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Research Article

Investigating dry ski–snow friction

Shiraz Ahmed Siddiqui[1] (✉), Michael Hasler[2], Martin Mössner[1], Joost van Putten[1,2], Werner Nachbauer[1,2]

[1] Department of Sport Science, University of Innsbruck, Innsbruck, 6020, Austria.

[2] Research Center Snow, Ski, and Alpine Sport, Innsbruck, 6020, Austria.

✉ Corresponding author. Shiraz.Siddiqui@uibk.ac.at

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Abstract: The easy gliding of skis on snow has long been attributed to several co-existing mechanisms, including dry friction, lubrication by frictional meltwater, and capillary suction, making it challenging to isolate their individual contributions. Experimental evidence that characterises ski–snow friction mechanisms remains scarce. In this study, we focus specifically on dry friction. Experiments were performed on a linear tribometer using a flat slider at –8 °C under conditions where previously no frictional meltwater was observed. The temperature was further reduced below –30 °C using dry ice to eliminate the potential influence of the quasi-liquid layer, thereby ensuring that dry friction was the only active mechanism. Additionally, frictional behaviour under conditions representative of cross-country skiing was investigated. The friction coefficient decreased with increasing speed at a temperature below –30 °C, but increased with speed at –8 °C. Increasing pressure reduced the friction coefficient at both temperatures. A comparison of the measured friction coefficients with theoretical considerations indicates that the primary friction mechanism is the tearing out of grains below –30 °C, and the shearing off the tips (abrasion) at –8 °C. Overall, the results demonstrate that friction under all the investigated conditions can be explained by the stated mechanisms, along with mechanical and thermal effects and granular lubrication, without invoking any influence from the quasi-liquid layer. While it is difficult to explain friction on ice without the help of the QLL, its role in friction on snow appears to be far less significant.

Keywords: Ski–snow friction, friction mechanisms, dry friction, granular lubrication, quasi-liquid layer.

1 Introduction

As skis slide over snow, complex interactions between the ski base and snow grains result in surprisingly low friction. George Klein [1] defined three key components of ski–snow friction: dry friction (solid-to-solid interaction), lubrication, and resistance arising from surface tension effects, also known as capillary suction. The formation of a meltwater layer has been primarily attributed to frictional heating [2]. The presence and thickness of this meltwater layer critically influence the spatial distribution and relative contribution of the various friction mechanisms along the ski base [3, 4]. It is currently widely accepted that a thin liquid layer, formed as a result of frictional heating, acts as a lubricant and substantially lowers the friction coefficient between the sliding surfaces [5–10]. When the thickness of this lubricating layer between the two surfaces is insufficient to separate the contacts, predominantly solid-to-solid interaction occurs. This results in several other mechanisms such as snow compaction, deformation, fracture of asperities, drag induced by entrained dirt particles, electrical charging, and adhesion that affect ski-snow friction [5, 11].

Michael Faraday [12] proposed that surface premelting is responsible for the adhesion observed between two ice cubes. This premelted layer, nowadays also referred to as the quasi-liquid layer (QLL), is a high-viscosity, water-like film that exists on the outermost surface of solid ice and is more weakly bonded than the bulk molecules [13, 14]. The thickness of the QLL is highly temperature-dependent, with reported values ranging from nearly 100 nm to well below 1 nm; at temperatures below –30 °C, it is generally considered to be extremely thin [15, 16]. The QLL has recently been widely recognized as a key mechanism governing friction on ice surfaces [17–19]. However, its specific contribution to sliding friction on snow surfaces has not yet been reported.

The current understanding of ski–snow friction encompasses several coexisting mechanisms [3], making it challenging to assess their individual contributions. The experiments conducted by Lever et al. [20] at approximately –8 °C, under pressure and speed conditions lower than those encountered during real skiing, showed no evidence of frictional meltwater formation. We extended this investigation by further lowering the snow temperature to below –30 °C, thereby eliminating the potential influence of the quasi-liquid layer. Under these cold conditions, only dry friction is expected. The aim of this study was therefore to investigate dry friction. In addition, friction measurements were also conducted at higher sliding speed and pressure to replicate conditions representative of cross-country skiing.

2 Materials and Methods

The experiments were conducted in the snow laboratory of the Research Center Snow, Ski and Alpine Sports at the University of Innsbruck (Austria), using a linear tribometer equipped with a 24 m-long sliding track. The precision of the friction measurements was previously assessed to be below 2.2 % at 6 $m \cdot s^{-1}$ [21].

The snow used for the experiments was produced using a snow lance positioned in a separate cold chamber, operated at temperatures between –16 °C and –19 °C. After production, the snow was sieved and manually placed into the tribometer trough. A steel blade was used to press and level the snow surface, ensuring a uniform test track. Air and snow temperatures were continuously monitored using SHT35 sensors (Sensirion AG, Stäfa, Switzerland) for air and DS 18B20 sensors (Maxim Integrated, San Jose, CA, USA) for snow. The temperature measurements had a precision better than 0.2 °C. To achieve the low-temperature condition, the snow was initially cooled overnight to –20 °C while in the trough. To further decrease the temperature, dry ice (sublimation temperature: –78.5 °C) was used as a cooling agent. For homogeneous cooling of the snow surface, U-shaped aluminium profiles (50 mm x 20 mm cross-section) were placed along a 5 m section of the snow track, and dry ice was evenly distributed within these profiles (Figure 1(a)). After placing the dry ice inside the aluminium profiles, a waiting period of 15 minutes was observed to allow partial sublimation, resulting in the snow surface temperature dropping below –30 °C. During the experiments, snow temperatures varied between –32 °C and –45 °C. For clarity, this condition is hereafter referred to as "below –30 °C". The cooling procedure using dry ice was repeated on each of the four tracks directly before the experiments to ensure consistent thermal conditions. An infrared sensor (Optris CTLaser, Optris infrared sensing, LLC, Portsmouth, USA) was mounted on the carriage to continuously monitor the snow surface temperature during the experiments. This infrared sensor continuously measured a spot on the snow surface with a diameter of 20 mm in front of the ski. In addition, an infrared camera (VarioCAM hr, InfraTech GmbH, Dresden, Germany) was positioned close to the trough to confirm a homogeneous temperature distribution.

The test specimen was a flat slider made of medium-density fibreboard (MDF) with an ultra-high molecular weight polyethylene (UHMWPE) base. A liquid wax (Hydro warm, HWK-Kronbichler GmbH, Ebbs, Austria) was applied to the base. The waxed slider was placed at –20°C overnight. The slider measured 100 cm in length and 5 cm in width (Figure 1(b)), resulting in a nominal contact area of 500 cm^2. Bowden et al. (1939) [22], Bäurle et al. (2007) [23] and Mössner et al. (2021) [24] reported real contact areas of approximately 1% of the ski base area under static loading conditions. Based on this, the absolute real contact area is 5×10^{-4} m^2, and with the load of 218 N, the normal pressure at the contact spots amounts to 0.44 MPa.

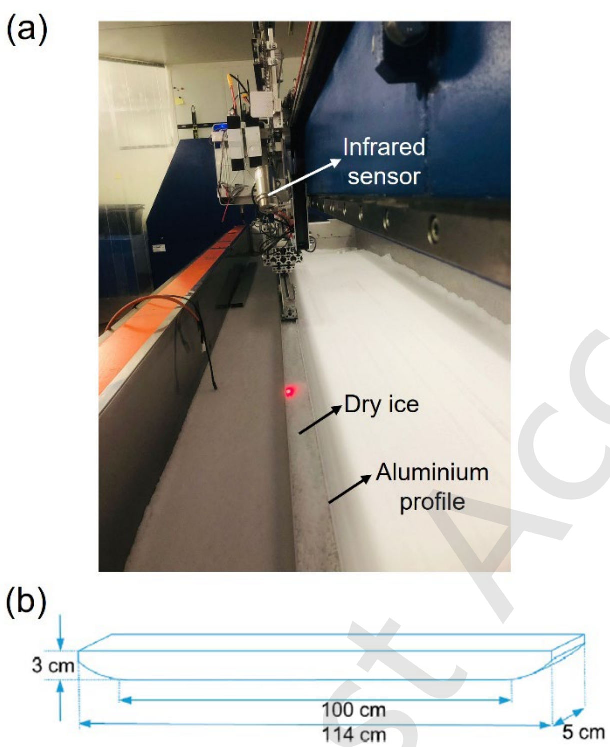

Figure 1: (a) Linear tribometer showing the experimental setup. (b) Dimensions of the flat slider**.**

Experiments were conducted at two different snow temperatures: below –30 °C and at –8 °C. The slider was attached to the tribometer and pressed against the snow surface using springs that applied normal pressures of 1.6 kPa and 4.4 kPa. In our experiments, a low contact pressure (1.6 kPa) was selected to replicate the conditions reported by Lever et al. (2018) [20] who observed low friction (μ < 0.03) without meltwater formation. As this finding challenges the widely accepted meltwater lubrication framework for ski–snow friction, these pressure and speed conditions were chosen to verify and critically investigate the underlying physical mechanism. After acceleration, the slider was moved 5 m over the snow surface at the selected sliding speeds of 2 and 5 $m·s^{-1}$. In this section, friction was measured. The sliding tests were performed ten times on each of the four separate snow tracks. Each track corresponded to one pressure–speed combination: 1.6 kPa/2 $m·s^{-1}$, 1.6 kPa/5 $m·s^{-1}$, 4.4 kPa/2 $m·s^{-1}$, and 4.4 kPa/5 $m·s^{-1}$. The average friction coefficient for each condition was then calculated from the ten repeated runs. To minimize the influence of ploughing and snow compaction, before the experiments, ten preliminary runs at a speed of 5 $m·s^{-1}$ were performed on each track, as these mechanisms are primarily active during initial runs [25]. The run-in was performed before the application of dry ice. No adhesion between the aluminium profiles and the snow surface was observed, and the snow surface remained undamaged.

3 Results

Figure 2 shows the average friction coefficient over the ten runs, with its standard deviation for the measured experimental conditions.

The friction coefficient was found to be significantly higher at a snow temperature below –30 °C compared to –8 °C. The friction coefficient decreases with the increase in normal pressure at both snow temperatures. The friction coefficient decreases with the increase in sliding speed at a snow temperature below –30 °C whereas it increases with the increase in sliding speed at –8 °C.

At a snow temperature below –30 °C and under a low normal pressure of 1.6 kPa, the average friction coefficients were 0.073 and 0.064 at sliding speeds of 2 $m·s^{-1}$ and 5 $m·s^{-1}$, respectively. When the snow temperature was increased from below –30 °C to –8 °C, the average friction coefficient decreased by 49.3% at 2 $m·s^{-1}$ and by 34.3% at 5 $m·s^{-1}$.

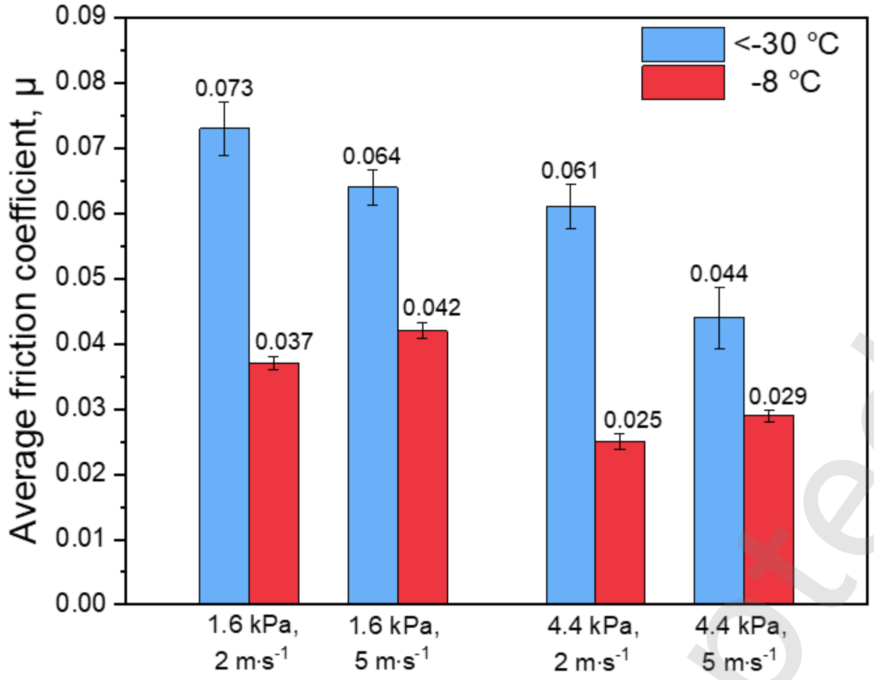

Figure 2: Average friction coefficient over ten runs with its standard deviation at normal pressures of 1.6 kPa and 4.4 kPa, and sliding speeds of 2 m·s^{-1} and 5 m·s^{-1}, measured at a snow temperature below –30 °C and at –8 °C.

At a snow temperature below –30 °C and with a higher normal pressure of 4.4 kPa, the average friction coefficients were 0.061 and 0.044 at sliding speeds of 2 m·s^{-1} and 5 m·s^{-1}, respectively. When the snow temperature was increased to –8 °C, the friction coefficient decreased by 59% at 2 m·s^{-1} and by 34% at 5 m·s^{-1}.

4 Discussion

The primary objective of this study was to analyse dry ski–snow friction. This was achieved by performing friction measurements at –8 °C under low-speed and low-pressure conditions, where no frictional meltwater was observed [20], and by further reducing the temperature to eliminate any potential influence of a quasi-liquid layer. Under these conditions, the measured frictional force is governed solely by dry mechanical interactions between the two solid surfaces. According to currently accepted models, dry friction force originates from the shearing off of grain tips on the contact surface of the body with lower shear strength and from the tearing out of snow grains [26–27].

Low-pressure and low-speed conditions

At a snow temperature below –30 °C, under low-pressure and low-speed conditions, the measured friction coefficient was 0.073. Analysis of micro-computed tomography images of snow revealed, that at –19.1 °C entire grains were torn out from the snow matrix, in contrast to higher temperatures where shearing off of the tips was observed [25]. According to a simple mechanical model of dry friction on snow proposed by Glenne (1987) [26], snow deforms when it is progressively loaded and yields until the applied normal stress equals the bearing (compressive) strength of the snow. At this point, the contact area is given as $A_c = F_n/\sigma_c$ where F_n is the normal load and σ_c is the unconfined compressive strength of snow. The coefficient of dry friction can be expressed as $\mu_{dry} = \tau_{snow}/\sigma_{snow}$ where τ_{snow} is the shear and σ_{snow} is the compressive strength of snow. Using τ and σ values reported by Carter (1970), Colbeck (1992) [27] estimated a theoretical dry friction coefficient of approximately 0.11 at −32 °C (see Table 1 in Colbeck, 1992). In our experiments, the measured average friction coefficient at a temperature below −30 °C was 0.073. This value lies within the same order of magnitude and suggests that the snow matrix yields during sliding, resulting in intergranular bond failure. Because the mechanical properties of artificial snow are varying, the theoretical estimate above should be regarded as a first-order approximation. Snow properties depend not only on grain size and temperature but also strongly on snow age. As snow undergoes sintering and metamorphism, intergranular bonds grow, strengthening the snow matrix. Consequently, snow exhibits a wide variability in mechanical and frictional properties over time. Microscale observations by Lever et al. (2019) [29], demonstrate that intergranular bond failure can lead to friction coefficients well below 0.1, even in the absence of meltwater lubrication. The sliding experiments performed by Bowden (1953) [28], using real skis on snow at −32 °C reported a friction coefficient of 0.10, further supporting the general range of values discussed here. A representative micro-CT image of the snow surface after 20 sliding runs, corresponding to identical snow preparation conditions at −19.1 °C and a sliding speed of 5 m/s is shown in Figure 3. The micro-CT observations reveal that the surface grains remain largely rounded and intact, with no evidence of grain fracture. This observation further supports our claim that the interaction is governed by tearing out of grains rather than shearing off of the tips of grains.

Figure 3. Micro-CT image of snow surface at a temperature of −19.1 °C after the 20 runs [25].

At a snow temperature of –8 °C, under low-pressure and low-speed conditions, the measured friction coefficient dropped to 0.037. The calculated friction coefficients based on the tearing out of grains mechanism are 0.17 and 0.24 at snow temperatures of –10 °C and –5 °C, respectively (see Table 1 in Colbeck [27]), exceeding our experimentally determined friction coefficients by approximately a factor of six. This discrepancy suggests that the tearing out of grains mechanism is unlikely to play a significant role at this temperature. The effect mainly described in the literature in connection with dry ski–snow friction is the shearing off of snow grain tips. This process occurs when the applied shear stress exceeds the shear strength of the ice grains. Since shear failure is localized at the asperity contacts between the ski base and individual ice grains, rather than within the snow matrix, the bulk properties of snow are not relevant to this failure mechanism. Therefore, the material properties of ice govern the shear response at these contact points. The friction coefficient can be expressed as the ratio of the shear strength τ_{ice} to the compressive strength of ice σ_{ice}, i.e., $\mu_{dry, shear} = \tau_{ice}/\sigma_{ice}$ [7, 30]. The shear strength of ice has been reported to range between 600 and 800 kPa [31, 32], while its compressive strength is approximately 14 MPa at –10 °C [33]. Based on these values, the theoretical friction coefficient is estimated to be 0.04. The experimentally measured friction coefficient of 0.037 is in good agreement with the theoretical predictions, thereby confirming that shearing off of the tips (abrasion) is the primary mechanism at a temperature of –8°C.

In brittle materials such as snow, the mechanical response under sliding is dominated by the initiation and propagation of microcracks. Consequently, the material's resistance to failure is governed by its fracture toughness rather than the shear strength of ice, making fracture toughness a critical factor in determining frictional behaviour. However, due to the lack of available fracture toughness data for the investigated artificial snow (amorphous ice), this criterion could not be applied in the present study.

To relate the laboratory findings to real-world skiing conditions, additional measurements were performed by increasing the sliding speed to 5 $m \cdot s^{-1}$ and the pressure to 4.4 kPa, which is representative of cross-country skiing.

Effect of increased sliding speed

As sliding speed increases, the strain rate at the snow surface rises correspondingly. Previous studies have shown that higher strain rates increase the shear strength of both snow and ice [34–37]. Consequently, friction is expected to increase with sliding speed. Shearing off of the tips occurring at higher temperatures maintains persistent ski–snow contact, allowing frictional heating to accumulate locally at the interface. This local heating contributes to thermal softening of the snow grains. In contrast, at lower temperatures, where entire grains are torn from the snow matrix, persistent contact is lost, substantially reducing interfacial frictional heating and preventing thermal softening.

As stated earlier, at a snow temperature below –30 °C, the primary mechanism is the tearing out of grains, which results in the fracture of intergranular bonds. This process generates loose wear particles that form a fragmented granular layer, thereby promoting easier sliding [38–41]. Increasing the sliding speed from 2 $m \cdot s^{-1}$ to 5 $m \cdot s^{-1}$ resulted in a 12.3% decrease of the friction coefficient. As the sliding speed increases, the particles become agitated and granular kinetic lubrication is supposed to occur, resulting in a reduction in the overall friction coefficient [42]. The present study provides the first experimental evidence of a decreasing coefficient of friction with increasing speed at a snow temperature below –30 °C.

At a snow temperature of –8 °C, the observed trend is reversed to the one observed below –30 °C − friction increases with sliding speed − indicating that different mechanisms dominate at –8 °C. The increase in friction with speed is consistent with previous reports [43-45]. It is commonly attributed to the formation and viscous shearing of a meltwater film at the interface, particularly at temperatures warmer than approximately –10 °C. However, the observed increase in friction can also be explained by the higher strength of the snow grain that develops at higher speeds prevailing the potential effects of snow grain warming and frictional meltwater formation.

<u>Effect of increased pressure</u>

Higher pressure increases frictional power (given by the product of normal force, sliding speed and the friction coefficient) and the real contact area between the ski base and the snow surface [26]. Both the frictional power and the contact area influence the heating of snow grains during sliding. An increased temperature reduces the shear strength of the grains, leading to lower friction. Conversely, an increased contact area increases the sheared off area and thus increases friction. Increasing the pressure from 1.6 kPa to 4.4 kPa (at 2 $m \cdot s^{-1}$) showed reductions in the friction coefficient of 16.4% and 32.4% at a snow temperature below –30 °C and at –8 °C respectively. The observed decrease in friction with increasing pressure is consistent with previous studies. Buhl et al. [4] found that an increased normal load significantly reduces friction at temperatures below –5 °C. Similarly, Auganæs et al. [46] and Sandberg et al. [47] observed that the friction coefficient decreases with increasing average contact pressure at a snow temperature of –10 °C and –8 °C respectively.

At a temperature below –30 °C, increasing the pressure may substantially increase the number of grains torn out of the snow matrix [48]. This increase in detached grains may cause the resulting granular layer to carry a greater share of the load than it would under lower-pressure conditions, thereby reducing direct ski–snow contact and potentially enhancing its friction-reducing effect. Accordingly, the observed decrease in friction with increasing pressure may be attributed to granular lubrication.

At a snow temperature of –8 °C, the observed decrease in the friction coefficient suggests that the thermal softening and potential melting of the snow grains predominate over the effect of increased contact area. The approximately two-fold greater reduction of the coefficient of friction at –8 °C suggests that, in addition to dry friction, other mechanisms—such as lubrication—may contribute to the decrease in friction at this temperature.

The results obtained at low-pressure and low-speed can be explained using simple mechanical models. In contrast to friction on ice, where the presence of a QLL is required to account for the low static friction, when skiing on snow can be explained by the failure of the snow matrix or shearing off of the tips of the grains.

The friction behaviour observed with increasing speed or pressure is consistent with the stated mechanisms, provided that the temperature- and rate-dependent properties of snow are considered, together with the additional influence of the granular lubrication.

The results do not fundamentally rule out the formation of a meltwater film due to frictional heat. However, no clear transition from dry friction to mixed or lubricated friction was observed. In general, the high friction levels predicted by Colbeck's curve [3] for dry friction are not supported by the experimental data.

5 Conclusions

- We found two sub-mechanisms of dry friction: tearing out of snow grains and shearing off grain tips.
- Friction at temperatures below −30 °C was attributed to the tearing out of snow grains and granular lubrication.
- Friction at −8 °C was attributed to the shearing off grain tips and thermal softening.
- With increasing speed and pressure, the formation of frictional meltwater at −8 °C could not be excluded.
- Under the investigated conditions, the quasi-liquid layer (QLL) does not appear to contribute significantly to friction.

Competing interests

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

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