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REVIEW ARTICLE

Current state-of-the-art review of footwear–ground friction

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Abstract: The most important role of footwear is to ensure safe, functional walking, and foot protection. For the proper functionality of not only the work shoes, the anti-slip behavior of the shoe under various conditions and environments plays an important role in the prevention of slips, trips, falls, and consequent injuries. This article is intended to review the current understanding of the frictional mechanisms between shoe outsoles and various counterfaces that impact the evaluation of outsole slipperiness. Current research focuses on the mechanisms driving outsole friction on different ground surfaces or the definition and description of parameters that influence outsole friction. Subsequently, the review discusses the effect of various surface contaminants on footwear friction. Lastly, challenges and outlooks in the field of footwear outsoles are briefly mentioned.

Keywords: shoe outsole; composite; slipperiness; coefficient of friction (COF); adhesion; safe walk

1 Introduction

Slips, trips, and falls are among the leading causes of accidental injuries with serious health and economic consequences [1, 2]. For example, Kemmlert and Lundholm [3] reported that slips, trips, and falls are the main cause of 17%–35% of occupational accidents. Moreover, falls are also the third most frequent cause of disability in the whole world [4]. Above that, the consequences can be far more serious. Nearly 17,000 people die annually due to falls in the United States [5].

At the same time, fall-related injuries are the source of significant financial losses. Florence et al. [6] reported a lifetime cost associated with falls of $169 billion in the United States in 2014, plus another $18 billion in worker's compensation claims [7]. Additional financial losses are further increased by the sick leave of injured workers. More than one-third of the injured workers stay away from work for more than a month [8]. Almost half of fall-related injuries are caused by an unexpected slip [9], and nearly 80% of slips occur due to an inappropriate ground surface or shoe material [10]. Therefore, slip-related research plays an important role in saving human lives and in saving a considerable amount of money spent on the treatment and recovery of the disabled workforce.

Slip can be defined as an unexpected loss of grip, frequently on contaminated surfaces, resulting in sliding between the shoe outsole and the ground due to a low coefficient of friction (COF) [11]. The outsole is the bottommost part of a shoe that comes in direct contact with the ground, commonly made out of rubber, polyurethane, polyvinyl chloride (PVC), or leather. The most common are slips at heel strike or toe-off phases of the gait cycle [12]. The center of gravity passes outside of the base support and the shear forces in the contact between the outsole and the ground are the highest [13, 14]. The shoe outsole and ground cannot provide sufficient resistance to counteract these shear forces. In other words, the available COF (ACOF) does not meet the values or the required

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COF (RCOF) for the required activity [15]. Brady et al. [16] reported that a slip velocity of 1.1 m/s and a slip distance of 0.2 m result in a fall.

The RCOF is usually determined based on the values of loading and frictional forces measured on a force plate during undisturbed human gait [17]. Additionally, ACOF is usually analyzed based on the normal and friction forces measured by sliding a shoe material sample or a whole shoe against the ground [18]. Sometimes, the risk of slippage is also analyzed by the difference between these two values [19]. Yamaguchi et al. [20] or Fino and Lockhart [21] reported an RCOF of up to 0.54 for transient movements such as turning, whereas an average RCOF of 0.23 was reported for level walking by Burnfield et al. [22]. A value of 0.4 is commonly considered a safe static or dynamic COF (DCOF) for slip prevention [23, 24]. However, under certain conditions, this may not be a sufficient value. Therefore, a DCOF greater than 0.75 is assumed for anti-slip floors [25]. The value of ACOF is related to many factors, such as material and surface roughness of contact pair, kinematics and kinetics of walking gait, tread design, etc. The effects of some parameters on COF and, consequently, the slip formation will be further discussed in Sections 4 and 5.

This review presents insight as well as topics for potential future research in the field of footwear slipperiness assessment. The main emphasis is placed on the analysis of COF between a shoe or shoe outsole sample and a ground. Different shoe–floor COF measurement approaches will be discussed, as well as parameters that influence the final value of COF, such as kinematic conditions, material properties, type of contaminant, etc.

2 Friction of compliant contacts

The friction of viscoelastic materials is mainly controlled by two different phenomena: adhesion friction and hysteresis friction (Fig. 1). Adhesion prevails on smooth surfaces and dry conditions, whereas hysteresis dominates on rough or lubricated surfaces [26, 27].

Adhesion friction is the result of the intermolecular interaction between the contacting surfaces [28]. For polymers, the main sources of adhesion are van der

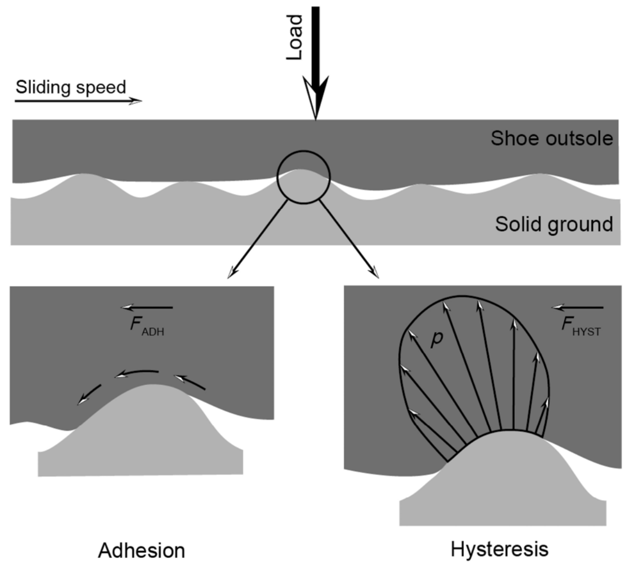

Fig. 1 Scheme of the contact between shoe and ground.

Waals (vdWs) and electrostatic forces [29]. Apart from that, several other contributions to adhesion friction were identified: opening crack propagation at asperities, wear of the material, plastic deformation, and plowing [30]. Due to direct bonding and debonding between molecules of contacting surfaces (so-called stick-slip effect), adhesion friction is proportional to the real contact area and shear strength of the bonds [31]. The size of the real contact area is then controlled by the geometry of the surface asperities, the surface roughness or elastic modulus, and the surface energy of the contacting surfaces [32].

Softer outsoles tend to make indentation with floor asperities, producing more slip resistance due to a higher adhesion friction between contacting surfaces. In contrast, harder outsoles make less adhesion with the floor because of more resistance to indentation and interlocking between them, producing lower kinetic friction [32]. Strobel et al. [10] published quite different results, primarily due to the varying surface roughness of the tested samples. The low roughness of the hard material resulted in a higher real area of contact compared to the soft but high-roughness polyurethane. The hard material formed stronger adhesion junctions with the floor surface that may have required higher shear forces to break.

The presence of liquid contaminants typically results in decreased surface energy and thereby decreased adhesion. The adhesion decrease is usually more pronounced at highly viscous fluid contaminants [32, 33]. Moreover, inhibition of adhesion by liquid contaminant is more distinct when the surface roughness decreases [34]. Rapid squeeze-out of the liquid contaminant from the contact area is limited as a result of the decreased surface roughness, leading to a smaller real contact area.

Hysteresis friction depends on viscoelastic properties and is a consequence of energy loss due to a cyclic deformation process during sliding motion [32, 35]. Energy loss arises from the stress asymmetry between the loading and unloading parts at the asperity and elastomer contact. The hysteresis friction depends on the volume of the deformed elastomer and the loss of tangent as an indicator of the loss of strain energy [28, 36].

Hysteresis friction tends to be high for soft composite materials and low for hard materials [10]. Increased surface roughness leads to significantly increased hysteresis [37], whereas larger asperities increase hysteretic deformation. A softer shoe material allows the floor asperities to achieve greater penetration depth, i.e., deformation volume. Greater deformation in the outsole material leads to an increase in the energy loss through the internal damping cycle that sliding across a hard surface creates in an elastomer [36]. It seems that these conclusions are not so unambiguous. The model by Moghaddam et al. [38] predicts that hysteresis friction increases for harder shoe materials and rougher surfaces. These results were also partially confirmed by experimental verification. Therefore, it seems that the role of different material properties in hysteresis friction is not yet fully understood.

Adhesion of the viscoelastic material on a wet surface can be inhibited by liquid contaminants within the contact. As a consequence of lower adhesion friction, the contribution of the hysteresis component of friction force increases. This leads to a better-wet grip performance of viscoelastic materials with high loss tangent [39, 40].

The hysteretic part of the friction can be more generalizable across various boundary conditions, such as the type of contaminants and the flooring material, than the adhesion friction [33]. Adhesion depends on several mechanical and chemical phenomena that lead to forces formed at the contact regions between two contacting surfaces. These forces are dependent on the combination of surfaces and a type of contaminant [10, 37]. Thus, hysteresis tends to be the dominant mechanism in the presence of contaminants. Hysteresis is a mechanical interaction that is highly sensitive to contact pressures [38, 41]. Shoes are expected to deform similarly across different floor surfaces, leading to similar contact pressures, explaining the strong correlation in the presence of hysteresis friction.

3 Methodologies and equipment for footwear friction measurements

Numerous devices and techniques have been used to analyze the shoe sole slipperiness. The results of laboratory measurements [42–44], as well as field measurements [45–47] have been reported. Most of the methodologies assess the slipperiness of outsole–floor interface based on frictional measurements, although questions about the dependency between friction and slipperiness remain [48]. Most methodologies evaluate the COF based on the values of normal and friction force within the contact. An alternative approach was reported by Hsu et al. [49, 50] or Bagheri et al. [51, 52]. In these studies, the test method called the maximum achievable angle (MAA) test was used to measure the steepest incline that participants can walk up and down without experiencing a two-foot slip on the icy surface. Chang and Chang introduced a more comprehensive approach to the assessment of shoe slipperiness [48]. Multiple linear regression was used to analyze the relationships between several variables (ACOF, utilized COF (UCOF), perceived rating, walking speed, and heel angle) to reflect a complex system for slipperiness detection. UCOF, perceived rating, and heel angle were proposed as suitable candidates reflecting slipperiness measurements.

3.1 Laboratory methodologies

Evaluation of the slip resistance of shoe outsoles or outsole materials can be studied in most detail under laboratory conditions, where individual influences can be studied separately, as well as phenomena connected with lubrication regimes within contact. The most common tribometer configurations used for the frictional measurements of polymeric materials intended as outsole materials are block-on-plate (Fig. 2(a)) [35, 53, 54], ball-on-plate (Fig. 2(b)) [44, 55, 56], pin-on-disc (Fig. 2(c)) [37, 57, 58], or cylinder-on-flat [59]. These simplified models of real-life outsole-floor contact are sometimes also capable of the *in-situ* observation of the contact area by optical methods. These optical methods are usually based on the principle of total reflection of light [60–62] or on fluorescent microscopy [63]. Due to the involvement of these optical methods, data about the distribution of the real contact area within an apparent contact area [59, 60] or about the film thickness [55, 56, 63] within contact contaminated with liquid lubricant can be obtained.

Another group of laboratory-based devices for the shoe slipperiness assessment are whole-shoe tribometers or step simulators. Typical representatives of these devices are STM 603 (SATRA Technology, UK) (Fig. 3), GSP 3034 (ISC Germany, Germany), or custom build portable slip simulator presented in a study by Iraqi et al. [64]. Whole shoe tribometers measure the slip resistance between the outsole of the shoe and the floor sample (glass, stainless steel, tile, etc.). Due to this configuration, they are more able to emulate conditions that occur after heel strike or before toe-off lift when the slip is most likely to occur. The effect of some important parameters, such as the geometry of the tread grooves [65, 66] or shoe–floor angle [19, 64], can be better studied with this type of tribometer rather than on a classical conventional tribometer, which was discussed in the first paragraph of Section 3.1. The slip resistance testing of shoes on whole-shoe tribometers is also standardized by several national and international standards, such as EN ISO 13287 [67], ASTM F2913 [68], or NFSI B101.7 [69].

3.2 Human-involved methodologies

Human-involved methodologies are the most biofidelic ways to analyze footwear slips. Usually, a group of people is asked to put on tested shoes and walk across the tested surface, which is or is not covered by contaminant. One of the ways to analyze the results of these experiments is through sensory evaluation. In a study by Choi et al. [70], 12 healthy adults compared the slipperiness of the floor samples tested with the standard floor sample using a 7-degree scale ranging from "very much more slippery" to "very much less slippery". Yamaguchi and Hokkirigawa [66] presented a quantitative approach. Participants in the trials were covered with reflective markers, and the kinematics (velocity and slip displacement) of the walk/slip was recorded by a motion capture system. A similar methodology was also published by Beschorner et al. [17] or Jones et al. [41]. In addition to the previous study, participants in the trials were walking across a force plate during experiments to record the ground reaction forces. On the basis of the values of ground reaction forces, the RCOF was calculated.

Another group of human-involved methodologies for the assessment of shoe slipperiness analyzes the maximum angle at which a person walking on the inclined floor begins to slip [71]. This methodology is also covered by German standard DIN 51130 [72] (Fig. 4). The same principle uses the previously mentioned MAA method [49–52] for the analysis of the resistance to slippage on icy surfaces.

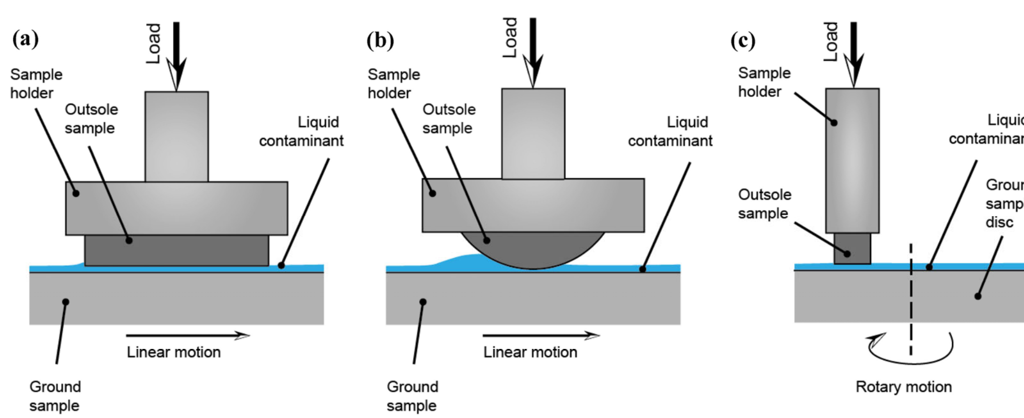

Fig. 2 Schemes of tribometer configurations: (a) block-on-plate, (b) ball-on-plate, and (c) pin-on-disc.

Fig. 3 SATRA STM 603, figures obtained from the official website at https://www.kemaskurnia.com/satra.html, © Kemas Kurnia Sdn Bhd 2023–2024.

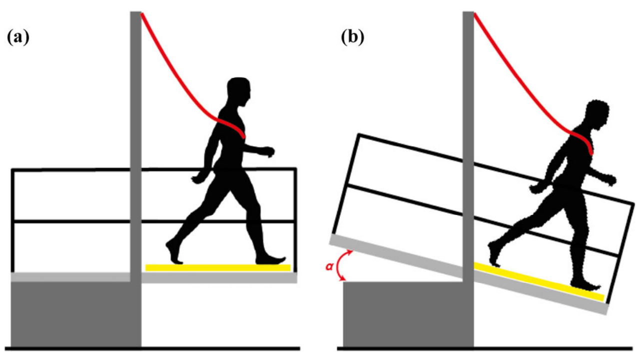

Fig. 4 Ramp test according to DIN 51130: (a) beginning of the test and (b) position at MAA.

3.3 Field methodologies

Field methodologies are intended to assess the slip resistance of outsoles, floors, or roads under real-life conditions. For this purpose, portable tribometers (slip meters) or pendulum simulators tend to be involved. Many of these methodologies are also covered by national or international standards. Pendulums (Fig. 5(a)) are one of the most widely trusted instruments to assess real-life slip resistance. They simply measure the energy loss of a pendulum with the heel material swiping across a floor surface. The criterion used for low-slip potential flooring is the pendulum test value (PTV) of at least 36. For example, according to the UK Slip Resistance Group [73], the probability of slipping increases from 1 : 1,000,000 to 1 : 20 when the PTV value decreases from 36 to 24. Pendulum skid resistance test methods are covered by the American standard ASTM E303-22 [74], European standard EN 13036-4 [75], Australian standard SA HB 198 [76], and many others.

Drag slip meters like Tortus 3 (Mastrad Limited, UK), FSC 2011 (Sassuololab, Italy), or BOT-3000E (Walkway Management Group, USA) (Fig. 5(b)) slide a loaded shoe sole sample across a test surface either manually or by an electric motor at a defined speed. These devices can, for example, analyze the slip resistance of hard surfaces according to NFSI B101.3 [77] or ANSI A137.1 [78]. However, Derler et al. [79] expressed concerns about the repeatability and reproducibility of this type of device. Due to the high sensitivity to mechanical abrasion and temperature of the standard rubber materials for the FSC 2000 slip meter, the increase in COF was observed with increasing temperature. This could lead to the overestimation of the floor's anti-slip properties.

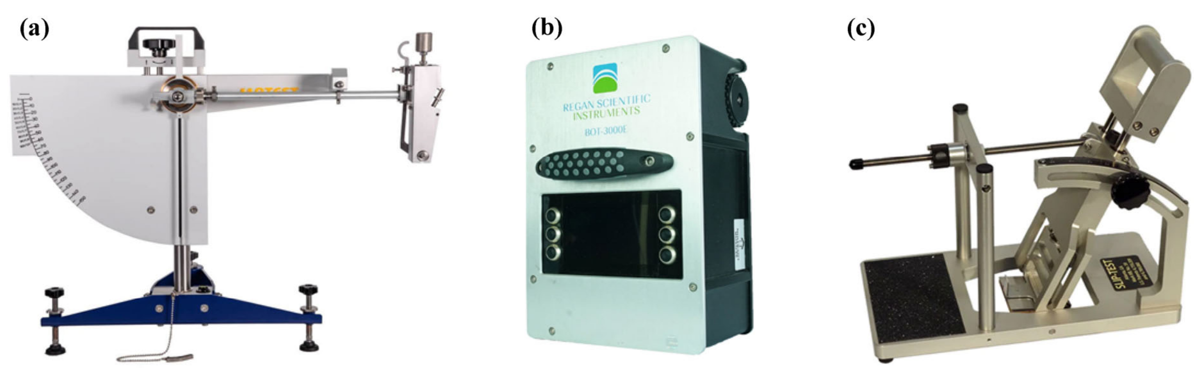

Fig. 5 Slip meters for field measurements: (a) British pendulum tester, figures obtained from the official website at https://7950d52f747ed57f.en.made-in-china.com/product/XFJTtZecHUag/China-The-Pendulum-Test-Skid-Resistance-Tester.html, © 1998–2024 Focus Technology Co., Ltd. (b) BOT-3000E, figures obtained from the official website at https://store.walkwaymg.com/pages/bot3000-old, © 2019 Digital Marketing by Thrive. (c) Brungraber Mark II, figures obtained from the official website at https://slipdoctors.com/collections/slip-resistance-meters-online/products/slip-test-mark-iiib.

Another group of portable slip meters is articulated strut slip meters. In this case, the COF is determined from the tangent of the angle between the strut and the vertical at which a slip between the footwear sample and the floor surface occurs. A typical representative of these devices, Brungraber Mark II (Slip-Test, USA) (Fig. 5(c)), is commonly used in Refs. [45, 48, 80, 81]. The methodology for the footwear sole slip resistance measurements by Brungraber Mark II was also covered by the ASTM F1677 standard [82]. Nevertheless, this standard was withdrawn in 2006 due to the poor repeatability in interlaboratory studies.

The last small group of tribometers/simulators intended for field measurements is portable whole-shoe devices. The main benefit of these devices consists of *in situ* COF measurements between a whole shoe mounted on a shoe last and a floor in real-life conditions. Recently, Beschorner et al. [83] validated a new type of potable shoe–floor friction device called NextSTEPS (XRDS Systems, USA) to predict human slips. In 2022, Gupta et al. [84] introduced and validated another low-cost slip-testing device.

3.4 Comparison

Commercial slip meters intended for field measurements tend to measure under different test conditions, i.e., load, contact area, contact pressure, sliding velocity, etc. [85], which can significantly influence the results of the measurements. Kim [86] compared the frictional results of the measurements with three different slip meters Bot-3000, Regan Scientific Instruments, USA; English XL, Excel Tribometers, USA; British Pendulum Tester, Munro Instruments, UK. On the same floor material, the scratch COF (SCOF) ranged between 0.63 and 1.14 for individual slip meters. In most cases, dynamic and kinematic characteristics of slip meters were outside the range of values measured for human gait. Slip meters tended to overestimate the friction between the floor and the slider. This could lead to several dangerous real-life situations. Similar phenomena were reported by Chang and Chang [48]. Especially on the contaminated smooth surfaces, ACOF values measured by Brungraber Mark II were lower than UCOF values measured during human gait trials. Chang et al. [85] attributed this behavior to the slip meter's excessive squeeze film effects on surfaces with liquid contaminants.

Sudoł et al. [71] also reported a strong relation between measurement methodology and slip resistance, especially on a low rough surface. Polished slabs were classified as low slip risk for PTV measured by British pendulum and satisfactory for the DCOF measured by pull slip meter. However, in the ramp test according to the DIN 51130, a relatively low acceptable angle nearly classified them in the lowest slip resistance class. Moreover, none of the test methods were assessed well in terms of accuracy and classification resolution. The overestimation of shoe slip resistance by the mechanical method was also reported by Fekr et al. [87]. However, this time, the COF between the shoe and the ice surface was analyzed by the whole shoe tribometer SATRA STM 603. So, it seems that even realistic configuration in laboratory-based methodologies is not a sufficient assumption for shoe slipperiness assessment.

Based on Ref. [88], it seems like standard mechanical methodologies for the shoe slipperiness assessment are inadequate due to the poor biofidelity and tend to overestimate shoe–floor friction. Beschorner et al. [19] suggested improving the predictive capacity of current testing standards by altering the testing conditions. Among others, changes in shoe–floor angle will have a major impact on ACOF. Different shoe–floor angles will lead to differences in the contact area, which is correlated with hysteresis friction. The contact area can also influence the hydrodynamic pressures between the heel and the floor.

Questions about the biofidelity of human-involved methodologies also remain. Iraqi et al. [89] reported changes in human gait kinematics during experiments when tested subjects expected a slip formation, which may not be common in real-life situations. Therefore, the accuracy of biofidelic methodology for assessing shoe slipperiness is still a challenge today. A possible solution is to measure friction between the shoe and the floor during normal daily activities such as walking or running. Moriyasu et al. [90] or Yamaguchi [91] developed a shoe sole mounted with miniature triaxial force sensors. This technology is capable of an investigation of force distribution within shoe–floor contact in real-life situations as well as of a local force distribution analysis during the gait cycle.

4 Parameters influencing the COF values

The tribological performance and behavior of the shoe outsoles are very difficult to generalize due to the wide range of operating conditions and parameters, which affect the final value of COF and, consequently, the appearance of a slip. Some of them, such as the loading force, sliding speed, shoe–floor angle, contact duration, or location of the center of pressure [18, 89, 92], are related to the kinematics and kinetics of human gait. Another group of parameters that influence COF within the shoe–ground contact is related to the material properties and the design of the shoe outsole. The most typical parameters from this group are the hardness and wettability of the polymer [32, 54, 55], its viscoelastic properties [93, 94], the geometry of the contact surfaces and tread grooves [42, 65, 95], surface roughness [66, 96], etc. Typical examples of anti-slip outsole designs can be seen in Fig. 6. The last group of parameters is related to the presence of contact contaminants such as solid particles, liquids, or their mixtures. This group covers parameters such as the size and shape of the solid particles [80, 97] or the viscosity of the fluid [37, 55, 58].

4.1 Kinematics

The vertical force and the sliding speed in shoe–floor contact change during the human gait cycle, as well as change during a slip. The normal force varies from 130 N at the start of the slip to over 500 N at maximum [89]. The sliding speed varies from 0.3 m/s at the slip start to more than 1.5 m/s at the peak [98]. In general, increasing the speed of sliding reduces the COF [32]. Faster sliding speeds reduced both hysteresis and adhesion frictions. With increasing sliding speed, the soft material of the outsole has less time to deform around the surface asperities of the harder material and reduces the real contact area [99], and mechanical losses increase due to increased deformation of the polymer structure [100]. Higher energy dissipation also leads to frictional heating. Because of this, the stiffness of the material decreases, and with the increasing temperature, the loss tangent (tanδ) increases [57]. Nevertheless, this insight cannot be applied under all conditions. Yamagughi et al. [101] reported higher COF values with increasing sliding velocity for porous ethylene vinyl acetate (EVA) blocks. This behavior was attributed to the increase in the shear strength of the EVA with the sliding velocity and to the stretching of the foam cell walls by the counterpart surface asperities. For liquid-contaminated surfaces, the increase in speed is associated with an increase in film thickness caused by a transition from the boundary lubrication regime to the mixed lubrication regime [37].

Under small loading conditions, the real contact area is regarded as the sum of the area of multiple small contact regions. The contact area increases linearly with the load [102], and the friction forces increase with the increasing normal load [59]. However, under higher loads, full contact may occur at the interface. In this case, the COF does not depend on the normal load that corresponds to the Amontons–Coulomb friction model [35].

Fig. 6 Design of shoe outsole samples.

4.2 Hardness and surface roughness

Materials properties influence the deformability of the surface, which can affect the contact region and, consequently, the frictional performance of the shoe outsole. In general, soft outsoles have better anti-slip properties. Due to the higher elastic modulus of the floor, floor surface asperities penetrate the surface of the outsole [103], and consequently, the outsole material better conforms to the asperities of the floor surface. A higher COF is reached as a result of the more pronounced microscopic deformations when the surface asperities are interlocked [32], as well as due to a greater contact area between the outsole and the floor, which is caused by a lower elastic modulus of the soft shoe outsole material [56]. In other words, both adhesion and hysteresis friction tend to be higher for soft materials [10], although studies that reported higher hysteresis friction for harder shoe materials were also published [38]. Moreover, soft materials suffer from more pronounced changes in friction depending on the sliding speed. The higher sliding speed leads to the reduction of the real contact area [99] and increased deformation of the polymer structure [100]. Soft outsoles are recommended mainly for smooth or wet surfaces. On the other hand, harder soles allow for less adhesion due to the higher resistance to indentation and interlocking with the asperities of the floor surface.

Surface roughness can also significantly affect shoe friction. For example, Elleuch et al. [104] reported a strong correlation between surface roughness and COF for elastomeric material. The positive correlation between COF and rubber sole roughness was also reported by Mohan et al. [32]. The low COF of smooth outsole materials can be explained by the lack of hard adhesion formation between the sole and floor asperities. The higher surface roughness of the rubber also leads to a stronger correlation between COF and $\tan\delta$ [34]. This means that for smooth rubber surfaces, COF mainly depends on the adhesion component of friction, whereas for rough surfaces, COF is affected by hysteresis friction. A high correlation between surface roughness and COF was also reported for floor materials [105, 106]. For smooth floors, friction depends mainly on the adhesion, while hysteresis becomes important for rough surfaces [26]. Higher asperities of rough floors cause greater deformation of the shoe material, leading to increased energy loss by the internal damping cycle [36].

4.3 Tread pattern

The anti-slip properties of the shoe outsole can be significantly affected by the design of the thread pattern. Parameters such as thread depth or width, their orientation, and density can significantly affect the COF values [107, 108].

The higher tread depth leads to a lower bending stiffness. Increased outsole deflection during sliding leads to a smaller contact area and consequently to lower friction [95]. Another reduction of contact area is caused by friction-induced torque [61]. In the case of height and short rubber blocks, this torque causes a large deformation of the tread block, leading to a lower contact area at the trailing edge of the contact [53, 109]. Due to this phenomenon, higher values of COF are also usually measured for parallel-oriented grooves rather than perpendicularly oriented-grooves.

For the liquid-contaminated surfaces, the situation can be quite different. In this condition, the main role of thread design is to allow fluid drainage from the contact area, thus reducing fluid pressure [110]. If the shoe threads do not adequately drain the fluid from the contact, lubricity increases, and friction performance is reduced [99, 111]. Higher fluid pressures of non-slip-resistant shoes are attributed to a combination of the squeeze-film effect and the wedge effect [88]. Conversely, good drainage capacity leads to a smaller hydrodynamic pressure in the squeezed film (reduced hydrodynamic load support) and enables the development of adhesion and hysteresis friction between the shoe outsole and the contaminated surface [100]. Therefore, higher COF values are reported for outsoles with deeper and wider grooves [112, 113].

The role of the tread groove orientation is also quite different for surface-contaminated conditions. For these conditions, the perpendicular and oblique orientation of the grooves leads to higher friction [65]. This is probably due to the longer distance that the liquid contaminant has to travel until it is completely squeezed out of the contact area.

4.4 Viscoelastic properties

Due to the viscoelastic properties, the frictional behavior of the outsole materials depends on the temperature and the time. Delays in material recovery after deformation caused by the surface asperities of the ground lead to the emergence of hysteresis friction. Derler et al. [79] reported a higher value of COF for viscoelastic materials with increasing temperature, which can be explained by a gradual softening of the viscoelastic material. The temperature increase may also arise due to frictional heating. Increasing sliding speed leads to higher energy dissipation, and with increasing temperature, the loss tangent (tanδ) increases [114]. Persson [36] reported that hysteretic friction for viscoelastic material increases with the sliding speed until a threshold speed is reached, and then it decreases.

Loss tangent can significantly affect the hysteresis friction of viscoelastic materials. In general, viscoelastic materials with high tanδ exhibit a higher COF under liquid-contaminated conditions [39, 40]. Under these conditions, the adhesion friction is inhibited by a liquid contaminant, and the hysteresis friction is the primary component, which affects the total value of COF. These findings were also confirmed by Ido et al. [34] for SBR rubber samples under water-lubricated conditions. Additionally, a stronger correlation was found between COF and tanδ for rubber surfaces with higher surface roughness. Higher energy dissipation, which is connected with increasing tanδ, increases the share of hysteresis friction in the overall value of COF. Yamaguchi et al. [44] reported that higher values of tanδ measured for EVA foam samples led to a higher value of COF in contact with abrasive paper, even under dry conditions. Hausberger et al. [114] also reported similar conclusions for dry contact between thermoplastic polyurethane (TPU) and steel. Sato et al. [115] reported a similar type of behavior, that is, a higher COF with increasing tanδ, for rubber surfaces sliding against counterpart materials with large surface roughness.

In addition to strain or frequency sweeps, the viscoelastic properties of rubber compounds are also characterized by temperature step tests. These measurements analyze the dynamic moduli dependency on temperature and, among other measures, are conducted to identify the bulk glass transition temperature. Pan et al. [116] analyzed the effect of glass transition temperature on the wet sliding friction of rubber compounds and a strong correlation was found. For butadiene rubber compounds, friction increased to a maximum and then decreased with the increasing glass transition temperature. The authors attributed the decrease in friction to the stick-slip process.

5 Surface contaminants

5.1 Solid particles

The presence of solid particles and their size can significantly affect the outsole–ground friction (Fig. 7), while the effect depends on outsole hardness, surface roughness, etc. The mechanisms of adhesive friction between the outsole and the ground are diminished by the presence of contaminant particles. As a consequence, according to Li et al. [80], solid particles tend to decrease COF when hard material (neolite, shore A hardness of 93) is used as the outsole material. The particles act as a lubricant, resisting the direct contact between the outsole and the ground and blocking the adhesion between these two surfaces. Large particles have better lubricant effects

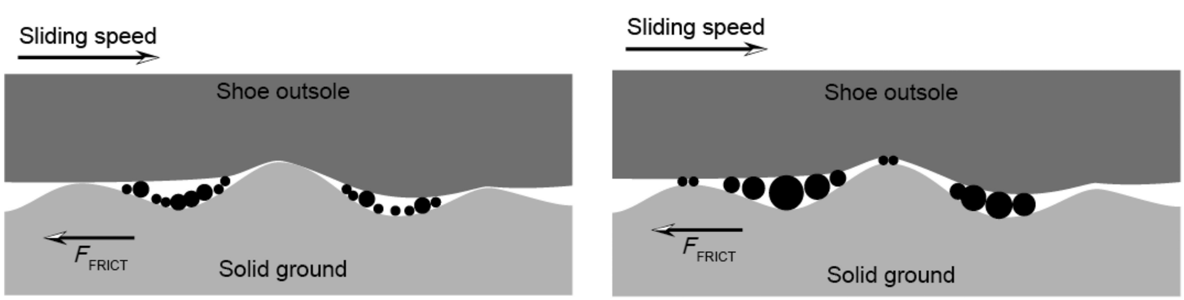

Fig. 7 Effect of solid particle size on friction between shoe outsole and the ground.

than small ones, whereas small particles are, due to the adhesion forces between the particles and the elastomer, able to adhere to the outsole surface [97]. Conversely, when the shoe outsole is made of soft material (EVA, shore A hardness of 45), solid particles provide additional friction and increase the COF between the outsole and the ground. Due to its softness and viscoelasticity, the EVA outsole can touch the floor despite the presence of the particles. This could reduce the loss of adhesion. The effects of solid particles on the reduction in friction are more significant in smooth floors than in rough ones [97].

5.2 Liquid contaminants

For the slip resistance of the shoe outsole on liquid-covered surfaces, the drainage capacity of the contact surfaces, the draping of the outsole around the surface asperities, and the size of the true contact area play a significant role [32]. Liquid contaminants decrease surface energy [117] and block adhesion, while the reduction in adhesion friction depends on the viscosity and length of the molecules. Large polar molecules of high-viscosity fluids tend to adhere to surface asperities, reducing adhesion between surfaces [118]. When the viscosity is relatively low, the outsole–ground contact operates in a mixed lubrication regime (Fig. 8(a)). The liquid contaminant does not fully separate the contacting surfaces, and the normal load is partially supported by a lubricant and partially by a solid-to-solid contact. As the viscosity increases, the contact surfaces are fully separated by the liquid contaminant (Fig. 8(b)), while the film thickness depends on the viscosity and speed [58]. The contact operates in a hydrodynamic lubrication regime in which the squeeze film has sufficient pressure to separate the surfaces.

The draining capability of the contact surfaces prevents the separation of the shoe outsole and ground by a liquid lubricating film. If the drainage time is too high, sufficiently high adhesion may not be produced, and an outsole slip may occur. When a shoe descends in a liquid film, the squeeze film thickness in the shoe–ground contact depends on vertical load, fluid viscosity, descending time, and thread design [99]. The draining capability could also be influenced by the surface roughness of the outsole or the ground. The increased roughness leads to a faster squeeze-out of the lubricant, which increases the dry contact area necessary for adhesion between contact surfaces [34]. However, some studies have not found such a trend [41].

5.3 Ice

At very low speeds and temperatures, the ice surface is dry and has a generally very high COF. However, very low friction can be achieved near the melting point or by frictional heating leading to formation of a water layer on the surface [99] (Fig. 9). Polar water molecules expose disordered hydrogen bonds that act as a lubricant [119] According to the literature, a sliding velocity of 0.01 m/s at a temperature above −10 °C produces enough frictional heating to melt the surface of the ice and create a liquid layer [120, 121]. The frictional heating increases with the sliding velocity [122] and the film thickness increases.

Even under these conditions, outsole roughness has been associated with the improved friction [123]. If the surface roughness is high enough, the viscoelastic deformations of the rubber can lead to significant friction even at temperatures close to the melting point. However, achieving sufficient friction on ice surfaces presents a real challenge. Fortunately, materials

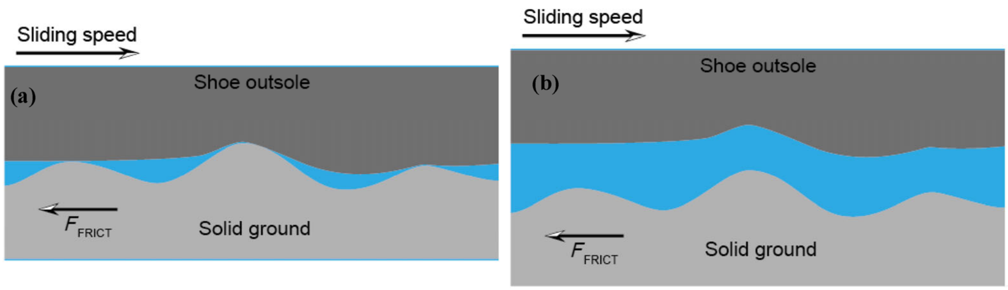

Fig. 8 Contact between shoe outsole and the ground operating in (a) mixed lubrication and (b) hydrodynamic lubrication.

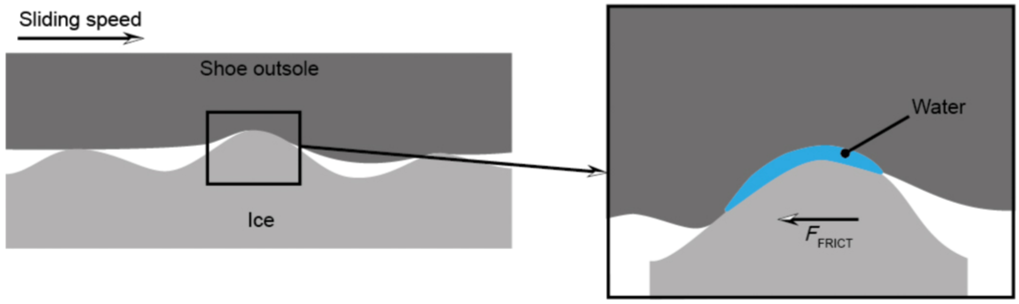

Fig. 9 Frictional heating.

with embedded abrasive particles or fibers reported promising results [122, 124]. Hard fibers (carbon or glass) that protrude from the soft elastomer surface penetrate the liquid-like water layer and the ice surface. Due to the mechanical interlocking, a highly shear-resistant surface is created, resulting in a high value of COF.

6 Current challenges and future directions

The average annual consumption of pairs of shoes per year, according to the World Footwear 2022 Yearbook [125] varies by continent from 1.4 to 5.3. It can be assumed that in the following years, there will be a slight increase in the volume of footwear consumption, likely to reach the level of 30 billion pairs per year. Major changes are expected in the structure of the footwear sold. There is an increasing interest in functional and/or specialized footwear that enables safe and comfortable walking. From this point of view, anti-slip soles have become important to a significant customer community. These are mainly various types of medical, work, and specialized footwear. At present, not enough attention has been paid to the research of anti-slip properties of the soles. Nevertheless, market demands can be expected to improve this key parameter.

The vast majority of studies mentioned in this review tested friction across flooring and contaminants for intact shoes or outsole samples. However, the effect of outsole wear on friction has not been studied much. According to Cook et al. [43], shoes worn in the workplace reported an average 25% lower values of COF compared to their new condition. Furthermore, the decline was more pronounced for shoes with higher initial COF values. Gupta et al. [126] reported ACOF reductions between 25% and 80% for progressively worn outsoles. Their results suggest that smaller threads are more prone to wear. The influence of thread design on the wear of shoes was reported by Walter et al. [127] with no effects due to hardness. Changes in rubber friction due to wear of thread design were also analyzed by Ishizako et al. [128]. Under liquid-contaminated conditions, wear or the thread pattern geometry is also associated with higher fluid pressures and a lower COF between the shoe and the ground [95]. It should also be noted that, under certain conditions, wear of the shoe outsole can lead to an increase in COF. Due to the light wear of the shoe, high-pressure regions of the outsole are worn, and the contact area increases as the shoe geometry conforms to the floor surface.

It looks like one of the challenges for the future of anti-slip footwear lies in the outsole materials or tread patterns that preserve their anti-slip properties throughout the entire life-cycle of the shoe. An alternative solution is the methodology to evaluate outsole wear. Using this methodology, workers' shoes could be replaced before losing their anti-slip properties. This will reduce the possibility of occupational slips and consequent injuries to workers.

7 Conclusions

The review of the current state of footwear-ground friction has shown a relatively small research volume with the comparison of other related shoe topics, such as biomechanics, diabetics, children's foot growth, or correct corpus structure. The reason may be the fading period of buying cheap products, which are based on the unification of footwear production, which, unfortunately, in many cases does not respect functionality nor the health and individual needs of customers. With deepening knowledge of the impact of footwear on our health, the market requirements for the quality of footwear are changing.

The main goal of the review was to analyze the current state of friction between the sole and ground so that the collected knowledge potential could be used to develop a new stage of friction research. Methodologies and parameters that influence coefficient of friction (COF) values were described. Special attention was also paid to the insecure walking on surfaces covered by solid particles, liquid contaminants, and ice.

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Declaration of competing interest

The authors have no competing interests to declare that are relevant to the content of this article.

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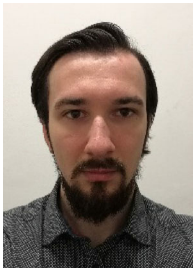

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