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Lower extremity corrective reactions to slip events

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Abstract

A significant number of injuries in the workplace is attributed to slips and falls. Biomechanical responses to actual slip events determine whether the outcome of a slip will be recovery or a fall. The goal of this study was to examine lower extremity joint moments and postural adjustments for experimental evidence of corrective strategies evoked during slipping in an attempt to prevent falling. 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 reactions by the body in an attempt to recover from slips became evident at about 25% of stance and continued until about 45% into stance, i.e. on average between 190 and 350 ms after heel contact. These reactions included increased flexion moment at the knee and extensor activity at the hip. The ankle, on the other hand, acted as a passive joint (no net moment) during fall trials. Joint kinematics showed increased knee flexion and forward rotation of the shank in an attempt to bring the foot back towards the body. Once again, the ankle kinematics appeared to play a less dominant role (compared to the knee) in recovery attempts. This study indicates that humans generate corrective reactions to slips that are different than previously reported responses to standing perturbations translating the supporting surface.

Keywords: Slips biomechanics; Gait biomechanics; Corrective reactions; Joint moments

1. Introduction

Falls are a major cause of work-related injuries. In 1998, the USA "Bureau of Labor Statistics" (BLS) reported that falls accounted for 16.8% of all non-fatal injuries involving days away from work and 11.9% of job-related deaths (Department of Labor, 1998). Injuries afflicted by falls are often severe. More than 25% of workers that sustain falling injuries miss 31 days at work or more (BLS, 98). The severity of fall-related injuries partially explains their substantial contribution to medical care costs. Leamon and Murphy, (1995) attributed 24% of the direct cost of all claims filed during the years 1989 and 1990 to fall-related injuries. Falls are often initiated by slips. 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 order to avoid a slip-initiated fall, the body must generate a quick and effective corrective response to reestablish balance. The biomechanics of postural control strategies, reflected in the lower extremity joint moments and postural adjustments, partially determine the outcome of a slipping perturbation and are therefore important in understanding the complex relationship between gait and falls. To our knowledge, such corrective responses have not been investigated on slippery surfaces. Instead, researchers have considered active reactions during supporting surface translation protocols designed specifically to simulate naturally occurring slips (Hsaio and Robinovitch, 1998; Tang and Woollacott, 1998, 1999; Tang et al., 1998). However, when examining body/heel dynamics and stability parameters, it is unclear whether active anteriorly directed translation of the base of support used in those recent studies evoke similar corrective movements to those recorded during naturally occurring slip events (Cham and Redfern, 2001b; Pai and Iqbal, 1999).

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The main goal of this study was to biomechanically quantify the corrective reactions generated by the body in response to real slipping perturbations on level, unmoving surfaces. Specific experimental questions include: (1) what are the corrective lower extremity joint moments evoked by slipping perturbations? (2) are those corrective moments, if any, accompanied by postural adjustments? and finally (3) what is the time interval between the slipping perturbation's application and onset of possible corrective reactions?

2. Methods

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

The force plate (Bertec, Inc., model 4060A, $0.6\,m \times 0.4\,m$) instrumented walkway was built as part of previous gait experiments (Redfern and DiPasquale, 1997). 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 better than 1 mm) attached to the left shoulder (acromion), 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 lightweight harness system with an overhead trolley caught the subject in case of a fall.

Two contaminant conditions were used: dry and oil. For the oily condition, 10W-40 motor oil was applied uniformly to the entire surface of a vinyl tile floor sample fixed to the force plate. The same brand and model of polyvinyl chloride (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 (Redfern and Bidanda, 1994). The mean (SD) 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 from the subject, the oily condition was mixed among a random number (1–3) of dry trials, during which the subject was unaware of the contaminant condition.

Written 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 starting line of the walkway, faced away from the walkway, waited for about 1 min while

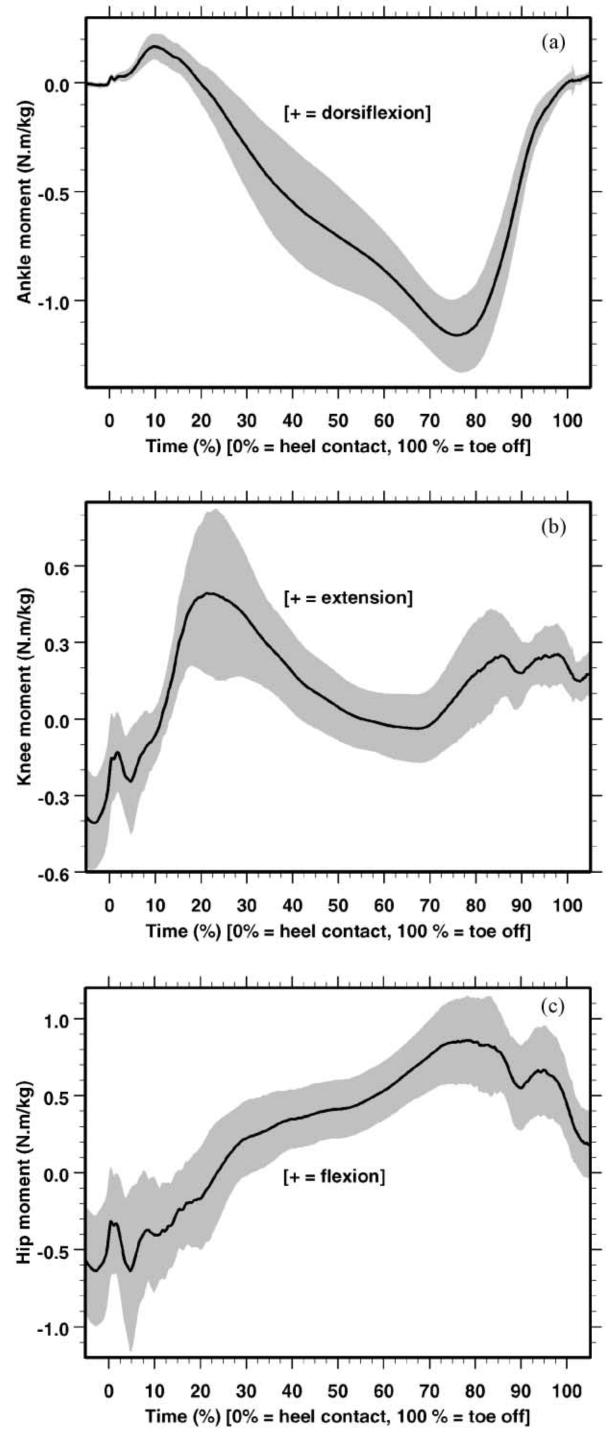

Fig. 1. Mean (± 1 SD) profile of moments generated at the lower extremity joints during stance phase on dry floors: (a) ankle moment, (b) knee moment and (c) hip moment. Joint moments generated at the ankle, knee and hip showed plantarflexor, extensor and flexor patterns during most of the stance period after the loading phase, respectively.

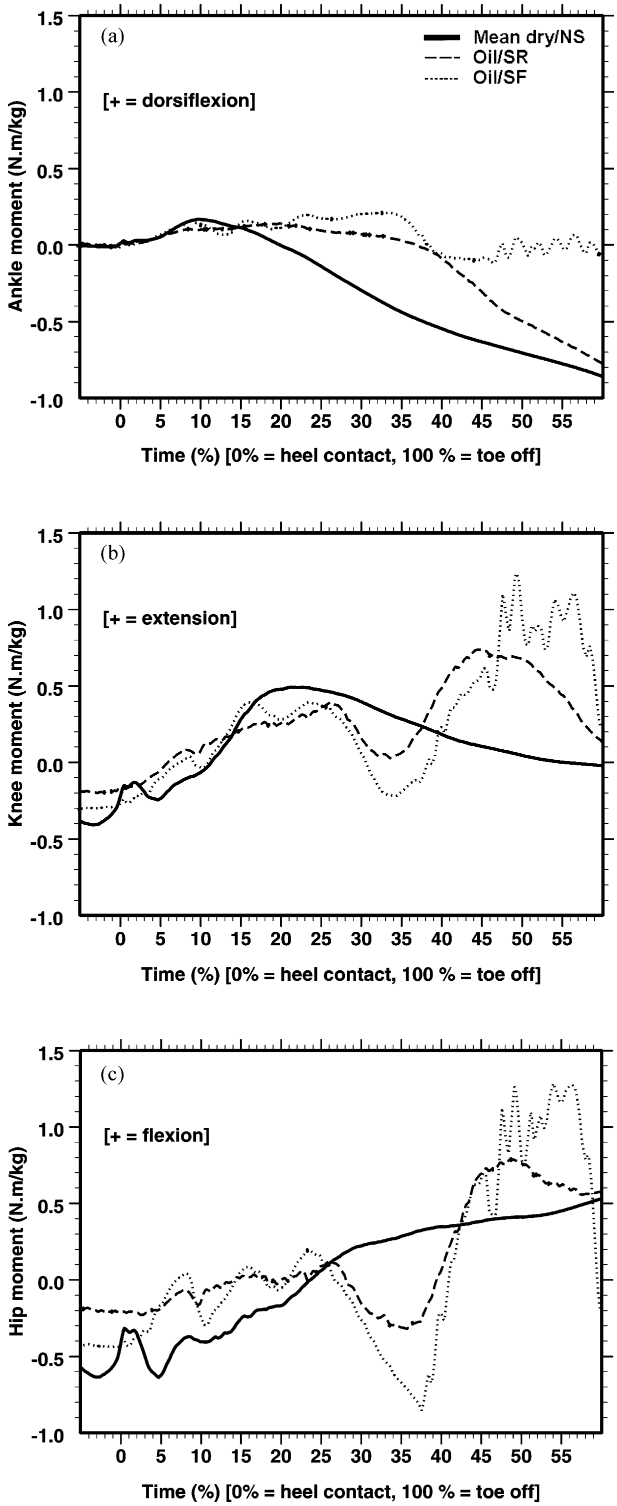

Fig. 2. Mean profile of moments generated at the lower extremity joints during stance phase on dry floors (dry/NS) compared to typical profiles recorded during oil/SR and oil/SF events: (a) ankle moment, (b) knee moment and (c) hip moment. The ankle moment decreased with the severity of the slip. Knee flexor and hip extensor moments were responsible for corrective reactions attempted between 25% and 45% into stance during slip events.

listening to loud music, distracting him/her from any possible contaminant application on the floor. At the end of the waiting period, the lights in the room were dimmed just enough to prevent the identification of any possible contaminant, and guiding lights, placed on the floor on each side of the walkway, were used. The subject turned around and walked while looking straight ahead at the opposite wall. Upon completing the trial, if the floor surface was contaminated, the shoes and floor sample were changed. Mistrials with subjects not fully contacting the force plate occurred in only 10% of the trials. For the two mistrials that occurred on oily conditions, a random number of dry trials followed by an oily condition were repeated again at the end of the testing session.

Ankle, knee and hip moment were calculated based on ground reaction forces, body kinematics and body segmental properties derived using Plagenhoef's formulas proportional to subject-specific height and weight characteristics (Plagenhoef et al., 1983). Lower extremity joint moments were normalized to the subject's body weight. Another kinetic variable derived from the force plate data was the center of pressure position (COP). Kinematic variables in the sagittal plane described lower extremity joint angles. Position data were filtered (FIR filter with a 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 the fall was arrested by the harness or (2) it was determined, based on the heel's kinematic data, that the foot continued to slide beyond the force plate (slip distance greater than 10 cm). A total of 80 dry trials were included in the analysis. When walking on oily floors, 8 out of the 16 trials were categorized as SRs, 4 were SFs and the last 4 were NS. (Oily NS trials were not further considered in the analysis). 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 (SD) stance duration was 776 (108) ms.

Mean profiles of gait variables of interest were first established on dry surfaces and then compared to slippery conditions. Within-subject repeated measures ANOVAs with the dependent variable being a specific gait variable evaluated at 30% or 50% into stance and the independent variables including the outcome were performed. When a significance level of $p \leqslant 0.01$ was found in the ANOVAs, Tukey comparison tests were used to further investigate the differences in a dependent measure among outcomes.

3. Results

3.1. Lower extremity joint moments

Joint moments generated during slipping were significantly different than those computed during normal locomotion on dry surfaces. On dry surfaces, joint moments generated at the ankle, knee and hip after the initial loading phase (~20–25% of stance) revealed plantarflexor, extensor and flexor patterns during most of the stance, respectively (Fig. 1). On oily surfaces, however, the plantarflexion ankle moment significantly decreased with the severity of the slip. In the most severe slips leading to falls, the ankle moment profile remained at very low levels throughout stance due to the COP's proximity to the heel (Fig. 2a and Table 1). By midstance, Tukey comparison tests on the ankle moment and COP position revealed comparable values between dry and oil/SR trials, indicating signs of equilibrium recovery (Table 1).

The large knee and hip moment deviations (from the unperturbed gait patterns on dry surfaces) during slip events revealed the importance of those joints in recovery biomechanics (Fig. 2). A significant bias (compared to dry recordings) towards flexion moment was observed at the knee during slip events between 25% and 45% into stance (Fig. 2b and Table 1). The hip moment was characterized by a significant extensor during that same time (Fig. 2c and Table 1). At 30% into stance, Tukey comparison tests on the hip moment revealed significant differences among dry and SR/SF outcomes (Table 1). Between 45 and 55% of stance, a second compensatory reaction occurred in the motor patterns of the knee and hip (Figs. 2b and c).

3.2. Lower extremity kinematics

At heel contact, body kinematics were not significantly different among outcomes, indicating that the subject did not have an a-priori knowledge of the contaminant condition, i.e. he/she walked with consistent gait patterns on all floors. During the early stance period following heel contact on slippery floors (prior to 20–25% into stance), the profiles of body kinematics variables were similar to those recorded on dry surfaces (Figs. 3 and 4). This finding suggests no postural adjustments in response to slips prior to that time. As a result, by the end of the first third of stance on oily floors, shank rotations were reduced, sending the ankle into plantarflexion and the knee into extension (Figs. 4 and 5, and Table 1). This effect that was especially evident during fall outcomes.

Later in stance, knee and hip moments differed from dry trials, resulting in postural adjustments during slipping. In particular, the knee flexor moment produced increased knee flexion reactions compared to the joint angle profile recorded on dry surfaces during unperturbed gait (Figs. 3 and 4). By midstance, this apparent recovery attempt resulted in knee flexion, especially pronounced in fall cases with an average 20° smaller included knee angle compared to dry values (Figs. 4 and 5, and Table 1). Finally, this flexion reaction of the knee was coincident with an attempt at a rearward motion of the foot towards the body to stop the slip.

Table 1
Mean (SD) of gait parameters (across all subjects) and statistical comparisons

Dependent variable	Mean (SD)			Statistical analysis *p*-value[a]/Tukey[b]
	Dry/NS	Oil/SR	Oil/SF	
Kinetic parameters[c]				
Ankle moment, 30% stance (N m/kg)	−0.30 (0.19)	−0.16 (0.14)	0.10 (0.09)	<0.01/(dry)–(SR)–(SF)
Ankle moment, 50% stance (N m/kg)	−0.71 (0.23)	−0.57 (0.13)	0.06 (0.06)	< 0.01/(dry & SR)–(SF)
Knee moment, 30% stance (N m/kg)	0.40 (0.24)	0.36 (0.37)	0.16 (0.19)	<0.05/not performed
Knee moment, 50% stance (N m/kg)	0.05 (0.13)	0.20 (0.24)	1.05 (0.15)	<0.01/(dry)–(SR)–(SF)
Hip moment, 30% stance (N m/kg)	0.22 (0.24)	0.00 (0.34)	-0.06 (0.21)	<0.01/(dry)–(SR & SF)
Hip moment, 50% stance (N m/kg)	0.41 (0.19)	0.51 (0.28)	0.78 (0.01)	<0.01/(dry & SR)–(SF)
COP–heel distance, 30% stance (mm)	104 (19)	85 (18)	65 (12)	<0.01/(dry)–(SR)–(SF)
COP–heel distance, 50% stance (mm)	159 (31)	136 (23)	74 (8)	<0.01/(dry & SR)–(SF)
Kinematic parameters				
Included ankle angle, heel contact (°)	84.92 (3.80)	85.37 (2.73)	88.57 (4.83)	Not significant
Included ankle angle, 30% stance (°)	82.72 (3.50)	83.80 (3.42)	90.85 (2.19)	<0.01/(dry)–(SR)–(SF)
Included ankle angle, 50% stance (°)	76.93 (2.55)	76.18 (2.25)	74.82 (4.34)	<0.05/not performed
Included knee angle, heel contact (°)	172.54 (5.83)	170.58 (6.84)	173.58 (3.17)	Not significant
Included knee angle, 30% stance (°)	160.85 (7.13)	160.66 (9.43)	165.88 (4.37)	<0.01/(dry & SR)–(SF)
Included knee angle, 50% stance (°)	165.93 (4.49)	163.77 (6.46)	146.42 (7.75)	<0.01/(dry & SR)–(SF)

[a] Results of ANOVA tests of the three conditions.
[b] Results of Tukey tests (performed only when ANOVA, $p<0.01$). Outcomes with comparable values ($p>0.01$) are grouped within parentheses.
[c] Joint moment sign convention: [+] = ankle dorsiflexion, knee extension, hip flexion.

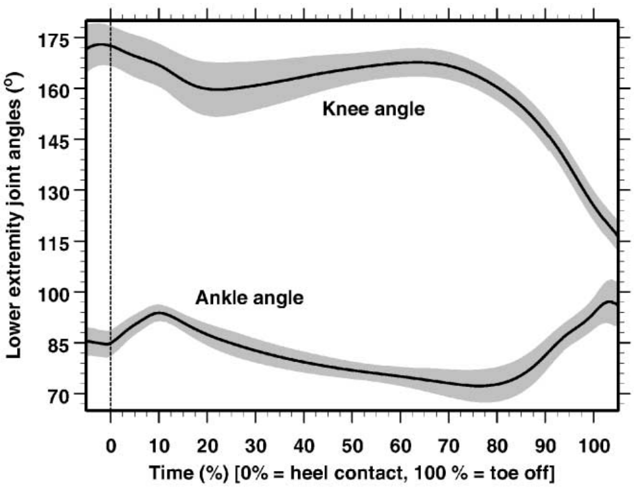

Fig. 3. Mean (±1 SD) profile of included ankle and knee angle recorded during stance phase on dry floors. The loading phase was characterized by an initial plantarflexion of the ankle as the foot rotated down on the floor and a slight flexion of the knee. As the body was moved forward over the base of support, peak dorsiflexion ankle angle and knee extension angle occurred at about 60–80% into stance, at which time, the preparation for toe-off phase started sending again the ankle into plantarflexion and the knee into flexion. Note: Increasing ankle angle and knee angle is reflective of plantarflexion and knee extension movements, respectively.

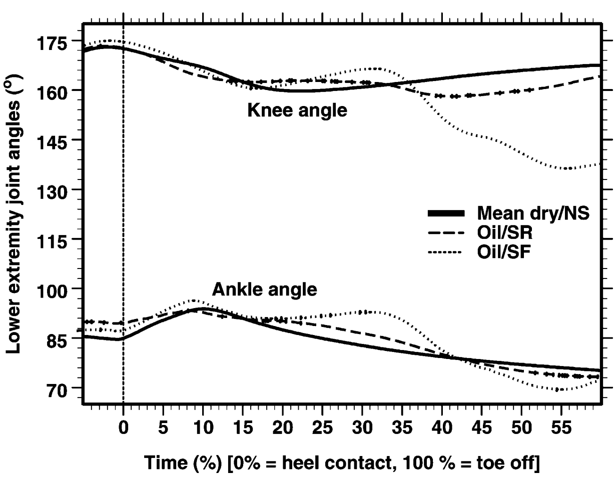

Fig. 4. Mean profile of included ankle and knee angle recorded during stance phase on dry floors (dry/NS) compared to typical profiles recorded during oil/SR and oil/SF events. Flexion reactions of the knee on oily conditions are believed to be related to recovery attempts of bringing the foot back near the body and stopping the heel's sliding motion, thus recovering the ankle angle profile by midstance. Note: Increasing ankle angle and knee angle is reflective of plantarflexion and knee extension movements, respectively.

The ankle joint appeared to play a less active role than the knee in response to a slip event (Fig. 4). At heel contact on oily surfaces, the ankle angle was not significantly different among outcomes (Table 1). As mentioned earlier, during slipping, increased plantarflexion angles were recorded. However, by midstance, the ankle angle profile of SR trials was similar to

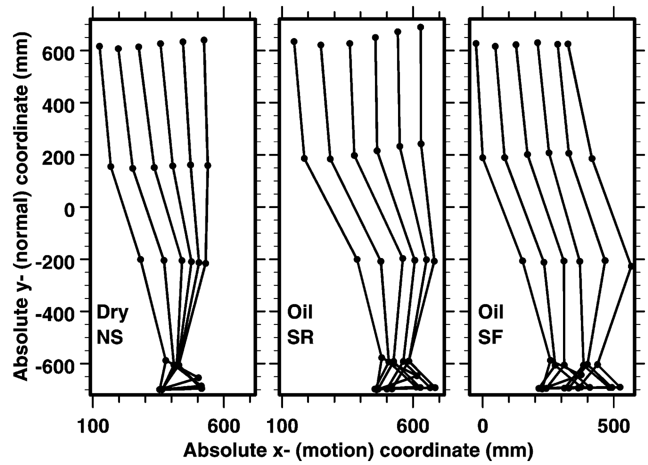

Fig. 5. Typical stick figures of body posture at heel contact, 10%, 20%, 30%, 40% and 50% into stance. The black dots represent the LEDS placed on the left shoulder, hip, knee, ankle, heel and toe.

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 more dorsiflexion (Fig. 4 and Table 1).

4. Discussion

Slipping perturbations on oily floors were used to investigate corrective strategies to prevent falling. Increased flexion knee moment and extension hip moment were identified as the dominant response to slips and appeared to be responsible for the generation of corrective reactions. The ankle, on the other hand, acted as a passive joint (no net moment) 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 leading foot. Corrective movements produced by the knee and hip moments included increased knee flexion reaction, allowing subjects to rotate the shank forward and restore included ankle angle profiles and in an attempt to bring the foot back near the body.

One limitation in this study was that the subjects knew there was a possibility of slipping. While they did not know the specific contaminant condition, there was the possibility to adopt a more cautious gait pattern to decrease slip potential when anticipating slippery surfaces, even when asked to walk as naturally as possible (Cham and Redfern, 2001a). However, just prior to heel contact, gait patterns were similar across slippery and dry conditions, indicating no difference in the a-priori knowledge of the contaminant condition. Another possible limitation in this study is that recovery biomechanics were recorded only unilaterally, i.e. side of the leading foot coming in contact with the slippery floor. Although corrective reactions generated by the leading lower extremity are believed to be of most importance, the potential assistive role of the trailing foot and upper extremities in regaining balance should also be described in future research.

Slipping perturbations elicited an ensemble of postural corrective reactions different than the set reported in response to translation of the supporting surface during standing perturbation protocols. Runge et al. investigated ankle and hip moments in response to posteriorly directed base of support translation at various speeds and found that (1) ankle strategy was present at all perturbation speeds and (2) ankle strategy was coupled with increased hip strategy at faster base of support translations (Runge et al., 1999). 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 knee and the hip with minimal (if any) ankle strategy. Another study by Horak and Nashner, (1986) examined the effect of the support surface's length (relative to foot length) on postural strategies during a given base of support 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, 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. Factors that could affect the type of corrective reactions used by the subjects include initial postural conditions at the onset of the perturbation, body dynamics during the perturbation (e.g. during locomotion, slips begin before body weight is fully transferred to the leading foot) and characteristics of ground reaction forces at the shoe–floor interface (e.g. lack of frictional forces during real slip events).

Reaction time, as measured by the occurrence of corrective moments at the knee and hip during slips, is comparable to the timing of responses reported by other researchers. During the first 150 ms following the applied perturbation, Runge et al. reported only passive joint movements resulting from the posteriorly directed translation of the base of support (Runge et al., 1998). However, active moments at the lower extremity joints became evident at about 150–200 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 definition of a fall is important in gait studies of this type. One question that arises for example in a trial where "fall" is arrested by a harness, is whether recovery from a slip would have been possible without the use of a harness. Thus, the criteria used to categorize the outcome of a slipping perturbation as a fall are critical, and have been subject of some disagreement among researchers. While in general a slip characterized by a slip distance greater than 10 cm is believed to result in a fall (Perkins, 1978; Strandberg and Lanshammar, 1981), other investigators suggested that it is possible to recover from slips greater than 10 cm. The differences in criteria used to define a fall among studies are believed to be at the source of this apparent disagreement. In particular, Brady and colleagues classified a slip trial as a slip-recovery if the integrated force (over time) measured in the safety harness rope was less than 8% of body weight $\times$ time (Brady et al., 2000). Thus, another question that arises in this case is whether a slip-recovery would have been possible if the subject did not have that small but still present amount of rope assistance. The fall criteria used in this study and defined in Section 2 are based on previous studies and believed to be justified. However, it is important for the reader to interpret the findings in light of those criteria.

The results of this study suggest that heel contact might not be the only time during stance important to tribology research, which is interested in measurement of slip resistance at the shoe–floor interface. Until now, biomechanically relevant slip resistance measures have been sought by simulating heel/foot dynamics occurring at heel contact (Grönqvist et al., 1989; Redfern and Bidanda, 1994; Wilson, 1990). Although forward slipping is certainly initiated shortly after heel contact (e.g. 60–80 ms on oily surfaces), 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. Thus the dynamics of the shoe–floor interface during these later times may also be relevant to slip measurements towards reducing falls.

In conclusion, responses to slips found in this study suggest that the primary postural reaction includes knee flexion and hip extension of the leading leg. This reaction occurs approximately 190–350 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. This underscores the task specificity of postural reactions to maintain balance.

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