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Relationship among several measurements of slipperiness obtained in a laboratory environment

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ABSTRACT

Multiple sensing mechanisms could be used in forming responses to avoid slips, but previous studies, correlating only two parameters, revealed a limited picture of this complex system. In this study, the participants walked as fast as possible without a slip under 15 conditions of different degrees of slipperiness. The relationships among various response parameters, including perceived slipperiness rating, utilized coefficient of friction (UCOF), slipmeter measurement and kinematic parameters, were evaluated. The results showed that the UCOF, perceived rating and heel angle had higher adjusted R^2 values as dependent variables in the multiple linear regressions with the remaining variables in the final pool as independent variables. Although each variable in the final data pool could reflect some measurement of slipperiness, these three variables are more inclusive than others in representing the other variables and were bigger predictors of other variables, so they could be better candidates for measurements of slipperiness.

1. Introduction

Data from the Liberty Mutual Workplace Safety Index (Liberty Mutual Research Institute for Safety, 2017) showed that the direct costs for disabling workplace injuries in 2014 due to falls on same level in the United States were estimated to be approximately 10.62 billion U.S. dollars or 17.7% of the total cost burden. In addition, slip or trip without fall accounted for 2.30 billion U.S. dollars or 3.8%. Earlier data reported in 2012 (Liberty Mutual Research Institute for Safety, 2012) show that the cost of falls on the same level increased by 42.3% between 1998 and 2010 after adjusting for inflation, while the overall costs of disabling workplace injuries decreased 4.7% over the same period. Falls on the same level continue to be a serious problem in occupational injuries.

Slippery floors, typically caused by contaminants, are a critical factor for falls on the same level (Chang et al., 2001b, 2016). Bell et al. (2008) indicated that liquid contamination was the most common cause (24%) of slip, trip and fall incidents in healthcare workers. Measurements of slipperiness can be used to identify potential areas that could cause slip or fall injuries or to evaluate potential interventions, so they play a crucial role in the prevention of falls on the same level.

Various approaches have been used to assess slipperiness. Chang et al. (2003) outlined biomechanics, human-centered approaches, available coefficient of friction (ACOF) and surface roughness as major elements in the measurement of slipperiness. The ACOF measured with a slipmeter represents the maximum coefficient of friction (COF) that can be supported without a slip at the shoe and floor interface and is the most common measure of slipperiness (Chang et al., 2001b). Levels of ACOF are typically used to assess the potential risk of slip and fall incidents, since slip and fall incidents are generally assumed more likely to occur on floors with a low ACOF. Perceptions can also be considered measurements of slipperiness. Perceptions, based on both visual cues and proprioceptive feedback, can be used retrospectively or prospectively to assess slipperiness and can supplement objective measurements of slipperiness.

In validating a particular measure of slipperiness, different measurements are usually compared. Quite often, a correlation between the perception and objective measures of slipperiness has been reported. The results published in the literature have shown that subjective ratings based on psychophysics have a statistically significant correlation with the measured ACOF (Swensen et al., 1992; Grönqvist et al., 1993; Myung et al., 1993; Cohen and Cohen, 1994; Li et al., 2004; Chang et al., 2004, 2006, 2008) and slip distance (Grönqvist et al., 1993). However, Cohen and Cohen (1994) reported a significant number of disagreements between the ACOF values of the tiles and subjective responses.

There are generally two approaches for quantifying biomechanical responses to slippery areas. One approach, summarized by Redfern

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et al. (2001), is to measure human responses to unexpected slippery conditions. Typical output measures are heel contact angle, and heel velocity and acceleration in horizontal and vertical directions at the instant of heel contact. The second approach is to investigate human adaptation to slippery surfaces by the altering of gait to avoid a slip. The utilized coefficient of friction (UCOF) represents the friction needed to walk on a surface that could be contaminated and is the maximum COF calculated from the ground reaction force (GRF) obtained with a force plate when walking on surfaces that could be slippery. Increases in stance times (Fong et al., 2005), stride times (Fong et al., 2005) and step width (Menant et al., 2009), as well as decreases in stride length (Swensen et al., 1992; Bunterngchit et al., 2000; Fong et al., 2005; Lockhart et al., 2007; Menant et al., 2009; Cappellini et al., 2010), walking speed (Fong et al., 2005; Menant et al., 2009; Cappellini et al., 2010), heel horizontal velocity (Fong et al., 2005; Lockhart et al., 2007), heel horizontal and vertical accelerations (Fong et al., 2005), heel and floor angle (Menant et al., 2009) and UCOF (Bunterngchit et al., 2000; Lockhart et al., 2007; Cappellini et al., 2010) are all used to avoid a slip on slippery surfaces.

The responses to proprioception, measured by human body movements and the contact force between the shoe sole and floor, represent strategies in response to the conditions experienced at the shoe and floor interface underneath. Besides biomechanical responses, additional parameters involved could include the perceived slipperiness rating and ACOF values of the walkways as pointed out earlier. Even within biomechanical responses, different parameters might represent different strategies simultaneously in use. Prior to stepping onto the surface, perception of slipperiness dominates kinematics. Continuous adjustments are needed in order to assure that the strategies employed can actually prevent a slip (Cappellini et al., 2010), so all variables could be interrelated and the relationships among them change as walking continues until a steady state is reached. Relationships among various response parameters might provide more insight into the issue of measuring slipperiness. The results reported by Kim et al. (2005) showed that the required COF could be predicted by walking velocity, transitional acceleration of the center of mass (COM) and step length for younger adults with R^2 of 0.58 and by heel contact velocity and transitional acceleration of COM for older adults with R^2 of 0.52. The required COF represents the maximum friction needed to support different types of human activities on dry surfaces. Burnfield and Powers (2007) reported that the angle between COM to the center of pressure and walking velocity predicted 62% of the variance in the required COF. Yamaguchi et al. (2013) reported that the angle between COM to the center of pressure predicted the required COF for heel contact with R^2 of 0.77. Lesch et al. (2008) attempted to use perceived slipperiness rating to predict the measured ACOF and moderate results were obtained. The level of friction and friction reduction were used in predicting the perceived slipperiness rating by Chang et al. (2008). In these studies, up to three variables were used as independent variables in predicting the outcomes. A more complex relationship could exist; additional variables could be used to broaden the domain. One frequently asked question is: which of the various parameters is a better measurement of slipperiness. Investigations of the relationship between a particular response and collective input from other responses could shed some light on the issue of the measurement of slipperiness.

Gait adjustments to avoid a slip have been reported, as summarized above. However, participants in these studies were exposed to a limited area with a low ACOF or to a very limited range of low friction conditions. The low friction area with the application of contaminants was limited to the force plate areas in the results reported by Fong et al. (2005) and Lockhart et al. (2007). Lockhart et al. (2007) exposed their participants to the low friction area only once, with prior knowledge, to quantify gait adaptation rather than motor learning. In real life, people often have to take several steps in order to negotiate walking across a large slippery surface. Asaka et al. (2004) and Cappellini et al. (2010) used entire walkways with a low ACOF, but they exposed the participants to only one low friction condition and the focus was solely on biomechanical responses. Swensen et al. (1992) focused on walking on narrow steel beams, not a normal gait. By exposing the participants to walkways with different degrees of slipperiness, the objective of the current study was to explore relationships among responses based on biomechanics, perception and friction measurements using multiple linear regression analyses. This approach, involving several disciplines, could lead to a better understanding of human responses to slippery conditions.

Table 1
Floor types used in the current experiment.

Floor type	Description
A	Metropolitan Ceramics quarry metrotread in Mayflower Red – 7731T
B	Metropolitan Ceramics quarry basics clear tones in Mayflower Red – 77310
C	Vinyl laminate with wood finish (Armstrong Rhythms in Olde Hickory – 92190)
D	Marble tile (Storm Cloud Grey)
E	Glazed porcelain tile with silver finish (Iris Ceramica Series: Metal 18 x 18 Color/Item: Titanium SKU No.: 745452)

2. Methods

In order to create a wide range of slipperiness, five different floor types and three different surface conditions were selected. These five floor types were chosen from among 37 common floor types, used in a previous study, due to their distinctive features that represented different combinations of friction levels and perceptual cues to slipperiness (Lesch et al., 2008). This study was a part of a larger experiment to investigate the issues of measurement of slipperiness and perceived slipperiness rating (Chang et al., 2015, 2017).

2.1. Floor tile selections

The five floor types used in the current experiment, referred to as floor types A to E, were: (A) a standard quarry tile with raised-profiled tread lines perpendicular to the walking direction, (B) standard flat quarry tile, (C) vinyl composition sheet, (D) marble tile and (E) glazed porcelain tile. Detailed information about these floor types is in Table 1.

2.2. Walkway construction

A multiple floor moveable walkway system was constructed, as shown in Fig. 1, consisting of two sections of five different moveable walkways, a stationary force plate area in the middle and a stationary straight extension at both ends. The extensions were connected and aligned with the moveable walkways and were covered with floor type B, the standard flat quarry tiles. In both moveable sections, each of the five walkways was covered with one of the floor types selected. Two force plates (Model 9281C, Kistler Instrument Corporation, Amherst, New York, USA) were installed in the middle of the walkway, lengthwise, to measure the GRF. These two force plates were installed along the length of the walkway, one right after the other, on the right hand side in the direction of walking chosen for collection of the biomechanical data. Although there was no force plate in the left side of the walkway in the force plate area, additional force plate covers were made to cover this area. When a particular floor type was selected during data collection, both sections of the desired walkway were moved to align with the extensions at both ends and four force plate covers of the same floor type were used to cover the force plate area. These four force plate covers were secured to the walkway with four screws each. Each section of the moveable walkway was approximately 2.44 m long. Each of the four force plate covers was approximately