically relevant measures of slip resistance (Grönqvist et al., 1989; Wilson, 1990; Redfern and Bidanda, 1994). 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 main 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 with the foot dynamics on dry floors. Another goal was to determine biomechanically relevant ranges of parameters needed for further development of slip resistance testers.

2. Methods

2.1. 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 62.6–82.4 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.

2.2. Experimental set-up

A ramp instrumented with a force platform (FP; Bertec, Inc., model 4060A) was used (Redfern and DiPasquale, 1997). The top surface of the ramp is made of vinyl tile over 1.9 cm thick plywood that is bolted to the frame. The FP was positioned such that the subject's 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 $\leqslant 1$ mm) record body movements. Seven Optotrak 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 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.

2.3. 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 FP (0.6×0.4 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 (1994). 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.

2.4. Experimental design

A full factorial within-subject, 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.

2.5. 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 FP. 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 min while listening to loud music, during which time, a contaminant (dry or oil) was applied to the surface of the FP. 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 FP data were recorded.

2.6. Data processing and analysis

Ground reaction forces were used to determine the HC frame, which was assigned a time value set at 0 ms. More specifically, the first frame characterized by a sharp increase in the normal ground reaction forces above usual FP noise levels was chosen to coincide with the HC frame. The description of heel and foot kinematics was then focused on a 450 ms time interval (-100 to $+350$ ms, with HC time $=0$). For each trial, the LEDs provided position data that were processed in the sagittal plane to derive instantaneous kinematic variables describing 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. The linear heel velocity was calculated by numerically differentiating the heel position. More specifically, instantaneous position data were passed through a two-time step differentiation routine, i.e. $\mathrm{HeelVel}_i = (\mathrm{HeelPos}_{i+1} - \mathrm{HeelPos}_{i-1})/2.\Delta t$, where the subscript "$i$" refers to the frame number (e.g. at $i=$ HC frame, $i+1$ and $i–1=$ frame after and before HC) and HeelPos and HeelVel are the instantaneous linear heel position and heel velocity, respectively. In addition, the information from the LED placed on the toe combined with the heel's position data were used to obtain the instantaneous foot-floor angle. Using a two-time step differentiation routine on the foot-floor angle, instantaneous foot angular velocity was calculated (similar numerical computations as for the linear heel velocity). Position data was filtered (least square low pass filter with an actual cutoff frequency of 12 Hz) only to derive acceleration variables (using the same two-time step differentiation routine twice on the position data).

The overall slip distance (SlipDist in Table 1), defined as the total heel movement that occurred along the floor between the time of HC and when the heel stopped moving ($\mathrm{Time}_{\mathrm{HeelStop}}$ in Table 1), was used to categorize the outcome of a walking trial into three possible events: no-slip (slip distance <1 cm, NS), slip-recovery (slip distance $\geqslant 1$ cm but came to a stop, SR), and slip-fall (foot never stops, SF). Specific parameters including heel slip/travel distance, velocity, acceleration and timing parameters (Table 1) were derived and compared among dry-NS, oily-SR and oily-SF trials within each ramp angle condition.

3. Results

3.1. Outcome distribution

A minimum of 70 to a maximum of 80 dry trials per ramp angle condition were included in the analysis. For level walking on oily floors, eight out of the 16 trials were categorized as SRs, four were SFs and the last four 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, seven subjects slipped and recovered while nine lost balance and fell. On the 10° oily ramp, recovering became more difficult: all trials resulted in falls.

3.2. Heel sliding patterns and velocities recorded upon HC

3.2.1. Dry condition

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 (Fig. 1). A closer examination of the velocity information showed that at the end of the swing phase, the heel indeed rapidly decelerated, however, upon HC a slight sliding motion of the heel occurred along the ramp surface (Fig. 2). In the majority of the dry trials, the HC heel velocity was positive as noted in Table 2 ($\text{HeelVelX}_{\text{HC}}$ 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 HC ($\text{Time}_{\text{ForwSlip}}$ in Table 2) before coming to a stop between 40 and 60 ms after HC ($\text{Time}_{\text{HeelStop}}$ in Table 2). During this sliding motion of the heel, peak velocities in the rearward (MinHeelVelX in Table 2) and forward (MaxHeelVelX in Table 2) directions did not exceed 0.2 m/s and occurred typically within 5–20 and 25–40 ms after HC ($\text{Time}_{\text{MinHeelVelX}}$ and $\text{Time}_{\text{MaxHeelVelX}}$ in Table 2), respectively. These velocity peaks occurred sooner on inclined surfaces due to the shorter stance duration compared with walking on level surfaces. Thus, in general a forward–rearward–forward sliding pattern of the heel was observed upon HC (Fig. 2). 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 instantaneous velocity at HC time was negative, i.e. the foot was moving in the rearward direction as it hit the floor, especially on inclined surfaces. In these trials, the initial forward sliding phase of the heel was missing, and upon HC, 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 Fig. 3a), with a rearward travel distance of about

Table 1
Abbreviation and definition of dependent parameters

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

[a] NS, no-slip; SR, slip-recovery; SF, slip-fall; HC, heel contact.

the same magnitude ($\text{TravDist}_{\text{rearward}}$ in Fig. 3b) and a typical total travel distance of 5 mm (TravDist in Fig. 3c).

3.2.2. Oily conditions (recoveries and falls)

Interestingly, on oily surfaces, similar forward–rearward–forward sliding patterns (Figs. 1 and 2) were observed during slip events as for the dry conditions with, in

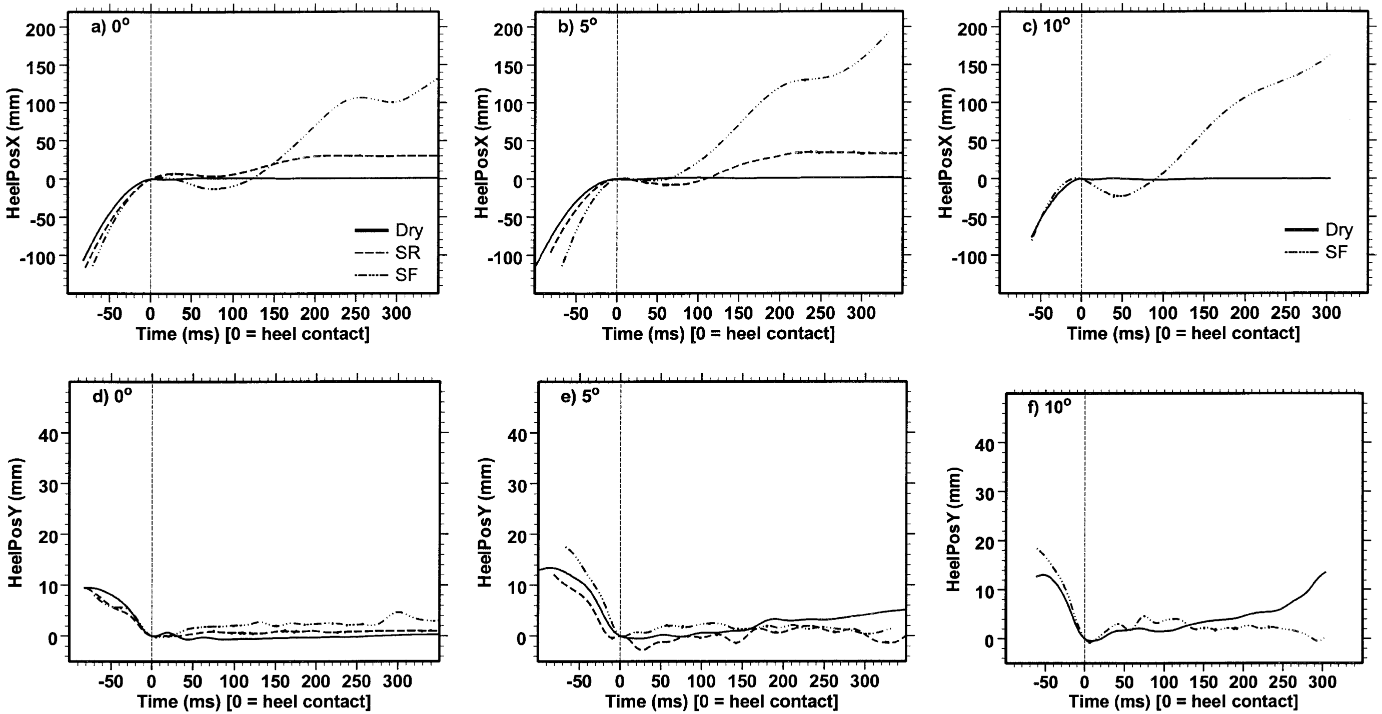

Fig. 1. Typical examples of heel position profile along the direction of motion (a–c) and normal to the floor surface (d–f) recorded during dry (no-slip) and oily (slip-recovery and slip-fall) conditions.

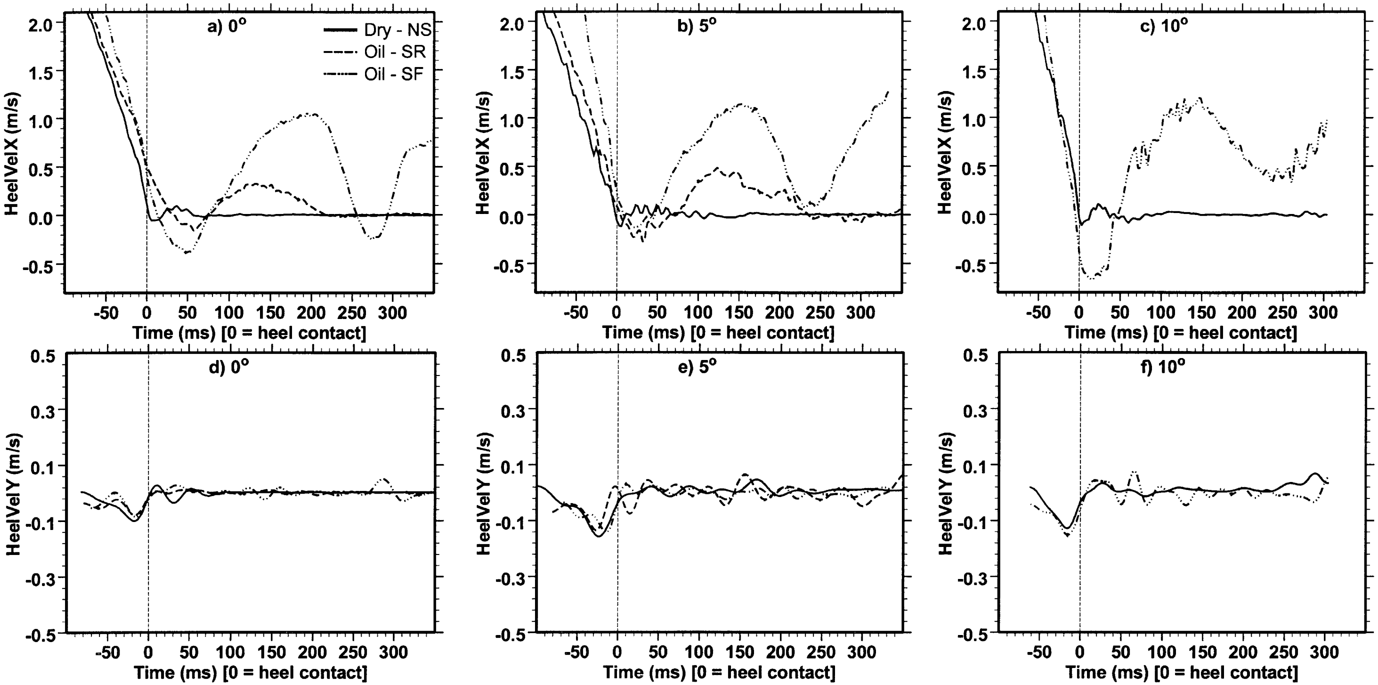

Fig. 2. Typical examples of linear heel velocity profile recorded along the direction of motion (a–c) and normal to the floor surface (d–f), during dry (no-slip) and oily (slip-recovery and slip-fall) conditions.

Table 2
Velocity related parameters [mean (S.E.)][a]

Angle (°)	0			5			10	
Outcome	Dry-NS	Oil-SR	Oil-SF	Dry-NS	Oil-SR	Oil-SF	Dry-NS	Oil-SF
Variable								
HeelVelX$_{\mathrm{HC}}$ (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$_{\mathrm{MinHeelVelX}}$ (ms)	16.25 (1.18)	53.21 (5.26)	46.43 (6.53)	12.39 (1.38)	37.55 (10.25)	26.98 (6.28)	8.65 (1.08)	31.62 (6.83)
Time$_{\mathrm{ForwSlip}}$ (ms)	27.64 (1.26)	78.93 (9.49)	65.71 (3.50)	21.81 (1.57)	61.63 (7.88)	72.38 (17.16)	18.65 (1.13)	54.29 (5.64)
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$_{\mathrm{MaxHeelVelX}}$ (ms)	37.18 (1.20)	121.43 (12.35)	171.43 (28.69)	32.96 (1.65)	123.27 (14.96)	172.06 (28.39)	28.53 (1.17)	138.48 (12.98)
Time$_{\mathrm{HeelStop}}$ (ms)	52.04 (1.22)	236.79 (30.31)		46.92 (1.86)	266.53 (36.83)		41.73 (1.31)	
Time$_{\mathrm{EndRecAttempt}}$ (ms)			263.57 (24.53)			260.00 (29.41)		248.38 (15.72)

[a] NS, no-slip; SR, slip-recovery; SF, slip-fall; HC, heel contact.

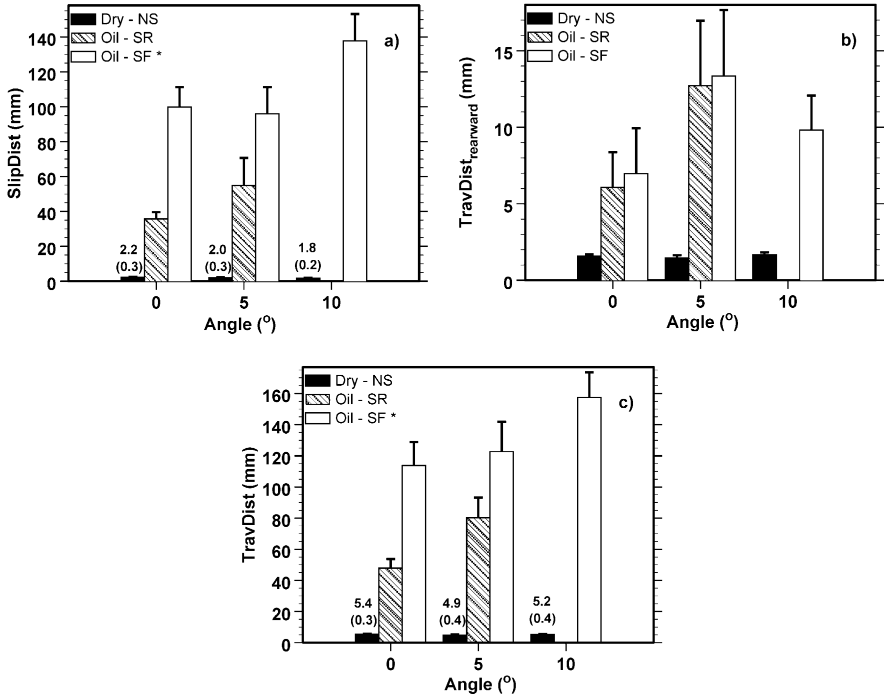

Fig. 3. Mean (S.E.) recorded values of overall slip distance (a), rearward travel distance (b) and total travel distance (c), recorded during dry (no-slip) and oily (slip-recovery and slip-fall) conditions. (* for fall trials, SlipDist and TravDist recorded up to $\text{Time}_{\text{EndRecAttempt}}$. Subjects continued slipping after this time.)

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, HC heel velocity during slip events reached values of 1.0 m/s for level walking, while this difference in $\text{HeelVelX}_{\text{HC}}$ between dry and oily conditions became less pronounced on inclined surfaces ($\text{HeelVelX}_{\text{HC}}$ in Table 2). 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 2). These peak rearward sliding velocities were recorded at about 30–55 ms ($\text{Time}_{\text{MinHeelVelX}}$ in Table 2) after HC. After sliding over 5–15 mm in the rearward direction ($\text{TravDist}_{\text{rearward}}$ in Fig. 3b), the heel's forward slippage (last phase of the heel's sliding pattern) on oily conditions started, on average, between 50 and 80 ms after HC ($\text{Time}_{\text{ForwSlip}}$ in Table 2). $\text{HeelVelX}_{\text{HC}}$, MinHeelVelX, $\text{Time}_{\text{MinHeelVelX}}$, $\text{TravDist}_{\text{rearward}}$ and $\text{Time}_{\text{ForwSlip}}$ values recorded during SR and SF outcomes were comparable.

3.2.3. Oily conditions (recoveries)

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 2) and maximum recorded values of 0.74 and 0.80 m/s on 0 and 5°, respectively (trials "SR1" in Figs. 4a, b). Typically, MaxHeelVelX occurred between 100 and 150 ms after HC ($\text{Time}_{\text{MaxHeelVelX}}$ in Table 2). Oily conditions produced mean SlipDist (and TravDist) values of about 4 (5) cm and 6 (8) cm on 0 and 5° (Fig. 3), 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 (Figs. 1 and 2) indicated recovery by about 200–250 and 250–300 ms after HC ($\text{Time}_{\text{HeelStop}}$ in Table 2) 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 Figs. 4a, b): 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.

3.2.4. Oily conditions (falls)

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

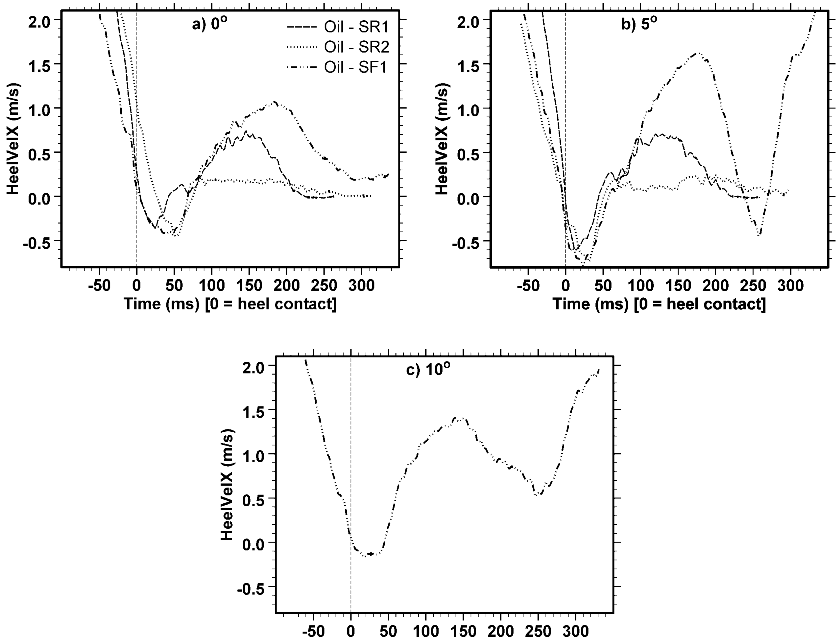

Fig. 4. Other examples of linear heel velocity profile recorded along the direction of motion, on oily (slip-recovery and slip-fall) conditions.

between 200 and 300 ms after HC (Fig. 2). As ramp angle increased however, it became more difficult for subjects to reach low-level velocities (Figs. 1 and 2). 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 Figs. 2a and 4b) compared with only 15% when descending the 10° ramp. At the end of this recovery attempt ($\text{Time}_{\text{EndRecAttempt}}$ in Table 2), the foot accelerated again, eventually leading to a fall (Figs. 1 and 2). Before the effects of this corrective reaction, mean peak forward sliding velocities of about 0.8–1.1 m/s (MaxHeelVelX (Table 2) increased on inclined surfaces) were typically recorded between 100 and 200 ms after HC ($\text{Time}_{\text{MaxHeelVelX}}$ in Table 2). 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 Fig. 4. The mean overall slip distance (calculated only up to $\text{Time}_{\text{EndRecAttempt}}$ 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 Fig. 3).

3.3. 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 (Fig. 5). On average, the absolute value of HC heel acceleration along the floor surface ($\text{HeelAccX}_{\text{HC}}$ negative indicating deceleration) decreased from an average of −33.6 (S.E. 1.9) m/s^2 for level walking to −24.5 (S.E. 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 HC heel acceleration ($\text{HeelAccY}_{\text{HC}}$) of only 5.2 (S.E. 0.3), 7.6 (S.E. 0.5) and 9.2 (S.E. 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 $\text{HeelAccX}_{\text{HC}}$ and $\text{HeelAccY}_{\text{HC}}$ among outcomes. One exception is on the steepest ramp, on which oily trials produced significantly greater $\text{HeelAccX}_{\text{HC}}$ values (mean of 33.2 (S.E. 5.3) m/s^2) compared with dry conditions.

During the first 50 ms into stance on dry conditions, mean peak heel accelerations of about 4.5 to 5.0 (S.E. 0.3) m/s^2 (all ramp angles) were recorded the first 50 ms into stance ($\text{HeelAccX}_{\text{peak}}$). On oily conditions however, the mean $\text{HeelAccx}_{\text{peak}}$, recorded between 50 and 100 ms after HC, increased significantly to about 11.8 (S.E. 1.4), 16.0 (S.E. 1.6) and 24.1 (S.E. 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 Fig. 5).

3.4. Foot angle and foot angular velocity

3.4.1. Dry conditions

Foot-ramp angle profiles showed a continuous rotation of the foot from a mean HC angle near 20° ($\text{FootAngl}_{\text{HC}}$ in Table 3), reaching foot flat position 80–130 ms after HC ($\text{Time}_{\text{FootFlat}}$ in Table 3, with earlier occurrence on inclined surfaces) or 14–15% of stance time (all ramp angle conditions). At the time of the heel's forward

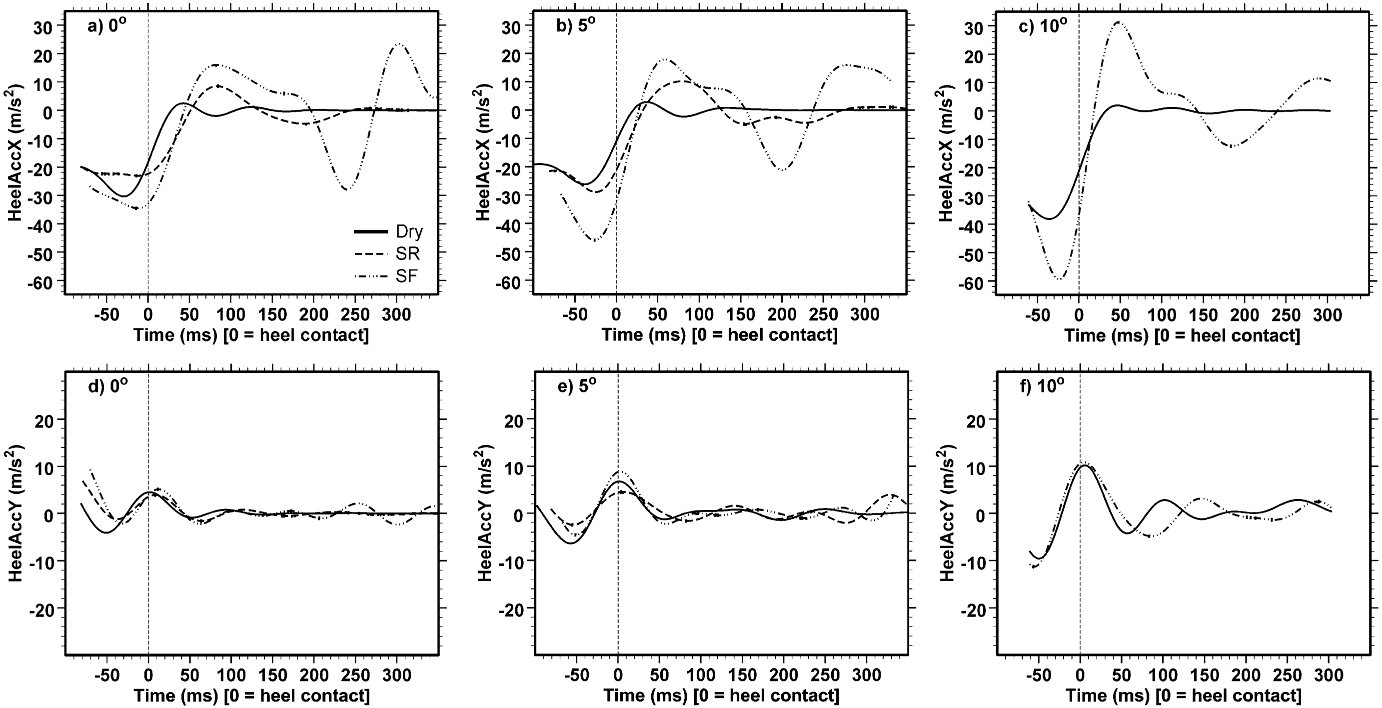

Fig. 5. Typical examples of linear heel acceleration profile recorded along the direction of motion (a–c) and normal to the floor surface (d–f), during dry

Table 3
Foot angle related parameters [mean (S.E.)][a]

Angle (°)	0			5			10	
Outcome	Dry-NS	Oil-SR	Oil-SF	Dry-NS	Oil-SR	Oil-SF	Dry-NS	Oil-SF
Variable								
$\text{FootAngl}_{\text{HC}}$ (°)	19.31 (0.06)	16.79 (1.45)	20.47 (0.87)	21.99 (0.71)	13.87 (2.38)	20.52 (2.42)	21.05 (0.70)	17.35 (1.71)
$\text{FootAngl}_{\text{ForwSlip}}$ (°)	12.61 (0.69)	1.49 (0.59)	2.22 (1.79)	16.24 (0.92)	1.34 (0.64)	5.95 (2.65)	15.79 (0.84)	4.33 (1.78)
$\text{Time}_{\text{FootFlat}}$ (ms)	121.86 (5.65)	118.57 (25.81)	91.43 (17.88)	109.09 (4.44)	86.12 (17.95)	110.79 (12.98)	90.23 (4.23)	90.48 (16.13)

slippage (i.e. $\text{Time}_{\text{ForwSlip}} = 15$–30 ms in Table 2), the mean foot angle was about 12–16° ($\text{FootAngl}_{\text{ForwSlip}}$ in Table 3), thus not having reached foot flat position yet. Foot angular velocity at HC ($\text{FootAngVel}_{\text{HC}}$) increased on inclined surfaces, with mean values of 168 °/s (S.E. 11.8 °/s), 220 °/s (S.E. 14.2 °/s) and 269 °/s (S.E. 12.4 °/s) for level walking and when descending the 5 and 10° ramp, respectively.

3.4.2. Oily conditions

Subjects who recovered from slip events (0 and 5° ramp angle conditions) walked with smaller HC foot-floor angles than the values recorded on dry conditions, which were, in general, similar to those observed during falling trials ($\text{FootAngl}_{\text{HC}}$ in Table 3). Due to the increased time spent in the rearward sliding phase, the heel has almost reached foot flat position when it started slipping forward ($\text{Time}_{\text{ForwSlip}} = 50$–80 ms on oily conditions), with foot angles ranging from 1–3° for level walking and 1–5° on inclined surfaces. As depicted in the examples of Fig. 6 (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 HC ($\text{FootAngVel}_{\text{HC}}$), with relative reductions from the dry conditions ranging from 25–65% (more pronounced differences recorded for level walking).

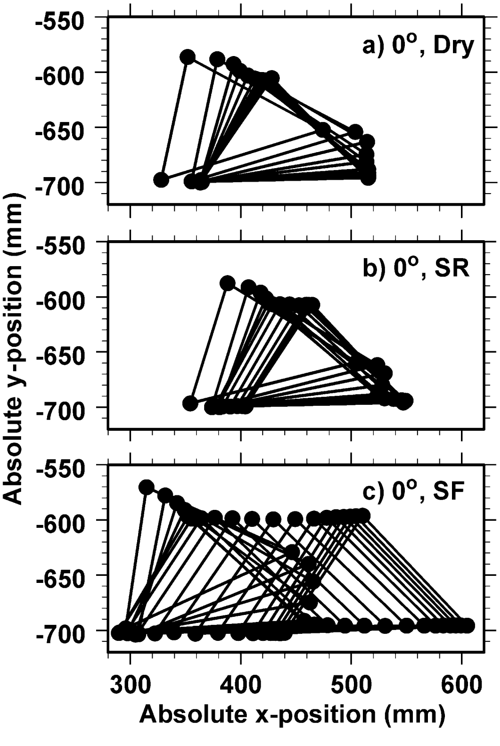

Fig. 6. Typical example of stick figure representing foot dynamics on level walking [$\Delta t \sim 15$–20 ms (2nd point is HC)].

4. Discussion

This study described in detail the heel's sliding motion recorded upon HC, 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 HC and peak acceleration recorded after HC along the floor surface were both greater during slip trials compared with dry conditions. On oily conditions (all ramp angles), the momentum generated during the swing phase and associated with the heel at HC 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 with 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 velocity 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 HC 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 with 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 (Cham and Redfern, 2000). These gait adaptations include changes in HC dynamics such as a significant decrease in the foot-ramp angle and reduction in the foot angular velocity at HC when anticipating slippery surfaces. In the results presented here, special precautions in the protocol were taken to ensure that HC 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 HC 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 HC was also observed in previous investigations (Perkins, 1978; Strandberg and Lanshammar, 1981). 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 HC dynamics were not always reported. Strandberg and Lanshammar (1981) reported a wide range of HC patterns, especially for the heel velocity, with velocity magnitudes ranging from 0.14 to 0.68 m/s and associated with standard deviations as large as 0.52 m/s. This wide range in HC strategies was also noticed across trials conducted in this study.

Another gait parameter that was subject of previous investigations is the foot angle with respect to the floor. At HC, Strandberg and Lanshammar (1981) published similar results [~21–22° (S.D. 5°)] to the ones computed here, which were, however, smaller than foot-floor angle values reported by Leamon and Son (1989) (~30°). The timing of the forward slipping phase ($\text{Time}_{\text{ForwSlip}}$ here) was in accordance to findings of Perkins (1978) and Strandberg and Lanshammar (1981), i.e. about 50–100 ms after HC. At that time, in this study, the foot was almost flat (mean $\text{FootAngl}_{\text{ForwSlip}}$ of 1–3°), while Strandberg and Lanshammar 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 (1978), on the other hand, discussed occasional fall trials (associated with large impact foot-ramp angles) during which the heel started forward slipping right at HC, 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 (1978) and characterized by slip distances greater than 10–15 cm resulted in falls, a finding that was later confirmed by Strandberg and Lanshammar (1981) 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 with 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 (1978) and Strandberg and Lanshammar (1981) 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 HC dynamics during locomotion on level and inclined vinyl flooring surfaces, which were then compared with 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).

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