Gait & Posture 48 (2016) 256–260

Contents lists available at ScienceDirect

Gait & Posture

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

Full length article

Required coefficient of friction during level walking is predictive of slipping

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ARTICLE INFO

Article history:
Received 13 February 2016
Received in revised form 4 May 2016
Accepted 3 June 2016

Keywords:
Slip and fall accidents
Required coefficient of friction
Gait biomechanics

ABSTRACT

The required coefficient of friction (RCOF) is frequently reported in the literature as an indicator of slip propensity. This study aimed to further develop slip prediction models based on RCOF by examining slips under moderately slippery conditions where the RCOF was approximately equal to the available coefficient of friction. Baseline RCOFs were found for normal walking trials and then an unexpected slip was introduced with a moderately slippery boot-floor contaminant combination for thirty-one subjects. Slip outcomes (i.e., whether a subject experienced a slip) were assessed based on the displacement of a marker placed on the heel. A logistic regression analysis was used to model the impact of RCOF on slipping. Results showed that subjects who walked with a greater RCOF were found to have a higher probability of slipping. The predicted probability of a slip across the RCOF ranged from 3% to 95% and an increase of 0.01 in RCOF was associated with a slipping odds ratio of 1.7. Thus, modest differences in RCOF can have a dramatic impact on slip propensity. This study shows that RCOF can be a sensitive and valid predictor of slipping in realistic frictional environments.

1. INTRODUCTION

Slip, trip and falling accidents account for approximately 27% of all non-fatal occupational injuries [1] and 17% of all fatal injuries [2] in the United States. The Centers for Disease Control estimates that falling accidents cost the US economy $180 billion in 2013 ($169 billion for non-fatal falls [3] and $11 billion for fatal falls [4]). Slips are a common initiating event accounting for approximately 40% of occupational falling events [5].

From a biomechanical perspective, slips occur when the frictional properties of the footwear-floor interface are not sufficient to counter the biomechanical requirements of walking. Probabilistic slip-prediction models have been developed based on the difference between the available coefficient of friction between the outsole and floor surface (ACOF) and the required coefficient of friction or RCOF due to the biomechanics of gait (Eq. (1)) [6–9]. In these studies, ACOF was measured using a tribometer or slip-tester, while RCOF was calculated from ground reaction forces during unperturbed walking. One limitation in these previous studies is that the difference between ACOF and RCOF is typically used as a single predictor of slipping [6,8–10]. By combining ACOF and RCOF into a single predictor, the individual contributions of ACOF and RCOF remain unknown. Also, previous research has typically developed these probabilistic models based on a wide range of ACOF values [10–12] and the sensitivity of these models to individual differences in RCOF, which can be rather small, has not been quantified. While RCOF is simply a ratio of the shear and normal forces during the stance phase of gait, the dynamics of locomotion that lead to these forces, and subsequently the RCOF, can be complex [13,14]. Therefore, the robustness of this single predictor model is questioned.

$$Slip_R isk = \frac{e^{\beta_0+\beta_1*(ACOF-RCOF)}}{1+e^{\beta_0+\beta_1*(ACOF-RCOF)}} \quad (1)$$

The current state of slip prediction models remains inconclusive regarding whether an individual's RCOF is an important predictor to slipping. Some studies have found that ACOF on its own can predict slipping accidents, which may indicate that ACOF is the main contributor to slipping and that RCOF may not be needed in these models [8,11]. Hanson et al. found that increasing the walkway inclination angle led to a substantial increase in RCOF (increase of ~0.14 for a 10° inclination and increase of ~0.25 for 20° inclination) and an increase in slip rates, which suggests that RCOF contributes to slip outcomes [10]. However, Hanson et al. did not directly quantify the impact of RCOF on slipping and did not develop a slip prediction model based on the RCOF. Thus, an

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http://dx.doi.org/10.1016/j.gaitpost.2016.06.003
0966-6362/

important gap in the literatures exists regarding how RCOF influences slip outcomes.

Several biomechanical factors influence individual RCOF. For example, RCOF has been found to be positively correlated with step length [13], negatively correlated with cadence [13], positively correlated with heel contact velocity [14] and negatively correlated with whole body translational acceleration [14]. Furthermore, RCOF has been observed to be lower in older adults than younger adults, primarily due to shorter step lengths [13]. Lastly, RCOF increased when the quadriceps muscle group was fatigued [15] and decreased when anticipating a slip event [16]. Many of these reported differences were relatively modest (differences of about 0.03–0.06) and it remains unclear if these differences are significant. Research that quantifies the relationship between RCOF and slipping outcomes would add important context to these previous studies.

This study aims to quantify the ability of individual RCOF to predict slip outcomes in moderately slippery conditions. We hypothesize that even moderately higher RCOF values will be associated with more frequent slipping.

2. Methods

2.1. Subjects

Thirty-one subjects were recruited to participate in the study including 14 female subjects (mean age: 24.4 ± 5.18 years; mean height: 170 ± 6.00 cm; mean mass: 77.4 ± 22.3 kg; mean boot size: 7.6 ± 0.76 US Men's Sizing) and 17 male subjects (age: 24.0 ± 4.19 years; height: 177 cm ± 7.89 cm; mean mass: 76.3 ± 17.1 kg; mean boot size: 9.6 ± 1.2 US Men's Sizing). Subjects were screened over the phone to initially determine eligibility in the study. Subjects were excluded if they reported a weight of over 136 kg; height over 1.94 m; age outside of a range from 20 to 35 years; history of neurological problems; orthopedic problems within the previous 3 years; osteoporosis; cardiovascular problems; balance or dizziness problems; taking cardiovascular, neurological or vestibular medication; or had cardiovascular, orthopedic, or ear surgery. In addition, female subjects were asked to take a pregnancy test and were excluded if the test was positive. Participants also needed to be able to wear a boot size between 7 and 12 on the US men's footwear size scale. Two subjects were removed from the analysis because they substantially changed their gait or frequently looked down when approaching the contaminant, indicating that they were anticipating a slip. All subjects provided informed consent prior to participation, and the study was approved by the University of Pittsburgh Institutional Review Board.

2.2. Procedure

Prior to testing, participants were fitted with tight fitting clothing, 79 reflective markers and a safety harness. The only relevant marker for this study was the inferior-most point of the back of the boot. Details regarding the full marker set can be found at [17]. Kinematics of the reflective markers were collected using a motion capture system (Vicon T40S, Oxford, UK), while ground reaction forces during walking were collected with a force plate (Bertec 4060A, Columbus, OH). Subjects were randomly assigned to wear boots with one of three outsole material formulations. The different boot outsole materials used different formulations of synthetic rubber, which gave them different hardness levels. The boots had the same tread pattern and surface roughness (Fig. 1). The reason for using multiple boot outsole designs was because the present study was part of a larger study that was examining the impact of subtle changes in outsole material on slipping. After subjects were assigned to a pair of boots, they completed five

Fig. 1. Picture of tread pattern (top), heel region (middle) and boot upper design (bottom). The close-up view of the heel region is consistent with the circle marked on the top figure.

baseline trials. If the subject missed the force plate with their left boot or hit the force plate with both feet, then an additional baseline trial was completed. Subjects were told to walk at a comfortable walking pace and walking speed was not controlled by the research team. The subject walked approximately 5 m preceding the force plate and 5 m after the force plate so that they reached steady state walking prior to striking the force plate (Fig. 2). Participants then experienced an unexpected slip event where a glycerol and water solution (50% glycerol and 50% water by volume) was placed on the floor without the subjects' knowledge. The contaminant was selected based on preliminary ACOF testing that revealed that this contaminant (along with the selected boots and flooring) was likely to cause some but not all subjects to slip. Participants experienced up to two additional slip trials after the first but this data was not analyzed in the present study. Boots were washed with detergent and water, rinsed and air-dried between testing sessions to ensure that they were clean for each testing session consistent with previous studies by our group [17,18].

The hardness, roughness and ACOF were characterized for the three boot outsoles. The average roughness (Ra), RMS roughness (Rq) and average peak-to-valley roughness (Rz) of the posterior-

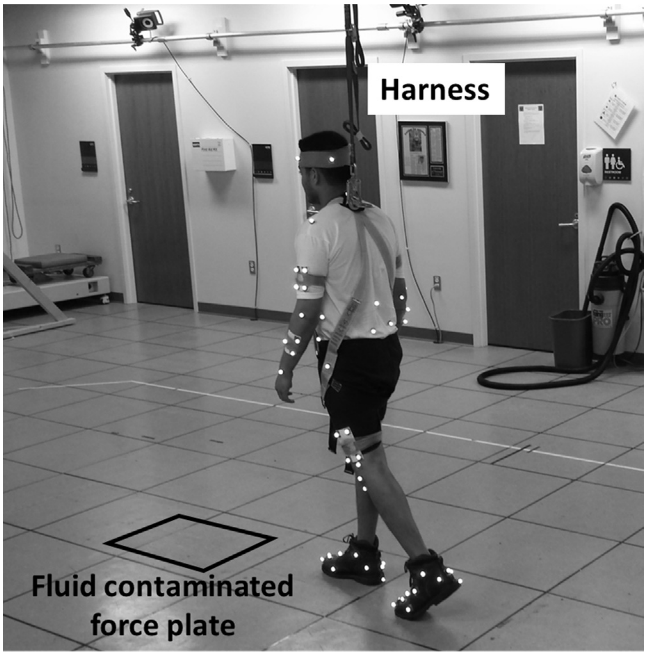

Fig. 2. Laboratory setup including subject with reflective markers, harness and force plate that was contaminated with fluid.

section of the outsole heel was measured four times in different locations and at different orientations with stylus profilometer (Taylor-Hobson Surtronic S100®, Leicester, UK) with a scan length of 6.2 mm and a low-pass cutoff filter of 0.8 mm (Table 1). Outsole material hardness was characterized using a Shore A Hardness scale [19] (Table 1). The ACOF of the outsole materials was measured using a custom-built whole-shoe/boot slip-testing device [20] that applied a normal force (250 N) with three vertical motors and traversed it across the floor surface with one horizontal motor at 0.3 m/s with a boot-floor angle of 7° [21]. ACOF values were averaged during the first 200 ms after a normal force of 250 N was reached [21] (Table 1). Each of the three boots were tested against the vinyl floor surface in the presence of diluted glycerol (50% glycerol/50% water).

2.3. Data Analysis

RCOF was calculated using ground reaction forces, while the slip outcome was calculated from heel kinematics. RCOF was determined for each subject using the five trials immediately preceding the slip where the subject cleanly hit the force plate with the same boot that experienced the slip. RCOF was measured as the peak ratio of resultant shear to vertical force once the vertical force was over 100 N and the anterior/posterior component of the force on the boot was in the posterior direction (i.e., force applied to the floor by the boot was in the anterior direction) [22]. Also, only data where the RCOF was higher than the previous datum were considered to avoid selecting erroneous RCOF data when the normal force initially reached 100 N and the RCOF was decreasing with time [22]. The ground reaction forces were filtered using a fourth-order low-pass Butterworth filter with a cutoff frequency of 36 Hz [22]. The slip outcome was categorized based on the slipping distance of the inferior-most heel marker. The slipping distance was calculated during the period of time between the first local minimum in the anterior heel velocity after heel strike and either the second local minimum in the anterior heel velocity or when the subject's boot slipped off of the force plate [23,24]. Subjects were considered to have experienced a slip if the slip distance exceeded the 30 mm since previous research has indicated that microslips during baseline gait are typically less than this distance [25]. Kinematic data were filtered with a 4th order low-pass Butterworth filter with a cutoff frequency of 6 Hz. Slipping trials where the boot did not cleanly strike the force plate were excluded from the analysis (n = 3/29).

Statistical analyses were used to determine the effects of RCOF on slipping. Two logistic regression models were developed with slip outcome as the dependent variable. The independent variables for the first multivariate model were RCOF and outsole material (a nominal variable to control for differences in slip rates across the three different outsole materials). The only independent variable for the second univariate model was RCOF (Eq. (2)). Odds ratios and confidence intervals were also calculated from the logistic regression coefficient, β_1. A receiver operating characteristic curve was generated from the univariate analysis in order to determine the best cutoffs for balancing sensitivity and specificity. All statistical analyses were conducted using commercially available statistical software (JMPV. 11.1.1, SAS Corp., 2013, Cary, NC) using a significance level of 0.05.

$$Slip_Risk = \frac{e^{\beta_0+\beta_1*(RCOF)}}{1+e^{\beta_0+\beta_1*(RCOF)}} \quad (2)$$

3. RESULTS

The mean (standard deviation) RCOF was 0.207 (0.027). Thirty-eight percent of the liquid-contaminated trials resulted in a slip. On average, subjects who slipped had a higher RCOF (mean: 0.224; standard deviation: 0.023) than those who did not experience a slip (mean: 0.196; standard deviation: 0.025). The multivariate logistic regression model revealed that RCOF was a significant predictor of slip outcomes (p = 0.011, χ^2 = 6.53) (Table 2). Outsole material did not affect slip outcomes in the multivariate model (p = 0.301, χ^2 = 2.40) (Table 2). The univariate logistic regression model also revealed that RCOF was a significant predictor of slip outcomes (p = 0.005, χ^2 = 7.80) (Table 2, Fig. 3A). The univariate logistic regression curve revealed that the predicted probability of slipping was 95% for the subject with the highest RCOF (0.272) but just 3% for the subject with the lowest RCOF (0.155). The odds ratio for each 0.01 unit increase in RCOF was 1.72 for the multivariate model and 1.74 for the univariate model. The interquartile range for RCOF was 0.188 to 0.229, which led to an interquartile range odds ratios of approximately 9 for both models (9.0 for the univariate model and 9.5 for the multivariate model). The receiver operating characteristic curve revealed that the two RCOF cutoffs that best handled the tradeoff between sensitivity and (1-specificity) (i.e., the points that deviated most from the gray line in Fig. 3B) were 0.181 and 0.206. The sensitivity (specificity) were 100% (32%) at a RCOF cutoff of 0.181 and 61% (65%) at a RCOF cutoff of 0.206 (Fig. 3B). The area under the receiver operating characteristic curve was 0.65.

4. Discussion

This study confirmed the hypothesis that RCOF is an important and sensitive variable for predicting slipping events. Specifically,

Table 1
Boot outsole roughness, hardness and ACOF values for the three outsole materials.

Outsole	Ra	Rq	Rz	Hardness	ACOF
Soft	5.4 (1.1)	6.8 (1.2)	25.4 (3.1)	64	0.179
Medium	5.3 (1.1)	6.8 (1.4)	24.4 (3.9)	76	0.168
Hard	5.3 (0.3)	6.7 (0.5)	23.5 (1.1)	85	0.149

Table 2
Logistic regression coefficients (β_0 and β_1) and odds ratios (OR) from the multivariate and univariate models.

Statistical Model	Predictor Variable	β_0 Estimate (Confidence Interval)	β_1 Estimate (Confidence Interval)	OR[a] Estimate (Confidence Interval)
Multivariate	RCOF	−12.4 (−25.8 to −3.0)	55.7 (11.5 to 117.8)	1.74 (1.12 to 3.25)
	Medium hardness[b]	N/A	0.9 (−0.5 to 2.4)	1.83 (0.20 to 20.43)
	High hardness[b]	N/A	2.0 (−0.5 to 5.3)	7.14 (0.61 to 198.3)
Univariate	RCOF	−11.9 (−24.3 to −3.3)	54.1 (14.0 to 111.8)	1.72 (1.15 to 3.06)

[a] The odds ratio (OR) for the RCOF predictor is for a 0.01 increment increase.
[b] The reference condition for medium and hard outsoles is the soft outsole.

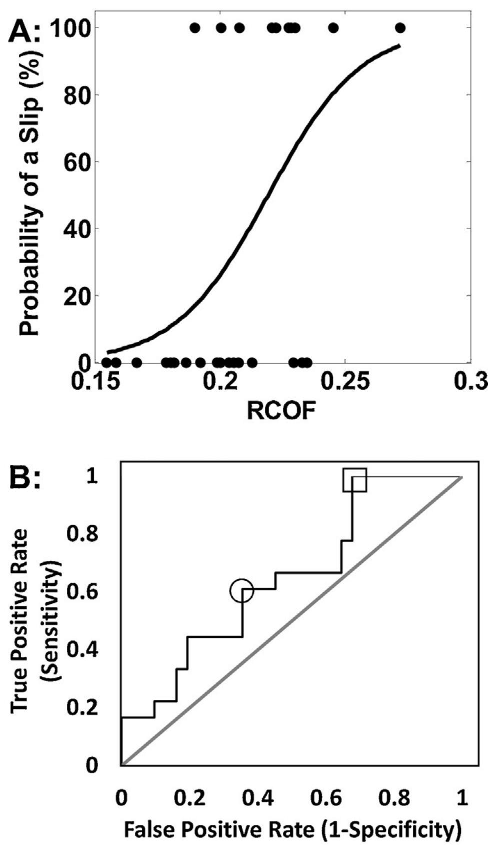

Fig. 3. A: Slip outcomes (solid circles) and predicted probability of a slip (solid line) plotted against the required coefficient of friction (RCOF). Slip outcomes were set to 100% if the subject slipped or 0% if the subject did not slip. The predicted probability of a slip was based on the univariate logistic regression fit. B: The receiver operating characteristic curve using RCOF as the predictor. The black line represents the True Positive Rate-True Negative Rate curve whereas the gray line represents a slope of 1. The square corresponds to an RCOF cutoff of 0.181 and the circle corresponds to an RCOF cutoff of 0.206.

individuals with a higher RCOF were more likely to experience a slip when stepping on a moderately slippery surface. Furthermore, this study demonstrated that slip outcomes were sensitive to small changes in RCOF since an increase of 0.01 in an individual's RCOF led to a 73% higher odds of slipping during normal walking.

The results of this study are consistent with other research that has suggested a relationship between RCOF and slipping. For example, Hanson et al. found that increasing inclination angle of ramps led to increased RCOF, which was accompanied by greater slipping rates [10]. Furthermore, the RCOF coefficient, β_1 (54.1), was in the range of coefficients as previously reported coefficients when the difference between ACOF and RCOF (12.9–54.7) was the predictor [6,8–10]. The results of the present study build on these previous studies and show how sensitive slipping can be to individual differences in RCOF.

Quantifying the relationship between RCOF and slipping outcomes provides important context for other studies that utilize RCOF as an outcome measure for slip propensity. For example, previous research has determined that controlling step length during fast walking can reduce RCOF by approximately 0.06 for young adults and 0.03 for older adults [13]. Previous studies have found that older adults have an RCOF that is about 0.03 or 0.04 less than young adults [13,26], that RCOF is reduced by about 0.04 when anticipating a slip [16] and that RCOF increases by approximately 0.03 when the quadriceps muscles have been fatigued [15]. The present study found that increasing RCOF by 0.01 led to an odds ratio of over 1.7. Thus, the previously reported RCOF increase of 0.03 and RCOF decrease of 0.06 would result in the odds of slipping increasing by over 400% and decreasing by 94%, respectively. The wide range in predicted probability of a slip across the observed RCOF values in this study (3–95%, Fig. 3) suggests that gait styles associated with reduced RCOF have a significant potential for reducing the probability of a slip. Given that RCOF is known to be affected by a number of dynamic and kinematic gait variables as previously reported in the literature and that it was a sensitive predictor of slipping in the present study, we contend that RCOF is a valid measure of slip risk that represents the net impacts of these gait variables on slipping.

Certain elements of this study are not generalizable and some important limitations should be acknowledged. The logistic regression curves that were developed are specific to the boot-floor-contaminant conditions considered in this study and may not be generalizable to other surfaces. Obviously, the impact of RCOF would be significantly diminished in cases where ACOF was very high and slipping would rarely occur or in cases where ACOF was very low and slipping would almost always occur. Furthermore, additional research should be conducted to determine if the odds ratios reported in this study are generalizable to other populations or conditions.

In summary, this study demonstrates that individual differences in RCOF have a substantial impact on slip outcomes. Specifically, small changes in RCOF during level walking can significantly influence slips. This study indicates that human factors interventions that reduce RCOF will likely be effective in reducing the occurrence of slipping.

Acknowledgements

This work was supported by funding from that National Institute of Occupational Safety and Health (NIOSH R01 OH008986) and the National Center for Research Resources (NCRR S10RR027102). Custom footwear was provided by Timberland ®.

Conflict of interest

None of the authors have a conflict of interest with this manuscript.

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