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EFFECT OF HAVING A-PRIORI KNOWLEDGE OF THE FLOOR'S CONTAMINANT CONDITION ON THE BIOMECHANICS OF SLIPS

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Injuries and deaths are often the result of slips/falls. The perceived danger of slipping affects gait biomechanics. This paper investigated the effect of having a-priori knowledge of the floor's contaminant condition on the biomechanics of slips. Five healthy young male subjects donned a safety harness and walked across a walkway, while ground reaction forces and whole body motion were recorded bilaterally at 60 Hz. Slips on soapy floors occurred under 3 "knowledge" conditions: (1) unexpected slips, (2) slips when uncertain of the contaminant condition, and (3) slips when walking onto known contaminated floors. In (2) and (3), i.e. anticipation of slippery surfaces, subjects generated proactive reactions (reduced stance duration and foot angle at heel contact as well as greater hip flexion) compared to unexpected conditions in (1). Those reactions reduced slip potential but also minimized gait disturbances (reduced slip distance and sliding velocity of the heel) when a slip occurred.

INTRODUCTION

Slips, trips and falls (STFs) are among the leading causes of accidental injuries and deaths in the workplace. An estimated 20 to 40% of work-related injuries have been attributed to STFs in industrialized countries including the USA (Courtney, Sorock, Manning, Collins, & Holbein-Jenny, 2001). Furthermore, those injuries are severe: More than 25% of the workers sustaining falling injuries miss 31 days or more at work (BLS, 1998). In 1998, STFs accounted for approximately 12% of job-related deaths (BLS, 1998). The loss of balance leading to falls is often the result of slipping. Courtney et al. (2001), for example, reported that about 40 to 50% of fall-related injuries are caused by slipping (Courtney et al., 2001). The direct costs of fall-related injuries in the US is substantial (US$6 billion /year, (Courtney et al., 2001)), and will continue to rise with the advancing age of the labor force (Englander et al., 1996).

Biomechanical gait studies are critical to the understanding of the relationship between gait and falls (Redfern et al., 2001). Most slips occur unexpectedly. A challenge in gait studies has been to reproduce the unexpected nature of real-life slipping accidents in laboratory settings. A previous study by Cham and Redfern has shown that, on dry floors, subjects changed their gait significantly when they anticipated slippery conditions (Cham & Redfern, 2002a). More specifically, Cham and Redfern reported that anticipation trials were accompanied by postural and temporal gait adaptations including reductions in stance duration, loading speed on the leading foot and foot-floor angle at heel contact (HC) (Cham & Redfern, 2002a). Those gait adaptations resulted in reduced peak required coefficient of friction values, i.e. slip potential (Cham & Redfern, 2002a). This finding has implications in the research focused on reducing slips and falls, more specifically in the development of biomechanically relevant slip resistance testers and setting of frictional thresholds to achieve slip-safe environments. Also, examining possible gait adaptations arising from anticipation effects provides insights on "control mechanisms" used to reduce slip potential prior to the occurrence of such incident, i.e. proactive reactions. Unfortunately, the study by Cham and Redfern has not investigated the effects of those adaptations on gait when walking on slippery conditions (Cham & Redfern, 2002a). Such investigation would answer the question whether proactive biomechanical responses are effective at controlling slipping.

Thus, the goal of this paper was to investigate the effect of having a-priori knowledge of the floor's contaminant condition on the biomechanics of slips. In particular, the biomechanics of gait were compared among slip events occurring under three "knowledge" conditions: (1) unexpected slips, (2) slips when uncertain of the contaminant condition, and (3) slips when walking onto known contaminated floor surfaces.

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METHODS

Five healthy male subjects, aged 35 years or less, participated in this study with informed consent approved by the Institutional Review Board of the University of Pittsburgh. Exclusionary criteria included a history of or current neurological, vestibular and orthopedic abnormalities and any difficulties impeding normal locomotion.

Subjects walked onto a vinyl tile walkway instrumented with two 4060A Bertec force plates (FP). The FPs were positioned in such a way that the subjects' right foot landed first on one FP during the third step from the starting line, while the left foot landed on the other FP. A safety harness was used to catch the subject in case of a fall. The lights in the laboratory were dimmed just enough to prevent recognition of possible contaminants on the floor. In addition to the FPs, the data acquisition system consisted of an analog to digital converter, a PC computer and two OPTOTRAK-3020 motion measurement systems. LABVIEW was used to synchronize and collect FP and motion data at 60 Hz. The OPTOTRAK system recorded 3-D whole body motion by tracking a total of 30 LEDs attached bilaterally to the subject. More specifically, LEDs were attached to the shoe/foot, ankle (lateral malleolus), knee (lateral femoral condyle), mid-thigh, hip (greater trochanter), sacrum, pelvis (anterior superior iliac spine), shoulder (acromion), elbow (lateral humeral epicondyle), wrist (radial styloid process), neck, tempo-mandibular joint and head.

A full factorial design was used such that each subject was tested on all three "knowledge" conditions described in the protocol below. First, anthropometric variables (stature and body weight, various body segments' length and circumference) were recorded. The subject was provided with polyvinyl chloride (PVC) hard-sole shoes. The subject was then equipped with the safety harness and LEDs, and instructed to walk naturally. Instructions to walk naturally were repeated throughout the testing session. Several practice trials were conducted in order to ensure that the subject was walking comfortably and maximize chances of each foot landing entirely on one and only one FP. For each trial (entire testing session), the subject was instructed to walk to the starting line, face away from the walkway, wait for about 1 minute while listening to loud music to distract him from any possible contaminant application on the floor. At the end of the waiting period, the subject stopped the music, turned around and walked while looking straight ahead at the wall on the opposite side of the room.

Ground reaction forces (GRFs) and motion data were recorded for all subsequent trials: The subject was informed that the first few trials would be non-slippery to ensure natural gait. Two dry trials were conducted (baseline "known dry" conditions). Next, without the subject's knowledge, while he was still expected dry trials, a dish-soap solution (2 parts soap, 1 part water) was applied to the FP on which the left foot landed. This is the "unexpected slippery" condition (legend in Figure 1). After the unexpected slippery trial, the floor was cleaned thoroughly; the subject was given a clean pair of shoes and was told that any of the subsequent trials could be slippery. No more information on the floor's contaminant condition was revealed for the next several trials. Five additional dry trials were conducted, followed by the same soapy condition as in our first slippery trial. This knowledge condition is termed "possibly slippery" (legend in Figure 1). Once again, the floor was cleaned and the subject wore a clean pair of shoes. Finally, for the last slippery trial, the "known slippery" condition (legend in Figure 1), the subject was informed that the floor would be contaminated.

Normal GRFs and body/foot motion data were used to calculate specific gait variables relevant to slip-related recovery biomechanics including foot kinematics (heel position, linear velocity and linear acceleration in the direction of motion and normal to the floor surface, foot-floor angle), whole body joint angles and moments generated at the lower extremity joints. The foot, body kinematics and GRFs are reported here. Normal GRFs were used to find the time of HC with the FP. Velocity information was calculated by numerically differentiating (using a 2-time step differentiation routine) the position data provided by the LEDs. Gait variables were evaluated at HC. In addition, maximum linear heel velocity values in both rearward and forward directions recorded shortly after HC were considered. Position variables were filtered (least square low pass filter) only to derive acceleration data, also used in lower extremity joint moments calculations. Finally, general gait variables such as normalized (to total stature) stride length (defined as the distance traveled in two steps from HC to HC) and stance duration were considered in the analysis. A within-subject repeated measures ANOVA of the effect of the knowledge condition was conducted on each of the dependent variables. Tukey comparison tests were used to further investigate the differences in dependent variables among contaminant knowledge conditions. A significance level of $p \leq 0.01$ was used.

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RESULTS, DISCUSSION AND CONCLUSIONS

During the unexpected soapy condition, gait biomechanics prior to HC with the soapy FP were found very similar to the data collected during known dry conditions (Figure 1). This finding suggests that the subject did not have an a-priori knowledge of the soapy condition, thus confirming the "unexpected" nature of the first slip. This proves the potential feasibility of reproducing scenarios of real-life slip events in laboratory settings.

A comparison analysis of the gait biomechanics on dry floors between anticipation trials, i.e. possibly slippery and known slippery conditions, and known dry conditions confirmed findings of Cham and Redfern (2002a): significant reductions in stance duration (Figures 1 and 2) and foot-floor angle at HC (Figure 1c). In addition, a greater hip flexion angle was recorded at HC during anticipation trials (Figure 1d). Thus, once again, subjects changed their gait patterns when anticipating slippery surfaces.

The proactive reactions adopted by the subjects proved effective at controlling the slipping motion of the foot. Overall, gait disturbances when slipping unexpectedly were more pronounced than those recorded during trials with anticipation of slippery surfaces. Furthermore, gait biomechanics generated during locomotion on anticipated slippery floors were comparable to gait onto known dry surfaces. This is evident both in the kinematics (Figure 1) and GRFs (Figure 2). More specifically, the forward slipping distance (Figure 1a) of the heel and its linear velocity in the direction of motion were reduced significantly when anticipating slippery conditions compared to gait on unexpected soapy conditions. For example, for the typical results presented in Figure 1, a slipping distance of approximately 10 cm was recorded during the unexpected slippery condition (Figure 1a) compared to less than 2 cm for the possibly slippery condition. Similarly, for the known slippery trial, the subject slid over a distance of less than 1 cm, i.e. this trial cannot be classified as a slip (Cham & Redfern, 2002b). Also, the maximum forward sliding heel velocity exceeded 1 m/s during the unexpected soapy condition compared to approximately 0.2 m/s during possibly slippery floors (Figure 1b).

As reported previously by Cham and Redfern (Cham & Redfern, 2001), flexion responses at the knee and extension reactions at the hip were among the corrective reactions generated at the leading foot (Figures 1d and 1e). In addition, this study has shown evidence of shoulder flexion as well (Figure 1f).

In conclusion, this study has shown that it is possible to generate unexpected slippery conditions in laboratory settings. Furthermore, the perception of the danger of slipping affects gait biomechanics: Humans generate proactive reactions that reduce slip potential and minimize gait disturbances when a slip occurs.

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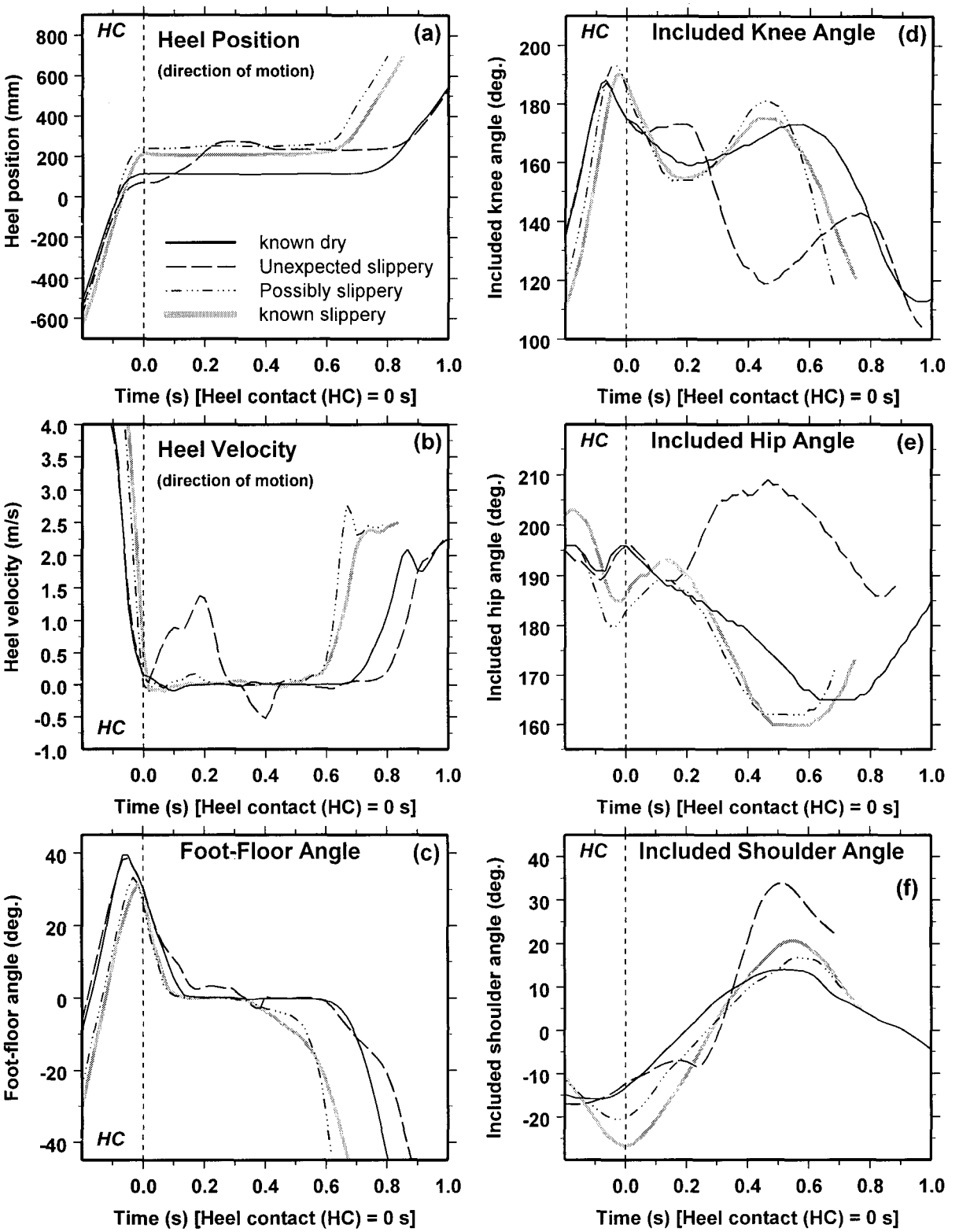

Figure 1: Kinematics of Slip

(a) Heel position in the direction of motion, (b) Heel velocity in the direction of motion, (c) Foot-floor angle, (d) Included knee angle in the sagittal plane, (e) Included hip angle in the sagittal plane, and (f) Included shoulder angle in the sagittal plane

[Vertical dashed line is the time of heel contact (HC)]

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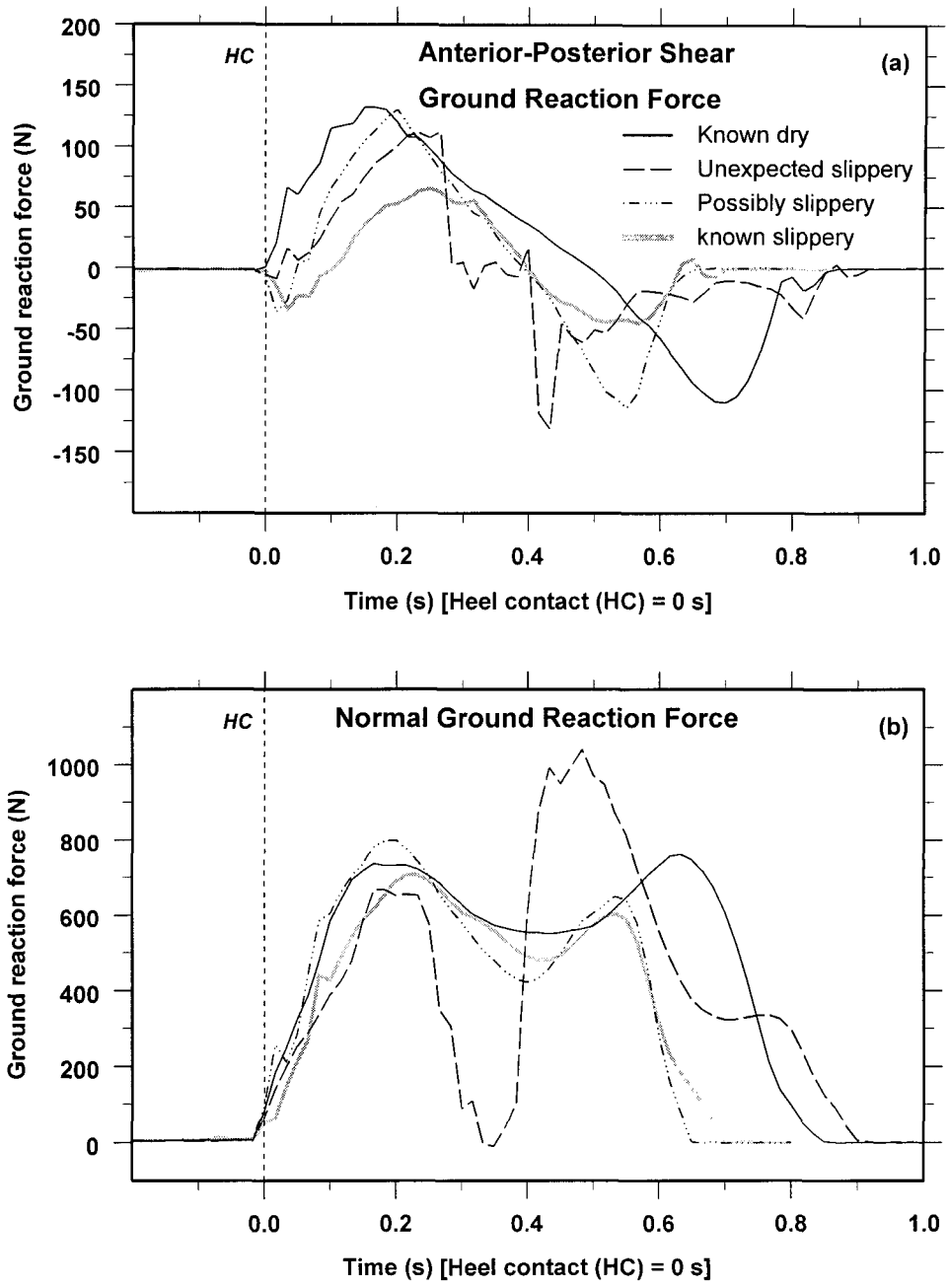

Figure 2: Ground Reaction Forces
(a) Anterior-posterior shear ground reaction force, and (b) Normal ground reaction force
[Vertical dashed line is the time of heel contact (HC)]

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