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Slip resistance of winter footwear on snow and ice measured using maximum achievable incline

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ABSTRACT
Protective footwear is necessary for preventing injurious slips and falls in winter conditions. Valid methods for assessing footwear slip resistance on winter surfaces are needed in order to evaluate footwear and outsole designs. The purpose of this study was to utilise a method of testing winter footwear that was ecologically valid in terms of involving actual human testers walking on realistic winter surfaces to produce objective measures of slip resistance. During the experiment, eight participants tested six styles of footwear on wet ice, on dry ice, and on dry ice after walking over soft snow. Slip resistance was measured by determining the maximum incline angles participants were able to walk up and down in each footwear–surface combination. The results indicated that testing on a variety of surfaces is necessary for establishing winter footwear performance and that standard mechanical bench tests for footwear slip resistance do not adequately reflect actual performance.

Practitioner Summary: Existing standardised methods for measuring footwear slip resistance lack validation on winter surfaces. By determining the maximum inclines participants could walk up and down slopes of wet ice, dry ice, and ice with snow, in a range of footwear, an ecologically valid test for measuring winter footwear performance was established.

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Slips and falls; gait kinematics; product safety; user testing; winter footwear

1. Introduction

Slip and fall accidents can lead to serious injuries to both pedestrians and outdoor workers. The direct cost of these accidents is estimated at $30 billion per year in the United States (Stevens et al. 2006). Snowy and icy conditions increase the risk of slip and fall accidents outdoors by reducing underfoot traction (Courtney et al. 2001). Such winter conditions contribute to two-thirds of outdoor pedestrian injuries (Rolfsman, Bylund, and Saveman 2012).

Slip resistant footwear plays an important role in the prevention of slips and falls by providing traction to prevent balance loss and to recover from perturbations. In indoor environments, improvements in the development and availability of slip resistant footwear for industries, such as food services and healthcare, have led to reductions in incidence rates of slips and falls (Staal et al. 2004; Verma et al. 2011). However, similar improvements have not been observed in outdoor worker industries. For example, letter carriers continue to experience high rates of on-the-job injuries related to weather (Bentley and Haslam 1998; Canada Post Corporation 2007, 2008).

Developing appropriate footwear for winter conditions is challenging because of the wide range of temperature and precipitation conditions that can occur. Furthermore, existing standard methods for testing the slip resistance of winter footwear have not been validated for winter test conditions. As a result, designers and manufacturers do not have an objective and reliable method for evaluating their designs and consumers are provided with limited and potentially misleading information when selecting winter footwear.

The coefficient of friction (COF) is the most common measure of footwear slip resistance. The standard tests for footwear slip resistance, ASTM F2913 and ISO 13287, have identical test procedures and calibration specifications (ASTM F2913-11 2012; ISO 13287 2013). These tests measure COF by applying a specified normal force pressing the test footwear onto a test surface and then moving the test surface horizontally at a set constant speed. Load cells measure the applied horizontal and normal forces and the horizontal to normal force ratio is the output COF. Calibrated test surfaces described in the standard methods include dry and wet quarry tiles and stainless steel. These

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standards also recommend that footwear be tested on surfaces over which they are expected to be used, such as ice; however, no specific guidelines or validation for winter test conditions have been accepted into the standards.

Mechanical devices such as the stationary step simulator (Grönqvist et al. 1990) have been used to test the relative slip performance of footwear in laboratories (Gao et al. 2004). The stationary step simulator was also adapted into a portable slip simulator (Aschan et al. 2005) which was used to measure footwear slip resistance outdoors on naturally occurring winter surfaces (Aschan et al. 2009). However, these test methods lack validation on winter surfaces. Tests of gait and footwear involving stepping or walking by human subjects on slippery slopes have been conducted in previous studies. By incorporating actual users in the testing of footwear, these studies have greater ecological validity than studies restricted to use of mechanical devices. However, the existing human-centred studies have typically involved only subjective ratings of slip resistance (Gard and Lundborg 2000; Gao and Abeysekera 2002), or short walkways (less than 3 m) and limited surfaces and contaminants (Skiba, Wieder, and Cziuk 1986; Jung 1989; Gao, Oksa et al. 2008). More recently, we have proposed a new test method for assessing footwear slip resistance using the maximum slope angle that users are able to achieve while walking over wet ice (Hsu et al. 2015). To the authors' knowledge, this study, which builds on our previous work, is the first study to incorporate more comprehensive environmental conditions (such as simulated snow conditions) in biomechanical testing of winter footwear.

The primary objective of this study was to determine the slip resistance of a range of footwear on snowy and icy surfaces based on the maximum angle of incline the users were successfully able to ascend and descend. Gait adaptations in response to each footwear–surface combination were also explored. A secondary objective of the study was to compare the results of the maximum incline method to the standard mechanical method (ASTM F2913) when used in conjunction with an icy surface.

2. Methods

2.1. Participants

A convenience sample of eight males took part in this study, testing the performance of six types of men's winter footwear. Participants were screened for exclusionary factors such as musculoskeletal and cardiopulmonary disorders, based on self-report. The participants were 26.3 years (±2.2 years) of age, 1.81 m (±0.02 m) tall and weighed 81.9 kg (±4.4 kg). Prior to participating in the study, all subjects provided informed consent as approved by the Toronto Rehabilitation Institute – UHN Research Ethics Board.

2.2. Footwear

Six styles of footwear were selected with the aim of testing a wide range of performance (Figure 1, Table 1). Each piece of footwear used in this study had been used previously in pilot testing but had never been used outdoors. Prior to testing, each piece of footwear was cleaned with soap and water and also pre-conditioned inside the cold laboratory environment for 30 min. The styles of footwear were then tested by participants in a random order.

2.3. Surfaces

This study was conducted in WinterLab, one of the Toronto Rehabilitation Institute's Challenging Environment Assessment Laboratories (Figure 2). WinterLab contains a 2.5 cm thick by 4.5 m by 4.6 m ice floor which was cooled to −1.9 °C (±0.8 °C) for the duration of the study. The ice temperature was recorded using a thermistor embedded halfway below the surface of the ice near the centre of the laboratory. The ambient conditions in WinterLab were maintained at 5.6 °C (±1.1 °C) and 85.4% (±1.1%) relative humidity. During testing in WinterLab, participants wore winter garments suitable for outdoor use in 0 °C weather. Participants also wore a full-body safety harness that was

Style-S Style-K Style-I Style-N Style-G Style-J

Figure 1. Test footwear. Six styles of footwear were selected for testing including a running shoe (Style-S), an indoor slip-resistant boot (Style-K) and four winter boots.

Table 1. Test footwear.

Footwear	Make/model	Details
Style-S	Athletic works Ted Men's jogging shoes, Walmart Canada Corp., Mississauga, Canada	Running shoe with thermoplastic rubber outsole
Style-K	Keuka SureGrip®, Tennessee, USA	Low-cut ankle boot developed for slip resistance on industrial surfaces
Style-I	Arctic Ice Boot, SureGrip®, Tennessee, USA	Winter ankle boot with rubber outsole designed for slip resistance
Style-N	Outsole and upper: Dakota, Mark's®, Alberta, Canada	NCI rubber compound outsole; Outsole tread identical to Style-G; Uppers identical to Style-G and Style-J
Style-G	Outsole: Green Diamond Tire, Colorado, USA; Upper: Dakota, Mark's®, Alberta, Canada	Outsole consisted of aluminium oxide and silicon carbide granules embedded in rubber to enhance underfoot traction; Outsole tread identical to Style-N Uppers identical to Style-N and Style-J
Style-J	Outsole: JStep Sole, Gimhae, Republic of Korea; Upper: Dakota, Mark's®, Alberta, Canada	No tread and outsole created using a sheet of a proprietary JStep compound; Uppers identical to Style-N and Style-G

attached with a line from the upper back to a motorised fall-arrest device that automatically followed directly overhead of the participants.

Pilot tests were used to select the surface conditions for testing. The surfaces were chosen to represent a range of reproducible and challenging outdoor winter conditions. In the full experiment, each participant attended two test sessions held on different days, to test all six types of footwear on three winter surfaces: dry ice, wet ice and snow. Dry and wet ice conditions were tested in the same session, in random order, and snow was tested in a separate session, with the order of the two sessions counterbalanced by participant.

During the experiment, participants walked across two 5.5-m long adjacent walkways along the diagonal of the laboratory to maximise walking distance. During the dry and wet ice sessions, a base layer of ice was created by flooding the floor surface of the laboratory with water. Ambient conditions, in combination with the ice temperature created a smooth, dull, ice surface with minimal melting at the interface (i.e. with no melted water visible on the ice surface) and this virgin base ice layer was the *dry ice condition*. Approximately 1 mm of water which was maintained at 5.6 ± 1.1 °C inside WinterLab was mopped over the dry ice to create a *wet ice condition*, which is considered to be a very challenging surface for walking (Grönqvist and Hirvonen 1995) (Figure 2(b)). To prevent contamination of the dry ice surface with water from the wet ice surface, footwear was tested first on dry ice before testing on wet ice.

A snowy walkway was created by spreading snow over the dry ice base layer (Figure 2(c)). Approximately 150 L of snow was created at −2.0 °C using a commercial snow machine (Snowstar Magic, Snowtech Co., Ltd, Chungbuk, Republic of Korea). The snow was then transported using an insulated cooler into WinterLab. A roughly 5-cm layer was shovelled over one walkway of dry ice. A CTI snow penetrometer (Smithers Rapra, Akron, USA), which is used in standard tests of tire traction on snow (ASTM F1572-08 2008, ASTM F1805-12, 2012), was used to measure the hardness of the fresh snow. The snow was classified as 'soft snow' providing a reading of less than 50 points on the 100-point compaction scale. The water content, or

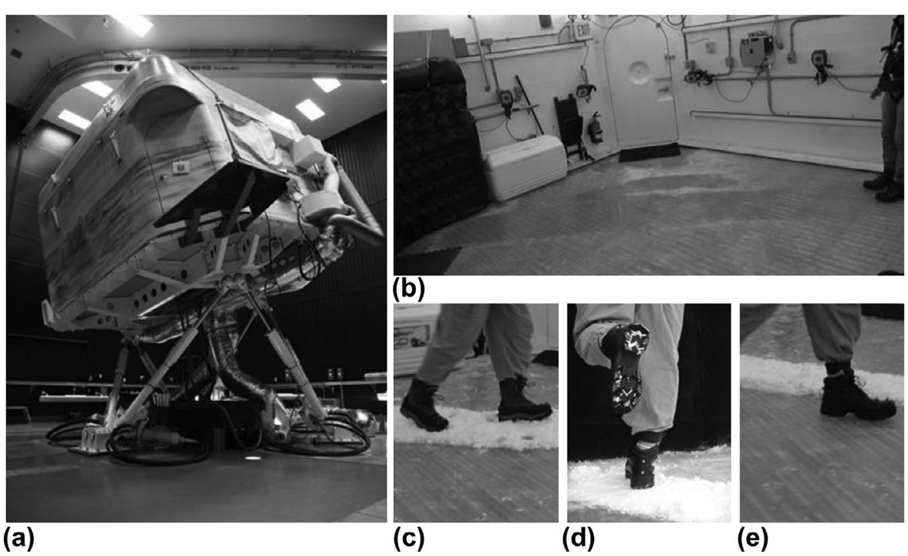

Figure 2. WinterLab test conditions. (a) Tilting WinterLab to create slopes; (b) dry and wet ice walkways; (c) walking over the snowy walkway; (d) snow accumulation underfoot; (d) walking in the snow condition on dry ice after walking in soft snow.

snow density, was 25%, or equivalently 250 kg/m^3, measured using a Brooks-Range Pocket Snow Density Gauge 100 (Brooks-Range Mountaineering Equipment, Fremont, USA). Participant testing began within 20 min of transporting snow into the laboratory. Because the snow was compressed with additional passes over the walkway, fresh snow replaced trodden snow after each participant completed every two styles of footwear. Between styles, when snow was not replaced, the snow was broken up using the edge of a shovel.

During pilot testing it was determined that while thick snow underfoot improved traction and allowed even running shoes to achieve steep incline angles, having some snow on the outsole and then walking on dry icy slopes was very challenging. This condition simulates the realistic scenario of encountering a patch of ice after having walked over snow. The *snow condition* selected for testing in this experiment was thus snowy footwear over dry ice, created by first walking over the snowy walkway surface (Figure 2(d)) and then walking on the adjacent dry ice walkway (Figure 2(e)). Remnants of snow left on the dry ice walkway from snowy footwear were cleared between test passes across the dry ice surface.

2.4. Incline angles

To conduct this experiment, WinterLab was mounted to a hydraulic powered motion base that tilted the laboratory, creating slopes for participants to ascend and descend along its diagonal. The first angle tested by each participant in each style of footwear and surface was 0°, or level. To minimise discomfort due to lengthy exposure to the cold temperature conditions, participants were not asked to test all possible incline angles. The second test angle was determined during pilot testing. Three degrees less than the smallest maximum incline angle achieved by either of the two pilot participants during ascent or descent was set as the second test angle for that footwear–surface combination in the full experiment with a minimum second test angle of 1°. After walking on the level, the laboratory was tilted at 0.25°/s to the second test angle so that the participant could then ascend or descend the walkway (in random order).

Starting from the second test angle, for each trial, participants walked from one end of the walkway to the opposite end and then returned to the starting position, thereby completing one ascent and one descent. They were instructed to walk at a self-selected pace in a controlled manner and if possible, without sliding. The incline angle was then adjusted incrementally by 1° until the participant failed to ascend or descend. A trial was considered a failure if the participant could not initiate gait or if both of the participants' feet slipped simultaneously while traversing the slope (but not including controlled slides to terminate gait). Following a first failed attempt, participants were asked to repeat the task at the same failed angle. If they failed again, the maximum achievable incline angle for the footwear–surface–slope direction combination was recorded as one degree less than that failed angle. If on the second attempt the participant successfully traversed the incline, the angle was increased by another degree and the process was repeated. In this way, maximum achievable angles were determined for both ascent and descent on dry and wet ice.

In the snow condition, participants would begin each trial by first walking across an adjacent snow-covered walkway before walking across the dry ice, with the exception of the first trial on the dry ice, before which participants walked both back and forth across the snow-covered walkway. The circuit was repeated at increasing angles of incline to determine the maximum achievable angle in the snow condition in one slope direction at a time (randomly starting with ascent or descent).

2.5. Data collection and analysis

The primary outcome measure collected was the maximum achievable incline angle for each footwear–contaminant combination while ascending and descending. This was determined to a resolution of 1° for both ascent and descent while participants tested each of the six styles of footwear on the three test surface conditions. The maximum achievable angles were also converted into their equivalent COF values by taking the tangent of the angle. This COF represents static friction at the point when traction is lost, as opposed to sliding friction which is the instantaneous ratio of the shear load to normal load during relative motion. Kinematic data were also collected during each walking trial using a 12-camera passive motion tracking system (Motion Analysis, Santa Rosa, California) that tracked the position of reflective markers on the subjects' footwear and upper body. Motion data were collected at 100 Hz and filtered using a fourth-order, zero-lag, dual-pass Butterworth filter with a 6 Hz cut-off frequency. Six locations were tracked on each participant. Markers on each piece of footwear were used to track the position of the anterior and posterior centres of each sole to approximate the points of contact with the ground at heel strike and toe off, respectively. Tracking markers were also placed on the anterior side of the upper body at the level of the second thoracic vertebra (T2) and at the level of the second sacral vertebra (S2) to measure flexion angle of the upper body.

Kinematic data were used to calculate gait characteristics while participants traversed the middle 2.5-m section of each test surface. To calculate gait parameters, heel strike and toe-off events were identified through visual inspection at the time points when the heel strike marker made contact with the ground surface and when the toe-off marker lifted off of the ground surface, respectively. *Step width, step length, step time and step speed* were calculated from heel strikes of each foot to the subsequent heel strikes of the contralateral foot and were averaged over all steps in the 2.5-m portion of the walkway. Step width was calculated as the horizontal distance between heel strike locations, perpendicular to the walking direction and step length was the distance between subsequent heel strike locations along the walking direction. Step time was the time between subsequent heel strikes and step speed was calculated by dividing step length by step time. *Heel strike foot angle* was calculated as the angle subtended by a line joining the heel and toe of the same foot to the ground surface plane at each heel strike event. *Upper body flexion* was calculated at heel strikes and measured as the angle in the direction of travel subtended by a line joining the S2 and T2 markers to a line normal to the ground such that positive angles represent upper body flexion with respect to upright stance on the level surface and negative angles indicate upper body extension.

A three-way repeated measures analysis of variance (ANOVA) with the factors of surface (dry ice, wet ice, snow), footwear (S, K, I, N, G, J) and slope (ascending, descending) was used to determine their effects on maximum achievable incline angle. Two-way repeated measures ANOVAs were run to determine the effects of surface (dry ice, wet ice, snow) and footwear (S, K, I, N, G, J) on each gait characteristic while participants walked on the level (0°) walkways. At the maximum achievable incline angles, three-way ANOVAs with the factors of surface (dry ice, wet ice, snow), footwear (S, K, I, N, G, J) and slope (level, ascending at the maximum achievable incline, descending at the maximum achievable incline) were used to determine their effects on each gait characteristic. For all main and interaction effects, the criteria for statistical significance were set at $p < 0.05$ and Bonferroni adjustments were used to correct for pairwise comparisons.

2.6. Bench testing

To compare the maximum achievable incline method of determining slip resistance to the standard method, one shoe of each style was also tested according to ASTM F2913-11 (ASTM F2913-11 2012). To utilise comparable test surfaces, ice surfaces which can be used in conjunction with the standard test machine (SATRA STM603) were created according to SATRA TM144 guidelines (SATRA TM144 2011). COF values were measured on a rough frosted ice surface and the dry ice surface below. Additionally, to simulate the wet ice condition used during dynamic testing, water was sprayed in a continuous layer over the dry ice to bench test the COF of each style of footwear on wet ice.

A limitation of the comparison between the bench tests and the walking tests was that it was not possible to use identical ice conditions. The ASTM standard requires all testing to be conducted in ambient temperatures of 23 °C (±2 °C) while the ambient temperatures in WinterLab were colder at 5.6 °C (±1.1 °C). Cooling elements embedded in a rigid 19 cm by 44 cm tray were used to continuously cool 0.5 cm of ice at −7 °C throughout the bench tests to maintain the ice temperature and prevent cracking. The ice temperature in WinterLab was controlled by cooling elements embedded in the 2.5 cm thick ice floor that maintained the temperature at −1.9 °C (±0.8 °C).

Prior to bench testing, the footwear was cleaned with soap and water and the soles were pre-conditioned in a −5 °C solution of ethanol (50%) and water (50%) for three hours. COF values for each type of footwear were collected in each of two test modes, as per the standard specifications. In the flat test mode, the footwear was slid flat against the test surfaces and in the heel test mode, the footwear was tilted at 7.0° (±0.5°) with its heel against the test surfaces. For both cases, COF was measured with the footwear moving forwards relative to the surface, simulating forward heel slips which can occur with the foot flat against the ground surface (simulated by the flat mode) or at an angle relative to the ground surface (heel mode). Because the frost layer was removed after the initial run, the COF measured on the first run was recorded as the frosted ice COF for each footwear and tilt angle combination. In accordance with the standard, the COF values on dry ice and wetted ice were calculated for each footwear and tilt angle combination as the average of the first five consecutive runs which did not show a systematic increase or decrease of greater than 10% of the measured value (ASTM F2913-11 2012). A three-way repeated measures ANOVA with the factors of surface (dry ice, wet ice; frosted ice was not included in the analysis as only a single run was conducted), footwear (S, K, I, N, G, J) and test mode (heel, flat) were used to determine their effects on the COF values obtained during the bench tests. Rankings of footwear slip resistance obtained from the bench tests were also compared to rankings obtained during maximum achievable incline testing.

3. Results

3.1. Maximum achievable incline angle

The main effects of surface, footwear and slope direction, as well as the surface–footwear interaction were significant for maximum achievable incline angle (Figure 3). Participants failed at the smallest angle while walking in the snow condition with maximum achievable angles

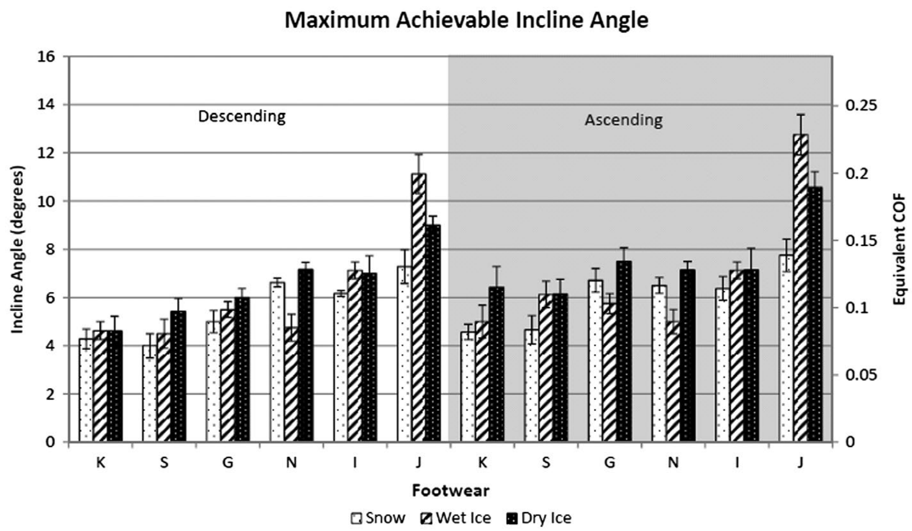

Figure 3. Performance of test footwear rated by the maximum achievable incline angle. The secondary axis shows COF values equivalent to the incline angles.

of 5.8° (0.2°) (mean (standard error)) followed by wet ice (6.6° (0.3°)) and then dry ice which was the least slippery (7.0° (0.4°)). Pairwise comparisons indicated that the snow condition was significantly more slippery than both the wet ice and dry ice conditions across all types of footwear and slope directions. Over all surfaces and slope directions, footwear ranked from most slippery to least slippery using maximum achievable incline in the following order: Style-K (4.9° (0.3°)), Style-S (5.1° (0.3°)), Style-G (6.1° (0.3°)), Style-N (6.2° (0.2°)), Style-I (6.8° (0.4°)) and Style-J (9.7° (0.4°)). Participants were also able to ascend significantly steeper slopes than they were able to descend with maximum achievable inclines averaged across all types of footwear and surfaces of 6.8° (0.3°) (mean (standard error)) for ascent and 6.1° (0.2°) for descent.

Significant interaction effects were observed between surface and footwear. In general, while walking upslope or downslope, the poorest performance was observed on the snow condition followed by the wet ice condition, while the best performance was observed on dry ice. However, while Style-G also performed from worst to best on snow, wet ice, then dry ice during descent, Style-G performed poorest on wet ice during ascent. Additionally, Style-J which outperformed all other styles of footwear on all surfaces demonstrated superior performance on wet ice during descent and ascent in comparison to its performance in the snow and dry ice conditions.

3.2. Gait analysis

Gait variables (temporal–spatial and kinematic measures) are summarised in Table 2. Two-way ANOVAs (footwear × surface) indicated that while walking on the level surfaces, only the main effect of footwear was significant for step length and step speed. However, using a conservative Bonferroni correction factor for multiple comparisons, the *post hoc* analyses revealed that no significant differences were observed between any two styles of footwear for step length or for step speed. All other main and interaction effects for tested gait characteristics were non-significant.

Three-way ANOVAs including the factor of slope type (level, ascent, descent) showed a significant main effect of slope type for step length, step time and step speed (Table 2).

Table 2. Estimated means of gait kinematic data (mean (SE)) at each level of the main effects of slope type, footwear, and surface.

		Step length (m)	Step time (s)	Step speed (m/s)	Step width (m)	Foot angle (°)	Upper body flexion (°)
Slope	Level	0.52 (0.02)	0.67 (0.02)	0.79 (0.03)	0.11 (0.01)	17.2 (0.9)	0.1 (2.1)
	Ascent	0.44 (0.01	0.84 (0.04)	0.56 (0.03)	0.09 (0.01)	8.6 (0.7)	11.3 (2.8)
	Descent	0.40 (0.01)	0.66 (0.03)	0.63 (0.04)	0.12 (0.01)	11.1 (0.7)	−5.5 (2.4)*
Foot-wear	K	0.45 (0.01)	0.73 (0.02)	0.63 (0.02)	0.10 (0.01)	10.8 (1.0)	2.2 (2.5)
	S	0.47 (0.01)	0.70 (0.03)	0.69 (0.03)	0.10 (0.01)	13.1 (0.7)	1.6 (2.3)
	G	0.46 (0.02)	0.74 (0.03)	0.65 (0.04)	0.11 (0.01)	12.4 (0.7)	1.4 (2.8)
	N	0.46 (0.01)	0.71 (0.02)	0.67 (0.03)	0.11 (0.01)	12.7 (0.9)	2.2 (2.8)
	I	0.45 (0.02)	0.72 (0.03)	0.66 (0.03)	0.10 (0.01)	10.8 (0.8)	1.7 (1.7)
	J	0.46 (0.01)	0.74 (0.03)	0.65 (0.03)	0.12 (0.01)	14.0 (0.5)	2.8 (2.2)
Surface	Dry ice	0.46 (0.01)	0.75 (0.02)	0.64 (0.03)	0.10 (0.01)	12.6 (0.70)	0.3 (2.5)
	Wet ice	0.46 (0.02)	0.71 (0.03)	0.67 (0.04)	0.11 (0.01)	11.7 (0.55)	5.7 (2.4)
	Snow	0.16 (0.01)	0.72 (0.03)	0.67 (0.04)	0.10 (0.01)	12.7 (0.86)	−0.1 (2.5)*

Note: Factors which were found to have significant main effects are highlighted in grey.
*Negative flexion angles indicate that the upper body was in extension.

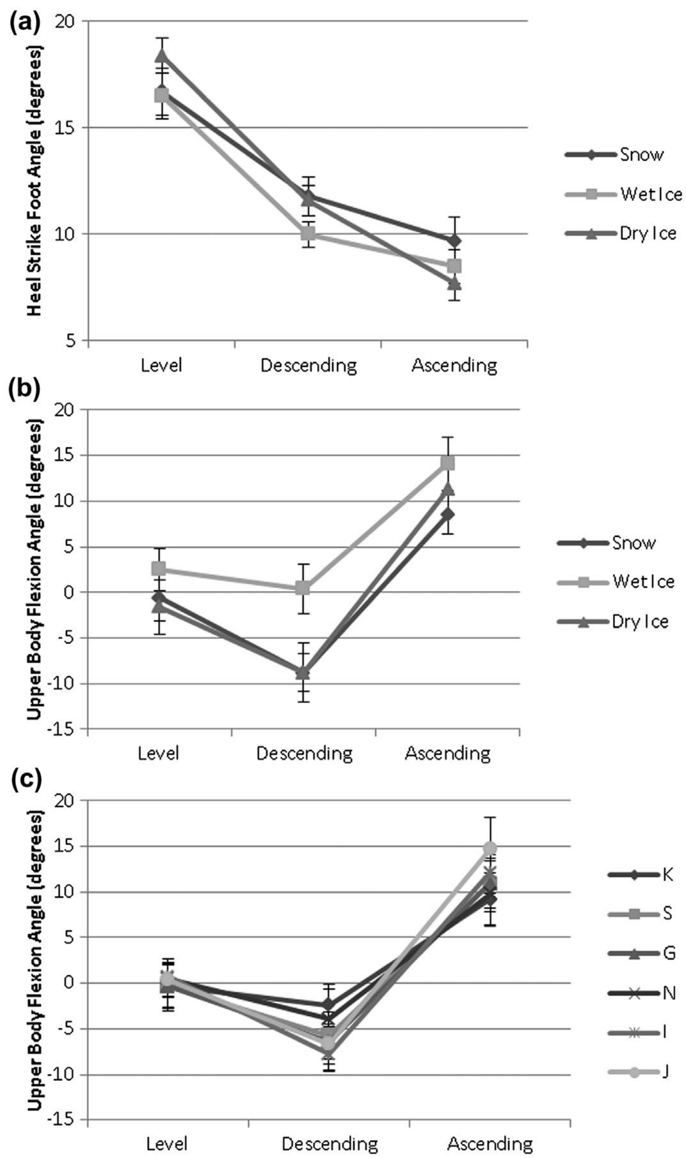

Figure 4. Interaction graphs for significant two-way interaction effects. (a) Surface–slope interaction for heel strike foot angle; (b) Surface–slope interaction for upper body flexion angle; (c) footwear–slope interaction for upper body flexion angle.

At the maximum achievable angles, participants took significantly shorter steps while descending compared to ascending and while ascending compared to walking on the level. Step times while walking upslope were significantly longer than step times while walking on the level or downslope. As a result, step speed while ascending was significantly slower than that while descending, which was significantly slower than step speeds on the level.

The main effects of slope type and footwear were significant for step width. Participants took significantly narrower steps while walking upslope at the maximum inclines than on the level or downslope at the maximum inclines. Pairwise comparisons indicated that participants took significantly wider steps while using Style-J footwear in comparison to Style-I and Style-S.

Heel strike foot angle was significantly affected by the main factors of slope type and footwear. Overall, all pairwise comparisons of the levels of slope type were significant. The angle between the foot and surface at heel strike was greatest on the level surface followed by the downslope angle and smallest on the upslope. The angle of the foot when contacting the ground surface was greatest for Style-J followed by Style-S. While wearing Style-J participants hit the ground at significantly larger foot angles than while wearing Style-I and Style-K and Style-S was associated with greater heel strike angles than Style-I. The two-way interaction of surface and slope type was also significant for heel strike foot angle (Figure 4(a)). During level and downslope walking at the maximum achievable angles, foot angles at heel strike were similar across all

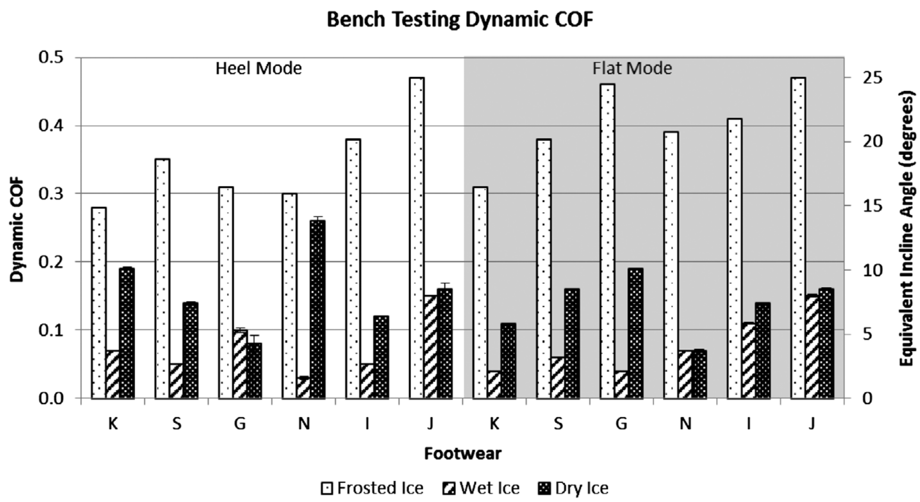

Figure 5. Dynamic COF measured during bench testing. The secondary axis shows incline angles equivalent to the COF values.

surfaces. During upslope walking however, foot angles at heel strike were significantly greater on the snow condition than on dry ice.

The main effects of slope and surface were significant for upper body flexion angle. Participants flexed their upper bodies the most relative to upright stance while walking upslope at heel strike. Upslope flexion at the maximum achievable inclines was significantly greater than on the level. Upslope flexion at heel strike on the level was significantly greater than while walking downslope at the maximum achievable inclines. Mean upper body flexion at heel strike on the snow condition was similar to that on the dry ice condition. On the wet ice condition, however, participants walked with significantly greater flexion of the upper body than in the snow condition. The two-way interaction between surface and slope as well as the interaction between footwear and slope were also significant for upper body flexion angle at heel strike. During level and upslope walking at the maximum achievable angles, upper body flexion was similar across all surfaces. During downslope walking participants walked with their upper bodies in significantly greater extension on the wet ice and snow conditions than on dry ice. During level walking across all surfaces, upper body flexion was negligible, with participants walking upright, for all types of footwear (Figure 4(b)). While descending, participants walked with significantly greater upper body extension in the better performing footwear (Style-I and Style-J compared to Style-K) and conversely while ascending, significantly increased upper body flexion was seen while walking in the better performing footwear (Figure 4(c)).

3.3. Bench testing

The COF values measured on frosted, dry and wet ice for each type of footwear tested in the heel and flat modes are shown in Figure 5. For each style of footwear, the initial run on frosted ice resulted in higher COF values than the subsequent tests on dry ice and wet ice. In the flat test mode, the dry ice consistently resulted in equivalent or higher COF values than on wet ice. In the heel mode, all types of footwear with the exception of Style-G also demonstrated greater slip resistance on dry ice than on wet ice.

The main effects of surface, footwear and test mode were all significant for the COF values obtained during the bench tests. Each of the two-way and three-way interaction effects was also significant. These results indicated that the COF values were significantly lower for the tests conducted on the wet ice (0.08 (0.002)) than on the dry ice (0.20 (0.005)) and the COF values were significantly lower for the tests in the heel mode (0.13 (0.003)) than in the flat mode (0.16 (0.003)). The significant two- and three-way interaction effects indicated that the COF values obtained for each style of test footwear were not consistent across surfaces and test modes as reflected in their inconsistent rankings (Figure 5).

In Figure 5, the COF values obtained during bench testing have been converted to their equivalent incline angles by calculating the inverse tangents of the COFs. In Figure 6, these values are plotted with the maximum achievable angles obtained while walking upslope and downslope. This figure shows results from the walking tests obtained on the wet ice and dry ice conditions as well as results from the bench tests using wet ice and dry ice.

4. Discussion

Performance as measured using maximum achievable incline angles indicated that the snow condition was the most challenging surface to walk across for all types of footwear. During our pilot studies, traction was observed to be high on thick (approximately 3 cm), soft, trodden

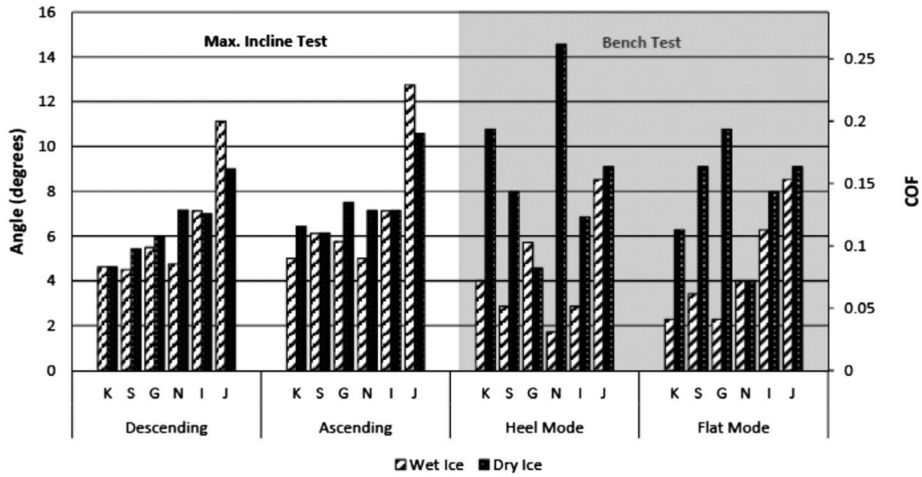

Figure 6. Results from the maximum achievable incline angle testing compared to bench testing on the dry and wet ice conditions.

snow. However, the snow condition tested in this study involved only a thin layer of snow transferred on the soles of the boots to the dry ice surface. This snow over ice condition highlights how snow can make maintaining balance while walking more difficult and why snow-related falls are so prevalent in winter. These results are in agreement with findings from Gao, Holmér, and Abeysekera (2008) that showed that ice covered in snow was considered by outdoor workers to be more slippery than melting ice, ice, melting snow and snow. The data suggest that additional studies are needed to show whether outsoles designed using materials and tread patterns that discourage the accumulation of snow underfoot or encourage uptake of snow into the tread and away from the outsole surface may be useful in mitigating snow-induced slips.

On snow, Style-K and Style-S achieved the smallest maximum incline angles. Both of these styles of footwear had very shallow treads, in the range of 2.5–3 mm in depth. Style-G, Style-N and Style-I performed moderately and all incorporated more aggressive, deeper tread patterns, in the range of 5.5–6 mm in depth. Style-J outperformed all other styles of footwear during both ascent and descent on all three surface conditions, with particularly good performance on wetted ice. Style-J had no tread pattern but utilised a specially designed outsole material. As with all the other styles of footwear, Style-J also showed a marked decrease in performance in the snow condition. JStep's proprietary outsole was different from the other tested outsoles and consisted of a soft rubber embedded with micro-scale protruding fibres. Future testing is required to show whether incorporating an aggressive tread (while optimising surface contact area) with the JStep outsole material might allow for the preservation of Style-J's performance on wet ice and simultaneously improve its capabilities after walking on snow.

As indicated by the results, different styles of footwear responded differently to the various winter surfaces and testing only one surface does not provide a complete picture of how the different types of footwear responded to a range of winter conditions. There is a need to survey the actual outdoor conditions that are most likely to contribute to slips and falls. Existing records of falls typically lack detailed information (Courtney et al. 2001) and since outdoor winter conditions can be highly transient, detailed environmental information at the instance of a fall can be very difficult to collect. More work is required in field studies of actual winter-related falls to record ambient temperatures, surface temperatures, surface characteristics and contaminant characteristics to guide the development of test conditions that are most relevant to footwear testing in the future. It should also be borne in mind that while maximum achievable angles are determined using this test method, tested footwear are not recommended for use at these slope angles. Rather, these angles provide a relative measure of performance of footwear expected during level-ground walking.

Measures of gait characteristics indicated the various strategies used to maintain stable balance on level slippery surfaces and while walking on slopes at the bounds of the participants' ability. Compared to the easier task of level walking, participants slowed down their step speeds while ascending and descending and walked slower upslope than downslope at the maximum achievable angles. Narrower steps were also taken while ascending compared to descending or walking on the level. Style-J footwear was associated with the widest steps, indicating that participants were able to most effectively adapt their gait for improved stability (Menant et al. 2009) which allowed them to achieve the steepest incline angles. It should be noted that while differences were observed between gait characteristics on ascent and descent, the strategies that were used for maintaining balance by the participants (such as slower stepping speeds and reduced heel strike foot angles) were the same for both slope types and differences in magnitude may be related to the fact that greater heel strike foot angles were achieved during descent than ascent.

Participants also decreased their foot-floor angles when ascending and descending compared to on the level. Smaller angles were utilised on the upslope than downslope at the maximum achievable angles. Style-J was associated with the largest foot-floor angles, which corresponds with a previous study showing that foot angles at heel strike decrease with increasingly slippery surfaces and increasingly steep surface angles (Cham and Redfern 2002). However, Style-S footwear which demonstrated poor performance was associated with the next highest foot-floor angles at heel strike. This is most likely due to the fact that the Style-S running shoes were lower cut than the other styles of footwear tested, and did not restrict motion at the ankle thereby allowing greater ankle flexion. Restricting ankle flexion may help to reduce slips as supported by results from Menant et al. (2009) which showed that high-collar shoes provide improved stability on slippery floors. Within our study, two-way interactions (Figure 4) between surface and slope type showed that while foot angles across surface conditions were consistent during descent and level walking, foot-floor angles were smaller on dry ice than on snow, while walking upslope at the maximum achievable angles. These smaller foot-floor angles at heel strike were expected because the snow condition was determined to be more slippery than the dry ice condition. It is possible that because of the tilt angle of the floor during ascent, participants were overcompensating in the snow condition by increasing dorsiflexion to achieve greater surface contact. This is also what the strategy of flat-footed walking on slippery surfaces aims to achieve.

Upper body flexion angles at heel strike while walking at the maximum achievable incline angles indicated that during ascent, participants flexed their upper bodies relative to level walking and during descent participants extended their upper bodies with respect to level walking. These strategies are understood to improve trunk stabilisation while walking on incline planes as they move the body's centre of mass over the base of support, which prior to heel strike is the stance foot (Leroux, Fung, and Barbeau 2002). The greater flexion angles upslope and the greater extension angles downslope while wearing the better performing footwear are likely to be due to the fact that these angles were assessed at the maximum achievable angles for the various footwear–surface combinations. These findings agree with those of Leroux, Fung, and Barbeau (2002) who found that increased incline angles were associated with greater upper body flexion and extension during ascent and descent, respectively.

Bench tests on winter test surfaces indicated that the dry and wet ice tests were most comparable, in terms of the range in COF values observed, to the results obtained from the human-centred incline approach. The frosted ice test surface produced a rough upper layer that was significantly more slip resistant across all types of footwear than the smooth ice surface below the frost or the surfaces used during biomechanical testing. Figure 6 shows that the range in COF values as well as the overall ranking of footwear slip resistance across the wet and dry ice test surface conditions were more consistent using the maximum achievable incline angle method than using the bench tests. In particular, large differences were observed between the heel and flat test modes on dry ice for Style-N and on both dry and wet ice for Style-G, whereas both styles performed relatively consistently during the upslope and downslope walking tests. Bench testing on wet ice also tended to underestimate anti-slip performance in comparison to the wet ice results obtained during maximum achievable slope testing. The inconsistent rankings of the footwear from the bench tests make interpretation of the results particularly challenging.

This study highlights differences between the standard bench-testing method and a human-centred approach to assessing footwear slip resistance. The bench tests have the benefits of being smaller scale; therefore, requiring less space, allowing expedited measurements (approximately 0.5 h per footwear for testing and 3 h to freeze the winter surface) and movement of the footwear relative to the surface are tightly controlled. The major limitation of the bench test is a lack of validation for winter use in terms of the motion that is simulated (for example, the tilt angle of the footwear in heel mode is 7°, which is less than half the angle at heel strike observed while participants walked on level ground) as well as the surface conditions that can be tested (which are limited by the fact that the test are required to be conducted at room temperature, in which winter conditions simply do not exist). The key advantages of the maximum incline test are in the incorporation of samples of the real user population, true gait kinematics and the ability to include more realistic surface conditions. However, as in the case of the bench tests, the maximum incline testing method utilised in the current work may not translate performance of footwear directly to slip incidence on level ground or uneven surfaces and thus requires further validation. Future work will compare the validity of the two methods by comparing their results to measures of slip magnitude and balance recovery from unexpected slips while walking on level ground.

5. Conclusion

In order to reduce the frequency of outdoor slips and falls in winter conditions, improved design and testing of winter footwear are imperative. This study showed that the performance of winter footwear changes depending on the walking surface and why it is therefore important to test on those surfaces that are most common and most challenging in the areas in which they are used. In particular, the results showed the importance of including snow surfaces when assessing winter footwear slip resistance.

The maximum achievable incline method produced consistent results across footwear and surface conditions. This human-centred method produces ecologically valid results that reflect both the characteristics of the footwear and users' ability to adapt their gait to prevent slipping. The results clearly indicate that participants adapt their gait to increasingly slippery conditions and incline angles. Despite these adaptations to the various underfoot conditions, the maximum incline method demonstrates that distinct performance differences can be detected between shoe types.

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