AVAILABLE COEFFICIENT OF FRICTION ASSOCIATED WITH DIFFERENT SLIP PROBABILITIES FOR LEVEL WALKING

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Different slip probabilities for level straight walking were investigated when comparing a given available coefficient of friction (ACOF) value with the stochastic distribution of the required coefficient of friction (RCOF). The RCOF of each foot for each walking condition by each participant was assumed to have a normal distribution. The slip probability was calculated by averaging the cumulative probabilities of the RCOF exceeding a given ACOF from both feet and evaluated at five levels, one out of 20, 200, 10,000, 100,000 and 1,000,000. The ANOVA results showed that both age group and walking speed had a statistically significant effect on the ACOF associated with all slip probabilities evaluated. The ACOF value obtained in an earlier study was less than that with the current study for higher slip probabilities, and greater for lower slip probabilities.

Introduction

In occupational injuries, falls on the same level are a serious problem. In 2010, costs in the US for disabling workplace injuries due to falls on the same level were estimated to be approximately 8.61 billion US dollars or 16.9% of the total cost burden for all and are listed as the second leading sources of occupational injuries (Liberty Mutual Research Institute for Safety, 2012). Courtney *et al.* (2001) reported that slipperiness or slipping contributed to between 40 and 50% of fall-related injuries.

The available coefficient of friction (ACOF) represents the maximum coefficient of friction (COF) that can be supported at the shoe and floor interface without a slip, while required COF (RCOF) represents COF needed at the shoe and floor interface to support human locomotion. A slip may occur when the RCOF value for an activity is lower than the ACOF (Chang, 2004). However, the RCOF is not a constant for each individual, even under the same walking conditions, as demonstrated by Chang *et al.* (2008, 2012b).

Pye and Harrison (1997) investigated the level of the ACOF associated with different slip probabilities. Their results showed that the ACOF values were 0.24, 0.27, 0.29, 0.34 and 0.36 for the slip probabilities of one out of 20, 200, 10,000, 100,000 and 1,000,000, respectively, for straight walking. No details were given of how their data were obtained. It was understood, however, that their results were derived from the data reported by Harper *et al.* in 1961 (Roys, 2011). In an attempt to understand the method used by Pye and Harrison (1997) by verifying their results, we undertook a preliminary analysis using the same Harper *et al.* (1961) data of both feet from 48 participants (35 males and 13 females) and demonstrated that Pye and Harrison had constructed a normal distribution based on the RCOF data. The ACOF value at which the cumulative probability of the RCOF exceeding the ACOF was calculated for five probability levels.

RCOF can be affected by walking speed, footwear type, age, gender and foot (Chang *et al*., 2012a, 2012b). Even under the same walking condition, there can be individual differences in the RCOF. Chang *et al.* (2012b) investigated the stochastic distribution of the RCOF with 50 participants who walked under four walking conditions. The results of the Kolmogorov-Smirnov two-sample test showed that 76% of the RCOF data had a difference in distribution between both feet for the same participant under each walking condition. The results of the Kolmogorov-Smirnov goodness-of-fit test showed that most of the distribution of the RCOF appeared to have a good match with the normal distribution (85.5%). By combining the RCOF data of different individuals, different walking conditions and different feet, the standard deviation would be substantially larger than that at the individual levels. In this study, approaches similar to that of Pye and Harrison (1997) were applied to the RCOF under each walking condition at the individual level with the consideration of individual contributions from each foot. The objective was to explore the effects of walking speed, footwear, gender and age group on the ACOF associated with different slip probabilities.

Methods

Data obtained in the previous study by Chang *et al*. (2012b) were used in the current study. Twenty five females and 25 males without active musculoskeletal disorders took part in this experiment. Three age groups were used to classify participants: 18 – 25 years old, 26 - 54, 55 and older, resulting in 7, 29, and 14 participants in each respective group. The mean and standard deviation of weight, height and age at each level of gender and age group are shown in Table 1. The protocol was approved by an institutional review board. The participants gave written informed consent. Details of the experimental setup with three force plates were described in Chang *et al*. (2008).

Table 1. Average and standard deviation of weight, height and age for each level of age and gender

Variable	Level	Weight (kg)	Height (cm)	Age (years)
Gender	female	64.8 ± 9.16	162.4 ± 5.54	45.2 ± 13.9
	male	80.9 ± 14.07	172.7 ± 8.46	45.4 ± 13.2
Age Group (years)	18-25	65.3 ± 16.96	163.0 ± 8.50	20.6 ± 3.15
	26-54	72.8 ± 13.93	169.2 ± 8.87	44.1 ± 6.64
	55 and higher	76.7 ± 13.09	166.5 ± 8.33	60.0 ± 3.76

The participants walked at self-selected normal and fast speeds. A sneaker and a leather loafer were the two types of footwear used. In this experiment, there were four different walking conditions: loafer-fast (LF), loafer-normal (LN), sneaker-fast (SF) and sneaker-normal (SN). These four walking conditions were randomized for each participant.

All the force plate data, sampled at 1000 Hz, were processed with the fourth order zero-lag Butterworth low pass filter with a cut-off frequency of 36 Hz. The method used to identify the RCOF was explained in detail by Chang *et al*. (2012b).

Based on the results obtains in the previous study (Chang *et al.*, 2012b), it was assumed that the RCOF of each foot under each walking condition by each participant had a normal distribution. The ACOF was obtained so that the average of the cumulative probabilities of the RCOF exceeding the given ACOF from both feet was equal to each slip probability value. The ACOF was represented by a constant and the stochastic distribution of RCOF of an individual under a given walking condition was represented by the probability density functions p_R and p_L for right and left feet, respectively. The cumulative probability of the RCOF exceeding the given ACOF was calculated by averaging the cumulative probabilities of the RCOF exceeding the given ACOF for both feet as shown below:

$$P(ACOF) = \frac{1}{2}\left(\int_{ACOF}^{+\infty} p_R(x)dx + \int_{ACOF}^{+\infty} p_L(y)dy\right).$$

Identical slip probabilities used by Pye and Harrison (1997) were used in the current study, i.e., one out of 20, 200, 10,000, 100,000 and 1,000,000.

A mixed linear model (models with both fixed and random effects) with four-way analysis of variance (ANOVA) was used for data analysis. The age group, footwear type, gender and walking speed were considered as fixed effects with participant as a random effect. Post-hoc analysis for the variable of age group (18 - 25, 26 - 54, 55 years and older) was carried out with the Bonferroni adjustment to counteract multiple comparisons. The ANOVA for each slip probability level was carried out individually.

Results and discussion

There were a total of 30,968 successful strikes. The averaged sample size, mean, standard deviation, skewness and kurtosis, and the minimum and maximum of the RCOF for each foot under each walking condition across 50 participants are shown in Table 2.

The Kolmogorov-Smirnov goodness-of-fit test was used to check if the normal distribution was a good representation for the RCOF for each foot under each walking condition for every participant. Among 400 data pools by 50 participants, four walking conditions and two feet, 344 (86%) cases reached statistical significance for a match with a normal distribution.

Table 2. Averaged sample size (n), mean, standard deviation (SD), skewness and kurtosis, and the minimum (Min) and maximum (Max) of the required coefficient of friction for each foot under each walking condition across 50 participants

Condition	Foot	n	Mean	SD	Skewness	Kurtosis	Min	Max
LF	left	78	0.2394	0.0138	0.018	0.096	0.143	0.352
LF	right	78	0.2398	0.0170	0.139	-0.097	0.148	0.353
LN	left	78	0.2172	0.0127	-0.039	0.271	0.120	0.324
LN	right	77	0.2163	0.0153	0.211	0.057	0.124	0.332
SF	left	77	0.2456	0.0138	-0.074	0.244	0.112	0.361
SF	right	77	0.2489	0.0159	-0.059	-0.007	0.145	0.368
SN	left	78	0.2286	0.0124	0.091	0.305	0.130	0.326
SN	right	76	0.2275	0.0147	0.247	0.058	0.149	0.413

Note: The kurtosis values presented reflect the deviations from a normal distribution.
LF=Loafer Fast, LN=Loafer Normal, SF=Sneaker Fast, SN=Sneaker Normal

The results of the four-way ANOVA show that only the speed ($p < 0.001$) and age group ($p = 0.009 \sim 0.029$) reached the statistical significance for all slip probabilities evaluated, but their interaction did not reach statistical significance. For all levels of slip probability, the ACOF values associated with age group 2 (26-54) had a statistically significant difference from that of age group 3 (55 and older) with $p < 0.05$. For the lowest two probability levels (1/100,000 and 1/1,000,000), the ACOF values of age group 1 (18 - 25) also had a statistically significant difference from those of age group 3 with $p < 0.05$. The mean and standard deviation of the ACOF values for each level of age group, footwear, gender and walking speed are shown in Table 3. The results show that the ACOF value for the age group 55 and older was lower than that for the other two age groups, while the ACOF value associated with a fast walking speed was higher than that for normal.

Pye and Harrison (1997) merged the data of the RCOF from both feet of 48 participants and did not monitor walking speeds, which would have led to an increase in the standard deviation of the RCOF. The variation was investigated at the level of each foot for each walking condition by each participant in the current study. Therefore, individual contribution to slip

probability from each foot was considered. The ACOF was shown to be significantly affected by the walking speed and age group. Compared with the results obtained in the current study, the ACOF value reported by Pye and Harrison (1997) for straight walking was lower for higher slip probabilities such as one out of 20 and 200, while the opposite was true for lower slip probabilities such as one out of 100,000 and 1,000,000.

Table 3. The means with standard deviations (in parentheses) of the available coefficient of friction (ACOF) associated with different slip probabilities obtained in the current study. The results of Pye and Harrison (1997) are included for comparison.

		Slip Probability				
		1/20	1/200	1/10,000	1/100,000	1/1,000,000
Age group	18-25	0.262 (0.0338)	0.280 (0.0356)	0.301 (0.0385)	0.311 (0.0401)†	0.320 (0.0417)†
	26-54	0.264 (0.0293)†	0.280 (0.0332)†	0.298 (0.0383)†	0.307 (0.0409)†	0.315 (0.0433)†
	55 and older	0.252 (0.0290)	0.266 (0.0306)	0.283 (0.0332)	0.291 (0.0347)	0.299 (0.0361)
Footwear	loafer	0.256 (0.0306)	0.272 (0.0333)	0.291 (0.0372)	0.300 (0.0392)	0.308 (0.0410)
	sneaker	0.265 (0.0292)	0.280 (0.0328)	0.298 (0.0377)	0.307 (0.0402)	0.314 (0.0425)
Gender	female	0.257 (0.0303)	0.273 (0.0342)	0.293 (0.0395)	0.302 (0.0421)	0.311 (0.0446)
	male	0.264 (0.0298)	0.278 (0.0321)	0.296 (0.0355)	0.304 (0.0373)	0.312 (0.0390)
Walking speed	fast	0.272 (0.0266)‡	0.289 (0.0289)‡	0.308 (0.0323)‡	0.317 (0.0341)‡	0.326 (0.0358)‡
	normal	0.249 (0.0288)	0.263 (0.0325)	0.281 (0.0375)	0.289 (0.0401)	0.297 (0.0425)
Pye and Harrison (1997)		0.24	0.27	0.29	0.34	0.36

† - statistically significantly different from group 3 (55 and older) ($p < 0.05$)
‡ - statistically significantly different from normal speed ($p < 0.05$)

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