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Technical note

The stochastic distribution of available coefficient of friction for human locomotion of five different floor surfaces

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A R T I C L E I N F O

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A B S T R A C T

The maximum coefficient of friction that can be supported at the shoe and floor interface without a slip is usually called the available coefficient of friction (ACOF) for human locomotion. The probability of a slip could be estimated using a statistical model by comparing the ACOF with the required coefficient of friction (RCOF), assuming that both coefficients have stochastic distributions. An investigation of the stochastic distributions of the ACOF of five different floor surfaces under dry, water and glycerol conditions is presented in this paper. One hundred friction measurements were performed on each floor surface under each surface condition. The Kolmogorov–Smirnov goodness-of-fit test was used to determine if the distribution of the ACOF was a good fit with the normal, log-normal and Weibull distributions. The results indicated that the ACOF distributions had a slightly better match with the normal and log-normal distributions than with the Weibull in only three out of 15 cases with a statistical significance. The results are far more complex than what had heretofore been published and different scenarios could emerge. Since the ACOF is compared with the RCOF for the estimate of slip probability, the distribution of the ACOF in seven cases could be considered a constant for this purpose when the ACOF is much lower or higher than the RCOF. A few cases could be represented by a normal distribution for practical reasons based on their skewness and kurtosis values without a statistical significance. No representation could be found in three cases out of 15.

1. Introduction

The data from the Liberty Mutual Safety Index (Liberty Mutual Research Institute for Safety, 2012) showed that costs for disabling workplace injuries in 2010 due to falls on the same level in the US were estimated to be approximately 8.61 billion US dollars or 16.9% of the total cost burden. The same data also showed that while the overall costs of disabling workplace injuries decreased 4.7% between 1998 and 2010, after adjusting for inflation, the cost of falls on the same level increased by 42.3% over the same period. Therefore, falls on the same level are a serious problem in occupational injuries.

As summarized by Chang et al. (2001b), friction plays an important role in injuries triggered by underfoot slips that could result in falls. The maximum coefficient of friction (COF) that can be supported at the shoe and floor interface without a slip is usually called the available coefficient of friction (ACOF) for human locomotion (Chang, 2004). The minimum COF needed at the shoe and floor interface to support human locomotion is called the required coefficient of friction (RCOF). A slip may occur when the RCOF for an activity exceeds the ACOF at the shoe and floor interface (Redfern et al., 2001). Hanson et al. (1999) developed a logistic regression model to estimate the probability of a fall in which actual fall incidents in a laboratory environment were related to the differences between the means of the RCOF and ACOF. Burnfield and Powers (2006) adopted a similar approach to investigate the probability of falls using a different slipmeter from the one used by Hanson et al. to measure the ACOF. In these two studies, the probability of slip incidents was predicted based on the differences between the means of the RCOF and ACOF without considering the contributions from their variations and potential dependency on the materials and conditions used.

A statistical model was developed to compare the ACOF and RCOF in estimating the probability of a slip or fall incident (Chang, 2004). A stochastic distribution was assumed in this model for both the ACOF (p_a) and RCOF (p_r) as shown in Fig. 1. According to Chang (2004), the cumulative probability for the RCOF (μ_r) to exceed the ACOF (μ_a) is

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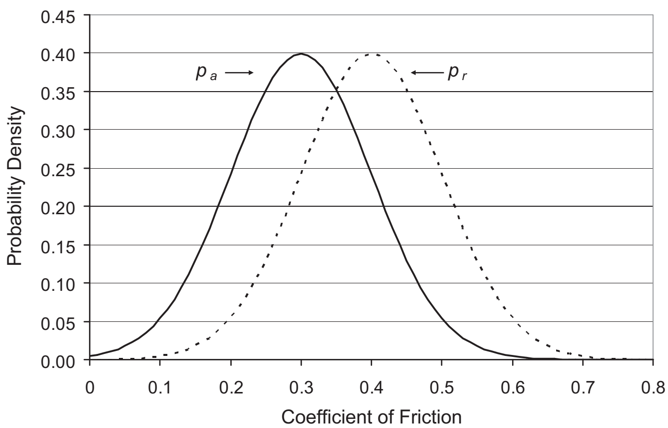

Fig. 1. Examples of the probability density function for the available (p_a) and required (p_r) friction coefficients (Chang, 2004).

$$P(\mu_a < \mu_r) = \int_{-\infty}^{+\infty} p_a(x) \int_{x}^{+\infty} p_r(y)\mathrm{d}y\mathrm{d}x$$

where p_r and p_a are the probability density functions for the RCOF and ACOF, respectively. In addition to differences in the mean values for the estimate of slip probability as used by Hanson et al. (1999) and Burnfield and Powers (2006), this statistical model demonstrated, as illustrated by Chang (2004), that the variations in the RCOF and ACOF could also contribute to the probability of a slip. Therefore, the estimate of the probability of a slip or fall incident may be improved by using stochastic distributions for the RCOF and ACOF with consideration of the difference between their means as well as their variations. A better understanding of the stochastic distribution of the RCOF and ACOF will help improve the inputs to the statistical model that could better predict slip probability. Chang et al. (2008, 2012b) recently reported an investigation on the stochastic distribution of the RCOF. Their results showed that the RCOF distribution for each individual under each walking condition had a slightly larger number of cases that had a good match with the normal distribution (85.5%) than the log-normal (84.5%) and Weibull (81.5%) distributions. Therefore, among three distributions evaluated, the normal distribution was a preferred representation for the RCOF with additional benefits of its simplicity, practicality and familiarity. However, in few cases (7.75%), none of the three distributions was a good match for the RCOF.

Mechanical devices, also called slipmeters, are usually used to measure the ACOF which always has random variations even when identical samples are used (Chang and Matz, 2001). In addition, variations in friction can result from measurements with different samples of identical floor and shoe materials, as shown by Chang and Matz (2001). Therefore, the ACOF is not a constant for a particular shoe and floor interface, but has a stochastic distribution. Barnett (2002) and Marpet (2002) discussed the concept of a stochastic distribution of the ACOF. Barnett (2002) reported that the distribution of the ACOF was near a Weibull distribution from 400 measurements of the ACOF over 100 new asphalt tiles under dry conditions with the Horizontal Pull Slipmeter (HPS).

Despite these preliminary examinations of the stochastic distributions of the ACOF, the published results are very limited in floor types and surface conditions evaluated. Most slip incidents occur on surfaces with contamination where the ACOF could be low and the probability of a slip incident could be higher than under dry conditions. The stochastic distribution of the ACOF could depend on the floor surfaces and surface conditions. Chang et al. (2012a) reported a preliminary study on the ACOF of quarry tiles under three surface conditions of dry, water and glycerol. They reported that the ACOF under the glycerol condition had a good match with all three continuous distributions, the normal, lognormal and Weibull, while the ACOF under wet condition had a good match with the normal and lognormal distributions. They further reported that the ACOF under the dry condition did not have a good match with any of the three distributions. The goal of the current study was to expand the investigation of the stochastic distributions of the ACOF by adding four more different floor surfaces under the dry, water and glycerol contaminated conditions as an input to the statistical model. These five different floor materials were selected out of 37 commonly used floor materials in a previous study due to their distinctive features that represented different combinations of friction levels and cognitive elements (Lesch et al., 2008). Since most slip incidents occur on contaminated surfaces, investigating the ACOF distributions on surfaces covered with water and glycerol is critical.

2. Method

As a part of a larger study, five walkways of approximately 6.1 m long and 81.3 cm wide were constructed. Each walkway was covered with a specific floor tile. The five floor types used in the experiment, referred to as floor types A to E, were: (A) standard flat quarry tile, (B) a standard quarry tile with raised-profiled tread lines perpendicular to the walking direction, (C) vinyl composition sheet, (D) marble tile and (E) glazed porcelain tile. Detailed information about these floor types is listed in Table 1. These five floor types with three different surface conditions (15 cases) provided a wide range of ACOF values.

In contrast to friction measurements on uninstalled floor tiles, measurements on installed tiles on walkways offered more realistic conditions that could potentially affect the ACOF values. Fifty tiles or locations along the walking path on each walkway were selected for friction measurements. Under each surface condition, two friction measurements were performed on each selected tile or location, one in each walking direction, for a total of 100 measurements. The portable inclinable articulated strut slip tester (PIAST), also known as the Brungraber Mark II, was used in this experiment. A standard test method for this slipmeter is published by the American Society for Testing and Materials (ASTM) (ASTM F-1677-05, 2005).

The ACOF was measured under three different surface conditions: dry, water and 45% glycerol concentration. Clean paper towels were used to apply a solution of diluted 50% ethanol mixed with de-ionized water for cleaning the floor surfaces before performing friction measurements. For the water condition, in order to help form a uniform water film over the surface, a wetting agent (Kodak Professional Photo-Flo 200 solution; Eastman Kodak Company, Rochester, NY, USA) was added to the water with a 1 to 200 ratio by volume as suggested by its manufacturer. A garden sprayer

Table 1
Floor types used in this experiment.

Floor type	Description
A	Metropolitan Ceramics quarry basics clear tones in Mayflower Red – 77310
B	Metropolitan Ceramics quarry metrotread in Mayflower Red – 7731T
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 × 18 Color/Item: Titanium SKU No.: 745452)