C28 In-Vivo Method to Characterize the Effects of Selected Contaminants & Walking Speed on Tendency to Slip During Walking

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After attending this presentation, attendees will become familiar with the history of gait studies relative to required and available slip resistance. This paper describes a gait study using a specific shoe outsole material, selected contaminants, and varying walking speeds on the tendency to slip. Force plate results are used to determine the available coefficient of friction. Portable tribometers were also used to measure the coefficient of friction of the same outsole/contaminant/ walkway combination.

Tribometer testing of RCOF (slip testing) was performed on the same combination of 'test foot', walkway surface, and contaminant. The methodology employed in this study will impact the forensic community and/or humanity by allowing the authors to characterize in vivo slipping in an adult walking on a flat surface. Comparisons between tribometer and in vivo data may give insight into the validity of generalization of tribometer results to real-life situations.

Slipping, and the potential for falling, is a major public health problem in the world. In the United States, in 2003, according to the National Safety Council's tabulation of Bureau of Labor Statistics data, 174,570 people fell in the workplace on the same level, resulting in lost time from employment and significant injuries (National Safety Council 2005-2006). Biomechanical studies of gait have resulted in the experimental determination and theoretical development of significant factors that affect the propensity for slip of test subjects during level walking (Perkins 1978, Strandberg and Lanshammer, 1981, Proctor and Coleman, 1988, Redfern and Boswick 1997, Gronqvist et al 2003). Analysis of gait, using biomechanical principles can be used to determine whether a shoe outsole/walkway surface can be slip resistant (Marpet 1996). The ground reaction forces used to characterize the tendency for slip to occur while level walking is the ratio of shear to normal forces (F_h/F_v). Under no-slip conditions, the ratio F_h/F_v is known as required coefficient of friction (RCOF) (Redfern and Andres 1984, Gronqvist et al 2001). Mathematical models have been developed to predict when a slip event is likely to occur (Batterman et al 2004). Portable tribometers can be used *in situ* to measure the available coefficient of friction between the walkway, shoe outsole material, and any contaminants present. Researchers have identified the required coefficient of friction (RCOF) as ratio between the horizontal ground reaction force to the vertical ground reaction force (F_h/F_v) as the minimum coefficient of friction that must be available at the shoe/walkway interface, during level walking, to prevent a forward slip (Redfern and Andres 1984, Hanson et al 1999). During level walking, if this required coefficient of friction is significantly less that the available coefficient of friction, the subject will be able to continue walking in an uneventful manner. Walking speed has been found to affect the required coefficient of friction (RCOF) –increasing the walking speed increases the RCOF (James 1983, Myung et al 1992). Heel velocity (generally) is forward immediately upon impact with the walkway surface, then the heel either comes to a stop or reverses its sliding direction before coming to a stop; however some researches have reported rearward sliding of the heel immediately upon contact with the walkway surface (Cham and Redfern 2001). Hanson et al attempted to develop a method to evaluate the relationship between slip resistance measurements and actual slip and fall events. The test subjects walked on a specially designed ramp. This ramp included an integral force plate, and the ramp angle could be varied (0^{o}, 10^{o} and 20^{o}). Lockhart et al measured age-related gait changes by having two age groups young (18-29 years) and old (65 years and over) walk over two separate floor materials – carpet and vinyl tile. The vinyl tile was covered with motor oil (10W40) to reduce its coefficient of friction. Test subjects walked around a circular track, while in a safety harness. A remote controlled floor changer (RCFC) was developed and used to change the floor surface to either of the floor materials to provide an unexpected low coefficient of friction walking surface. This changed floor surface was placed over a force plate, allowing for the measurement of ground reaction forces during any slip event. Dynamic coefficient of friction (DCOF) measurements were made on both floor surfaces using a laboratory produced drag tester with a rubber sole shoe surrogate.

Brady et al induced slips in barefoot young healthy adults walking on a vinyl floor material contaminated with mineral oil. The subjects were blindfolded during this test. The contaminated vinyl surface was placed over a force plate. Lower body kinematics was measured using a video-based motion capture system. Burnfield and Powers (2006) investigated the relationship between slip resistance (shoe outsole/walkway) and the peak utilized coefficient of friction. This was related to the probability of slip during level walking. Test subjects were asked to walk across an instrumented force plate while their kinematics was being recorded. During some tests, the force plate was contaminated with WD-40. The available slip resistance on this contaminated surface was measured using a portable tribometer (VIT). Logistic regression analysis was used to compare the probability of slip to the difference between available and utilized coefficient (RCOF).

In the present study, a flat, level walkway was used to determine the effect of walking speed and

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contaminants on the tendency to slip. The test subject was a young healthy male, with no history of foot or musculo-skeletal problems. Data were collected on a 10 m long walkway. To protect the subject from falling, a safety harness was used. The harness was suspended from a rolling frame (BIODEX Body Weight Support System), which was constrained using wooden rails to roll straight down the walkway. No body weight was supported by the system during testing; however, the harness would prevent the subject from falling. The walkway was instrumented with a 4.3 m GAITRite mat (CIR Systems, Clifton, NJ) for measurement of temporal and spatial gait parameters, and an AMTI biomechanical force platform (AMTI, Watertown, MA), model OR6-5, for measurement of ground reaction forces. The force platform was the designated 'slip' location. The platform surface was covered with a commercially available marble (Carrerra) surface (46 x 51 x 1.3 cm). The subject's foot motion on the force platform was recorded using a digital video camera (Canon ZX80) for qualitative analysis. The walkway was 10 m long, sufficient to allow the subject to continue walking well past the slip location without slowing. The GAITRite mat collects temporal and spatial parameters with a sampling rate of approximately 80 Hz; ground reaction forces were collected at a sampling rate of 1000 Hz. The surface conditions of this marble plate were: dry, wet (distilled water), wet (soap solution) and wet (mineral oil).

The shoes worn by the test subject were specially prepared with a Polyurethane elastomer outsole (integral sole and heel), with a 'diamond type' grooved pattern. These sole materials were affixed to an "oxford-type" shoe. Markers were applied to the outside of the shoe to allow the video camera to record the position of the test foot. Three initial trials were conducted with the dry marble surface, no support frame, and the subject wearing his own shoes to be used as baseline data. These initial trials were used to determine the subject's self-selected walking speed (SSWS). From this self-selected speed, a "slow" speed (80% of SSWS) and a "fast" speed (120% of SSWS) were calculated. These were used as target speeds for the test trials. Walking speed for each trial was measured using the GAITRite mat. The subject was given the opportunity to practice to allow them to acclimate to the new speed each time the speed was changed.

Trials for each surface condition (dry, wet-water, wet-soapy water, and wet-mineral oil) were collected at each speed (SSWS, Slow, and Fast). For each test, the test subject was asked to walk along the walkway. Using the handles on either side of the movable BIODEX frame, researchers pushed the frame along as the test subject walked inside this frame. The subject began walking approximately 2 meters before the beginning of the GAITRite mat, and continued past the end of the mat, over the force plate, and on approximately 3 meters past the end of the force plate. A number of trials were performed, under dry conditions, with the frame being 'pushed' and the test subject walking within the frame, to establish repeatability of walking speed of the test subject. Data were then collected on the test subject, wearing the supplied footwear, at each of the three walking speeds, under each of the four surface conditions. Five trials were collected for each combination of conditions. The order for conditions was kept consistent for the experiment: floor conditions were dry, then wet-water, then wet-soapy water, then wet-mineral oil; under each condition, data were collect at the slow speed, SSWS, and then fast speed. For each trial, walking speed as reported from the GAITRite system and the vertical and horizontal ground reaction forces were exported to be processed using Microsoft Excel (Microsoft Corporation, Redmond, WA). Required Coefficient of Friction (RCOF) was calculated for each sample as follows:

$$RCOF = \frac{GRF_{horizontal}}{GRF_{vertical}} \text{, where } GRF_{horizontal} = \sqrt{(GRF_{ML})^2 + (GRF_{AP})^2}$$

The subscripts AP and ML refer to the anterioposterior (fore-aft) and mediolateral (side-to-side) directions respectively. Peak values of RCOF were noted for the braking (initial) and pushing (final) phases of the gait cycle. Peak pushing and braking RCOF were plotted against velocity for each testing condition. For trials with no slip, RCOF increased with increased walking speed. RCOF at toe-off (pushing phase) was slightly greater than RCOF at initial contact (braking phase).

RCOF was noted on dry trials, and these were compared to contaminated trials. When available COF was less than RCOF, the subject would slip. Slips were characterized as 'heel slips' (at initial contact) or 'toe slips' (at terminal stance, push off). For most conditions, toe slips were seen at a lower velocity than were heel slips.

Walkway Safety, Forensic Science, Tribometry

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