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# Development of an In-situ Method for Measuring Coefficient of Friction between Footwear and Roof Surface – A Preliminary Study

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**Abstract:** Roofers are highly vulnerable to both traumatic injuries (TI) and musculoskeletal disorders (MSD). Slips on a sloped roof surface are likely one of the major causes for falls and TIs, but may also be associated with MSDs. Previous studies showed that the slip potential is associated with the difference between the available friction force and the actual friction force required to provide the traction for walking or the resistant force for stopping walking while maintaining balance stability. The coefficient of friction (CF) between the footwear and the roof surface is the essential physical property to determine the available friction force. Although numerous studies have examined the CF of footwear in various conditions, the in-situ CF on a roofing surface has not been reported. As the first step of a systematical investigation, the current study is aimed at the development of a practical and efficient method for measuring the in-situ CF between footwear and roofing surfaces. A custom-built roofing simulator is used, which can vary slope angle, is equipped with force plates covered with a roofing surface material. To assure the proposed in-situ method can provide reliable measurement of the CF, a series of experiments were conducted to test, evaluate, and improve the proposed method. Three different boots were used to represent the footwear. The footwear, placed on the simulator which was covered in a roof surface material and at a typical roof pitch, was pulled along the uphill slope via a thin string so that the footwear could keep moving slowly and steadily on the surface. The ground reaction forces in the shear and normal directions were simultaneously measured using the force plate. Their ratio was used to determine the CF. The static CF ($CF_S$) and kinetic CF ($CF_K$) were identified from the measured data. The $CF_S$ was also measured using the angle of repose method and was compared with that measured with the proposed method. The results suggest that the method can not only provide reliable measurement of the $CF_S$ but it also be used to examine the influences of various factors on the $CF_K$.

*Keywords:* Roofers, Coefficient of Friction, Kinetic, Static, Footwear

## 1. Introduction

Roofers are highly vulnerable to both traumatic injuries (TI) and musculoskeletal disorders (MSD). Between 2003 and 2015, there were between 256 and 440 fatal falls annually in construction (CPWR, 2018). Roofing contractors experienced the highest rate of fatal falls to a lower level between 2011 and 2015, at 34.2 per 100,000 FTEs. That rate was 10 times greater than that of all construction trades combined (3.3 deaths per 100,000 FTEs) (CPWR, 2018). According to BLS data, 54.5 roofers per 10,000 had some form of MSD injury in 2017 (BLS, 2018). Slips on a sloped roof surface are likely one of the major causes for TIs, but may also be associated with MSDs.

Previous studies showed that slip or fall potential is associated with the difference between the available friction force and the actual friction force required to provide the traction for walking or the resistant force for stopping walking while maintaining balance stability (Beschorner, Albert, & Redfern, 2016). The coefficient of friction (CF) between the footwear and the roof surface is an essential physical property to determine the available friction force. An increase of 0.01 in required CF was associated with a slipping odds ratio of 1.7 (Beschorner et al., 2016). Their study shows that required CF can be a sensitive and valid predictor of slipping in realistic frictional environments. Previous studies have investigated the slip resistance of footwear by testing the slip resistance of materials taken from the footwear using commercial slipmeters (Chang & Matz, 2001; Chang & Maynard, 2006). Slipping tests have also been conducted using whole-shoe samples under different combinations of normal force, sliding speed, and shoe-floor angle using a standardized method (Blanchette &

Powers, 2015) and using a customized portable slip simulator (Iraqi, Cham, Redfern, & Beschorner, 2018). The measurements of CF of footwear obtained via objective method (Gronqvist, Chang, et al., 2001) have been compared with those obtained via subjective walking experiments with human subjects (Gronqvist, Abeysekera, et al., 2001; Gronqvist, Hirvonen, & Tuusa, 1993; Iraqi, Cham, Redfern, Vidic, & Beschorner, 2018).

Although there are numerous studies for friction measurement of footwear, all previous tests have been performed in ideal laboratory conditions. There are many factors that could affect the available CF on a sloped roofing surface in a working environment, such as slope, sliding speed, realistic covering materials, and sliding direction. The purpose of the current study was to develop a reliable and efficient method to quantify the static coefficient of friction ($CF_S$) and kinetic coefficient of friction ($CF_K$) of footwear on roof surfaces mimicking in-situ working conditions.

## 2. Methods

### 2.1 Experimental set-up

Two different testing methods were used to test for the $CF_S$ and $CF_K$ of the footwear. The first method (Method A) was the angle of repose approach (Fig. 1A & C), which only determined the $CF_S$. The footwear was placed on an oriented strand board (OSB), a common wood board used for roofing purposes. The OSB was attached to a base using a piano hinge. Retro-reflective markers were placed on the OSB and footwear to be tested. The opposite end of the OSB was slowly lifted at a constant speed until the footwear slid down the board, while the marker locations were recorded using 14 MX Vicon cameras (Vicon Inc., Oxford, England) at a sample rate of 100 Hz.

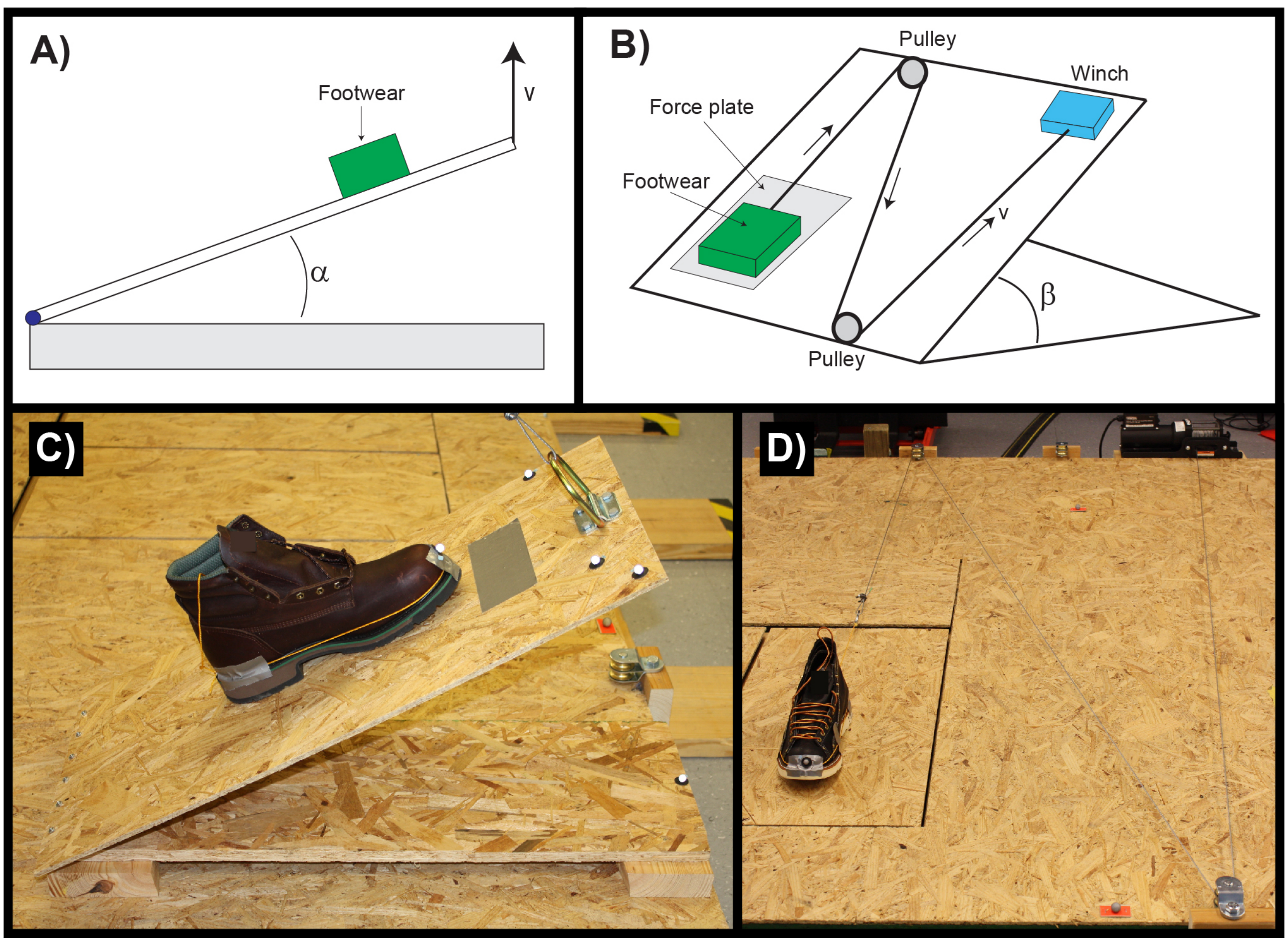


Figure 1. Experimental set-ups for testing friction coefficients. A & C) Method A, the inclination angle of a surface will be slowly increased until the footwear begins to slide. B & D) Method B, the footwear is placed on a force plate and is pulled slowly via a pulling-sliding system.

The second method (Method B) was a pulling-sliding approach, which was used to capture both the $CF_S$ and $CF_K$. The footwear was placed on top of a force plate (Bertec, Ohio, USA), which measures three-dimensional forces at 1000 Hz and was mounted in a simulated roof section with an adjustable pitch; the footwear was pulled at a constant speed using a pulley-winch system (Fig. 1B & D). The pulling speed can be reduced by using different combinations of the pulley system, from the original speed to ¼ speed.

Three different footwear were chosen for testing: two representative roofing boots (RB1 and RB2) and one representative general work boot (GB), as seen in Figure 2. All three boots were tested using both methods of determining the CF, and 35 N of weight was added to each boot for more consistent surface contact. For the pulling-sliding method, trials were conducted at a roof angle of both 0° and 26°, and pulling speeds of 68 mm/s and 17 mm/s. For all combinations of tests, five trials were performed.

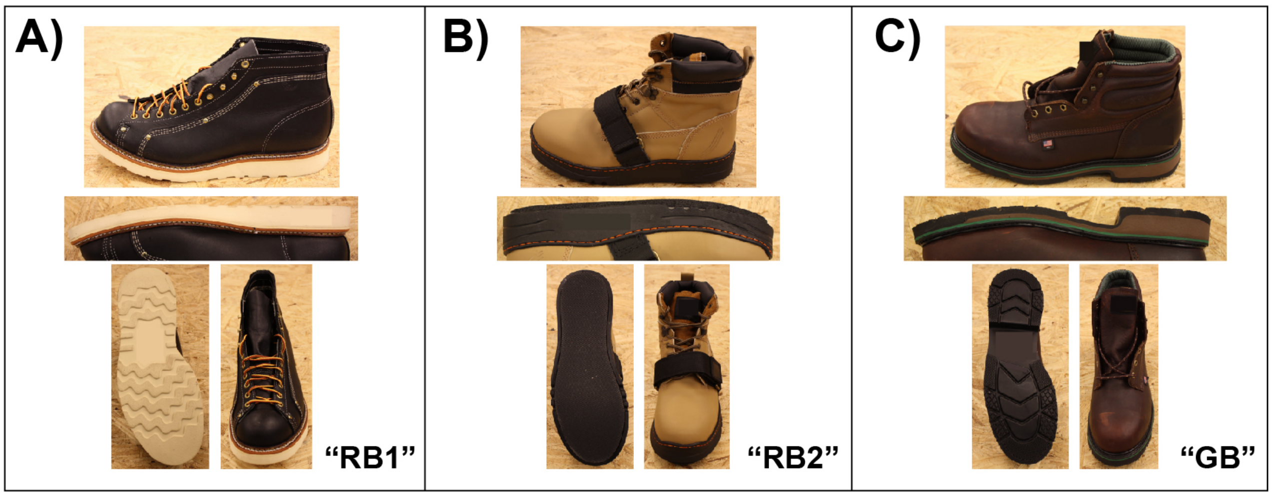


Figure 2. The side, outsole, and front of the three footwear chosen for CF testing: A) roofing boot #1 (RB1), B) roofing boot #2 (RB2), and C) general work boot (GB).

## 2.2 Data analysis

All marker and force plate data were exported from Vicon Nexus and imported into a custom-coded Matlab program (MathWorks, Massachusetts, USA). For the angle of repose method, the $CF_S$ was determined by using the angle of the slope surface, α, when the footwear begins to slip:

$$\mu_s = tan(\alpha) \qquad (1)$$

For the pulling-sliding method, the time history of the CF was determined using $F_S$, the shear force, and $F_N$, the normal force:

$$\mu = \frac{F_S}{F_N} \qquad (2)$$

While the pulling force ramps up, and the footwear is still stationary, the $F_S$ will also increase while the $F_N$ stays the same, increasing the CF value. When the CF reaches a certain value, $CF_S$, the footwear begins to slide. After that, CF magnitude should decrease and reach a steady state level, $CF_K$. The peak value of the CF in the time history is the $CF_S$ and the value at the steady state motion of the footwear is the $CF_K$.

The test results were then analyzed using a commercial statistical software (SPSS 25, IBM, New York, USA) to determine if any statistical significant differences existed between the different methods, footwear, slopes or speeds. Repeated measures analysis of variance (ANOVA) was performed to determine the differences between the $CF_K$ using the pulling-sliding method, applying the Bonferroni correction to reduce the likelihood of making a Type 1 error. A one-way ANOVA with a Bonferroni post-hoc test was used to determine the differences between the $CF_S$ measured using the angle of repose method. All significance levels were set at 0.05.

## 2.3 Method validation

To validate the testing methods, a smooth wooden block (WB) was tested using both methods. As a material with a more homogeneous contact surface profile, the block was expected to provide a more consistent CF result. A mass of 3.6 kg was added to the WB, and it underwent both methods of testing: the angle of repose method and the pulling-sliding method. Paired sample t-tests, using a significance level of 0.05, were used to determine statistical significance between the $CF_S$ of the WB found in the different testing methods.

## 3. Results

The angle of repose method was able to produce results for the $CF_S$ for all objects. The pulling-sliding method did not consistently produce $CF_S$ results, but did consistently yield results for the $CF_K$. The $CF_S$ of the WB was successfully measured using both the angle of repose method, and the pulling-sliding method for 3 out of the 4 combinations used (the combination of 26° pitch angle and slower pulling speed did not produce any $CF_S$ results). The paired t-tests determined that there was no statistical difference between the $CF_S$ of the WB measured using the angle of repose method against those measured in the other three combinations using the pulling-sliding method: 0° pitch angle and faster pulling speed, 0° pitch angle and slower pulling speed, and 26° pitch angle and faster pulling speed.

The pulling-sliding method did not produce any results for the $CF_S$ for the footwear, only for the WB. Therefore, no comparison could be made between the two testing methods for the $CF_S$ of the footwear. The pulling-sliding method did produce results for $CF_K$ for the footwear. The footwear ($p<0.001$), pitch angle ($p=0.047$) and speed ($p<0.001$) were all found to have significant effects on the $CF_K$, as did the interaction effects: footwear and slope ($p<0.001$), footwear and speed ($p<0.001$), slope and speed ($p<0.001$), and footwear, slope and speed ($p=0.008$). The $CF_S$ and $CF_K$ for the three footwear can be seen in Table 1. The angle of repose method produced results for the $CF_S$ for the footwear. The $CF_S$ for RB1 was not significantly different than that of the GB, but both were significantly different than the $CF_S$ of RB2 ($p=0.002$ for both).

Table 1. Static and kinetic coefficients of friction for the three different footwear, where the static coefficient of friction is from the angle of repose method and the kinetic coefficient of friction is from the pulling-sliding method (avg. ± s.d.).

| Parameter (↓) / Footwear (→) | RB1 | RB2 | GB |
|---|---|---|---|
| **$CF_S$** | 1.161 ± 0.044 | 1.360 ± 0.028 | 1.171 ± 0.035 |
| **$CF_K$** | 1.070 ± 0.146 | 1.320 ± 0.229 | 1.202 ± 0.144 |

## 4. Discussion and Conclusion

The results show no significant difference between the $CF_S$ of the wooden block found in both the angle of repose method (Method A) and pulling-sliding method (Method B). This suggests that the pulling-sliding method proposed in this study is fundamentally acceptable. However, the $CF_S$ of the footwear on the roof surface could not be clearly and consistently identified from the measured time-history data. This may be because the initial pulling acceleration was too large. In principle, the measurement of the static CF requires a very slow starting speed to minimize the dynamic effect. This issue may be resolved by reducing the initial pulling speed. Nevertheless, this is not a critical issue, as the focus of the proposed method is to measure the $CF_K$ of the footwear. As shown in Table 1, the $CF_K$ values measured in this study seem very reasonable, which are either marginally less than or similar to the $CF_S$ values. This also suggests the proposed method is at least acceptable for measuring the $CF_K$ of the footwear.

Some rocking motions of the footwear were observed in the experiment, which introduced a large variation of the measured data. This may be due to the asperities in the interaction between the rough OSB and the outsole of the footwear, or possibly because the outsoles of the footwear were not perfectly flat. Further reducing the pulling speed may increase the stability and consistency of the measured data.

Another remaining issue of the test method is that it is the difficulty to apply a high percent of the in-situ ground reaction force to each shoe for the CF measurement. The applied 35 N may represent the low level of normal ground reaction force observed in the initial and end stages of each walking stance. The further development of the testing device requires the design of a special load device to apply various loads in the measurement experiment.

The results listed in Table 1 suggest that the roofers' boots or shoes do have higher CF values than those of many regular shoes. It is also interesting to note that one of the tested shoes (RB2) had significantly higher $CF_S$ and $CF_K$ than the other two models of footwear. These observations suggest that the appropriate footwear selection could make a substantial difference in helping to improve the safety of construction workers. As many professional roofers do not wear roofing boots or general work boots, it is very important to measure their CF values and provide them with reliable information so that roofers or construction workers can make informed decisions.

## 5. Disclaimer

The findings and conclusions in this report are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention. Mention of any company or product does not constitute endorsement by the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention.

## 6. References

Beschorner, K. E., Albert, D. L., & Redfern, M. S. (2016). Required coefficient of friction during level walking is predictive of slipping. *Gait Posture, 48*, 256-260. doi:10.1016/j.gaitpost.2016.06.003

Blanchette, M. G., & Powers, C. M. (2015). Slip prediction accuracy and bias of the SATRA STM 603 whole shoe tester. *J. Test. Eval., 43*(3), 491-498.

BLS. (2018). Occupational Requirements Survey, Physical Demands. Bureau of Labor Statistics, http://www.bls.gov/ncs/ors/physical.htm.

Chang, W. R., & Matz, S. (2001). The slip resistance of common footwear materials measured with two slipmeters. *Appl Ergon, 32*(6), 549-558.

Chang, W. R., & Maynard, W. S. (2006). Factors influencing the slip index measurements with the Horizontal Pull Slipmeter. *Work, 26*(2), 99-105.

CPWR. (2018). Fatal Injuries from Falls to a Lower Level in Construction. In *The Construction Chartbook, The U.S. Construction Industry and Its Workers, sixth edition*. Silver Spring, MD: CPWR.

Gronqvist, R., Abeysekera, J., Gard, G., Hsiang, S. M., Leamon, T. B., Newman, D. J., . . . Pai, C. Y. (2001). Human-centred approaches in slipperiness measurement. *Ergonomics, 44*(13), 1167-1199. doi:10.1080/00140130110085556

Gronqvist, R., Chang, W. R., Courtney, T. K., Leamon, T. B., Redfern, M. S., & Strandberg, L. (2001). Measurement of slipperiness: fundamental concepts and definitions. *Ergonomics, 44*(13), 1102-1117. doi:10.1080/00140130110085529

Gronqvist, R., Hirvonen, M., & Tuusa, A. (1993). Slipperiness of the shoe-floor interface: comparison of objective and subjective assessments. *Appl Ergon, 24*(4), 258-262.

Iraqi, A., Cham, R., Redfern, M. S., & Beschorner, K. E. (2018). Coefficient of friction testing parameters influence the prediction of human slips. *Appl Ergon, 70*, 118-126. doi:10.1016/j.apergo.2018.02.017

Iraqi, A., Cham, R., Redfern, M. S., Vidic, N. S., & Beschorner, K. E. (2018). Kinematics and kinetics of the shoe during human slips. *J Biomech, 74*, 57-63. doi:10.1016/j.jbiomech.2018.04.018