MAXIMUM ACHIEVABLE INCLINES FOR FOOTWEAR WHILE WALKING ON ICY SLOPES AND CROSS-SLOPES

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More informative tests of winter footwear performance are required in order to prevent injurious slips and falls on icy conditions. In this study, 8 participants tested 4 styles of winter boots on longitudinal and cross-sloped surfaces consisting of smooth, wet ice as it was progressively tilted until participants could no longer continue standing or walking. The maximum achievable slopes provided consistent measures of slip resistance, demonstrated over a wide range of observable performance. One footwear soling material and tread combination outperformed the others on the wet ice surface allowing participants to successfully walk on longitudinal slopes of 17.5° ± 1.9° (mean ± SD) while others failed beyond 3.3° ± 0.5°, 5.1° ± 0.8°, and 7.5° ± 0.9°. By further exploiting the methodology to include additional surfaces and contaminants, such tests can be used to optimize tread designs and materials that are ideal for reducing the risk of slips and falls.

Introduction

Slips and falls are one of the most prevalent and injurious types of accidents on-the-job and in public spaces. Winter conditions increase the likelihood of pedestrian slips and falls as precipitation and cold temperatures create hazards and obstacles (Gard & Lundborg, 2000). In winter-experiencing environments, foot slippage is estimated to account for 43% of all falls and 16% of all accidents in Nordic countries (Lund, 1984). Medical care costs of slipping injuries are estimated to be the same as that of all traffic injuries in the same period (Björnstig *et al*., 1997).

Slip-resistant footwear can reduce the risks of slips and falls (Abeysekera & Gao, 2001). In order for footwear designers and manufacturers to optimize the slip resistant properties of winter footwear and to appropriately inform consumers of footwear performance, it is imperative that methods of footwear assessment be relevant and reliable. However, the measurement of footwear slip resistance is not straightforward (Chang *et al*., 2001) and while there are standard mechanical methods for measuring footwear coefficient of friction (COF), the output validity is dependent on their ability to simulate human gait (Chang *et al*., 2001b). To improve validity and because users sometimes prefer direct walking tests, small-scale ramp tests have been developed to assess footwear slip resistance (James, 1999). In this study, a novel ramp test allowing sustained, natural gait was used to evaluate the slip resistance of winter footwear.

Methods

Footwear

A total of 8 young, healthy males took part in this study to test the performance of 4 men's winter boots with different outsole designs. Three of the styles consisted of identical uppers. Of these, 2 styles used identical tread patterns composed of different materials: NCI rubber compound (Boot N) and Green Diamond technology which consists of aluminium oxide and silicon carbide granules embedded in rubber (Boot G). The outsole of the third boot style had no tread and consisted of a proprietary JStep rubber compound (Boot J). The final boot style tested was a lighter-weight boot, whose outsole includes a proprietary (IcePaw) design embedded in rubber. The test boots are depicted in Figure 1. An active motion tracking system (Phoenix Technologies Inc., British Columbia, Canada) was used to identify the positions of markers attached to the heels and toes of each pair of boots during participant testing.

Figure 1. Test footwear; from left to right: Boot B, Boot G, Boot J, and Boot N

Test Conditions

The boots were tested on a 5.5m long walkway of smooth, wet ice. Ice was created by freezing water and maintaining the ice temperature at -0.5°C ± 0.5°C via glycol tubes below the ice surface. The ambient temperature of the room was held at 10.6°C ± 0.6°C and all test boots were conditioned at this temperature for 1 hour prior to testing. The warmer ambient temperature in combination with the near freezing ice temperature maintained a thin layer of melting water over the ice surface. The COF of the ice floor was measured according to ASTM F1679 using a Neolite pad on the English XL Variable Incidence Tribometer. The ice conditions were measured before and after each test session and the average COF across all readings was 0.08 ± 0.05. The entire laboratory was mounted over a motion base which could tilt the entire floor surface in any direction to create sloped conditions. The laboratory could be tilted up to maximum slopes of 20°.

Test Protocol

Participants wore typical winter garments including winter coats throughout this study under a full-body safety harness. The harness was attached to a fall-arrest system connected to a robotic overhead gantry that automatically followed the position of the participant. A controlled-descent line, balanced at 2kg, prevented injury from falls by allowing a maximum downward velocity of 0.7m/s. This study was approved by the Research Ethics Board of the Toronto Rehabilitation Institute–UHN.

During the experiment, participants were asked to complete two sets of tests while wearing each style of footwear: standing tests followed by walking tests. For the standing tests, participants were asked to stand with their feet shoulder-width apart. They were instructed that they could adjust their posture as required to maintain balance while the laboratory was tilted. The floor was tilted from level at a rate of 0.25° per second, pausing for 5 seconds at each full degree, until both of the participants' feet began to slide simultaneously. This test was conducted in 4 slope directions, in random order, with the participant facing downhill, uphill, with their left side higher, and their right side higher, see Figure 2. The final angle at which the participant was able to prevent both feet from sliding simultaneously was recorded as the maximum achievable angle for each piece of footwear in each slope direction.

Figure 2. Two slope types (longitudinal and cross-slopes) and 4 slope directions (downhill, uphill, left side higher, and right side higher) tested while standing and walking

The walking tests were conducted on longitudinal slopes and cross-slopes, with the tilting axis of the floor perpendicular to the direction of travel and parallel to the direction of travel, respectively. For each slope type, participants walked in 2 slope directions; downhill and uphill on the longitudinal slope and right side higher and left side higher on the cross-slopes, see Figure 2. In these tests, participants were asked to walk at a natural pace and in a controlled manner from one end of the laboratory to the other and back again. Between laps, the slope angle of the walkway was progressively increased. Each style of footwear was first tested on the level at 0° and subsequent tests started from 5° less than the critical angles determined during standing tests, changing in 1° increments until failure. For each participant, critical angles for each type of footwear were computed as the lowest maximum slope achieved in any slope direction during the standing tests. If the critical angle was less than 5°, walking tests after the level began at 1° and for critical angles greater than 16° participants included a 10° trial. A test angle for each slope type was deemed a failure if both feet slipped simultaneously (not including controlled slides to terminate gait), or the participant could not initiate gait, in either slope direction. The order of slope type and starting directions were randomized.

Results

Participants

The 8 males who participated in this study were 31.6 ± 8.1 years of age (mean ± SD), 179cm ± 7cm in height, and weighed 80.2kg ± 15.4kg. All participants had lived in a winter-experiencing climate for at least one winter season, averaging 18.5 ± 11.8 years spent living in winter-experiencing regions. All participants indicated via questionnaire that they spent at least 3-5 days per week outdoors in winter and on average 1-2 hours outdoors during those days. 62% of the participants indicated that they engage in winter sports such as skiing, skating or snowboarding. Half of the participants had fallen in the previous 2 years but only one participant had fallen outdoors and indicated that the fall was on ice. None of the participants had experience using the test footwear prior to the experiment and all participants in this study were right-foot dominant.

Standing Tests

A two-way repeated measures analysis of variance (ANOVA) was used to determine the effects of footwear and slope direction on the maximum achievable slope angle while standing. The results show that footwear significantly affected the maximum achievable angle, $F(3,21)=1476.22$, $p<.001$. The main effect of slope direction and the interaction effect between slope direction and footwear were not significant. All pairwise comparisons were corrected using Bonferroni adjustments. Comparisons showed that there were significant differences between all types of footwear (all $p<.001$). Boot J significantly outperformed all other footwear with an average maximum achievable slope angle of 19.3° across all slope directions. Boot G allowed participants to climb on average 9.4° slopes and performed significantly better than Boot N and Boot B. Boot N averaged 6.0° slopes, which was significantly steeper than the 3.4° slopes achieved by Boot B. Figure 3 shows the average maximum achievable inclines while standing in each boot for each slope direction along with the equivalent static coefficient of friction (static COF). The equivalent static COF is calculated as the tan of the maximum achievable angles while standing. In increasing order, mean static COF for Boots B, N, G, and J were therefore 0.06, 0.11, 0.17, and 0.35, respectively, on the smooth, wet ice surface.

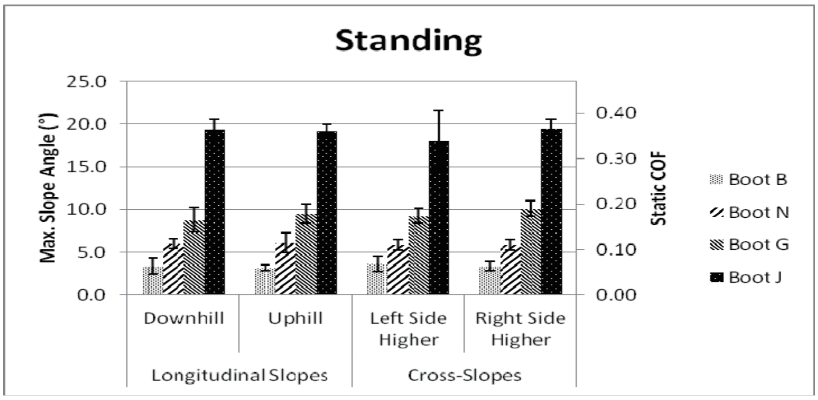

Figure 3. Average maximum slope angles (and equivalent static COF) at which participants could maintain standing posture without sliding plotted with standard deviation error bars

Walking Tests

A two-way repeated measures ANOVA was also used to determine the effects of footwear and slope type on the maximum slopes achieved during the walking task. The main effects of footwear ($F(1.7,11.9)=397.94$, $p<.001$) and slope type ($F(1,7)=36.76$, $p<.05$) were significant and there was a significant interaction effect between footwear and slope type ($F(3,21)=13.86$, $p<.001$). Pairwise comparisons indicated that each type of footwear performed significantly differently from one another (all $p<.05$) during the walking tests, but ranked in the same order as that of the standing tests. The results also showed that the maximum achievable angles were significantly lower while walking on cross-slopes than on longitudinal slopes. This phenomenon is most evident with Boot J indicating that at steeper angles, differences between maximum achievable angles on the longitudinal slope compared to cross-slopes are more pronounced, which also gives rise to the significant interaction effect. Maximum achievable angles while walking on ice are shown in Figure 4 along with the equivalent dynamic COF, calculated as tan of the maximum achievable angles while walking.

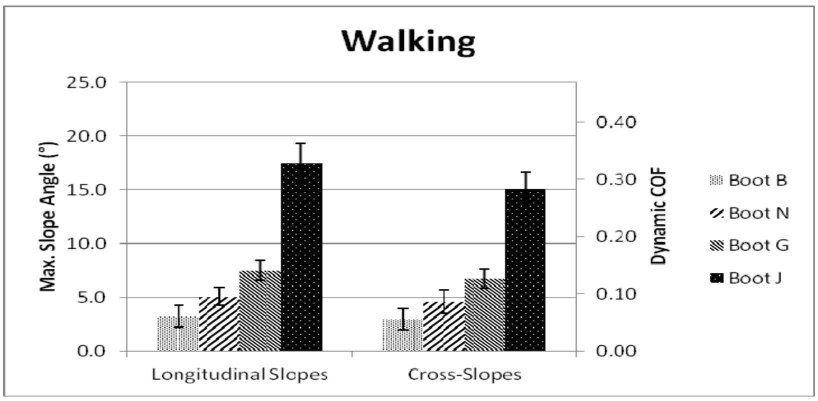

Figure 4. Average maximum achievable slope angles (and equivalent dynamic COF) while walking plotted with standard deviation error bars

When test type was included for analysis, a three-way ANOVA indicated that participants were able to achieve significantly steeper slopes while standing compared with walking ($p<.05$). As expected, static COF was thus significantly greater than dynamic COF.

Gait speed

Gait speed was calculated across the middle 2.5m section of the walkway for successful walking trials using the position of the heel at the first heel strike in the 2m section and the position of the same heel at its final heel strike in the section. A one-way ANOVA indicated that gait speed on level ice was siginificantly affected by footwear ($F(3,21)=6.47$, $p<.05$) and participants walked significantly slower in Boot B (0.72m/s ± 0.16m/s) than in Boot J (0.99m/s ± 0.24m/s) at 0° incline, $p<.05$. Gait speed decreased linearly with increasing slope angles in all slope directions for each type of footwear with R^2 values of .77 ± .22, see Figure 5. The ratio of change in gait speed per degree change in slope angle was analyzed using a two-way repeated measures ANOVA to determine the effects of footwear and slope direction. Only the main effect of footwear was significant, $F(3,21)=5.62$, $p<.05$). Results showed that participants walked significantly slower per degree of incline in Boot B than in Boot G. See Table 1 for mean reductions in gait speed per degree change in incline angle, for each type of footwear.

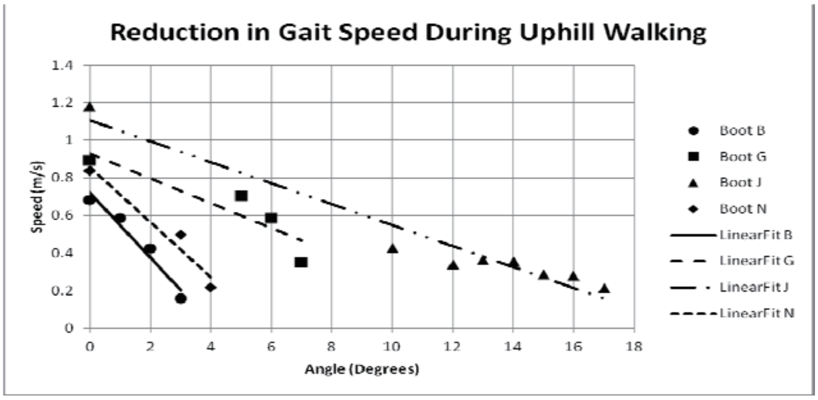

Figure 5. Representative data from one participant showing reduction in gait speed at increasingly steep slope angles

Table 1. Mean and standard deviation of change in gait speed per degree of incline

Footwear	Mean ± SD (cm/s/°)
Boot B	-10.0 ± 5.7
Boot N	-7.19 ± 5.4
Boot G	-4.91 ± 3.8
Boot J	-4.94 ± 4.1

Discussion

The smooth, JStep sole significantly outperformed all of the other boots in both the standing tests and walking tests on the smooth, wet ice surface, allowing participants to walk on longitudinal slopes of 17.5° ± 1.9° and cross-slopes of 15.1° ± 1.6°. The second best performing footwear utilized the Green Diamond sole followed by the NCI rubber footwear, and finally the IcePaw sole. Because the material and tread of the JStep footwear differed from those of the other test boots, further testing is required to determine the contribution of tread material and tread pattern independently, in the performance observed in this study. Furthermore, while the smooth, wet ice represents one challenging winter surface, tests involving snow and other typical winter conditions are necessary to develop complete performance ratings.

This study showed that steeper inclines could be achieved while walking on longitudinal slopes than cross-slopes. Postural changes on longitudinal inclines moved the body's centre of mass along the longer axis of the base of support while on cross-slopes the body's centre of mass was more likely to move outside the shorter axis of the base of support.

It should be noted that the two poorer performing styles of footwear failed beyond 3.3° ± 0.5° and 5.1° ± 0.8°, respectively, on longitudinal slopes. The maximum allowable slope of curb ramps is 5.7° as specified in the Americans with Disability Act Standards for Accessible Design (Kirschbaum *et al.*, 2001). Results of this study indicate that while wearing Boot B or Boot N, users would be unable to maintain stable balance on standard curb ramps covered with wet ice.

Gait speed decreased the most per degree of incline while using the worst performing boots in which gait speed decreased at a rate of 10cm/s per degree of incline while speed in the other boots styles reduced at rates of 5cm/s/° to 7cm/s/°. In this experiment, participants were asked to self-select gait speed in order to complete the walking task. The young, healthy participants were able to dramatically reduce their gait speed when necessary. However, for older users or users with mobiltiy limitations, failure may have occurred at less steep angles. Alternative definitions of footwear failure, such as speed thresholds may be explored for determining failure.

The results also indicated that neither measuring gait speed on slippery level surfaces nor determining the reduction in gait speed at steeper inclines could provide ratings of performance to the resolution accomplished in this study. The performance outcomes from this study can be used to inform consumers making decisions regarding winter footwear. Current standard assessments of footwear slip resistance measure coefficient of friction. However, there are no standards for thresholds of COF, the results are difficult for consumers to interpret, and the measurement mechanisms do not replicate all aspects of human gait. User-based determination of maximum achievable angle on slippery slopes is a more useful representation of footwear performance, which could also be interpreted using equivalent static and dynamic COF values, if desired (as shown in Figure 3 and Figure 4).

This experiment showed that a wide spread of footwear performance can be assessed by walking on increasingly steep slopes under controlled surface conditions, and that the results are consistent and require a relatively small sample size. This study also demonstrates the feasibility of conducting similar tests for other types of protective footwear, such as those for indoor workers where floor surfaces and contaminant conditions are easier to predict and recreate.

References

Abeysekera, J., & Gao, C. (2001). The identification of factors in the systematic evaluation of slip prevention on icy surfaces. *International Journal of Industrial Ergonomics*, *28*(5), 313.

Björnstig, U., Björnstig, J., & Dahlgren, A. (1997). Slipping on ice and snow--elderly women and young men are typical victims. *Accident Analysis & Prevention*, *29*(2), 211–215.

Chang, W.-R., Grönqvist, R., Leclercq, S., Brungraber, R. J., Mattke, U., Strandberg, L., Thorpe, S. C., et al. (2001b). The role of friction in the measurement of slipperiness, Part 2: Survey of friction measurement devices. *Ergonomics*, *44*(13), 1233–1261.

Chang, W.-R., Grönqvist, R., Leclercq, S., Myung, R., Makkonen, L., Strandberg, L., Brungraber, R. J., et al. (2001). The role of friction in the measurement of slipperiness, Part 1: Friction mechanisms and definition of test conditions. *Ergonomics*, *44*(13), 1217–1232.

Gard, G., & Lundborg, G. (2000). Pedestrians on slippery surfaces during winter - methods to describe the problems and practical tests of anti-skid devices. *Accident Analysis and Prevention*, *32*(3), 455–460.

James, D. I. (1999). The theory behind the DIN ramp tests. *Polymer Testing*, *18*(1), 3–10.

Kirschbaum, J. B., Axelson, P. W., Longmuir, P. E., Mispagel, K. M., & Stein, J. A. (2001). Part 2: Designing Sidewalks and Traisl for Access Best Practices Design Guide. *Performer: Federal Highway Administration*.

Lund, J. (1984). Accidental falls at work, in the home and during leisure activities. *Journal of Occupational Accidents*, *6*(1-3), 177.