Published in final edited form as:
IIE Trans Occup. 2015 ; 3(2): 115–126. doi:10.1080/21577323.2014.1001501.

Slip Potential for Commonly Used Inclined Grated Metal Walkways

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Abstract

Background—No specific guidelines or regulations are provided by the Mine Safety and Health Administration for the use of inclined grated metal walkways in mining plants. Mining and other companies may be using walkway materials that do not provide sufficient friction, contributing to slip and fall injuries.

Purpose—The purpose of this study was to determine if there are significant differences in the required friction for different grated metal walkways during walking in diverse conditions.

Methods—The normalized coefficients of friction were measured for 12 participants while walking up and down an instrumented walkway with different inclinations (0°, 5°, 10°, 15°, and 20°) and with and without the presence of a contaminant (glycerol). Self-reported slip events were recorded and the required coefficients of friction were calculated considering only the anterior/posterior components of the shear forces. Additionally, the available coefficients of friction for these walkway materials were measured at the 0° orientation using a tribometer, with and without the presence of the contaminant, using a boot heel as well as Neolite as the test feet.

Results—The number of slips increased when the inclination angle reached 10° and above. Of all materials tested, the diamond weave grating was found to have the best performance at all inclines and when contaminated or dry. A high number of slips occurred for the perforated grating and serrated bar grating at 20° when contaminated.

Conclusions—Results of this study suggest that the diamond weave grating provides significantly better friction compared to serrated bar and perforated gratings, especially at inclines greater than 10°.

Keywords

Required coefficient of friction; available coefficient of friction; inclined walkway; walkway grating; slip

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CONFLICT OF INTEREST
The authors declare no conflict of interest.

INTRODUCTION

Inclined walking surfaces are common in mining plants where materials are transported between processing equipment and storage locations via conveyor belts. These belts are usually flanked by grated inclined walkways for users to gain access to the belts for inspection, maintenance, and repair. Level grated walkways are also common. Grated walkway materials are used to discourage accumulation of debris and liquids on the walkways. However, several types of grated walkway materials exist, all with different performance and recommended usages. When walkway materials offer less friction than required by the particular conditions, the likelihood of a slip event is increased (Redfern et al., 2001). Slip events in industrial settings are attributable to biomechanical factors, frictional factors, or combinations of both. Biomechanical factors which affect slip events include factors such as stride length, heel strike velocity, cadence, and center of mass kinematics, each of which vary by the person and are therefore hard to modify in an industrial setting (Chang, Matz, & Chang, 2013). Frictional factors consider the interaction between the shoe and the floor, which has the potential to be better controlled in an industrial setting.

On any walking surface, a slip occurs when the friction utilized by the person during walking (known as the required friction) exceeds the available friction at the shoe-floor interface (Leamon & Li, 1991). The required coefficient of friction (RCOF) is typically determined during a person's gait. Over the period from heel strike to toe off, most of the body's weight is supported by one foot. During this time, there are normal and shear components of the ground reaction forces acting on the person's foot by the floor. These normal and shear forces are measured and used to determine the peak RCOF during walking. The available coefficient of friction (ACOF) is determined from testing a walkway material using a slipmeter or tribometer. The ACOF is considered a material property; however, it is dependent upon the material of the foot/shoe surface that is used for testing.

Many factors have been correlated with slip probabilities including the ACOF as well as the computed difference between the ACOF and RCOF (Hanson, Redfern, & Mazumdar, 1999; Chang, 2004; Burnfield & Powers, 2006). Using logistic regression models, Burnfield and Powers (2006) estimated the probability of a slip occurring for participants performing level walking at a self-selected pace on normal and reduced friction surfaces. Two regression models were generated, one utilizing the computed difference between the ACOF and the RCOF as the predictor variable and the other using the ACOF as the predictor variable. Both models used the slip outcome as the dependent measure. The authors reported a 1% probability of a slip occurring when ACOF exceeded RCOF by 0.077, a 50% probability when RCOF exceeded ACOF by 0.006, and a 99% probability when RCOF exceeded ACOF by 0.090. Using ACOF alone, they reported an 81% chance of slipping when ACOF = 0.153, which was decreased to only 6% when the ACOF was nearly doubled to 0.308. In an analysis of a ramp inclined to 0°, 10°, and 20°, Hanson et al. (1999) reported that when the dynamic coefficient of friction (DCOF) provided by the walking surface exceeds the RCOF by 0.52, the probability of a slip is 1%. When the DCOF exceeds the RCOF by 0.16, the probability of a slip increases to 50%. In Hanson and colleagues' (1999) work, the DCOF was measured using a programmable slip resistance tester, which recorded the horizontal and vertical forces while a shoe assembly was moved across a level flooring-surface. The heel of the shoe contacted the floor at a 5° angle with respect to the horizontal. The DCOF was calculated as the ratio of the horizontal force measured by the tester to the vertical force applied by the tester, and is a measure of the dynamic friction during this motion. Unlike the DCOF, the ACOF reported by Burnfield and Powers (2006) was measured using a variable incidence tribometer, and the slip index was based on the angle of incidence between the test foot and test surface at the time when the test foot slipped on the test surface.

In addition to walkway angle and frictional requirements, walking direction is an important factor for slips on inclined surfaces. Gait characteristics and frictional requirements change when walking uphill versus downhill. When compared to level walking, walking uphill causes increased stride lengths and decreased cadences and walking downhill causes shorter stride lengths and faster cadences (Kawamura, Tokuhiro, & Takechi, 1991; Sun, Walters, Svensson, & Lloyd, 1996). When walking downhill, there is an increase in shear force, thereby increasing the RCOF necessary for safe walking. Some believe this contributes to the increase in slip events occurring when walking down inclined walkways (Greive, 1983; Redfern & DiPasquale, 1997). By taking shorter strides, which is thought to reduce the frictional demands, people attempt to compensate for this increased requirement (Sun et al., 1996). Redfern and DiPasquale (1997) found the RCOF when descending ramps to increase from 0.2 for a level surface to 0.45 for the same surface inclined at 20°. McVay and Redfern (1994) also found RCOF values ranging from 0.6 to 1.10 when participants ascended inclined walkways of 20° and 0.45 to 0.60 when descending these walkways. Peak RCOF values are generally higher when walking uphill than downhill. However, most injuries from falls occur when walking downhill and are likely attributable to the momentum of the body in addition to the properties of the walkway. With the higher RCOF comes a higher potential for slip and fall accidents. Predicting the risk of these accidents for grated metal inclined walking surfaces based on frictional measures is an area of occupational safety that has not received any attention.

In this research study, the ACOF and RCOF of three commonly used grated metal walkways were examined at a range of inclination angles, with and without a glycerol contaminant, and for both uphill and downhill walking. Results of this research will aid in providing guidance for the design and usage of inclined grated metal walkways in mining and other industrial settings.

METHODS

Walkway Materials

Three types of grated metal walkway materials commonly observed in mining plants were selected for investigation (Figure 1). These materials were (1) a diamond weave material (Grip Strut®, McNichols Company, New Brunswick, NJ, USA, galvanized ASTM A525, 12 gauge, 8 diamond plank, hereafter referred to as Grip Strut), (2) a circular perforated pattern (Perf-O Grip®, McNichols Company, New Brunswick, NJ, USA, galvanized ASTM A525, 13 gauge, 10 hole plank, hereafter referred to as Perf Grip), and (3) a serrated rectangular bar type (McNichols Company, New Brunswick, NJ, USA, galvanized, hereafter referred to as Ser Bar).

ACOF Testing Procedure

ACOF testing was used to determine a baseline measure of the slip resistance afforded by the differing walkway materials. Although the materials did not appear to be directional, friction measurements were taken in the uphill and downhill directions at the level position. A portable, inclinable, articulated strut tribometer (PIAST; Qualitest, Plantation, FL, USA, slipmeter model QT-7012-M2) was used to measure ACOF for all walkway materials, contaminated and dry. To improve stability, the three rubber feet on the base of the PIAST were replaced with larger diameter magnetic feet. This did not change the height of the base and allowed for sturdier placement on walkway surfaces. To prevent the PIAST from moving around on the walkways during testing, angle iron was cut to fit the walkway width, placed at each end of the PIAST and clamped to the walkway frame (Figure 2). Not only did the angle iron hold down the PIAST and prevent it from sliding on the walkways, it also ensured that the PIAST was placed at the same position for each surface material during multiple trials.

The test method used for PIAST testing has been previously described (Chang, 2002; American Society for Testing and Materials, 2005; Chang, Lesch, & Chang, 2008; Li, Chang, & Chang, 2009; Chang, Brunette, & Chang, 2010; Liu, Li, Lee, Chen, & Chen, 2010; Li, Chen, Chen, & Liu, 2012). Two samples of each walkway material were used in the study to create the dry and contaminated surface conditions. A 19.7 cm × 38.1 cm section of each walkway material was outlined as the testing area for the PIAST to ensure consistent placement of the PIAST. Care was taken to ensure that the PIAST was situated so that the ends of the footwear pads would not catch on the tread of the walkway surfaces. Before each friction measurement, all footwear materials were wiped with a 50% denatured alcohol solution, wiped with a clean paper towel, and blown dry with a hair dryer on the lowest heat setting. The blow dryer was used to provide air motion on the surface of the footwear samples and not to dry via heat. For the contaminated conditions, a glycerol solution (2:1 Glycerol to water solution) was sprayed on the walkway materials after cleaning with the 50% denatured alcohol solution (Chang et al., 2008).

Commonly used Neolite was used as the test material (test foot) along with a boot heel (Figure 3). The Neolite was purchased from a local cobbler and the boot heel was removed from the sole of a pair of boots (Swat Work Boot, BRAHMA®, China, U.S. size 13) used in the RCOF portion of this study. The boot heel was used as the test foot of the PIAST since inclined strut devices simulate a slip from a heel strike (Chang & Matz, 2001). Both samples were cut to 7.62 cm × 7.62 cm squares and attached to the PIAST specimen holder. Two of each footwear sample were also used—one set for contaminated conditions and the other for dry conditions. Each footwear sample was sanded with 150-grit silicon carbide abrasive paper followed by 400-grit silicon carbide abrasive paper, as described by Chang and Matz (2001). Multiple samples of Neolite were used, as it often became pitted after testing and had to be replaced if the pits were not easily removed by sanding.

Initial ACOF testing found the Ser Bar grating to have a dramatic reduction in ACOF when the contaminant was used. The authors believed this degradation was likely attributable to the surface features of this walkway material. Ser Bar features a series of serrated bars which are connected by perpendicular straight rounded metal bars, (see Figure 4). When mounted per the manufacturers' specifications, these rounded bars created a level surface above the height of the serrations in the direction of walking. When contaminated, these bars significantly reduced the available friction at the floor surface. When conducting ACOF testing, the authors initially oriented the PIAST such that this rounded bar was in the center of the test foot. This resulted in ACOF values less than 0.15, which the authors believed were too low and would bias results. During RCOF testing, participants were not given any instructions on how to walk up or down the walkway. It is likely that many participants did not contact the walkway material in a manner such that their heel landed on the elevated round bar portion of the surface. For these reasons, we decided to conduct ACOF testing of Ser Bar a second time, but to change the test location such that the test foot was located on an area with only the horizontal serrated bars. Although the results from the initial test were valid, the results for the second set of testing were more consistent with results for the other materials. We did not want to improperly characterize a material that is commonly used in many environments, including those outside of mining. Therefore, we repeated the frictional measurement on a different portion of the surface which did not have the raised bars. The results from ACOF testing on the section of the walkway without the rounded bars are presented subsequently.

All measures were taken until the PIAST had three sequential tests yielding the same ACOF. ACOF analysis was conducted using a four-factor (three walkway materials × two sole materials × two contaminant conditions × two directions) randomized experimental design. The protocol for judging a slip or non-slip of the PIAST is described in Chang (2002).

RCOF Testing Procedure

A custom designed instrumented walkway was used to simulate an inclined walkway in a mining plant (Figure 5). This walkway included handrails and toe plating along both sides as seen in typical mining plants. The handrails provide the first line of protection in the event of a slip event, with additional body support provided by a fall-arrest system equipped with a self-retracting fall limiter. A standing platform was provided at the top of the walkway to allow participants to rest between walking trials and to serve as a flat surface for initiation of the downward walking trials. The incline of the ramp was increased (or decreased) by moving the standing platform upward (or downward) using a forklift. When the ramp was at the 0° condition (no incline), the standing platform was flat on the floor and parallel to the walkway surface. This simulated walkway was equipped with two strain gauge-based force plates (OR6-7-1000, AMTI, Watertown, MA), which were mounted below the walkway material, in the center of the walkway, and hidden from participant view.

Twelve participants (3 women, 9 men) were recruited from the National Institute for Occupational Safety and Health (NIOSH) in Pittsburgh, PA, USA. Their mean (standard deviation) age, height, and body mass were 31 (6) years, 176.3 (8.4) cm, and 89 (21.1) kg, respectively. After reading and signing an informed consent form approved by the NIOSH

Institutional Review Board (IRB), all participants were required to wear standardized safety equipment which included a fall-protection harness connected to a self-retracting fall limiter (3.35 m Miller MiniLite® Fall Limiter Model FL11-3-Z7-11FT; Miller Fall Protection by Honeywell, Franklin, PA, USA) and steel-toed safety boots (Swat Work Boot, BRAHMA®, China). For standardization, all participants wore the same make and model boots. Boot sizes were available from men's 7 to men's 13 in half-size increments. Participants were instructed to walk at a self-selected pace up the instrumented walkway without grasping the handrails, to stop when they reached the top, and then to walk back down the walkway without grasping the handrails. Participants were not told to make contact with the force plates. If the participant failed to make contact, they were instructed to repeat the trial after having their starting point adjusted by a researcher. Although two force plates were mounted in the walkway, the participant was only required to make full foot contact with one plate. After each trial, the participants were asked if they "felt like they slipped" and their responses were recorded.

Testing consisted of three walkway materials (Grip Strut, Perf Grip, and Ser Bar), five inclines (0°, 5°, 10°, 15°, and 20°), two walking directions (up and down), and two surface conditions (contaminated and dry). All walkway materials were installed per manufacturer specifications for the length of the walkway. Testing conditions occurred in blocks (six blocks) classified by the surface conditions (contaminated Ser Bar, contaminated Perf Grip, contaminated Grip Strut, dry Ser Bar, dry Perf Grip, and dry Grip Strut). The order of these blocks was randomized, and within these blocks, the order of the angles was randomized. Participants always walked up the walkway first then completed the down trials. Two sets of walkway materials were used such that one set remained dry and the other set remained contaminated for the duration of the study. The contaminated materials were initially coated in 99.99% Glycerol using a deck brush and sprayed with a rewetting solution (2:1 Glycerol to water solution) between trials. Participants were told that the walkway was contaminated or dry prior to the start of each trial. Participants' boots were cleaned with water and dried between contaminated and dry conditions to remove any contaminant. For each trial, the slip outcome had two levels (no slip and positive slip). A positive slip consisted of a self-perceived slip (a slip where the participants felt themselves slip) and a negative slip was when the participants did not feel themselves slip.

RCOF and NCOF

Normal forces (*Z*-axis) were perpendicular to the surface of the walkway and shear forces were in the anterior/posterior (*X*-axis) direction with the positive *X*-axis in the direction of the bottom of the ramp (Figure 5). Heel strike was determined from force plate data as the first data point with a normal force larger than 15 N to account for any noise in the force measures (O'Connor, Thorpe, O'Malley, & Vaughan, 2007). Normal force plots were inspected to ensure that clear heel strike and toe-off events were present. Trials without such clear events were excluded from this analysis. Additionally, data from those participants who did not show a characteristic heel strike and toe-off (e.g., those who walked on the balls of their feet) were excluded from this analysis. The period from heel strike to toe-off was normalized to a unit length of 1000 points. The RCOF for dry conditions and the achieved coefficient of friction for the contaminated conditions in the anterior/posterior direction (hereafter referred to as $RCOF_x$ for both dry and contaminated conditions) was calculated for all trials by dividing the absolute value of the anterior/posterior ground reaction force by the normal force for all points where the normal force exceeded 50 N. If the normal force was less than 50 N, $RCOF_x$ was set to zero (McVay & Redfern, 1994). The peak $RCOF_x$ was determined for early stance (10%–30% of the stance) for the downhill walking trials and late stance (70%–90% of stance) for the uphill walking trials. The normalized coefficient of friction (NCOF) was defined as the difference between the ACOF value found using the boot sole and the peak $RCOF_x$ values (Siegmund, Heiden, Sanderson, Inglis, & Brault, 2006).

Separate repeated measures analyses of variance (ANOVA), each with an alpha level of 0.05, were conducted on the NCOF and $RCOF_x$ values for no slip outcomes. No RCOF values were available for trials where participants slipped, so these trials were necessarily excluded. Uphill and downhill walking are very different from a biomechanical perspective and therefore were analyzed separately.

RESULTS

ACOF Testing

Results of the ACOF testing are shown in Table 1. ACOF values of ">1" are cases where the PIAST did not slip within its calibrated range, indicating an ACOF greater than 1.

RCOF Testing

A total of 44 slip events were reported by participants. Slips occurred on all walkway surfaces, in both contaminated and dry conditions, as well as up and down directions. Most (75%) slips occurred at the 20° incline when walking on contaminated walkways. An equal number of slips (22) occurred for the uphill and downhill walking directions. The distribution of slip events is provided in Table 2. Results for uphill and downhill walking are presented in Figures 6 and 7, respectively.

For both walking directions, statistically significant differences in $RCOF_x$ measures were found between participants ($p < 0.001$) and materials ($p < 0.001$). Downhill walking was also found to have significant differences in $RCOF_x$ measures between contaminant conditions ($p = 0.001$) and walkway angles ($p < 0.001$). Significant interactions were found between the walkway material and angle for both downhill ($p = 0.0004$) and uphill ($p = 0.004$) walking directions. Uphill walking also showed a significant interaction between walkway material and contaminant ($p = 0.003$).

NCOF Values

Table 2 shows NCOF values with corresponding $RCOF_x$ measures for all trials. Scatter plots showing the number of slip events by the NCOF values for uphill and downhill trials are shown in Figures 8 and 9, respectively. In general, slips occurred more frequently for uphill trials at lower NCOF values compared to the downhill trials. Significant differences in NCOF measures were found between participants ($p < 0.001$), materials ($p < 0.001$), and contaminants ($p < 0.001$) for both uphill and downhill trials. Downhill trials also showed significant differences in NCOF measures between walkway angles ($p < 0.001$). Significant interactions were found between the material and angle ($p = .004$), as well as between the material and contaminant ($p < 0.001$), for both uphill and downhill trials. Perf Grip was the only material found to have slips when dry, and which occurred at 20° for both uphill and downhill walking. One slip event occurred for contaminated Grip Strut when walking downhill at 20°.

DISCUSSION

Many studies have examined the slip probabilities and frictional requirements for inclined and level walking on a variety of surfaces. To the authors' knowledge, though, this is the first study to examine the effect of grated metal walkways on frictional requirements when walking up and down inclined walkways. Moreover, this study is the first to examine grated metal walkways with and without the presence of a contaminant.

The ACOF represents the maximum friction that can be supported without slipping at the shoe-floor interface (Chang et al., 2013). The higher the ACOF, the less likely a slip will occur. Under this theory, and given the present results (Table 1), it would be expected that the least number of slips occur using Grip Strut, more slips occur using Perf Grip, and even more slips would occur using Ser Bar. As previously noted, the ACOF depends on the material being tested as well as the material being used as the test foot. Differing ACOF values were found here when using the boot sole and Neolite. It was expected that higher ACOF values would be found when using the Neolite instead of the boot sole because the boot soles were also treaded, and may not allow for full contact with the treaded walkway materials. This was true for Grip Strut and Perf Grip but was not evident for the dry and contaminated downhill and the dry uphill Ser Bar conditions. It is unclear what properties of Ser Bar gave it an increased available friction when using the boot sole. This may also have been an effect of the PIAST and there is potential that using a different method to evaluate available friction, such as one that utilizes actual test feet capable of producing heel contact in a way comparable to human gait, may have led to more consistent values using the Neolite and boot sole. Available friction provided by walkway materials should be investigated further with different boots that are worn by mine workers and other industrial workers.

Of the materials examined, Grip Strut showed the best performance in the contaminated and dry conditions, in terms of yielding the fewest perceived slip events. Ser Bar led to the next fewest events, followed by Per Grip. These results appeared to contradict static ACOF results. Ser Bar had a smaller ACOF than Perf Grip for both contaminated and dry conditions. This was unexpected when considering the open area of these grated materials. The authors expected Ser Bar to provide better slip prevention than Per Grip in the contaminated conditions because there is less available surface area for the contaminant to accumulate. This effect was not seen in the ACOF measurements, but may have contributed to the reduced number of slips when compared to Perf Grip. Conversely, less open area would also mean more area for surface contact, which may improve traction through increased friction.

Dry slips only occurred for the Perf Grip grating at the 20° incline. In all glycerol contaminated cases, participants were told that the surface was slippery, which allowed them to manipulate their gait as they deemed necessary for safe walking without grasping the handrails. Siegmund and colleagues (2006) evaluated the effect of subject awareness on tribometer-based predictions of slip probability and found that normalizing the friction by using the computed difference between the ACOF and the RCOF removes about half of the bias introduced by awareness and prior slip experience. Moreover, they found that having a prior slip experience generated a slip risk curve that was not significantly different from that of a deceived subject. Gait modifications due to knowledge of the slippery surface may have allowed some (but not all) participants to safely walk along the surfaces examined in this study. These adaptations may also explain how, in some of the trials, the $RCOF_x$ in the contaminated conditions were higher than those in the dry conditions. Further research is necessary, though, to determine why only three out of 12 participants did not slip on any of the contaminated inclined surfaces.

Downhill walking is considered inherently more dangerous than uphill walking due to the increased risk of a slip resulting in a fall. As such, the conditions associated with the slip events in the downhill direction are more relevant to fall risk. Slips are most dangerous when they occur during early stance when walking downhill and late stance when walking uphill. For these reasons, the peak $RCOF_x$ values were only found during these time periods. Higher $RCOF_x$ values were present at differing points during the stance period; however, we focused on those values that would likely be more dangerous.

LIMITATIONS

In this study, every participant wore the same make and model of new work boots with ample tread. Additionally, walkway materials were all new and free from wear. In practical applications, however, normal wear and tear will reduce the traction provided by both the footwear and the grating materials, resulting in reduced slip protection. As such, material performance is expected to decline when subjected to the normal wear and tear of industrial settings. All employee work boots and walkway materials should be monitored and routinely assessed to ensure adequate slip protection is provided in contaminated and clean conditions. Additionally, even though glycerol is ubiquitous in tri-bology lab studies, and was used as the contaminant here, it may not be the typical contaminant in mining environments where ice, snow, motor oil, or lubricants are more likely to contaminate walkways.

Although other studies have included both the medial/lateral and anterior/posterior components of the shear force in the calculation of the RCOF, the medial/lateral force was neglected here for several reasons. A primary focus of this research was to compare the RCOF to the ACOF. Furthermore, the PIAST did not have a medial/lateral shear component. Therefore, we believe that it would not have been valid to compare a frictional value that included medial/lateral shear to one that did not. Additionally, inclined walkways are flanked with handrails to provide protection on either side and would provide fall protection from a side-to-side slip. On these types of walkways, a fall would be more likely to result from a slip in the forward or backward direction, not to the side. In these slips, the anterior/posterior component of the shear force would make a greater contribution to a slip;

the medial/lateral shear force could reduce this contribution, implying a reduced frictional requirement.

The PIAST uses impact and is not biomechanically fidelic, which did not allow the serrations of the grating materials to dig into the test surface the same way a heel would during a step. Using a different method to evaluate available friction, which utilizes actual test feet capable of producing heel contact in a way comparable to human gait, may have alleviated this issue. Therefore, using the PIAST was a limitation of this study.

In this study, self-reported slip events were recorded. The goal of this research was to contribute to prevention of those slips which would require corrective action or result in a fall in an industrial setting. Leamon and Li (1990) determined that slip distances less than 30 mm (microslips) may not always be detected, but that slip distances exceeding 30 mm would be consistently perceived as slippery. Slips between 30 to 100 mm may result in corrective action and those exceeding 100 mm most often result in falls. Those slip distances which will have the greatest potential for slipping or requiring a corrective action, such as grabbing a handrail, were of interest in this study. In contrast, those microslips that happen frequently without being detected were not of interest. As such, we consider that it was reasonable to use self-reported slipping to determine the slip rates.

Participants were not given any specific instructions on how to walk during experimental trials and were told to simply “walk normally.” Some participants may have modified their gait for both the dry and contaminated trials due to their anticipation of a slippery environment. This was likely constant throughout the experimental conditions, but should be considered a limitation of this research. Normal force plots were inspected to ensure a clear heel strike and toe-off for all non-slip trials, and trials without clear data were excluded from this analysis. In some instances, participants did not show the characteristic heel strike and toe-off because their heels did not make contact with the force plates or the walkway during the trial. Eleven trials were identified where the participant exhibited a gait pattern where they walked on their toes or the balls of their feet, thereby never making heel contact with the walkway surface. We excluded these data from analysis because the ACOF measurements were conducted using heel samples from the boots, not mid-sole samples, and we believed that this would not have been a valid comparison.

The authors acknowledge that a small sample size was used; however, an estimate of the slip rates may still provide meaningful results. The current experimental design included randomization and a naïve participant population, both of which should have minimized any learned effects or expectancy bias associated with previous knowledge of the walkway materials. Additionally, the results from the study conducted by Hanson et al. (1999) included a sample of five healthy adults and has made a significant contribution to the understanding of required and available friction. Other than the current study, no data were available to help choose walkway materials and despite the noted limitations, the results do provide evidence of differences between the grated walkway materials examined.

CONCLUSIONS

Inclined grated metal walkways are common in many industrial settings and should be considered when preventing slip and fall accidents. Although MSHA provides no specific regulations for the usage of metal gratings or the specific design angles at U.S. mine sites, results of this study indicate that grated metal walkways installed at angles exceeding 10° should be closely monitored due to the increased risk for slip events. In cases where walkways are necessary, grated metal with the diamond weave pattern may be preferred over those with serrated bars or circular perforation patterns for reducing slip events. The presence of the glycerol contaminant increased the chances for slipping at walkway angles as small as 10° from the horizontal. Companies should be discouraged from using perforated and serrated bar gratings in any areas where ice, water, or grease are common and should be cautioned when installing these materials on inclined surfaces greater than 10°. Manufacturers of serrated bar grating should attempt to recess the vertical, supporting bars such that the serrated grating extends at least 2 mm (typical safe tread depth for shoes) above the height of the supporting bars. This will eliminate the elevated metal rod, which the authors believe contributed to the poor performance of this material in the initial testing of the contaminated ACOF conditions. Serrated bar grating may only afford good slip-resistance when workers are careful to avoid the raised rods, though this may not be possible due to worker fatigue, poor visibility, or worker distraction. In practical applications, and depending on where along the serrated bar grating surface a person makes heel contact, heel strike could likely result in a slip under wet conditions.

Acknowledgments

The authors acknowledge the technical contributions of Timothy Matty, Mary Ellen Nelson, and Albert Cook for designing and constructing the inclined walkway and April J. Chambers, PhD, for assistance with data analysis methodologies. The authors also wish to thank the employees of the Office of Mine Safety and Health Research in Pittsburgh, PA, for their willingness to participate in this study. The findings and conclusions in this report are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health. Mention of any company or product does not constitute endorsement by the National Institute for Occupational Safety and Health.

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OCCUPATIONAL APPLICATIONS

Grated walkway materials are used to discourage accumulation of debris in environments where spillage is likely. Several types of grated walkway materials exist and the choice of walkway material impacts the likelihood of a slip event. In this research, the normalized coefficients of friction were examined for three commonly used grated metal walkways at 0°, 5°, 10°, 15°, and 20°, during both contaminated and dry conditions, and for uphill and downhill walking. Slips were found to occur at inclines as low as 10° from the horizontal, with a high proportion of slips occurring at 20° in the contaminated conditions. The fewest slips occurred during trials for the diamond weave grating. As such, the authors suggest that this grating is preferable for preventing slips, compared to serrated bar or perforated gratings similar to those examined here.

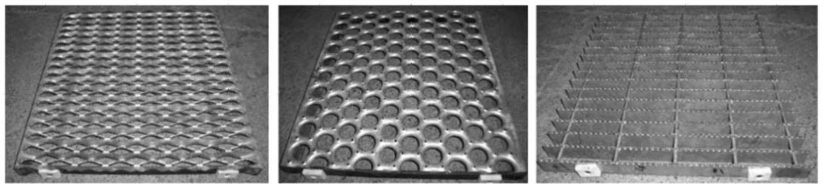

FIGURE 1.
Images of Grip Strut (left), Perf Grip (middle), and Ser Bar (right) materials used in this study.

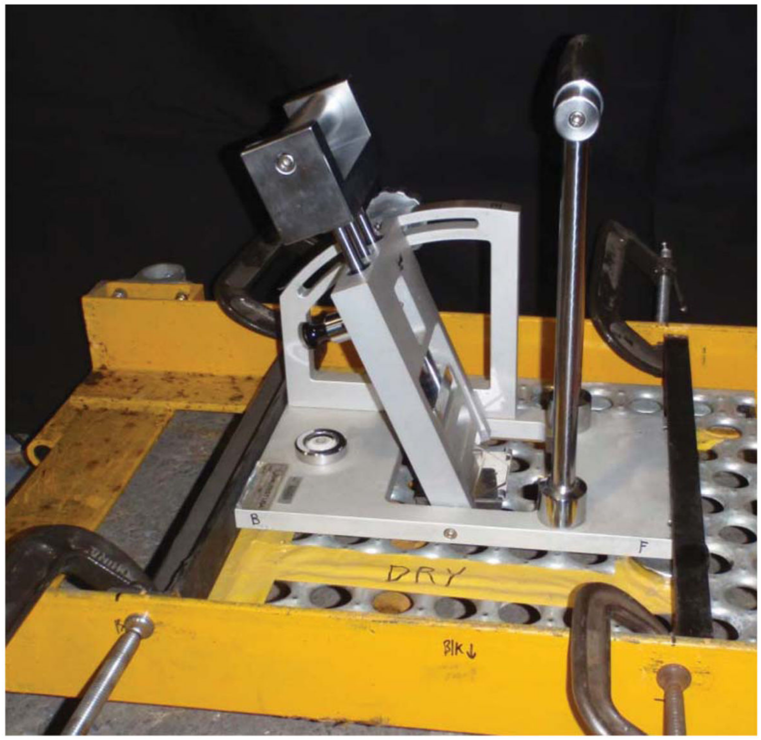

FIGURE 2.
PIAST secured to walkway on a level surface in marked area for the dry Perf Grip condition.

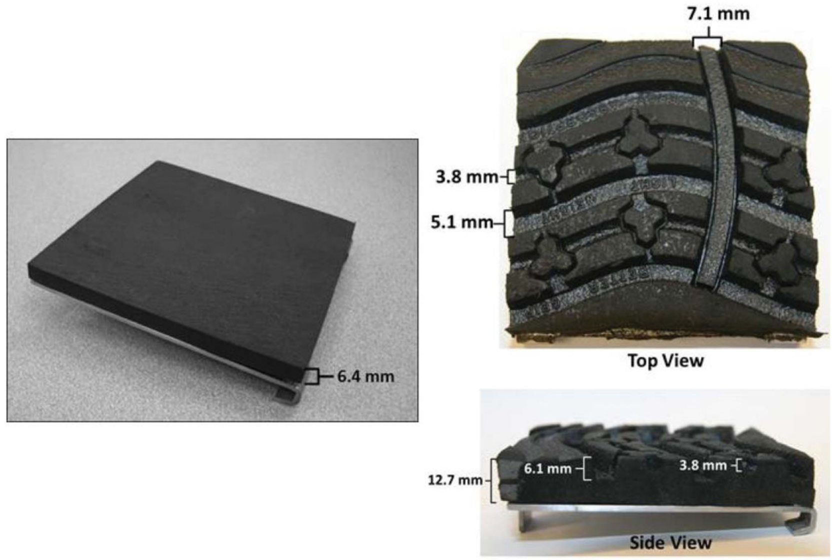

FIGURE 3.
(Left) Smooth Neolite footwear sample and (right) boot sole sample front and side views. Relevant measurements of the samples are also indicated.

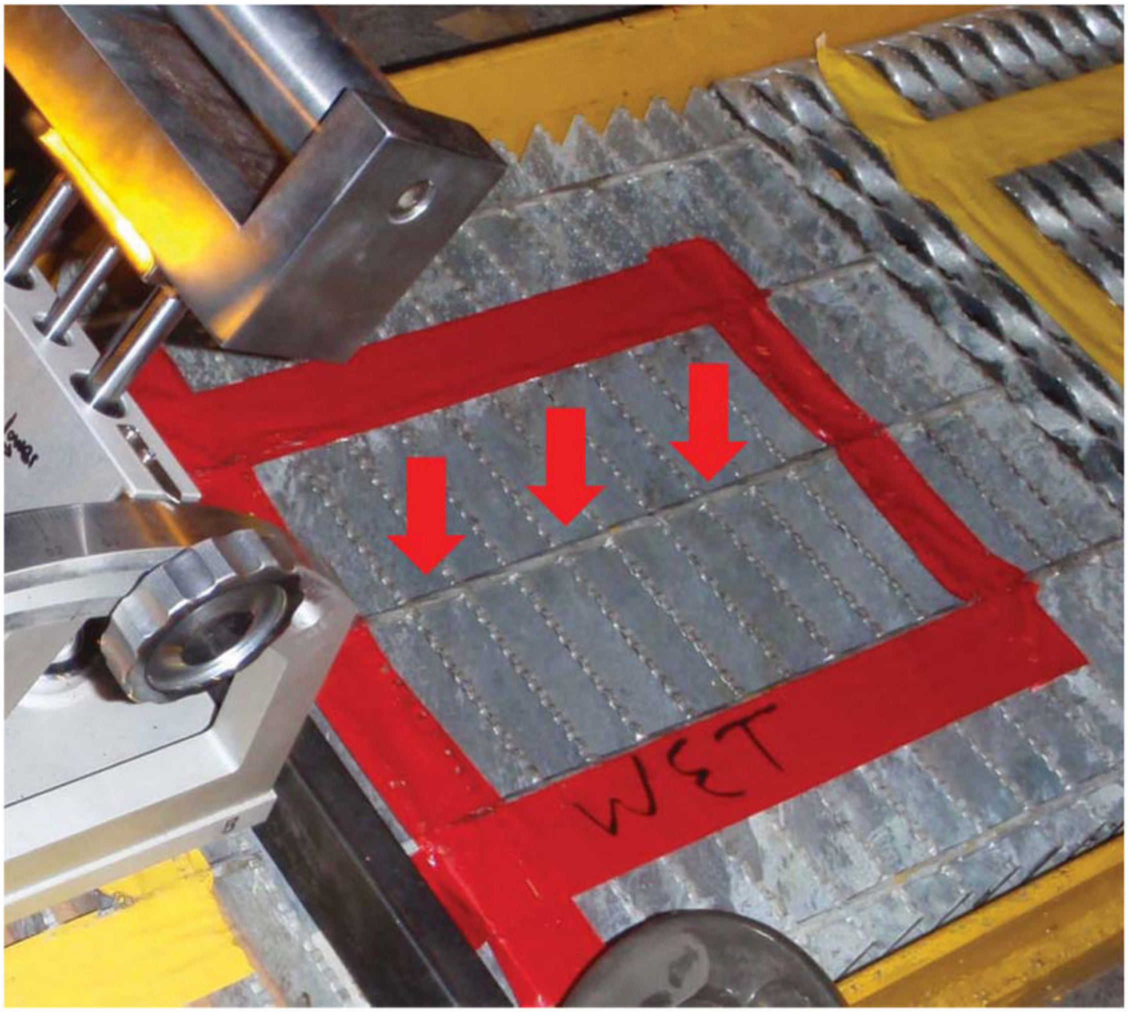

FIGURE 4.
Close-up view of serrated bar grating; notice the raised height of the perpendicular, straight, rounded bars.

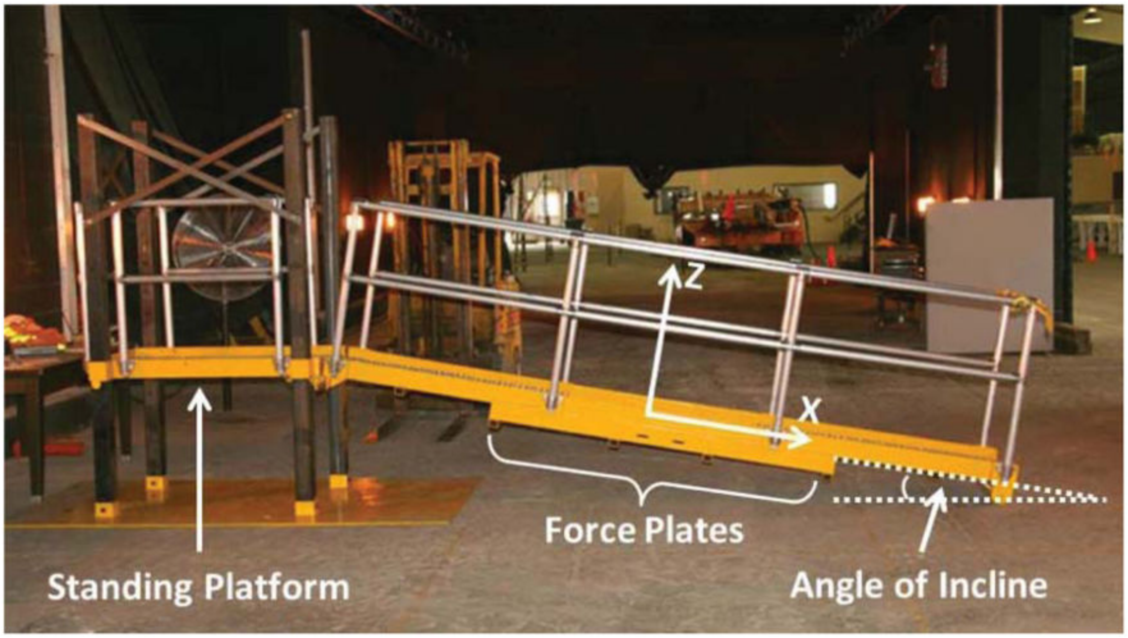

FIGURE 5.
Instrumented walkway used in the study showing the standing platform and location of force plates.

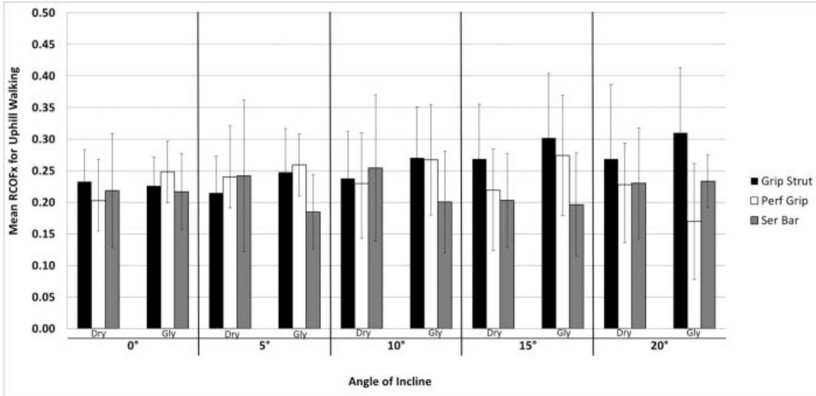

FIGURE 6.

Mean $RCOF_x$ measures for uphill walking on dry and glycerol contaminated (Gly) walkways at the five angles of incline. Error bars denote one standard deviation. Results are presented for those trials in which the participants did not slip.

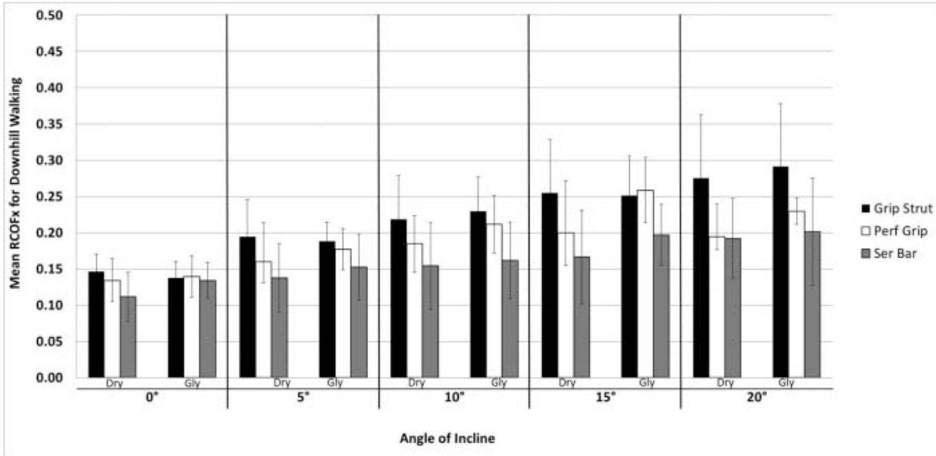

FIGURE 7.

Mean $RCOF_x$ measures for downhill walking on dry and glycerol contaminated (Gly) walkways at the five angles of incline. Error bars denote one standard deviation. Results are presented for those trials in which the participants did not slip.

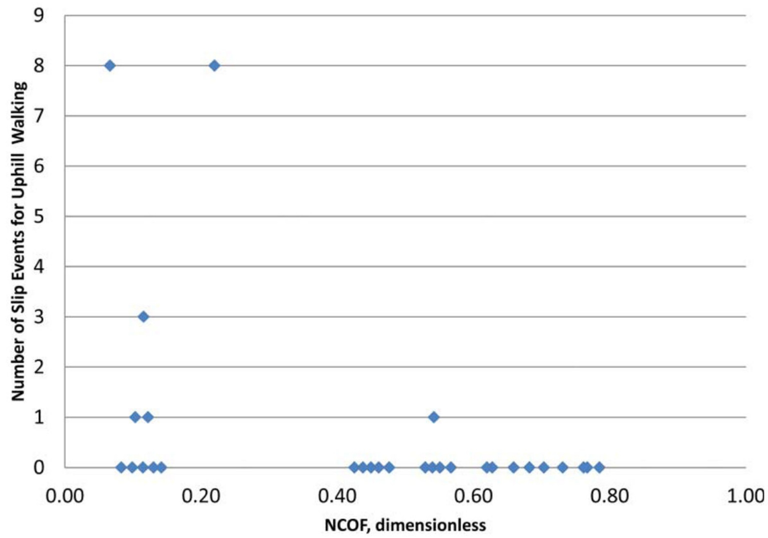

FIGURE 8.
Number of slips for uphill walking trials by NCOF for all materials at all inclines with or without contaminants. NCOF values shown are for all walkway materials and angles.

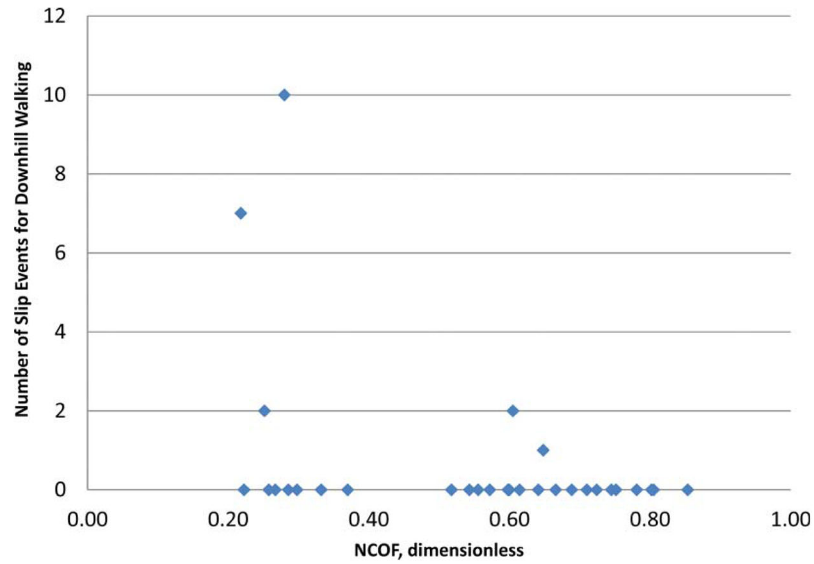

FIGURE 9.

Number of slips for downhill walking trials by NCOF for all materials at all inclines with or without contaminants. NCOF values shown are for all walkway materials and angles.

TABLE 1

ACOF values when using Neolite and the boot sole for all walkway materials at 0° of incline

Material	Direction	Contaminant	ACOF using Neolite	ACOF using boot
Grip Strut	Up	Gly	0.96	0.93
	Up	Dry	>1.00	>1.00
	Down	Gly	>1.00	0.94
	Down	Dry	>1.00	>1.00
Perf Grip	Up	Gly	0.70	0.39
	Up	Dry	>1.00	0.77
	Down	Gly	0.78	0.51
	Down	Dry	0.91	0.80
Ser Bar	Up	Gly	0.39	0.30
	Up	Dry	0.53	0.68
	Down	Gly	0.36	0.42
	Down	Dry	0.58	0.71

TABLE 2

Distribution for slip events by walkway material showing the $RCOF_x$ means and NCOF values

			Uphill trials			Downhill trials		
Material	**Angle**	**Contaminant**	**Mean $RCOF_x$**	**Slip rate**	**NCOF**	**Mean $RCOF_x$**	**Slip rate**	**NCOF**
Grip Strut	0	Dry	0.23	0	0.77	0.40	0	0.85
Grip Strut	5	Dry	0.21	0	0.79	0.32	0	0.81
Grip Strut	10	Dry	0.24	0	0.76	0.33	0	0.78
Grip Strut	15	Dry	0.27	0	0.73	0.28	0	0.75
Grip Strut	20	Dry	0.27	0	0.73	0.46	0	0.72
Grip Strut	0	Gly	0.23	0	0.70	0.34	0	0.80
Grip Strut	5	Gly	0.25	0	0.68	0.64	0	0.75
Grip Strut	10	Gly	0.27	0	0.66	0.48	0	0.71
Grip Strut	15	Gly	0.30	0	0.63	0.64	0	0.69
Grip Strut	**20**	**Gly**	**0.31**	**0**	**0.62**	**0.50**	**0.08**	**0.65**
Perf Grip	0	Dry	0.20	0	0.57	0.36	0	0.67
Perf Grip	5	Dry	0.24	0	0.53	0.26	0	0.64
Perf Grip	10	Dry	0.23	0	0.54	0.28	0	0.61
Perf Grip	15	Dry	0.22	0	0.55	0.23	0	0.60
Perf Grip	**20**	**Dry**	**0.23**	**0.08**	**0.54**	**0.22**	**0.17**	**0.61**
Perf Grip	0	Gly	0.25	0	0.14	0.33	0	0.37
Perf Grip	5	Gly	0.26	0	0.13	0.32	0	0.33
Perf Grip	**10**	**Gly**	**0.27**	**0.08**	**0.12**	0.49	0	0.30
Perf Grip	**15**	**Gly**	**0.27**	**0.25**	**0.12**	**0.32**	**0.17**	**0.25**
Perf Grip	**20**	**Gly**	**0.17**	**0.67**	**0.22**	**0.49**	**0.83**	**0.28**
Ser Bar	0	Dry	0.22	0	0.46	0.28	0	0.60
Ser Bar	5	Dry	0.24	0	0.44	0.32	0	0.57
Ser Bar	10	Dry	0.25	0	0.43	0.30	0	0.56
Ser Bar	15	Dry	0.20	0	0.48	0.27	0	0.54
Ser Bar	20	Dry	0.23	0	0.45	0.34	0	0.52
Ser Bar	0	Gly	0.22	0	0.08	0.29	0	0.29
Ser Bar	5	Gly	0.18	0	0.12	0.30	0	0.27

			Uphill trials			Downhill trials		
Material	**Angle**	**Contaminant**	**Mean $RCOF_x$**	**Slip rate**	**NCOF**	**Mean $RCOF_x$**	**Slip rate**	**NCOF**
Ser Bar	10	Gly	0.20	0	0.10	0.35	0	0.26
Ser Bar	**15**	**Gly**	**0.20**	**0.08**	**0.10**	0.27	0	0.22
Ser Bar	**20**	**Gly**	**0.23**	**0.67**	**0.07**	**0.36**	**0.58**	**0.22**

Notes. Contaminated conditions are denoted by "Gly." Bold denotes conditions resulting in slips.