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INFLUENCE OF HYDRODYNAMIC FLUID PRESSURE AND SHOE TREAD DEPTH ON AVAILABLE COEFFICIENT OF FRICTION

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ABSTRACT

Slip and fall accidents are a major occupational health concern. Identifying the lubrication mechanisms affecting shoe-floor-contaminant friction under biofidelic (testing conditions that mimic human slipping) conditions is critical to identifying unsafe surfaces and designing a slip-resistant work environment. The purpose of this study is to measure the effects of varying tread design, tread depth and fluid viscosity on underfoot hydrodynamic pressure, the load supported by the fluid (i.e. load carrying capacity), and the coefficient of friction (COF) during a simulated slip. A single vinyl floor material and two shoe types (work shoe and sportswear shoe) with three different tread depths (no tread, half tread and full tread) were tested under two lubrication conditions: 1) 90% glycerol and 10% water (219 cP) and 2) 1.5% Detergent-98.5% (1.8cP) water solutions. Hydrodynamic pressures were measured with a fluid pressure sensor embedded in the floor and a forceplate was used to measure the friction and normal forces used to calculate coefficient of friction. The study showed that hydrodynamic pressure developed when high viscosity fluids were combined with no tread and resulted in a major reduction of COF (0.005). Peak hydrodynamic pressures (and load supported by the fluid) for the no tread-high viscous conditions were 234 kPa (200.5 N) and 87.63 kPa (113.3 N) for the work and sportswear shoe, respectively. Hydrodynamic pressures were negligible when at least half the tread was present or when a low viscosity fluid was used despite the fact that many of these conditions also resulted in dangerously low COF values. The study suggests that hydrodynamic lubrication is only relevant when high viscous fluids are combined with little or no tread and that other lubrication mechanisms besides hydrodynamic effects are relevant to slipping like boundary lubrication.

INTRODUCTION

Slip related fatal injuries are the second most fatal work related injury and 14 % of total fatal occupational injuries were due to falling events in 2009 [1-3]. Slipperiness is a major factor contributing between 40 % and 50 % to fall injuries [4]. A floor surface often becomes slippery when a fluid contaminant lubricates the shoe-floor interface. Boundary, mixed or elastohydrodynamic lubrication have all been suggested to be relevant to slipping but the exact mechanism(s) have not been verified experimentally [5].

Friction plays an important role in slipperiness and probability of a slip decreases when the difference between available and required coefficient of friction decreases [6]. Therefore available friction typically must be above the required value of friction for normal walking to avoid a slip [7]. The variation of coefficient of friction in different lubrication regimes as speed increases is explained by the Stribeck [8] curve. In boundary lubrication regime, the fluid contaminant thickness and hydrodynamic pressure is minimal but increases as the lubrication transitions to mixed and elastohydrodynamic lubrication [9]. During the transition from boundary to mixed and elastohydrodynamic lubrication, the asperity contact also decreases , causing a decrease in coefficient of friction [9].

The purpose of the study is to measure the effects of shoe tread design, tread depth, viscosity of contaminant on underfoot hydrodynamic pressure and the load supported by the fluid (i.e. load carrying capacity). Furthermore, the effect of hydrodynamic pressure development on the available coefficient of friction will be analyzed. by a custom-developed robotic slip simulator tribometer (SST).

METHODS

Apparatus

A custom developed robotic slip simulator tribometer (SST) was developed to reproduce the approximate loading and sliding velocity of human slipping. The apparatus composed of three vertical motors and one horizontal motor and was programmed to produce the vertical loading force of around 500N (70 % of the 70 Kg human). To produce the relevant biomechanical slip, the horizontal motor was programmed to reach a peak sliding speed of up to 0.8 ms^{-1} [10, 11]. A dummy foot and a shoe were attached to the three vertical motors with an angle to the floor of 10°, which is similar to shoe-floor angles during slipping [11, 12]. For measuring the hydrodynamic effects in the fluid contaminant, a pressure transducer was embedded in the floor tile. A forceplate was used for measuring the shear and normal loading force during the simulated slip. The assembly is shown in Fig. 1 with a pressure transducer diagram.

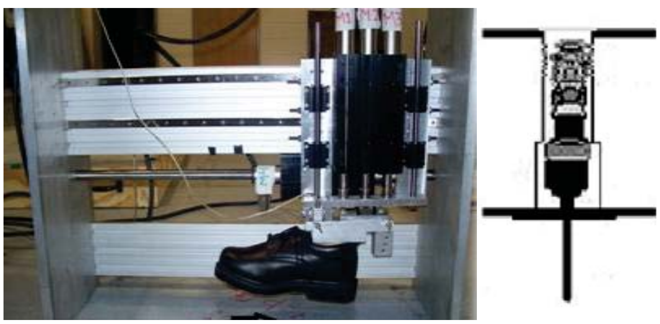

Figure.1. A custom developed robotic slip simulator tribometer (a) and the pressure transducer embedded in floor (b)

Experimental protocol and testing conditions

To measure the hydrodynamic contaminant pressure, the contaminant was uniformly spread over the floor and inlet of the pressure transducer was also filled with the same fluid. Simulated slips were performed at seven different location relative to the pressure transducer. The time series data of a single scan over the pressure transducer yielded hydrodynamic pressure data in the anterior/posterior direction along the shoe while the different scans provided pressure readings across the medial/lateral direction. The floor and pressure sensor were cleaned between different footwear or contaminant conditions. The shear and normal force was measured by repeating the testing conditions over the force plate for different shoe and contaminant type.

Two different shoe types: sportswear shoe and work shoe were tested at three tread depth levels: no tread (0 mm deep), half tread (1.4 mm deep) and full tread (2.4 mm deep). Two fluid contaminants were used: 1) 90% glycerol and 10% water (219 cP) and 2) 1.5% Detergent-98.5% (1.8cP). Before the data collection, the shoe sole interface was abraded with silicon paper. Shoe roughness and harness of all the shoe was examined using a 2D profilometer and durometer, respectively.

Analysis

Load carrying capacity (i.e. load supported by the contaminant) was calculated by integrating the contaminant pressure (p) over the surface area (A) of the shoe sole interface shown in Eq.1. Increase in load supported by the contaminant indicates that the fluid is supporting more of the load and that the interaction between shoe tread and the floor is decreased. The peak pressure was measured over the shoe to see the high pressure zone in shoe during slipping.

$$Fluid\_Force = \int pdA \qquad (1)$$

The ratio of shear and normal loading force was calculated over 250 msec window to find the available coefficient of friction in shoe-floor-contaminant.

RESULTS AND DISCUSSION

The hydrodynamic contaminant pressure and load supported by the contaminant was high when no tread shoes were combined with the glycerol contaminant (Table 1). The maximum contaminant pressure in the no-tread work shoe and sportswear shoe was 234 kPa and 87.63 kPa respectively, and was centrally located underneath the shoe heel. The result supports the literature that combination of less tread shoe and hydrodynamic pressure development is considered as an important condition for reduction in coefficient of friction [12, 13]. The total load supported by the contaminant in the no-tread work shoe was 200.5 N, which is roughly 40% of the total vertical loading, while the no tread sportswear shoe supported 113.3 N, roughly 20 % of total vertical loading. The testing conditions where half or full tread was present or when the low viscosity fluid was used resulted in negligible hydrodynamic pressure. The maximum hydrodynamic pressure for the no tread, half and full tread shoes in detergent contaminant was less than 5 kPa and the load supported by the contaminant was less than 4 N. Since the contaminant pressure is related to film thickness [14], the film thickness can be assumed to minimal for all conditions where fluid pressure was negligible.

The lowest COF value was observed in the no-tread work shoe/high viscosity fluid condition, which was the condition resulting in the highest hydrodynamic pressures. The second lowest COF value (sportswear shoe with no tread/high viscosity fluid) was observed for the second highest hydrodynamic pressures (Table 1). This result is likely due to the development of hydrodynamic contaminant pressure causing the asperity interaction between the shoe and floor to decrease. When hydrodynamic pressures were found to be negligible, COF values were found to be higher than when the hydrodynamic pressures were low. Specifically, detergent conditions had higher COF values than glycerol conditions. A significant amount of COF variation occurred across the different tread styles and tread depth levels despite even for the conditions where hydrodynamic pressure remained negligible. This phenomenon may be due to changes in adhesion and hysteresis within the boundary lubrication regimes.

CONCLUSIONS

The study showed that a high viscous contaminant combined with no tread shoe results in development of significant fluid pressures that contribute to reduction in friction coefficient. This study demonstrated that mixed-lubrication or elastohydrodynamic lubrication is relevant only for high viscous fluids. A small amount of shoe tread depth was found to be capable of relieving hydrodynamic effects. The experimental data also demonstrated that in the absence of fluid pressures, the coefficient of friction can vary greatly and result in slippery surfaces (COF values less than 0.2 are considered slippery). This suggests that other lubrication mechanisms (likely boundary lubrication) have a major effect on coefficient of friction and are relevant to slipping accidents.

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Table 1 Peak hydrodynamic pressures, load carrying capacity and coefficient of friction for each of the shoe conditions.

	Sportswear Shoe			**Work Shoe**		
	Full Tread	**Half Tread**	**No Tread**	**Full Tread**	**Half Tread**	**No Tread**
Tread depth	3.7 mm	1.8 mm	0.0 mm	2.8 mm	1.4 mm	0.0 mm
Peak hydrodynamic pressure	< 5 kPa	< 5 kPa	87.63 kPa	< 5 kPa	< 5 kPa	237 kPa
Load carrying capacity for Glycerol condition	3 N	3.8 N	113.3N	3.7 N	3.5 N	200.5N
Load carrying capacity for Detergent condition	2.8 N	2.9 N	3 N	2.4 N	3.1 N	3.1 N
COF in Glycerol condition	0.062	0.058	0.024	0.08	0.09	0.005
COF in detergent condition	0.14	0.22	0.29	0.26	0.38	0.29