Applied Ergonomics 70 (2018) 118–126

Contents lists available at ScienceDirect

Applied Ergonomics

journal homepage: www.elsevier.com/locate/apergo

# Coefficient of friction testing parameters influence the prediction of human slips

Arian Iraqi, Rakié Cham, Mark S. Redfern, Kurt E. Beschorner*

Department of Bioengineering, University of Pittsburgh, Benedum Engineering Hall #302, 3700 O'Hara St., Pittsburgh, PA 15261, United States

ARTICLE INFO

*Keywords:*
Slip and fall accidents
Coefficient of friction
Footwear

ABSTRACT

Measuring the available coefficient of friction (ACOF) of a shoe-floor interface is influenced by the choice of normal force, shoe-floor angle and sliding speed. The purpose of this study was to quantify the quality of slip prediction models based on ACOF values measured across different testing conditions. A dynamic ACOF measurement device that tests entire footwear specimens (Portable Slip Simulator) was used. The ACOF was measured for nine different footwear-contaminant combinations with two levels of normal force, sliding speed and shoe-floor angle. These footwear-contaminant combinations were also used in human gait studies to quantify the required coefficient of friction (RCOF) and slip outcomes. The results showed that test conditions significantly influenced ACOF. The condition that best predicted slip risk during the gait studies was 250 N normal force, 17° shoe-floor angle, 0.5 m/s sliding speed. These findings can inform footwear slip-resistance measurement methods to improve design and prevent slips.

## 1. Introduction

Falls on the same level due to slippery conditions are among the leading causes of fatal and non-fatal occupational injuries. Slips, trips and falls accounted for 27% of non-fatal (U.S. Department of Labor-Bureau of Labor Statistics, 2016b) and 16.5% of fatal occupational accidents in 2015 (U.S. Department of Labor- Bureau of Labor Statistics, 2016a). According to the 2017 Liberty Mutual Safety Index, falls on the same level were ranked second among the leading causes of disabling U.S. workplace injuries, cost businesses $10.62 billion in direct costs, and accounted for 17.7% of the overall national burden in 2014 (Liberty Mutual Research Institute for Safety, 2017). Slipperiness and slipping are among the primary factors responsible for falling events (Courtney et al., 2001).

A slip is likely to initiate when the friction required (as measured by the RCOF) to sustain gait is greater than the available friction at the contact between the footwear and floor (ACOF) (Burnfield and Powers, 2006; Hanson et al., 1999). ACOF is typically measured using a number of portable mechanical devices such as a drag slip-meter (Powers et al., 2007; Yamaguchi et al., 2015) and variable incidence tribometer (Burnfield and Powers, 2006; Powers et al., 2007); as well as whole-shoe tribometers like the Portable Slip Simulator (Aschan et al., 2005) and the SATRA STM 603 (Blanchette and Powers, 2015). RCOF is measured on dry surfaces by using a force plate during human gait (Beschorner et al., 2016; Cham and Redfern, 2002a; Chang et al., 2011; Hanson et al., 1999; Yamaguchi and Masani, 2016). Thus, a reduction in slipping events can typically be achieved by increasing the ACOF between a shoe and floor surface or reducing an individual's RCOF.

Human risk of slips and falls have been evaluated by comparing measured ACOF with human slips. A logistic regression approach developed by Hanson et al. (Hanson et al., 1999) has been broadly used in shoe-floor friction research to assess the empirical relationship between slip outcome and slip-testing measurements (Blanchette and Powers, 2015; Burnfield and Powers, 2006; Siegmund et al., 2006; Tsai and Powers, 2008). According to the logistic regression model, the difference between the ACOF and RCOF predicts the probability of slipping (Burnfield and Powers, 2006; Hanson et al., 1999; Siegmund et al., 2006). Moreover, Burnfield and Powers (Burnfield and Powers, 2006) and Seigmund et al. (Siegmund et al., 2006) developed a logistic regression with ACOF as the only predictor of slip risk. Another approach has been used to rank surfaces of slipperiness by determining differences in unexpected slip rates across surfaces using a $\chi^2$ test (Powers et al., 2007). Rank-based approaches have been used to test if a slip-testing device can correctly rank and differentiate the level of slipperiness across these categories (Powers et al., 2007). One advantage of the logistic regression approach is its ability to quantify the goodness of fit using receiver operating characteristic curves (Beschorner et al., 2016) whereas rank based methods tend to have binary outcomes (i.e., pass/fail) (Powers et al., 2007).

Mechanical friction-testing devices generally fall into two groups:

* Corresponding author. 302 Benedum Hall, 3700 O'Hara Street, Pittsburgh, PA 15261, United States.
*E-mail addresses:* ari16@pitt.edu (A. Iraqi), rcham@pitt.edu (R. Cham), mredfern@pitt.edu (M.S. Redfern), beschorn@pitt.edu (K.E. Beschorner).

https://doi.org/10.1016/j.apergo.2018.02.017
Received 25 July 2017; Received in revised form 8 January 2018; Accepted 17 February 2018

**Table 1**
Normal forces, shoe-floor angles and sliding speeds reported by biomechanical studies during slip initiation. (§ at forward slipping during slip recovery; * at forward slipping for slip leading to a fall). NA indicates that this variable was not reported for this study.

| Study | Normal force (%BW) | Shoe-floor angle (°) | Sliding speed (m/s) |
|---|---|---|---|
| (Strandberg and Lanshammar, 1981) | 64 ± 16 | 5.5 ± 5.9 | 0.08–0.32 |
| (Cham and Redfern, 2002b) | NA | 1.5 ± 0.6§, 2.2 ± 1.8* | NA |
| (Albert et al., 2017) | NA | 14.7 | 0.27 |
| (Iraqi and Beschorner, 2017) | 24.5 ± 13.4 | NA | NA |

(1) portable devices that use a sample of footwear outsole as the specimen and exert low normal forces relative to human body mass (Burnfield and Powers, 2006; Chang et al., 2001a; DiDomenico et al., 2007), and (2) whole-shoe testers that use an entire footwear as the specimen and exert a wide range of normal forces, shoe-floor angles and sliding speeds (Aschan et al., 2005; Blanchette and Powers, 2015; Chang et al., 2001a; Redfern and Bidanda, 1994). Whole-shoe testers are often selected over portable devices when assessing footwear due to their ability to test an entire footwear outsole design and their ability to exert normal forces, shoe-floor angles and sliding speeds that approximate gait.

Measuring ACOF is dependent upon the normal force, shoe-floor angle, and the horizontal sliding speed. There is general agreement that the conditions of the test should be 'biofidelic' (i.e. match the biomechanical conditions that are found during walking) (Redfern et al., 2001). Biomechanical studies have reported values of these key parameters during the initiation of a slip (Table 1). Normal force (normalized to body weight) has been reported to be 24.5 ± 13.4% (Iraqi and Beschorner, 2017) and 64 ± 16% (Strandberg and Lanshammar, 1981) at the onset of slipping. Shoe-floor angle has been reported at heel contact as 28.2 ± 3.0° (Chambers et al., 2002) and 25.3 ± 5.4° (McGorry et al., 2010), and at slip initiation as 14.7° (Albert et al., 2017), 5.5 ± 5.9° (Strandberg and Lanshammar, 1981), 1.5 ± 0.6° in the case of a slip recovery and 2.2 ± 1.8° for a slip leading to a fall (Cham and Redfern, 2002b). The horizontal sliding speed of the shoe is reported as 0.08–0.32 m/s (Strandberg and Lanshammar, 1981) and 0.27 m/s (Albert et al., 2017). However, few studies have compared different test parameters for their ability to predict slips based on ACOF using whole-shoe testers. This gap is evident in the literature, where a wide range of normal forces (40–810 N), shoe-floor angles (0–20°) and sliding speeds (0.01–0.5 m/s) are used for measuring ACOF (Aschan et al., 2005, ASTM F2913-11-11, 2011; Beschorner et al., 2007; Blanchette and Powers, 2015; Gronqvist et al., 2003; Grönqvist et al., 1989; Hanson et al., 1999; Menz et al., 2001; Redfern and Bidanda, 1994; Wilson, 1990). Since ACOF has a complex dependency on these testing parameters (Beschorner et al., 2007; Blanchette and Powers, 2015), finding the best set of conditions is important. Some research has used whole-shoe testers that are operated under different combinations of normal force, horizontal speed and shoe-floor angle, to predict slip outcome (Blanchette and Powers, 2015). However, the Blanchette and Powers' study was limited to a single footwear-floor-contaminant condition (2015). Thus, more robust research is needed for identifying the levels of normal force, shoe-floor angle and horizontal sliding speed that best predicts human slip risk across different footwear-floor-contaminant conditions.

Previous efforts to validate slip-testing devices based on human slipping studies have primarily focused on differentiating slip risk across floors (Powers et al., 2007; Siegmund et al., 2006), and are commonly limited to one type (Blanchette and Powers, 2015; Burnfield and Powers, 2006; Powers et al., 2007; Siegmund et al., 2006) or two types (Tsai and Powers, 2008) of footwear. Gronqvist et al. tested six pairs of boots and shoes (Gronqvist et al., 2003); however, they repeatedly slipped a small set of subjects (N = 5). Multiple repeated slips within subjects may be inappropriate since subjects alter their gait when they anticipate a slipping incident (Cham and Redfern, 2002a). Studies that have included more than one design of footwear outsoles have shown differences in the ACOF across footwear indicating differences in slip rate would also be expected (Gronqvist et al., 2003; Jones et al., 2018; Tsai and Powers, 2008). Few efforts have been made to validate the ability of slip-testers to differentiate across footwear using human slipping data.

The primary purpose of this study was to investigate the impact of testing conditions on ACOF and quantify the prediction quality of ACOF values for predicting human slips across these testing conditions. We hypothesized that the biomechanical parameters will impact ACOF values and that ACOF as well as ACOF-RCOF values using different testing parameters would predict human slips. The study used an experimental design, where the footwear conditions and testing parameters were controlled, and was cross-sectional, where the human gait and slipping data were used from a single testing session. The goal is to quantify the validity of slip-resistance measurements and guide further development of methods that accurately evaluate footwear traction.

## 2. Materials and methods

This study consisted of two components: ACOF measurements and gait experiments. ACOF measurements were conducted for nine footwear-floor-contaminant conditions using a whole-shoe tester. In the gait experiment, between eight and nineteen subjects walked across dry and liquid-contaminated flooring per footwear-floor-contaminant condition.

### 2.1. Subjects

Biomechanical data from four previously published human gait and slipping studies were pooled (Beschorner et al., 2016; Chambers and Cham, 2007; Jones et al., 2018; Moyer et al., 2006). This data was for shoes S1, S3-S5, B1-B3, which are furthered described in Section 2.2 and Table 2. Data for additional footwear-contaminant conditions (S2T and S2NT, which are described in Section 2.2 and Table 2) were added to the study to improve statistical power and generalizability. The inclusion criteria were that the study involved young adults (18–35 years); an experimental protocol where the exposure to a liquid-contaminant occurred on a force plate; and there had to be at least three gait trials on a dry force plate prior to liquid-contaminant exposure where their left foot completely landed on the force plate (not on the

**Table 2**
Footwear-floor-contaminant conditions included in this study.

| Footwear | Shore A Hardness | Liquid contaminant | Floor |
|---|---|---|---|
| S1 | 61.0 (2.1) | 75% glycerol-25% water | Vinyl |
| S2T | 62.4 (3.2) | 90% glycerol-10% water | Vinyl |
| S2NT | 71.0 (1.9) | 90% glycerol-10% water | Vinyl |
| S3 | 56.2 (2.9) | Canola oil | Vinyl |
| S4 | 60.6 (3.0) | Canola oil | Vinyl |
| S5 | 48.6 (1.5) | Canola oil | Vinyl |
| B1 | 54.0 (5.8) | 50% glycerol-50% water | Vinyl |
| B2 | 70.4 (4.5) | 50% glycerol-50% water | Vinyl |
| B3 | 79.2 (4.8) | 50% glycerol-50% water | Vinyl |