A Novel Method for Evaluating the Effectiveness of Shoe-Tread Designs Relevant to Slip and Fall Accidents

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Slip and falls account for a large share of occupational accidents. Slips are typically initiated when an insufficient amount of friction is present between the shoe and floor surfaces during walking. Shoe tread is thought to enhance the friction by channeling fluid contaminants away from the shoe and floor surface thus mitigating the fluid's ability to lubricate the two surfaces and reduce friction. This study presents a novel method for evaluating the effectiveness of shoe tread by measuring fluid pressures during simulated slips. Sensors embedded into the floor measured fluid pressure while a robotic slip-tester simulated a human slip. A work shoe with three different tread depths (no, medium and full tread) was tested against a vinyl floor using a diluted (90%) glycerol and diluted detergent (2% detergent, 98% water) contaminant. Fluid pressures were high in the no tread condition but negligible in the other two tread depth conditions for the diluted glycerol and were negligible for all diluted detergent conditions. The no tread (COF: 0.005) also had lower friction coefficient values than treaded conditions (COF: 0.08-0.38). This study suggests that the effectiveness of tread to reduce the lubricating quality of the fluid can be directly measured using a robotic slip-tester and a fluid pressure sensor embedded in the floor. This method has the potential for developing tread depth recommendations and in evaluating the validity of slip-testers to simulate under-shoe conditions.

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INTRODUCTION

Falling accidents from the same level accounted for 15% of non-fatal accidents in 2010 (U.S. Department of Labor- Bureau of Labor Statistics 2011) and are the fastest growing source of worker's compensation claims over the past 10 years (Liberty Mutual Research Institute 2009). Slipping is known to cause a majority of same-level falling accidents (Courtney et al. 2001). Thus preventing slip and fall accidents has high potential for reducing occupational injuries.

A slip is typically initiated when the friction between the shoe and floor surface (known as the available coefficient of friction) is less than the amount of friction needed to sustain walking (known as the required coefficient of friction) (Hanson et al. 1999). Lower available coefficient of friction values are typically associated with increased slip and fall risk (Burnfield and Powers 2006) and prospective studies in restaurants have demonstrated that an increase of 0.1 in coefficient of friction reduces rate of slipping by 21% (Verma et al. 2011). Coefficient of friction is a complex multifactorial phenomenon that is affected by the shoe material (Tsai and Powers 2008), shoe tread (Li et al. 2006), flooring (Chang et al. 2001) and fluid (Beschorner et al. 2007). With so many contributing factors, identifying interventions using just the available coefficient of friction to reduce slipperiness can be challenging.

Shoe tread has been shown to contribute to shoe-floor coefficient of friction (Li et al. 2006) and insufficient tread is often a contributing factor in slip and fall accidents (Bentley and Haslam 2001) (Fig. 1). The purpose of shoe tread is to help channel fluid from the shoe-floor interface much like the purpose of tread on a vehicle tire is to channel water from between the tire and road (Strandberg 1985; Tisserand 1985). When shoe tread becomes insufficient, the fluid becomes pressurized and causes a film layer to separate the shoe and floor surface. This separation of shoe and floor surfaces reduces the friction between these surfaces (Tisserand 1985). Therefore, high fluid pressures may be indicative of inadequate shoe tread.

Fig. 1: Boot with worn tread pattern.

While shoe tread is clearly a contributing factor, the amount of tread needed for different circumstances is not currently known. Liberty Mutual Research Institute has made recommendations of tread width and channel width but not tread depth (Liberty Mutual Research Institute 2004). Research by Li et al. describes that friction coefficient is higher for larger tread depths in the range of 1-5 mm (Li et al. 2006). This study, however, used a slip-tester with very low vertical loads and the results may not apply similarly to the high vertical force conditions experienced during human slips. In addition, coefficient of friction provides a gross approximation of the overall shoe-floor interaction and cannot be used to specifically evaluate if tread is contributing to the friction.

The purpose of this study is to apply a novel experimental technique of measuring fluid pressure and friction coefficient while simulating a slip to assess the effectiveness of tread. Pilot data from this experimental technique will be provided for a shoe-floor-fluid combination using three different tread depths.

METHODS

Apparatus

Experiments were performed using a custom-developed device that simulated loading and kinematic conditions (vertical force and sliding speed) of human slips similar to (Aschan et al. 2005). The device used three vertical motors to apply the vertical force, while a horizontal motor moved the shoe horizontally (Fig. 2). Vertical force levels were approximately 500N (~70% body weight for a 70kg individual), sliding velocities were approximately 0.8 m/s, shoe-floor angle was 10° and the friction value was recorded within 500 ms of heel contact. The testing parameters were within the range deemed biomechanically relevant to slipping (Chang et al. 2001).

A fluid pressure sensor was embedded into the floor to measure fluid pressures as the shoe moved over the floor surface (Fig. 2). This method has been used in other disciplines such as chemical mechanical polishing to better understand the role of the fluid between two surfaces (Shan et al. 2000). The top of the pressure sensor was embedded slightly (1 mm) beneath the floor surface and the sensor was filled with the testing fluid up to the floor surface to ensure that fluid pressures are transmitted to the trasnducer.

A forceplate was used to measure shear and vertical forces in order to calculate coefficient of friction. Identical experimental conditions were used when the slip tester was on the forceplate and fluid pressure sensor so that the fluid pressure results could be compared with the coefficient of friction values. The slip-tester was positioned so that only the foot came in contact with the forceplate.

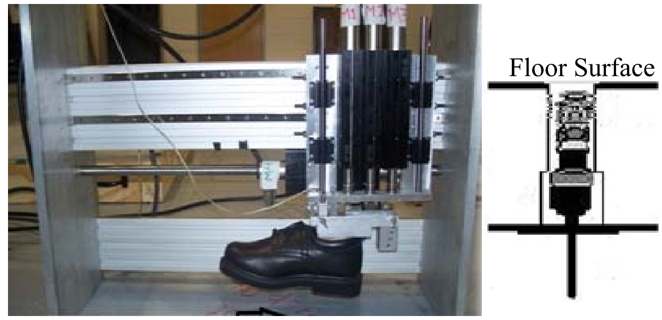

Fig. 2: Slip-testing apparatus (left) and fluid pressure sensor that is embedded in the floor (right).

Experimental Protocol & Testing Conditions

Fluid pressures and coefficient of friction were measured by operating the slip tester over the pressure sensor and force plate, respectively. Fluid pressure measurements for the entire shoe surface were found by using seven different passes of the slip simulator over the fluid pressure sensor. The shoe was moved medial-laterally relative to the pressure sensor between each pass so that each trial provided a fluid pressure profile for a different part of the shoe. An even and consistent amount of fluid was spread across the floor surface before each trial. Fluid was filled in the inlet of the fluid pressure sensor with no bubbles to ensure that pressures were transmitted to the transducing portion of the sensor.

Testing samples included a work shoe with rubber outsole and vinyl tile flooring. Two fluid conditions were considered using a diluted detergent solution (2% detergent, 98% water, viscosity: 1.8 cP) and diluted glycerol (90% glycerol and 10% water, viscosity: 219 cP). The diluted detergent concentration ratio was selected to be consistent with the detergent manufacturer's recommendation. The high concentration of glycerol was intended to provide a high viscous fluid. Three different shoe tread depths were considered: full tread (2.4mm deep), medium tread (1.4 mm deep) and no tread (0 mm). Tread was removed by abrading the surface with silicon paper. The abrading of the material to remove tread did not generate major changes in shoe hardness or roughness as measured by a durometer and stylus profilometer, respectively.

Data Analysis

Three measures were used to describe the shoe-floor interaction: coefficient of friction, peak fluid pressure and the total force supported by the fluid. Coefficient of friction was calculated as the average ratio of shear to normal force over a 250 ms window using data from the forceplate. The coefficient of friction provides an overall measure of the slip-risk associated with the shoe-floor-contaminant combination with a low coefficient of friction values indicating that the floor is slippery. The force supported by the fluid was found by integrating fluid pressure (p) over the surface area (A) of the shoe (Eq. 1). Total force supported by the fluid provides a measure for the overall effectiveness of the shoe tread design with low fluid-forces indicating that the shoe tread is effective. The peak fluid pressure was taken as the maximum fluid pressure over the area of the shoe. Peak pressure can be used to identify the location on the shoe where tread is most-needed.

$$Fluid\_Force = \int pdA \qquad \text{(Eq. 1)}$$

RESULTS

Fluid pressures were high for the no tread shoes when in the presence of the glycerol contaminant. Fluid pressures were negligibly small for the medium tread and full tread conditions when combined with the glycerol contaminant and all tread depths for the low viscosity fluid. The peak fluid pressure in the no-tread conditions was 234 kPa. The peak pressure was located centrally in the medial-lateral direction and about 30-50 mm anterior to the heel. The total force supported by the fluid in the no-tread condition was 200.5 N, which accounted for 40% of the total vertical force. The peak fluid pressure for the medium and full tread shoe and detergent contaminant (all tread depths) was less than 5 kPa and the force supported by the fluid was less than 4 N (i.e. <1% of the total vertical force) (Table 1).

Table 1: Summary of coefficient of friction and load supported by the fluid results

Fluid	Tread Depth (mm)	Load Supported by Fluid (N)	Coefficient of Friction
Glycerol	0	200.5	0.005
	1.4	3.5	0.09
	2.4	3.7	0.08
Detergent	0	3.1	0.29
	1.4	3.1	0.38
	2.4	3	0.26

The no-tread condition yielded the lowest coefficient of friction value. The medium-tread and full tread conditions had coefficient of friction values that were similar to each other and larger than the no-tread condition. The coefficient of friction for the medium tread and high tread conditions with glycerol are still lower than typical required coefficient of friction values (0.2) suggesting that these conditions are still likely to be considered slippery (Redfern et al. 2001). The friction coefficients were higher for the diluted detergent condition than the diluted glycerol condition.

DISCUSSION & CONCLUSIONS

This study describes a method for evaluating the effectiveness of shoe tread by measuring the resulting fluid pressures in the shoe-floor interface. The large reduction in fluid pressures between no tread and medium tread indicates that a modest amount of tread (1.4mm depth) may be sufficient to relieve most of the fluid pressures in the shoe-floor interface. Coefficient of friction was nearly zero when fluid pressures were large and about an order of magnitude larger when fluid pressures were absent.

The results of this study are consistent with previous theory that indicates insufficient tread may lead to high fluid pressures and lower friction coefficient. Tisserand suggested that shoe tread was particularly important in conditions where the fluid may become pressurized (Tisserand 1985). Shoe tread was, in fact, capable of reducing fluid pressures in the glycerol condition and increased the coefficient of friction. Higher viscosity fluids are associated with greater film thicknesses and fluid pressures (Chang et al. 2001), which explains why fluid pressures were high for the high viscosity diluted glycerol but low for the low viscosity diluted detergent condition.

The method described in this proposal may provide several opportunities for reducing slip and fall accidents caused by insufficient tread. This methodology can be used to establish minimum tread depth requirements by the amount of tread required to eliminate fluid pressures. This study suggests that for the shoes and floor surfaces evaluated in this study, no tread is needed for very low viscous fluids while about 1.4 mm of tread is sufficient for the diluted glycerol fluid that was considered. In addition, this method was used to locate the part of the shoe that had the highest fluid pressures. This information can be used by shoe manufacturers to ensure that shoe tread is greatest in this region.

While coefficient of friction values were larger in the medium-tread and full-tread conditions for the glycerol contaminant, they were still lower than typical required coefficient of friction values suggesting that a slip would still be likely. Therefore, shoe tread may be a necessary but insufficient criterion for preventing slips. Other interventions may also be needed including increasing floor roughness (Chang et al. 2001), changing shoe material (Tsai and Powers 2008) or using housekeeping efforts to prevent high-viscous fluids from being present on the floor (Bell et al. 2008).

While this study shows promise for the use of fluid pressure sensors in evaluating tread depth, the study used a relatively limited set of experimental conditions and used a robotic device to simulate slips instead of measuring human slips. Future studies should determine the effects of footwear, different flooring and additional fluid contaminants on fluid-pressures. Also, recording fluid pressures during human slips would be an effective method of validating the ability of the slip-tester used in this study and other common slip-testers (i.e. English XL, Brungraber II and Pendulum Slip Tester (Chang et al. 2001)) to mimic the under-shoe conditions of slipping.

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