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The effect of tread patterns on slip resistance of footwear outsoles based on composite materials in icy conditions

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ABSTRACT

Introduction: Falls on icy surfaces are the leading cause of injuries for outdoor workers. Footwear outsole material and geometrical design parameters are the most significant factors affecting slips-and-falls. Recently, composite materials have been incorporated into outsoles to improve traction, yet the best design parameters are not fully understood. *Method:* In this effort, based on Taguchi orthogonal array design, 27 outsole prototypes were fabricated with different tread pattern features using our patented composites and tested in a simulated winter condition. *Results:* An analysis of variance (ANOVA) showed that surface area ($p = 0.041$, *Contribution* = 15.63%) was the only factor significantly affecting the slip-resistance of our prototypes. The best performance was observed for the maximized surface area covered by our composite material with circular and half circular plugs laid obliquely, mostly in the forefoot area. *Practical Applications:* These findings suggest that some tread design features of composite-based footwear have a great role in affecting slip-resistance properties of composite-based footwear.

1. Introduction

Slip-and-fall incidents are one of the leading causes of workplace injuries for workers exposed to outdoor conditions during winter seasons (Bagheri et al., 2019c, 2021). According to the U.S. Bureau of Labor Statistics, there were 42,480 workplace slip and fall injuries involving ice, sleet, or snow in 2014, and these injuries are projected to double by 2050 (Bureau of Labor Statistics, 2014). The problem is more serious for workers in industries that have been identified as the most hazardous workplaces in the United States, in particular the agricultural, forestry, fishing, and hunting (AFFH) industries, who reported a fatal injury rate of 23.4 per 100,000 workers along with a nonfatal injury rate double the national average (Baidwan et al., 2021). Being recognized as the leading cause of slip- and fall-related injuries, lack of traction has resulted in 15.8% of nonfatal and 25.8% of fatal injuries in AFFH industries (Baidwan et al., 2021).

For context, in the Alaskan commercial fishing industry, fall overboard caused 26% of serious injuries resulted in hospitalization (Thomas et al., 2001). Another study comparing the rate of slip-incidents for fishermen wearing slip-resistant footwear versus regular boots reported more frequent slips with regular boots at a rate of 74% as opposed to slip-resistant footwear at a rate of 52% (Jensen & Laursen, 2011). Workers in the agricultural industry are another group of workers who are exposed to outdoor winter condition and are at high risk of experiencing slips-and-fall incidents. For instance, in a study from Florida agriculture, falls were reported to account for nearly 25% of all serious disabling work injuries (NASD, 2022). In another study from New Zealand, workforce in the dairy farming industry reported a notably larger number of slips, trips, and falls, mainly in wet, icy, and relatively uncontrolled environments, compared to other major industry sectors (Bentley et al., 2005). Another group of workers who are at high risk of experiencing slip-and-fall incidents are Personal Support Workers (PSWs) since they have to travel to and from their clients' houses during different weather conditions, including icy and snowy weather (Bagheri et al., 2019b). A recent survey study of 740 PSWs in Illinois found that 12% of these worker groups experienced a slip, trip, or fall during their travel to their client visits (Muramatsu et al., 2018), most of which were caused by slipping on ice (Elfering et al., 2018). Efforts have been done to minimize the occurrence of slip and fall incidents and subsequent injuries by enhancing footwear-floor traction via production of novel composite material as well as other contributors to enhance coefficient of friction (COF) between the footwear outsole and the floor sur-

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face underneath (Bagheri et al., 2019c; Bagheri, 2019). Some examples include outsole material, surface area, orientation, edge shape, roughness, groove depth, and groove width (Blanchette & Powers, 2015; Li & Chen, 2004; Li, Chen, & Lin, 2006; Petersen et al., 1996), yet mostly for indoor surfaces.

Slip-resistant footwear has been identified as a promising solution to enhance traction and minimize the risk of slip and fall incidents (Aschan et al., 2009; Gao et al., 2004). However, until recently, most of the previous efforts in this regard were limited to indoor surfaces only (Bagheri et al., 2022; Health & Excecutive, 2023; Verma et al., 2011). For instance, Verma et al. (Verma et al., 2011) reported that slip-resistant footwear reduced the risk of slipping by 54% among the restaurant workers. Though promising, these findings are not representative of the performance of the footwear on icy condition, experienced often during winter seasons (Bagheri et al., 2021, 2019a, 2020). It should be noted that features of footwear outsole that make it favorable for indoor surfaces may not necessary be applicable to outdoor icy surfaces (Bagheri et al., 2019b, 2022). Materials that are slip resistant on contaminated surfaces may not be the best material candidates for icy surfaces (Skouvaklis et al., 2012). More importantly, rubber friction on ice is highly dependent on ambient air temperature (Gao et al., 2004; Jakobsen et al., 2023; Lahayne et al., 2016). For instance, Jackson et al. (Jakobsen et al., 2023) compared between the friction properties of three elastomeric outsoles, including low-pressure injection of polyurethane (PU), injection molding of thermoplastic polyurethane (TPU) and vulcanization of rubber (RU) and reported high static and dynamic ice friction for RU and PU, in turn, at low and high temperatures. In icy weather, slipping accidents occur because of inadequate friction between the shoe outsole and the underfoot surface (Bagheri et al., 2022; Bagheri, 2019), which makes it very difficult to maintain grip as a person walks. This is related to the formation of inherent quasi-liquid layer at footwear-ice interface even at very low temperature. This layer acts as a lubricant and makes the traction on ice much more challenging compared to non-icy surfaces (Bagheri et al., 2022; Bagheri, 2019). It should be noted at temperatures closer to the melting point of ice, the thickness of this layer increases, reducing the friction on ice even more. The reason is that at such temperatures adequate latent heat will be provided (i.e., 80 cal/g or1.4 kcal/mol) that enables breaking about 10% of dangling hydrogen bonds in polar water molecules (Rosenberg, 2005). In addition, frictional heating as well as surface pressure that happen at sliding speed above $\sim$10 mm/s contribute to an increase in the thickness of this liquid-like layer, making ice surface more slippery (Bowden & Hughes, 1939; Colbeck, 1988; Dash et al., 2006; Kietzig et al., 2010; Li & Somorjai, 2007). As such, there is a need to develop footwear that can provide traction on ice for real-world application, thus preventing balance loss and potentially reducing the risk of slip-and-fall related injuries during winter seasons. In this effort, part of our team at Toronto Rehabilitation Institute has come up with a novel methodology called Maximum Achievable Angle (MAA) test in a simulated winter condition, called WinterLab, which measures the steepest ice-covered slope on which a participant can walk up and down on without experiencing a slip (Hsu et al., 2015, 2016).

To date, all the commercial footwear that performs relatively well in our MAA testing protocol are based on composite material. These composites utilized soft rubber layers with hard particles protruding out to the surface on a microscopic level, as such they can penetrate ice substrate underneath and provide traction via mechanical interlocking (Bagheri, 2019; Shaghayegh Bagheri et al., 2019). Our previous work showed that composite materials provide a better grip on ice than conventional outsole materials for footwear application (Anwer et al., 2017; Bagheri, 2019; Rizvi et al., 2015, 2016). While composite-based footwear are promising, there are a few shortcomings associated with their long-term use (Bagheri et al., 2021, 2022). For instance, in a previous study done by members of our team, a significant loss in the ice friction performance of composite-based footwear was noticed just after 75,000 steps (Bagheri et al., 2022). For context, it is not uncommon for a person to walk around 10,000 steps in a day (Tudor-Locke & Bassett, 2004), but may be required, especially in the agricultural and fishing industry, where one must be active (Cutler et al., 2003; Ogden, 2017). Therefore, this threshold will be reached within a few weeks and the footwear will need to be replaced quite often, which is impractical for most users.

To address these shortcomings, part of our team has developed and patented a new composite material for use with slip-resistant footwear with durable properties using Thermoplastic Polyurethane (TPU), Carbon Fiber (CF), and Zylon Fiber (PBO) (Shaghayegh Bagheri et al., 2019). Previous lab-based testing based on SATRA measurements has demonstrated that these materials can provide COF five times greater than the best composite-based footwear in the market (Shaghayegh Bagheri et al., 2019). The reason is that flexible PBO fibers embedded in the TPU matrix absorb the energy generated from friction while the rigid CF protects the PBO-TPU substrates from mechanical damage, these two features along with lower elastic modulus of the TPU matrix resulting in durable slip-resistant properties (Shaghayegh Bagheri et al., 2019). Even though our novel composite material shows many promises to be used with winter footwear, its proper use with the footwear outsole tread design for icy conditions is not yet known. Previous research has shown that there are a variety of geometrical factors of outsole tread design that can affect a shoe's COF (Chang, 2004; Li, Chen, & Lin, 2006; Liu et al., 2013), yet all of these efforts are focused on indoor surfaces. For instance, it has been shown that tread groove orientation, location, shape, and surface area, all have a large impact on the COF on indoor surfaces (Blanchette & Powers, 2015; Li & Chen, 2004; Li, Chen, & Lin, 2006); however, their effect for use in outdoor surfaces, in particular on icy conditions, is not yet known. As such, to develop composite-based footwear with durable ice-friction properties to be used in outdoor surfaces, it is essential to develop a solid understanding of how slip-resistant properties of composite-based footwear are governed by its tread design features.

Therefore, this study aims to investigate the interplay between tread design features and slip-resistant properties of composite-based footwear on icy conditions. To the best of authors' knowledge, this is the first study to explore the relationship between ice friction properties and tread design of footwear outsole for use with composite materials. To guide the design of this research, the Taguchi fractional factorial experimental method was utilized to recognize several potential design variables that may significantly affect slip-resistant properties of composite-based footwear (Baidwan et al., 2021; Freddi & Salmon, 2019; Tsui, 1992). This allows us to find the most efficient combination of geometrical parameters without having to test every single combination, as opposed to full factorial design, thus lowering the number of samples needed to be tested (Freddi & Salmon, 2019; Tsui, 1992).

This study is the first to evaluate both the individual and combined impact of tread design parameters utilizing the composite materials on slip-resistant properties of footwear outsole in icy conditions. The composite material used in this study is our patented CF-PBO-TPU, which has been shown to have a high COF in our previous studies (Bagheri, 2019; Shaghayegh Bagheri et al., 2019). This study aims to determine if adjustments to any of these design parameters would have any significant effect on the slip-resistant properties of the shoe outsole. For this purpose, four parameters each at three levels were selected to cover the range of values based on findings reported in the literature. Three out of four parameters, including surface area, orientation, and edge shape, were selected according to the relevant literature as they were shown to considerably affect the slip-resistant properties of the shoe outsole in indoor surface (Blanchette & Powers, 2015; Li & Chen, 2004; Li, Chen, & Lin, 2006; Petersen et al., 1996). Plug distribution, however, was chosen due to its potential theoretical impact on the gait cycle analysis as well as its correlation with other (i.e., surface area, orientation, and edge shape) design parameters. Using plug distribution term, we explain the location and arrangements of the plugs on the outsole based on pressure distribution and gait cycle analysis. The reason is that a proper outsole design must have adequate support where it is necessary (Luger et al., 1999; Soames, 1985). These design criteria were utilized to develop composite-based footwear prototypes, which were tested in a simulated winter condition (i.e., WinterLab) to evaluate their ice-friction properties.

2. Materials and methods

To determine the tread design parameters that have the most significant effect on slip-resistant properties of footwear based on our composite material, we decided to use the Taguchi method to conduct our experiment. This method allows us to find the most optimal combination of geometrical parameters such as surface area, orientation, edge shape, plug distribution and their internal interactions to identify the most slip-resistant footwear outsole design for use with composite materials. Based on the Taguchi L_{27} orthogonal array table, 27 pairs of footwear prototypes with unique combinations of plugs based on our composite material were made and tested in WinterLab facility for their ice-friction performance. First, all the composite plugs for this research were fabricated using a custom-made mold through a plastic injection molding process. Second, the plugs were abraded with an abrasion tester machine and detected via scanning electron microscopy (SEM) for their surface topography. Finally, composite plugs were utilized to create footwear outsole prototypes.

2.1. Mold design for plugs

To fabricate our composite plugs through injection molding process, a house-made cylindrical mold with a diameter of 15.87 mm and a thickness of 38.1 mm was designed and manufactured. These dimensions were chosen to ensure the diameter of the final samples meet the size required for the holder of the abrasion tester machine. The mold was comprised of two parts combined by bolts as depicted in Fig. 1. Each of these parts has four regions: (1) the gate, (2) the runner, (3) the desired sample region, and (4) the oval shaped region. Considering the injection molding machines' requirements, a standard gate diameter and thickness of the mold were chosen in a way to enable proper mating between the machine nozzle and the mold. The exit diameter of the gate was designed to allow a continuous flow of the melted composites through connection with the runner, while slope of the runner determines how quickly the composite material fills out the cavity of the mold. The oval shaped region helped us to cut our mold in the milling machine by using a ball nose end mill.

2.2. Composite formation

Weighed on a precision scale (USS-DBS8 Digital Analytical Balance Scale), CF: PBO fibers at the volume of 8 vol% and 2:1 weight ratio were used to fabricate TPU-CF-PBO composite material based on our previous study (Shaghayegh Bagheri et al., 2019). The compound was mixed properly in a speed mixer (Hauschild Speed Mixer, Germany) at 2500 rpm for two minutes, and then added through a plastic injector (AB-100 Plastic Injector, Canada) with a controlled temperature range of 436°F-467°F and a pressure of 110 psi to ensure vertical alignment of the fiber relatively. Having manufactured the cylindrical samples successfully with a 31 mm length, the samples were cut into three pieces of 8 mm thickness using a bandsaw (Anbull Portable Bandsaw) to expose the embedded fibers to the surface. While only a 6 mm sample is needed for creating footwear prototypes, the extra height accounts for the composite lost during the abrasion tests, a step necessary to evaluate the composite material's resistance to wear and abrasion. The entire process diagram is depicted in Fig. 2.

2.3. Abrasion test

We selected to test our composites in abrasion to simulate real-world wear that happens during daily normal activities. This is because abrasion is reported to be one of the primary wear mechanisms observed in the outsole due to the sliding nature of walking mode (Kim, 2015). For instance, abrasive wear was reported as the predominant wear type on the heel area, which affects both the upper and lower layers of the heel surface (Kim, 2000). Moreover, our recent study showed that composite-based footwears are quite sensitive to wear and abrasion in real-world application, as they lose their ice friction properties for as little as 75,000 steps (Bagheri et al., 2022).

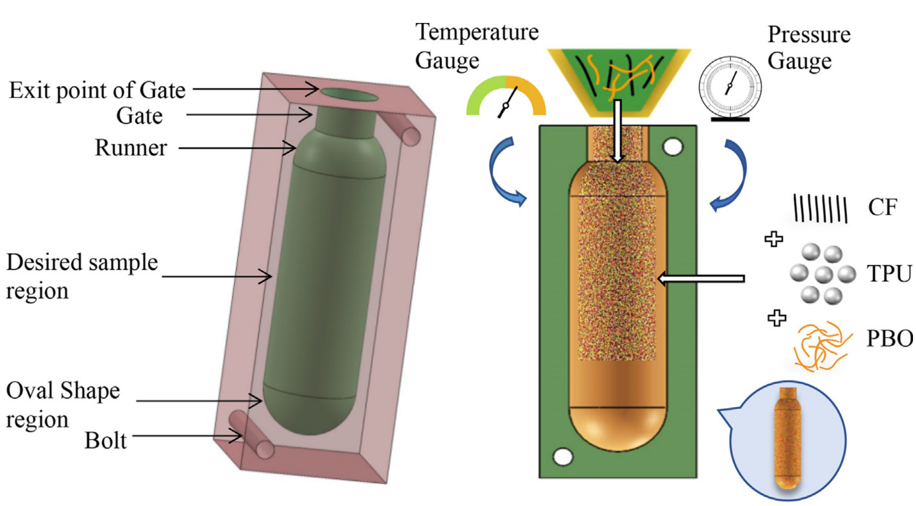

Fig. 1. Mold for making plugs based on our composite materials to be used in footwear prototyping.

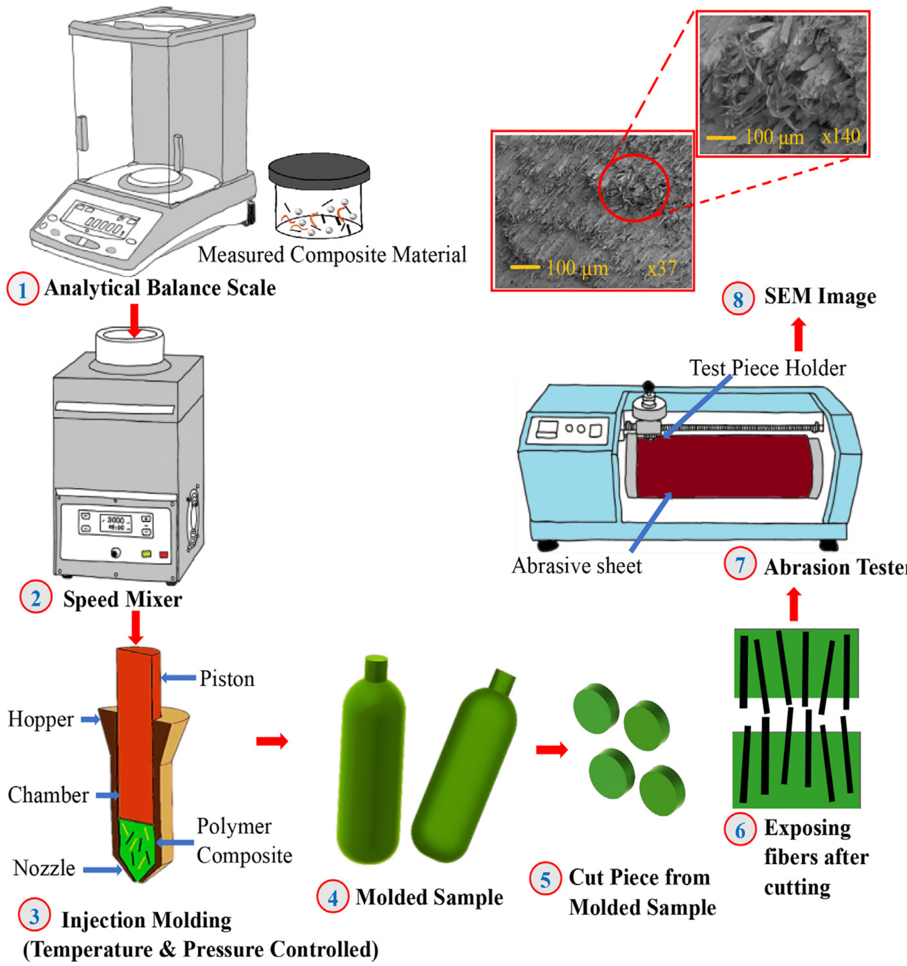

Fig. 2. Process diagram for composite material.

An abrasion test was carried out using a rotating drum abrasion tester (DIN Abrasion Tester NextGen Material Testing, Canada) to determine wear resistance properties of our composites and how it affects their surface properties. Abrasion Resistance Index (ARI) was calculated to measure the abrasiveness of our composite samples with respect to standard rubber samples using Eq. (1), where Δs_1 is the change in mass (milligrams (mg)) for standard rubber, Δs_2 is the change in mass (mg) for the composite, d_1 is the density of the rubber, and d_2 is the density of our sample. The mass of each sample was initially weighed, recorded, and the sample was placed in test piece holder of the abrasion tester. The samples were run for 1.5 cycles or 126 rotations against 60 grit sandpaper with a 10 N load applied based on the standard of the abrasion tester machine. During this process, the sandpaper is brushed with a paintbrush to remove excess material ingrained in the sandpaper.

$$\text{ARI} = \frac{\Delta S_1 * d_2}{\Delta S_2 * d_1} \times 100 \quad (1)$$

2.4. Scanning electron microscopy (SEM)

Under a Jeol JSM-7200F Field Emission Scanning Electron Microscope (SEM) (Musashino, Akishima, Tokyo), we observed the topography of the composite surface before and after abrasion test. SEM was also performed at high magnifications to qualitatively compare between the surface topography of our composites before and after abrasion. To make our samples conductive for SEM imaging, all samples were gold coated using a Denton Vacuum Desk V sputter coater (Moorestown, New Jersey, USA) in a pure argon chamber for 15 seconds. Carbon and copper tape were used to secure the coated sample and to provide grounding between the surface of the sample and the stub holder. We used 2.0 kV with the magnification of x 37, x 40, x 75 and x 140 to capture the image of the sample's surface.

2.5. Taguchi orthogonal array design

This study was designed using the Taguchi fractional factorial design method for four control factors each at three levels. Without the need for a full factorial study, this method is often used to find the effect of various parameters on selected outcome measures. For a full factorial design, four factors at three levels would require $3^4 = 81$ experiments. The Taguchi method allows for a fractional factorial approach decreasing the number of experiments from 81 to 27, while also analyzing individual and synergic effects of studied factors. The result is optimized with respect to the mean to standard deviation ratio, or the signal to noise ratio (S/N). The control parameters and levels used in this study are summarized in Table 1. These control parameters were chosen because there were several reports in the literature on their effect on the COF between the outsole and floor interface (Blanchette & Powers, 2015; Jones et al., 2018; Li, Chen, & Lin, 2006; Liu et al., 2013) where COF has been widely-used measure for determining the slipperiness level (i.e., the lower the COF, the greater the risk of slip (Liu et al., 2013).

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Table 1
Control factors and their level were used for this study.

Control Factor	Level			Unit
	1	2	3	
A: Surface area	2345.65	3127.54	3518.49	mm^2
B: Orientation	Perpendicular	Oblique	Hybrid	
C: Edge Shape	Circular	Half Circular	Mixture	
D: Plug Distribution	More on Toe area	More on Heel area	Spread Equally	

The first parameter used was the surface area of the outsole covered by the composite plugs. This is because increased surface areas covered will likely increase the contact area between the outsole and the ground, as such reduce contact pressure leading to higher COF and minimizing risk of slip-related injuries (Chang et al., 2001; Iraqi et al., 2020; Jones et al., 2018). In addition, shoe and plugs, along with various shoe-surface interface combinations, are significant contributors to knee and ankle injuries. There were reports in the literature where variation in shoe-surface interface combinations affects the degree of foot fixation and stresses imparted to knee structures in the articular and periarticular regions (Iraqi et al., 2020; Torg et al., 1974). When it comes to the loading of a human body, translational and rotational frictional forces seem to be important variables, which are highly dependent to the COF between the shoe and underfoot surface (Iraqi et al., 2020; Milburn & Barry, 1998). Some studies affirm that shoes with a minimum of 15 plugs of a 0.5 inch diameter (1899.18 mm^2 surface area) are safe and recommended for reducing ankle injuries (Milburn & Barry, 1998; Torg et al., 1974). A few other studies have shown that wider tread grooves result in better COF (Blanchette & Powers, 2015; Li, Chen, & Lin, 2006). The second parameter was plug orientation at three levels, including oblique (i.e., directed at a 45^0 angle to the length of the shoe), perpendicular (i.e., directed at a 90^0 angle to the length of the shoe), and hybrid orientation (i.e., combination of oblique and perpendicular) based on the previous literature (Blanchette & Powers, 2015; Li, Chen, & Lin, 2006). It was reported that oblique and perpendicular groove orientation resulted in greater COF compared to parallel grooves orientation (i.e., directed along the length of the shoe) in laboratory conditions for indoor surfaces (Blanchette & Powers, 2015; Li, Chen, & Lin, 2006). However, their effect on outdoor icy surfaces is not yet known. The third parameter was the edge shape with three levels, including circular, half circular, and hybrid consisting of both circular and half circular. Previous studies have shown that edge shapes are responsible for gripping the floor and can affect COF significantly in indoor surfaces (Blanchette & Powers, 2015; Chen et al., 2012). Simple geometric, regular, and repeatable shapes such as rectangular, circular, and square are used as slip-resistant pattern designs because of their maximum gripping for indoor surfaces (Chen et al., 2012; Irzmańska, 2015). Among all the tested geometries, circular shapes were recommended the most as other shapes could act as a barrier through creation of a wall that prevents liquid from moving away from the outsole (Chen et al., 2012; Irzmańska, 2015). The last parameter was the location of the plugs with three different levels: (1) composite plugs more concentrated on the toe area of the outsole, (2) composite plugs more concentrated on the heel area of the outsole, and (3) composite plugs spread equally throughout the outsole. These three levels were selected because the heel and the toe areas are the two regions that play major roles in human locomotion with gait parameters (Grönqvist et al., 2001; Luger et al., 1999; Redfern et al., 2001). For context, the value of the COF is highly dependent on the part of the foot that comes in contact with the floor during the gait cycle (Jones et al., 2018; Liu et al., 2013). Finally, we set the height of our composite plugs to 6 mm to follow the recommended range in the literature(i.e., 2–7 mm), which enables liquid drainage from areas underfoot that experience the greatest pressure during the gait cycle (Chen et al., 2012; Li, Chen, & Lin, 2006; Tisserand, 1985).

For each of the 27 runs, sample prototypes were made and tested for their MAA score in the WinterLab facility with two participants, leading to 54 trials in total (27 experiments according to Taguchi design × 2 = 54 trials). The MAA number was transformed into signal-to-noise ratio as the logarithmic transformation of the loss function using the "larger-is-better" performance characteristic as follows:

$$\frac{S}{N} = -10 \times log\left(\frac{\sum\left(\frac{1}{y^2}\right)}{n}\right) \tag{2}$$

where "n" is the number of observations and "y" is the observed data. This "larger-is-better" characteristic is suitable for determining the optimal tread design features leading to maximized MAA (i.e., improved slip-resistance properties on ice). The Analysis of Variance (ANOVA) was also performed to determine the factors that have the most significant impact on the slip-resistance performance of the footwear outsole. The optimal combination of outsole parameters was determined using the S/N ratio and ANOVA results. Minitab 21 (October 2021, Minitab Inc, Pennsylvania, USA) was used for all statistical analyses.

2.6. Shoe outsole (Prototype)

In total 141 composite plugs with 47 circular and 97 half circular shapes were made with an ARI score above 110 for footwear prototype preparation. To prepare footwear prototypes, the outsole of a normal boot was first covered using an overshoe (veloToze Roam, commuting shoe cover, Malaysia) to create a complete flat surface to attach our composite plugs. The composite plugs were attached to the overshoe according to Taguchi design as per Table 2 using Velcro. The schematic of our footwear prototype along with its mechanism of traction (i.e., mechanical interaction through penetration of hard fiber to the underfoot ice surface) is depicted in Fig. 3. All the footwear prototypes (Fig. 4) were tested for their slip-resistant properties with two participants (for a total of 54 trials) in Winterlab facility using the MAA protocol as discussed in Section 2.7.

2.7. Slip-resistance testing

For slip-resistance testing, MAA test, previously developed by part of our team, has been utilized (Hsu et al., 2015, 2016). This test method was approved by the Research Ethics Board at University Health Network (UHN), Toronto, Canada. During the MAA test, participants were required to walk up and down the steepest ice-covered incline they could walk without experiencing a two-foot slip, defined as an event when: (a) both feet slide on the ice surface or (b) one-foot slides on the ice surface while the other is in the air (Hsu et al., 2015, 2016). The first trial consisted of participants walking on a level walkway. Afterward, the ice-covered slope gradually increased while participants climbed and descended the

Table 2
Experimental design and output results using Taguchi L_{27} orthogonal array design. A 27-row orthogonal array design corresponding to 8 columns with three levels of experiments, where MAA scores represent the average of two trials. S/N: Signal to Noise ratio, C_i: Circular Plugs, HC_i: Half Circular Plugs.

Run	A (mm^2)	Number of Plugs	B	C	D	MAA	S/N
1	2345.65	12 C_i	Perpendicular	Circular	More on Toe area	3	9.54
2	2345.65	24 HC_i	Perpendicular	Half Circular	More on Heel area	4	12.04
3	2345.65	6 C_i + 12 HC_i	Perpendicular	Mixture	Spread Equally	4.5	13.06
4	2345.65	12 C_i	Oblique	Circular	More on Heel area	5	13.97
5	2345.65	24 HC_i	Oblique	Half Circular	Spread Equally	5.5	14.80
6	2345.65	6 C_i + 12 HC_i	Oblique	Mixture	More on Toe area	7	16.90
7	2345.65	12 C_i	Hybrid	Circular	Spread Equally	3.5	10.88
8	2345.65	24 HC_i	Hybrid	Half Circular	More on Toe area	5.5	14.80
9	2345.65	6 C_i + 12 HC_i	Hybrid	Mixture	More on Heel area	4.5	13.06
10	3127.54	16 Ci	Perpendicular	Circular	More on Toe area	5.5	14.80
11	3127.54	32 HC_i	Perpendicular	Half Circular	More on Heel area	6	15.56
12	3127.54	8 C_i + 16 HC_i	Perpendicular	Mixture	Spread Equally	5	13.97
13	3127.54	16 Ci	Oblique	Circular	More on Heel area	4.5	13.06
14	3127.54	32 HC_i	Oblique	Half Circular	Spread Equally	4	12.04
15	3127.54	8 C_i + 16 HC_i	Oblique	Mixture	More on Toe area	5	13.97
16	3127.54	16 Ci	Hybrid	Circular	Spread Equally	6	15.56
17	3127.54	32 HC_i	Hybrid	Half Circular	More on Toe area	4	12.04
18	3127.54	8 C_i + 16 HC_i	Hybrid	Mixture	More on Heel area	5	13.97
19	3518.49	18 Ci	Perpendicular	Circular	More on Toe area	6.5	16.25
20	3518.49	36 HC_i	Perpendicular	Half Circular	More on Heel area	5.5	14.80
21	3518.49	9 C_i + 18 HC_i	Perpendicular	Mixture	Spread Equally	6	15.56
22	3518.49	18 Ci	Oblique	Circular	More on Heel area	5.5	14.80
23	3518.49	36 HC_i	Oblique	Half Circular	Spread Equally	5	13.97
24	3518.49	9 C_i + 18 HC_i	Oblique	Mixture	More on Toe area	5.5	14.80
25	3518.49	18 Ci	Hybrid	Circular	Spread Equally	5	13.97
26	3518.49	36 HC_i	Hybrid	Half Circular	More on Toe area	5.5	14.80
27	3518.49	9 C_i + 18 HC_i	Hybrid	Mixture	More on Heel area	5	13.97

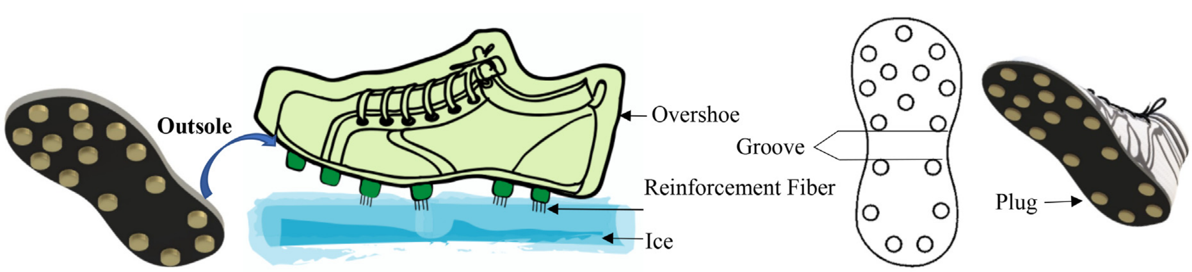

Fig. 3. Footwear prototype on ice using plugs attached to the overshoe and outsole.

incline. During each trial, the angle was adjusted until the maximum achievable angle was reached.

3. Results

3.1. Abrasion resistance index (ARI)

The abrasion resistance index was calculated according to ASTM standards for abrasion resistance of rubber using rotary drum abrader (Arayapranee, 2012), where the abrasion of the surface is determined by two competing factors: (i) fragmentation, which increases wear, and (ii) surface saturation with the wear particles. The composite samples used in footwear prototype preparations have an average ARI score of 140 ± 30.

3.2. Surface syntax

Fig. 5 shows SEM image of CF-PBO-TPU composite before and after abrasion. These images exhibit a considerable amount of fiber exposure to the surface following abrasion. Existence of the fiber on the surface of the composite following abrasion can potentially lead to retaining slip-resistant properties and maintain ice frictional performance over extended use. (Rizvi et al., 2016; Shaghayegh Bagheri et al., 2019).

3.3. MAA test analysis

The MAA scores as well as S/N ratio of all the tested prototypes are reported in the seventh and eighth columns of Table 2. Using the larger-the-better criterion, the most optimal performance of the outsole would be the factors leading to the highest S/N ratios (13.96 dB). Fig. 6 also demonstrates the effects of control factors on the tested footwear outsole, when an overall mean for each control factor is represented by a reference line. The deviation from a horizontal line indicates the size of an effect of a given control factor, where the steeper slope indicates the larger effect of the control factor. From Fig. 6, it can be observed that surface area results in the steepest slope and has the largest effect on the S/N ratio of the MAA score among all the four tested factors.

3.4. Statistical analysis

ANOVA test was done to determine individual and synergic effect of tread design features on ice-friction performance of our composite-based footwear prototypes. Tables 3 and 4 contain the results of the test run for composite-based footwear prototypes. Our results showed that the only control factor that affects the ice-friction performance in a simulated winter condition was the plug surface area with a contribution of 15.63% ($p = 0.041$). All

Fig. 4. Twenty-seven unique schematic outsole thread design (left side of each box) as well as footwear prototypes (right side of each box) according to Taguchi orthogonal L_{27} table.

the other factors including orientation ($p = 0.549$), edge shape ($p = 0.404$), and plug distribution ($p = 0.683$) do not show a statistically significant effect.

The interaction effect of control parameters is depicted in Fig. 7. An interaction plot illustrates how one control factor affects shoe outsole properties in relation to another. On the interaction plot, parallel lines indicate no interaction, whereas crossed lines indicate strong interaction. Interaction effects were found between surface area-edge shape, surface area-orientation and edge shape-orientation.

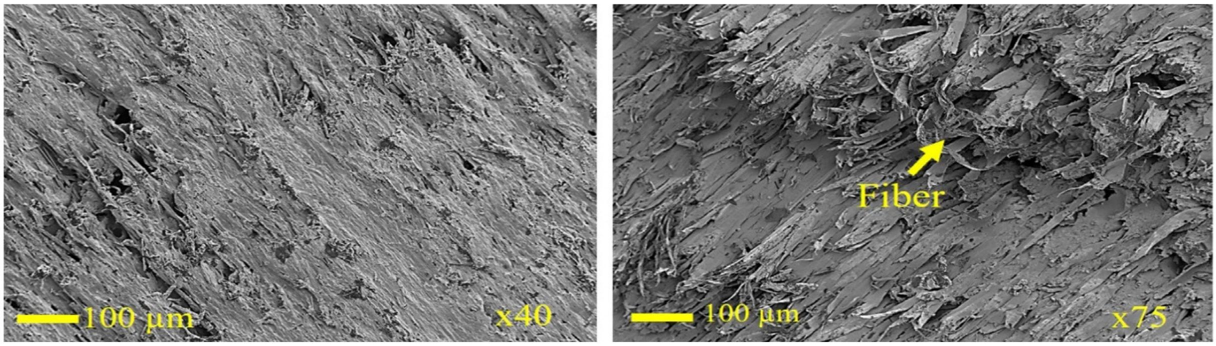

Fig. 5. Scanning electron microscope image of CF-PBO-TPU composite surface texture before (left one) and after (right one) abrasion.

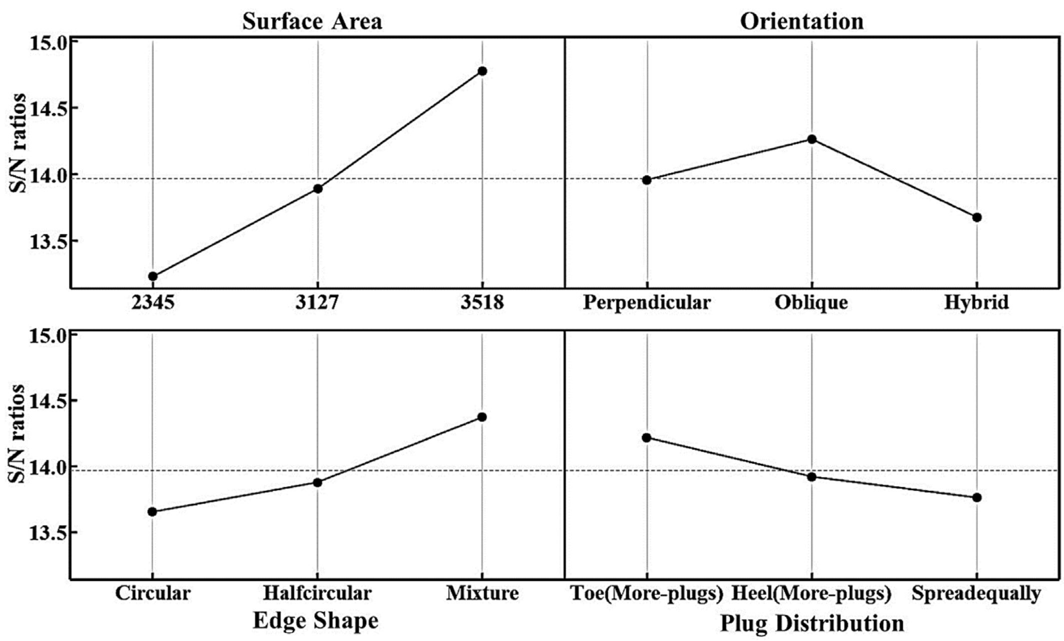

Fig. 6. Main effects plot (data means) for S/N ratio of CF-PBO-TPU composites for the average of two trials.

Table 3
Response table for signal-to-noise ratio for CF-PBO-TPU composite where MAA represents the average value for two trials. Delta represents the difference between the maximum and minimum average signal-to-noise ratios.

Level	Surface area (A)	Orientation (B)	Edge Shape (C)	Plug Distribution (D)
1	13.23	13.96	13.65	14.22
2	13.89	14.26	13.88	13.92
3	14.78	13.68	14.37	13.76
Delta	1.54	0.58	0.72	0.45
Rank	1	3	2	4

Table 4
Analysis of variance for signal-to-noise ratios for shoe outsole properties of CF-PBO-TPU composite for an average of two trials. Seq SS: sequential sum of squares, P: percentage of contribution.

Source	Seq SS	F test	P value	P (%)
A: Surface area	10.8098	4.47	0.041	15.63%
B: Orientation	1.5408	0.64	0.549	2.23%
C: Edge Shape	2.4087	1.00	0.404	3.48%
D: Plug Distribution	0.9596	0.40	0.683	1.38%
A*B	26.6014	5.49	0.013	38.48%
A*C	14.6949	3.04	0.070	21.26%
ERROR	12.1029			
TOTAL	69.1181			

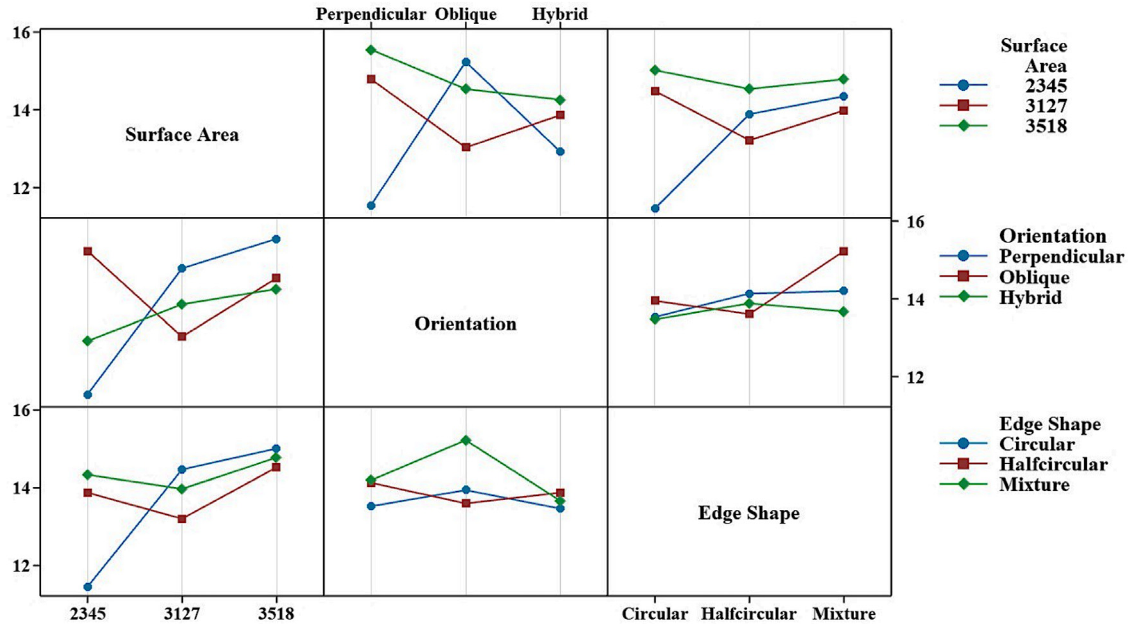

Fig. 7. Interaction plot (Data Means) between control factors for CF-PBO-TPU composites for an average of two trials.

4. Discussion

4.1. General findings

Our results demonstrate that some of the outsole tread design features have a significant effect on ice-friction performance of composite-based footwear. In this study, we tested 27 pairs of footwear prototypes with unique tread pattern design based on our novel composite materials for their ice-friction performance in a simulated winter condition. Among all the tested designs, footwear prototypes that were made of a combined combination of 9 circular and 18 half circular plugs, laid obliquely, for a total surface area (3518.49 mm^2), resulted in the maximum slip-resistance properties. It was also found that the surface area of our composite plugs was the only factor that resulted in a statistically significant effect on the ice-friction properties of our prototypes. We believe that the positive effect of larger composite surface area on the slip-resistance properties of the outsole on ice can be related to the larger number of fibers that come into contact with ice through mechanical interlocking. Considering the mechanical interlocking mechanism of fiber on ice (Bagheri, 2019; Liu et al., 2010; Rizvi et al., 2016), we hypothesize the friction performance of composite-based outsoles will vary depending on the number of fibers in contact between the outsole and the ice substrate underneath. Since the number of fibers increases with increasing surface area, we postulate to have improved friction and traction on ice. From ANOVA analysis, it was also found that the surface area-orientation interaction effect showed a significant contribution of 38.48% (*p = 0.013*) to ice-friction performance in icy conditions.

4.2. Comparison with previous work

It is well-known that footwear outsole's geometrical tread design parameters affect the COF between the shoe outsole and floor interface level for indoor surfaces, where higher COF results reduce the risk of slipping (Li, Chen, & Lin, 2006; Liu et al., 2013). Several factors have been reported to influence COF between the footwear and under-foot surfaces, including outsole material, surface texture, tread groove width, depth, contact surface area, orientation, edge shape (Blanchette & Powers, 2015; Li & Chen, 2004; Li, Chen, & Lin, 2006; Petersen et al., 1996). In addition, several studies in the past concluded that deeper and wider grooves increased COF since they allowed the liquid to drain, improving contact with the ground (Blanchette & Powers, 2015; Chang, 2004; Li, Chen, & Lin, 2006). However, all of these efforts were limited to indoor surfaces. As such, it is not possible to directly compare our finding with previously published works given the different testing environments. Yet some partial comparisons were made to understand how surface area would affect slip-resistance properties on icy surfaces versus indoor conditions.

Using ANOVA analysis, our results showed that surface area (*p = 0.041*) had a statistically significant effect on ice-friction properties of the footwear outsole. Our analysis demonstrated that among three tested surface areas in this study, the largest one (3,518.49 mm^2) performed the best. According to Persson's theory of rubber friction, one contributor to the friction of rubber is the real contact area. Considering the contribution of the real contact area on the friction of rubber (Persson, 2001; Tiwari et al., 2018), the COF decreases as the contact area decreases. In a study of water and canola oil contaminant on vinyl, ceramic and quarry surfaces for indoor condition, Jones et al. (Jones et al., 2018) investigated the effect of outsole's heel area on COF and reported that increased surface area is likely to increase the contact area and reduce contact pressure, resulting in a better grip. This is because the fact that coefficient of friction increases as surface area increases (Moghaddam et al., 2018), which results in a greater hysteresis friction in shoes and lowering contact pressure across the shoe surface (Jones et al., 2018; Moghaddam et al., 2018; Moghaddam, 2022). These findings are aligned with our observation, where the largest surface area showed the best slip-resistance properties.

4.3. Limitations and Future studies

The main limitation of this study was that all the tested prototypes were assessed on ice-covered inclined surfaces. As such, future works should study outsole prototype with the composite materials for different conditions to examine their performance on other slippery winter surfaces, including snow and slush, as well as rough surfaces like pavements materials such as asphalt or concrete. Secondly, our outsole prototypes have been designed primarily for neutral pronators. Future studies should consider studying outsoles designs based on composite materials for the overpronators and the supinators. Thirdly, only one form of wear was evaluated for this study. Our study focuses only on abrasive wear (when softer surface slides against the hard and rough surface) (Padhan et al., 2020). Adhesive wear is another type of common wear mechanism in footwear outsole due to the contact nature of walking mode (Kim, 2015). As such, more research needs to consider the effect of this wear mechanism on the ice-friction properties of the composite-based outsole. Finally, we only focused on circular and half circular plugs with one plug thickness in the current study. Future works should investigate the effect of different plug thicknesses as well as edge shapes to identify the tread design combinations leading to the highest slip-resistant properties.

5. Conclusion

In this study, 27 different designs of footwear outsole prototypes using the Taguchi method were created and tested in simulated winter conditions to assess the significance of various tread design parameters for use with novel composite materials for ice-friction properties. Our results demonstrated that surface area of composite plugs was the only factor with a statistically significant effect ($p = 0.041$) on ice-friction properties, while the other factors that were evaluated (plug orientation, shape and distribution) had no significant effect. Our results also confirmed that the most effective outsole tread design features for enhanced grip on ice comprise a design based on a combination of circular and half circular plugs with oblique arrangements that are mostly distributed in the forefoot area. This is the first study to consider the effect of outsole tread design parameters for use with composite-based footwear on ice-covered surfaces in an environment that replicates winter conditions. Future studies may aim to enhance slip-resistant properties of composite-based footwear by optimizing the tread design parameters based on the results of this study.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Other interests include pressure injury prevention and fall prevention for older adults through improved footwear slip-resistance testing and the development of footwear outsole materials that perform better on ice and snow.

Tilak's team designs, builds, tests, refines, and commercializes these tools in collaboration with commercial partners and policymakers. The process involves iteratively testing prototypes in simulation labs, often with older adults as participants. Tilak holds cross-appointments at the Institute of Biomedical Engineering and the Rehabilitation Sciences *Institute* at the University of Toronto.

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