Using High-Fidelity Physical Simulations of the Environment to Evaluate Risk Factors for Slips and Falls in the Mining Industry

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Abstract. The shoe-floor interface is a key element in preventing slips and falls. The design of footwear and the floor surface should be considered to ensure worker safety. Testing various floor surface materials and boots in a real-world setting would impose unnecessary risk to participants and limit the extent of testing possible. Hence, two examples of high-fidelity physical simulation—an inclined grated metal walkway and a grated metal stairway—were built to evaluate risk factors for slips and falls associated with various walkway materials and boots with metatarsal guards. This paper discusses details and findings of the two studies. Also discussed are the advantages and disadvantages of using physical simulations of the environments, including decreased risk for participants and large space requirements for the experiment. Findings of the research can help select appropriate floor surface materials and boots for the mining industry and inform the use of future high-fidelity physical simulations.

Keywords: Physical simulation · Inclined walkway · Boots · Slip
Fall · Mining

1 Introduction

Slip, trip, and fall research has been vital to ascertain the root causes of slip, trip, and fall events, determine contributing factors, and develop guidelines for safe working conditions. Field research occurring in natural environments with slip, trip, and fall hazards can pose significant risks to participants and limit the extent of testing possible. However, simulations can be used to minimize participant risk while collecting the measures of interests. Different types of simulations have previously been used to create scenarios depicting falls from height, ladder falls, slips and falls on the same level, and to determine the influence of safety footwear in construction and the food service industries.

1.1 Use of Simulations in Slip and Fall Research

Virtual simulations of the environment in the laboratory allowed researchers to examine the human response to working at height [1]. The detection of elevation by humans occurs purely through visual stimulus. Virtual simulations allow researchers to

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induce the physiological and psychological effects of height exposure, without placing someone in a truly dangerous environment. Virtual simulations of elevation using virtual reality result in increased anxiety, increased perceived risk of falling, increased postural instability, and changes in skin conductance, which are similar to the reactions during exposure to real elevation [2]. Moreover, a virtual simulation of the environment significantly decreases perceptions of stability and balance confidence [3]. Virtual simulations of the environment with good visual fidelity may provide a safe and cost-effective means to assess working at heights and the risk for falls, evaluate fall prevention strategies, and study postural control in populations at risk for falls [2–4].

In contrast, physical simulations of the environment are used when the individual needs to physically interact with the environment. Physical simulations have been used in the past to research occupational ladder climbing and descending in laboratories. Ladders instrumented with force sensors allowed researchers to determine the force requirements for ladder climbing [5]. A ladder that simulates rung failure was used to examine the effect of ladder climbing pattern on fall severity [6]. In addition, a ladder equipped with a spinning, low-friction rung was used to examine the effect of hand position, age, and climbing dynamics on ladder slip outcomes [7, 8]. These studies utilized fall-arrest harnesses to ensure participants' safety. In Pliner and Beschorner [6], fall severity was evaluated by quantifying the peak weight supported by the harness that was attached to a load cell. These types of studies would not be feasible in a real-world setting due to the risk of falls and the need for custom-fabricated apparatuses and specialized instrumentation.

Level and inclined walkway slips have been examined using physical simulations of environment in the laboratory setting to determine performance of slip-resistant footwear, the effects of wearing personal protective equipment, slip recovery mechanisms, load carriage, age, and obesity. Participants have been subjected to dry, wet, and soapy conditions on carpeted and tiled floors, simulating slippery walkway conditions in restaurants [9]. Older and younger participants have been subjected to slippery floor conditions to determine the effects of aging on the slip initiation and fall frequency [10]. The objective of most of these studies is to improve the understanding of how humans slip, trip, or fall to help develop preventive measures. Prevention of slips, trips, and falls is most often multi-faceted and focuses on a number of areas including workplace design, personal protective equipment, maintenance of walking structures and equipment, and housekeeping.

1.2 Importance of the Shoe-Floor Interface

The footwear-floor interface is a key element in preventing slips, trips, and falls to the same level as it forms the interface between the human and the working environment. The type of floor surface used can be critical in preventing slips and falls and should be considered to ensure worker safety. Floor surfaces that do not provide adequate friction will pose slip hazards; and contaminants on the surface can modify the available friction. Grated metal is the material of choice for walkways at mines and is commonly used on level and inclined walkways, platforms, and stairs as it is rugged and prevents the accumulation of material on the walkway while offering some slip resistance. Level and inclined walkways that run along conveyers and equipment are often exposed to the environment; and, even though they are made of grated metal, they often have a buildup of contaminants on them (Fig. 1). In addition, anecdotal evidence indicates that these walkways along conveyers can have inclinations of over 20° to the horizontal. There is little guidance available on which grated metal flooring material can help reduce the risk of slips or on what inclinations may increase the likelihood of slips on grated metal walkways when contaminants are present.

Fig. 1. Examples of contaminants (*left*: snow and ice; *right*: rocks and accumulation) found on inclined grated metal walkways along conveyer belts at mines.

Footwear is the second component of the footwear-floor interface, and the critical aspects of footwear include tread design, sole flexibility, and shaft stiffness. A number of mines have recently been encouraging their miners to wear safety toe boots with metatarsal guards. Although boots with metatarsal guards may increase protection from falling objects, the slip or trip risks associated with wearing these boots is largely unknown. Boots with metatarsal guards may increase shaft stiffness, which has been shown to modify gait [11, 12]. In addition, for specific tasks such as stair ascent, where ankle range of motion and flexibility is necessary, footwear that reduces metatarsal motion could restrict ankle movement, thereby increasing slip or trip risks [12]. Safe footwear should have soles that allow for adequate traction and an overall design that does not affect personal walking characteristics [13].

Testing floor materials and footwear in the field or in a real-world setting would impose unnecessary risks to participants and limit the extent of testing that is possible, as seen in other slip and fall research. In addition, the use of high-precision, advanced measurement technologies to evaluate changes in gait or to detect the occurrence of a slip, such as motion capture and force plates, would not be viable in a real-world setting. In contrast, investigating these factors in a simulated environment are more viable. The objective of this work is to demonstrate the use of high-fidelity physical simulations of the environment to evaluate risk factors for slips and falls in the mining industry in two example studies.

2 Example Studies

2.1 Testing Walkway Materials on an Inclined Grated Metal Walkway

Simulation of Inclined Walkway Along Conveyers. A grated metal walkway, similar to what would be found beside a conveyer at a mine site (Fig. 2), was built with an adjustable inclination from the floor surface in 5° increments up to 20°. The walkway was 3.65 m long with a platform at the end that extended another 1.25 m. The width of the walkway and platform was 0.5 m. With the walkway raised to 20°, the platform was elevated 1.4 m above the ground. The walkway had handrails on both sides and the platform had handrails on the three exposed sides. The grated metal used as the flooring surface along the entire length of the walkway could be interchanged to use three different materials: (1) diamond weave material, (2) serrated, rectangular bar-type material, or (3) circular, perforated pattern material. The flooring materials and handrails used were those commonly encountered at mines and were installed per manufacturers' specifications.

Fig. 2. Adjustable inclined grated metal walkway built to simulate walkways along conveyers commonly found at mines.

Participants and Procedures. Detailed descriptions of the participants and experimental procedures can be found in Pollard et al. [14]. Twelve participants (including three women and nine men) participated in the study. In addition to the three-floor surface materials tested, the floor surface was tested in both a dry condition and in a contaminated condition. For the contaminated condition, the surface was coated with 99.99% Glycerol, using a brush and sprayed with a 2:1 Glycerol to water solution between trials. The contaminated condition simulated slippery conditions commonly encountered when these walkways are covered in ice, snow, grease, or oil. A ceiling-mounted fall arrest system was provided along the length of the walkway and two strain-based force plates were mounted in the center of the walkway to measure ground reaction forces that were used to calculate the required coefficient of friction. Participants were aware that the floor surface was contaminated and were instructed to walk across the walkway in both directions (up and down) without using the handrails.

Results. Figure 3 provides the number of slip events that occurred (out of 24 trials) for all participants for that condition. It is evident that a greater number of slips occurred at higher inclinations with slip events at inclinations as low as 10°. The circular, perforated material led to the most slips and the diamond weave led to the least number of slips. In addition, slips occurred more often on the contaminated metal gratings than on the dry metal grating. These findings can help make very specific recommendations to improve the workplace, including limiting walkway inclinations to less than 10° or utilizing the diamond weave materials for higher inclinations, up to 20°.

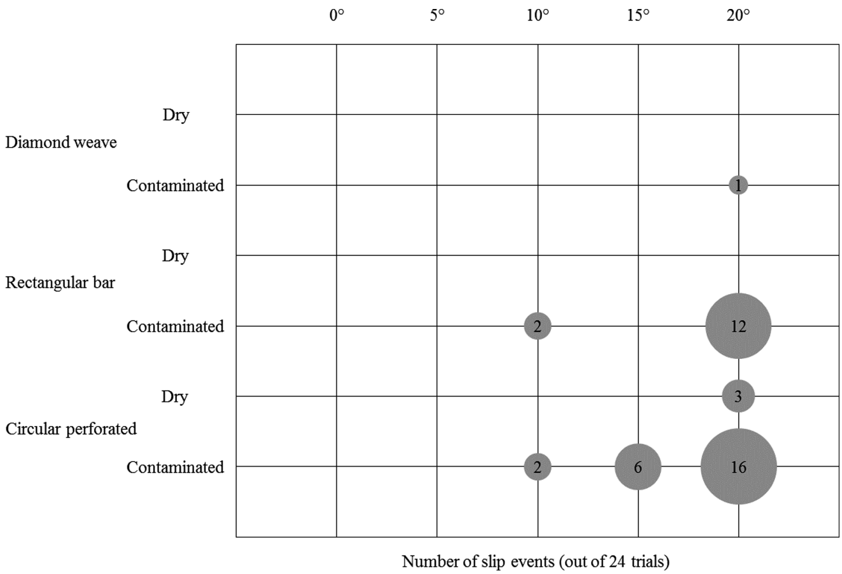

Fig. 3. Number of slips observed (out of 24 trials) for each combination of surface material, contaminant condition, and inclination of walkway.

2.2 Testing Boots with Metatarsal Guards on a Grated Metal Stairway

Simulation of Stairways at Mines. A stairway, similar to that traversed between levels at a mine, was constructed with steps made from the diamond-weave grated material. The stairway had five steps, each with a rise of approximately 0.2 m and a step depth of approximately 0.25 m, which led to a platform 1 m in length, for an overall rise of 1.22 m. The stairway was 0.6 m wide and had handrails on both sides of the stairs and on the three exposed sides of the platform.

Participants and Procedures. Detailed descriptions of the participants and experimental procedures can be found in Pollard et al. [15]. Five participants, wearing men's size 10 boots, participated in the study. Boots selected for the study were hiker-style Dr. Marten's Ironbridge Steel Toe boots with and without metatarsal guards. A motion capture system was used to track movement of the feet, using retro-reflective markers placed on the boots and the stairway. Toe clearance was measured when the toe crossed the front edge of the third step from the ground as the absolute horizontal distance (X), absolute vertical distance (Z), and the length of the resultant vector (shortest distance) between the reflective toe marker and the edge of the step in the direction of travel.

Results. Figure 4 shows the differences in toe clearance between the steel-toe boots with metatarsal guards and those without metatarsal guards in the horizontal (X) direction, the vertical (Z) direction, and the resultant vector (greater positive values indicate the metatarsal boots were closer to the edge of the stair tread). Although, there are minor differences between the boots, with metatarsal boots being on average 10 mm closer to the edge for the resultant vector, these differences are not statistically significant. However, due to the limited sample size and only a single pair of boots being tested, additional research is needed to evaluate the influence of metatarsal boots on toe clearance during ladder ascent, as well as heel clearance and foot placement during stair descent.

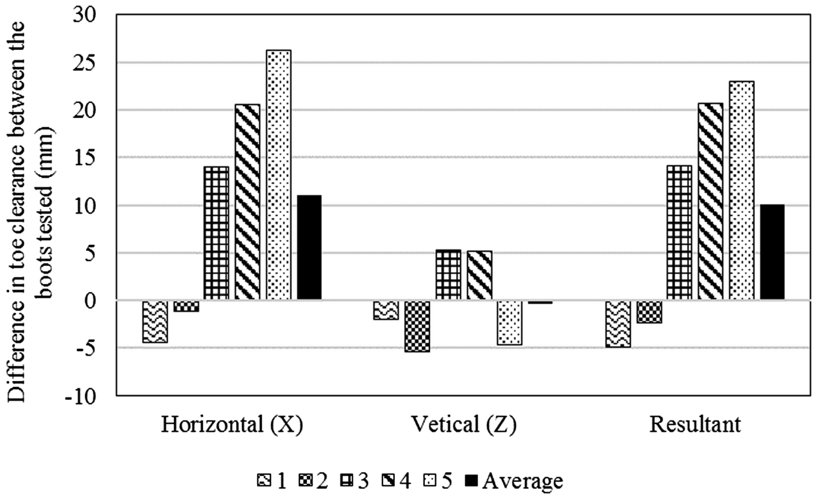

Fig. 4. Difference in toe clearance (in mm) between the two boots tested for the participants and the average in the horizontal direction, vertical direction, and the resultant vector (greater positive values indicate that the metatarsal boots were closer to the edge of the tread or less toe clearance).

3 Discussion

Slips, trips, and falls are a significant burden to the mining industry. Conducting detailed slip, trip, and fall research would be a challenge in the field due to hazards commonly encountered in the environment and the limited ability to use advanced measurement techniques. The objective of this work was to provide examples of how high-fidelity physical simulations of the environment can be used to evaluate risk factors for slips, trips, and falls in the mining industry. Research where participants are expected to slip, trip, or fall would not be possible without the use of safety precautions [6–10, 14]. Participant safety during slip and fall research is critical and can be ensured during simulations in laboratory environments by using systems that may not be practical in the field.

Laboratory simulations (both virtual and physical) also allow for the use of high-precision measurement techniques or systems. In our investigation of metatarsal boots [15], toe clearance was measured using an optical motion capture system. In our study on walkway materials [14], a similar system was used, along with force plates. It would be extremely difficult to set up this equipment in a field setting, therefore making laboratory simulation a preferred method.

The fidelity of the simulation should be selected based on the need for realism, study conditions tested, and the ability to generalize the findings beyond the laboratory simulation. For testing walkway materials, it was critical to ensure that there was an adequate length for participants to walk across and to test only those materials found in the field at inclinations observed at mine sites. Hence, the scale of the simulation, and materials used had to match the real environment closely, increasing the fidelity of the simulation. In contrast, as precise control of the contaminants was necessary to ensure conditions were repeatable between the walkway conditions and across all participants, glycerin was used as a contaminant to simulate slippery conditions like ice or snow. Hence, for the contaminant, the fidelity of the simulation did not match the real conditions encountered; but were instead selected to ensure repeatability and generalizability of the findings, while remaining practical for the researchers. Table 1 shows a list of advantages and disadvantages of using simulations in slip, trip, and fall research.

Table 1. A few advantages and disadvantages of using simulations in slip, trip, and fall research.

Advantages	Disadvantages
- Increased safety	- Space required for the simulation
- Can use advanced and precise measurement techniques	- Lack of participant access
- Can vary the fidelity	- Loss of context or realism

Using high-fidelity simulations in the laboratory also has some disadvantages. One potential limitation of this research was that the walkway materials tested were new. Grated metal walkaways at mines will wear over time due to exposure to the environment and pedestrian traffic and are often not replaced until they are significantly damaged. Our testing reflected a best-case scenario with new walkway materials. In our study on testing walkway materials [14], a minimum space of 8.2 m long by 4 m wide was required to house the simulated walkway with a minimum head clearance of 4.25 m (including accommodations for the fall harness). This space represents a large volume in an indoor laboratory. Similar studies, such as those carried out on ladders, would also require large volumes of space with additional head clearance to accommodate the ladders and required fall-arrest systems [6, 8]. Participant selection or access to participants is another concern when conducting laboratory simulations. In our two studies [14, 15], we did not use miners due to challenges with access to the population; however, there is unlikely to be a difference in gait between miners and the subject population tested. Other studies, such as in Pliner et al.'s research [7], recruited participants from populations that use ladders as part of their jobs, as there was likely to be an influence of expertise and comfort based on the frequency of ladder use. Participant selection needs to consider the necessity of having (or not having) prior knowledge or experience in the area of interest.

Simulations in the laboratory also have the potential to result in the loss of environmental context. In some scenarios, simulating the virtual environment alone is adequate because participants do not need to interact with objects within the environment to elicit a response [2]. In other scenarios, the physical interaction with objects within the environment is essential, requiring the simulation to mirror the physical interaction with the environment and work scenarios as closely as possible [7, 8, 14]. Combining high-fidelity physical simulations with virtual simulations could increase the realism of the simulation and are often used for motor vehicle research and training where both visual and physical interactions are necessary. In these scenarios, the physical interaction is a result of visual cues in the environment; hence, to study human responses both aspects of the environment need to be simulated.

4 Conclusions

Slip, trip, and fall research poses significant risks to participants, requiring safety precautions that are likely not present in field settings. These risks can often be minimized through the use of physical and virtual simulations in the laboratory. Simulations also allow the use of high-precision data collection systems, such as force plates and motion capture systems that are impractical for many field environments. Proper participant selection and the fidelity of the simulation is key to eliciting subject responses and ensuring the validity of the data.

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.

References

1. Simeonov, P., Hsiao, H., Powers, J., Ammons, D., Kau, T., Amendola, A.: Postural stability effects of random vibration at the feet of construction workers in simulated elevation. Appl. Ergon. **42**(5), 672–681 (2011)
2. Simeonov, P., Hsiao, H., Dotson, B.W., Ammons, D.: Height effects in real and virtual environments. Hum. Factors **47**(2), 430–438 (2005)
3. Cleworth, T.W., Horslen, B.C., Carpenter, M.G.: Influence of real and virtual heights on standing balance. Gait Posture **36**, 172–176 (2012)
4. Wang, S., Liu, Y., Hoerter, M., Moreland, J., Page, G., Krotov, Y., Crites, S., Zhou, C.: Development of a safety training simulator for fall protection. In: AISTech-Iron and Steel Technology Conference Proceedings, United States, vol. 1, pp. 45–50, 8–11 May 2017
5. Bloswick, D.S., Chaffin, D.B.: An ergonomic analysis of the ladder climbing activity. Int. J. Ind. Ergon. **6**(1), 17–27 (1990)
6. Pliner, E.M., Beschorner, K.: Effects of ladder climbing patterns on fall severity. Proc. Hum. Factors Ergon. Soc. Annu. Meet. **61**(1), 940–944 (2017)
7. Pliner, E.M., Campbell-Kyureghyan, N.H., Beschorner, K.E.: Effects of foot placement, hand positioning, age and climbing biodynamics on ladder slip outcomes. Ergonomics **57** (11), 1739–1749 (2014)
8. Schnorenberg, A.J., Campbell-Kyureghyan, N.H., Beschorner, K.E.: Biomechanical response to ladder slipping events: effects of hand placement. J. Biomech. **48**(14), 3810–3815 (2015)
9. Hanson, J.P., Redfern, M.S., Mazumdar, M.: Predicting slips and falls considering required and available friction. Ergonomics **42**(12), 1619–1633 (1999)
10. Lockhart, T.E., Woldstad, J.C., Smith, J.L.: Effects of age-related gait changes on the biomechanics of slips and falls. Ergonomics **46**(12), 1136–1160 (2003)
11. Chiou, S.S., Turner, N., Weaver, D.L., Haskell, W.E.: Effect of boot weight and sole flexibility on gait and physiological responses of firefighters in stepping over obstacles. Hum. Factors **54**(3), 373–386 (2012)
12. Cikajlo, I., Matjacic, Z.: The influence of boot stiffness on gait kinematics and kinetics during stance phase. Ergonomics **50**, 2171–2182 (2007)
13. Gronqvist, R.: Mechanisms of friction and assessment of slip resistance of new and used footwear soles on contaminated floors. Ergonomics **38**(2), 224–241 (1995)
14. Pollard, J.P., Heberger, J.R., Dempsey, P.G.: Slip potential for commonly used grated metal walkways. IIE Trans. Occup. Ergon. Hum. Factors **3**(2), 115–126 (2015)
15. Pollard, J.P., Merrill, J., Nasarwanji, M.F.: Metatarsal boot safety when ascending stairs. In: IIE Annual Conference Proceedings, pp. 2064–2068 (2017)