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Kinematics and kinetics of the shoe during human slips

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ABSTRACT

This paper quantified the heel kinematics and kinetics during human slips with the goal of guiding available coefficient of friction (ACOF) testing methods for footwear and flooring. These values were then compared to the testing parameters recommended for measuring shoe-floor ACOF. Kinematic and kinetic data of thirty-nine subjects who experienced a slip incident were pooled from four similar human slipping studies for this secondary analysis. Vertical ground reaction force (VGRF), center of pressure (COP), shoe-floor angle, side-slip angle, sliding speed and contact time were quantified at slip start (SS) and at the time of peak sliding speed (PSS). Statistical comparisons were used to test if any discrepancies exist between the state of slipping foot and current ACOF testing parameters. The main findings were that the VGRF (26.7 %BW, 179.4 N), shoe-floor angle (22.1°) and contact time (0.02 s) at SS were significantly different from the recommended ACOF testing parameters. Instead, the testing parameters are mostly consistent with the state of the shoe at PSS. We argue that changing the footwear testing parameters to conditions at SS is more appropriate for relating ACOF to conditions of actual slips, including lower vertical forces, larger shoe-floor angles and shorter contact duration.

1. Introduction

Slips and falls are among the leading causes of occupational injuries. Slips, trips and falls (STF) lead to over 9 million treated cases in hospital emergency departments (Centers for Disease Control and Prevention, 2017) and more than one-fourth of the non-fatal occupational injuries in 2015 (U.S. Department of Labor- Bureau of Labor Statistics, 2016). A survey among young adults indicated that about half of the falling accidents are caused by slips (Heijnen and Rietdyk, 2016). STF prevention programs often recommend use of slip-resistant footwear to reduce slip risk (Bell et al., 2008).

Mechanical slip-testing devices that measure available coefficient of friction (ACOF) are frequently utilized to assess the slip-resistant performance of footwear and flooring. These devices sometimes attempt to simulate the dynamics of the foot slip in order to achieve "biofidelity" (i.e., similarity between test conditions and shoe dynamics during slipping) since the kinematics and kinetics applied to footwear affect ACOF measurements (Chang et al., 2016). For instance, ACOF measurements are affected by shoe-floor angle (Beschorner et al., 2007; Blanchette and Powers, 2015b), vertical force (Beschorner et al., 2007; Blanchette and Powers, 2015b), horizontal sliding speed (Beschorner et al., 2007; Blanchette and Powers, 2015b; Redfern and Bidanda, 1994) and contact duration (Gronqvist et al., 2003). Prior research has suggested that using test conditions that are more biofidelic improves the ability of ACOF measurements to predict slips (Iraqi et al., 2018). Furthermore, other biomechanical parameters that have not been formally incorporated in ACOF testing may need to be considered to improve biofidelity. For example, the side-slip angle (i.e., direction of heel velocity relative to the footwear orientation in the transverse plane) (Albert et al., 2017) has generally been limited to sliding the footwear specimen along the axis of the shoe (toe-to-heel) during ACOF measurements. This testing parameter may be important since the orientation of tread design affects ACOF (Blanchette and Powers, 2015a; Li and Chen, 2005; Yamaguchi et al., 2017). Another parameter that has not been considered is the location of the center of pressure (COP) for ground reaction forces, which may affect the portion of the tread in contact during ACOF testing. Thus, additional studies that report biomechanics of slipping would contribute knowledge towards developing ACOF measurement methods with improved biofidelity.

Biomechanical studies have reported certain kinematic and kinetic variables during slipping. These variables have been parameterized at times including heel strike (HS) (Chambers et al., 2002;

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Table 1
Vertical force, shoe-floor angle, sliding speed, contact time, and side-slip angle reported by biomechanical studies at HS, SS and PSS. Values are reported as mean ± standard deviations.

Study	Time points	Vertical force (%BW)	Shoe-floor angle (°)	Sliding speed (m/s)	Contact time from HS (ms)	Side-slip angle (+Medial)	Floor with liquid contaminant
Strandberg and Lanshammar (1981)	HS	NA	21.3 ± 5.5	0.67 ± 0.76[a]	NA	NA	NA-soap
	SS	64 ± 16	5.5 ± 5.9	0.15 ± 0.12[a]	48 ± 21	NA	
Cham and Redfern (2002b)	HS	NA	16.8 ± 1.5[b], 20.5 ± 0.9[c]	1.01 ± 0.20[b], 0.62 ± 0.41[c]	NA	NA	Vinyl with motor oil (10 W-40)
	SS	NA	1.5 ± 0.6[b], 2.2 ± 1.8[c]	NA	78.9 ± 9.5[b] 65.7 ± 3.5[c]	NA	
	PSS	NA	NA	0.31 ± 0.06[b], 0.78 ± 0.16[c]	121.4 ± 12.4[b], 171.4 ± 28.7[c]	NA	
Chambers et al. (2002)	HS	NA	28.2 ± 3.0	NA	NA	NA	Vinyl with glycerol
	PSS	NA	NA	1.79 ± 0.37	NA	NA	
McGorry et al. (2010)	HS	NA	25.3 ± 5.4	1.10 ± 0.74	NA	NA	Delrin dry, Teflon dry, Teflon with aerosol furniture polish
Albert et al. (2017)	SS	NA	14.7 ± 6.9	0.27 ± 0.18	NA	66° ± 54.1	Vinyl with 90% glycerol-10% water solution
	PSS	NA	9.5 ± 7.0	1.72 ± 0.71	NA	3.2 ± 15.9	

NA indicates that this variable was not reported for this study.
[a] The average sliding speed have been calculated based on the individual results reported from each subject in the study.
[b] At forward slipping during slip recovery.
[c] At forward slipping for slip leading to a fall.

McGorry et al., 2010), slip start (SS) (Albert et al., 2017; Strandberg and Lanshammar, 1981), and peak sliding speed (PSS) (Albert et al., 2017; Lockhart et al., 2003; Moyer et al., 2006; Strandberg and Lanshammar, 1981). These times represent the initial condition of the step, beginning of slip, and most severe portion of the slip, respectively. Table 1 summarizes key biomechanical variables at the times of HS, SS, and PSS reported in previous studies. The reported values are variable within each time and across times. These biomechanical studies serve as an important resource regarding the slipping biomechanics, which can be used to guide ACOF measurement techniques.

Gaps in the literature exist regarding the biomechanical state of the foot during slipping. One limitation is that some studies only considered one type of footwear (Albert et al., 2017; Cham and Redfern, 2002b), which might not be generalizable. Other studies have been limited to few participants repeatedly exposed to slippery conditions (Strandberg and Lanshammar, 1981). Data from repeated slips may not represent the dynamics during unexpected human slips since participants alter their gait when anticipating a slippery condition (Cham and Redfern, 2002a). The limitations in the previous biomechanical studies impede the development of test methods that are biofidelic. Thus, additional research on this topic is needed.

The aim of the current study was to quantify biomechanical variables during unexpected human slips to guide biofidelic measurements of ACOF. Additionally, this study will determine if these variables deviate from the ACOF testing parameters recommended by a footwear traction testing standard (ASTM F2913-11, 2011) (Table 2) for variables specified in this testing standard.

Table 2
ACOF testing parameters recommended by footwear traction testing standards (ASTM F2913-11, 2011; EN ISO 13287, 2012).

ACOF testing parameters	Levels
Vertical force (N)	400, 500
Shoe-floor angle (°)	7
Side-slip angle (°)	0
Sliding speed (m/s)	0.3
Contact time (s)[a]	0.10–0.30
Contact time (s)[b]	0.30–0.60
Contaminants[a,c]	Water, detergent aqueous solution, oil
Contaminants[b]	Glycerol aqueous solution, detergent aqueous solution, ethanol aqueous solution

[a] ASTM F2913-11.
[b] EN ISO 13287.
[c] The ACOF testing methods specified by ASTM F2913 are reportedly applicable to a wide variety of surface contaminants including but not limited to liquid water, ice, grease and oil.

2. Methods

2.1. Subjects

Kinetic and kinematic data for 39 subjects (18 female; mean age: 22.3 ± 3.3 years; mean height: 173.1 ± 8.3 cm; mean body mass: 68.3 ± 10.0 kg; mean BMI: 22.8 ± 3.2) were extracted from four different human slipping studies performed in the same laboratory (Beschorner et al., 2016; Chambers and Cham, 2007; Iraqi et al., 2018; Jones et al., 2018; Moyer et al., 2006). The exclusion criteria for subject recruitment were any conditions that potentially impede regular gait such as orthopaedic, cardiovascular, neurological and pulmonary abnormalities. The human slipping protocols were authorized by the University of Pittsburgh Institutional Review Board and subjects were provided with informed consent. The inclusion criteria into this post-hoc analysis were: 1. young adults (18–35 years), 2. slips that were preceded by at least three gait trials where their left foot landed clearly on the dry force plate preceding the exposure to liquid-contaminant, and 3. a slip distance of greater than 3 cm (Albert et al., 2017; Beschorner et al., 2016; Leamon and Li, 1990). In addition, subjects or liquid-contaminated trials were further excluded during data processing based on the following criteria: 4. subjects' left foot did not land completely on the liquid-contaminated force plate, 5. if the subject experienced a heel slip in the first liquid-contaminated exposure, then their second exposure was discarded, 6. if the subject's required coefficient of friction (RCOF) changed more than 16% after exposure to the first liquid-contaminated trial, their second exposure was discarded, and 7. the subject reported that they noticed the liquid contaminant before stepping on it (Iraqi and Beschorner, 2017; Iraqi et al., 2018; Jones et al., 2018). The rationale for criteria 5–7 were that these subjects might be anticipating a slip and could have different gait patterns. These criteria were established *a priori* (i.e., prior to performing statistical analyses).