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The use of a heel-mounted accelerometer as an adjunct measure of slip distance

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Abstract

A human-centered measure of floor slipperiness could be useful as an adjunct to conventional tribologic measures. This paper reports on the development and evaluation of a measure of slip distance based on variables derived from the signal of a heel-mounted accelerometer. Twenty-one participants walked on a laboratory runway under several surface slipperiness conditions at three walking speeds during a protocol designed to produce a wide range of slip distances at heel strike. Analysis of variance showed significant effects of slip distance (no-slip, micro-slip and slide), walking speed (1.52, 1.78 and 2.13 m/s) and their interactions on peak forward acceleration, peak vertical acceleration and deceleration time of the heel following heel strike in 704 trials. Regression analysis of slip distance and deceleration time showed the strongest relationship with $R^2 = 0.511$. Large individual variation in the strength of this relationship was observed. The heel-mounted accelerometer may have utility as an adjunct measure in the evaluation of floor slipperiness, particularly for field applications where direct measurement may not be feasible.

Keywords: Accelerometer; Slip; Micro-slip; Slip distance; Gait; Deceleration time

1. Introduction

Falls related to slipping are a major source of injury at the workplace. In 1996, slips were a factor in 40–50% of fall-related occupational injuries in the USA, and the annual cost associated with these injuries was approximately US$6 billion (Courtney et al., 2001). Slips and trips were factors in 18% of injuries at a major US public works construction project (Lipscomb et al., 2006). According to the Bureau of Labor Statistics, in 2004 non-fatal fall-related injuries had an incidence rate of 28.7 per 10,000 full time employees (US Department of Labor, 2006).

One area of slips and falls research has been to examine the tribologic properties of shoe heels and soles, flooring materials, and the interactions at the shoe–floor interface. Various slip meters have been developed to measure the coefficient of friction (COF) during the transition from a static to dynamic state as a shoe material strikes a floor surface (Chang et al., 2001). Results of such tests vary greatly depending on factors such as the type of slipmeter used for the measurement, the speed of impact of shoe material with the floor, and the thickness of the contaminant film (Grönqvist, 1999). Li and Chen (2004) demonstrated that additional factors, such as the width of tread grooves on the heel of a shoe, affect the COF of the shoe–floor interface in the presence of a liquid contaminant. Using a profilometer, Chang et al. (2004a) examined features such as roughness and waviness of floor surfaces and their effect on the COF of a liquid contaminated surface. An alternative measurement approach has focused on simulation of the slip event and making measurements with actual footwear, assuming that a more accurate representation of human gait would yield a more accurate appraisal of slip resistance (Aschan et al., 2005).

The tribology of the shoe–floor interface is an important part of the risk analysis for slips and falls. A more complete evaluation of the "slipperiness" of a workplace might include the human and environmental factors associated

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with the worker walking in their work environment. Human factors include issues of postural control, aging, attentiveness and perception (Grönqvist et al., 2001). Environmental risk factors include lighting and ambient noise levels. These factors can act independently or interact to affect the risk of occurrence of a slip or fall.

Most studies that investigate gait kinematics and kinetics related to slips and falls are conducted in the laboratory setting, where sophisticated equipment is available and environmental variables can be well controlled. Drawbacks to laboratory-based investigations include loss of spontaneity in the gait being studied and subconscious changes in gait in anticipation of a slip. It is also difficult to replicate the workplace floor conditions, which may vary greatly from location to location, whether it is an office lobby or a restaurant kitchen (Chang et al., 2004b). Though it would be advantageous to assess worker exposure in the workplace, slips and falls are rare events and it would not be practical or ethical to either create or passively monitor workplace conditions that are likely to produce them. Thus, a measure of slip potential that does not necessitate progression to a slip or fall would be a useful tool.

One human-centered approach with such potential would be to quantify the forward displacement of the heel following heel strike, or slip distance. Myung et al. (1992) and Leamon and Son (1989) reported that slip distance tends to vary inversely with COF. The required COF (shear force/normal force) reported in the literature for normal walking speeds typically ranges from 0.17 to 0.20 (Redfern et al., 2001). When the required COF exceeds the available COF of the floor surface, a slip of some magnitude becomes likely (Cham and Redfern, 2002a; Hanson et al., 1999). However, to our knowledge, direct measurement of slip distance in the workplace has not been reported. One likely reason is the difficulty inherent in measuring small heel movements outside of the laboratory setting.

Accelerometers have been used to study the kinematics of various aspects of human motion and may be a viable tool for developing a surrogate or adjunct measure for slip distance. An accelerometer mounted to the trunk was used to evaluate gait parameters (Auvinet et al., 2002; Moe-Nilssen, 1998). Hirvonen et al. (1994) were able to detect loss of balance and slip events with a trunk mounted accelerometer. Others have proposed the use of accelerometers to evaluate body segment kinematics in both the laboratory and in the workplace (Mayagoitia et al., 2002; Estill et al., 2000). Ledoux and Hillstrom (2001) used an accelerometer mounted to the skin overlying the calcaneus (heel bone) to evaluate differences in heel strike between normal and "flat feet" (pes planus). However, there are no reports in the literature of the use of accelerometers or related devices to quantify heel movement following heel strike.

The purpose of this study was to investigate whether a simple and unobtrusive device such as an accelerometer has potential as a measure of slip distance, and to validate the system performance against a "gold standard", the direct measurement of heel movement after heel strike. We hypothesize that a variable derived from the output of a heel-mounted accelerometer, will provide a reasonable approximation of the forward displacement of the heel following heel strike, as measured with a motion tracking system.

2. Method

2.1. Participants

Twenty-one individuals (9 men and 12 women) were recruited to participate in a study conducted in our biomechanics laboratory. After the protocol was explained, each participant gave written informed consent to participate in the study that was approved by the institutional review board. Anthropometric and demographic data were collected. The means (standard deviations) of ages, heights and weights of the subjects were 40.9 (14.3) years, 168.2 (9.8) cm, and 77.6 (16.1) kg, respectively.

2.2. Hardware

Kinematic data of the right shoe was collected at around the time of heel strike, using a passive reflective cinematographic motion tracking system (Eagle Digital camera system, and EVaRT 4.01 Beta 12 software, Motion Analysis Corp, Santa Rosa, CA, USA). The motion tracking system, with a 2 m^3 viewing volume calibrated to a residual error of less than 0.4 mm, was used to collect position displacement data from two 10 mm diameter reflective markers located on the heel of the right shoe. Marker position was sampled at 400 Hz.

The nitrogen damped, capacitive tri-axial accelerometer (2422-50, Silicon Devices, Issaquah, Washington, USA) used in this study had a 50 g (gravitational unit = 9.81 m/s^2) measurement range in each of three orthogonal axes, and a frequency response from 0 Hz (DC) to 1600 Hz. The accelerometer, a cube measuring 2.5 cm on a side, had a mass of 21 g. The accelerometer leads were connected to a transmitter worn on a waist belt. The signals were telemetered to a receiver located within 20 m of the participant. A 40 cm × 60 cm force plate (Model # 9281CA, Kistler Instruments AG, Winterthur, Switzerland) mounted to a concrete footing in the runway of our biomechanics laboratory was used to record foot contact forces. The signals from the accelerometer and the force plate were sampled at 1200 Hz.

During the experimental session one of three 12 mm thick surfaces was bolted to the force plate. Pilot testing was conducted to guide selection of floor and heel materials that, with or without contaminant, would produce a range of heel slippage in sufficient numbers within the constraints of the experimental protocol. The researchers walked on various surfaces wearing shoes with several heel materials. These materials were selected for evaluation because the COF of the surface and heel material combinations were in