Measuring the Slip Resistance of Winter Footwear

by

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A thesis submitted in conformity with the requirements for the degree of Doctor of Philosophy
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2015

Abstract

Slip and fall accidents represent an enormous burden in terms of human suffering and economic costs. In winter conditions, outdoor falls increase as cold temperatures and precipitation create hazardous conditions underfoot. An effective method of reducing falls is the use of slip resistant footwear. However, the optimization of this footwear is hindered by the fact that slip resistance is not easily measured and the validity of existing measurement devices is questionable. The series of four studies presented here show the progression of work utilizing human-centred approaches to evaluating the performance of winter footwear on real winter surfaces and have led to the development of a new test method. To start, traditional measures of slip severity were used to evaluate the effectiveness of winter boots and cleated footwear devices while subjects walked in common winter conditions. Walking trials on level and uneven icy surfaces showed that while cleated footwear did reduce slip frequency, they did not prevent dangerous slips from occurring. Further testing showed that the current standard test conditions and parameters used for determining footwear slip resistance do not adequately simulate gait in winter conditions. As a result, a new user-centred protocol was developed for testing footwear. Subjects were asked to stand and walk
across a wet, icy surface that was tilted progressively until they could no longer maintain balance, thereby establishing the maximum achievable incline angle for a variety of styles of footwear. This method proved to be reliable on wet ice so a refined protocol was applied to a larger sample of footwear which was then tested on dry ice as well as snow conditions. The results showed the importance of testing winter footwear in snow conditions, which had not been done before. These studies demonstrate the viability of testing footwear without removing the critically important human component.
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List of Acronyms

COF – Coefficient of friction
COM – Centre of mass
ACOF – Available coefficient of friction
ASTM – American Society for Testing and Materials
DCOF – Dynamic coefficient of friction
HPS – Horizontal Pull Slipmeter
PU – Polyurethane
RCOF – Required coefficient of friction
SATRA – Shoe and Allied Trades Research Association
TFU – Time-based frictional utilization
UCOF – Utilized coefficient of friction
Chapter 1
An Introduction to Slips and Slip Resistance

1.1 Slip and Falls

Falls are widely studied because of their prevalence around the world and because of their associated costs both in terms of human suffering and economic burden. Falls are categorized into falls from an elevation or same-level falls. Falls from an elevation are those where the point of contact is below the level of the original supporting surface of the faller. Same-level falls are those where the point of contact is on the same level or above the original supporting surface of the faller. Falls from an elevation are considered more likely to lead to severe injuries but same-level falls occur far more frequently. The Bureau of Labour Statistics in the United States reported that from 1999 to 2001, 65% of all fall-related occupational injuries were a result of same-level falls whereas only 32% were a result of falls from elevation (Yoon & Lockhart, 2006).

In some cases, factors intrinsic to the human are solely responsible for same-level falls. But more often, these falls are at least partially induced by environmental factors. For example, trips occur during gait when the leading foot is arrested by an obstruction which interrupts the smooth movement of the body’s centre of mass. Slips are a more common cause of same-level falls, contributing to up to 85% of all fall-related occupational injuries (Courtney et al., 2013). They occur when the underfoot conditions induce a sudden loss of grip because the coefficient of friction between the footwear (or bare foot) and the floor is insufficient to resist the forces at the point of contact (Leamon, 1992). Foot trips and slips are injurious when they result in harmful loading of body tissues as a result of a sudden release in energy (Grönqvist, Chang, et al., 2001).

Studies of slip biomechanics have confirmed that slips typically occur either when the trailing foot is pushing off (toe-off) or when the leading foot contacts the ground (heel strike) (Perkins & Wilson, 1983; Redfern et al., 2001). At toe-off, the forces generated at the foot are used to propel the body’s center of mass forward after the majority of weight has already been transferred to the contralateral foot. At heel strike, the vertical component of weight is...
transferred onto the leading foot. As weight is being transferred the body is inherently unstable, relying on safe planting of the striking foot for momentary stabilization. Accelerations at the heel during heel strike can therefore lead to balance loss and potential falls. As such, slips at toe-off are less hazardous than those at heel strike (Leamon, 1992).

Slip resistance is a term used to describe properties of underfoot surfaces and footwear that resist the tendency to slide relative to one another (ASTM F1637, 2013; Grönqvist et al., 2001). The provision of adequate slip resistance is important in reducing the risk of slips and falls. Figure 1.1 depicts the typical sequence of normal walking followed by slip initiation at heel strike due to inadequate slip resistance. This then leads to balance loss, fall, and injury.

![Figure 1.1 Typical event sequence for slips and falls. Adapted from Grönqvist et al., 2001.](image)

Courtney et al. (2001) attempted to isolate the contribution of slipperiness to slip, trip, and fall-related injuries using data from various injury surveillance systems in the United States, United Kingdom and Sweden, which range in their capture and documentation of slip exposures. The U.S. NHIS and Swedish ISA systems were the only ones to provide codes that differentiated slips from other causes of fall events. Their data showed that slips were associated with 40-50% of same-level-falls.

Some individual studies have also reported industrial incidence rates of slips and falls. A total of 42.5% of falls experienced by Royal Mail letter carriers were due to slips and falls (Bentley & Haslam, 1998), 13.5% of all injuries in the trucking industry were a result of slips (Lin & Cohen, 1997), 11% of grease burns in the fast-food industry resulted from slips.
(Hayes-Lundy et al., 1991), slips led to 25% of injuries in construction, (Niskanen, 1985), slips led to 8% of injuries in petroleum drilling (McNabb et al., 1994), and slips were the most frequent cause of disabling events contributing to 27% of lost-time due to injuries in automobile manufacturing (Shanon & Manning, 1980).

### 1.1.1 Winter Slips and Falls

The likelihood of experiencing slips and falls increases during the winter season. Winter conditions such as snow and ice reduce underfoot traction and make it difficult to maintain balance and execute effective balance recovery strategies (Abeysekera & Gao, 2001; Courtney et al., 2001; Gao & Abeysekera, 2004; Gard & Lundborg, 2000). A trend of increasing slips and falls during winter has been reported for several decades in areas across the world with the most comprehensive winter data originating in Canada and the Nordic regions.

Throughout Canada, falls on ice are the single most common cause of serious traumatic injuries, excluding motor vehicle collisions. The Canadian Institute for Health Information published data regarding emergency room visits resulting from slips and falls on ice that occurred in 2002-2003. Nearly 12,000 Ontarians visited an emergency room due to an injury on ice during that time period. The greatest number of injuries occurred in February (30%) followed by January (24%) (Canadian Institute for Health Information, 2005).

In 2010-2011, falls on ice led to 7,138 hospital admissions across Canada, exceeding admissions due to all winter sports and recreational activities combined. Women accounted for more falls on ice (56%) than men (44%). Over half of the falls occurred in people who were 60 years of age and older and 70% of the falls occurred in people 50 years of age and older (Canadian Institute for Health Information, 2012).

Honkanen (1982) showed that in Finland, slip-induced falls led to three times more injuries in the winter months. Winter conditions contributed to 47% of all same-level falls, 25% of all same-level falls and 7% of all emergency room visits.
Lund (1984) studied 4500 same-level falls in the home and during leisure activities from hospital admissions data collected between 1977 and 1980 in three Nordic countries. The study showed that 16% of all accidents were a result of slips (separate from trips). Of all slipping accidents, snow and ice were determined to have contributed to 73% in Norway, 57% in Sweden, and 74% in Finland. These types of accidents most often resulted in fractures and sprains.

Eilert-Petersson and Schelp (1998) analyzed data from all patients who had visited a physician or dentist as a result of a non-fatal injury in Västmanland, Sweden from November 1st 1989 to October 31st 1990. Over half of all pedestrian injuries occurred in the three winter months of November, December, and January. Slips were more common for both males and females during the winter months. Slips were found to have contributed to 49% of all falls. Environmental factors contributed to 92% of these falls with snow and ice being the most prevalent environmental factor.

Kemmlert and Lundholm (2001) studied occupational accident reports from 1994 that were recorded by the Swedish Occupational Injury Information System. Out of 1025 slip, trip, and fall accidents, slips on snow or ice were responsible for 25% of accidents in women under 45 years of age, 30% of accidents in women 45 and above, 13% of accidents in men under 45 and 18% of accidents in men 45 and above. For women, the largest proportion of slip and fall accidents as a result of ice and snow were reported by social workers and home helpers who accounted for 56% of all cases.

According to the Swedish hospital-based injury registration database, pedestrian injuries occurring in the winter due to slips and trips accounted for more than 50% of all in-patient days for injuries incurred in a traffic environment (Rolfsman et al., 2012). This study found that two-thirds of the reported pedestrian injuries were slips and falls on surfaces covered with ice or snow.

Outdoor workers such as postal delivery personnel, are particularly vulnerable to slip and fall accidents (Bentley & Haslam, 1998). Canada Post reported that in 2007, 46% of lost-time due to accidents was a result of slips, trips, or falls (Canada Post Corporation, 2008). Letter carriers experienced more than 1500 on-the-job injuries related to the weather.
British researchers analyzed 1734 fall cases of Royal Mail Midlands workers during mail delivery and showed that the most common initiating events were slips and trips with slips mostly occurring on snow, ice, and grass and trips most often involving uneven pavement, obstacles, and curbs. Their data showed that half of all falls occurred between November and February (Bentley & Haslam, 1998). A follow-up study conducted in 1998 of 40 postal delivery worker slip, trip and fall accidents between October and March found that 70% of accidents involved snow and ice (Haslam & Bentley, 1999). Key risk factors leading to slips, trips and falls during mail delivery were slippery underfoot conditions, non-weather related environmental hazards, poor slip-resistance from footwear, unsafe working practices, and poor management safety practices (Bentley & Haslam, 2001).

1.1.2 Injuries

Slips and falls are hazardous because of the injuries they cause. Common injuries include sprains and fractures often affecting the wrists, pelvis and lower extremities. Hip fractures are of particular concern in falls involving older adults. While same-level slips and falls are rarely immediately life-threatening, patients are at increased risk of premature death for several years following a hip fracture (Abrahamsen et al., 2009). Injuries resulting from falls have also been found to profoundly affect the activity level and life-style of older adults. Alexander et al. (1992) showed that 43% of adults over 65 discharged from Washington State hospitals in 1989 after treatment for a fall-related injury were discharged to a nursing facility.

Data from the Bureau of Labor Statistics show that over 70% of fall-related occupational accidents result in sprains, strains, fractures, and bruises. Slips and falls most commonly result in injuries to the lower extremities (32.8%) and back injuries were also commonly cited as a result of slips (23.2%) and falls (15.9%) (Yoon & Lockhart, 2006). Back injuries have been shown to be common even when slips do not result in a fall because of forces in the lumbosacral region during slip recovery (Rashedi et al., 2012).

In the workplace, the frequency of injurious slips and falls also affect the older population more than younger people and can impact men and women differently. Nenonen (2013) used
data mining techniques to analyze occupational slips, trips and falls from the Finnish occupational accidents and diseases statistics database. Males were found to incur 66% and females 34%, of slip, trip, and fall accidents, respectively. Layne and Landen (1997) studied hospital emergency department records of 136,985 work-related injuries involving workers over the age of 55 across the United States in 1993. Fall-related incidents accounted for 26.3% of all non-fatal injuries, of which same-level falls were the most common (55.9%). Women experienced more same-level falls (67.9%) than men. Falls were also the leading cause of hospitalization (43.9%) and fractures and dislocations sustained as a result of falls accounted for the greatest proportion of hospitalizations (36.1%).

Winter conditions are linked to not only higher rates of hospital visits, but also increases in rates of fractures. A study of winter conditions from Umea, Sweden showed that women over 50 years of age and young men (20 to 29 years of age) were at greatest risk of same-level slip and fall injuries (Björnstig et al., 1997). Women there were more likely to sustain moderate to severe injuries while men tended to experience minor injuries.

The Canadian Institute for Health Information found that from 2002 to 2003 injuries due to slips on ice in Ontario were most common in the 40-59 age-group (30%) and the 20-39 age-group (24%). Across all age groups, 17% of injuries resulted in overnight stays in the hospital and the 60-79 age-group accounted for the majority of these stays (34%). Fractures accounted for the most ER visits, overnight stays, and hospital admissions. Of the visits to the ER, 16% of cases were diagnosed with head injuries and 19% had hip fractures. 84% of patients with hip fractures were over the age of 60. A total of 15 patients died after admission to hospital as a result of a fall on ice. Of the 15 deaths, 11 were admitted for hip fractures and all were over 65 years of age (Canadian Institute for Health Information, 2005).

Ytterstad (1996) found that fractures sustained by older adults were five times more frequent during months with snow than the rest of the year. Bulajic-Kopjar (2000) conducted a prospective population based study of older adults (65-79 years of age) in Norway and found that the relative risk of fall-related fractures in the winter months of October through March, compared to the rest of the year was 1.39. The study also indicated that the increase in
fracture risk to the arms and hips in winter could be entirely attributed to the presence of ice and snow.

The slippery conditions associated with winter weather not only lead to a greater likelihood of injuries in the winter but also to many older adults being trapped in their homes throughout the season due to a fear of falling in icy conditions (Row et al., 2004). Older adults can also be discouraged from going outdoors in winter because the protective clothing can be heavy, restrictive, inconvenient and tiring to don and doff. The fear of falling due to hazardous winter conditions is known to reduce activity in older adults which can lead to deconditioning of the body, seclusion, and mobility difficulties.

1.1.3 Economic Costs

Falls are the leading cause of injury-related deaths and hospitalizations for older adults (Li et al., 2006) and the costs associated with treating fall-related injuries are significant. The direct medical cost of falls in the United States have been estimated at over $30 billion per year as of the year 2000 (Stevens et al., 2006). These costs include expenditures for hospitalizations, emergency department visits, and treatments in outpatient settings for the 2.6 million medically treated non-fatal fall injuries each year.

In 2010, same-level falls in occupational settings in the United States were calculated by the Liberty Mutual Workplace Safety Index at $8.61 billion in direct workers compensation costs. These costs increased by 42.3% from 1998 to 2010, increasing more than any other category of worker-related injury (Liberty Mutual Research Institute for Safety, 2012).

Leamon and Murphy (1995) estimated the direct costs of slips and falls from 1998 to 1990 using data from Liberty Mutual (which insures 11% of the private insurance market). While the study was inconclusive regarding the link between slip and fall incidence rates and precipitation, they did find that costs for same-level falls are highest in the winter months (in order from highest to lowest: February, January, December, March).
1.1.4 Footwear and Fall Prevention

Various protective measures such as balance training and fitness programs have demonstrated the potential of modifying behaviour in individuals to reduce their fall risk (Troy et al., 2009; Troy et al., 2008). Perturbation platforms for example, have been used to safely induce slips and elicit and train balance recovery responses (Bhatt & Pai, 2005; Maki et al., 2008). The balance skills acquired using a low friction perturbation platform have also been shown to carry over when walking on a slippery, oily surface reducing balance loss and falls (Bhatt & Pai, 2008). The practice of Tai Chi has also been recognized for its ability to reduce fall risk in older adults (Gatts & Woollacott, 2007). But while training and exercise programs are targeted towards the individual, environmental changes have the potential to mitigate fall risk on a wider scale.

In indoor settings in particular, high traction surfaces and proper maintenance procedures have been found to reduce slips and falls. Specialized flooring materials for increased traction including abrasive paints and tactile strips have been shown to be useful (Bell, 1997). Careful and timely removal of spills and other contaminants on floor surfaces as well as removal of obstacles are also important for reducing falls (Weisberger, 1994). Other environmental changes that can reduce fall risk include the application of warning signs (Gadomski, 1998) and improving lighting conditions (Maynard, 2006).

The control of outdoor environmental conditions, however, is far more difficult than indoors. Effective winter maintenance includes the timely removal of ice and snow (Maynard, 2006) and spreading of sand or salt (Abeysekera & Gao, 2001; Gard & Lundborg, 2000). Although these can be effective means of reducing fall risk in winter environments, in practice, their effectiveness is highly variable and dependent on timeliness and quality (Legget & Gold, 1965).

Bentley (2009) describe the importance of perception and cognition of hazards in the prevention of slips, trips, and falls. His study of construction workers in New Zealand found that in 75% of cases, workers did not perceive the hazard prior to the incident. Typical reasons for having not perceived hazards a priori include distraction or divided attention or
the hazard was obstructed from view. In winter conditions, a general awareness of potential slip hazards may be heightened as temperatures drop below freezing but snow conditions can often obstruct icy surfaces from view. Daylight hours are also shortened reducing visibility in the early morning and late evening hours. In a review of the literature, Bell (1997) suggested that aside from improving floor surface slip resistance, the only other effective method for preventing slips and falls in the workplace was through footwear. Targeting improvements in footwear for increasing slip resistance has the potential to impact falls on a large scale as evidenced by various cases in indoor industrial environments. Verma et al. (2011) showed that the use of slip resistant shoes in 36 limited-service restaurants across the United States reduced rates of slipping by 54%. A further analysis of the use of slip resistant footwear in these restaurants showed that the provision of slip resistant footwear by employers increased their use by 1.52 times and that older workers and women were more likely to use them (Verma et al., 2011).

Courtney et al. (2013) studied the link between the subjective perception of slipperiness and the risk of slipping in the workplace. They found that when the perception of slipperiness (rated on a 4-point scale and accounting for footwear, surfaces, and contaminants) was aggregated across restaurants, perception of slipperiness was strongly associated with rates of slipping. For every 1-point increase in the mean restaurant rating of slipperiness there was a 2.71 times increase in the rate of slipping.

Staal et al. (2004) studied the effectiveness of wearing positive-grip (high traction) shoe covers in a hospital setting where rates of slipping incidents had increased as a result of changing the hospital floors from carpet to porcelain tile. In the initial phases of this study, the researchers found that the majority of accidents had occurred while employees were helping patients transfer from shower chairs on wet floors. From a small sample of observations they concluded that high traction shoe covers were effective in preventing slips, trips, and falls.

Ensuring that outdoor footwear is adequately slip resistant, particularly in winter conditions is far more challenging than in indoor environments because of the range in temperatures, surface conditions, and precipitation that the footwear encounters. In 2007 Canada Post
reported that the greatest proportion of lost-time due to accidents resulted from slips, trips, and falls (Canada Post Corporation, 2007). Because many of these incidents resulted from snowy and icy conditions at private residences, an awareness initiative was undertaken to inform homeowners of the need to eliminate hazards on paths and driveways. In the same year, letter carriers and union representatives tested five sets of ice cleats on an ice rink and selected three sets to make available to employees. Approximately 16,000 sets of new anti-slip devices were distributed to delivery personnel. In 2008, Canada Post continued employing strategies and programs to prevent slips, trips, and falls throughout the winter season (Canada Post Corporation, 2008). In 2008 and 2009, despite ongoing efforts, the percentage of lost-time due to accidents resulting from slips, trips, and falls remained unchanged from 2007 at 46% (Canada Post Corporation, 2009) and by 2012, 50% of lost-time were attributed to slips, trips, and falls (Canada Post Corporation, 2012). While the precise statistics regarding exposure rates are not publicly available, because such a large proportion of the total lost time is still due to slips, trips, and falls, they remain an ongoing, high priority, safety concern.

Many other studies have also indicated a need for specialized winter footwear and many researchers have suggested the use of spikes or studs for added traction on snow and ice (Radomsky et al., 2001). However, there remains very little evidence to show how such anti-slip devices actually impact slip and fall risk. Pedestrians continue to experience high rates of slips and falls despite using them (Rolfsman et al., 2012). Similarly, while certain outsole materials and tread designs have been touted to potentially reduce slips, highly effective designs have not been established. In order to find effective footwear solutions for preventing winter slips and falls, an understanding of the interacting factors between the human, the footwear, and the environment is necessary (Gao & Abeysekera, 2004).

1.2 Slip Biomechanics

1.2.1 Characteristics of Normal Gait

Falls are commonly caused by a combination of both intrinsic and extrinsic factors (Tideiksaar, 1990). The ability to walk safely and maintain balance in the event of a slip is
dependent on intrinsic factors such as the visual, vestibular, proprioceptive, and musculoskeletal systems. Physiological changes associated with aging can affect these systems and increase the risk for slips and falls.

These systems work together to achieve normal gait. The challenge while walking is that the body’s centre of mass (COM) is continually thrown ahead of its base of support and safe placement of the swinging foot is critical for preventing a fall at each step. Furthermore, because the location of the COM is at approximately two-thirds of body height above the ground, the body acts as an inverted pendulum which is inherently unstable due to the forward momentum of the head, arms, and trunk while walking (Winter, 1995).

![Diagram of gait cycle](image)

**Figure 1.2. Features of a gait cycle. Adapted from Pierson, 2007.**

The events occurring over the course of a typical gait cycle, also considered one stride, are depicted in Figure 1.2. Each stride starts from heel strike of one foot and ends at the next heel strike of the same foot. Each stride consists of two steps with a step beginning from heel strike of one foot and ending at heel strike of the contralateral foot. Each foot is considered to be in stance phase when it is in contact with the ground and in swing phase when it is not in contact with the ground. Double support phases occur when both feet are in contact with the
ground while single support phases are those when only one foot is in contact with the ground (equivalent to swing phase).

![Diagram of ground reaction forces during normal walking from heel strike (HS) to toe-off (TO). Adapted from Lockhart, 2008.]

Typical ground reaction forces measured using a force platform and the associated coefficient of friction during walking are shown in Figure 1.3. Horizontal forces or shear forces ($F_{HH}$) are those applied in the plane of the walking surface while the vertical or normal forces ($F_N$) are those applied perpendicular to the walking surface. At heel strike, there is a forward thrust of the foot against the floor surface and simultaneously an increase in vertical force as body weight is loaded onto the striking foot. During toe-off, there is a rearward thrust of the foot and a decrease in normal force as weight is transferred to the next foot. Because slips occur when there is insufficient friction to counteract the forces being applied to the ground, coefficient of friction (COF) is an important measure in slip dynamics. During
gait the COF underfoot is also considered the utilized coefficient of friction (UCOF). UCOF is calculated as the ratio of the horizontal to normal force ($F_H/F_N$).

During normal gait without slipping, five peaks are generally observed in the UCOF ratio during each step (Figure 1.3). Peak 1 depends on the angle of approach of the heel and because a minimal vertical force has been applied at this point, this peak has been found to be inconsistent in determining slip severity. Peak 2 occurs if a backward force is exerted shortly after heel strike (McGorry et al., 2008). Although some evidence suggests that the shear forces and UCOF values at these earlier time-points are linked to slip severity (Osis, 2012), their implications are generally considered to be inconsistent. Peak 3, which occurs 70ms to 120ms following heel strike, is considered the most representative of the coefficient of friction that is required for safe walking (Lockhart, 2008). At Peak 3, a significant proportion of bodyweight is over the stepping foot and frictional demand is at a maximum. In the literature, the UCOF at this peak is considered a key outcome measure and is typically referred to as peak UCOF or the required coefficient of friction (RCOF) for safe walking without slipping. Following Peak 3, frictional demand decreases as the body’s COM continues to move forward over the foot. During toe-off, the frictional demand increases again as shear force is applied through the foot to propel the body forward during toe-off (Peak 4 and Peak 5).

Although only the shear forces in the fore-aft direction are depicted in Figure 1.3 Chang et al. (2011) showed that consideration of forces in the medial-lateral direction is also important when analyzing coefficient of friction. The lateral component of shear forces during walking (perpendicular to the direction of progression) were found to contribute to more than 10% of the calculated UCOF values in over 7% of nearly 25,000 steps analyzed. In terms of timing of RCOF, in more than 10% of steps, RCOF occurred over 20ms earlier when lateral shear forces were considered.

Furthermore, there are differences in the selection method of the RCOF value between studies. As RCOF is typically selected as the UCOF value at Peak 3, various methods have been used to bypass Peak 1 and Peak 2, if they have been observed. Buczek et al. (1990) use a threshold normal force of 50N before finding peak UCOF while Lockhart et al. (2003b) use
a 10N threshold and Chang et al. (2011) use a 100N threshold. Others have extracted RCOF based on the percentage of the stance phase, for example between 10% and 30% of stance (Chang, 2012) or after 5% of the stance (Cooper et al., 2008). Chang et al. (2011) also limited RCOF to within 200ms following heel strike. Burnfield and Powers (2006) restricted RCOF to include only those involving anterior movement at the instant of the RCOF.

A comparison of the various methods for extracting RCOF values was conducted by Chang et al. (2012) and found that the various methods yielded inconsistent results and that the various thresholds need more careful consideration. The authors also suggest that a hybrid method that incorporates a normal force threshold, positive anterior shear force, includes the lateral shear component, and is time limited may be best able to capture RCOF at Peak 3.

1.2.2 Gait on Slippery Surfaces

As previously discussed, slips are most likely to occur during heel strike and toe-off because of the increase in frictional demand. Heel slips (slips occurring at heel strikes) are more hazardous because they occur when the body’s COM is less stable. Kinematic measures are collected experimentally by tracking locations on the body in space using a motion capture system. Figure 1.4 illustrates kinematics and kinetics of a typical heel slip as described by Lockhart (2005). At the instance of heel strike, the foot may not immediately begin to slip (Figure 1.4(c)) because very little weight (Figure 1.4(d)) has been transferred onto the stepping foot. From here, heel velocity decreases (Figure 1.4(b)) and decelerates (Figure 1.4(a)). As the COM shifts onto the stepping foot (Figure 1.4(d)), the magnitude of the shear force increases (Figure 1.4(e)), increasing the frictional demand (Figure 1.4(f)) and causes the heel to begin slipping forward. If recovery from the slip is achieved, the heel will accelerate to a maximum (considered mid-slip) before decelerating. The heel then reaches peak sliding velocity before slowing to a stop at the end of the slip (not shown in Figure 1.4).
To avoid falling in the presence of slippery surfaces, humans adapt their gait to increase stability. Cappellini et al. (2010) compared gait patterns while walking on slippery surfaces to those on non-slippery surfaces. On a slippery surface, step length, step time, and horizontal shear forces were significantly smaller. Head orientation was more stabilized in space while both arm movement and trunk rotation were increased. The heel-to-toe rolling pattern during gait was diminished. However, with practice, the hips and the body’s COM became more
stabilized in the frontal plane. Chambers et al. (2003) showed that foot kinematics during gait in environments that are known to be slippery are different from those during unexpected slippery conditions. When a participant was aware of the environment being slippery, the heel’s vertical velocity prior to heel strike and the heel contact angle at heel strike decreased. Recovery attempts at the heel were also observed earlier on known slippery surfaces. Increased stance and stride time, shortened stride length, and decreased propagation speeds have also been identified as key strategies for maintaining balance while walking on slippery surfaces (Fong et al., 2008).

Fong et al. (2005) showed that the ankles play the most important role in adaptation to slippery conditions by reducing range of motion, maintaining a stiffer joint and achieving greater plantarflexion (flat-footedness) at heel strike. Using plantar pressure insole systems, it has been shown that greater toe grip (increased pressure under the hallux and lateral toes) and gentler heel strikes are used to prevent slips on slippery surface conditions (Fong et al., 2008).

During slips, the ground reaction forces are more variable across slip trials although general trends can be identified. During slips, peak shear and peak normal loads are reduced. After a slip is initiated, a corrective response to bring the slipping foot back under the body’s COM can sometimes be associated with a reduction in shear force (Cham & Redfern, 2001).

1.2.3 Recovery Responses

In the event of a slip occurring, the person may or may not engage in a recovery response depending on whether or not the slip was perceived. Slip distances of 2mm to 3mm are considered a feature of normal gait (Cham & Redfern, 2002). Longer slips have been categorized based on slip length, their ability to be perceived, and whether balance recovery is possible. Microslips are considered imperceptible. Perkins and Wilson (1983) reported microslip lengths from 10mm to 20mm, Strandberg and Lanshammar (1981) reported microslips of up to 12mm ± 4mm, and Leamon and Li (1992) reported up to 30mm long microslips. Strandberg and Lanshammar (1981) also described perceivable slips that occurred without apparent disturbances in gait patterns of up to 51mm ± 47mm. Macroslips
are considered to be normally perceivable, eliciting postural responses such as movement of
the arms or lunging or jerking of the upper body. Leamon (1992) reported macroslips
between 2cm and 10 cm in length. Several studies have reported that slips longer than 10 cm,
categorized as slides, result in total loss of balance control typically leading to impact with
the floor or other object (Cham & Redfern, 2002; Perkins & Wilson, 1983; Strandberg &
Lanshammar, 1983). However, these categorizations are by no means certain. There continue
to be discrepancies between studies as to cutoff values for determining microslips,
macroslips, and slides (Brady et al., 2000; McGorry et al, 2007). Brady et al. (2000) showed
that subjects could recover from unexpected slips greater than 10cm in length and 50cm/s in
velocity when walking on oily surfaces.

Many studies have also attempted to determine kinematic differences between micro-slips,
macro-slips and slides, to determine characteristics of slip initiation that lead to balance loss.
Beschorner and Cham (2008) showed that subjects were better able to recover from slips if
they contacted the floor with greater heel deceleration. This was largely achieved through
greater knee flexion, suggesting that walking with reduced knee flexion at heel contact is a
potential risk factor for slip induced falls. Brady et al. (2000) showed that with longer stride
lengths, the resulting smaller shank-floor angles at heel contact (the angle between the floor
surface and a line joining the knee and ankle joints) were associated with a significantly
greater proportion of slips resulting in falls rather than recoveries.

Cham and Redfern (2001) studied balance recovery responses to slips during gait on oily
surfaces. Subjects adopted a wide range of corrective strategies. These included pure ankle
reactions, pure hip reactions, as well as a complex combination of lower extremity joint
moments. During both fall and recovery trials, the ankle of the slipping foot acted more
passively compared to the knees and hips which increased both their flexion and extension
moments, respectively. The postural conditions of the body and the characteristics of the
ground reaction forces at the onset of the perturbation were found to affect the balance
recovery responses and their effectiveness.

McGorry et al. (2010) studied 47 pairs of slip and non-slip trials matched by participant and
surface-contaminant combinations on surfaces including Delrin, Teflon with furniture polish,
and Teflon without polish. Higher utilized COF and horizontal heel velocity were observed 25ms to 30ms following heel strike. These results indicated that interventions for preventing slip propagation need to be effective very soon following heel strike.

Another factor greatly impacting slip recovery is aging. Lockhart et al. (2007; 2003; 2002) conducted a comprehensive series of experiments to determine effects of aging on slip biomechanics, identifying age-related differences in the initiation, propagation, and recovery of slips. In one of the studies, 42 subjects divided into young, middle aged, and older adult categories, walked around a rectangular track at a natural pace and stepped on a force plate with a slippery surface, unaware of the slippery condition. RCOF was not found to be significantly different between the young or middle-aged groups but older adults fell more often. Fall recovery threshold measures showed that younger subjects were able to recover from slips at higher sliding speeds and longer slip distances. The data indicated that falls in older adults were due to poor recovery responses to slips as opposed to gait characteristics influencing slip initiation (Lockhart et al., 2002).

Recovery responses have also been shown to vary depending on whether participants in slip studies were aware that the walking surfaces would be slippery. Heiden et al. (2005) studied differences between awareness of a possible slip and prior slip experience on normal gait and found that awareness of a possible slip primarily affects how the slip-limb approaches the floor while prior slip experience changes the anticipatory muscle activation and how the foot interacts with the floor. Moyer et al. (2006) showed that for both younger and older adults, unexpected slips were associated with increased slip severity (measured as the maximum slipping velocity within 50ms of heel strike). Unexpected slips were also characterized by longer step lengths, larger foot angles at heel strike, and increased cadence in comparison to anticipated slips. Consideration of the cautious gait patterns adopted as a result of awareness of slippery conditions is necessary when determining the applicability of various slip and fall experiments.

Slip responses and the ability to recover while walking also depend on the walking task. For example, descending slopes, carrying loads, and turning, can all increase slip propensity and impede recovery. Chiou et al. (2003) compared walking on a straight path to walking along a
turn in a range of oily surface conditions and showed that slip occurrence on turns were significantly higher. In this study, Chiou et al. (2003) also found that frictional demand measured as RCOF was a poor indicator of slip frequency.

Cham and Redfern (2002) studied slips on inclined planes by giving subjects PVC hard-soled shoes to use while walking down vinyl tiles at 0°, 5°, and 10° ramp angles. The two test conditions were dry and oily and participants were unaware of the condition being tested beforehand. On the oily level planes, slip-and-recovery events occurred in 50% of the trials while 25% fell. On the 5° oily ramp 44% slipped and recovered while 56% fell. All subjects slipped and fell on the 10° ramp. Peak UCOF required to prevent slippage was also found to increase with ramp angle (Cham & Redfern, 2002b).

Nearly all studies of gait in slippery conditions have been conducted indoors, generally utilizing glycerin or water contaminants on tile or steel floor surfaces. In order to prevent outdoor slips and falls in winter conditions, a better understanding of the biomechanics of slips on actual snow and icy conditions is needed and it is necessary to determine whether there are any differences between slip mechanisms induced using indoor surfaces and contaminants compared to real winter conditions. Other aspects of winter environments such as the cold temperatures are also known to affect footwear characteristics and may impact gait and should be further explored. Gao et al. (2008) conducted one of the only biomechanics studies using a winter surface and measured lower extremity muscle activity and ground reaction forces while stepping on a short icy ramp. Steps taken on a 2.7m ice walkway inclined at 0°, 6°, and 8° were compared to those on a non-ice inclined treadmill. The results showed that EMG amplitudes in the tibialis anterior and rectus femoris at heel strike were significantly lower on the ice platform than the non-ice platform, thereby reducing RCOF at contact. It would be of interest to determine how temperature conditions (-10°C for both ice and treadmill trials) affected muscle activity and how the results from Gao et al. (2008) might compare to the results for inclined oil-covered surfaces used in many studies.

Redfern et al. (2001) presented a review of the state of the science with regards to the biomechanics of slips, summarizing kinematic and kinetic responses to walking on level and
inclined surfaces. He concluded that the wide breadth of data regarding slip biomechanics should be used to develop biofidelic testing devices for measuring slip resistance and that these tests should be conducted in environments where actual slips occur with careful control of the environmental and surface conditions.

### 1.3 Measuring Slip Resistance

The relative slip resistance between various footwear-contaminant-surface combinations has been assessed using walking trials and through analysis of slip severity. Different types of footwear can be tested on a single surface-contaminant condition to develop relative ratings of footwear slip resistance for the given surface condition. Conversely, the footwear and contaminants can be kept constant while the surfaces are varied in order to determine the relative slip resistance of a range of surfaces. However, absolute measures of slip resistance remain controversial. Slip severity used in subject-based tests can be evaluated using slip frequency or probability, slip lengths, and peak slipping velocities. When care is given to designing the test conditions to be representative of naturally occurring slip scenarios, these classic measures of slip severity are considered the most ecologically valid and are used to test the validity of readings derived from mechanical devices used to measure slip resistance.

However, biomechanical studies for determining slip severity can be time-consuming, costly, and require specialized equipment. There is a need for testing slip resistance of different floor surfaces and contaminants in everyday environments. To address this need, many researchers have worked towards developing mechanical devices for measuring slip resistance of floor surfaces as well as at footwear-surface interfaces.

The devices developed for measuring slip resistance use a variety of methods to measure the maximum coefficient of friction available (ACOF) at the surface interface. In principle, higher ACOF values will reduce the probability of slipping because slips occur when the frictional demand (RCOF) exceeds that which is available, i.e. slips occur when RCOF>ACOF. The challenge in measuring ACOF is that it is affected by a complex combination of factors.
1.3.1 Available Coefficient of Friction

The difficulty in determining the available coefficient of friction at any given point on a surface during gait lies in the fact that footwear is elastomeric and does not behave according to the classic laws of friction. The first classic law of friction is (Moore, 1972):

\[ F_\mu = \mu F_N \] (1.1)

This law states that the frictional force \( F_\mu \) between two surfaces that are in relative motion is proportional to the normal force \( F_N \), where \( \mu \) is the coefficient of friction. When the relative velocity of the two surfaces is zero, the frictional force and normal force are related by the static coefficient of friction \( \mu_s \) and when the relative velocity is non-zero they are related by the kinetic coefficient of friction \( \mu_k \). Grönqvist (1995) stated that during walking, the kinetic frictional properties are more relevant than static friction as the critical phase of gait for slipping is immediately following heel strike of the leading foot and the foot is generally moving at this point. However, Grönqvist (1995) also recognized that static frictional properties may be important if the foot is moving at slow speeds, if there is a long contact time, or if the slip starts from standing.

The second law of friction states that the coefficient of friction is independent of the apparent contact area. However, this is not valid for elastomeric friction. Empirically, the coefficient of friction has been found to be a function of normal pressure \( p \) (Thirion & Chasset, 1966):

\[ \mu = 1/ap + b \] (1.2)

where \( a \) and \( b \) are constants. Normal pressure is defined as the ratio between normal force and contact area \( A \):

\[ \mu = A/aF_N + b \] (1.3)

Thus, the coefficient of friction increases with contact area. The true contact area is complicated by the existence of lubricants between the surfaces. As such, coefficient of friction is regarded as a function of sliding velocity, contact area, normal force, and its time derivative.
The two principal components contributing to frictional forces between dry, unlubricated surfaces are the forces of adhesion \( F_a \) and hysteresis \( F_h \).

\[
F_\mu = F_a + F_h \tag{1.4}
\]

Both adhesion and hysteresis are caused by the dissipation of visco-elastic energy (Kummer, 1966). Adhesion is caused by molecular-level stick-slip and hysteresis is the ability of elastomers to store elastic energy upon deformation when stressed. Adhesion dominates while walking on smooth dry surfaces while hysteresis dominates while walking on rough, dry surfaces. However, slipping occurs most often in the presence of contaminants (lubricating layers) such as water, oil, or snow. The presence of contaminants prevents the true area of contact from increasing with increasing normal load as it would in dry conditions. In contaminated cases, the total frictional force is affected by viscous drag forces and squeeze film processes.

Grönqvist (1995) described the three mechanisms that determine friction during walking on contaminated surfaces as similar to those of a rolling pneumatic tire on wet roadways (Figure 1.5). These mechanisms are:

1) The squeeze film process and drainage capability at the footwear-floor contact surface (A-B)
2) Draping of the sole about the asperities of the underfoot surface (deformation and hysteresis) (B-C)
3) True contact between the surfaces (traction and adhesion) (C-D)

The squeeze film process depends on viscous or hydrodynamic forces in the lubricant which generate hydrodynamic pressure that can separate the shoe and the walking surface, thereby reducing or eliminating the frictional forces due to adhesion and hysteresis. The lubricant drainage time is the time that it takes for the contaminant to be displaced such that the two surfaces make contact. In Strandberg’s model (1985) of the squeeze film process, drainage time is described as being dependent on the lubricant’s viscosity, the contact area between the two surfaces, the vertical load, and the descent time during downward motion of the foot. For a constant fluid viscosity, vertical load, and descent time, drainage time increases four-
fold when contact area is doubled. Increased drainage time reduces the coefficient of friction and can therefore increase the risk of slippage at a critical moment during heel strike. Proctor and Coleman (1987) included tangential sliding motion in their hydrodynamic squeeze-film model. In this model, at constant viscosity, vertical load, and contact area, film thickness varies with the square root of sliding velocity. Therefore, in order to minimize lubricant film thickness and obtain a good grip at the footwear-floor interface, it is extremely important to reduce the sliding velocity.

Figure 1.5. Mechanisms of friction during walking on a contaminated surface. Adapted from Grönqvist (1995)

Draping is time-dependent. At slower sliding velocities there is a greater draping effect and therefore a higher coefficient of adhesional friction. The coefficient of hysteretic friction is small at low velocities and rises with increasing sliding velocity. Hysteresis is directly proportional to contact pressure while adhesion is proportional to the inverse of contact pressure.

During walking, macro-elastohydrodynamic effects are important because the footwear is moving at high speeds and applying high contact pressures on the lubricant. These are the hydrodynamic and elastic effects occurring at each contact point that the elastic footwear makes with the underfoot surface through the lubricant. During dynamic loading, maximum pressure in the squeeze film increases with decreasing film thickness. This works to separate the footwear sole from the underfoot surface during heel strike, thereby increasing the risk of slipping.

The boundary lubrication phenomenon may also increase the risk of slipping. Boundary lubrication exists where there are contact areas that are part-liquid and part-solid. The phenomenon is characterized by low and unstable coefficients of friction and is most likely to
occur at high normal loads and pressure, moderate sliding speeds, and with fluids of relatively low viscosity. It is therefore an important consideration during heel strike on wet floors.

Walking on ice is challenging because of specific mechanisms that make ice slippery as described by Rosenberg (2005). When pressure is applied to an ice surface, melting is induced at the interface. This creates a film of water that makes the surface more slippery. This is most commonly seen in ice skating. While skating, high pressure is spread over the small surface area where the blades are in contact with the ice and temperatures are near freezing. Pressure-induced melting is not the sole contributor to slipperiness on winter surfaces as the pressure applied on snow by a skier’s skis is insufficient to cause melting at low temperatures. Frictional heating has been shown to cause localized heating that creates a thin water layer that induces slipperiness. The third mechanism involved in making ice slippery is the existence of a liquid film on the surface of solid ice resulting from inherently unstable molecules at the ice surface.

A study by Chang et al. (2001) showed that the coefficient of friction of ice was lowest (less than 0.01) at high temperatures (-1°C) and high velocities (3m/s). At very low temperatures (-40°C) and velocities (0.001m/s), the ice surface was relatively dry and behaved like a dry surface with high COF (0.67). Grönqvist and Hirvonen (1995) described specific implications when the walking surface is icy. On ice, the frictional force \( F_\mu \) may be assumed to be caused only by viscous shear in the water layer at the surface of the ice (Oksanen, 1982). In this case, all other phenomena such as ploughing into the surface are omitted:

\[
F_\mu = \tau A = u_\nu \nu / dA
\]  

(1.5)

\( \tau \) is shear stress, \( A \) is contact area, \( u_\nu \) is the viscosity of water, \( \nu \) is the sliding velocity and \( d \) is the thickness of the water layer. The coefficient of friction (\( \mu \)) is therefore:

\[
\mu = F_N / F_\mu = (u_\nu \nu / dA) / F_N
\]  

(1.6)

Near the melting point, ionic impurities in the ice water will lower its melting point forming a liquid brine which acts to lower the effects of adhesional friction. At these warmer
temperatures, ice is also sensitive to the effects of pressure such as those applied at heel
strike. The ice will melt or flow to relieve this pressure. Melting and flowing lower the
coefficient of friction when ice temperatures are above -10°C (Grönqvist & Hirvonen, 1995).

Table 1.1. Summary of coefficient of friction terms and definitions.

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Available COF (ACOF)</td>
<td>COF at the interface of the footwear, surface, and contaminant that is</td>
</tr>
<tr>
<td></td>
<td>dependent on the relative motion of the surfaces</td>
</tr>
<tr>
<td>Dynamic COF (DCOF)</td>
<td>COF measured using a slip resistance measurement device during relative</td>
</tr>
<tr>
<td></td>
<td>motion between two surfaces</td>
</tr>
<tr>
<td>Kinetic COF (μk)</td>
<td>COF at the interface of two surfaces in relative motion</td>
</tr>
<tr>
<td>Required COF (RCOF)</td>
<td>COF necessary for safe (non-slip) walking, typically measured at Peak 3 of</td>
</tr>
<tr>
<td></td>
<td>the UCOF curve after heel strike and also referred to as peak UCOF</td>
</tr>
<tr>
<td>Static COF (μs)</td>
<td>COF at the interface of two surfaces at rest relative to one another</td>
</tr>
<tr>
<td>Utilized COF (UCOF)</td>
<td>Ratio of shear to normal forces applied to the ground surface during gait</td>
</tr>
</tbody>
</table>

It is extremely difficult to measure the available coefficient of friction between two surfaces
because it is dependent on so many factors including sliding speed, contaminant thickness,
contact pressure and contact area. Devices that claim to measure ACOF are designed to
simulate very specific motion and contact profiles that cannot replicate the dynamics of every
slip incident. As such, the coefficients of friction measured by these devices when they
measure sliding or dynamic friction should not be termed the available coefficient of friction,
as is often seen in the literature. Rather, they should be considered a measure of the dynamic
coefficient of friction (DCOF). A summary of the terms and definitions used to describe
coefficients of friction are presented in Table 1.1

Although there is no direct method for measuring ACOF, it is believed that even small
increases in available friction can theoretically have a major impact on reducing slips. Chang
et al. (2013) plotted the normal distributions of RCOF values obtained from each of 50
participants who took a combined total of nearly 31,000 steps on force plates, in order to
determine the ACOF beyond which a slip would be expected at discrete slip probability
levels. By averaging ACOF values across participants, they showed that in theory, very small
increases in ACOF could dramatically reduce the probability of slipping (as shown in Table
1.2).
Table 1.2. Reduction in slip probability with increased ACOF.
Adapted from Chang et al., 2013.

<table>
<thead>
<tr>
<th>Slip Probability</th>
<th>Available COF</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/20</td>
<td>0.272</td>
</tr>
<tr>
<td>1/200</td>
<td>0.289</td>
</tr>
<tr>
<td>1/10,000</td>
<td>0.309</td>
</tr>
<tr>
<td>1/100,000</td>
<td>0.317</td>
</tr>
<tr>
<td>1/1,000,000</td>
<td>0.326</td>
</tr>
</tbody>
</table>

1.3.2 Floor Surface Tribometers

As of 1983 over sixty different devices for measuring slip resistance were already available (Strandberg, 1983). Such devices are designed to measure slip resistance either primarily on floor surfaces or at the interface between surfaces and footwear. Devices designed to measure DCOF of floor surfaces are commonly referred to as tribometers. It should be kept in mind that all measures of DCOF are a reflection of both surfaces in relative motion. Floor surface tribometers are generally fitted with calibrated materials against which different floor surfaces are tested. Scientific grade Neolite® is an example of a typical material used by many different devices because of its wear resistance, production consistency, and low water absorption properties (Di Pilla et al., 2003).

There are three main approaches to measuring DCOF of floor surfaces: pulling an instrumented load (drag sled) over a surface, using a pendulum to strike a surface, or displacing an articulated strut (Figure 1.6). Drag sleds which are pulled over test surfaces can sometimes also attach a sample of footwear outsole material for assessment. As a known normal load is applied and the load is dragged at a constant velocity, an attached load cell measures the peak force to start movement (static COF) and the steady-state force to continue moving (DCOF) according to the classic law of friction (Equation 1.1). Use of a drag sled, the Horizontal Pull Slipmeter (HPS), for measuring slip resistance is described in the internationally accepted standard from the American Society for Testing and Materials (ASTM), ASTM F609 (ASTM F609-13, 2013). According to this standard, the HPS uses a 2.7kg ± 0.03kg sled moving at 1.5mm/s ± 0.2mm/s. However, these values are significantly lower than the normal loads and sliding speeds that are associated with actual gait. An alternate method, ASTM C1028, incorporated a larger drag sled which applied a much
greater normal force of 23kg. However, ASTM C1028 was withdrawn in 2014 due to its limited use in industry. Drag sled devices can be used on sloped surfaces, in which case the applied normal load used in Equation 1.1 then becomes the component of the load perpendicular to the surface. ASTM F609-13 explicitly states that the drag sled device should not be used on wet surfaces as the slip index that is output is applicable only to dry conditions. This is because the vertical and horizontal loads cannot be applied simultaneously at the instant of contact with the surface to accurately simulate the hydrodynamics while stepping on contaminated surfaces. In contrast, the pendulum and articulating strut devices apply simultaneous horizontal and vertical loads at contact for use on contaminated surfaces.

Pendulum testers only measure DCOF. The device is designed to sweep a sample of sole material, attached to an unbalanced weight on the arm of the pendulum, over a test surface, thereby allowing contact between the two surfaces to occur with a predefined time dependency. The loss of energy during contact between the surfaces is a reflection of the DCOF. The difference in potential energy from the height at the point of release \( (PE_{H}) \) of the pendulum arm to the height that it reaches after one contact over the surface \( (PE_{h}) \) is equivalent to the work done in sliding the test sample over the surface (Sigler, Geib, & Boone, 1948), which is by definition the average frictional force \( (F_{\mu}) \) multiplied by the contact distance \( (d) \):

\[
PE_{H} - PE_{h} = F_{\mu}d \quad (1.7)
\]

By substituting in Equation 1.1 for the frictional force (where \( F_{N} \) is the average normal force applied during contact) and because potential energy is equivalent to the mass of the unbalanced weight \( (m) \) multiplied by the acceleration due to gravity \( (g) \) multiplied by the height of the mass \( (height \ H, \ at \ release \ and \ height \ h, \ post-contact) \), Equation 1.7 becomes:

\[
mg(H - h) = \mu F_{N}d \quad (1.8)
\]

By rearranging Equation 1.8, the coefficient of friction \( (\mu) \) from the pendulum tester is calculated as:

\[
\mu = mg(H - h)/F_{N}d \quad (1.9)
\]
ASTM E303 describes the use of a pendulum tester for measuring the slip resistance of surfaces (ASTM E303, 2013). Because the coefficient of friction is gravity-dependent, pendulum testers cannot be used on sloped surfaces. Pendulum devices are used primarily in Europe and Australia to measure dry and wet road conditions because the results are considered highly repeatable.

Transitional or articulated strut devices apply a known force through a rigid member to a material (such as Neolite® or a sample of outsole material) that contacts the test surface. Starting from vertical, the angle between the applied force and the floor surface is reduced until a slip occurs and the product of the applied force and the cosine of the failure angle is the DCOF. By using a compressed air canister and pressure regulator to generate the striking force, its magnitude is constant and independent of gravity so that the device can be used on sloped surfaces. Although these portable, lightweight devices are still widely used in North America, ASTM standards describing their use have been withdrawn because they have demonstrated poor precision, outputting widely ranging results when tested on identical surfaces in different laboratories.

Figure 1.6. Examples of floor surface tribometers. From left to right: The Horizontal Pull Slipmeter (drag meter), The Sigler Pendulum Tester, EnglishXL Variable Incidence Tribometer (articulated strut).

Multiple studies have attempted to validate surface tribometers against severity of slips in human subjects and these typically measure frequency and lengths of slips (Brady et al., 2000; Hanson et al., 1999; Kulakowski et al., 1989; Myung et al., 1992; Myung & Smith, 1997). In general, the studies have associated a higher frequency of slips and longer slips with low floor friction. However, the validity of floor surface tribometers has been shown to
vary between testing approaches and devices. Tests of three tribometers performed directly on dry, wet, and oil-covered force platforms showed that the Gabbrielli SM, a drag sled tester, lacked both precision and accuracy while the pendulum Portable Skid Resistance Tester was relatively accurate but lacked precision and the Brungraber Mark II, an articulating strut tester was relatively precise but lacked accuracy (Grönqvist et al., 2000). Powers et al. (2007) tested the validity of tribometers by comparing readings on four wet walkway surfaces to slips during gait with 80 participants walking over them (20 per walkway). The likelihood of slipping greater than 4cm was used to rank slip resistance of the four walkways. Only four of eleven tested tribometers were able to rank the four walkway surfaces in the same order as the biomechanical study (Sigler and Wessex pendulums and Mark II and Mark III articulating struts).

Marpet (2001) reported that across categories, tribometers tended to produce similar results when testing dry, uncontaminated surfaces. However on wet, contaminated surfaces, pendulum and articulated strut devices were considered more valid than drag sleds because they applied both lateral and normal forces which better simulate the hydrodynamic forces during gait. In a survey of the devices used to measure friction, Chang et al. (2001) concluded that while most devices are generally reliable in terms of producing consistent readings, their validity can be improved by bringing the measurement parameters within the range of human slipping conditions observed in biomechanical studies.

Because of the complexity in establishing methods that result in precise and accurate outcomes, the development and acceptance of methods into standards can be a long and arduous process that comes with its own limitations. For example, standard methods tend to be specific to devices. As a result, different standards will differ in their output measures because the devices have been built on fundamentally different principles. ASTM also discourages the inclusion of patented devices at the exclusion of other devices and stipulates that efforts must be made to identify alternative devices. Variability of results obtained from different types of devices that are based on the same underlying principles can further limit the usefulness of standard methods. In the standardization process, affirmative votes of at least 90% are required by voting members of technical committees in charge of producing standards in order to amend an existing standard or accept a new standard (Regulations
Governing ASTM Technical Committees, 2013). For smaller or under-represented committees, attaining a 90% plurality can be extremely challenging and it is important that knowledgeable users and members of the scientific community take on the responsibility of joining committees to better represent the interests of the general public.

1.3.3 The Standard Footwear-Surface Slip Tester

Mechanical devices that have been developed specifically for testing footwear slip resistance tend to be far more sophisticated than floor surface tribometers and attempt to simulate natural gait. As such, they are often referred to as step simulators. The key test parameters that should be biomechanically relevant when measuring DCOF at the footwear-surface interface are heel velocity, vertical force, and shoe angle (Redfern & Bidanda, 1994). While several test devices have been developed for footwear slip resistance testing (Aschan et al., 2005; Ertas et al., 1990; Grönqvist et al., 1989; Redfern & Bidanda, 1994) the current international standard for measuring footwear slip resistance is ASTM F2913-11 (ASTM F2913-11, 2012).

Under ASTM F2973-11, a piece of test footwear is securely fit over a stiff shoe last (a block of plastic shaped like a foot) and is moved at a constant velocity horizontally against a specified test surface or surface-contaminant combination. The outcome measure of the standard method is DCOF, measured during relative motion between the footwear and surface. Specifications are provided for measuring DCOF on calibrated quarry tiles or stainless steel tiles that are dry or wetted with distilled water. The standard also recommends that footwear be tested on surfaces and contaminants relevant to the conditions in which they are normally worn. SATRA TM144 provides a guideline for testing footwear on icy surfaces, but these guidelines have not been made standard. As it stands, the standard does not contain specific criteria for preparation of icy surfaces (SATRA TM144, 2011).
Figure 1.7. Sample output from SATRA STP603. Adapted from ASTM F2913-11. At point ‘A’, 50N is reached; point ‘B’ occurs within 0.2s of point ‘A’ and full force is achieved and sliding begins; points ‘C’ and ‘D’ indicate the horizontal force and COF reading that is output, respectively, measured 0.1s ± 0.01s after sliding begins.

The critical parameters under which DCOF is measured according to ASTM F2913 are the footwear test angle, horizontal velocity, and applied normal force which are meant to reproduce those observed during normal gait (Wilson, 1990). DCOF is measured with the footwear angled at $7^\circ \pm 0.5^\circ$ to the horizontal and while flat against the test surface. At these angles, DCOF is measured while the footwear is moved at a constant velocity of $0.3m/s \pm 0.03m/s$ with respect to the test surface. To accomplish this movement, the footwear is fitted over solid, stiff forms (shoe lasts) and pistons drive the horizontal and vertical motions. For footwear fitting lasts of size 40 (Paris Points) and above, the footwear is tested using a normal load of $500N \pm 25N$. For smaller last sizes, $400N \pm 20N$ normal loads are applied. Shear forces in the fore-aft direction are measured using a load cell and DCOF is calculated as the ratio of shear force to normal force at an instant when the critical parameter settings have been met (ASTM F2913-13, 2012). Figure 1.7 shows sample output from SATRA STM603, a standard-compliant device, and depicts the force, COF, and motion profiles.
Jung and Fischer (1993) conducted inter-laboratory trials in eight laboratories spanning seven countries to determine the repeatability and reproducibility of results from the ISO draft proposal for “The Measurement of the Slip Resistance of Safety, Protective and Occupational Footwear for Professional Use” (Doc. ISO/TC 94/SC3:N155). This document described the specific conditions for measuring the coefficient of friction when a load is applied to a piece of footwear on a surface and then moved horizontally relative to the surface. It has since been adapted into the current ASTM F2913 standard. Results from the eight laboratories showed that both repeatability for individual laboratories and reproducibility across laboratories were highly dependent on the lubricant used. While repeatability was considered acceptable (individual machines could reproduce their own result for 95% of cases within 10% of the average COF) the reproducibility was deemed unacceptable (between different machines, in 95% of cases there were differences of 70% to 100% in the average COF output) (Jung & Fischer, 1993).

The original test parameters specified for standardized testing were based on 39 forward slips of the heel observed out of 124 trials involving four subjects (Strandberg & Lanshammar, 1981). The subject sample characteristics and footwear were not described. According to the protocol, participants walked on a 3m long walkway with a soapy patch that was applied or removed between trials to reduce anticipation effects. Ground reaction forces and foot kinematics were tracked during the single step on the slippery patch to determine percentage of body weight applied (64% ± 16%), foot angle (5.5° ± 5.9°) and forward heel velocities (0.08m/s to 0.32m/s) at the start of the slip. The parameter values used in the current standard still reflect the upper limits of these values.

Strandberg (1985) acknowledged that analysis of the single slip step and average friction over that step might not be valid for assessing the risk of falling. To assess the validity of mechanical bench tests, Strandberg compared their results to outcomes while walking on a triangular path. Number of falls and a time-based friction utilization (TFU) outcome was measured using 12 subjects walking five laps (TFU averaged over laps 2-5) on each of 13 footwear-flooring-contaminant combinations as fast as possible. This outcome reflects the higher frictional demands during deceleration and turning that are typically not captured. Strandberg found that devices which most closely simulated the squeeze-film and hysteresis
processes produced results that were the most similar to the walking trials. However, Strandberg concluded that average COF measures produced by the mechanical tests should not be the only factor considered when determining slip resistance, as he found that the number of falls that occurred in some footwear-flooring combinations were not consistent with the mean COF values obtained in bench-tests.

Proctor and Coleman (1987) illustrated the shortcomings of slip resistance test devices that did not adequately reproduce hydrodynamic forces during slips due to insufficient contact pressures and inaccurate simulation of heel speeds. According to the squeeze film theory, lubrication present at the interface between two surfaces increases the time of separation between the two surfaces as the lubricant is being penetrated (or squeezed). As such, it is important to accurately reproduce the contact pressures applied in normal gait when measuring slip resistance at the interface. It is also important to accurately reproduce speeds at the heel because of the linear relationship between the forward velocity of the heel and the film thickness that is generated. At the same heel speed, more viscous fluids like oils generate thicker films than less viscous fluids such as water. The greater the film thickness, the longer the separation time between the footwear and underfoot surface and therefore the greater the potential for slips. Proctor and Coleman (1987) described the main advantage of the current standard test as having the most realistic simulation of heel dynamics, in comparison to other mechanical tests, but critiqued the absence of foot rotation and the long delay between the application of the normal force and the onset of horizontal movement.

Another limitation of the standard test is how well the specified mechanical test parameters reflect the range of gait characteristics of actual users, which vary with such factors as age, sex, and weight (Chumanov et al., 2008; Lockhart et al., Wu et al., 2012). These parameters also vary when walking in expected slippery conditions versus unexpected slippery conditions, transitioning between high and low friction areas, or on different terrain such as slopes, cross-slopes, and uneven surfaces (Bunterngchit et al., 2000; Dixon & Pearsall, 2010; Heiden et al., 2005; McVay & Redfern, 1994). Different types of activity, such as walking versus running, or load carrying, which are associated with different movement patterns (Cham & Redfern, 2001; Chiou et al., 2003), are also not reflected in standard tests.
Reviews of existing slips and falls studies have suggested that a more integrated approach that considers biomechanics, mechanics, anatomy, neuromuscular control, and tribology is necessary to determine sufficient fall prevention strategies. The reviews also recommend that experiments should be conducted under natural movement conditions and functional postural perturbations (Gielo-Perczak, 2001; Lockhart, 2008).

1.3.4 Human-Centred Footwear Tests

Because of continued uncertainty regarding the validity of mechanical slip resistance test devices and their ability to simulate real gait and real slips, human-centred testing is still commonly used and often used in conjunction with mechanical tests (Grönqvist et al., 2001). Subjective human-centred approaches use rating scales, rankings, and paired comparisons of floors and footwear. Joh et al. (2007) conducted a series of experiments that showed that visual cues are not sufficient for estimating slip resistance and that participants tended to overestimate their ability to safely descend slopes based only on visual cues. Judgement improved when participants stood on the slippery surface. This approach is often used to rate slipperiness in winter conditions because typical measures of coefficient of friction are difficult to conduct on ice and snow (Gard & Berggard, 2006). In subjective assessments, participants have been asked to walk on winter surface conditions and then to rate footwear slip resistance and other footwear characteristics. While some assessments have been shown to correlate with DCOF readings (Abeysekera & Gao, 2001), in general, perceived slipperiness has been found to poorly correlate with performance (Joh et al., 2007). As such, there has been an emphasis on developing more objective participant-based methods of measuring slip resistance.

Three objective human-centred methods that have been developed for testing footwear slip resistance are the drag test, the instrumented spring test (Manning et al., 1991), and the ramp test. The drag test is based on the same principles as drag sled tribometers but rather than pulling a weight over a surface, a human tester is pulled along a surface. In the drag test developed by Bruce et al. (1986), a single tester wearing the test footwear stands and is dragged by a metal bar placed behind the feet at a constant rate of 0.05m/s across a surface. The horizontal force required to pull the tester over the surface is measured using a load-cell
and is divided by the tester’s weight to determine the COF. The advantages of this test are that a human subject and his or her full weight are utilized in this method and also that the test can be conducted on site provided there is enough space (Proctor & Coleman, 1987). However, it presents the same issues as those of drag sleds in that the hydrodynamic forces underfoot during gait are not simulated.

Manning et al. (1991) created a test involving a single test subject stepping forwards and backwards on a selected floor and contaminant condition. The subject is connected to a spring and load cell which measures the maximum force generated by the test subject before the feet slip and the subject falls into an overhead safety harness. The COF at the point of failure is determined by dividing the maximum generated force by the subject’s weight. Limitations of this method are that the maximum force depends on the subject’s strength and the stepping patterns are unnatural.

Another human-centred test used primarily in the United Kingdom and Australia uses adjustable inclined surfaces to determine the slip resistance of footwear and/or flooring materials (Perkins & Wilson, 1983). According to the Australian Standard® two trained testers facing down-slope, take half-steps forwards down and half-steps backwards up a 2m long by 0.6m wide test surface that is increasingly tilted to steeper slope angles (AS 4526, 2013). The maximum slope angles on which subjects are able to step without slipping are used to assess slip resistance of footwear-surface combinations. The COF at the point of failure can be calculated by taking the tangent of the slip angle (Brungraber et al., 2003). The human testers are trained to walk with an upright posture and walk to the beat of a metronome at a rate of 144 half steps per minute, although it is noted that at incline angles greater than 15°, the cadence is less important. The testers are calibrated daily using standardized footwear on three standardized test surfaces with known slip angles and must achieve a mean within 2° of each known angle (averaged across five trials) prior to testing other styles of footwear or surfaces. During the actual tests, the testers use the same walking method and the slip angles obtained from five repeats for each of the two testers are averaged to determine the overall slip angle for each test condition. These tests have the advantages of providing objective outcomes along with improved validity over mechanical tests by involving users, who often prefer direct walking tests (James, 1999). Industrial floors with
contaminants such as water, oil, and soap are most commonly used as test surfaces. Another advantage of these ramps is that low-viscosity contaminants can be continually streamed from the top of the ramp slope so that clearing of the contaminant during testing is avoided, however this does alter the hydrodynamic forces of the contaminant which is no longer still as a real-world spill or puddle would be. Ramps used in these tests have also traditionally been small-scale with subjects taking few steps or walking with unnatural gait, such as shuffling with small steps forwards and backwards or stepping in place (Jung & Schenk, 1990; Skiba et al., 1986).

1.3.5 Threshold Values

Empirically, increased values of DCOF have been linked to reduced probability of slips. Hanson (1999) used a small sample of five subjects walking on an inclined soapy surface to show that when DCOF measured using a tribometer exceeded RCOF by 0.52, the probability of slipping was only 1% but when DCOF exceeded UCOF by 0.16 the probability of slipping increased to 50%. Kulakowski et al. (1989) measured RCOF of five subjects while walking quickly over a dry surface. They showed that when RCOF on the dry surface exceeded the DCOF measured using an articulating strut tribometer on different slippery surfaces, slips occurred on the slippery surfaces 79% of the time.

Although larger DCOF values are considered indicative of greater slip resistance, there is still no consensus regarding the validity of current measurement methods. As such, there remains no standard threshold DCOF criteria for labelling footwear or surfaces as slip resistant (Grönqvist et al., 2001). Kim and Nagata (2008) discuss the limitations of DCOF indices derived from various measurement devices and describe the general consensus for what is considered “very slip resistant” as 0.3 or 0.4 or greater. However, what should be considered a minimum acceptable value of slip resistance is still controversial. The authors acknowledged that with the differences between measurement devices, setting minimum thresholds without reference to a measurement device is not useful.

Using the Finnish Institute of Health and Safety (FIOSH) step simulator, Grönqvist et al. (1989) classified DCOF values of 0.3 and over as “very slip resistant” and those below 0.05...
as “very slippery” (Table 1.3). Curry et al. (2004) report higher recommended slip-resistance values for flooring and floor-covering materials at greater than 0.50. For people with mobility limitations, they recommend minimum DCOF values of 0.60 for accessibility routes for people who use crutches, canes, or walkers and 0.80 for ramps. However, it is not clear how these values were derived.

Table 1.3. Classification of DCOF values obtained using a step simulator.
Adapted from Grönqvist et al. (1989).

<table>
<thead>
<tr>
<th>DCOF</th>
<th>Classification</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>≥0.30</td>
<td>Very slip resistant</td>
<td>Slip is likely to unlikely to occur during normal level walking</td>
</tr>
<tr>
<td>0.20-0.29</td>
<td>Slip resistant</td>
<td>Slip is possible but the loss of balance is often recoverable</td>
</tr>
<tr>
<td>0.15-0.19</td>
<td>Unsure</td>
<td></td>
</tr>
<tr>
<td>0.05-0.14</td>
<td>Slippery</td>
<td></td>
</tr>
<tr>
<td>&lt;0.05</td>
<td>Very slippery</td>
<td>Sudden slip most probably leads to a fall</td>
</tr>
</tbody>
</table>

Researchers who have explored whether safety thresholds might be different for different population groups have reported mixed results. Burnfield et al. (2005) found that there were no differences in frictional demand measured by RCOF between healthy young adults (mean age of 29), older adults (mean age of 73), groups of older adults post-stroke, groups with diabetes mellitus, or groups with lower extremity arthritis. Kim et al. (2005) found that while walking at a self-selected pace, older adults had lower frictional demand (reduced RCOF) but also tended to walk slower and as a result imparted slower heel strike velocities than younger adults.

Buczek et al. (1990) studied differences in RCOF between a small sample (n=16) of participants that included able-bodied and mobility disabled subjects (including walker users, crutch users, and lower limb amputees). They found that utilized coefficient of friction at touch-down for the affected side, unaffected side, and walking aid were higher than the COF utilized by able-bodied participants. Durá et al. (2005) suggested that DCOF (using a portable step simulator) should be greater than 0.4 based on tests of 205 participants with five different pathologies (below knee amputee, hip arthritis, knee arthritis, hemiplegia, Parkinson’s) of whom, below knee amputees had the highest frictional demand.
While the focus has generally been on increasing DCOF as much as possible by providing highly slip resistant flooring, there is also evidence indicating that upper limits of DCOF may be necessary. Zamora et al. (2011) asked six women to walk for 15 minutes over five different ceramic tile floors ranging in DCOF from 0.19 to 0.63 measured using a portable step simulator. They found that reports of pain in the knees, metatarsal heads, and toes increased with increasing DCOF while pain in the thighs was related to lower DCOF surfaces. Based on their results, the authors recommend a DCOF greater than 0.25 to reduce slip resistance and DCOF less than 0.55 to minimize pain. The hardness of the flooring surfaces which may be a confounding factor was not reported.

### 1.3.6 Slip Resistant Characteristics of Footwear

The existing mechanical devices for measuring slip resistance along with biomechanical tests for assessing slip resistance have been useful for comparing footwear or surfaces relative to one another. Using indoor surface-contaminant testing, characteristics that have been associated with greater slip resistance or decreased falls risk include lower heels, harder soles, increased roughness of the sole, higher collars, larger contact areas, treads with grooves perpendicular to the direction of travel, and the use of microcellular polyurethane (PU) materials.

Menant et al. (2008) conducted a systematic review of the literature to determine the types of footwear typically worn by older adults and compiled evidence pertaining to how specific footwear characteristics impact balance to older adults. Findings of the systematic review indicated that low heels and hard, slip-resistant soles should be worn both indoors and outdoors. It was also concluded that additional research is necessary to determine the benefits of treadsed soles in preventing slips. Menant et al. (2009) confirmed the review results using kinematic variables comparing a standard Oxford-type shoe and seven modified versions of the shoe each differing by a single feature: elevated heel, soft sole, hard sole, flared sole, beveled heel, high-collar, and sole tread. The findings indicated that elevated heels and soft soles impaired walking stability while the high-collared shoe with medium sole hardness optimized stability for older adults walking on a variety of surfaces. Menant et al. (2009) also point out that their finding that softer soles resulted in greater instability was in contradiction
to Redfern and Bidanda (1994) who found that soft shoes provided better slip resistance on smooth, wet surfaces and that these differences likely resulted from differences between the material and hardness of the soft sole shoes in the two experiments.

Tencer et al. (2004) followed a cohort of 1371 adults over the age of 65 for a two-year period and studied the footwear worn by 327 participants who experienced a fall and 327 age and sex-matched controls who had not experienced a fall over that period. Heel height and, heel width, collar height, sole contact area, forefoot stiffness, foresole thickness, sole material, and COF were recorded for footwear worn at the time of falls for the fall group, and matched to someone in the control group performing a similar activity. Fall risk was nearly double for heel heights of 2.5cm or greater while fall risk decreased with increasing contact area between the sole and floor surface. The effects of other factors including collar height and COF (using an articulated strut) were not found to be statistically significant. However, it should be recognized that the majority of shoe-surface combinations measured during this study resulted in high friction readings (89% were over 0.5). Had the falls occurred in more slippery conditions, other footwear factors may have been found to be significant.

For both wet and dry surfaces, DCOF measured using the SATRA device decreases with increasing sole hardness (Wilson, 1990). Tsai and Powers (2009) found differences in gait dynamics between walking while wearing a soft outsole shoe (measuring a DCOF of 0.91 using the SATRA device) compared to a hard outsole shoe (measuring 0.62 DCOF). The softer outsole was associated with higher resultant shear forces and peak UCOF at heel strike, an increase in total body COM acceleration prior to and immediately following heel strike, as well as increased walking velocity, stride length and ankle dorsiflexion at heel strike. Tsai and Powers (2013; 2008) also reported that harder shoe soles were associated with a greater proportion of initiated slips. However, sole hardness did not significantly influence the probability of a fall.

Although no clear designs for outsole treads have demonstrated clearly superior performance, testing has shown that their orientation and width do affect slip resistance. Li et al. (2006) tested the relationship between DCOF and tread groove orientation and tread groove width using an articulating strut tribometer. Six configurations of treads tested under 27 footwear
material/floor/contaminant conditions revealed that wider grooves and grooves perpendicular to the direction of motion increased DCOF.

Liu et al. (2013) also used an articulating strut tribometer to test DCOF at the footwear-floor interface for composite rubber sole shoes with grooves either parallel or perpendicular to the walking direction, in conjunction with walking trials. Three ceramic flooring surfaces including a smooth surface, a surface with grooves parallel to the walking direction, and a surface with grooves perpendicular to the walking direction, each spread with glycerol, were tested. The combination of both shoe sole and flooring with perpendicular tread patterns had the highest DCOF values, the shortest slip distances, and the lowest percentages of macroslips and slides.

Beschorner et al. (2012) described the purpose of shoe tread as being able to enhance friction by channeling fluid contaminants away from the shoe-floor interface, reducing the ability of the fluid to lubricate the contact surfaces which thereby reduces friction. They tested three work shoes with different tread depths (0mm, 1.4mm, 2.4mm) on a vinyl floor with glycerol and detergent contaminants using a step simulator. They found that a modest (1.4mm) tread may be sufficient for reducing fluid pressure and increasing interface DCOF but not necessarily enough to prevent slips.

The SATRA device has been used to make a variety of recommendations for footwear outsoles. DCOF results from the SATRA device suggest that the following designs increase footwear slip resistance: patterned and round or chamfered heels (up to 20°), leading edges of treads in many directions, a minimum tread depth of 5mm for outdoor boots), a minimum width of 2mm between tread channels to allow lubricant dispersal, treads with well-defined square leading edges, patterns extending over the whole sole and heel area, flat, flexible bottom construction such that the sole can conform to the ground maximizing contact area (e.g. using a low density midsole), smooth, flat wearing surfaces, and a square heel breast (Wilson, 1990).

Various materials have also been identified as having relatively enhanced slip resistance properties. Grönqvist (1995) tested the slip resistance of three styles of safety shoes (compact nitrile rubber, compact styrene rubber, and micro-cellular PU soles) on four floor-
contaminant combinations (rough plastic carpet, uncontaminated stainless steel, stainless steel with glycerol, and stainless steel with water and detergent). Each pair of shoes was classified into four categories (new, good, satisfactory, poor, worn out) based on how long they had been used for. Slip resistance was measured using a step simulator and indicated that in general, new shoes were less slip resistant than those with slight wear. Worn out shoe patterns were associated with a dramatic reduction in slip resistance presumably as a result of insufficient drainage once the tread pattern wore off. The relatively softer micro-cellular PU demonstrated superior performance, especially after slight wear. Grönqvist (1995) suggested that the microporosity of the material, which could increase DCOF on smooth surfaces, was only revealed with some wear and that this softer material improved deformation and damping properties, which could increase DCOF on rough surfaces. The footwear with the smoothest surface and the lowest tread profile depth were associated with the lowest DCOF values.

In terms of specific types of microcellular PU, AP66033 was regarded as the most slip-resistant safety footwear sole material on oily and wet surfaces for many years but it has largely replaced in the marketplace by dual density PU (DDP) which has a dense outer layer and soft microcellular backing (Manning & Jones, 2001). Manning and Jones conducted pendulum tests comparing the two soles on 19 water wet surfaces. The soles were tested brand new, with abrasion, and after polishing over four oily surfaces after abrasion or polishing to roughen the sole and floor. AP66033 was found to have higher DCOF on oily and wet floors. DCOF was also reduced for all floor polishes when they were. The authors therefore recommended a return to AP66033, abrasion of all new and smooth footwear using a P100 grit belt sander, and avoidance of floor polish.

1.3.7 Winter Footwear Slip Resistance

Only a handful of studies have targeted the measurement of winter footwear slip resistance, likely because of the challenges associated with reproducing realistic, controlled, and repeatable winter surface conditions (Björnstedt et al., 1997; Tisserand, 1985). Slip measurement devices in general have not been validated for use in winter conditions and the current ASTM standard specifies that it should not be used for footwear with studs or cleats.
Bruce et al. (1986) were the first to test the slip-resistance of footwear on ice. They did so by measuring the horizontal force used to drag subjects wearing various shoes, crampons (steel studs in a rubber strip), and chains on unwetted ice. The chains gave poor traction on ice and although softer sole materials provided higher frictional forces, they were still inadequate for preventing slipping accidents. Crampons provided the best traction on the dry ice surface and studs with a Shore A hardness of 20-30 were suggested as being optimal for ice. Dragging traction, however, is not indicative of the kinetics involved in normal gait or hydrodynamic effects underfoot. Measuring traction during natural heel strike and toe-off phases would provide a more accurate depiction of the protective capabilities of the various types of footwear.

To more closely reproduce the forces of friction experienced during natural gait, Gao et al. (2004) tested the slip resistance properties of four footwear outsole materials on ice that was formed on a forceplate with an apparatus that simulates the movement and forces applied during a human stepping slip. They concluded that while PU soling has demonstrated higher DCOF values than synthetic, nitrile, and natural rubbers when used on wet and lubricated floors it does not perform significantly better on ice and thus may not provide sufficient slip resistance on ice (Gao et al., 2004). Using the same apparatus, Grönqvist and Hirvonen (1995) tested 49 types of footwear on wet and dry ice and found that none of the PU and thermoset plastic materials increased DCOF on wet ice. Flat cleats with the largest possible apparent contact area resulted in the highest friction readings on dry ice and sharp cleats with very hard heel materials provided the highest friction on wet ice due to the formation of scratches (Grönqvist & Hirvonen, 1995).

Gard and Berggard (2006) assessed three anti-slip devices: a heel device (with metal studs under the heel), a device with metal studs under the ball of the foot and toe area, and a whole-foot device (chains crossing the length of the foot), on plain ice as well as on ice covered with gravel, sand, salt, and snow. Overall, the heel device was perceived by subjects to be the safest on all ice surfaces (Gard & Berggard, 2006). A 2009 study using a portable device for measuring pedestrian slip resistance by simulating heel contact found that on icy surfaces none of the nine styles of treded winter footwear that were tested provided enough
grip, with all DCOF values measured at less than 0.14, and the authors concluded that in such situations anti-slip devices should be used (Aschan et al., 2009).

Other studies have also indicated a need for specialized winter footwear. Bell (1997) suggested the use of soles with multi-layer polymers with a hard aluminum oxide or silicon carbide grit for use on oil, water, ice, and snow contaminants. In that report, Bell also recommended the use of footwear appliances such as spikes, chains, and screw heads for penetration into packed snow and ice. Radomsky et al. (2001) also suggest that spikes and studs could improve traction on ice, and that a beveled edge or rounded heel edge with slightly worn soles could improve traction.

One product marketed as a gait-stabilizing device is the Yaktrax Walker which consists of bands of steel coil that conform to the length and width of shoes and boots. McKiernan (2005) studied 109 seniors randomized to wear or not wear the Yaktrax Walker. Ice was found to be the most common surface involved in outdoor slips and falls with boots being the most commonly worn footwear at the time of the slips and falls. McKiernan concluded that for every six people assigned to wear the Yaktrax Walker one non-serious injurious fall of a fall-prone ambulatory older person could be prevented. Of note, approximately one-third of all outdoor slips and two-thirds of all outdoor falls recorded in the Yaktrax group occurred when subjects were not wearing their assigned devices (McKiernan, 2005). Participants in the device-wearing group in this study were instructed to only wear the devices under appropriate environmental conditions, i.e. not indoors or on smooth outdoor non-ice surfaces. Although the author concluded that this evidence supports that the Yaktrax Walker is effective for preventing outdoor falls, details of non-compliance or inappropriate use of the device, were not discussed. The consequences of wearing this type of device on non-ice surfaces is a major concern, as transitions between slippery and non-slippery surfaces occur routinely throughout most pedestrian routes in winter.

The step simulator developed at the Finnish Institute of Occupational Health and Safety has been the primary tool that has been used to assess winter footwear slip resistance (Grönqvist et al., 1989). Abeysekera and Gao (2001) collected objective and subjective data from 25 participants who conducted walking trials while wearing four types of shoes. Footwear was
tested on pure ice, ice with gravel, sand, snow, and salt. DCOF was measured using the step simulator in conjunction with ice formed on a force platform. Sole hardness, sole roughness, footwear centre of mass, and tread area data were also collected. DCOF was the only measure that significantly correlated with subjective ratings of slip resistance ($r= .9$, $p=.037$).

The same stationary step simulator was also used to measure DCOF of 9 types of footwear with and without abrasion on melting and hard ice (Gao et al., 2003). The test footwear was artificially abraded with 400 grit silicon carbide paper. At -10°C hard ice, abrasion increased DCOF and a smaller difference in DCOF was observed on melting ice at 0°C. New footwear was therefore determined to be more slippery than artificially abraded footwear on hard ice.

Gao et al. (2004) used the stationary step simulator to determine whether microcellular PU, which was considered to be the most slip resistant material on lubricated flooring, was similarly effective on ice. The DCOF of four sole materials (synthetic rubber, nitrile rubber, natural rubber, and microcellular PU) were measured on ice at -12°C. The findings indicated that the COF of microcellular PU was not significantly different from that of the rubbers when tested on ice, demonstrating that materials that performed well on indoor surfaces and contaminants did not necessarily perform well in winter conditions.

1.4 Addressing the Gaps

The wide breadth of literature regarding slips and falls describes the magnitude of the problem both in terms of the often severe injuries that are incurred as a result as well as the associated economic impact. Slips and falls cost the health care system $30 billion per year in the United States (Stevens et al., 2006), largely because the injuries associated with slips and falls can be extremely serious and debilitating. Typically injuries include sprains and fractures to the wrists, lower extremities, and the hips. For older adults especially, such injuries can significantly diminish quality of life. Winter conditions are also associated with double the rates of slips and falls in comparison to the rest of the year (Eilert-Petersson & Schelp, 1998), with ice and snow contributing to two-thirds of all pedestrian accidents (Rolfsman et al., 2012) and 85% of slip-related injuries in winter-experiencing environments.
(Kemmlert & Lundholm, 2001). There is also increasing significant evidence indicating that these problems are exacerbated by winter conditions.

Footwear can reduce the likelihood of slipping and falling by increasing the coefficient of friction at the interface between the footwear and walking surface as slips occur when there is insufficient friction underfoot to resist the forces at the point of contact. However, the measurement of the available coefficient of friction at the interface footwear-surface interface while walking is extremely difficult especially when the surfaces are complicated by contaminants such as water, ice, or snow and existing measurement devices lack repeatability and validity.

To develop a valid device, the literature indicates that measures should be dynamic and should replicate the kinematics of actual walking as closely as possible so that the characteristics of the footwear sole are tested in the same manner in which they function during real-world activities. Key considerations are the forward sliding speeds, sagittal foot angles, and normal loads. While these factors are considered in standard bench tests of footwear slip resistance, other factors such as horizontal sliding speed, coronal and transverse foot angles, and person-to-person variability are not simulated. The human-centred test devices also poorly replicate normal gait. Across all footwear testing devices, the test conditions, specifically winter test surfaces, are inadequate, limiting the applicability of results to winter conditions.

The four studies presented in the following chapters target several gaps in the current state of falls research. Of main concern is the lack of focus on outdoor winter-related slips and falls despite the epidemiological evidence indicating the breadth of the problem for both pedestrians and outdoor workers. The lack of data available in terms of the specific dynamics of walking in various winter conditions such as ice and snow as well as appropriate methods for creating, maintaining, controlling, and describing these conditions also needs to be addressed.

In an effort to reduce winter slips and falls, studying footwear and the use of footwear by actual users as a means of improving resistance to slip events was targeted in this work. Winter footwear, including boots and cleats were compared to determine their effectiveness
in mitigating slip severity. The critical biomechanical parameters measured while walking on winter surfaces was compared with parameters used in the measurement of footwear slip resistance to better understand why standard measurements do not reflect their ability to prevent winter slips and falls. From there, an ecologically valid method of assessing slip resistance involving user-centred testing was developed and used to test footwear in snow and ice conditions that are both challenging and realistic with the overall goal of optimizing footwear slip resistance characteristics to protect the end-users.

The specific research objectives of this work were to firstly, evaluate the slip resistance of a range of winter footwear on challenging winter conditions using biomechanical measures, the current standard method, and a novel method; secondly, to determine recommendations for improving the ecological validity of the current standard method for use in winter conditions; and thirdly to develop and test a novel method for rating footwear slip resistance over a range of winter conditions and to use this new method to assess the effects of icy and snowy surfaces on footwear slip resistance.

References
Aschan, C., Hirvonen, M., Rajamäki, E., Mannelin, T., Ruotsalainen, J., & Ruuhela, R.


people at risk of falls. *Journal of Rehabilitation Research and Development, 45*(8), 1167–1181.


Chapter 2
Study I: Footwear and Anti-Slip Device Testing in Simulated Winter Conditions

Preface

The following sections of this chapter were submitted along with co-authors Kathleen Denbeigh, Yue Li, Tilak Dutta, and Geoff Fernie to the International Journal of Industrial Ergonomics (July 2014). As the first study comprising the thesis, its purpose was to examine a variety of winter footwear including both boots and cleats on a range of winter surfaces. The data collected during this study was novel in that for the first time, kinematics and kinetics were assessed while walking with cleats on controlled ice conditions. Furthermore, while previous studies of slip biomechanics have been largely focused on indoor surfaces and contaminants, gait during both level and down-sloped walking on wet ice were studied here to develop a comprehensive evaluation of the test footwear.

Abstract

Anti-slip winter footwear is crucial for reducing the risk of slips and falls in winter conditions. The objective of this study was to compare the slip resistance of four styles of footwear in challenging winter conditions. Twenty-nine participants tested winter boots, two styles of winter cleats, and a smooth rubber sole as a control. The tests involved walking on level and sloped walkways with concrete, ice, or concrete with a patch of ice. Gait biomechanics and participant questionnaires were analyzed to determine footwear performance. Cleated footwear reduced the frequency of detectable slips on ice, though incidents of severe slips on ice were still observed while wearing cleats. The boots and control footwear in this study resulted in frequent and severe slips but received high ratings for comfort. Overall, participants did not show a preference for one type of footwear.
2.1 Introduction

2.1.1 Winter Slips and Falls

Slip and fall accidents are a major concern for outdoor workers because of the severity of resulting injuries and their associated costs (Courtney et al., 2013; Courtney et al., 2001). Winter conditions can increase the risk of slips and falls as snow and ice reduce underfoot traction and make it difficult to maintain balance and execute effective balance recovery strategies (Abeysekera & Gao, 2001; Gao & Abeysekera, 2004).

Data released by the Canadian Institute for Health Information (2012) showed that in Canada, falls on ice are the most common cause of serious injuries during the winter months (excluding motor-vehicle accidents) and lead to more hospital admissions than all winter sports and recreational activities combined. Over 21,000 people in Ontario alone visit an emergency room each year because of slips and falls on ice and snow and over 10% are hospitalized as a result (Ontario Injury Prevention Resource Centre, 2009). Across Canada, roughly 7000 people are hospitalized due to falls on ice each year and half of these people are over the age of 60 (Canadian Institute for Health Information, 2012). Outdoor workers, such as postal delivery personnel, are particularly vulnerable to such accidents (Bentley & Haslam, 1998). Canada Post reported that in 2007, 46% of lost-time due to accidents was a result of slips, trips, or falls and letter carriers experienced more than 1500 on-the-job injuries related to the weather (Canada Post Corporation, 2008).

To date, the vast majority of slip and fall research has focused on the prevention of indoor accidents where surfaces are relatively uniform and the environment can be more easily controlled. Few studies have focused on outdoor environments which, particularly in winter, are far less predictable. Research has already shown the importance of appropriate footwear for preventing slips and falls in winter (Gao & Abeysekera, 2004). However, more data are necessary to build an understanding of gait dynamics and strategies for maintaining balance in controlled winter conditions in order to develop better approaches for preventing winter-related accidents. These approaches might include improved training and educational programs for falls prevention as well as better slip resistant winter footwear.
2.1.2 Winter Boots and Footwear Devices

The slip resistance of winter footwear is typically measured as the coefficient of friction (COF) between the footwear sole and underfoot surface. COF is expressed as the ratio of shear to normal forces at the footwear-surface interface and slips occur when the COF at the interface is lower than that which is instantaneously required for the intended activity (Grönqvist et al., 2001). Bruce et al. (1986) were the first to test the slip-resistance of footwear on ice. They measured the horizontal force required to drag subjects wearing various shoes, crampons, and chains on unwetted ice. The chains gave poor traction on ice and although softer sole materials provided higher frictional forces, they were still inadequate for preventing slipping accidents. Crampons consisting of steel studs on a rubber strip provided the best traction on the dry ice surface (Bruce et al., 1986). Dragging traction, however, is not indicative of the kinetics involved in normal gait and measuring traction during natural heel strike and toe-off phases would provide a more accurate measure of the protective capabilities of the various types of footwear.

To more closely reproduce the frictional forces experienced during natural gait, Gao et al. (2004) tested the slip resistance of four footwear outsole materials with an apparatus that simulated the movement and forces applied during a single step. The tests were conducted on ice that was formed on a force plate. They concluded that while polyurethane outsoles demonstrated higher COF values than synthetic rubber, nitrile rubber, and natural rubber on wet and lubricated floors, the polyurethane did not perform significantly better on ice and therefore may not provide sufficient slip resistance on ice (Gao et al., 2004). Using the same apparatus, Grönqvist and Hirvonen (1995) tested 49 types of footwear on wet and dry ice and found that none of the polyurethane and thermoset plastic materials resulted in COF values over 0.3 on wet ice, which they have suggested as a minimum safe COF value. Of the footwear that was tested, flat-bottomed (non-conical) cleats with the largest possible apparent contact area, resulted in the highest friction readings on dry ice and sharp (conical) cleats with very hard heel materials provided the highest friction on wet ice due to the formation of scratches (Grönqvist & Hirvonen, 1995).

Gard and Berggard (2006) assessed three anti-slip devices: a heel device (with metal studs under the heel), a device with metal studs under the ball of the foot and toe area, and a
whole-foot device (chains crossing the length of the foot), on ice and also on ice covered with gravel, sand, salt, and snow. Overall, the heel device was perceived by subjects to be the safest on all ice surfaces (Gard & Berggard, 2006). A 2009 study using a portable device for measuring pedestrian slip resistance by simulating heel contact found that on icy surfaces none of the nine styles of treaded winter footwear that were tested provided enough grip, with all COF values measured at less than 0.14, and the authors concluded that in such situations anti-slip devices should be used (Aschan et al., 2009).

During gait, measures of slip frequency, total slip distance, slip velocity, and peak utilized coefficient of friction (UCOF) can be used to assess the slipperiness of various footwear-surface-contaminant combinations. These measures are useful as human-centred approaches are more likely to be valid than mechanical gait simulators. The frequency of slips is important in that initiated slips require recovery responses in order to prevent falls. Lockhart et al. (2005) showed that while younger and older adults may initiate the same number of slips, the ability to recover from slips degrades with age. Larger total slip distances and higher peak forward sliding velocities have also been associated with increased likelihood for falls (Cham & Redfern, 2002b).

UCOF is the ratio of shear to normal force underfoot during gait. Peak UCOF is the maximum UCOF during weight acceptance onto the stepping foot shortly after heel strike. It has been suggested that higher peak UCOF (often referred to as required COF or RCOF) values are indicative of poorer slip resistance as higher UCOF values approach the maximum COF that is available at the footwear-surface interface (Blanchette et al., 2011; Tsai & Powers, 2009). Despite this usage of peak UCOF to indicate slip resistance, it is important to note that peak UCOF on its own does not indicate relative margins of safety between different footwear-surface combinations. The margin of safety is the difference between the COF that is available at the interface at any given instant and the maximum COF required to resist slipping on it at that instant. The true available COF is not known at any particular instant as it depends on a complex interaction of factors including the ploughing and adhesive forces at the footwear-surface interface and the kinetics and kinematics of the striking foot (Kim & Nagata, 2008). As such, peak UCOF should not be used to conclude
differences in slip resistance of footwear, particularly if the mechanisms for slip resistance are not the same (i.e. ploughing vs. adhesion).

With cleated footwear becoming an increasingly popular choice of winter footwear, it is necessary to understand how effective they are at preventing slips and how they might be optimized. Two types of cleats commonly used by Canada Post letter carriers were selected for our study, along with a typical transitional winter boot. The boot was considered transitional because it was classified as being between a heavy-duty work boot and a casual winter boot, which both outdoor workers and pedestrians might wear. The test conditions simulated baseline (concrete) and challenging (icy) outdoor sidewalks. A longer ice path on which participants had to take multiple steps was compared to an icy patch condition simulating a frozen puddle which one might step on with one foot only before crossing. All three surface conditions were tested on a level walkway as well as over a short incline representative of uneven, challenging terrain (Cham & Redfern, 2002b).

2.2 Methods

A total of 29 subjects (16 male, 13 female) participated in this study. The participants ranged in age from 19 to 58 and included 8 letter carriers and 21 non-outdoor workers. All subjects self-reported that they did not have any mobility impairment that would impact normal gait or cardiovascular conditions that could be aggravated by exposure to cold temperatures. The study was approved by the Toronto Rehabilitation Institute Research Ethics Board.

2.2.1 Footwear

Four types of test footwear were used in this study: a control footwear, a transitional winter boot, and two types of cleated anti-slip devices (refer to Figure 2.1). The control footwear was specially devised for the experiment by removing the anti-slip mechanisms from an off-the-shelf anti-slip device. This produced a treadless pull-on sole consisting of a smooth proprietary rubber compound (Jordan David, Winter Walking™, Pennsylvania). The boots and both types of cleats were commercially available for purchase. The winter boots were comprised of a rubber outsole with a molded proprietary design (IcePaw, Baffin, Ontario). There were slight differences in the tread pattern of the men’s (Baffin Logan, Ontario) and
ladies’ (Baffin Mawa, Ontario) boots although both outsoles were created from the same materials and used IcePaw technology (Figure 2.2). The uppers of the men’s and ladies’ boots also differed as the men’s boots were lace-ups while the ladies’ were pull-ons. Both men and women wore the same control and cleated footwear.

Figure 2.1. Test footwear. Left to right: the control footwear (a treadless pull-on rubber sole), a transitional winter boot, Cleat-A (1.5mm spike height), and Cleat-B (2.5mm spike height).

Figure 2.2. Men’s and ladies’ winter boots. There were differences in treads and uppers between the men’s (left) and ladies’ (right) test boots.

Cleat-A and Cleat-B were anti-slip devices consisting of cylindrical metal cleats embedded in rubber soles. Both styles incorporated tungsten carbide studs mounted on tough plastic discs. Cleat-A (Grip-X™, Jordan David, Pennsylvania) had three spikes at the heel and five spikes at the forefoot while Cleat-B (Get-A-Grip Xtreme, California) had two spikes at the heel and four spikes at the forefoot. Participants were fitted to their nearest full boot size and the control footwear and cleats, sized XS to XL, were selected to fit snugly over the boots.
2.2.2 Experimental Setup

Walking trials were conducted in a climate controlled chamber at the Toronto Rehabilitation Institute-UHN. During participant testing, an ambient temperature of 3°C was held to simulate outdoor conditions with wet ice. Participants wore typical winter clothing including a winter coat and gloves, hats, and scarves if needed. For safety, participants also wore a full-body harness over their coat that had an attachment point at their upper back. The harness was connected by a height-adjusted, fixed length line, to an overhead track mounted to a free-standing structure in order to passively arrest falls. The track could be positioned over either of two walkways and allowed the participant to walk freely forwards and backwards.

Two 3.5m by 0.75m walkways were used for testing. Each walkway consisted of a series of 5 interchangeable panels with a 2mm gap between panels (Figure 2.3 and Figure 2.4). One walkway was used to test the level condition, consisting of 5 level walkway panels. The second walkway was used to test down-sloped walking and utilized a centre panel which was sloped at a 1:10 rise to run ratio with level panels leading to and away from the slope on either end. Each of the three surface conditions (concrete, ice, or concrete with a patch of ice) was tested on both the level and sloped walkways.

![Figure 2.3. Level (top) and sloped (bottom) test walkways. The two test walkways were rigidly attached to wooden spacers or force plates mounted over the laboratory floor.](image)

Walkway panels were separated by 2mm gaps.
Concrete panels were situated at both ends of each walkway while the centre three panels were either 5cm thick slabs of ice or concrete. Three surface conditions were tested: a baseline \textit{concrete} condition of all concrete panels, an \textit{icy patch} condition whereby the centre panel consisting of ice was flanked on either end by concrete panels, and an \textit{ice} condition whereby all three centre panels were ice. The concrete panels were formed to simulate brushed concrete sidewalks while the ice surfaces were created by freezing water at -5°C for at least 12 hours. The ambient temperature was raised to 3°C one hour prior to testing and held for the duration of the experiment. Prior to testing each type of footwear, each ice panel was wiped with a damp cloth and wetted with approximately 2mm (equivalently 0.2mL/cm²) of 22°C water. Over the course of the experiments, some degradation of the surfaces could be observed as a result of walking trials, particularly with the cleated footwear. Between tests of different footwear, the ice surface was cleaned and re-wetted for consistency. Also, the order of footwear and surfaces were quasi-randomized to minimize the effects of changes in surface characteristics as well as effects of learning and fatigue. A tribometer (English XL Sliptester, South Carolina) was used to measure slip resistance of the ice surface along the walkway panels before and after pilot testing in order to gauge consistency of the ice surfaces, (refer to Table 2.1). Slip readings on concrete was marginally higher in the medial-lateral (ML) direction than in the anterior-posterior (AP) direction and decreased marginally over the course of testing while slip readings on ice increased over the course of testing.
Table 2.1. Slip index readings from the English XL Sliptester. Readings in the AP and ML directions averaged across 4 random locations along the walkway taken before and after single participant pilot testing.

<table>
<thead>
<tr>
<th></th>
<th>Concrete</th>
<th>Ice</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pre-Test</td>
<td>Post-Test</td>
</tr>
<tr>
<td>Slip Index (AP)</td>
<td>1.08 ± 0.18</td>
<td>0.92 ± 0.12</td>
</tr>
<tr>
<td>Slip Index (ML)</td>
<td>1.14 ± 0.13</td>
<td>1.00 ± 0.17</td>
</tr>
</tbody>
</table>

The centre panel of each walkway was mounted over a force plate (BP400600HF, AMTI, Massachusetts) sampling at 1000Hz. The sloped portion of the inclined walkway was built as a wedge mounted over the level force plate. Four motion capture tracker bars (VZ4000v, Phoenix Technologies Inc., British Columbia) were set up around the walkways to track motion of the feet at a sampling rate of 100Hz. Three active LED markers were secured to each piece of footwear: one at the heel, one above the first metatarsal and one lateral to the fifth metatarsal. The three markers were used during analysis to form a rigid body which was used to calculate the positions of virtual markers approximating the point of initial contact at heel strike and the point of final contact at toe off. Heel strike and toe off locations were landmarked at the posterior centre of the sole and anterior centre of the sole, respectively (refer to Figure 2.5). Three markers placed on the non-interchangeable concrete panels were used to create a coordinate reference frame for the test volume and dimensions of the walkway were measured relative to the origin.

2.2.3 Data Processing

Force and motion data were filtered using zero-lag, fourth order, dual-pass Butterworth filters. Kinematic data were filtered using a cutoff frequency of 6Hz and kinetic data were filtered at a cutoff frequency of 45Hz.

Foot kinematics and ground reaction forces were analyzed for the step on the centre walkway panel during each trial. Heel motion was analyzed at the virtual position of the heel strike landmark at the posterior centre of the footwear sole (shown in Figure 2.5). Total slip distance was calculated for each trial as the total heel displacement from heel strike to the end of heel slip. Time of heel strike was identified from force plate data as the frame at
which the vertical force applied by the foot surpassed a threshold of 10N. The end of the heel slip was defined as the time-point at which heel velocity, in the anterior-posterior direction of the walkway, dropped below 0.05m/s and remained below this threshold for the subsequent 50ms.

*Heel strike foot angle* was measured as the angle between the plane of the test surface and a vector joining the virtual points of heel contact and toe-off at the instant of heel strike. *Peak sliding velocity* was calculated as the maximum instantaneous velocity from the time of heel strike to the time of slip end. Utilized coefficient of friction (UCOF) was calculated as the ratio of shear force to normal force (measured from the force plates) while stepping. *Peak UCOF* was the maximum COF after 10% of the step (from heel strike to toe off) (Lockhart et al., 2005).

Figure 2.5. Motion tracking marker positions. Tracking (“O”) and virtual (“X”) marker positions for the boot are shown with (left) and without (right) an anti-slip device. Active tracking markers over the heel, first metatarsal, and fifth metatarsal were used to create a rigid body. Their positions were tracked to calculate the position of virtual points at the posterior and anterior centres of the sole which were used to approximate the initial point of contact at heel strike and the final point of contact at toe-off, respectively.
2.2.4 Experimental Protocol

Prior to testing in the cold environment, participants completed a questionnaire regarding demographic information, past falls, and participation in winter activities. Measurements of height, weight, and grip strength were also recorded. Participants were then asked to complete three blocks of test trials with 15 minute breaks between blocks. During the breaks, participants left the cold environment and were asked to complete questionnaires regarding the preceding test block and whether they had experienced slips on the tested surfaces in each of the 4 types of footwear.

Participants were asked to walk at a natural pace starting at one end of the walkway and stopping at the opposite end. Participants were instructed to take exactly one step on each of the three centre walkway panels and not to step on the gap between panels. At the beginning of the first test block, participants were given time to practice walking over one walkway and adjust their step lengths as necessary. Practice was always completed on the full concrete condition either on the level or the sloped surface. Participants conducted practice trials until they were comfortable walking across the test surfaces without stepping on the gaps between panels. Following the initial practice period, for each combination of footwear type, surface, and slope, the participants were asked to complete six passes for a total of three laps. Data obtained during the first, third, and fifth passes (i.e. only down-slope on the sloped walkway) were analyzed. Down-slope trials were the focus of this study as steps down-slope are more likely to lead to slips at the heel and more likely to result in falls than slips moving up-slope (Redfern et al., 2001). During each test block, all four types of footwear were tested on one sloped test surface and one level test surface, in random order. 4 types of footwear x 2 walkways x 3 repetitions = 24 trials per block. Each block consisted of one sloped and one level walkway. The walkway condition could be full ice, an icy patch, or full concrete such that all 6 walkway conditions (2 slopes x 3 surfaces) were covered by the three blocks. Between blocks, walkway panels were exchanged to create the walkway surface conditions for the subsequent block.

After all three test blocks were completed, and all three questionnaires regarding the preceding test block were complete, participants were asked to fill out a final questionnaire
consisting of a paired comparison of perceived slipperiness, comfort, and overall preference for each of the four types of footwear.

2.3 Results

2.3.1 Questionnaires and Participant Information

Participant information and responses to questionnaires are presented in Table 2.2 and Table 2.3, respectively. The questionnaire responses showed that 55% of the participants had experienced a fall within the previous two years and 38% had experienced a fall outdoors in winter in the previous two years. Overall, 38% of participants, including each of the 8 letter carriers, indicated that they had worn a winter anti-slip device in the past. For each participant, a hand dynamometer was used to measure the grip strength of each hand. The maximum grip strength measured on the stronger hand is an indicator of general muscle strength (Trampisch et al., 2012).

Table 2.2. Participant information.

<table>
<thead>
<tr>
<th></th>
<th>Age (yrs.)</th>
<th>Height (cm)</th>
<th>Weight (kg)</th>
<th>BMI</th>
<th>Left grip strength (kg)</th>
<th>Right grip strength (kg)</th>
<th>Winter residency* (yrs.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>32.4</td>
<td>171</td>
<td>72.1</td>
<td>24.2</td>
<td>34.5</td>
<td>37.2</td>
<td>24.8</td>
</tr>
<tr>
<td>SD</td>
<td>12.1</td>
<td>9</td>
<td>16.9</td>
<td>4.7</td>
<td>11.4</td>
<td>12.6</td>
<td>15.2</td>
</tr>
<tr>
<td>Max.</td>
<td>58</td>
<td>191</td>
<td>105.9</td>
<td>36.0</td>
<td>65</td>
<td>65</td>
<td>58</td>
</tr>
<tr>
<td>Min.</td>
<td>19</td>
<td>156</td>
<td>47.6</td>
<td>16.8</td>
<td>10</td>
<td>10</td>
<td>5</td>
</tr>
</tbody>
</table>

* Winter residency was defined as the number of years spent living in winter-experiencing climates

Table 2.3. Responses to questionnaires.

<table>
<thead>
<tr>
<th>General questions</th>
<th>% of participants</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fallen in past 2 years</td>
<td>55%</td>
</tr>
<tr>
<td>Fallen outdoors in past 2 years</td>
<td>38%</td>
</tr>
<tr>
<td>Previously used anti-slip device</td>
<td>38%</td>
</tr>
<tr>
<td>Participates in winter sports</td>
<td>58%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Days outdoors per week</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>6-7 days per week</td>
<td>93%</td>
</tr>
<tr>
<td>3-5 days per week</td>
<td>7%</td>
</tr>
<tr>
<td>&lt; 3 days per week</td>
<td>0%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Time outdoors per day*</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 30 min</td>
<td>14%</td>
</tr>
<tr>
<td>30 min to 1 h</td>
<td>45%</td>
</tr>
<tr>
<td>1 h to 2 h</td>
<td>17%</td>
</tr>
<tr>
<td>&gt; 2 h</td>
<td>24%</td>
</tr>
</tbody>
</table>

* Time outdoors per day for during days when time is spent outdoors
Following each test block, participants were asked to indicate on the questionnaire whether or not they had felt uncontrolled or unintentional slips at the heel for each of the footwear-surface combinations tested in the preceding block. This information provided a subjective measure of footwear slipperiness and was also used to confirm slip instances from biomechanical data during later analysis. Because the data were binary, a logistic regression was run to determine the effects of surface, slope, and footwear on self-reported slips at the heel. For all statistical analyses, effects are reported as significant at $p<.05$ and significance levels for multiple comparisons were adjusted using the Tukey-Kramer correction method. First, to test differences between reported slips in the men’s and ladies’ boots, sex was modeled as a covariate in a logistic regression with surface and slope as factors to determine their effects on self-reported heel slips. Sex did not significantly affect the likelihood of reporting heel slips while wearing boots ($p=.42$) and so men’s and ladies’ boots were collapsed into one level for further analysis of self-reported slips. The logistic regression indicated that the main effects of surface and footwear were significant while slope type was not significant. Significantly more participants reported slips on the full ice surface than on both the patch of ice and the concrete surface. There was no significant difference between self-reported heel slips on the icy patch and the concrete surfaces. All pairwise comparisons between footwear were significant with the exception of Cleat-A in comparison to Cleat-B. When comparing across all surface conditions, significantly more participants reported slips while wearing the control footwear than the boots and significantly more slips were reported in the boots than both styles of cleats. When surface condition was isolated to consider only the full ice condition, slips in both types of uncleated footwear were reported more frequently than in cleated footwear, with no significant difference between the styles of uncleated footwear or between the styles of cleated footwear. The percentage of participants who self-reported uncontrolled, or unintentional, heel slips for each condition is depicted in Figure 2.6.
After completing all test trials, participants gave pairwise comparisons of each combination of test footwear to indicate which footwear they found to be more slippery, more comfortable and more preferred (Figure 2.7). One point was given for a specific style of footwear each time it was selected over its comparator. If the styles were rated equal, both styles were given 0.5 points. For the four pieces of footwear, each participant could give a maximum score of 3 points per footwear in each category. One-way repeated measures analyses of variance were used to analyze the effect of footwear type on the mean scores from pairwise comparisons. Mauchly’s test indicated that the assumption of sphericity had been violated for the main effects of slipperiness, $\chi^2(5)=20.00$, and comfort, $\chi^2(5)=17.87$. Therefore degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity, $\varepsilon=.67$ for slipperiness and $\varepsilon=.74$ for comfort. The results show that the participants did not significantly prefer any type of footwear tested, $F(3,84)=1.16$. There was a significant main effect of the type of footwear on ratings of slipperiness, $F(2.01,56.30)=26.36$ and ratings of comfort, $F(2.23,62.42)=34.06$. Post hoc tests were used to compare ratings of each type of footwear for slipperiness and comfort. These tests revealed that the boots were rated significantly more slippery than the control footwear, Cleat-A, and Cleat-B. The control footwear was also rated significantly more slippery than Cleat-A and Cleat-B. The boots were rated significantly more comfortable than the control footwear and both Cleat-A and Cleat-B. The control footwear was also rated more comfortable than Cleat-A and Cleat-B.
eval uate each over 2.3. To delineate slope assumptions and limits 2.3.

During the experiment, Figure 2.7 shows box-plots of the maximum total slip distances observed for each participant by footwear and condition. It should be noted that while the more rare longer slips are considered statistical outliers and far outliers, these are the events that are most clinically significant in slip studies as longer slips are indicative of a greater potential for falling.
Figure 2.8. Box-plot of maximum total slip distances for each test condition. Within each test condition, the maximum total slip distance across the three test repetitions was found for each participant.

General linear mixed models with subject as a random effect were used to determine the effects of footwear, surface, and slope on total slip distance, foot angle, peak sliding velocity, and peak UCOF. Two and three-way interactions were also considered. Total slip distance, peak UCOF, and foot angle data were rank transformed to meet the assumption of normality and $p$-values were reported from analyses of the rank transformed data. Subject weight ($p=.11$), height ($p=.43$), grip strength of the dominant hand ($p=.44$), and whether the participants were outdoor workers ($p=.39$) were included as covariates but the covariates had no significant effect on total slip distance.

The main effects of footwear, surface, as well as slope on total slip distance were significant. Contrasts revealed that participants slipped for significantly shorter distances while wearing Cleat-B than in each of the other types of footwear. The total slip distances on ice were also significantly longer than those on icy patches and concrete, and total slip distances on icy
patches were significantly longer than those on concrete. The contrasts also indicated that participants slipped longer distances on the level surface than on the sloped surface.

Figure 2.9. Significant two-way interactions. (a) Footwear-surface interactions for total slip distance; (b) Footwear-slope interactions for total slip distance; (c) Footwear-surface interactions for foot angle; (d) Surface-slope interactions for foot angle; (e) Surface-footwear interactions for peak sliding velocity; (f) Surface-slope interactions for peak UCOF.

Significant two-way interactions of surface and footwear, and slope and footwear were also observed as depicted in Figure 2.9(a,b). The control footwear and boots displayed contrasting
levels of performance on the icy surfaces. On average, on the full ice surface the boots slipped for longer distances than the control footwear, while on the icy patch the control footwear slipped for longer distances than the boots. Across all surface conditions, the boots had longer slips on the level than on the down-slope, while the control footwear had shorter slips on the level than on the down-slope. The three-way interaction was not significant for total slip distance ($p = .46$). However, as shown in Figure 2.10(a), while walking down-slope on the full ice surface and in both slope conditions on the icy patch, participants experienced longer (on average by 4.1mm) slips while wearing the control footwear than the boot. On the full ice surface, total slip distance while wearing the boots was on average 9.4mm larger than while using the control footwear leading to the significant two-way interaction.

### 2.3.2.2 Heel Strike Foot Angle

The main effects of footwear, surface and slope on foot angle were significant. Participants walked with a significantly more flat-footed heel strike when using Cleat-B than when wearing any of the other types of footwear. Foot angles at heel strike were also smaller when wearing Cleat-A than while wearing either the boots or the control footwear. Participants walked with a significantly more flat-footed heel strike on the full ice surface than on the icy patch or concrete, and were significantly more flat-footed on the icy patch than on the concrete surface condition. Significantly smaller heel strike angles were observed on the level surface than down-slope.

Moderate, though significant two-way interactions of factors on foot angle at heel strike are shown in Figure 2.9(c,d). The two types of non-cleated footwear were associated with larger foot angles on the icy patch than the full ice surface. However, foot angles for the cleated footwear remained relatively unchanged between the full ice and icy patch conditions. On concrete, all foot angles increased relative to the ice surfaces, but the control footwear heel strike angle increased less relative to the other types of footwear and foot angles for both styles of cleats were lower than for those in the boot or control. During down-sloped walking on concrete, foot angles were larger than on the level walkway with this trend reduced on the icy patch. On ice, participants walked with smaller down-slope foot angles than on the level walkway.
Table 2.4. Pearson correlation coefficients for bivariate correlation analysis of total slip distance and foot angle.

<table>
<thead>
<tr>
<th></th>
<th>Trial 1</th>
<th>Trial 2</th>
<th>Trial 3</th>
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<tbody>
<tr>
<td></td>
<td>Level</td>
<td>Sloped</td>
<td>Level</td>
</tr>
<tr>
<td>By Footwear</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control</td>
<td>-.05</td>
<td>-.38</td>
<td>-.18</td>
</tr>
<tr>
<td>Boot</td>
<td>-.63**</td>
<td>-.32**</td>
<td>-.17</td>
</tr>
<tr>
<td>Cleat-A</td>
<td>.02</td>
<td>-.21</td>
<td>-.05</td>
</tr>
<tr>
<td>Cleat-B</td>
<td>.08</td>
<td>.21</td>
<td>-.01</td>
</tr>
<tr>
<td>By Surface</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ice</td>
<td>.17</td>
<td>-.18</td>
<td>-.13</td>
</tr>
<tr>
<td>Icy Patch</td>
<td>-.56**</td>
<td>-.32**</td>
<td>-.01</td>
</tr>
<tr>
<td>Concrete</td>
<td>.05</td>
<td>.10</td>
<td>.06</td>
</tr>
</tbody>
</table>

** Correlation is significant at the .01 level (two-tailed).

For each of the three analyzed trials (first, third, and fifth passes) a further analysis of the relationship between total slip distance and foot angle was conducted by determining the bivariate correlations when grouped by footwear or by surface on each of the two slope conditions. The resulting Pearson correlation coefficients are shown in Table 2.4 with significant correlations indicated for \( p < .01 \). During the first trial, smaller heel contact angles were significantly correlated with larger total slip distances for the boot condition on the level \( (r = -.63) \) and down-slope \( (r = -.32) \) walkways. Similarly, with the control footwear smaller heel contact angles were significantly correlated with larger total slip distances down-slope \( (r = -.38) \). When grouped by surface, during the first trial, on the icy patch condition smaller foot angles were also significantly correlated with larger total slip distances both on the level \( (r = -.56) \) and down-slope \( (r = -.32) \). During the second trial, only while walking with boots down-slope was there a significant correlation between foot angle and total slip distance \( (r = -.40) \). No significant correlations were observed during the third trial.

2.3.2.3 Peak Sliding Velocity

Footwear and surface were significant main effects for peak sliding velocity. Across all types of footwear and slope conditions, average peak sliding velocities for both the full ice and the concrete conditions were significantly higher than those on the icy patch. The second order interaction term of surface by footwear was significant for peak sliding velocity (Figure 2.9(e)). While velocities in Cleat-A and the control footwear remained relatively constant across all three surface conditions, velocities of the boots decreased significantly from the
full ice to the icy patch condition and the velocities for Cleat-B decreased significantly from the concrete to the icy patch condition. Figure 2.10(b) shows the effects of the third order interactions between footwear, surface, and slope on peak sliding velocity. Although the third order interactions were non-significant ($p=.36$) the data indicate that peak sliding velocities for boots on the level, full ice surface were more than 0.04m/s higher than that for all other footwear on the other surface and slope conditions. It should be noted that total slip distances were calculated from heel strike to the time-point when the heel stopped moving and some imperceptible relative sliding is expected during normal gait (McGorry et al., 2007). On concrete, these slides were consistent across footwear and relatively small compared to that on the icy surfaces (see Figure 2.9(a)). Similarly, because peak sliding velocity was calculated from heel strike to slip end, peak sliding velocities seen on concrete reflect higher velocities of the foot at the end of swing phase which is followed by high magnitude deceleration as the foot comes to a stop in a short distance.

2.3.2.4 Peak Utilized Coefficient of Friction

There were significant main effects of footwear, surface, and slope on peak UCOF. Peak UCOF on concrete was significantly higher than that on the full ice surface and the icy patch. Peak UCOF while wearing Cleat-A was significantly lower than for all other footwear and peak UCOF walking on the level was significantly lower than down-slope. There was a significant interaction effect between the surface and slope conditions on peak UCOF. Peak UCOF on the icy patch was higher than that on the full ice surface and on concrete while going down-slope, but on the level was similar to that on ice and lower than that observed on concrete as indicated in Figure 2.9(f). The third order interaction did not significantly affect peak UCOF. The data indicate that while peak UCOF values were consistent for all types of footwear on the two icy conditions and two slope conditions, the exception is during down-slope walking on the icy patch. In the case of down-slope walking on the icy patch, the control footwear was associated with peak UCOF (1.74 ± 0.26) values that were three times that of the others on icy surfaces and double that observed for any footwear on concrete (Figure 2.10(c)). Frictional coefficients greater than 1 indicate that the shear force applied during sliding exceeded the normal force exerted on the surface.
Figure 2.10. Three-way interactions. Although the three-way interactions (footwear x surface x slope) were non-significant, they illustrate key contributors to significant two-way interactions for (a) total slip distance, (b) peak sliding velocity, and (c) peak UCOF.
2.4 Discussion

The sample population represented a wide range of healthy adults with respect to age, anthropometrics, strength, and winter walking experience. Participants varied in the length of time spent living in winter climate areas, whether they were outdoor workers, whether they had fallen in the recent past, and whether they participated in winter sports. All participants indicated that they spent at least a few hours outdoors each week during the winter season.

Participants reported slips at the heel in many of the conditions tested. This information was collected after each test block had been completed but because of difficulty with detailed recollection after-the-fact, it was only feasible to ask participants if, on the whole, they had experienced a heel slip in a particular condition rather than asking about the number of slips they experienced. While self-report did provide a general sense of the effectiveness of each type of footwear on each surface, for future studies it would be more valuable for participants to indicate whether a slip was detected after each pass along the walkway.

Interestingly, participants indicated that the boots were more slippery than the control footwear. The two non-cleated styles of footwear differed in many ways. The boot utilized a harder sole material, a specialized tread design, and a rounded heel edge while the control footwear sole was softer, had no tread, and a sharp heel edge. While any and all of these characteristics may have contributed to differences in performance as indicated by the participants, in optimizing the design of winter footwear, more work is necessary to identify how each characteristic influenced its slip resistance.

It should be noted that while participants clearly recognized the control footwear and boots as being more slippery, in agreement with the longer slip distances they demonstrated on the icy surfaces, the participants also put a high weighting on comfort, for which the boots and control ranked higher than the cleats. These contradictory ratings led to a lack of consensus as to overall footwear preference. This reflects concerns regarding compliance rates for use of anti-slip footwear devices such as cleats. Discomfort may result from uneven distribution of plantar pressure, particularly after long periods of walking (Burnfield et al., 2004), and/or from the prolonged effects of unnatural gait. Unnatural gait was observed while wearing
cleated footwear in this study where participants walked with significantly lower heel strike angles in cleats (20.6° ± 0.8° for Cleat-B) than non-cleated footwear in the concrete condition. On the concrete conditions, participants struck the ground at 23.4° ± 0.8° while wearing boots, which is comparable to natural mean heel strike foot-floor angles of 24.1° and 29.0° while walking on non-slippery floors reported by Cham and Redfern (2002a) and Chambers et al. (2003), respectively.

An important result that was not captured in the questionnaire data but was revealed from biomechanical analysis is that while the maximum total slip distances across all participants were clustered about relatively low means, multiple large magnitude slips were observed (Figure 2.8). Moreover, these large slip cases were not confined to the control and boot footwear but were also observed in cases of cleated footwear. The relatively small frequency of slips in the cleated footwear may provide participants with a false sense of security, potentially leading to a longer recovery reaction time when a slip is initiated. The overall number of slips that occurred while wearing cleats was lower but the slips that were observed resulted in large slip distances which are more difficult to recover from (Cham & Redfern, 2002b). This is of note, particularly when one considers the relative simplicity of the task that participants were asked to achieve in this study. While walking from one end of the walkway and stopping at the other, participants were fully aware of the surface, slope, and footwear that were being tested. A more in-depth study of differences in recovery response magnitude and timing between the cleated and non-cleated types of footwear would be useful for determining their effects on slip anticipation, as anticipation of slip events has been shown to induce more cautious gait strategies that reduce the risk of falls (Heiden et al., 2005; Oliveira, 2012). This study differs from the majority of past studies that have analyzed the biomechanics of slip events because participants were aware of the slippery conditions. The more cautious gait strategies were likely the main contributor to the shorter slip distances, slower peak sliding velocities, and the fact that there were no falls observed in this study in comparison to previous studies of unanticipated slips (Lockhart et al., 2005; Moyer et al., 2006; Redfern et al., 2001)

The bivariate correlation analysis indicated that some participants adopted the more cautious gait strategy of flat-footed walking. Walking with a smaller foot contact angle at heel strike
can allow quicker engagement of underfoot surface area during weight transfer and can indicate a more anterior position of the centre of mass for added stability over the planted contralateral foot (Fong et al., 2008; Marigold & Patla, 2002). However, this strategy did not necessarily reduce the total slip distance of the heel, particularly in the initial trials. Conversely, it was associated with longer slips on the icy patch in the boot condition, and on the down-slope in the control footwear, perhaps because the strategy was insufficient for mitigating the poor performance of footwear in slippery conditions. In subsequent trials such correlations were no longer significant indicating that some gait and/or postural adaptation, such as increased flexion moment at the knee (Cham & Redfern, 2001), had been achieved to reduce slip severity. In real-life winter scenarios, this learning factor may not come into play as pedestrians are constantly exposed to different surface conditions in terms of the angle of incline and the various types of underfoot contaminants.

An unexpected result was longer total slip distances observed on the level surfaces than on the sloped surfaces. This phenomenon may have been a result of participants walking more carefully down the sloped surfaces than the level surfaces. Another cause, as observed by the researchers during the experiment, was that participants were careful to maintain stable footing and short swing phases while on the full ice surface in the down-slope condition. However, the down-slope caused larger total slip distances in the subsequent step with the contralateral foot. Unfortunately, motion of this subsequent step was not captured in this study.

The non-cleated types of footwear were associated with larger total slip distances and smaller foot angles at heel strike on the full ice surface in comparison to the icy patch. The larger total slip distances likely reflect increased instability when stepping from one icy panel onto another icy panel in the full ice condition in comparison to stepping from rough concrete onto a patch of ice. The more flat-footed gait on the full ice also reflect this increased instability as smaller heel strike foot angles are associated with more cautious gait (Cham & Redfern, 2002a). There were differences observed between the two non-cleated styles of footwear as the winter boots were associated with the longest slips and highest peak sliding velocities on the full ice level surface while the control footwear demonstrated the highest peak COF for walking down-slope on the icy patch. Differences in footwear characteristics
such as tread, surface contact area and hardness of the winter boot compared to the control footwear should be further examined to determine their contributions to differences in performance.

The sliding velocity and coefficient of friction results should be considered when designing automated methods for assessing the slip resistance of winter footwear. The current standard for measuring the slip resistance of footwear is ASTM F2913-11 which measures coefficient of friction when footwear is moved at a constant velocity over a standard test surface (Wilson, 1990; Wilson, 1996). The standard specifies that footwear shall be tested at fixed angles of 0° and 7° and a constant sliding velocity of 0.03m/s. The foot angles at heel strike observed in this study were in the range of 18° to 24°, far exceeding the standard test angles. These angles are comparable to those observed by Cham and Redfern (2002a) who measured mean foot angles of 23.5° to 26.4° at heel strike on dry vinyl tiles and rough flooring tilted at 0° and 5° and showed that when participants anticipated that the flooring might be slippery, their foot angles reduced by an average of 3.5° to 5.5°. These data indicate that standard tests of slip resistance may be testing footwear at tilt angles that are too low. On rounded edge heels, the smaller standard test angles would not measure slip resistance on the correct area of the footwear making contact at heel strike, which is important for resisting slip initiation. The standard test speed is also lower than the peak instantaneous velocities observed in this study; however, the lower test velocity may be representative of motion in other phases during the gait cycle. It should be noted that there are no standard tests for measuring the slip resistance of cleated footwear, as coefficients of friction are not meaningful in the traditional sense when one surface penetrates through another surface. In this situation, whether the footwear will slide becomes dependent on the interaction between the penetrability of the ground surface, the profile and hardness of the cleat, and the ability of the ground, or in this case ice, to withstand applied shear forces (or ploughing) (Kim & Nagata, 2008). This is reflected in the peak UCOF results that were obtained in this study where UCOF values for Cleat-A were found to be significantly lower than that of all other types of footwear. This may indicate that Cleat-A was unable to penetrate through the ice as well as Cleat-B, thereby reducing the magnitude of shear ploughing force, which is in line with its longer total slip distances.
Because many characteristics of the cleated footwear differed it is difficult to deduce what aspects of the design would be most effective in preventing slips. However, observations from this study indicate that multiple longer spikes closer to the rear of the heel may be optimal. Cleat-A, which had three shorter (1.5mm) spikes at the rear, led on average to higher total slip distances than the cleats with two longer (2.5mm) rear spikes. However, the two longest total slip distances measured across individual trials were both recorded while using Cleat-B which had two longer rear spikes. Cleat-B also demonstrated higher peak sliding velocities on the level full ice than Cleat-A. For Cleat-B, initial contact at heel strike was made on the boots because the anti-slip soles on Cleat-B do not cover the posterior section of the heel and the boots remain exposed. This likely contributed to two long slips and higher peak sliding velocities. Further study of the optimization of length, positioning, number, and profile of cleats are necessary for mitigating slips and understanding the role of cleats in trip and stumble incidents. Forefoot cleat positioning should also be tested further as they are likely to be beneficial for push-off during gait and stabilization if a slip is initiated (Fong et al., 2008).

2.5 Conclusion

This study establishes representative foot kinematics while walking in simulated, challenging winter conditions while wearing a range of winter footwear. The information about foot dynamics during slip and non-slip trials can be used to improve the design and testing of footwear and anti-slip devices.

Cleated footwear or crampons can be a source of discomfort, particularly over long-term use, and this discourages their adoption. However, results from this study indicate that such anti-slip devices should be made available to outdoor workers on days when icy conditions persist, as they reduce the frequency of longer foot slips where recovery is difficult. Of the two styles of crampons utilized in this study, neither performed significantly better than the other, and neither were able to prevent slips entirely. Users should be regularly cautioned that anti-slip devices will not prevent slips altogether and complacency or over-confidence in them may increase the potential for more hazardous slip outcomes.
Results of this study also emphasized the importance of slip resistant winter boots, particularly where icy surfaces are intermittent. Careful selection of winter boots is extremely important but challenging. Comfort, warmth, and water-resistance play major roles in the selection of winter footwear by outdoor workers. These factors can be relatively easy to test. However, boots that appear to have adequate tread may not be effective on all types of surfaces. The boots selected for use in this study performed poorly on wet icy conditions. Better methods for assessing the performance of footwear are necessary and boots should be evaluated in ecologically valid tests with foot angles and velocities being representative of those observed during winter gait.

References


Preface

The following sections of this chapter were submitted along with co-authors Yue Li, Tilak Dutta, and Geoff Fernie to Industrial Health (April 2014). This study builds on the previous, which used a human centred approach to footwear testing by further analysing the biomechanical data collected while walking on ice at a normal walking pace along with additional data obtained while walking at a controlled pace. This work was undertaken to address the ongoing need for test methods that are as valid as biomechanical studies requiring large numbers of participants but more efficient than such studies. Because Study I highlighted the typical current consumer’s prioritization of comfortable, non-cleated winter footwear, the international standard for measuring non-cleated footwear slip resistance was compared to kinematic measures while walking on icy surfaces. This work presents a critique of the current standard method and provides an empirical basis for test parameters that should be used in the development of more ecologically valid test methods. Bench tests on the SATRA STM603 machine were conducted by Yue Li.

Abstract

The standard method for assessing slip resistance of footwear prescribes the vertical load, sliding speed, and foot angle at which footwear shall be tested. However, these mechanical test parameters may not reflect normal gait in winter conditions. In this study, 16 participants used winter boots and smooth rubber-soled footwear to determine vertical load, sliding speed, and foot angle while slipping in simulated winter conditions. Slips occurred while walking in a cold environment on smooth wet ice on a level walkway and while walking down a short slope. Motion capture and force plates were used to measure foot kinematics, ground reaction forces, and utilized coefficient of friction while walking. The 2 types of footwear were also tested according to ASTM2913-11 using the standard test surfaces as
well as an ice surface. The parameters used in standard tests and the output frictional coefficients were compared to those measured during foot slips. The results showed that footwear should be tested at greater than double the angle currently specified, testing at an additional higher sliding velocity is warranted and consideration should be given to testing in cold temperature conditions.

3.1 Introduction

Over 25% of fall-related injuries in older adults result from slips and 66% of fall-related hip fractures occur on surfaces that are wet or slippery (Norton et al., 1997). Slips also contribute to up to 85% of fall-related occupational injuries (Courtney et al., 2013). Foot slippage accounts for 43% of all falls and 16% of all accidents in Nordic countries and snow-related injuries to seniors over age 60 account for 37% of total pedestrian injuries (Lund, 1984).

Low friction at the interface between footwear and the underfoot surface is a major risk factor for slips (Smith & Falk, 1987). Slips can occur when the coefficient of friction (COF) at the interface is insufficient to counteract the forces at the point of contact. During the gait cycle, the most dangerous and frequent slips occur at heel strike, as weight is transferred to the leading foot (Leamon, 1992). Footwear with sole properties that allow for adequate friction at the footwear-surface interface is necessary for preventing slips and falls. As such, various devices have been developed to measure friction at the sole (Chang et al., 2001). The key challenges for such machines are the realistic simulation of gait biomechanics and the simulation of realistic and appropriate underfoot surface conditions (Marpet, 2001).

The current international standard for measuring footwear slip resistance is ASTM F2913-11 (ASTM F2913-11, 2012). Under this method, a piece of test footwear is securely fit over a stiff shoe last (a block of plastic shaped like a foot) and is moved at a constant velocity horizontally against a specified test surface or surface-contaminant combination. The outcome measure of the standard method is dynamic COF (DCOF), measured during relative motion between the footwear and surface. Specifications are provided for measuring DCOF on calibrated quarry tiles or stainless steel tiles that are dry or wetted with distilled water. The standard also recommends that footwear be tested on surfaces and contaminants relevant to the conditions in which they are normally worn. SATRA TM144 provides a guideline for
testing footwear on icy surfaces, but these guidelines have not been accepted into the standard and the standard does not contain specific criteria for preparation of icy surfaces (SATRA TM144, 2011).

Devices used to assess slip resistance simulate only the parameters critical to determining DCOF because it would be very difficult to model human gait perfectly, (Fischer et al., 2009). The critical parameters under which DCOF is measured according to ASTM F2913 are the footwear test angle, horizontal velocity, and applied normal force. DCOF is measured with the footwear angled at 7° ± 0.5° to the horizontal and while flat against the test surface. At these angles, DCOF is measured while the footwear is moved at a constant velocity of 0.3m/s ± 0.03m/s with respect to the test surface. For footwear fitting lasts of size 40 (Paris Points) and above, the footwear is tested using a normal load of 500N ± 25N. For smaller last sizes, 400N ± 20N normal loads are applied. Shear forces in the fore-aft direction are measured using a load cell and DCOF is calculated as the ratio of shear force to normal force at the instant when the critical parameter settings have been met (ASTM F2913-11, 2012).

The parameter settings were established based on slip experiments conducted at the Shoe and Allied Trades Research Association (SATRA) (Perkins, 1977; Perkins & Wilson, 1983). During the experiments, six male participants using a safety harness and identical rubber-soled shoes walked from a non-slippery surface onto a slippery steel surface covered in oil. Although subjects were aware of the slippery surface, they were instructed to walk normally. The length of the walkway and approach to the slippery surface are not described. Although the standard parameters for foot angle, sliding speed, and normal load were informed by the values measured during forward accelerating slips while stepping onto the oiled surface in these experiments, more specific details regarding how the exact parameter values were selected are not described.

Because the standard test was based on a specific level walking task over an oily surface, the validity of this test on ice and snow is not well understood and researchers have been unable to determine threshold values of COF for deeming footwear slip resistant. Before a threshold can be established, it is necessary that the set of gait parameters used for testing winter footwear reflect those observed while walking in winter conditions. The objective of this
study was to measure the foot angles, foot velocities, normal forces, and COF values
demonstrated while walking with winter footwear on icy conditions and to compare them to
those parameters simulated in current standard tests.

3.2 Subjects and Methods

3.2.1 Winter Slips and Falls

This study was approved by the Toronto Rehabilitation Institute Research Ethics Board. A
total of 16 healthy males participated in this study. Their average age (mean ± standard
deviation), height and weight were 34.3 years ± 12.5 years, 175.8cm ± 8.5cm, and 78.8kg
±15.3kg, respectively. Participants walked over icy walkways in ambient temperatures of
3°C while wearing two types of footwear, a men’s winter boot and a smooth pull-on rubber
sole. For warmth, participants wore winter clothing. In order to prevent injury from possible
falls, participants wore a full body safety harness connected to an overhead track.

3.2.2 Footwear

Two types of footwear soles were used to conduct this study: rubber soled winter boots and
the same boots worn with a smooth (treadless) pull-on rubber sole, see Figure 3.1. The men’s
winter boots were ankle-high transitional winter boots (Logan, Baffin, Ontario). The boots
were marketed as transitional indicating that they are more robust than casual footwear but
not to the extent of occupational footwear. The boot midsoles were comprised of ethylene
vinyl acetate (EVA) thermoplastic rubber while the outsoles were rubber and included a
moulded proprietary compound (IcePaw, Baffin, Ontario). The treadless pull-on soles were
devised specifically for this study using the interior, flat, smooth portion of an anti-slip
device, with the anti-slip mechanisms removed. The treadless pull-on sole consisted of a
proprietary rubber compound (Jordan David, Winter Walking ™, Pennsylvania) moulded to
fit securely over boots. All participants were fitted in footwear to the nearest full U.S. size
boot and corresponding treadless soles were selected to fit snuggly over the boot. All test
footwear were cleaned using soap and water and conditioned at 3°C for 30 minutes prior to
testing.
3.2.3 Surfaces and Configurations

Participants were asked to walk over two walkways (level and sloped) which could each be configured with two surface conditions (full ice surface and patch of ice) creating a total of four walkway conditions (Figure 3.2). Each participant tested all 4 walkway conditions while wearing the winter boots both with and without the pull-on soles. Each 3.5m long by 0.75m wide walkway consisted of 5 walkway panels. The level walkway consisted of panels at the same level. Because sloped surfaces increase the propensity to slip (Redfern et al., 2001), a short sloped panel was also used to test each type of footwear. The sloped panel was 0.44m long with a rise-to-run ratio of 1:10 and was flanked on either end by level panels. Panels at either end of the walkways were textured concrete and the centre panel consisted of wetted ice mounted over a force plate. The two panels flanking the centre panel consisted of either wetted ice, forming the full ice condition or of concrete, creating a patch of ice between the concrete panels. Each walkway panel was separated by 2mm gaps. Ice panels were prepared by freezing water in 4cm deep trays. The water was frozen a minimum of 12h at -5°C and the temperature was raised to 3°C two hours before participant testing, and held at 3°C during testing. Prior to testing on each walkway configuration, the ice surfaces were wiped clean and covered with approximately 2mm thick layer of water (0.2mL/cm²).
Figure 3.2. Four test walkway conditions. Participants walked on level and sloped walkways configured as a full ice surface or a patch of ice.

3.2.4 Test Protocol

While wearing each type of footwear, participants were first asked to walk at a self-selected pace starting from one end of the test walkway and stopping at the opposite end, without stepping on the gaps between panels and with only one foot stepping on each of the middle three panels. After stopping at the end of the walkway, participants were instructed to turn around and return to their starting position. Following three laps at a self-selected pace, participants walked for an additional three laps, this time at a controlled pace. Walking cadence was controlled using a metronome set at 100 beats per minute. Because the walkway panels constrained step lengths to approximately 0.75m per step, by walking to the beat of the metronome, participants’ gait velocity was controlled at approximately 1.25m/s. While this is slower than published walking speeds of 1.39m/s ± 0.21m/s in cold weather conditions (Li & Fernie, 2010), speed was constrained by the short length of walkway. Prior to data collection, participants practiced the walking protocol over walkways identical to the level and sloped walkway except that all five panels consisted of concrete. Participants practiced walking until they were able to walk to the beat of the metronome and complete three consecutive laps without stepping on a gap in the walkway both at a self-selected and controlled cadence. For each of the four walkway conditions, participants tested one type of footwear for three laps at a self-selected pace followed by three laps at the controlled pace and then repeated the six laps with the second type of footwear. For each participant, the
order of the walkway conditions was randomized and the order of footwear testing was also randomized for each walkway condition. To reduce exposure to the cold environment, participants took five minute breaks, sitting in room temperature conditions between testing on each subsequent walkway condition. During breaks, participants completed questionnaires indicating whether they had experienced uncontrollable slips while walking in the different footwear on the different test conditions.

3.2.5 Data Collection

A 3D motion tracking system (PTI, British Columbia) was used to track foot movement while walking on the test surfaces. Active LED markers were placed on the top of the footwear over the 1st metatarsal, on the side of the footwear adjacent to the fifth metatarsal, and at the heel to track the point on each foot at the bottom-rear of the heel of each piece of footwear. To measure ground reaction forces, the middle panel of each walkway was rigidly attached to the top of a force platform (BP400600 from AMTI, Massachusetts) sampling at 1000Hz. Kinematic data were synchronized with the force plate data and sampled at 100Hz.

Apart from the biomechanical tests, the DCOF values of the two types of test footwear were evaluated according to the standard procedure for measuring slip resistance ASTM F2913-11 using a SATRA Slip Resistance Testing Machine, SATRA STM603 (Figure 3.3). The pieces of footwear were tested on unwetted (dry) quarry tile, wetted quarry tile, frosted ice, unwetted ice, and wetted ice. Quarry tiles were calibrated in accordance with ASTM F2913-11 and, as per the standard, the wetted condition was created by spraying a thin and continuous layer of distilled water over the tile. SATRA STM603 can also be used for measuring COF on ice surfaces. However, there is no internationally accepted standard test method for testing on ice. The test surfaces were created according to the SATRA guideline for testing on ice using SATRA STM603 (SATRA TM144, 2011). A frost-covered ice test surface was created using distilled water frozen for 2 hours at -7°C in a 19cm x 44cm x 0.5cm deep tray. Cooling elements in the tray froze the water in ambient conditions of 23°C ± 2°C and 37% ± 5% relative humidity. During bench testing, the ice tray was transferred to the test machine with its temperature maintained at -7°C. DCOF values were recorded for the frosted ice surface, the unwetted ice surface beneath the frost layer, and this same surface wetted with water. The single initial run over the virgin frost surface provided the DCOF
value on frosted ice. Subsequent runs were carried out over the same area. The DCOF value for unwetted ice was calculated as the mean DCOF of 5 consecutive runs once a sequence of five runs did not show a systematic increase or decrease of greater than 10%. The same test area was then sprayed with a thin and continuous layer of distilled water. Additional runs were conducted to find the mean DCOF for wetted ice, taking the average of the first five consecutive runs showing no systematic increase or decrease greater than 10%.

For each piece of footwear, all 5 surfaces were tested in 2 test modes: forward heel slip and forward flat slip. These tests simulate slips in the anterior direction which are more likely to result in falls than slips in the posterior direction which largely occur at the forefoot during toe-off (Redfern et al., 2001). For both test modes the footwear was dragged forward relative to the test surface. For testing at the heel, the heel of the footwear was tilted downwards at 7.0° ± 0.5°, and for flat testing, the sole was placed flat against the test surface. A new ice surface was created in each test mode for each individual piece of footwear. The soles of each piece of test footwear were conditioned for 3 hours prior to testing on ice in a -5°C water-alcohol solution.

Figure 3.3. ASTM standard footwear slip resistance test machine, SATRA STM603.

All pieces of footwear used in bench testing were new and cleaned using soap and water. The uppers of the winter boots were trimmed for mounting to the test machine and the pull-on soles were put over the winter boots for testing. One size 9 (US) winter boot fitting a last size of 39 was tested using 400N vertical loads with and without a pull-on rubber sole (size large)
and one size 11 (US) winter boot fitting a last size of 42 was tested using \(500\text{N}\) vertical loads with and without a pull-on rubber sole (size extra-large).

### 3.2.6 Data Analysis

During biomechanical tests, motion data and ground reaction forces were analyzed for 3 steps on the centre walkway panel on the level and down-slope walkways. Force and motion data were filtered using zero-lag, fourth order, dual-pass Butterworth filters with motion data filtered using a cutoff frequency of 6Hz and force data filtered at a cutoff frequency of 45Hz.

The steps which resulted in forward slips of the foot were further analyzed to compare their characteristics to characteristics of the forward slips simulated by the standard test device. Forward slips were identified as those resulting in positive forward acceleration of the heel after heel strike. These slips were also checked for agreement with the instances of slips indicated by participants in their questionnaire responses. For all forward slips, foot angle, foot speed, normal force, and utilized COF were analyzed from the time of heel strike to the end of the slips. Foot angle was calculated as the angle between the walkway surface to a line connecting the toe and heel of the footwear. Foot speed was calculated as the instantaneous forward velocity of the heel. Normal force was the component of the vertical force perpendicular to the walkway surface measured by the force plate. UCOF was calculated as the ratio of the resultant shear forces in the forward and medial-lateral directions along the walkway plane to the normal force applied. For the purposes of discussion each slip characteristic (angle, speed, normal force, and UCOF) was compared to its analogous standard parameter at five key time-points over each slip. These time points were heel strike, slip onset (slip-start), mid-slip, and peak slip velocity (peak sliding heel velocity), as described by Lockhart et al. (2003) and slip end, defined as the point when forward foot and acceleration go to zero following peak slip velocity. Slip onset was defined as the point when positive forward acceleration following heel contact occurred. Mid-slip was defined as the point of maximum heel acceleration following slip-onset. Peak sliding velocity was defined as the point when maximum forward heel velocity occurred following slip onset.

General linear mixed models with subject as a random effect were used to determine the effects of footwear (winter boot or smooth rubber sole), surface (full ice surface or patch of
ice), slope (level or down-slope), cadence (self-selected or controlled), footwear size (less than 11 or greater than or equal to 11) and slip phase (heel strike, slip onset, mid-slip, peak slip velocity, or slip end) on foot angle, sliding speed, normal force, and COF. Non-significant main effects were collapsed for further analyses when comparing the gait variables to their standard analogues. Survey means t-tests that took into account correlations within subjects were used to compare differences between the mean kinematic and kinetic measures recorded while walking on the icy surfaces to the parameters used in and produced by standard bench-tests. For foot angle, sliding speed, and normal force, two one-tailed t-tests were used to compare the mean values measured during gait to the allowable test parameters individually. The one-tailed t-tests showed whether the values measured during gait were either less than the lower limit or greater than the upper limit of the test parameters. Two-tailed t-tests were used to compare the mean UCOF measured during gait to the DCOF measured using SATRA STM603. For all analyses, the criteria for statistical significance was set at $p<.05$.

During participant-based testing, 10 participants were fitted to smaller winter boot sizes (US men’s size 7-10) and 6 participants were fitted to larger sizes (US men’s size 11-13). Smaller sizes were assessed in the standard test using a size 9 boot fitting a size 40 shoe last while the larger sizes were assessed using a size 11 boot that fit a last size of 42. Thus, for slips from participants who used the smaller sized footwear, normal forces were compared to a 400N ± 20N load and UCOF were compared to standard DCOF values measured at this lower load. Slips measured from participants who used the larger sized footwear were compared to 500N ± 25N normal load and standard DCOF values measured at this higher load.

### 3.3 Results

A total of 523 steps with complete data sets were analyzed. Of those, 325 resulted in forward acceleration of the foot following heel strike and these slips were utilized in further analyses. In this experiment, all slips resulted in slip recoveries and no falls occurred. The slip frequency and mean slip distances (calculated as the total displacement of the heel from heel strike to slip end) for each combination of test conditions are shown in Table 3.1. For each
size-cadence-footwear-slope-surface combination, from 4 to 18 slips were analyzed and these slips ranged in slip distance from 5mm to 20mm.

Table 3.1. Frequency (n) of forward accelerating slips out of total number of steps (nT) and associated slip distances by test condition. Slip distances, presented in mm, were calculated as the total displacement of the heel from heel strike to slip end. In each category, 4 to 18 forward accelerating slips were analyzed. These slips were in the range of 5mm to 20mm.

<table>
<thead>
<tr>
<th>Self-Selected Pace</th>
<th>Smaller Boot Size</th>
<th>Larger Boot Size</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Level</td>
<td>Down-Slope</td>
</tr>
<tr>
<td></td>
<td>n/nT mean(SD)</td>
<td>n/nT mean(SD)</td>
</tr>
<tr>
<td>Smooth Sole</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Full Ice Patch</td>
<td>13/24 12.9(8.5)</td>
<td>10/16 10.5(5.2)</td>
</tr>
<tr>
<td></td>
<td>13/26 5.3(4.3)</td>
<td>14/20 6.1(5.6)</td>
</tr>
<tr>
<td>Winter Boot</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Full Ice Patch</td>
<td>12/17 7.2(2.7)</td>
<td>11/15 9.5(3.7)</td>
</tr>
<tr>
<td></td>
<td>14/27 8.0(8.8)</td>
<td>10/21 9.9(5.7)</td>
</tr>
<tr>
<td>Controlled Pace</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Smooth Sole</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Full Ice Patch</td>
<td>12/20 13.7(9.2)</td>
<td>18/18 9.4(7.5)</td>
</tr>
<tr>
<td></td>
<td>9/25 4.2(2.5)</td>
<td>13/18 10.4(8.9)</td>
</tr>
<tr>
<td>Winter Boot</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Full Ice Patch</td>
<td>9/18 11.0(6.2)</td>
<td>13/19 11.2(6.9)</td>
</tr>
<tr>
<td></td>
<td>10/27 9.2(7.6)</td>
<td>13/22 5.5(2.2)</td>
</tr>
</tbody>
</table>

Figure 3.4. DCOF results measured from bench tests using SATRA STM603.
Results from bench tests using SATRA STM603 are shown in Figure 3.4 for the two types of test footwear at the two applicable test loads on dry and wet quarry tile, frosted, smooth, and wet ice. DCOF values greater than 1 indicate that the shear forces generated during the drag test were greater than the applied normal force.

The linear mixed model analysis of foot angle indicated that main effects of footwear and footwear size were not significant and as such, footwear and footwear size were collapsed for comparing foot angle during gait to the standard footwear test angle of 7.0° ± 0.5°. Results of the one-tailed t-tests comparing the biomechanical and standard foot angles are shown in Figure 3.5.

Figure 3.5. Differences between foot angles during gait and the standard footwear test angle. Asterisks (*) indicate significant differences from the ASTM testing standard of 7.0° ± 0.5°.
Horizontal foot speed was analyzed at heel strike, slip onset, mid slip, and peak slip velocity. Foot speed at slip end was not analyzed as it is defined by foot speed reaching zero following slip onset. The linear mixed model indicated that the main effects of footwear and footwear size were not significant for foot speed and were collapsed when comparing foot speed during gait to the allowable range prescribed by the standard (0.3m/s ± 0.03m/s). Significant differences between the standard speed and that during gait, obtained through one-tailed t-tests, are shown in Figure 3.6.

![Foot Speed Diagram](image)

Figure 3.6. Differences between sliding speed of the stepping foot during gait and the standard footwear test speed. Asterisks (*) indicate significant differences from the ASTM testing standard of 0.3m/s ± 0.03m/s.

The loads applied normal to the stepping surface were analyzed from slip onset through slip end. Heel strike is defined by a threshold normal force of 10N and was therefore not analyzed. The main effects of footwear, surface, slope, cadence, and footwear size were all...
significant for normal force according to the linear mixed model. Figure 3.7 shows the results of one-tailed t-tests to determine differences between the applied normal force during slips and the vertical loads used in standard tests of footwear slip resistance (400N ± 20N and 500N ± 25N) for all test conditions.

Figure 3.7. Differences between the normal force applied by the stepping foot to the walking surface and the standard normal forces used to test footwear slip resistance. Asterisks (*) indicate significant differences from the ASTM testing standard of 400N ± 20N and 500N ± 25N.
Figure 3.8. UCOF (shown as bars) compared to mean DCOF results from bench-tests (shown as lines) measured on wetted and unwetted ice in the heel and flat footwear test modes. For clarity, non-significant differences between UCOF and DCOF are indicated on the applicable test surface DCOF curves (‘o’).

As with normal force, UCOF during slips was also analyzed from slip onset through slip end. The UCOF ratio is not meaningful at heel strike as the applied shear force and normal forces are minimal with weight transfer to the stepping foot negligible. The mixed model indicated that the main effects of footwear, surface, slope, cadence, and footwear size were all significant for UCOF. DCOF results from bench tests of the two types of footwear on the wetted and unwetted ice surfaces were most similar to the UCOF values collected. The
frosted ice and quarry tile DCOF values were far greater than the range of UCOF values observed. Comparisons between the wetted and unwetted ice surface DCOF values from both heel and flat tests and UCOF during slips for all test conditions are shown in Figure 3.8 (for clarity, non-significant differences have been marked in this figure).

### 3.4 Discussion

The slips analysed in this study were relatively small slips and did not lead to falls. The mean slip distances, shown in Table 1, were in the range of 5mm to 20mm. Slip distances in this range have been categorized in some studies as micro-slips and are considered to not necessarily be perceptible to the individual (McGorry et al., 2007). However, each of the slips included for analysis in this study was also characterized by positive forward acceleration, which standard test devices were originally designed to replicate (Perkins & Wilson, 1983). The slips were also roughly corroborated by participant questionnaire responses indicating perceived slips, defined to the participants as uncontrolled or unintentional motion of the foot following heel strike. Participants did not indicate perceived slips for each step, but rather over the full 3 laps for each test case. Regardless of whether each slip was perceived by the individual, understanding the gait mechanics for these steps is important in that they reflect how the two types of footwear are used in a variety of conditions, and therefore how they should be tested when determining slip resistance.

The small slip distances observed in this study were also related to the participants’ ability to anticipate the slippery ice surfaces they were walking on. Cham and Redfern (2002a) reported that when anticipating a potentially slippery, oiled surface, foot-floor angles reduce by 11-27%, forward slip velocity decreases by 14-19%, loading rate onto the stepping foot is reduced and peak UCOF is reduced by 16-33%. This study simulates real-world conditions in which pedestrians are aware of slippery conditions underfoot. A limitation of this study is that it does not simulate the higher risk case when pedestrians are not aware of slip hazards underfoot, such as black ice conditions, which can lead to larger slips that are more likely to lead to falls (Cham & Redfern, 2002b).
3.4.1 Bench Testing

The DCOF values measured using SATRA STM603 indicate that the surfaces used for testing critically affected the test outcomes (Figure 3.4). Calibrated surfaces, such as quarry tile or stainless steel, are recommended for testing so that consumers can see data comparing different footwear relative to the same test surface. However, better results (higher DCOF values) on the calibrated test surfaces do not necessarily translate to better results on the actual surfaces on which the footwear is meant to be used. For example, Figure 3.4 indicates that DCOF values measured on the dry and wet quarry tiles are higher for the smooth rubber sole than for the winter boot. However, the superiority of the smooth rubber sole is not shown in the DCOF values on the frosted or unwetted ice surfaces.

ASTM F2913-11 does suggest that footwear be tested using surfaces and contaminants that the footwear is expected to be exposed to. However, all of these tests were conducted at room temperature, as dictated by the standard. Winter surfaces cannot be accurately simulated at room temperature despite the ability to continuously cool the ice tray and the ability to pre-condition test footwear. It should also be noted that due to limitations of the testing environment, preparation of the ice tray and footwear conditioning were conducted in ambient conditions of 37% ± 5% relative humidity which is lower than the 50% ± 5% RH prescribed in the standard. This difference is likely to have minimal impact on the test results as local relative humidity in all tests vary when the footwear is conditioned in a water-alcohol bath and when water is sprayed over the test surfaces.

As expected, the DCOF results were fairly consistent for the two load conditions with neither load condition indicating a systematic tendency to affect the results. Larger differences in the load conditions were observed for two of the test cases. The winter boot on unwetted ice in the flat test mode with the 400N load produced a DCOF that was 0.18 higher than that with the 500N load. The smooth rubber sole in the heel test mode with the 500N load produced at DCOF that was 0.22 higher than that with the 400N load.

DCOF values obtained in the flat test mode were generally higher than those obtained in the heel tests. This result agrees with the unified theory of rubber adhesion as the larger surface contact area engaged during flat testing should increase adhesion in comparison to the small
area of contact at the heel when the footwear is tilted $7.0^\circ \pm 0.5^\circ$ (Kim & Nagata, 2008). Exceptions to this result were observed for the winter boots on unwetted ice at 500N and for the smooth rubber sole on wetted ice at 400N. It is not clear what contributed to the anomalous loading and test mode results.

### 3.4.2 Foot Angle

The foot angles measured in this study were comparable to previous studies conducted on slippery surfaces. Cham and Redfern (2002a) reported heel strike foot-floor angles when anticipating slippery conditions of approximately $20.0^\circ$ when walking on level ground and $20.9^\circ$ while descending a $5^\circ$ slope. In this study, the average foot angle across all conditions was $20.6^\circ \pm 1.2^\circ$ at heel strike and $14.8^\circ \pm 1.1^\circ$ at the onset of slips. The heel strike angles observed were nearly three times that prescribed in the standard and slip onset angles were more than double the standard parameter. To prevent slips, it is important that footwear be slip resistant from the instant of heel strike, as this is when dangerous slips begin to propagate. It is therefore important that footwear be tested at the angles of these earliest slip phases, particularly at slip onset, at which point the normal force analysis revealed that approximately 307N of force, or equivalently 39% of body weight, had been loaded onto the stepping foot.

The importance of accurately simulating foot angles for testing was studied by Grönqvist et al. (1995). They showed that the design of the back edge of the heel greatly affects slip resistance when COF was measured using a portable step simulator device. Sharp or square-edged heels were found to be the most dangerous and more sensitive to changes in the foot angles used for testing than bevelled edge designs. Beschorner et al. (2007) further illustrated the importance of accurately simulating foot angles by measuring COF between footwear and flooring conditions using a six degree of freedom manipulator and increasing test foot angles and normal loads. The relationship between COF and applied normal force was shown to change when foot angles were increased to $10^\circ$ and to $20^\circ$.

Although the mixed model showed differences in foot angles resulting from differences in test surfaces slopes and cadence, significant differences between the angles observed during gait and that specified for standard testing were consistent across all conditions, as shown in
Figure 3.5. While walking at a self-selected pace, for all conditions the foot angles observed at mid-slip are significantly higher than those prescribed for the standard tests while the observed angles at peak slip velocity and slip end are within the range of 7.0° ± 0.5°. While slipping in the controlled cadence condition, foot angles are slightly lower than those at self-selected paces and are within the specified test range from mid-slip to slip end.

A limitation of the standard test is that footwear is tested while moving only in the fore-aft direction, with the footwear aligned for testing in this direction and tilted at a pitch angle relative to the direction of motion. This test therefore does not account for foot pronation or supination or abducted or adducted gait. Furthermore, because motion is constrained in the anterior-posterior direction, applied medial-lateral forces during normal gait are not incorporated into standard DCOF testing.

3.4.3 Sliding Speed

Friction is dependent on the relative sliding speed of the two surfaces for compressible solids such as rubbers and in the presence of contaminants (Bowden, 1953; Perkins & Wilson, 1983). Almost all of the foot speeds observed in this study lay significantly outside of the range of values specified for standard testing (Figure 3.6). For a self-selected pace, at heel strike on the level walkway in the full ice surface and on the down-sloped walkway on both the full ice and ice patch, foot speed was within 0.3m/s ± 0.03m/s. For all other conditions, foot speed was higher than the prescribed range at heel strike but lower than the prescribed range from slip onset through peak sliding velocity. These results suggest that footwear could be tested at two speeds: a higher speed simulating heel strike and a lower speed simulating foot motion during slips. In the development of the standard method, Perkins and Wilson (1983) also suggested that slip resistance testing be conducted at two speeds as contaminant penetration, and therefore friction, is speed dependent.

A limitation of the study was that participants did not reach steady state walking speed and walking speeds were below those normal for real-world cold weather walking (Li & Fernie, 2010). The current standard speed may be warranted for simulating steady state conditions and situations in which slips are not anticipated, such as black ice. Results of this study suggest that the higher test speed for simulating movement at heel strike should be at or
above the range of 0.48m/s ± 0.06m/s. Hunwin et al. (2010) varied the relative sliding speed between wetted steel and a standard rubber slider (slider 96) tilted at 7° to determine the impact of sliding speed on COF. They also recommended increasing test sliding speeds to 0.5m/s and showed that COF was constant from 0.1m/s to 0.3m/s and decreased linearly from 0.3m/s to 0.5m/s. This suggests that all other parameters being equal, increasing the standard sliding speed to the ranges observed in our study might decrease the output DCOF values. An increase in DCOF could bring measures on unwetted ice closer to the human-based UCOF values observed but would increase the differences between DCOF and UCOF on wetted ice.

### 3.4.4 Normal Force

The normal forces observed over the course of the slips is in general within the specified ranges used in standard testing. In nearly all cases, the applied loads during slips at the self-selected pace are lower than those at the faster controlled pace. This is in agreement with past findings that the body’s centre of mass moves anteriorly with increasing walking speed (Bhatt et al., 2005). As shown in Figure 3.7, for the smaller sized footwear, loading at the controlled pace tended to be higher than 400N ± 20N and for the larger footwear, there was a tendency at self-selected cadences for the applied normal force to be lower than 500N ± 25N. As such, at the self-selected pace, the standard loads were significantly higher than the observed loads, whereas at the controlled pace the standard load tended to be lower than the observed loads. The results indicate that it may only be necessary to test men’s US sizes 7 to 13 at a single load condition because the DCOF results at these two load conditions were relatively consistent and the forces appear to be a compromise between higher load and lower load conditions.

It should be noted that while the normal forces used to measure DCOF were relatively similar to the loads applied to the men’s footwear by the healthy young males who participated in this study, these loads are likely higher than that which would be applicable for use in ladies’ footwear or in footwear for children. Hunwin et al. (2010) and Adam and Piotrowski (2012) studied how DCOF was affected by increasing normal loads applied to rubber sliders tilted at 7°. Hunwin et al. (2010) found that COF increased linearly for increasing normal loads from 150N to 500N, when a standard rubber slider (slider 96) moved
at 0.5m/s on wetted quarry steel. Conversely, Adam and Piotrowski found that DCOF decreased linearly for increasing normal loads from 200N to 900N, when a variety of rubber sliders moved at the standard speed of 0.3m/s ± 0.03m/s on wetted quarry tile. Further examination of the effects of changing normal load on the DCOF on ice is necessary before changes to standard load conditions can be recommended.

3.4.5 Coefficient of Friction

In most cases UCOF decreased following slip onset. Figure 3.8 shows that UCOF values were not comparable to the DCOF values measured on any of the standard test surfaces. For the smaller footwear using the 400N load, only testing of the smooth rubber sole in the flat test mode was able to produce results similar to the UCOF measured from mid-slip to slip end. In general, the larger footwear using the 500N loads produced DCOF values more similar to those observed during gait. Flat mode tests of the winter boot showed the most similarities to the UCOF in the winter boot. For the smooth rubber sole, the wetted ice DCOF values were comparable to down-slope UCOF values and heel mode tests on unwetted ice produced the most comparable results to level UCOF values. Beyond difference in foot angle, sliding speed, sliding direction, and loading, a major contributor to the differences in DCOF values in comparison to UCOF values should be attributed to differences in the simulated test conditions.

3.4.6 Testing Environment

A major limitation of the standard method is the specification that all tests, including testing on ice be conducted at room temperature conditions. At room temperature, effects of pre-conditioning rapidly deteriorate during testing after the footwear is removed from the cooling bath and relevant ice conditions cannot be simulated or maintained. For valid testing of winter footwear, surfaces must simulate actual conditions which develop in winter environments and testing in cold-temperature conditions would solve many of the issues related to simulation and maintenance of appropriate test conditions.
3.5 Conclusion

This study illustrated many shortcomings of the current standard method in its ability to test the slip resistance of winter footwear. The standard tilt angle for testing footwear is too small to simulate foot angles at heel strike and throughout slips, higher sliding speeds should be included during slip testing. Also, the environmental conditions used for winter footwear testing should better replicate actual winter climates. We believe footwear should be tested at tilt angles of at least 14°, at sliding speeds of 0.5m/s in addition to the current test speed, and that pre-conditioning and testing should be carried out a subzero temperatures.

References


Chapter 4
Study III: Assessing the Performance of Winter Footwear Using a New Maximum Achievable Incline Method

Preface

The following sections of this chapter were submitted along with co-authors Yue Li, Tilak Dutta, and Geoff Fernie to Applied Ergonomics (April 2014). The previous chapter details inadequacies in the current standard method for measuring slip resistance of winter footwear, namely that the parameters used for testing do not reflect those observed while walking in winter conditions. As a result of those shortcomings, a new test method with improved ecological validity was developed for assessing the slip resistance of winter footwear. This chapter discusses a new human-centred approach and results of this new approach when applied to a range of winter footwear. The original concept for the new test method was developed by Geoff Fernie who was also responsible for the design and construction of WinterLab. Bench tests on the SATRA STM603 machine were conducted by Yue Li.

Abstract

More informative tests of winter footwear performance are required in order to identify footwear that will prevent injurious slips and falls on icy conditions. In this study, eight participants tested four styles of winter boots on smooth wet ice. The surface was progressively tilted to create increasing longitudinal slopes and cross-slopes until participants could no longer continue standing or walking. Maximum achievable incline angles provided consistent measures of footwear slip resistance and demonstrated better resolution than mechanical tests. One footwear outsole material and tread combination outperformed the others on wet ice and allowed participants to successfully walk on steep longitudinal slopes of $17.5^\circ \pm 1.9^\circ$ (mean $\pm$ SD). Gait characteristics on level and near failure angles were also analysed. By further exploiting the methodology to include additional surfaces and contaminants, such tests could be used to optimize tread designs and materials that are ideal for reducing the risk of slips and falls.
4.1 Introduction

Slips and falls are one of the most prevalent and injurious types of accidents on-the-job and in public spaces. The direct cost of falls in the United States is estimated at $30 billion per year (Stevens, et al., 2006). 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 (Lund, 1984) with ice and snow contributing to two-thirds of outdoor pedestrian injuries (Rolfsman et al., 2012). Medical care costs of slipping injuries are also 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). Slip resistance is generally measured as the coefficient of friction (COF) between the footwear sole and underfoot surface as slips occur when the COF is lower than that required for the momentary intended activity (Grönnqvist et al., 2001). During gait, the COF underfoot can be measured using force plates as the ratio of the applied shear force to the applied normal force over the ground surface (Redfern et al., 2001). This ratio represents the friction that is utilized. The maximum utilized friction during normal gait is often referred to as the required COF (Chang, 2012). Slips are more likely to occur when the required COF exceeds that which is available at the footwear-surface interface. Therefore, the measure that most critically determines whether slips can be resisted is the available COF and methods that are used to assess footwear slip resistance attempt to estimate the available COF.

The major challenge in the assessment of footwear slip resistance is that the measurement of available COF is not straightforward (Chang et al., 2001). The COF available at any given instant is dependent on the contact surface area and characteristics of the interface (including the adhesional and hysteretic properties of the footwear sole), the applied forces, and moving speed. Contaminants at the interface further increase the complexity in estimating the available COF as it is further affected by properties of the contaminant layer such as its viscosity and thickness (Grönnqvist, 1995). The output validity of mechanical methods for estimating available COF therefore depends on its ability to simulate human gait over appropriate test surfaces (Chang et al., 2001b).
According to current international standards for testing footwear slip resistance (ASTM F2913-11 and ISO 13287:2013), pieces of footwear are rigidly mounted to a test rig and COF is determined as the ratio of horizontal to normal load measured using load cells while dragging the footwear sole across standardized test surfaces such as quarry tile or stainless steel. Test specifications for foot angles, sliding velocities, and normal loads are meant to reproduce those observed during normal gait (Wilson, 1990). It is understood that larger output COF (i.e. greater available COF) values are indicative of greater footwear slip resistance. However, there are major limitations to this method and there remains no standard threshold COF criteria for labelling footwear as slip resistant (Grönqvist et al., 2001).

One important limitation of the mechanical method is how well the specified mechanical test parameters reflect the range of gait characteristics of actual users, which vary with factors such as age, sex, and weight (Chumanov et al., 2008; Lockhart et al., 2005; Wu et al., 2012). These parameters also vary when walking in slippery conditions, transitioning between high and low friction areas, or on different terrain such as slopes, cross-slopes, and uneven surfaces (Bunternchit et al., 2000; Dixon & Pearsall, 2010; Heiden, Sanderson et al., 2005; McVay & Redfern, 1994). Types of activity, such as walking, running, turning, or load carrying, also affect the COF required to resist slips (Cham & Redfern, 2001; Chiou et al., 2003).

Standard tests are further limited by how accurately the surfaces over which the pieces of footwear are tested reflect the surfaces on which they are intended or actually used. The standardized test surfaces described in the current standard test methods (ASTM F2913-11 and ISO 13287:2013) do not include any winter surfaces or contaminants such as snow or ice. Therefore, the ability of the standard tests to reflect slip resistance in winter conditions is particularly poor. It is however, possible to fit standard test rigs with winter surfaces. For example, a frosted ice surface can be used in conjunction with the SATRA STM 603 Slip Resistance Testing machine. The caveats to using such a surface are the repeatability of such tests and that the winter conditions they represent have yet to be established. Also, these testing methods have not been accepted into standard guidelines.
The difficulty of producing and maintaining consistent winter test conditions is why few have studied footwear slip resistance or gait biomechanics on actual winter surfaces. Gao et al. (2008) used a short, 2.7m ice walkway inclined at 0°, 6°, and 8° to compare lower extremity muscle activity during gait on ice at -10°C to gait on a reference, non-icy ramp. In studies of footwear slip-resistance, Gao et al. conducted experiments using a stationary mechanical portable step simulator device on surfaces including ice to show the effects of abrasion, sole material, hardness, and roughness on relative COF for a variety of footwear (Gao et al., 2003; Gao et al., 2004; Gao et al., 2008). Bruce et al. (1986) measured the COF of winter anti-slip devices by attaching subjects in series to a load cell and a winch that dragged the subjects across a hockey rink. More commonly, evaluations of winter footwear performance have utilized subjective ratings of slipperiness. In these studies, participants or observers rank different types of footwear while participants use them on outdoor winter surfaces (Gao & Abeysekera, 2002; Gard & Lundborg, 2000).

Outside of winter testing, adjustable inclined surfaces have been used in the past to determine the slip resistance of footwear and/or flooring materials. Although testing is carried out on sloped surfaces, the underlying assumption is that the relative differences in slip resistance will translate to walking on level ground. The maximum slope angles on which subjects are able to step, typically facing downhill, without slipping is used to assess slip resistance of the footwear-surface combinations. The tangents of the maximum slope angles are used as estimates of the available COF (James, 1999; Brungraber et al., 2003). These tests have the advantage of providing objective outcomes and have improved validity by involving actual users, who often prefer direct walking tests (James, 1999). Ramps used in these tests have traditionally been small in scale, with subjects taking only a few steps or walking with an unnatural gait such as shuffling with small steps forwards and backwards or stepping in place (Jung & Schenk, 1990; Skiba et al., 1986). Test surfaces on these ramps often consist of indoor industrial floors covered with contaminants such as water, oil, and soap (Brungraber et al., 2003). To the authors’ knowledge, there have been no published works involving a large-scale adjustable ramp that allows for sustained walking on winter test conditions.

In order for footwear designers and manufacturers to optimize the slip resistant properties of winter footwear and appropriately inform consumers of footwear performance, it is
imperative that methods of footwear assessment be relevant and reliable. The primary objective of this study was to use the maximum incline angle that participants were able to maintain balance while standing and walking in order to assess the slip resistance of a range of footwear on ice. This human-centred method reflects not only the properties of the footwear but also the interaction between the user, the footwear, and the test conditions. The secondary objective was to determine how participants adjusted their normal gait in response to the footwear and the icy sloped surfaces. Additionally, results of this new method were compared to those of the current standard mechanical test (ASTM F2913) using an ice tray attachment.

4.2 Methods

4.2.1 Participants

A convenience sample of eight young, healthy males took part in this study. Only participants between 20 and 45 years of age who had lived in a winter-experiencing climate for at least one winter season and reported routinely walking outdoors in the winter were included in this study. The participants in this study averaged 18.5 ± 11.8 years spent living in winter-experiencing regions. Participants were 31.6 ± 8.1 years of age (mean ± SD), 179cm ± 7cm in height, and weighed 80.2kg ± 15.4kg. Participants were fitted to the closest full size footwear and tested a range of U.S. men’s sizes from size 9 to 12. Subjects who self-reported cardiovascular conditions that could be affected by cold exposure, an inability to sustain 30 consecutive minutes of ambulation, or the use of medication that could affect balance were excluded from the study. Each subject provided signed informed consent to participate in this study as approved by the Research Ethics Board of the Toronto Rehabilitation Institute–University Health Network.

4.2.2 Footwear

Participants in this study tested the performance of four styles of men’s winter boots with different outsole designs (Figure 4.1). The four styles of test footwear are described as follows:
- Style B: boot with proprietary IcePaw design embedded in rubber (upper and outsole: Baffin, Ontario, Canada);
- Styles, N, G, and J consisted of identical uppers (uppers: Dakota, Mark’s®, Alberta, Canada);
- Styles N and G had identical tread patterns composed of different materials;
- Style N: NCI rubber compound outsole (outsole material: Dakota, Mark’s®, Alberta, Canada);
- Style G: Green Diamond outsole technology consisting of aluminium oxide and silicon carbide granules embedded in rubber (outsole material: Green Diamond Tire, Colorado, USA);
- Style J: JStep proprietary rubber compound outsole embedded with glass fibres that protruded approximately 10μm (outsole material: JStep Sole, Gimhae, Republic of Korea).

Figure 4.1. Test footwear. From left to right: Boot B, Boot N, Boot G, and Boot J.

Prior to testing, all pieces of test footwear were worn by volunteers equipped with pedometers for approximately 1000 steps per piece of footwear. The footwear were worn indoors in an office environment on carpet and vinyl tile in order to naturally remove any mould release agent and provide an initial level of wear. Soap and water were used to clean the soles prior to all participant and bench tests.
4.2.3 Bench Friction Testing

Each type of footwear was tested on a SATRA STM 603 test machine (SATRA Technology Centre, Northamptonshire, UK), calibrated to the standard for testing footwear slip resistance ASTM F2913-11 (ASTM F2913-11, 2012). The SATRA COF of each type of footwear was measured at the heel and forepart of the soles according to established standard methods. According to the standard method, the test footwear applies a vertical force of 400N to 500N (depending on the footwear size) to the test surface and is then moved horizontally relative to the surface at 0.3m/s. Load cells measure the resulting horizontal and vertical forces during constant velocity and the SATRA COF that is output is the ratio of horizontal to vertical force. The heel and foreparts of the sole were tested by tilting the footwear 7° with the heel lower and the toe lower, respectively. To test the heel, the footwear slid anteriorly with respect to the test surface to simulate heel slips and for forepart testing, the toe slid posteriorly relative to the test surface to simulate toe slips.

All test parameters were set and carried out according to those specified in ASTM F2913-11. The only aspect of the bench tests that was outside the specifications of the ASTM standard was the preparation of the winter test surfaces because there are no internationally accepted standards for doing so. Preparation of ice surfaces was conducted according to an alternate source, SATRA TM144 (SATRA TM144, 2011). The TM144 guidelines were developed specifically for preparing ice trays to be used in conjunction with the SATRA STM 603 test machine. A 19cm x 44cm x 0.5cm deep tray was filled with water and attached to cooling elements forming ice with a thin top layer of frost. The ice was cooled to -7°C at ambient testing temperatures of 23°C ± 2°C. Throughout testing, the ice was continuously cooled at -7°C. SATRA COF values were recorded for the frosted surface, the unwetted ice surface immediately below the frost, and then after wetting the ice surface (Figure 4.2). The initial test run yielded a COF value on frosted ice. With subsequent runs over the same area, the footwear penetrated through the frost and a mean COF value for the unwetted ice surface below was recorded over five consecutive runs once a sequence of five runs did not show a systematic increase or decrease of greater than 10%. To more closely simulate smooth wet ice, a thin and continuous layer of water was applied over the ice using a spray bottle and tests were run again to find the mean of five consecutive trials once the five trials showed no systematic change of
greater than 10%. The boot soles were preconditioned to -5°C in an alcohol solution for three hours prior to testing. All the SATRA tests were performed after the participant trials had been completed using the same footwear.

Figure 4.2. Ice surfaces tested using SATRA STM 603. From left to right: frosted ice surface, unwetted ice surface, and wetted ice surface.

4.2.4 Human-Centred Test Conditions

Participant testing was conducted in WinterLab at the Toronto Rehabilitation Institute’s Challenging Environment Assessment Laboratories. WinterLab is a self-contained laboratory with a 4.5m by 4.6m ice floor. Participants were asked to walk 5.5m across its diagonal. The test walkway surface consisted of smooth wet ice. Ice was created by freezing water and maintaining the ice temperature at -0.5°C ± 0.5°C using glycol tubes below the ice surface (Figure 4.3). 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 one 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 and no special preparations of the surface were required between trials. The COF of the ice floor was measured according to ASTM F2508 using a Neolite pad on the English XL Variable Incidence Tribometer (ASTM F2508, 2013). The ice conditions were measured before and after each test session and the average COF across all readings was 0.08 ± 0.05. WinterLab was mounted to a hydraulic-powered motion base which could tilt the entire floor surface in any direction to create sloped conditions. In this experiment, the laboratory was tilted to a maximum slope of 20° (Figure 4.3).
An active-marker motion tracking system (Phoenix Technologies Inc., British Columbia, Canada) was used to identify the positions of three tracking markers attached to each piece of footwear. Tracking markers were placed over the first metatarsals, lateral to the fifth metatarsals and at the rear of the footwear above the calcanei. These markers were used to calculate the positions of virtual heel markers at the posterior centres of the footwear soles and virtual toe markers at the anterior centres of the sole so as to estimate the points of initial contact at heel strike and the final point of contact at toe off, respectively. All kinematic data were collected at 100Hz and filtered using a fourth-order, zero-lag, low-pass Butterworth filter with a 6Hz cutoff frequency.

![Image](image-url)

**Figure 4.3.** WinterLab. The smooth, wet ice surface used for testing (left) and tilting of the laboratory to create sloped conditions (right).

### 4.2.5 Test Protocol

Prior to testing in WinterLab, participants completed questionnaires indicating the number of days and length of time they typically spend outdoors per week during winter, winter sports that they take part in, whether they had fallen in the past two years, whether they had any experience using the test footwear prior to participating in the study, and which foot they would normally kick a ball with (to determine their dominant foot). Once the questionnaire was complete, participants were fitted with typical winter garments including winter coats as well as a full-body safety harness. Inside WinterLab, the harness was attached to a fall-arrest system connected to a robotic overhead gantry that automatically followed the position of the participant to stay directly above them. A controlled-descent line, balanced at 2kg, prevented injury from falls by allowing a maximum downward velocity of 0.7m/s.
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 five seconds at each full degree, until both of the participants’ feet began to slide simultaneously. This test was conducted in four slope directions, in random order, with the participant facing downhill, uphill, with their left-side-higher, and their right-side-higher (Figure 4.4). 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. The lowest maximum slope achieved in any slope direction during the standing tests were considered the critical angles and were used to determine appropriate incline angles for walking tests in each type of footwear. Critical angles were used to prescribe test angles for the walking tests in order to reduce the variability in the number of walking test trials between better and worse performing styles of footwear. This served to minimize the effects of fatigue and exposure to the cold environment.

The walking tests were conducted on two slope types: longitudinal slopes and cross-slopes, with the tilting axis of the floor either perpendicular to the direction of travel or parallel to the direction of travel, respectively. Participants walked in two slope directions; downhill and uphill on the longitudinal slope and right-side-higher and left-side-higher on the cross-slopes for each slope type (Figure 4.4). In these tests, participants were asked to walk at a natural pace and in a controlled manner (without sliding their feet against the ice surface) from one end of the laboratory to the other and back again. 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. 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. Between laps, the slope angle of the walkway was progressively increased, in 1° increments until failure. 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 direction was randomized. A limitation of this study was that the failure angle for the cross-slopes pooled together both the left-side-higher
and right-side-higher conditions and the failure angle on the longitudinal slopes pooled together both the uphill and downhill conditions. Rather than determining individual failure angles for each slope direction, for each participant, the first tested direction to result in a failure was used to determine the maximum achievable angle for that slope type.

![Longitudinal and Cross-Slopes](image)

Figure 4.4. Slope types and directions. 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.

### 4.2.6 Dependent Variables

The primary outcome measure in this study was the maximum achievable incline, recorded during both standing and walking as described above in Section 2.3. The equivalent static COF was calculated as the tangent of the maximum achievable angles attained while standing and equivalent dynamic COF was calculated as the tangent of the maximum achievable angles achieved during the walking tests. Equivalent static and dynamic COF values were compared to SATRA COF values measured on ice using the standard testing device. The purpose of this comparison is to determine whether the bench and biomechanical tests ranked footwear slip resistance in the same order and how well each test was able to discriminate between types of footwear.

Kinematic parameters were also measured to determine how the various styles of footwear affected gait and strategies that were used to maintain balance while walking on icy slopes. All kinematic variables were calculated across the middle 2.5m section of the 5.5m long walkway for successful walking trials where gait was least affected by acceleration and deceleration. All heel strike and toe-off events were identified through visual inspection as the points at which the virtual heel marker contacted the ground surface plane, and the points
where the virtual toe marker lifted off of the ground surface plane, respectively. Marker
timing and locations were used to measure gait speed, step width, step length, step time, step
speed, stance time, swing time, and foot angle at heel strike.

4.2.7 Statistical Analysis

For all analyses of variance (ANOVAs), repeated measures (n=8) designs were used and
along with main effects, all interaction effects were considered. Post-hoc pairwise
comparisons using Bonferonni adjustments to account for multiple comparisons, were
conducted for all significant main effects and all effects are reported as significant at $p<.05$.

A two-way ANOVA was used to determine the effects of footwear (B, G, N, J) and slope
direction (left, right, up, down) on the maximum achievable incline angles when standing.
For the walking tests, a two-way ANOVA was used to determine the effects of footwear and
slope type (longitudinal, cross-slope) on the maximum achievable angle. One-way ANOVAs
were used to determine the effect of footwear on the COF readings obtained at the forepart
and at the heel of the test footwear during bench-testing.

Gait speed while walking on the level ice surface (at a 0° slope) was also analysed using a
one-way ANOVA to determine the effect of footwear. All step characteristics including foot
angle, swing time and stance time during level walking were analysed using two-way
ANOVAs to determine the effects of footwear and the stepping foot (left, right). The left and
right foot were separated for analysis as the two cross-sloping conditions were expected to
affect them differently.

Gait speed and step characteristics while walking at the maximum achievable incline angles
were analysed. Gait speed at the maximum angles were analysed using two-way ANOVAs
for the effects of slope direction and footwear while step characteristics were analysed with
the additional main effect of the stepping foot. Because gait speed and some step
characteristics appeared to change with increasing slope angle, the change in each variable
per degree change in slope angle was linearly fit for each participant. Variables that were
found to change linearly with slope angle (as shown through correlation coefficients) were
analysed using ANOVAs to determine how the gait adaptations, defined by ratios of each
variable per degree change in slope, were affected by footwear and slope direction. The stepping foot was also included as a main factor in the test procedure for variables other than change in gait speed (which is not associated with a single stepping foot) per degree change in slope angle.

4.3 Results

4.3.1 Participants

All participants indicated via questionnaire that they spent on average, 1-2 hours outdoors at least 3-5 days per week outdoors in winter. Five of the eight participants indicated that they engaged in winter sports such as skiing, skating or snowboarding. Half of the participants had fallen in the previous two years but only one participant had fallen outdoors and indicated that the fall was on ice. None of the participants indicated that they had experience using the test footwear prior to the experiment and all participants in this study were right-foot dominant.

4.3.2 Standing Tests

Only the main effect of footwear \(F(3,21)=1476.22, p<.001, \eta^2=1.00, \beta=1.00\) was significant for the maximum achievable angle and equivalently, the static COF while standing (Figure 4.5). Pairwise 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 incline angle of 19.3° across all slope directions (six participants achieved the 20° maximum capability of the tilting platform while one participant achieved a maximum of each of 17° and 18° in Boot J). Boot G allowed participants to stand on 9.4° slopes on average 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 4.5. Maximum slope angles while standing. Average maximum slope angles (and equivalent static COF) at which participants could maintain standing posture without sliding plotted with standard deviation error bars. Pairwise comparisons indicated that each type of footwear was significantly different from the others for all slope directions ($p<.001$).

### 4.3.3 Walking Tests

The main effects of footwear ($F(1,11.9)=397.94$, $p<.001$, $\eta^2=.98$, $\beta=1.00$) and slope type ($F(1,7)=36.76$, $p<.05$, $\eta^2=.84$, $\beta=1.00$) were significant for the maximum achievable incline angle and equivalently, the dynamic COF while walking (Figure 4.6). There was a significant interaction effect between footwear and slope type ($F(3,21)=13.86$, $p<.001$, $\eta^2=.66$, $\beta=1.00$). Pairwise comparisons indicated that each type of footwear performed significantly differently from one another ($p<.05$) during the walking tests, and 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. This indicated that at steeper angles, differences between maximum achievable inclines on the longitudinal slope compared to cross-slopes were more pronounced, which also gave rise to the significant interaction effect.
Figure 4.6. Maximum slope angles while walking. Average maximum achievable incline angles (and equivalent dynamic COF) while walking plotted with standard deviation error bars. Pairwise comparisons indicated that each type of footwear was significantly different from the others for all slope directions and for Boot J, steeper slopes were achieved on the longitudinal slopes than the cross-slopes ($p<.05$).

### 4.3.4 Bench Tests

Equivalent static and dynamic COF values were compared to the SATRA COF values measured from the heel and forepart for each type of footwear (Figure 4.7). The wetted ice surface was the only surface to replicate the order ranking for the four types of footwear seen during tests of maximum achievable incline. On wetted ice, for both the forepart ($F(3,12)=348., p<.001, \eta^2=1.00, \beta=1.00$) and the heel ($F(3,12)=276.56, p<.001, \eta^2=.99, \beta=1.00$), the type of footwear significantly impacted the SATRA COF. Pairwise comparisons using the SATRA method indicated that at both the forepart and heel, Boot J produced significantly higher COF values than the other three types of footwear and Boot G had significantly higher COF values than Boot N and Boot B. However, no significant difference was seen between SATRA COF values for Boot B and Boot N at either the forefoot or heel. SATRA COF means and associated errors for each type of footwear are presented in Table 4.1. Post-hoc comparisons of results from bench testing indicated that each type of footwear was
significantly different from the others with the exception of Boot B and Boot N which showed no significant difference.

Table 4.1. SATRA COF values on wetted ice (mean ± SD).

<table>
<thead>
<tr>
<th>Footwear</th>
<th>At Forefoot</th>
<th>At Heel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boot B</td>
<td>0.05 ± 0.004</td>
<td>0.03 ± 0.002</td>
</tr>
<tr>
<td>Boot N</td>
<td>0.06 ± 0.003</td>
<td>0.04 ± 0.005</td>
</tr>
<tr>
<td>Boot G</td>
<td>0.16 ± 0.004</td>
<td>0.11 ± 0.005</td>
</tr>
<tr>
<td>Boot J</td>
<td>0.20 ± 0.004</td>
<td>0.15 ± 0.002</td>
</tr>
</tbody>
</table>

Figure 4.7. Measured footwear COF values. Comparison of COF values obtained through the mechanical SATRA test and equivalent COF values converted from tests of maximum achievable inclines.

4.3.5 Gait Speed

Gait speed on level ice was significantly affected by footwear \((F(3,21)=6.47, p<.05, \eta^2=.43,\ \beta=.88)\) and participants walked significantly slower in Boot B \((0.72\text{m/s} \pm 0.16\text{m/s})\) than in Boot J \((0.99\text{m/s} \pm 0.24\text{m/s})\) at 0° incline \((p<.05)\). Gait speed decreased linearly with increasing slope angles in all slope directions for each type of footwear with correlation coefficient values of \(R^2 = .77 \pm .22\) (Figure 4.8). Only the main effect of footwear was
significant for the ratio of change in gait speed per degree change in slope angle 
\(F(3,21)=5.62, p<.05, \eta^2=.55, \beta=.98\). Results showed that participants walked significantly slower per degree of incline in Boot B than in Boot G. See Table 4.2 for mean reductions in gait speed per degree change in incline angle for each type of footwear.

![Reduction in Gait Speed During Uphill Walking](image)

Figure 4.8. Reduction in gait speed with increasing angle. Representative data from one participant showing reduction in gait speed at increasingly steep slope angles.

Table 4.2. Mean and standard deviation of change in gait speed per degree of incline.

<table>
<thead>
<tr>
<th>Footwear</th>
<th>Change in gait speed per degree incline (cm/s/°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boot B</td>
<td>-10.0 ± 5.7</td>
</tr>
<tr>
<td>Boot N</td>
<td>-7.19 ± 5.4</td>
</tr>
<tr>
<td>Boot G</td>
<td>-4.91 ± 3.8</td>
</tr>
<tr>
<td>Boot J</td>
<td>-4.94 ± 4.1</td>
</tr>
</tbody>
</table>

4.3.6 Step Width, Length, Time, and Speed

On level ice, the only significant main effect indicating a difference in stepping foot was observed in the measure of step length \(F(1,7)=6.18, p<.05, \eta^2=.47, \beta=.57\) with right steps (0.58m ± 0.08m) being longer than left steps (0.52m ± 0.04m). The main effect of footwear was significant for step width and step length. Participants had wider steps \(F(3,21)=3.56,\)
while using Boot G (0.17m ± 0.01m) than they did while using Boot B (0.14m ± 0.01m). Participants also took significantly longer steps ($F(3,21)=6.90$, $p<.05$, $\eta^2=.50$, $\beta=.95$) while wearing Boot G (0.57m ± 0.02m) than Boot B (0.48m ± 0.03m). No significant interaction effects were observed for any of the step characteristics.

Key findings from the analysis of step width, length, time, and speed at the maximum achievable incline angles were significant interaction effects between the stepping foot and slope direction for step length ($F(3,21)=13.02$, $p<.001$, $\eta^2=.65$, $\beta=1.00$) and step speed ($F(3,21)=10.63$, $p<.001$, $\eta^2=.60$, $\beta=1.00$). At the maximum achievable incline angles, pairwise comparisons indicated that while walking with the left-side-higher, stepping speed of the left foot (0.53m/s ± 0.22m/s) was faster than that of the right (0.46m/s ± 0.18m/s). Alternatively, while walking with the right-side-higher, stepping speed of the right foot (0.59m/s ± 0.18m/s) was faster than that of the left (0.48m/s ± 0.17m/s) and longer steps were also taken with the right foot (0.39m ± 0.05m) than the left foot (0.32m ± 0.07m). These differences were only observed on the cross-sloped surfaces. No differences between the left and right foot were seen while walking on longitudinal slopes at the maximum achievable angles.

When the change in step characteristics per degree change in slope angle was linearly fit, correlation coefficients for step length ($R^2=.75 ± .27$), step speed ($R^2=.77 ± .26$), and foot angle ($R^2=.66 ± .31$) indicated that each one decreased linearly with increasing slope angle. The step width, step time, stance time, and swing time fit only moderately well to lines ranging in $R^2$ values from .51 to .54. No significant main effects or interaction effects for stepping foot, footwear, and slope direction were observed for change in step length per degree change in slope. When run on change in step speed per degree change of slope angle, the ANOVA showed that the main effects of foot ($F(1,7)=6.80$, $p<.05$, $\eta^2=.49$, $\beta=.61$) and footwear ($F(1.45,10.13)=7.05$, $p<.05$, $\eta^2=.50$, $\beta=.95$) were significant and indicated that the reduction in step speed per degree angle was greater for the left foot (0.07m/s/° ± 0.03m/s/°) than the right foot (0.05m/s/° ± 0.03m/s/°) and greater in Boot B (0.11 m/s/° ± 0.07m/s/°) than Boot J (0.04m/s/° ± 0.02m/s/°)
4.3.7 Stance/Swing Time and Foot Angle

On level ice, stance time was not affected by which foot was on the ground throughout stance or by the type of footwear being worn. For swing time, while the swing foot did not significantly affect swing time, swing times while wearing Boot G (0.51s ± 0.05s) were significantly longer than those while wearing Boot B (0.45s ± 0.06s) ($F(1.52,10.61)=5.83$, $p<.05$, $\eta^2=.45$, $\beta=.91$). Swing times at the maximum achievable incline angles were significantly affected by slope direction ($F(3,21)=9.92$, $p<.001$, $\eta^2=.59$, $\beta=.99$) with shorter swing times on both left-side-higher (0.44s ± 0.06s) and right-side-higher (0.43s ± 0.07s) cross-slopes in comparison to walking uphill (0.53s ± 0.10s).

At a slope angle of 0°, the foot angle at heel strike was not significantly affected by which foot was striking the ground or the type of footwear being used and no interaction effects were observed. Similarly, at the maximum achievable incline angles, the stepping foot, footwear, and slope direction did not significantly affect the foot angle at heel strike or the change in foot angle at heel strike per degree of change in slope angle.

4.4 Discussion

4.4.1 Ecological Validity

The methods described in this study for determining the maximum achievable incline angles of footwear on a simulated winter surface provide an ecologically valid approach to determining footwear slip resistance. The experimental setup allowed for sustained walking over 5.5m, both on the level and while sloped. This is an improvement upon prior techniques involving short ramps (Jung & Schenk, 1990). Participants also walked naturally at a self-selected pace throughout the walking tests in contrast to other studies that have involved altered styles of gait such as backwards walking (Manning et al., 1991) or foot dragging (Bruce et al., 1986) which changes loading through the footwear and the surface contact areas. Furthermore, the robotic overhead safety harness allowed participants to safely test to failure angles at the limits of their ability as opposed to studies where participants decide a priori whether a tilt angle is too steep (Jung & Schenk, 1990). In those cases, achievable
incline angles may not have been tested and participant trepidation might have had a greater impact on experimental results.

The most important test scenario conducted in this study was downhill walking as most falls occur with forward slips of the foot at heel strike (Redfern et al., 2001). Since the longitudinally sloped walking tests yielded results consistent with those during cross-sloped walking, this study shows that in future applications of the maximum achievable incline method it would be reasonable to test only to the limits of walking on longitudinal slopes. The current study was limited by the fact that maximum angles were not tested for both uphill and downhill walking independently as the tests on the longitudinal slope were terminated once failure was observed in either direction. If both uphill and downhill testing are conducted in order to determine their independent maximum achievable incline angles and they too are found to be consistent, it would be reasonable to include only downhill tests in the future. The standing tests, which are better indicators of static COF, were used in this study to determine the critical angle and therefore the starting point (5° less than the critical angle) from which to test the performance limits while walking. This study showed that the maximum achievable angles while standing could be determined during pilot testing with a single subject, thereby omitting the necessity of the standing tests as well in future uses of the method because inter-subject variability, particularly on the longitudinal slopes was small (maximum standard deviation was less than 1.5°). It should be noted that conducting the standing tests prior to the walking tests gave participants a chance to experience greater tilt angles than they might have been comfortable with if only walking tests had been conducted and may therefore have inflated the resulting maximum angles while walking. This effect should be considered if the standing tests are to be omitted in the future.

### 4.4.2 Footwear Performance

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 and allowed participants to walk on longitudinal slopes of $17.5° \pm 1.9°$ and cross-slopes of $15.1° \pm 1.6°$. The second best performing footwear utilized the Green Diamond sole (longitudinal: $7.5° \pm 0.9°$, cross-slope: $6.8° \pm 0.9°$) followed by the NCI rubber footwear (longitudinal: $5.1° \pm 0.8°$, cross-slope: $4.6°$
± 1.1°), and finally the IcePaw sole (longitudinal: 3.3° ± 0.5°, cross-slope: 3.0° ± 0.8°).

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, to 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 more complete performance ratings.

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 4.8° as specified in the Americans with Disability Act Standards for Accessible Design (Kirschbaum et al., 2001). Therefore, users would be unable to maintain stable balance on standard curb ramps covered with wet ice while wearing Boot B or Boot N. It should also be noted that as is the case with other ramp tests (James, 1999), the purpose of testing footwear to extreme angles is to obtain a measure of its slip resistance on a slippery surface and not to suggest that the footwear can be worn safely up to the tested limits. In future work, results of this new method for assessing footwear slip resistance should be validated against slip frequency and slip severity on level surfaces.

Although exploration of refinements to the current methodology are recommended, such as simplification to only include down-sloped walking tests, results obtained in this study can be used to estimate required sample sizes. To calculate the sample size \( n \) required to determine with 95% confidence that the mean maximum achievable incline angle is within a specified range of the sample mean, the following equation for a 95% confidence interval can be solved:

\[
\text{Allowable Error} = \frac{(1.96 \times \text{SD})}{\sqrt{n}}
\]

Assuming that the greatest standard deviation observed in this study (SD=1.9° for Boot J) exceeds that observed using a refined study protocol with different types of test footwear, the required sample size for an error of ±1° is 14. For footwear that demonstrates smaller variances (SD ≤ 0.9° on longitudinal slopes), for an error of ±1° the required sample size is only 3 and for ±0.5° error, the required sample size is 13.
4.4.3 Bench Testing vs. Maximum Achievable Incline

The comparison between the bench and maximum achievable incline methods was conducted in the same manner described by Powers et al. (2010) for validating slip resistance measurement devices: by comparing the order in which the methods ranked footwear slip resistance and the ability of each test to differentiate between footwear slip resistance. The comparisons made here should not be considered to be a system-wide comparison between the methods but rather a demonstration of the potential of the new method over the existing standard because only a small sample of footwear was compared and the reproducibility of the bench tests is questionable (Jung & Fischer, 1993).

Comparison of the equivalent static and dynamic COF values from the maximum achievable inclines to the SATRA COF test outcomes showed that wetting the SATRA ice test surface most closely reproduced the order in which footwear ranked in terms of slip resistance based on the human-centred tests. While SATRA specifies methods for testing on frosted and unwetted ice surfaces, there is no specification for testing on wetted ice. Because melting or wet ice is considered one of the most slippery winter conditions (Aschan et al., 2009) and because our tests indicate that even the ranking of footwear slip resistance changes with different test surfaces (Figure 4.7), a wet ice condition is important in the testing of winter footwear.

The human-centred approach to testing was also able to discriminate between all four types of footwear, while the mechanical test could not identify a significant difference between the two poorer performing types of footwear. This suggests that the human-centred approach, even without adjusting for inter-subject variability, produced higher resolution results than the mechanical test. Higher resolution tests would be able to detect differences owing to more subtle changes in footwear sole tread and material design that current tests may not be able to detect and would be valuable for the optimization of slip resistant soling. However, there were differences between the test surface conditions in terms of the surface temperatures and ambient temperature conditions and these may have contributed to the differences between SATRA COF of values measured during bench testing (ice -7°C, ambient 23°C) and those derived during the human-centred tests (ice -0.5°C, ambient
10.6°C). Additionally, more types of footwear and additional winter surface and ambient conditions should be tested using the maximum achievable incline approach in order to determine the sensitivity of the test and improve generalizability of the test results.

4.4.4 Gait Characteristics on Ice and Slopes

The primary outcome measure utilized in this study was defined by the maximum angle at which the healthy, young participants were able to stand or walk without sliding. However, for older users or users with mobility limitations, failure may occur at less steep angles. In future work, alternative definitions of footwear failure, such as speed thresholds may be explored for determining failure. Gait speed was found to decrease the most per degree of incline while using the worst performing boots. Here, 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. This sample of participants was able to dramatically reduce gait speed when necessary which would be difficult for less able-bodied populations. Alternate definitions of footwear failure may be of particular relevance in assessing slip resistance for footwear targeted towards older consumers.

The walking task that participants were asked to achieve was kept simple and naturalistic by not regulating gait speed in this experiment. Therefore, the primary outcome indicated the individual participant’s ability to adapt to the conditions while using the different styles of footwear. Regulating gait speed or cadence is considered unnatural (Mallinson & Longridge, 2008) and confounds the primary outcome measure as it becomes a reflection of both the ability to achieve the desired speed and the ability to achieve the slope angle. Despite differences in gait speed, variability in maximum achievable incline angles using the different footwear was small. This shows that control of speed is not necessary. 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.
In terms of the step characteristics measured while walking on the smooth, wet ice at 0°, the only difference observed was between Boot B and Boot G, with participants taking wider and longer steps in Boot G than Boot B. This suggests that participants may have been more confident while walking in Boot G on the level ground, even though Boot G was not the best performing footwear in terms of achievable slopes.

The analysis also showed that as expected, there were gait asymmetries (differences between step characteristics of the left and right foot as determined via statistical analyses) while walking on the cross-sloped surfaces at extreme angles. Swing times, equivalent to single support time (when the body is supported only by one foot) were shorter while walking on cross-slopes than uphill on longitudinal slopes. Stepping speeds were consistently faster for the foot placed higher on the cross-slope than for the foot placed lower. With the right side higher, the right foot also took longer steps than the left. During gait, the centre of mass (COM) is continually moved ahead of the base of support (BOS) and balance must be achieved by the positioning of the swing limb at heel strike (Winter, 1995). On slopes, postural compensations move the body’s COM in the direction of the higher ground to stay over the BOS (Leroux et al., 2002). Cross-sloped walking is challenging in that the COM shifts lateral to the direction of progression, as Dixon and Pearsall (2010) showed with increasing lateral ground reaction forces of the higher (up-slope) limb and increasing medial forces at the lower (down-slope) limb. The COM is thus farther outside the BOS when the body is only supported by the lower foot. Therefore, stepping more quickly with the higher foot can reduce the time when the COM is outside the BOS. This also explains why steeper inclines were achieved while walking on longitudinal slopes than on cross-slopes in this study (Figure 4.6).

The longer right foot steps while walking with the right foot higher as well as on level ice may be due to the fact that all participants in this study were right-foot dominant. The right-foot dominant sample also explains the greater variability of the maximum achievable incline angle while standing with the left-side-higher as the COM is over the non-dominant limb than if the subject is standing with the right foot higher and having the dominant limb supporting the COM (Figure 4.5). It would be beneficial in future studies to track the position of the upper body more precisely to characterize strategies of postural adaptation on extreme
slopes. Some strategies for maintaining balance observed in this study were the linear reduction in gait speed, step length, and step speed with increasing slope angles which helps to stabilize the COM position. The linear decrease in foot angle at heel strike with increasing slope angle also allowed for greater contact area between the footwear and ice surface which can increase surface adhesion (Strobel et al., 2012) thereby increasing slip resistance.

Because participants clearly altered their gait with increasing incline angles, the next step in this work is to determine the relationship between the maximum achievable incline angles observed in a range of footwear and how the footwear is able to resist slips during level walking. Future validation studies of this method should utilize classic measures of slip severity such as slip frequency and average slip distance under unanticipated slippery winter conditions (Redfern et al., 2001). By examining level-ground performance of different types of footwear that are able to achieve a wide variety of incline angles, Bland-Altman plots will reveal how the results are correlated with increasing achievable incline angles.

### 4.4.5 Study Limitations

As previously described, limitations of this study include the fact that maximum achievable incline angles for uphill and downhill walking and the two cross-slope conditions were not determined separately. Furthermore, comparisons between the bench and human-centred tests are limited by the fact that there were differences between the testing conditions. Future work should be targeted towards measuring the maximum achievable incline angles during downhill walking and comparisons between methods using more similarly prepared surfaces.

Additional future work is necessary to determine the most important surfaces and conditions for testing footwear. Wet ice near the melting point was selected for testing because it is considered extremely slippery (Grönqvist & Hirvonen, 1995) but other conditions such as a thin layer of snow over ice are also known to cause accidents and footwear slip resistance under such conditions should be analyzed. Unfortunately, current injury reporting systems tend to poorly describe the conditions associated with falls (Courtney et al., 2001) and as such, a field study should be conducted to determine precise conditions that contribute to
winter slips and falls and in order to determine which conditions should be used in further testing.

Although the walkway used in this study was longer than most inclined walkways used in gait trials, it still likely did not allow participants to reach steady state walking as the number of steps required to reach steady state walking has been shown to vary with footwear and in one study it was shown to take up to six steps to reach steady state (Najafi et al., 2010). The motion capture system was also unable to capture the full length of the walkway and so was not able to adequately assess acceleration and deceleration effects. Braking and propulsion increase frictional demand (Strandberg, 1985) and these effects should also be studied in the future. Another limitation related to the length of walkway was that participants were all right-foot dominant. Participants thus began the majority of trials by stepping with their right foot. This impacts which foot first entered the 2.5m section of walkway that was analyzed and if steady-state gait was not reached at that point, this limits the generalizability of the results in the event of left and right foot gait differences.

4.5 Conclusion

The performance outcomes from this study can be used to inform consumers making decisions regarding winter footwear. Maximum achievable inclines are more ecologically valid than mechanical tests. This objective, user-based assessment of footwear slip resistance on slippery slopes is a more useful representation of footwear performance for consumers than in-lab testing following standard SATRA methodology. This experiment showed that a wide spread of footwear performance can be assessed by walking on increasingly steep slopes under controlled surface conditions. The results also indicated that only a relatively small sample size is required and that results are consistent, ranking footwear and discriminating between footwear types equally well for standing tests in all directions and walking tests for both longitudinal and cross-slopes.
References


to describe the problems and practical tests of anti-skid devices. Accident Analysis and Prevention, 32(3), 455–460.


Chapter 5
Study IV: Slip Resistance of Winter Footwear on Snow and Ice Measured Using Maximum Achievable Incline

Preface

The following sections of this chapter were submitted along with co-authors Robert Shaw, Alison Novak, Yue Li, Marcus Ormerod, Rita Newton, Tilak Dutta, and Geoff Fernie to Ergonomics (July 2014). The previous chapter describes the utilization of a new method for assessing the slip resistance of winter footwear and presents results of four styles of winter footwear evaluated on a wet ice condition. In this chapter, the maximum achievable incline method is refined to include only walking tests on longitudinal slopes based on the previous results, such that ascent and descent are tested independently. The new method is also applied to a broader range of footwear, three which were included in Study III along with three additional styles. To determine the effects of changing surface conditions, the footwear testing is extended to include dry ice, wetted ice, as well as a controlled snow condition. This utilization of reproducible snow conditions to optimize testing of winter footwear is the first test of its kind and shows the value of testing in realistic climatic conditions. The original concept for the new test method was developed by Geoff Fernie who was also responsible for the design and construction of WinterLab. Bench tests on the SATRA STM603 machine were conducted by Yue Li.

Abstract

Protective footwear is necessary for preventing injurious slips and falls in outdoor winter conditions. Valid methods for assessing the slip resistance of footwear on winter surfaces are needed in order to evaluate footwear and outsole designs. To establish an ecologically valid method of testing winter footwear, eight participants tested the performance of six styles of footwear on wet ice, dry ice, and dry ice after walking over soft snow. Slip resistance was measured by determining the maximum incline angles that participants were able to walk up and down in each footwear-surface combination. The results indicated that testing on a range
of winter surfaces is necessary for establishing winter footwear performance and that across test modes, results of standard mechanical bench tests for footwear slip resistance are not as consistent as those of the maximum incline test.

5.1 Introduction

Slip and fall accidents can lead to serious injuries to both pedestrians and outdoor workers. The direct cost of these accidents was estimated at $30 billion per year in the United States (Stevens et al., 2006). The likelihood of experiencing slips and falls increases during the winter season. Snowy and icy conditions common in winter environments increase the risk of slip and fall accidents outdoors by reducing underfoot traction (Courtney et al., & Holbein-Jenny, 2001). Such winter conditions contribute to two-thirds of outdoor pedestrian injuries (Rolfsman et al., 2012).

Slip resistant footwear plays an important role in the prevention of slips and falls by providing traction to prevent balance loss and 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 (Verma et al., 2011; Staal et al., 2004). 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 & Haslam, 1998; Canada Post Corporation, 2007, 2008).

Improvements in the slip resistance of winter footwear are necessary to protect pedestrians outdoors. However, developing appropriate footwear for winter conditions is challenging because of the wide range of temperatures and precipitation conditions that can occur. Furthermore, existing standard methods for testing the slip resistance of winter footwear have not been validated for actual winter test conditions. As a result, consumers are provided with limited and potentially misleading information when selecting winter footwear as designers and manufacturers do not have an objective and reliable method for evaluating their designs.

Coefficient of friction (COF) is the most common measure of footwear slip resistance. The standard test for footwear slip resistance (ASTM F2913) measures 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 (ASTM F2913-11, 2012). Calibrated test surfaces described in the standard methods include dry and wet quarry tile and stainless steel. The standard also recommends 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.

In the past, mechanical devices such as the stationary step simulator (Gronqvist et al., 1990) have been used outdoors on naturally occurring winter surfaces to test the relative slip performance of footwear (Gao et al., 2004). However, these test methods are not the standard and 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. These studies have greater ecological validity than studies using only mechanical devices but have typically involved only short walkways (less than 3m) and a limited range of surfaces and contaminants (Gao et al., 2008; Jung, 1989; Skiba et al., 1986). 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 (submitted for publication). 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 the 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 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 results of the maximum incline method to the standard mechanical method (ASTM F2913) when used in conjunction with an icy surface.
5.2 Methods

5.2.1 Participants

A convenience sample of eight males took part in this study and tested 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, 1.81m (±0.02m) tall, and weighed 81.9kg (±4.4kg). Prior to participating in the study, all subjects provided informed consent as approved by the Toronto Rehabilitation Institute–UHN Research Ethics Board.

5.2.2 Footwear

![Image of six footwear styles with labels: Style-S, Style-K, Style-L, Style-N, Style-G, Style-J]

Figure 5.1. 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.

Six styles of footwear were selected with the aim of testing a wide range of performance (Figure 5.1). Style-S was a running shoe with a thermoplastic rubber outsole (Athletic Works Ted Men’s Jogging Shoes, Walmart Canada Corp., Mississauga, Canada). Style-K was a low-cut ankle boot developed to be slip resistant on various industrial surfaces (Keuka SureGrip®, Tennessee, U.S.A.). Style-I was a winter ankle boot consisting of a rubber outsole designed for slip resistance (Arctic Ice Boot, SureGrip®, Tennessee, U.S.A.). Style-G, Style-N, and Style-J all utilized the same over the ankle uppers (Dakota, Mark’s®, Alberta, Canada) with three different outsoles. Style-G and Style-N had identical tread
patterns made from two different materials. The outsole of Style-G consisted of aluminium oxide and silicon carbide granules embedded in rubber to enhance underfoot traction (Green Diamond Tire, Colorado, USA) and NCI rubber compound was used for the outsole of Style-N (Dakota, Mark’s ®, Alberta, Canada). Finally Style-J had no tread and the outsole was created using a sheet of a proprietary JStep rubber compound (JStep Sole, Gimhae, Republic of Korea). 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 minutes. The styles of footwear were then tested by participants in a random order.

5.2.3 Surfaces

This study was conducted in WinterLab, one of Toronto Rehabilitation Institute’s Challenging Environment Assessment Laboratories (Figure 5.2). WinterLab contains a 4.5m by 4.6m ice floor which was cooled to -1.9°C (±0.8°C) for the duration of the study. 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 wore a full-body safety harness which attached with a line from the upper back to a motorized fall-arrest device that automatically followed participants from directly overhead. Participants practiced falling into the safety harness to acclimate themselves to the sensation prior to conducting test trials.

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 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 one session and snow was tested in the other. The order of the sessions was counterbalanced for each participant.

During the experiment, participants walked across two 5.5m long adjacent walkways along the diagonal of the laboratory to maximize 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. Tubes circulating glycol coolant along the floor surface controlled the ice temperature.
The cold air that circulated to create the cold ambient conditions, in combination with the ice temperature created a smooth, dull, ice surface with minimal melting at the interface. This virgin base ice layer was the *dry ice condition*. Approximately 1mm of water which was maintained at 5.6°C (±1.1)°C inside WinterLab was spread over the dry ice using a clean mop to create a *wet ice condition*. This is considered to be a very challenging surface for walking (Grönqvist & Hirvonen, 1995) (Figure 5.2b). The wet ice walkway was re-wetted prior to testing each additional style of footwear. 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 5.2c). Snow was created using a commercial snow-machine (Snowstar Magic, Snowtech Co., Ltd, Chungbuk, Republic of Korea). The machine worked by pressurizing cold water and spraying it through 6 rotating nozzles onto a fixed chilled stainless steel disk. The water froze into snow crystals as it hit the disk and was scraped off by rotating blades. Approximately 150L of snow was created inside the snow-machine’s temperature controlled chamber which was held at -2.0°C. The snow was then transported using an insulated cooler into WinterLab. A roughly 5cm layer was shoveled 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 snow density, was 25% (or equivalently 250kg/m³) measured using a Brooks-Range Pocket Snow Density Gauge 100 (Brooks-Range Mountaineering Equipment, Fremont, USA).

Participant testing began within 20 minutes 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 footwear 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 hitting 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 5.2d) and then walking on the adjacent dry ice walkway (Figure 5.2e). Remnants of snow left on the dry ice walkway from snowy footwear were cleared between test passes across the dry ice surface.

Figure 5.2. 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.

5.2.4 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 minimize 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. In the full experiment, 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. For instance, if during the pilot, the smallest maximum incline was less than or equal to 4°, the second test angle was set at 1°. After walking on the level, while the participant stood at one end of the walkways, the laboratory was tilted at 0.25°/s to the second test angle such that the participant could then ascend or descend the walkway (in random order). Throughout testing, participants were not informed of the magnitude of the incline angles being tested.

Starting from the second test angle, participants were asked to start walking from one end of the walkway, stop at the opposite end, turn around, and return 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, to walk 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 for terminating 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. The exception was the first trial on dry ice. Here, participants walked both back and forth across the snow-covered walkway first. The circuit was repeated at increasing angles of incline to determine the maximum achievable angle in the snow condition for one slope direction at a time (randomly starting with ascent or descent).
5.2.5 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 equivalent COF values by taking the tangent of the angle. This COF represents friction at the point when traction is lost (i.e. at the maximum angle, beyond which, subjects could no longer walk without both feet slipping simultaneously), as opposed to sliding friction which is the instantaneous ratio of the shear load to normal load during relative motion. Kinematic data was also collected during each walking trial using a twelve-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 100Hz and filtered using a fourth-order, zero-lag, dual-pass Butterworth filter with a 6Hz cutoff 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 2.5m 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 2.5m 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, G, N, 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 (G, I, J, K, N, S) on each gait characteristic while participants walked on the level (0°) walkways. Three-way ANOVAs with the factors of surface (dry ice, wet ice, snow), footwear (S, K, I, G, N, 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. Homogeneity of variance was checked using Mauchly’s test of sphericity and Greenhouse-Geisser corrections for degrees of freedom were used in cases when the assumption of sphericity was violated. For all main and interaction effects, the criteria for statistical significance was set at $p < .05$ and Bonferroni adjustments were used to correct for pairwise comparisons.

### 5.2.6 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 utilize 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 19cm by 44cm tray were used to maintain 0.5cm of ice at -7°C throughout the bench tests. The ice temperature in WinterLab was controlled by cooling elements embedded in the 2.5cm 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 preconditioned in a -5°C water-alcohol bath for three hours. COF values for each type of footwear were collected with the footwear flat against the test surfaces and with the footwear 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. Rankings of footwear slip resistance obtained from the bench tests were compared to rankings obtained during maximum achievable incline testing.

5.3 Results

5.3.1 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 5.3). Participants had maximum achievable angles of 5.8° (0.2°) (mean (standard error)) while walking in the snow condition 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 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 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 up-slope or down-slope 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, and dry ice during descent, it performed poorest on wet ice during ascent. Additionally, Style-J outperformed all other styles of footwear on all surfaces and demonstrated superior performance on wet ice during descent and ascent in comparison to its performance in the snow and dry ice conditions.

![Maximum Achievable Incline Angle](image)

Figure 5.3. Performance of test footwear rated by maximum achievable incline angle. The secondary axis shows COF values equivalent to the incline angles.

### 5.3.2 Gait Analysis

Gait variables (temporal-spatial and kinematic measures) are summarized in Table 5.1. Two-way ANOVAs (footwear x surface) indicate 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 (summarized in Table 5.1; the complete dataset averaged across subjects can be found in the Appendix). 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 up-slope were significantly longer than step times while walking on the level or down-slope. As a result, step speed while ascending was significantly slower than that while descending, which in turn was significantly slower than step speeds on the level.

Table 5.1. Estimated means of gait kinematic data (mean(SE)) at each level for the main effects of slope type, footwear, and surface. Factors which were found to have significant main effects are highlighted in grey.

<table>
<thead>
<tr>
<th>Slope</th>
<th>Step Length (m)</th>
<th>Step Time (s)</th>
<th>Step Speed (m/s)</th>
<th>Step Width (m)</th>
<th>Foot Angle (°)</th>
<th>Upper Body Flexion (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level</td>
<td>0.52(0.02)</td>
<td>0.67(0.02)</td>
<td>0.79(0.03)</td>
<td>0.11(0.01)</td>
<td>17.2(0.9)</td>
<td>0.1(2.1)</td>
</tr>
<tr>
<td>Ascent</td>
<td>0.44(0.01)</td>
<td>0.84(0.04)</td>
<td>0.56(0.03)</td>
<td>0.09(0.01)</td>
<td>8.6(0.7)</td>
<td>11.3(2.8)</td>
</tr>
<tr>
<td>Descent</td>
<td>0.40(0.01)</td>
<td>0.66(0.03)</td>
<td>0.63(0.04)</td>
<td>0.12(0.01)</td>
<td>11.1(0.7)</td>
<td>-5.5(2.4)*</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Footwear</th>
<th>Slope</th>
<th>Step Length (m)</th>
<th>Step Time (s)</th>
<th>Step Speed (m/s)</th>
<th>Step Width (m)</th>
<th>Foot Angle (°)</th>
<th>Upper Body Flexion (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>K</td>
<td>Ascent</td>
<td>0.45(0.01)</td>
<td>0.73(0.02)</td>
<td>0.63(0.02)</td>
<td>0.10(0.01)</td>
<td>10.8(1.0)</td>
<td>2.2(2.5)</td>
</tr>
<tr>
<td>S</td>
<td>Level</td>
<td>0.47(0.01)</td>
<td>0.70(0.03)</td>
<td>0.69(0.03)</td>
<td>0.10(0.01)</td>
<td>13.1(0.7)</td>
<td>1.6(2.3)</td>
</tr>
<tr>
<td>G</td>
<td>Descent</td>
<td>0.46(0.02)</td>
<td>0.74(0.03)</td>
<td>0.65(0.04)</td>
<td>0.11(0.01)</td>
<td>12.4(0.7)</td>
<td>1.4(2.8)</td>
</tr>
<tr>
<td>N</td>
<td>Indent</td>
<td>0.46(0.01)</td>
<td>0.71(0.02)</td>
<td>0.67(0.03)</td>
<td>0.11(0.01)</td>
<td>12.7(0.9)</td>
<td>2.2(2.8)</td>
</tr>
<tr>
<td>I</td>
<td>Style-J</td>
<td>0.45(0.02)</td>
<td>0.72(0.03)</td>
<td>0.66(0.03)</td>
<td>0.10(0.01)</td>
<td>10.8(0.8)</td>
<td>1.7(1.7)</td>
</tr>
<tr>
<td>J</td>
<td>Style-S</td>
<td>0.46(0.01)</td>
<td>0.74(0.03)</td>
<td>0.65(0.03)</td>
<td>0.12(0.01)</td>
<td>14.0(0.5)</td>
<td>2.8(2.2)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Surface</th>
<th>Step Length (m)</th>
<th>Step Time (s)</th>
<th>Step Speed (m/s)</th>
<th>Step Width (m)</th>
<th>Foot Angle (°)</th>
<th>Upper Body Flexion (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry Ice</td>
<td>0.46(0.01)</td>
<td>0.75(0.02)</td>
<td>0.64(0.03)</td>
<td>0.10(0.01)</td>
<td>12.6(0.70)</td>
<td>0.3(2.5)</td>
</tr>
<tr>
<td>Wet Ice</td>
<td>0.46(0.02)</td>
<td>0.71(0.03)</td>
<td>0.67(0.04)</td>
<td>0.11(0.01)</td>
<td>11.7(0.55)</td>
<td>5.7(2.4)</td>
</tr>
<tr>
<td>Snow</td>
<td>0.16(0.01)</td>
<td>0.72(0.03)</td>
<td>0.67(0.04)</td>
<td>0.10(0.01)</td>
<td>12.7(0.86)</td>
<td>-0.1(2.5)*</td>
</tr>
</tbody>
</table>

*Negative flexion angles indicate that the upper body was in extension

The main effects of slope type and footwear were significant for step width. Participants took significantly narrower steps while walking up-slope at the maximum inclines compared to walking on the level or down-slope 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 down-slope angle and smallest on the up-slope. The angle of the foot when contacting the ground surface was greatest for Style-J followed by Style-S. While wearing Style-J footwear participants hit the ground at significantly larger foot angles than while wearing Style-I and Style-K. 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 5.4a). During level and down-slope walking at the maximum achievable angles, foot angles at heel strike were similar across all surfaces. During up-slope walking, 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 up-slope at heel strike. Up-slope flexion at the maximum achievable inclines was significantly greater than that on the level which in turn, was significantly greater than while walking down-slope 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 up-slope walking at the maximum achievable angles, upper body flexion was similar across all surfaces. During down-slope 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 5.4b). 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 accordingly while ascending, significantly increased upper body flexion was seen while walking in said better performing footwear (Figure 5.4c).
Figure 5.4. 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.
5.3.3 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 5.5. 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.

![Bench Testing Dynamic COF](image)

Figure 5.5. Dynamic COF measured during bench testing. The secondary axis shows incline angles equivalent to the COF values.

In Figure 5.6, the COF values obtained during bench testing have been converted to their equivalent incline angle. These values are plotted with the maximum achievable angles obtained while walking up-slope and down-slope on each surface. Results on the wet ice and dry ice conditions, prepared for the bench tests and the walking tests, as described previously, are shown in Figure 5.6.
5.4 Discussion

Performance as measured using maximum achievable incline angles indicate that the snow condition was the most challenging surface to walk across for all types of footwear. Snow has been found to improve underfoot traction (Aschan et al., 2009). During our pilot studies,
traction was observed to be high on thick (approximately 3cm), soft, trodden snow. However, the snow condition tested in this study highlights how snow can make maintaining balance while walking more difficult and why snow-related falls are so prevalent in winter. Within our study while walking on the snow-covered walkway, snow that collected beneath the outsole had the effect of preventing the footwear from making direct contact with the ground surface. The relative sliding surfaces on ice were then underfoot snow over dry ice rather than the bare outsole over dry ice. The low-friction interaction between dry ice and underfoot snow thus increased the likelihood of slipping. 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 2.5mm-3mm in depth. Style-G, Style-N and Style-I performed moderately and all incorporated more aggressive, deeper tread patterns, in the range of 5.5mm-6mm 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 utilized 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. Upon closer analysis of the material properties of JStep’s proprietary outsole, it was found to be quite different from the other tested outsoles. It consists of a soft rubber embedded with micro-scale protruding fibres. Future testing is required to show whether incorporating an aggressive tread (while optimizing 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.

The results show that different styles of footwear respond differently to different winter surfaces and testing on only one surface does not provide a complete picture of how the footwear responds to a range of winter conditions. Each individual style of footwear demonstrated the poorest performance on either the snow condition or on wet ice. This suggests that testing on dry ice conditions may not be necessary for future evaluations of
winter footwear. The data also showed that the three test surfaces ranked identically during ascent and descent for each individual style of footwear, except for Style-G. During ascent in Style-G, performance was poorest on wet ice followed by snow and dry ice. During descent, the snow condition was the most challenging surface for Style-G followed by wet ice and then dry ice. The main difference in Style-G from the other types of test footwear was that its Green Diamond sole had hard granules embedded in the rubber. It is not clear how this may have contributed to the different ascent and descent results. What is known is that descent testing is more representative of forward foot slips which are more likely to lead to falls than the backwards slips that occur during ascent testing (Leamon, 1992). Testing maximum achievable incline only during down-slope walking may therefore be a greater challenge to the footwear and a better representation of their general safety. The fact that the results for ascent and descent largely agree further supports the use of down-slope testing alone as being sufficient for assessing footwear performance.

While contrasting results for various styles of footwear on snow and wet ice showed the necessity of testing winter footwear on snow and wet ice surfaces, these conditions are not exhaustive of all winter climatic conditions. A wider range of ambient and ice temperatures as well as snow consistencies should be tested to fully understand how varying conditions affect footwear performance. In practice, the most important conditions that footwear should be tested in are those typical to the region in which the footwear is intended for use. 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 expected performance for the footwear during level-ground walking.

Measures of gait characteristics indicated the various strategies used by subjects 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 up-slope than down-slope 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 while wearing this footwear. 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 angles were achieved during ascent than descent.

Participants also decreased their foot-floor angles when ascending and descending compared to walking on the level. Smaller angles were utilized on the up-slope than down-slope 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 heel strike decrease with increasingly slippery surfaces and increasingly steep surface angles (Cham & Redfern, 2002). However, Style-S footwear, which demonstrated relatively 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 and thereby allowed 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 5.4) between surface and slope-type showed that while foot angles across surface conditions were consistent during descent and level walking, foot-floor angles while walking up-slope at the maximum achievable angles were smaller on dry ice than on snow. 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 which is 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 stabilization 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 et al., 2002). The greater flexion angles up-slope and the greater extension angles down-slope while wearing the better performing footwear are likely due to the fact that these angles were assessed at the maximum achievable angles for the various footwear-surface combinations as increased incline angles are known to be associated with greater upper body flexion and extension during ascent and descent, respectively (Leroux et al., 2002).

Bench tests on winter test surfaces indicated that the dry and wet ice tests were most comparable 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 5.6 shows that the range in COF values across all tested surface conditions were more consistent, showing less variability, for each type of footwear using the maximum achievable incline angle method than on 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 such differences were not observed during the up-slope and down-slope walking tests. Bench testing on wet ice also tended to underestimate slip performance in comparison to the wet ice results obtained during maximum achievable slope testing. These differences may have also been a result of differences in the kinematics of walking on the inclined surfaces in comparison to those of natural walking on level ground which the bench test aims to simulate. In future work, the validity of both the bench test and maximum incline test should be determined by correlating their results to the severity of slips (measured as frequency, total slip distance, and/or sliding speed) on level, slippery winter surfaces. Tasks that challenge the slip resistance of footwear such as turning or load carrying and encountering unexpected slippery surfaces would be ideally suited for validating tests against real-world performance.

This study shows differences between the standard bench-testing method and a human-centred approach to assessing footwear slip resistance. However, the maximum incline testing method utilized in the current work may not translate performance of footwear directly to slip incidence on level ground or uneven surfaces. Future work should 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. This follow-up study would also be useful in determining whether human-centred methods require greater control of gait characteristics such as speed and cadence. Furthermore, a field study in which the two methods will test footwear associated with a range in frequency of slips and falls in the community should be conducted to compare the validity of these test methods.

5.5 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 it is therefore important to test on actual real world surfaces that one might encounter in a winter environment. In particular, the results showed the importance of using 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 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.

The results appear to be more consistent than those obtained during mechanical bench tests. Possible simplifications to the current method, such as testing only down-slope walking and requiring fewer test conditions, would result in a method that is not only useful for rating footwear slip resistance but is also feasible for large-scale footwear testing.

References


6.1 Overall Discussion

The four studies comprising this thesis have provided important insight into the effects of different winter surfaces, footwear, and test methodologies on the measurement of slip resistance. The findings indicated that cleated footwear may lessen the occurrence of slips and falls but their designs still need to be optimized to improve compliance and prevent infrequent long slips without inducing pain. In order to represent winter performance, the current standard test method for non-cleated footwear should be changed to test footwear at steeper foot angles and increased sliding speeds. Furthermore, the studies showed that human-centred methods that are ecologically valid can be used to test slip resistance. The new method utilizing the maximum achievable incline angle while walking proved to be a viable method that produced consistent results that were more sensitive to differences in slip resistance than the standard while using only a small number of participants. The results also showed the importance of testing footwear in environmental conditions under which the footwear is intended for use. Specifically, the work highlighted the importance of using both ice and snow surfaces for testing winter footwear.

6.1.1 Surfaces

Each of the studies highlighted the importance of testing footwear under conditions in which the footwear is intended to be worn, supporting previous studies that have demonstrated similar results (Grönqvist & Hirvonen, 1995). The different types of surfaces tested, including concrete, wet ice, dry ice, snow, level, sloped, and cross-sloped surfaces were shown to affect the various styles of footwear in different ways. It is important to note that subtle differences between surface conditions had a clear impact on measured slip resistance. For example, in Study IV there were significant differences between the wetted ice surface and the dry ice surface with footwear generally performing better on the dry ice than the wet, except in the case of the JStep outsole.
A less obvious difference was observed between the two wet ice conditions created in Studies III and IV. In Study III, the wet ice surface was created at a higher ice temperature (-0.5°C ± 0.5°C) in combination with a higher ambient temperature (10.6°C ± 0.6°C) leading to a visible layer of water that was self-maintained throughout the experiment. During Study IV, in order to be able to simultaneously test dry ice and wet ice conditions, the ice floor and ambient temperatures were held at lower set-points (-1.9°C ± 0.8°C and 5.6°C ± 1.1°C, respectively) and water (at 5.6°C) was manually applied to create the wet ice surface prior to testing. While there were differences in the test protocols between the two studies (notably, the inclusion of static testing, thereby increasing participant exposure to steeper test angles in Study III and the separation of ascent and descent angles in Study IV), the differences in test surfaces also impacted the maximum achievable incline angles observed. When comparing the same styles of footwear tested in the two studies (Styles G, N, and J), the maximum achievable angles were marginally lower in Study IV than in Study III for the poorer performing footwear (Styles N and G) and considerably lower in Study IV than Study III for the best performing footwear, Style J, by approximately 4°. The results indicate that the JStep sole may perform better on warmer wet ice conditions than colder wet ice conditions.

These differences show that the repeatability of results is highly dependent on how tightly the conditions under which the surfaces are created can be controlled. Careful documentation and ongoing monitoring of the conditions being created is imperative to the production of reliable and consistent results. In order to have good control of the surface conditions, having separate control of the ice and ambient temperatures was important. In Study I and Study II, ice formation relied entirely on ambient temperature controls. To create ice that was hard enough to prevent cracking and splitting over the course of the experiment, adequate cooling temperatures and cooling time (-5°C for 12 hours used in this case) were required. However, cold ambient temperatures can become extremely uncomfortable for participants and lengthy exposure can affect the experimental outcomes as well as pose a hazard to cardiorespiratory health. As such, the temperatures were raised to 3°C during testing and breaks from the cold temperatures were used to minimize cold-induced discomfort. Unfortunately, breaks lengthen the experiment and can cause fatigue. The higher ambient temperatures during testing also gradually warmed the ice surfaces, thereby enhancing melting at the surface over time and
changed the test conditions. By having separate ice and ambient temperature controls, as was the case in Study III and IV, the ice can be maintained indefinitely while the ambient temperatures are above 0°C, allowing subjects to comfortably sustain longer periods of footwear testing. While these conditions may not exactly replicate ice as it is formed outdoors because outdoor conditions are so varied, the surface will demonstrate the hydrodynamic properties of ice near the freezing point, which is critical during footwear testing.

Study I showed that when slippery surfaces are anticipated, the size of the slippery surface area is important. Having to take more than one consecutive step on an icy surface led to more frequent and longer slips. When only a single step was taken on an icy patch participants were able to adjust their gait and minimize the effects of instability under the one foot. In this first study, while walking at a self-selected pace and anticipating slips, only minimal differences were observed between walking on the level or stepping down a shallow slope. However, closer analysis of the subsequent steps following the down-sloped step may elucidate greater differences between the two conditions.

During human-centred testing, analyses of gait and slips over a longer walkway that allows participants to reach steady-state gait is likely to provide the most representative information as to how footwear will perform during regular outdoor walking beyond gait initiation and termination. In the first two studies, the short (3.5m) walkways did not allow steady-state gait to be reached. The four steps taken allowed for gait initiation followed immediately by gait termination. At 5.5m, the walking distance in Studies III and IV was a substantial improvement although participants with long stride lengths likely still did not achieve steady-state gait in the better performing footwear which allowed participants to walk at faster speeds with larger stride lengths (Lockhart et al., 2007). Nevertheless, at 5.5m participants were taking at least eight steps for the least challenging footwear-surface combinations in the latter two studies, which was sufficient for inter-footwear comparisons.

Study IV showed how important the incorporation of snow conditions is to winter footwear testing. The study indicated that while some footwear may perform well on icy conditions, snow underfoot consistently worsened performance. As the first study of its kind to include
testing on snow conditions, we are only beginning to understand the impact of snow underfoot while walking. Future testing and development of more outsole designs targeted at high slip resistance on ice and maintenance of such characteristics in snow is crucial for preventing winter slips and falls.

There is also a need to survey the actual outdoor conditions which 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. Specialized tools are often necessary to precisely measure the surrounding conditions, such as the hardness and density of snow. Furthermore, the number of measurements needed and the precise locations in which to take them are important but not easy to determine. More work is required in field studies of actual winter-related falls to record ambient and surface temperatures, time of day, precise location, surface and contaminant characteristics, as well as footwear worn. Such information needs to be collected in order to guide the development of test conditions that are relevant to footwear testing in the future.

### 6.1.1 Footwear

Not only are surface conditions important in winter footwear testing, but the testing temperatures and their impact on the properties of the footwear materials should also be considered. During prolonged wear outdoors in winter, ambient and surface temperatures will cool the footwear. Typically, cooling has a hardening effect on rubber and plastics (Gao et al., 2004) and increased hardness is associated with reduced slip resistance (Redfern & Bidanda, 1994). However, different materials will conduct heat and change hardness at different rates. In Studies I and II testing was conducted at an ambient temperature of 3°C, and the ambient temperature during Study IV was 5.6°C. For these studies, the footwear was conditioned at the ambient test temperatures for 30 minutes prior to testing. During Study III the ambient temperature was warmer at 10.6°C and the footwear was pre-conditioned for a longer period of 1 hour before testing. During human-centred testing, while it is important to pre-condition footwear, when the entire footwear is cooled, it may become too uncomfortable for the participants to wear. Other methods for pre-conditioning, such as soaking the outsole
only in a cooling bath may be a possible method for cooling the sole without having a significant effect on the uppers. However, it must be kept in mind that the effects of the bath can be lost quickly once the footwear is removed from the cooling bath if the bath is much cooler than the ambient conditions. In future studies, changes in the sole temperatures and hardness throughout the course of experiments can also be tracked so as to determine their effects on slip resistance.

The types of footwear used throughout the four studies were a combination of market-available and experimental footwear including both cleated and non-cleated devices. An important outcome of Studies III and IV was the superior anti-slip properties of the JStep outsole on ice. The outsole performed particularly well on wet ice, which is typically considered to be very slippery and proved to be the most challenging surface for the other styles of footwear tested in Study IV. The JStep outsole also outperformed the others on dry ice and in the snow condition, warranting closer analysis and indicating that material optimization likely has more impact on slip resistance than tread design. Upon closer analysis, this proprietary design was found to consist of glass fibres embedded in a soft rubber, with the fibres aligned perpendicular to the rubber surface and protruding at the micron level out of the surface. The exact mechanisms that contribute to the effectiveness of this design remain unclear. The roughness of the exposed surface may enhance ploughing at the ice interface and the glass fibres may promote capillary suction thereby enhancing adhesion at the interface (Chang et al., 2001; Colbeck, 1992). Further work to understand why this material is so effective in resisting slips on ice is required. Determining whether integrating tread designs into this type of outsole material might enhance traction in snowy conditions is the next logical step in the development of slip resistant winter footwear.

For appropriate footwear testing, the target populations that the footwear is designed for should also be considered. In these studies, footwear was tested by a range of healthy participants (both males and female in Study I and only males in Studies II through IV). The footwear sizes were selected to fit the participants with only whole sizes provided. In Study I a larger range of sizes was utilized and the participant-base included a subset of letter carriers. The results showed that there were no differences between the slip characteristics (slip distance and peak utilized COF) of the letter carriers and non-letter carriers or the males
and females suggesting that both sexes can be involved in footwear testing and industrial footwear need not be tested only by industrial workers. Because size and weight do impact the underfoot forces, surface contact area, and therefore dynamics at the footwear-surface interface (Strandberg, 1985), it is recommended that footwear be tested in a range of sizes fitted to persons in the target consumer population. For specialized footwear, for example walking shoes for older adults, it would be informative to involve an older adult group in participant-testing.

The data obtained in Study IV also indicate that the footwear uppers may impact changes in gait and adaptation to slippery surfaces thereby affecting test outcomes. Higher cut boots, for example, could restrict motion at the ankle thereby limiting ankle flexion and thus also reducing the foot-floor contact angle which can minimize slipping (Menant et al., 2009). Footwear flexibility at the midsole is also known to have similar effects (Tencer et al., 2004). Therefore, for testing aimed at determining the specific contributions of the outsole to footwear slip resistance, the outsole should be attached to and tested using identical uppers.

In terms of footwear design and development, Study I highlighted the importance of other factors beyond slip resistance in the selection of winter footwear. For instance, comfort was considered as important to participants as slip resistance. Other characteristics that have been recognized as important in winter footwear selection include aesthetics, cost, water resistance, and thermal comfort (Gao & Abeysekera, 2002). In improving winter footwear for consumers, the role that each of these characteristics play in determining whether people will select the footwear and use them in winter conditions must be considered.

Study I showed that cleats may be effective in reducing the size and frequency of slips. However, the styles that were tested, which are those selected for use by Canada Post, were unable to prevent all slips, and in some cases led to long and potentially hazardous slips. It is clear from this work that more emphasis on the optimization of the design of cleated footwear for improving slip resistance is required.

Poor compliance with the use of cleated footwear due to issues of comfort as well as the requirement that they only be worn on icy surfaces (McKiernan, 2005) is a critical consideration. These issues also suggest that optimization of cleated footwear may require
active or passive mechanisms for extending and retracting the spikes underfoot as needed. The reality is that non-cleated winter footwear is used by more people and for far greater proportions of time than cleated footwear. The ubiquity of non-cleated winter footwear and the ongoing need for improved slip resistance for non-cleated footwear are why they became the focus of the latter three studies.

6.1.2 The Current Standard Method

Study II describes critical parameters that should be used for simulating normal gait in the current standard test for the assessment of footwear slip resistance when testing on ice, which is a non-standard test surface. However, even if the current standard were to be adjusted to simulate the average speeds, loads, and angles observed during a typical step, the relative motion still only represents a fraction of true gait and therefore there is doubt as to whether it can possibly capture the likelihood of slipping in reality. As such, the test in its current state and even with the suggested changes in parameters and test conditions (i.e. testing in realistic winter conditions) must be further validated. The ecological validity of the current standard is limited in that the dynamics of walking, including the role of the full body, shifting of weight, rocking motion of the foot, and any laterally applied forces are not simulated. Human-centred approaches are more effective in integrating all the various factors associated with maintaining stable gait and therefore may be better suited for determining footwear slip resistance.

6.1.3 Maximum Achievable Incline

The maximum incline method was developed to allow subjects to walk as they naturally would while using a variety of test footwear. By walking naturally, the hydrodynamic forces at play on snowy and icy surfaces are more accurately represented than by putting two surfaces in contact with one another and mechanically applying a single axis sliding motion. Natural gait allows the footwear to be used as they would be in a natural environment. Step characteristics, heel contact angles, supination or pronation of the feet, and control of the upper body are all captured in this human-centred test.
Studies III and IV show that the test method for determining the maximum achievable incline angles of footwear can be simplified in future iterations. Testing can be limited to only level and down-sloped walking. Furthermore, while it was of interest in these experiments to track kinematics of the feet and upper body, these are not necessary for determining maximum inclines. Evaluating gait characteristics in these two studies did show that comparing step characteristics on only level slippery surfaces was not sufficient for making inter-footwear comparisons. For example, footwear that was associated with higher step speeds and longer step lengths on level surfaces were not necessarily associated with greater maximum achievable incline angles. The range in gait characteristics indicated also that participants did not need to be prescribed specific walking speeds or cadences to produce consistent results. Prescribed walking speeds and cadences, such as those used in Study II, are often unnatural (Mallinson & Longridge, 2008) and can introduce confounding factors as it may serve to test the participant’s ability to achieve the required speed or cadence as opposed to testing the isolated effects of footwear.

The standard deviations calculated in Study IV can be used to determine the sample size \( n \) required to show with 95% confidence that the mean maximum achievable incline angle of each footwear-surface combination of the sample is within one degree of the population mean (or the true mean). For a 95% confidence interval, the \( z \)-score is 1.96 and thus the bounds of the confidence interval can be calculated by the following:

\[
\text{Lower boundary} = \text{sample mean} - \frac{1.96 \times \text{sample standard deviation}}{\sqrt{n}} \tag{6.1}
\]
\[
\text{Upper boundary} = \text{sample mean} + \frac{1.96 \times \text{sample standard deviation}}{\sqrt{n}} \tag{6.2}
\]

Considering only descent trials, the greatest standard deviation observed during the fourth study was for Style-J footwear on wetted ice (SD=2.3). Assuming the standard deviations of future test samples are less than or equal to 2.3, the required sample size is calculated at 20. Thus, based on the protocol used in the fourth study, a sample size of 20 is sufficient for determining with 95% confidence that the true mean, or the mean maximum achievable incline angle of the population is within plus or minus one degree of the sample mean. For footwear-surface combinations that demonstrated smaller variances, the required sample size is smaller. For example, across each of the poorer performing styles (K, S, G, and N), the
The greatest standard deviation across all surfaces was 1.7, corresponding to a required sample size of only 11 participants.

In selecting the participant sample, past experience is also important to consider. In the maximum achievable incline studies, naïve testers were used. The ability to use naïve testers who do not require training or calibration using standardized footwear or surfaces (as is used in the Australian Standard® short adjustable incline tests (AS 4526, 2013)) is an advantage of this test. However, there are implications with the use of naïve testers that must be considered. Because the strategies for maintaining and recovering balance on slip resistant surfaces are learned, and it is not well understood how long such techniques take to learn or how they change over time, people who are completely naïve to winter conditions may perform significantly more poorly on winter test surfaces than those who have previously experienced wintry surface conditions. For all four studies, while participants were naïve to the test protocols, only people who had lived in a winter-experiencing climate for at least one winter season and also self-reported routinely walking outdoors in the winter, were recruited. Furthermore, when comparing the same footwear, participants were able to achieve greater angles on the wet ice in Study III than on the wet ice used in Study IV. Inherent differences between the two test surfaces likely contributed to the distinct results but differences between the test protocols of the two studies likely also played a role. Participants in the third study completed standing tests prior to the walking tests and were generally able to stand without sliding at greater angles than they were able to successfully achieve while walking. The initial exposure to the tilting walkway while standing may have affected the outcome of the walking trials as participants were familiarized with the steep tilt angles prior to walking. During the pre-exposure, participants may have learned how to shift their weight in response to the tilting platform and/or become more comfortable with the safety harness system. Participants also wore the test footwear for longer periods of time. Learning and fatigue effects over the course of the experiment were accounted for by randomly assigning the test order of footwear for each participant but these effects limit how comparable results are between experiments utilizing different protocols.

The learning and fatigue effects are extremely important when it comes to standardizing the measurement of footwear slip resistance using the maximum achievable incline method. In
future work, these effects must be quantified and appropriately controlled across experiments. A repeated measures design, whereby each participant tests a number of types of footwear on one or more surfaces is the most feasible for this type of testing because it reduces the time required for preparation and recruitment. However, the number of styles of footwear tested in one session may need to be limited depending on the significance of learning and fatigue effects. These combined effects can be assessed by measuring the intra-participant repeatability of the outcome when a single participant repeats the same test protocol for determining the maximum achievable incline using a single footwear-surface combination multiple times during one session (Bartlett & Frost, 2008). Similarly, if non-naïve subjects are to participate in multiple test sessions testing different footwear, whether a wash-out period is required and how long it should last must be determined. This can be determined by testing intra-participant outcomes with the same footwear-surface with varying lengths of washout periods (overnight, one week, two weeks, etc.). The washout period should be set as the minimum amount of time necessary for the same subject to attain the same test results for a single footwear-surface combination.

If the maximum achievable method is to be used on a wider scale to test footwear slip resistance, reproducibility of the results should also be assessed. Once a complete protocol has been fully established, reproducibility can be assessed by comparing outcomes from different laboratories using the same method to assess the same footwear using different participant samples (Bartlett & Frost, 2008). The acceptability of the repeatability and reproducibility of standard test methods should be assessed according to ISO 5725 (ISO 5725, 2005) which describes methods for calculating precision and accuracy of measurement methods and results (Jung & Fischer, 1993).

6.2 Advantages and Limitations

In these four studies, three approaches to testing footwear slip resistance were utilized: bench-testing according to ASTM F2713-11, participant-based tests on short level and uneven walkways, and participant-based tests using maximum achievable inclines. Each approach is associated with its own advantages and limitations.
Bench tests of footwear slip resistance allow expedited testing of footwear in controlled conditions. These tests do not require recruitment of subjects or training of testers who may experience fatigue over time. Testing of a single type of footwear on a non-winter surface requires approximately 30 minutes. Additionally, three hours is required to prepare ice surfaces according to SATRA TM144. Because of the tight controls in terms of the movement of the footwear and the formation of the test surface, the repeatability of this method is theoretically high. However, the literature suggests that this is not the case, particularly in inter-laboratory comparisons (Jung & Fischer, 1993). The biggest problem associated with the standard mechanical test is its validity as discussed previously and the fact that the parameters used do not replicate those observed during normal walking as shown in the second study. Furthermore, the conditions used are not representative of realistic winter conditions.

The human-centred method of measuring slip severity while walking on a variety of commonly occurring surface conditions in different types of footwear utilized in Study II demonstrates superior ecological validity in comparison to the bench tests. The human-centred method allowed participants to walk at self-selected and faster cadences on level surfaces and slopes existing in outdoor environments using a realistic simulation of icy winter conditions. However, the short walkway did not allow participants to reach steady-state gait. The walkway lengths were maximized in the test space but the need to isolate the force plates situated below the walkway panels meant that it was necessary for participants to adjust their step lengths in order to take a single step on each of the centre walkway panels. The panel positions and sizes were optimized in the limited space through pilot work to accommodate a wide range of participant heights and therefore step lengths. The fixed positions of the panels however, meant that even though participants could walk at a self-selected cadence, they did have to adjust their step length to avoid stepping on the gaps between walkway panels, thereby affecting their natural gait.

A major limitation of Studies I and II that continues to pose challenges in the testing of cleats is the effect that the sharp cleats have on the icy surfaces during testing. More efficient methods of resurfacing and maintaining the ice surface would be very useful for future
experiments and limiting the number of consecutive trials over a small surface area would also be useful.

Another limitation of Studies I and II was in the reporting of slips at the instance of a slip. This information was not collected during each step or each trial but was reported after multiple trials. Because recollection after-the-fact can be inaccurate, a synchronized signal indicating slips at each step would be a better method for recording participant-detected slips. Ideally, methods of automatically detecting slips in real-time could be used but such methods remain under development (Lincoln & Bamberg, 2010; McGorry et al., 2007).

The major advantages of the maximum achievable incline method have been described previously. Most importantly, this method was shown to produce consistent results while incorporating natural human gait and adaptations to slippery surfaces. Although there was inter-participant variability in gait kinematics, the maximum achievable incline provided a holistic measure of slip resistance that was consistent between participants. The winter conditions that can be maintained in Winterlab are also wide-ranging and can be carefully controlled. A limitation of testing in Winterlab is that it is costly to use the facility and especially to use the six degree of freedom motion simulator. However with simplifications to the test protocol, for example measuring maximum achievable inclines only during descent, the time required for testing could be significantly reduced. The capabilities of the current laboratory space also far exceed the needs of the test method. Only a single-axis tilting platform is required (with a safety harness) and adjustable ramps can be built inside climate-controlled environments as opposed to tilting entire laboratories which would reduce the costs and time necessary to test footwear. Furthermore, the time and costs associated with equipping the facility and participants with a motion capture device for collecting kinematic data could be eliminated because the primary outcome measure is simply the incline angle of the surface. In Studies III and IV, capturing foot and trunk motion was an asset, allowing for the determination of strategies used to maintain balance at increasing inclines. These strategies were useful for comparison against walking on the level and since the variables were selected based on established literature, the kinematic outcomes could also be compared to those of previous studies.
Currently, the maximum achievable incline methods as per the protocols used in Studies III and IV were able to distinguish between surfaces and footwear. Further validation is required to relate results while walking on increasingly steep slopes to the likelihood of slipping and falling on level surfaces and additional work is required to develop a meaningful threshold for acceptable maximum achievable angles. Such issues are addressed in the following section.

6.3 Future Works

6.3.1 Cleated Footwear

More definitive recommendations are required with respect to the design of cleated footwear. The number of cleats, the shape of the cleats, and the locations of the cleats underfoot, specifically how far back along the heel the cleats should be positioned in order to prevent slips at the heel without increasing the likelihood of tripping, must be optimized. To do so, human-centred tests should be undertaken to examine the effects of varying each characteristic at multiple levels, for example comparing 1.5mm, 2.5mm and 3.5mm long spikes while keeping all other characteristics the same. Interactions between characteristics should also be explored, such as whether multiple shorter spikes is more or less effective than fewer longer spikes.

Ideally, the test method should be sensitive to small differences in the footwear without requiring a large sample size because there are so many characteristics and potential levels of testing. Although slips were observed while wearing both the cleated and non-cleated footwear during Study I, the experimental setup was not ideally suited to truly challenge the test footwear. While wearing cleats, very few slips were observed. Increasing the likelihood for slipping while still using realistic winter conditions, would improve the ability to discern differences between various characteristics of the cleats. Possible approaches to increasing the likelihood of slipping include using a longer walkway or track that would allow for faster walking speeds, and using steeper slopes which would be more slippery. Visually obscuring the icy surfaces to the participants and changing the location of the slippery surfaces to reduce the effects of anticipation would also be effective. Darkening the room and/or asking
participants to wear glasses that block the lower portion of their field of view are methods that can be used to conceal the icy surface(s) from participants (Cham & Redfern, 2002). Study I also demonstrated that in tests where slips are anticipated, a small patch of ice does not adequately induce slips and that sections of ice that require at least two steps to traverse are more challenging.

Another consideration for future work is the use of the maximum incline method to study cleat designs. A major caveat in doing so is that the effectiveness of cleats is largely determined by their ability to penetrate into surfaces and this is critically affected by the angle of impact and shifting of body weight over the ground surface. Non-cleated footwear relies on friction rather than penetration to provide slip resistance. As such, specific validation of the maximum achievable incline method for determining the effectiveness of cleats while walking on level ground is necessary.

6.3.2 Validating the Maximum Incline Method on Level Ground

For non-cleated footwear, there are many approaches that can be taken to validate the maximum achievable incline method once a definitive test protocol is established (including the minimum number of subjects, allowable number of test footwear, appropriate test conditions, and precise walking task). Bench-tests should also be similarly validated. A potentially distinct advantage of the maximum incline method is that because naïve testers are involved, different populations who may demonstrate different results can be used to test footwear. For footwear specifically designed for use by older adults for example, older adult testers should be involved. Because older adults tend to have poorer balance and may not be as strong as younger adults (Lockhart et al., 2003), it is expected that their maximum achievable incline angles would be smaller than those of younger adults when testing the same footwear. Similarly, population groups with specific mobility deficits such as arthritis of the lower extremities or an obese population may show similarly reduced results. This information would serve to inform the development of thresholds in terms of acceptable achievable inclines for different populations. For the young, able-bodied population that was
studied along with results from additional populations of interest must be further validated against normal walking activities.

The results of the maximum achievable incline method should be compared to measured outcomes of slip severity during normal walking on corresponding test conditions for level ground. In Chapter 1, many different methods that have been used by a host of different researchers studying slips and falls during level walking were described. For example, Lockhart et al. (2002) had participants walk on a closed circular track and step on unexpected slippery surfaces and measured the frequency of slips, slip distance, slip velocity, and the likelihood of slipping. Strandberg (1985) measured lap times as participants walked as quickly as possible around a triangular track without slipping. Level walking tasks may also include walking on uneven ground, turning, stopping, and load carrying tasks. Any of these measures of performance during level-ground walking can be compared to measures of the maximum achievable incline angles using identical test conditions and test footwear. By testing a wide range of footwear-surface combinations, Bland-Altman plots (Bunce, 2009) could be created to determine whether there is good correlation and agreement between the level ground and maximum incline methods and to observe how the methods relate to one another. With increasing incline angles, gait is adapted not only as a response to the increasingly slippery condition but also as a response to the tilt angle itself. Gait adaptations to steeper slope angles may impact the correlation between slip severity on level ground and the maximum achievable incline angle. Potential impacts include the linearity of this relationship or how highly correlated they are with increasing incline angles.

Outside of the laboratory, another method for validating the maximum achievable incline method against performance in the field is to test the hypothesis that winter footwear that allows for steeper slopes to be achieved will lead to fewer outdoor slips and falls in winter. To test this hypothesis, the maximum achievable incline method can be used to select various styles of footwear that demonstrate a range of maximum achievable incline angles when averaged over multiple winter test surfaces. The footwear can then be randomly assigned to groups of consenting participants for use over the course of a winter. Their outdoor exposure (including number of steps and environmental conditions) could then be carefully tracked using tools such as pedometers and GPS and occurrences of significant slips or falls could be
recorded. By testing a large sample of users, the correlation between maximum achievable incline angle and the likelihood of slipping can then be determined. To conduct such a study, safety issues must be very careful considered and participants should not be put in any danger beyond that which they would normally be exposed to. For example, only winter footwear already available on the market could be tested, and perhaps only those that have been labelled “slip resistant”.

The existing criteria for the labelling of slip resistant footwear, or the determination of whether a type of footwear is safe or unsafe, must also be addressed in future work. The simple requirement that footwear be tested according to ASTM F2713-11 and that the results be published is unacceptable. Consumers need to be given meaningful thresholds of slip resistance based on empirical evidence. The validation studies described previously can provide important information for determining appropriate thresholds for deeming footwear slip resistant and these results can be made specific to different test populations so that eventually slip-resistant footwear can be prescribed to consumers based on their needs and abilities. Population-specific kinematic measures collected during slips on level surfaces should also be used to further verify the validity of standard bench tests for different populations. Differences in gait kinematics described by Lockhart et al. (2003) such as increased heel contact velocity and reduced transitional centre of mass acceleration in older adults suggest that a faster sliding speed and lower vertical load may better simulate stepping patterns of older adults on the bench test. The data regarding frequency and likelihood of experiencing hazardous slips, as defined by peak sliding velocities or slip distances (Moyer et al., 2006), can be used to determine acceptable rates and corresponding maximum achievable incline angles. At a minimum, footwear that is failing at or below slope angles allowed for ramps under current building codes should not be labelled slip resistant. Beyond labelling footwear as safe or unsafe, once a validated maximum achievable incline method is established, it can also be used to optimize footwear designs. Any combination of materials, tread shapes, tread depths, and heel contours can be used to determine their effectiveness on a range of surface conditions with the ideal footwear consisting of a sole design that demonstrates excellent performance across conditions.
6.4 Significance

The work conducted in the four studies comprising this thesis, has contributed to the understanding of the design of winter footwear, the effects of winter surface conditions, and the measurement of footwear slip resistance. Cleated winter footwear was found to reduce slip frequency but also be associated with occasional severe slips while walking on icy surfaces, demonstrating the need to further optimize cleated footwear for enhanced effectiveness and improved compliance.

The mechanics of slips while using non-cleated footwear were also examined and used to propose improvements to the current standard method of assessing footwear slip resistance. Recommended changes to the current method are: increasing the maximum test foot angle from 7° to 14° and increasing the test sliding speed from 0.3m/s to 0.5m/s.

A new test method was also developed to differentiate between the slip resistance of different styles of footwear that was also straightforward and ecologically valid. The developmental work to establish this method of finding the maximum achievable slope angles on a variety of winter surfaces while walking, was shown to be a viable approach to measuring footwear slip resistance. This work indicated that for footwear that is intended for use in winter conditions, testing on both snowy and icy conditions is imperative. While future work is necessary to fully validate results of this method against slips and falls during level-ground walking, because the maximum incline method is conceptually easy for consumers to understand, it shows promise as a powerful tool for the development and proliferation of effective footwear for preventing winter slips and falls.

References


Appendix
Gait Kinematic Data for Study IV

Table A.1. Kinematics averaged across eight subjects (mean (standard error)) during level-ground walking.

<table>
<thead>
<tr>
<th>Surface</th>
<th>Footwear</th>
<th>Gait speed (m/s)</th>
<th>Step width (m)</th>
<th>Step length (m)</th>
<th>Step time (s)</th>
<th>Step speed (m/s)</th>
<th>Foot angle (°)</th>
<th>UB Flexion (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Snow</td>
<td>K</td>
<td>0.78(0.03)</td>
<td>15.5(1.6)</td>
<td>0.51(0.02)</td>
<td>0.66(0.02)</td>
<td>0.78(0.03)</td>
<td>15.5(1.6)</td>
<td>88.7(3.0)</td>
</tr>
<tr>
<td></td>
<td>S</td>
<td>0.79(0.05)</td>
<td>17.1(1.4)</td>
<td>0.51(0.02)</td>
<td>0.65(0.03)</td>
<td>0.79(0.06)</td>
<td>17.1(1.4)</td>
<td>89.1(2.6)</td>
</tr>
<tr>
<td></td>
<td>G</td>
<td>0.76(0.02)</td>
<td>14.4(0.8)</td>
<td>0.52(0.02)</td>
<td>0.69(0.01)</td>
<td>0.75(0.02)</td>
<td>14.4(0.8)</td>
<td>88.7(3.1)</td>
</tr>
<tr>
<td></td>
<td>N</td>
<td>0.80(0.04)</td>
<td>18.2(1.9)</td>
<td>0.53(0.01)</td>
<td>0.68(0.03)</td>
<td>0.80(0.04)</td>
<td>18.2(1.9)</td>
<td>88.9(2.8)</td>
</tr>
<tr>
<td></td>
<td>I</td>
<td>0.85(0.06)</td>
<td>15.2(1.6)</td>
<td>0.54(0.02)</td>
<td>0.64(0.02)</td>
<td>0.85(0.06)</td>
<td>15.2(1.6)</td>
<td>90.9(2.7)</td>
</tr>
<tr>
<td></td>
<td>J</td>
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<td>20.2(1.3)</td>
<td>0.55(0.02)</td>
<td>0.66(0.03)</td>
<td>0.85(0.06)</td>
<td>20.2(1.3)</td>
<td>90.2(2.2)</td>
</tr>
<tr>
<td>Wet Ice</td>
<td>K</td>
<td>0.77(0.04)</td>
<td>14.0(0.9)</td>
<td>0.50(0.02)</td>
<td>0.66(0.03)</td>
<td>0.77(0.03)</td>
<td>14.0(0.9)</td>
<td>91.3(2.2)</td>
</tr>
<tr>
<td></td>
<td>S</td>
<td>0.81(0.05)</td>
<td>16.0(1.1)</td>
<td>0.51(0.03)</td>
<td>0.64(0.03)</td>
<td>0.80(0.05)</td>
<td>16.0(1.1)</td>
<td>91.8(2.6)</td>
</tr>
<tr>
<td></td>
<td>G</td>
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<td>16.7(1.3)</td>
<td>0.54(0.03)</td>
<td>0.67(0.02)</td>
<td>0.82(0.05)</td>
<td>16.7(1.3)</td>
<td>92.6(2.8)</td>
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<tr>
<td></td>
<td>N</td>
<td>0.75(0.04)</td>
<td>15.7(0.7)</td>
<td>0.50(0.02)</td>
<td>0.67(0.03)</td>
<td>0.75(0.04)</td>
<td>15.7(0.7)</td>
<td>93.0(2.5)</td>
</tr>
<tr>
<td></td>
<td>I</td>
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<td>16.0(1.0)</td>
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<td>0.64(0.02)</td>
<td>0.85(0.03)</td>
<td>16.0(1.0)</td>
<td>94.3(1.5)</td>
</tr>
<tr>
<td></td>
<td>J</td>
<td>0.80(0.05)</td>
<td>20.6(1.4)</td>
<td>0.54(0.02)</td>
<td>0.68(0.02)</td>
<td>0.80(0.05)</td>
<td>20.6(1.4)</td>
<td>92.3(2.0)</td>
</tr>
<tr>
<td>Dry Ice</td>
<td>K</td>
<td>0.74(0.05)</td>
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Table A.2. Kinematics averaged across eight subjects (mean (standard error)) at the maximum achievable incline angles during ascent.

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<th>Angle (°)</th>
<th>Gait speed (m/s)</th>
<th>Step width (m)</th>
<th>Step length (m)</th>
<th>Step time (s)</th>
<th>Step speed (m/s)</th>
<th>Foot angle (°)</th>
<th>UB Flexion (°)</th>
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<tbody>
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<td>K</td>
<td>4.6(0.3)</td>
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<td>0.09(0.01)</td>
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<td>98.8(3.1)</td>
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<tr>
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<td>0.93(0.08)</td>
<td>0.51(0.05)</td>
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<td>100.8(3.2)</td>
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<td>0.93(0.08)</td>
<td>0.53(0.05)</td>
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<td>101.8(3.4)</td>
</tr>
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Table A.3. Kinematics averaged across eight subjects (mean (standard error)) at the maximum achievable incline angles during descent.

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<th>Footwear</th>
<th>Angle ('°)</th>
<th>Gait speed (m/s)</th>
<th>Step width (m)</th>
<th>Step length (m)</th>
<th>Step time (s)</th>
<th>Step speed (m/s)</th>
<th>Foot angle ('°)</th>
<th>UB Flexion ('°)</th>
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<tbody>
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<td>4.3(0.4)</td>
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<td>0.11(0.01)</td>
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