The Role of Ice Indentation in the Friction Produced Between the Blade and Ice during Ice Skating

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Abstract

Ice skating is an astonishing feat of grace, strength, precision, and speed that has made its way into popular recreation, online media, and international competitions. However, while the remarkable slipperiness of ice is well-known and the creation of a shallow rut where the skater skates can be easily observed, the mechanisms behind these two phenomena remain unclear and debated. The extraordinarily low friction coefficient of ice was first attributed to a meltwater layer forming from pressure melting, but this was later largely disproven and replaced with a frictional melting theory. Later studies revealed nano-scale quasi-liquid layers acting as a lubricant, and more recent research has factored in the role of ejected ice particles in forming an ice-rich slurry at the blade-ice interface. The latter theory invites discussion of ice indentation processes to explain how brittle failure occurs and how crushing impacts friction. High-pressure zones enable pressure melting, microcracking, and spalling; crushing depends on ice hardness which varies with temperature and plowing velocity; and the plowing force contributes about half of the experienced frictional force and changes with blade geometry. Ice indentation can be a complex process with many factors, but it is instrumental in the generation of a lubricating slurry and, thus, in the low friction experienced by skaters.

Introduction

Ice skating has long captured the attention of thousands: figure skating for its beautiful display of athleticism, artistry, and emotion; hockey for its fast-paced, high-stakes games; and speed skating for the incredible speeds that skaters are able to reach. Central to all forms of skating on ice is the remarkably low coefficient of friction of ice, allowing skaters to glide and travel quickly with ease on the surface. This has consequently captured the attention of many researchers, who sought and continue to clarify the reasons behind why ice is so slippery and what makes ice unique in that it is one of the only materials on which one can skate.[1] Many theories have been proposed, scrutinized, altered, and dismissed since the 19th century, most of which are centered around a thin lubricating film of melted ice, otherwise referred to as a meltwater film. The earliest theory involved pressure-melting, in which it was proposed that the high pressure beneath a blade bearing a skater's weight helped melt a thin lubricating layer that lowered the friction of ice.[2] Later studies argued that frictional heating was the cause.[3] More recent research has brought up the role of dislodged ice particles and possible dry lubrication, although the latter was more focused on sliding on snow rather than on ice.[1, 4] Still another significant factor was proposed to be in pre-existing, nanoscale quasi-liquid layers, in which surface diffusion provides the necessary mobility of water particles to allow blades to glide easily on the ice surface.[5, 6] More details, untouched upon by this paper, involving heat flow, lubricant fluid dynamics, and a flash heating theory can be found in the paper of Lever et al..[4] Each theory proposes a factor or some combination of factors, and debate and speculation continues as to what exactly governs ice friction and how to best model and assess the scenario.

Regardless of how exactly the ice achieves its low coefficient of friction, the fact remains that a shallow, relative to the blade's height, indent is left in the ice when a skater glides on the ice–an easily observable phenomenon. Such an indent can be seen in Figure 1, where the skater's path is clearly visible along with many other ruts that were formed by other paths a blade once took when gliding on the ice. This indent, whether it is created through pressure or frictional melting, crushing of the ice due to its brittle nature, some combination of the two, or neither, is evident and likely plays a significant role in not only the friction mechanics in the blade-ice interface but also the skater's control. If the blade were to experience low friction at all times, it would be incredibly difficult for the skater to accelerate, making speeding up, abrupt stops, turns, and spins all but impossible. This paper thus explores the role of this indent: how it may be formed, how it affects the skater, and its influence in a unified hypothesis proposed by Lever et al. 2022 and 2023 for ice-blade friction involving the formation of ice-rich slurries.[4, 7]

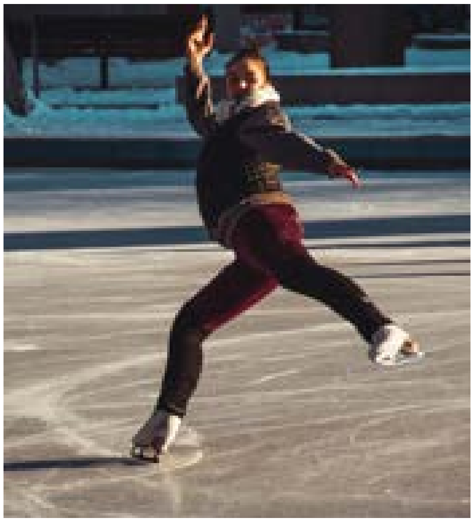

Fig. 1. A skater gliding backwards on one foot on the ice. A clear path can be seen on the ice in front of the skater's right foot, where she curved and traveled backwards. Many other fainter white lines are seen on the ice surface. Each white line is an indent left behind by a blade that glided along that path.[8]

Section 1: Overview of Existing Theories Explaining Low Friction of Ice

Meltwater Film

Perhaps the most prevalent accepted theory behind the low friction of ice is the presence of a meltwater film. This thin layer of water acts as a lubricant, allowing blades to glide effortlessly across the ice. However, the origins of this film are unclear, along with its exact thickness, properties, and overall influence over friction. The two main proposed causes for this lubricating film are pressure melting and frictional melting. The former came first, but the latter is now much more widely accepted and studied.[2, 4]

Pressure Melting

Pressure melting was the first well-known theory behind the low friction coefficient of ice, the earliest literature on which was found in Reynold's paper accrediting the formation of a thin water film to pressure melting.[2] This idea hinges on the unique property of ice, where water's solid form is less dense than its liquid form, and increasing the pressure on ice can subsequently lower its melting point. Because ice blades are so thin and support the entirety of a skater's weight, it can be imagined that the pressure from such a small surface area relative to the force exerted down onto the ice surface would be enough to result in melted ice beneath the blade, facilitating movement. However, subsequent studies soon questioned Reynold's propositions and found that the pressure exerted by the blade on the ice was too little (tens of MPa) to result in a significant melting point drop (less than 1℃).[9] Considering the fact that most ice rinks are kept at temperatures more than 1℃ below the melting point (about -3.5℃ for figure skating, between -5℃ and -8℃ for hockey, and between -5℃ and -6℃ for speed skating), it is thus unlikely that pressure melting is able to produce the needed meltwater film.[10] Bonn also noted that pressure melting is impossible for ice below -20℃, while skating is still possible below that temperature, so there must be some other factor at play.[1]

Frictional Melting

Pressure melting was a prevailing theory for some time, but the scientific community has largely put it aside and focused more on frictional melting, as it poses a more plausible explanation. After Bowden and Hughes in 1939 published the first systematic study, where they suggested frictional heating was responsible for the lubricating meltwater film that lowers friction on both ice and snow, numerous studies have followed suit in examining frictional melting as opposed to pressure melting.[3, 4, 11, 12] Bowden and Hughes first proposed that as the blade slides across the ice, solid-on-solid rubbing results in mechanical energy lost from the system of ice and blade in the form of heat, and this heat then melts the ice beneath.[3] With heat-budget estimates, it can then be assumed that that thin film can supply enough frictional heat for ice to continue melting as a blade continues sliding, maintaining consistently low friction.[4] Later studies began examining also the lubrication regime at the blade-ice boundary and frictional heat that could arise from the shear forces of the lubricating film and the plowing force as a blade pushes forward onto clean ice, leaving an indent behind.[11, 13, 14]

However, direct confirmation for frictional melting and the creation of a film by skates still does not exist, and some studies have questioned the effectiveness of frictional melting.[1, 4, 5] For instance, Bonn argues that since frictional heating is not unique to ice, yet ice is one of the only materials that can be skated on, frictional melting cannot be the driving factor behind the low friction of ice skating.[1] Interestingly, Colbeck et al. measured skate-bottom temperatures and found that they remained well below 0℃ during skating, which leads to doubt as to whether or not the sliding friction is sufficient to melt ice and produce a film quickly enough for a skater to always experience low friction when gliding at high speeds.[15]

The relationship between the amount of frictional heat generated and the friction of ice also remains unclear. In experiments examining the effect of thermal conductivity on friction, Kietzig et al. found that materials with a lower thermal conductivity were generally accompanied by lower friction.[12] However, this effect became less significant as sliding velocity increased, whereby the effect of surface wettability increased. Kietzig et al. hypothesized that, because materials with lower thermal conductivity trapped heat better at the interface (thermal energy travels away from the interface through the sliding material at a slower rate), this heat would then melt more ice, resulting in a thicker film, better lubrication, and lower friction.[12] Combined with the conclusion by Colbeck et al. that faster skating speeds produced higher blade temperatures, one can infer that higher skating speeds will produce more frictional heat, more frictional heat will melt more ice and create a thicker lubricating layer of water, and the coefficient of friction will be lower.[15] However, Weber et al. also found that, at temperatures between -7℃ and 0℃, changes in sliding velocity did not significantly affect the measured friction coefficient (found using glass and steel beads sliding across ice).[5] This raises questions as to just how much frictional melting lubricates the ice surface since changes in velocity should hypothetically be changing the amount of heat, melting, lubrication, and finally friction between the slider/blade and the ice, but no significant variation is observed.

Nanoscale Quasi-Liquid Layers

Quasi-liquid layers (QLLs) are extremely thin lubricating films that lower friction on ice. They are very similar to meltwater films, but they are much thinner and are a result of premelting–that is, pressure and frictional melting are not used to explain the origins of these lubricating layers. QLLs have been found to be both viscous and elastic, existing somewhere between water and ice due to the top layer of water molecules making up the QLL having unsatisfied hydrogen bonds to the bulk ice.[1, 4, 5] The thickness of these layers also decreases with decreasing temperature, which could explain an observed increase in ice friction at colder temperatures.[5] Weber et al. found that as the temperature of ice nears -100℃, the friction coefficient increases, approaching around 0.5, compared to a more slippery coefficient of around 0.01 at -7℃.[5] To examine the influence of this layer, Bluhm et al. also conducted experiments using an atomic force microscope, finding that, if the tip is placed below the QLL and moving very slowly (5 μm s^{-1}), the coefficient of friction of the ice without the QLL could be measured: 0.6 for temperatures ranging from -24℃ to -40℃.[16]

Figure 2 provides a close-up model of the water molecules in both the ice and QLL, where a structured lattice makes up the solid ice, and more mobile molecules are able to roll about on the surface. Weber et al., in their paper, suggest that the reason behind QLLs' ability to lower friction is the process of highly-mobile water molecules quickly filling in gaps on the ice surface, making the surface smoother.[5] To test this self-healing ability of ice, they observed a mark manually made by a screwdriver fill in in a matter of minutes, seen in Figure 3.[5]

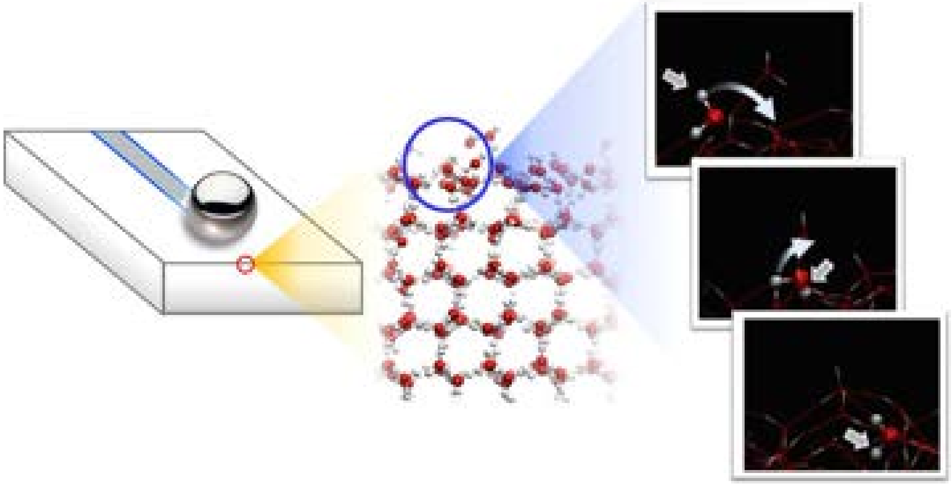

Fig. 2. A close-up of how water molecules in a QLL may behave under a slider (in this case, a metal ball). The molecules diffuse over the ice surface in a rolling motion.[5]

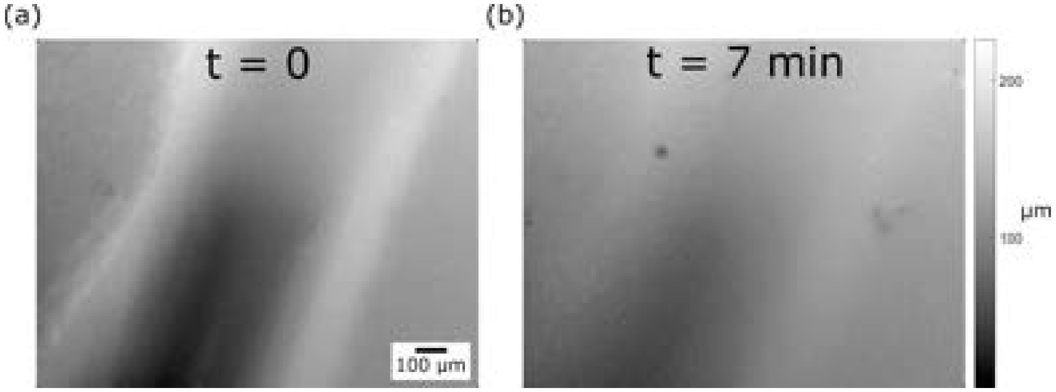

Fig. 3. Images with interferometer measurements from the experiment by Weber et al. display the self-healing of ice at -10℃.[5] (a) An image right after a scratch was manually made with a screwdriver. (b) An image 7 minutes later, with a much less visible scratch. The mobility of the water molecules helped fill the gap and result in indents of less depth.

However, considering the need for a Zamboni (a tractor-like machine that dispenses warm water and collects shaved ice to re-smoothen the ice surface), this surface diffusion is far from enough to fill in indents from actual skating. Though it can be assumed that this nanoscale layer of water molecules are mobile enough to rapidly fill in smaller, microscale asperities that might otherwise increase the friction of ice, explaining the results found by Bluhm et al..[16]

QLLs acting as the major factor in low friction on ice is doubted for varying reasons: the layers are very thin (usually less than 3nm),[14, 16] focusing only on microscale QLLs neglects the role of plowing and dislodged ice and snow particles,[1,4] and QLLs are more accepted as an explanation for temperatures under -20℃, a significantly colder temperature than that of ice rinks.[9] Considering plowing becomes significant at ice temperatures above -20℃ and QLLs do not prevent brittle failure of ice, there is likely more to the picture.[14]

Ice-Rich Slurries: A Combination of Factors

To develop a more complete explanation for ice friction is to take into account the many processes that occur at the blade-ice interface. Blade-wide meltwater films and QLLs both address the existence of a liquid lubricant lowering friction, but explanations focusing solely on one or a combination of the two can fail to address factors like ice particles resulting from crushing, surface asperities and roughness, and the displacement of a lubrication film due to squeezing. Consequently, numerous papers have more recently explored ice friction by combining existing lubrication theories,[6] factoring in plowing,[11, 14] and addressing the role of abrasive wear. [1, 4, 6, 7, 17]

The process occurring at the blade-ice interface as proposed by Lever et al. involves pressure melting, frictional melting, abrasive wear, and lubricating films, and while QLLs are not identified as having a major role, they can and likely do, according to Baran et al., contribute to lowering friction without interfering with ice crushing or the formation of an ice-rich slurry.[4, 6, 7]

Starting with the role of pressure melting, a key factor in the process lies in surface asperities. Both the blade and ice surfaces are unlikely to be completely smooth, and Figure 4 provides a simplified illustration of what the two surfaces could look like once examined closely.

Blade and ice surfaces exhibit microscale roughness, so the real contact area is less than the apparent contact area, the majority of the force exerted on the ice is isolated at numerous asperities rather than uniformly across the entire blade-bottom, and high-pressure zones (HPZs) form as a result.[4] Figure 5 offers a visual representation of surface asperities and the difference between apparent and real contact area. Because of very small asperities on both the ice and blade surfaces, pressure is concentrated at HPZs where asperities meet.

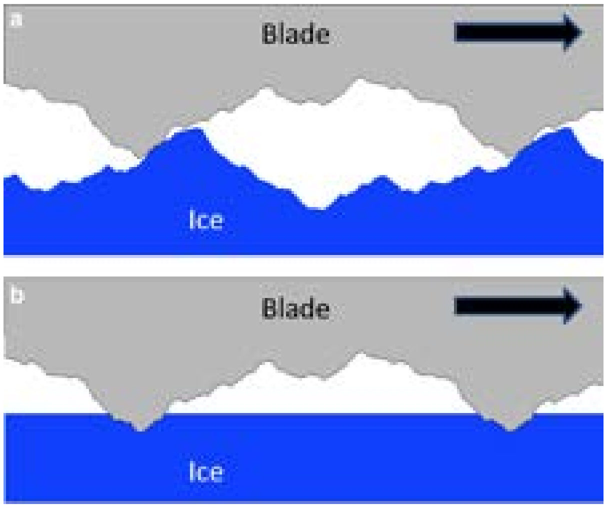

Fig. 4. Two idealized blade-ice interfaces. (a) Both the blade and the ice are rough. (b) The blade is rough, but the ice is smooth. Most skate blades are rough, so the area of real contact is limited by asperities. Choosing whether or not to simplify ice as a smooth surface can impact what models to use when calculating theoretical data, but that is beyond the scope of this paper.[4]

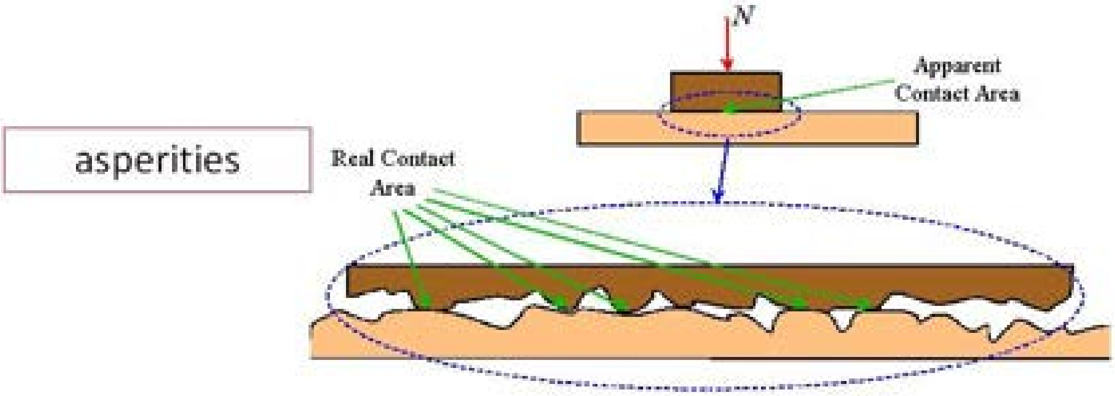

Fig. 5. The load is supported by several asperities rather than spread uniformly over the entire surface area of the blade. The apparent contact area is larger than the real contact area,which is seen only when magnifying the interface.[18]

While blade-wide pressure melting raised doubts as to whether or not the pressure between the blade and the ice could lower the melting point of ice enough for a consistent meltwater film to be produced, the pressures at HPZs have been measured to approach or exceed the needed pressure-melting point.[4, 19] Therefore, pressure melting is viable in this model, and while high pressure will continue to squeeze the lubricant out, a dynamic balance is achieved by continuous melting restoring the film.[6, 9]

Lever et al. emphasize the role of ice particles generated through abrasive wear, noting their incorporation with melted ice to generate a lubricating film with viscoelastic properties.[4, 7] These wear particles can be clearly seen in hockey games when skaters stop abruptly and send a spray of scraped ice flying into the air, but they can also be ejected, albeit fewer are, during normal strides, as seen in Figure 6.

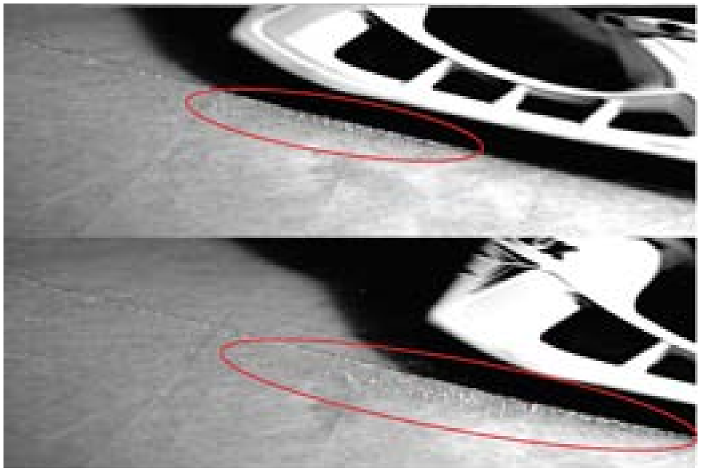

Fig. 6. Two high-speed camera images of a hockey skate during the push-off phase of a stride at approx. 9 m/s. A rut/indent can be seen behind the blade, and scattered ice particles are circled in red. [4]

Gagnon, in an ice-crushing experiment using a rotating slider, observed the presence of an ice-rich slurry separating the bulk ice from the slider.[20] Canale et al. also performed tests using a tuning fork and an oscillating bead, seen in Figure 7, to determine the viscosity and elasticity of the lubricating layer on ice.[17] The lubricating layer was more viscous than bulk liquid water, so they discouraged focusing solely on a meltwater film and hypothesized that the presence of ice particles within the film contributed to its viscosity.[17]

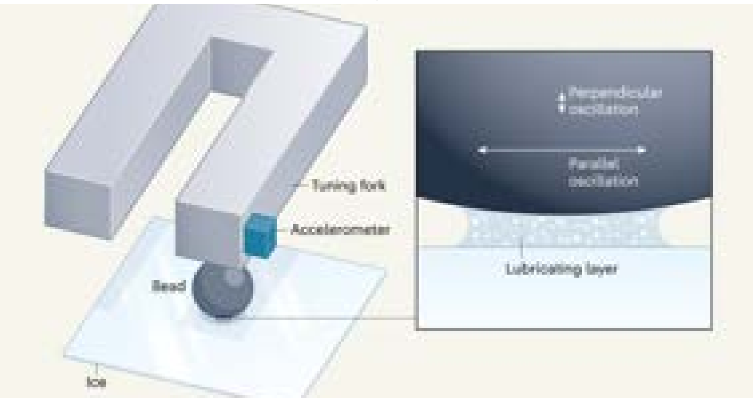

Fig. 7. An illustration of the experiment by Canale et al..[17] A millimeter-scale glass bead was attached to a prong of a tuning fork, and the fork's vibrations caused the bead to oscillate, allowing the researchers to study the viscosity and elasticity of the lubricating layer.[1]

However, it was still unclear whether or not these ice particles could be sufficiently generated when ice is not repeatedly abraded,[1] an important point considering skaters very rarely trace over the same path on ice, as getting caught in an existing rut can disrupt their balance. Lever et al. addressed this by pointing out that ice is very brittle, even at temperatures nearing the melting point, and skating speeds greater than 1 mm/s can cause brittle failure of ice, generating ice spalls (chips of ice that break apart from the larger substrate).[4] As seen in Figure 8, ice spalls and the lubricating slurry are continuously squeezed and extruded from beneath the blade, bearing a significant load, as it slides across the ice.

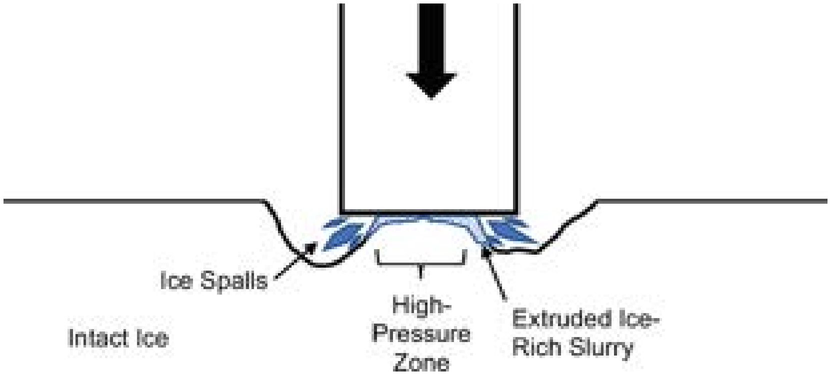

Fig. 8. A simplified diagram of what happens below the skating blade. Several HPZs form where the blade (which is curved rather than flat if it is a hockey or figure skate blade) meets the ice, the ice rich slurry is squeezed out toward the edges of the blade, and ice spalls form from brittle failure.[4]

After considering how crushing introduces ice particles to form an ice-rich slurry, it is also important to note the role of frictional melting. Heat is mainly generated from crushing of ice near the front of the blade; abrasion as the rough edges, or asperities, of the blade and ice surfaces rub against one another; and the slurry's resistance to sliding, or viscous shearing, as the blade interacts with the viscous slurry.[7] The heat works to melt the ice particles within the slurry whose melting points are sufficiently lowered by HPZs.[7] In this way, pressure and frictional melting work with squeeze flow to lower the viscosity and thickness of the slurry, while crushing, abrasion, and heat conduction from the slurry into the blade and bulk ice perpetuate the viscous lubricating film.

Lever et al. addressed, however, that their 1D model is very simplified, and it may over-predict ice friction at higher ice temperatures and under-predict at lower temperatures due to the variability of ice hardness with sliding velocity and temperature as addressed by numerous ice indentation studies.[7, 11, 14, 21] Although Baran et al. assumed atomically smooth surfaces in their study, they agreed with Lever et al. that at a larger scale, with microscale roughness present, indentation hardness would play a larger role in determining the friction coefficient of ice, and the formation of a slurry would make the process even more complex.[6]

The formation of an ice-rich slurry incorporates the role of pressure and frictional melting, abrasion, crushing, and dislodged ice particles, creating a hypothesis that merges meltwater lubrication theories with ice indentation research. This process emphasizes the role of HPZs and pressure melting at discontinuous points, countering the blade-wide lubricating film explanation. Ice-rich slurries also put more emphasis on crushing, bringing into question the influence of plowing and ice hardness and encouraging further investigation of ice indentation.

QLLs, while not identified as major contributors, likely facilitate, to some extent, low friction on a very small scale and are less influenced by the complex results of larger-scale surface roughness and ice particles.[6]

Section 2: Discussion on Ice Indentation

To summarize the hypothesis of Lever et al., the ice and blade surfaces are rough, so the majority of the skater load is supported by numerous surface asperities. Localized HPZs form at those asperities, and a combination of pressure melting, frictional melting, and brittle ice failure generates a lubricating ice-rich slurry. Crushing of the ice near the front of the blade, diagrammed in Figure 10, during forward gliding is a key process, resulting in both ice particles that become incorporated into the slurry and heat that helps to melt the particles. However, it is also important to note the variability of ice hardness and relationships between plowing force, blade geometry, and contact area in order to better examine the interactions between the skating blade and the ice substrate. Therefore, ice indentation research is crucial in understanding the processes occurring at the blade-ice interface, especially as, unlike QLLs, the lubricating slurry, and melting at the interface, ice indents are easily observable in the ice that skaters glide over.

Lever et al. suggest that downward crushing is the primary cause for the indent in the ice, and melting only deepens the rut once all of the ice particles in the slurry melt.[7] To further examine how an indent is formed, one can look to the more specific processes occurring at HPZs. First, HPZs are not consistent–they vary with time and change location and size depending on the specific surface topography, load size, and duration of crushing.[22, 23] Brittle failure and extrusion of ice particles also results in dynamic loading, where the load experienced by the ice significantly decreases as ice fractures and increases again afterward.[22, 23] The pressures experienced by the ice due to the weight of the blade, referred to as confinement pressures, also vary across the HPZ, making the process dynamic and complex. The pressures are the highest in the center of the HPZ, resulting in crystal defects, pressure melting, and recrystallization processes that vary with temperature and leave behind damaged ice that can present viscoelastic rheology (viscoelasticity describes a material whose stress response is time-dependent, varying with both applied strain and strain rate).[23] Meanwhile at the edges of the HPZs, where confinement pressures are lower and one can observe the presence of highly micro-cracked and crushed ice, micro-fracturing occurs and ice fragments are broken apart and ejected.[4, 22, 23] These processes are summarized in Figure 9, which displays what happens in each area of a HPZ as ice is crushed against a surface. Once brittle failure occurs and HPZs fail, ice is crushed and flows toward areas of lower pressure at the edges of the HPZs.[4, 22]

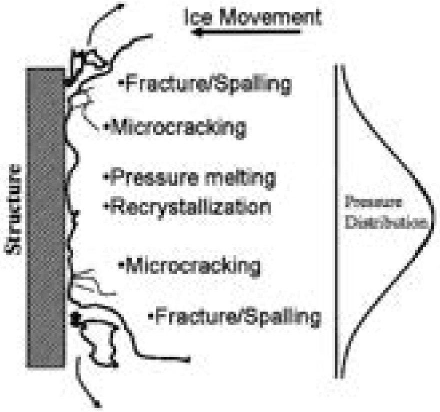

Fig. 9. A diagram of the processes occurring around and within a HPZ as ice is crushed against a structure. Pressure melting and recrystallization occur in the center where the pressure is the highest, microcracking occurs farther out, and fracturing/spalling occurs at the edges (ice spalls then travel outward away from the HPZ).[23]

Crushing at the front of the blade is also referred to as plowing, and plowing friction has been found to constitute about half of the total friction experienced by the blade during sliding indentation tests (the other half is produced by the shear forces caused by the lubricating layer).[11] Plowing and shearing forces both act against a blade's movement, and Figure 10 provides a simplified model of how a rounded skate blade moves through the ice surface.

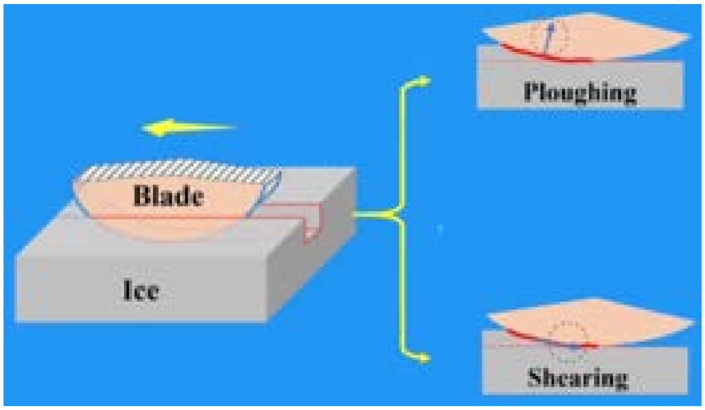

Fig. 10. A rockered blade plows through the top surface of the ice, experiencing both plowing and shearing forces. As indicated by the blue arrows, plowing forces are perpendicular to the blade surface as the blade pushes further into the ice, while shearing forces are parallel to the blade surface as the two parallel interfaces slide past each other. Plowing and shearing forces both contribute to the coefficient of friction. The directions of the plowing and shearing forces by the ice on the blade are shown in blue arrows.[11]

Plowing occurs when the blade plastically deforms the ice in the normal direction, and such deformation is only possible once the contact pressure exceeds the penetration hardness of ice.[14] Contact pressure is also almost independent of normal force since the area of real contact increases linearly with normal force, making changes in ice hardness a chief reason behind changes in indentation depth and the magnitude of the plowing force.[14] Hardness varies with temperature, decreasing linearly with increasing temperature from -110℃ up to -1.5℃.[14] Between -1.5℃ and 0℃, the hardness sharply decreases due to pressure melting.[14] So ice at higher temperatures is softer and unable to support as much pressure before fracturing (therefore maximum contact pressure decreases with increasing temperature), and an identical sliding velocity and load will result in more crushing and a greater plowing force. This, in turn, suggests a deeper rut and a higher fraction of ice within the lubricating slurry, making it more viscous.[7] Penetration hardness also increases as the sliding velocity increases, suggesting that faster skating will leave shallower indents and decrease the plowing force.[14]

Plowing is also heavily influenced by blade geometry. As a skate glides forward, it applies a force on the ice in the downward direction, due to gravity, and in the forward direction, since the blade is within an indent and plowing through the ice.[14] Blade curvature therefore plays a substantial role in how much plowing force is experienced. All ice skating blades (figure skating, hockey, and speed skating) are rockered, meaning the bottom of the blade is rounded to match the curvature of the outline of a circle with a certain radius. A larger radius corresponds with a shallower curve, while a smaller radius corresponds with a deeper curve. Figure skates typically have a smaller rocker radius in the front of the blade near the toe-pick and a larger rocker radius for the middle and back of the blade, as seen in each blade in Figure 11. Each blade model also has its own unique combination of rocker radii that influences the skater’s balance. These differences, perhaps less noticeable for the skater but more important when analyzing skating friction, also affect the plowing force. Skates typically have a large radius of curvature, 3 to 22 m,[14] in the sliding direction. Lieferrink et al. found, through ball-on-ice experiments, that balls with larger radii experienced less plowing force–in other words, decreasing radius corresponds with increasing plowing force.[14] This helps to explain the large radii of skate blades since it allows skaters to glide forward and backward with minimal plowing friction. Combined with the fact that higher surface roughness results in higher contact pressures and a higher friction coefficient,[14] it becomes clearer how important the large radius of curvature in the sliding direction and low surface roughness of skate blades is to decreasing skating friction.

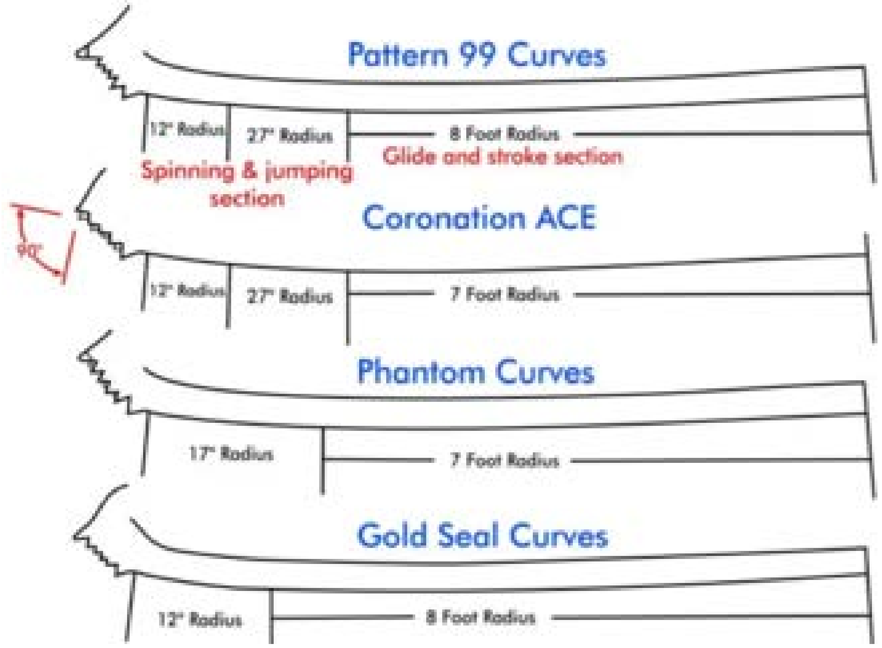

Fig. 11. Four figure skate blade models with varying rocker radii. For example, the model named "Coronation ACE" has three different rocker radii: a 12 inch radius for the front, a 27 inch radius in the middle, and a 7 foot radius for the back and majority of the blade. In general, the front of the blade interacts with the ice more when spinning and jumping, while the middle and back of the blade interacts with the ice more when gliding and stroking (stroking is a simple move where skaters push off of the ice with one foot turned perpendicular to the direction they are skating in).[24]

Another important characteristic of ice skate blades is that the bottoms of the blades, in the case of hockey and figure skates, have a negative radius of curvature along the width, creating sharper edges (speed skates have 90° edges, meaning the bottom of the blade is flat). As a result, one blade has two edges, on the left and on the right when viewing a blade from the direction a skater glides in. The radius of the circle the blade aligns to is referred to as the hollow radius, and smaller hollow radii result in sharper edges. Several hollow radii and the circles used to determine the hollow radii are shown in Figure 12.

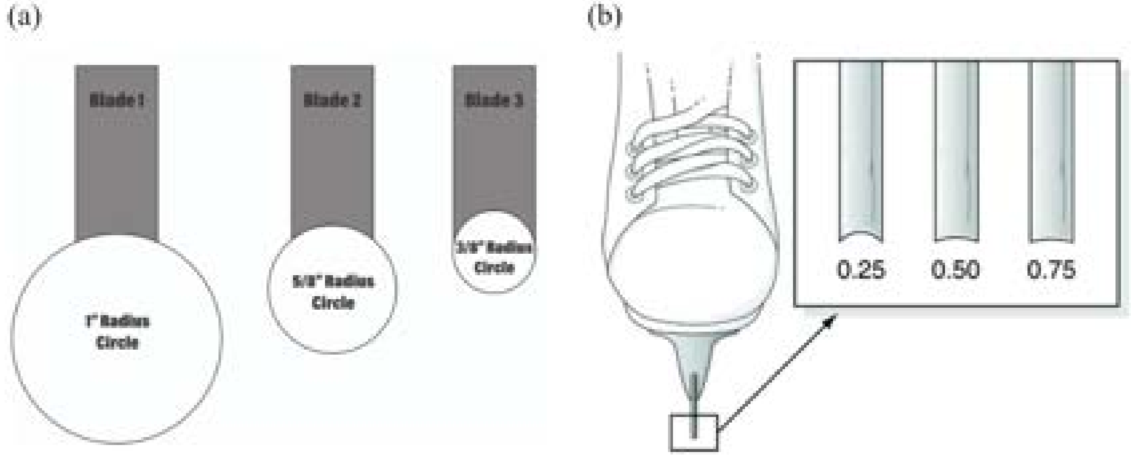

Fig. 12. Diagrams of skate blade hollow radii. (a) Hollow radii are determined by the radius of a circle pressed up against the bottom of the skate blade. Three blade hollow radii are shown: 1 inch, ⅝ inch, and ⅜ inch from left to right.[25] (b) A close-up of the front-view of a skating blade. Three blade hollow radii are shown: 0.25 inches, 0.50 inches, and 0.75 inches from left to right. Smaller radii correspond with sharper edges, as seen in the sharper corners of the 0.25-inch-hollow blade on the left when compared with the 0.75-inch-hollow blade on the right.[26]

Skaters use these edges to push off of the ice and accelerate, making them crucial in skater control. When gliding in a straight line along the length of the blade, the skater is met with minimal resistance. However, when the skate is tilted, a quick increase in the friction coefficient is found.[14] This can be attributed to deeper indentation, as the same load is supported by a reduced contact area (a singular edge of a blade rather than both) and the contact pressure increases, and a larger plowing force, as the side of a blade provides a much larger plowing area than the narrow front of a blade.[14] Plowing force, then, provides insight into how skaters can abruptly stop themselves just as easily as they can glide with minimal deceleration on the ice. Lever et al. also observed differences between hockey skates and speed skates in their experiment, where hockey skates scattered many more warm particles and left behind a deeper rut.[4] One can infer that, due to the sharper edges that hockey skates have, greater plowing forces and contact pressures were experienced below the hockey blade. This resulted in higher crushing rates, as the maximum contact pressures exceeded the ice hardness, and more particles were then released into the slurry. Referencing the conclusion by Lever et al. that a higher fraction of ice particles in the slurry results in higher viscosity, hockey blades likely experienced stronger resistive shear forces than speed skates did. A higher slurry viscosity could offer some assistance to hockey skater control since about half of the friction experienced by a blade is a result of shear forces in the lubricating layer, but the extent of that assistance is unclear.

Crushing or plowing is an important process in the formation of an ice-rich slurry and an observable indent in skating, but assessing the factors involved in ice indentation as well as the model by Lever et al. leaves some processes unclear. One significant concern is temperature. Temperature has been shown to influence ice hardness, affecting plowing and the crushing of ice to introduce particles into the slurry, and melting, as lower temperatures may no longer permit pressure melting. Contact pressures significantly below the ice hardness results in elastic indentation, where the ice will simply regain its original shape and no plowing or crushing occurs, and since lower temperatures increase the ice hardness, it could be beneficial to examine skating in colder climates.[14] If ice skating is indeed possible below -20℃,[1] examining whether a slurry continues to form and whether an indent remains visible in the ice can provide insight into how crucial plowing and the formation of a slurry is to lowering friction.

Most skating studies have also examined only forward skating,[4, 27, 28] and it may be beneficial to examine backwards gliding as well since the figure skate blade radius is larger in the back. Greenhalgh et al. found that plantar pressure (the pressure between a foot and the insole of the ice skate) was mostly concentrated at the forefoot and midfoot regions during forward gliding.[28] Considering the observation by Lever et al. that most of the indentation occurs near the front of the blade,[4] this could correspond with the concentration of pressure near the front of the foot inside the skate. One could observe crushing and plantar pressure in backwards gliding to see if the majority of crushing and pressure is alternatively concentrated near the back of the skate blade.

Considering how instrumental HPZs are in the lubricating slurry-theory and ice indentation, examining the recrystallization of ice and its resulting viscoelasticity could also prove valuable. Skaters almost never skate on the same thin path of ice twice, and doing so can trap the blade in the rut and disturb a skater's balance, so the effect of already damaged ice on skating is unclear. It may then be of interest to observe skating or sliding on crushed and weakened recrystallized ice and compare the friction and plowing with similar interactions on intact ice.

Conclusion

Ice skating is a complex sport, and the processes dictating extraordinarily low friction continue to be questioned, reexamined, and clarified. Consistent with most if not all theories, however, has been the formation of some kind of lubricant between the blade and the ice. It was first suggested to be a film of meltwater generated by pressure melting, but frictional melting later became a much more widely accepted explanation due to the temperature constraints of the former theory. Quasi-liquid layers were brought into question, and the most widely accepted explanations now involve these microscale lubricating films and/or a combination of pressure and frictional melting. The combined hypothesis and model of an ice-rich slurry formed by high-pressure-zones and semi-melted ice particles suggested by Lever et al. brings in the essential role of crushing and plowing,[4, 7] making ice-indentation research crucial in understanding how a blade interacts with the ice and how the measured friction coefficient can be so low. Understanding the effects of ice fracturing, recrystallization, ice hardness, surface roughness, and blade geometry makes it increasingly clear just how complex the blade-ice interface can be, but each relation can help shed a little bit more light on the mechanisms behind skater control and ice skating friction. HPZs occurring where asperities meet play a key role in allowing pressure melting to occur, and the variety of processes that take place throughout a HPZ–pressure melting, recrystallization, microcracking, and spalling–all contribute to the formation of a lubricating slurry. The dependence of crushing on ice hardness makes temperature and sliding velocity significant factors to consider, as hardness decreases with increasing temperature and decreasing velocity. The rocker and hollow radii of the skate blade also impacts the plowing force the blade experiences, as a larger radius curve experiences less plowing force and creates a shallower indent in the ice, and the resulting variations in plowing friction, indent depth, and slurry viscosity help skaters accelerate or glide easily on the ice. However, the precise mechanisms governing blade-ice interaction remain unclear, and studies concerning lower ice temperatures, skating trials not limited to forward gliding, and recrystallized ice may all help to bolster understanding.

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