A review on the physics of ice surface friction and the development of ice skating.

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Abstract

Our walking and running movement patterns require friction between shoes and ground. The surface of ice is characterized by low friction in several naturally occurring conditions, and compromises our typical locomotion pattern. Ice skates take advantage of this slippery nature of ice; the first ice skates were made more than 4,000 years ago, and afforded the development of a very efficient form of human locomotion. This review presents an overview of the physics of ice surface friction, and discusses the most relevant factors that can influence ice skates' dynamic friction coefficient. It also presents the main stages in the development of ice skating, describes the associated implications for exercise physiology, and shows the extent to which ice skating performance improved through history. This article illustrates how technical and materials' development, together with empirical understanding of muscle biomechanics and energetics, led to one of the fastest forms of human powered locomotion.

THE PHYSICS OF ICE SURFACE, A SLIPPERY MATTER

A few miles from One Ton Depot, Ross Ice Shelf, Antarctica; Saturday 3rd March 1912
"The (ice) surface, lately a very good hard one, is coated with a layer of woolly crystals […] (that) cause impossible friction to the runners. God help us, we can't keep up this pulling, that is certain". Captain Robert Falcon Scott (1913).

The surface of ice is made of a thin layer of molecules that behaves like a liquid, in several natural conditions

Ice as a solid material is truly peculiar: it is a solid, but one of its most distinct characteristics is that, even when air is below freezing temperature, its surface is covered with a thin layer of water, the presence of which still puzzles many physicists (Rosenberg 2005, Kietzig, Hatzikiriakos et al. 2010, Watkins, Pan et al. 2011). A block of ice floats on water because it is less dense than water. The increase in the volume of water with temperature decreasing below 0º C also explains why a bottle full of water can 'explode', if we forget it in the freezer for too long. The reverse also applies: if we compress ice hard enough, it melts and turns into water. This melting caused by pressure was proposed in the mid 19th century as the main mechanism through which a water film would form under ice skates' blades' pressure, which were assumed to be sufficiently high. However, it was later understood that the magnitude of the pressure increase caused by a skater would generally not be sufficient to determine the melting of the ice. In fact, this increase in pressure would result in a small temperature increase, say in the order of 1º C, insufficient to explain the low friction of ice skates at very low temperatures. Moreover, it was observed that the pressure required for melting ice at low temperatures is so great that it would squeeze the water film away from the underside of the skate's blade (Colbeck 1995). Overall, it is now generally accepted that pressure melting plays a minor role in determining the low friction of skates on ice, other than at temperatures near the melting point.

Whenever motion with friction occurs, some of the kinetic energy is converted to heat. This is why our hands become warmer when we rub them together rapidly; here, some of the heat caused by friction between our hands warms them up, and some heat is lost in the air. Bowden and Hughes (1939) applied this concept to the study of skis sliding on ice and snow. Their experiments took place in an ice cave near the High Altitude Research Station Jungfraujoch in Switzerland, at

an altitude of 3,346 m above sea level, where they observed that miniature sliders made of brass were characterised by a considerably greater dynamic coefficient of friction than miniature sliders made of ebonite, and they explained this phenomenon through the materials' thermal conductivity. During the sliding process, brass would take up much of the heat generated through friction, so relatively little heat would be available to melt the ice. Colbeck *et al.* also supported that heat would decrease the coefficient of friction on ice through experiments where temperature was measured underneath skates (Colbeck 1995, 1997). He observed that blades' temperature increases with velocity, and with thermal insulation of most of the blade; also, he observed that the blade's sliding leaves warm tracks on the surface of ice behind the skates, suggesting that frictional heating may be an important determinant of ice skates' low dynamic coefficient of friction. This finding was replicated in more recent experiments (Baurle, Szabo et al. 2006).

Neither of the two scenarios presented above, namely pressure melting and frictional heating, can explain why ice is slippery even when we simply stand on it. One of the first experimental observations on the liquid-like nature of the ice surface was presented by Michael Faraday (1859). In simple terms, he observed that, although the surface of ice is slippery, two ice blocks would stick if put one on top of the other, like if there were some water that would freeze in between, a phenomenon called regelation. Following these observations made in the mid 19th century, studies on the physics of ice surface have not made much progress until the second half of the 20th century, when the wide multidisciplinary importance of ice as a material became apparent. Several mechanisms have been proposed in order to explain the slippery nature of ice surface. One of the most recent and plausible explanations is that, at molecular level, the surface of ice vibrates.

In most crystalline materials each surface molecule has an identical binding energy, while in the surface of ice molecules are bound by different forces (Watkins, Pan et al. 2011). In the lower part of Figure 1 the solid ice layer is represented by a frame of hexagons with a periodic structure, characterised by several and regular chemical bonds represented by thin lines. In contrast, the liquid-like layer on the surface of ice is represented with relatively fewer and less regular bonds. Due to this weaker physical structure, atoms in the ice surface can move rather freely, similarly to what they do in water. It is thought that the interaction of these moving atoms in the surface of ice with the solid ice immediately underneath generates the superficial lubricating film of water (also known as the liquid-like layer), independently of any frictional heat or pressure generated by ice skates. This can explain why ice is slippery even when we simply stand on it, a situation where we do not generate much frictional heat on the surface of ice and where, as discussed above, the

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pressure exerted on the ice by our body would not contribute much to the melting of the ice surface. In order to understand the functional significance of the liquid-like layer, a comparison with water slides may help, where the slide itself represents ice, water represents the liquid-like layer on the ice surface, and the person sliding represents a skate's blade. In this comparison, with its implicit limitations, it seems clear how friction is greatly reduced by a relatively thin water layer between the person and the slide.
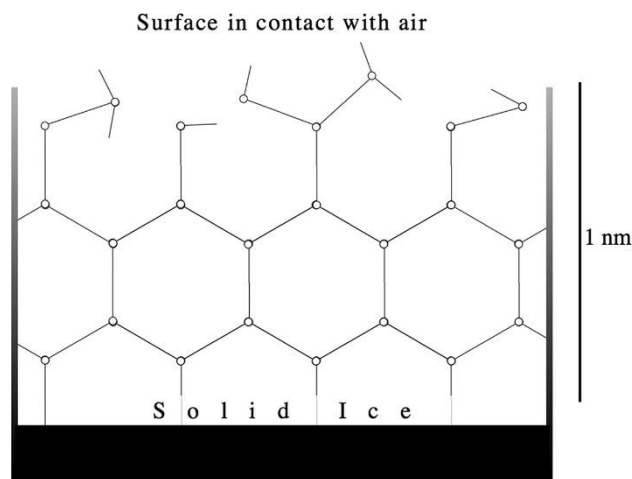

Figure 1. The presence of a liquid-like layer on the outermost surface of ice, even at air temperatures below freezing, is possibly one of the main reasons for ice surface slipperiness. *This schematic diagram shows a representation of the solid ice layer (bottom), and the liquid-like layer on the outermost surface of ice (top). Image adapted from Ikeda-Fukazawa and Kawamura (2004).*

The determinants of the friction coefficient between skates and ice presented above are naturally affected by a variety of factors. Temperature is certainly an important one, as at very low temperatures friction on ice surface can increase dramatically. Captain Scott, quoted in the opening of this paragraph, tragically experienced this increase of skis' and sledges' friction at temperatures below – 30º C during the *Terra Nova* expedition at the beginning of the 20th century, when sadly he and his team did not survive the extremely low temperatures, great resistance to sliding, and strong winds. Apart from temperature, other factors like skate's sliding velocity, thermal conductivity, area of contact, and roughness of the blade determine the friction coefficient between ice and skates. The next paragraph presents an overview of the most important

determinants of ice skates' friction coefficient; more extensive reviews on this topic are published elsewhere (Rosenberg 2005, Kietzig, Hatzikiriakos et al. 2010).

Several physical factors can influence ice skates' friction coefficient

Ambient and blades' temperature influence the thickness of the superficial layer of water on ice, which is ultimately the greatest determinant of skates' dynamic coefficient of friction. The layer of water becomes thinner with decreasing ambient temperatures, and this reduction in thickness is normally associated with an increase in the friction coefficient. At ambient temperatures close to the melting point, the thickness of the layer of water becomes relatively excessive, resulting in drag forces that increase friction between ice and skate. This concept is illustrated in Figure 2. As mentioned above, some of the earliest experiments investigating the effects of temperature on ice friction were performed by Bowden and Hughes (1939). In their experiments, they used solid carbon dioxide and liquid air to alter temperature, and observed a marked increase in the dynamic coefficient of friction between slider and ice for temperatures decreasing to – 40º C and below. Bowden's experimental results showing a relationship between temperature and ice friction were replicated in more recent studies, which considered different materials, sliders' velocities and ice conditions (Calabrese, Buxton et al. 1980, Slotfeldt-Ellingsen and Torgensen 1983, de Koning, de Groot et al. 1992, Albracht, Reichel et al. 2004). The minimum coefficient of friction is often recorded at temperatures around – 5º C in most of these studies.
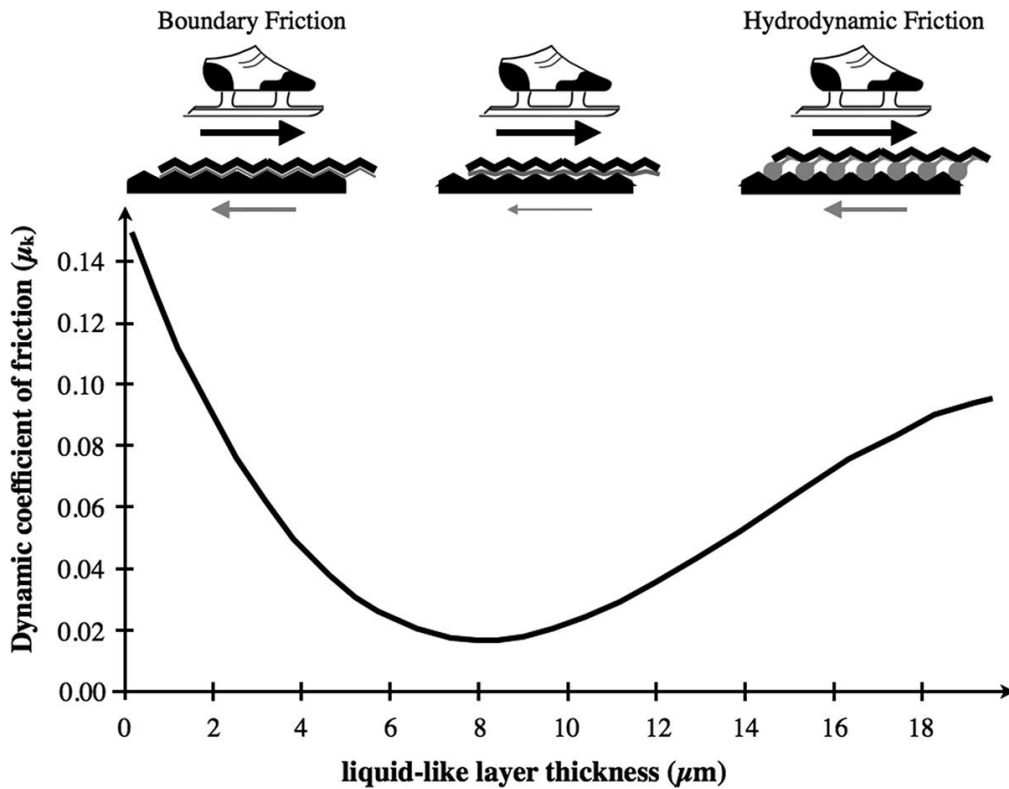
Figure 2. An optimal water (lubricating) layer thickness is associated with the lowest dynamic coefficient of friction.

The relationship between water layer thickness and dynamic coefficient of friction is illustrated. The figures at the top of the diagram represent the friction regimes observed between skates' blades and ice, for the corresponding liquid-like layer thickness on the horizontal axis beneath. Black and grey arrows represent ice skate's and ice friction energy respectively (not to scale). Further details are reported in the text. Adapted from Colbeck (1988) and Kietzig (2010).

Ice surface temperature can also be altered by ice skates' blades' temperature, which in turn is influenced by heat generated through friction. Faster sliding velocities are associated with higher blade's temperature, ice surface frictional melting effect, and consequently lower dynamic coefficient of friction (de Koning, de Groot et al. 1992, Colbeck 1994, Colbeck, Najarian et al. 1997). The heat generated through friction can be retained by low thermal conductivity materials, where heat is partly stored in the material itself, and contributes to the melting of the ice. This was initially observed by Bowden and Hughes when they compared the friction coefficient of a copper, 'air-filled' slider with a mercury-filled slider (Bowden and Hughes 1939). Air has a much smaller thermal conductivity than mercury, so the air-filled slider appeared to have a smaller coefficient of

friction. This finding was replicated in different materials by Itagaki *et al.* (1989). The roughness of skates' blades' material also influences blades' temperature and dynamic coefficient of friction (Calabrese, Buxton et al. 1980, Itagaki, Huber et al. 1989). A rough material would determine a great friction, hence a great increase in temperature and great melting effect; however, the roughness of the surface would also be associated with an increased actual contact surface area (for a given apparent contact area), and greater interlocking asperities that would work against the sliding movement. In this respect, a smooth material is preferred for skates' blades because it is characterised by a reduced surface asperity, and ultimately results in a lower coefficient of friction. For a material with a given roughness level, the orientation of polishing marks (e.g. on the blade's lateral or sagittal plane) can also influence the friction coefficient (Itagaki, Huber et al. 1989). A large-scale example is the underside of cross-country skis, where the deep groove represents a sagittal plane polishing mark. Clearly, polishing marks that are aligned with the blade's direction of motion are associated with low dynamic coefficient of friction, and may contribute to the control of the blade too.

The pressure exerted on a surface is a function of a normal force, and the contact area over which the force is applied. As discussed above, pressure does not appear to be a strong determinant of ice skates friction, so changes in normal force or blades' contact area would not be expected to affect skates' friction coefficient significantly. Studies investigating effects of different normal forces and geometric contact areas on the dynamic coefficient of friction reported contrasting evidence (Bowden and Hughes 1939, Calabrese, Buxton et al. 1980, Albracht, Reichel et al. 2004, Baurle, Szabo et al. 2006, Baurle, Kaempfer et al. 2007), where no clear relationship between these variables appeared. It is possible that the variety of experimental conditions (e.g. temperatures, materials, velocities) have determined different outcomes that are difficult to compare. In this regard, possibly through empirical understanding of skates' friction on ice, the geometry of skates' blades has changed through history (Formenti and Minetti 2007). The apparent contact area of modern ice skates' blades is only about a third of blades used centuries ago. For a given skater's weight, this decrease in blades' contact area results in a greater pressure exerted on ice, and in a relatively greater pressure-melting effect. However, as mentioned before, a skater is unlikely to generate the amount of pressure required for ice melting. Supporting the minor role of pressure for ice skates' low friction, modern ice skates' blades are relatively long (more than 400 mm). Rather than a small contact area, it seems important for a blade to have a small frontal area in contact with the ice, so that 'frontal' friction is as low as possible (Houdijk, Wijker et al. 2001), and to distribute the skater's weight over a great length; in other words, modern long blades allow the

skate to 'float' on (not sink in) the water layer on the surface of ice. It is possible that the length of modern blades is an optimum in terms of low pressure levels on ice, and manoeuvrability. Shorter blades would be associated with greater pressure levels that may still not be sufficient to generate a pressure-melting effect on the ice, but could be sufficient to squeeze part of the water film away from the blade, resulting in greater solid-solid contact and high wear rates; longer blades would be heavier, and could be more difficult to manoeuvre. Recalling the water slide example, a comparison could be drawn with a person sliding in the seated position (short blade), when the pressure they exert on the water is relatively big, so water is squeezed out from below the person, determining solid-solid contact (person-slide) and relatively great friction. In contrast, when the person slides in a supine position (long blade), the smaller pressure exerted on the water allows some water to remain between person and slide, resulting in the presence of a lubricating water layer that reduces friction. This hypothesis needs to be tested through models and experiments.

In conclusion, several physical factors contribute to determining skates' friction on ice. Findings from previous studies have only in part elucidated the physics of ice skates' friction, with results often difficult to compare due to different experimental conditions, including ice properties that change significantly at different temperatures and humidity levels. Nevertheless, it seems generally accepted that an optimum water layer thickness exists where the dynamic coefficient of friction is minimum. The possibility to skate on this optimum water layer thickness depends on a combination of ice skates and ice properties.

Different friction regimes can co-exist between skate and ice

Due to the presence of the water layer on the surface of ice, dry friction between ice skate's blade and ice may be observed only over an extremely limited actual contact area, at least in natural conditions. As discussed in the previous paragraph, the thickness of the water layer varies depending on multiple factors, and is associated with different friction regimes. Figure 2 illustrates the three main different friction regimes that characterise ice skates' gliding. Especially at very low temperatures, a very thin liquid-like layer (left, thin grey line) is associated with boundary friction, where the thickness of the liquid-like layer is smaller than the 'height' of ice and blade surface asperities. This boundary friction regime is similar to that observed when rubbing two solids on each other, but the friction coefficient is lower than in dry friction. In contrast, at ambient temperatures near the melting point or above, an excessively thick liquid-like layer (right,

grey icons represent water drops with capillary water bridges between asperities (Colbeck 1988)) is associated with hydrodynamic friction, a regime similar to that observed between a boat and water. In the hydrodynamic friction regime, the thickness of the liquid-like layer is greater than the 'height' of the surface asperities. An optimal liquid-like layer thickness, where the dynamic coefficient of friction is minimum, can be observed at intermediate thickness values (middle, thicker grey line). This scenario if often called mixed friction regime, where the thickness of the liquid-like layer is greater than in boundary friction, but still smaller than the 'height' of the surface asperities, so relatively limited capillary water bridges form between surface asperities. In the schematic diagram at the top of figure 2, black and grey arrows represent ice skate's and ice friction energy respectively. Greater friction energy is encountered in boundary (left) and hydrodynamic (right) friction regimes than in the intermediate friction regime. Here, the optimum lubricating layer thickness affords the minimum loss of energy caused by friction.

In contrast with this simplified model, a blade most likely shows a variety of friction regimes when we skate. This variety may be influenced by ice surface's irregularity, blade's velocity (even within the gliding phase), blade's orientation, distribution of pressure over the blade, blade's and ambient temperature, and several other skater's related factors. The schematic representation above is only a reduced model of a rather complex physics problem: some of the main variables that influence ice friction are fairly well understood (e.g. temperature, velocity), but others (e.g. surface structure) are still an exciting area of exploration.

HUMAN LOCOMOTION ON ICE

Ice was certainly a surface that humans tried to avoid travelling on for millennia, as its slippery nature increases risks of falls and injury, limits walking velocity, and increases walking metabolic energy cost. However, as early as four thousand years ago, our ancestors realised that this slipperiness could be used to their advantage, and invented an entirely new form of human-powered locomotion: bone skating. The next part of this chapter presents the development of human locomotion on ice through history, and discusses the relevant biomechanical and physiological implications.

Skating on animal bones may have reduced time and energy cost for human powered transport in Scandinavia more than three thousand years ago

Most research studies on human locomotion on ice focused on its current relevance for sport and exercise physiology and biomechanics (di Prampero, Cortili et al. 1976, Marino 1977, van Ingen Schenau and Bakker 1980, de Groot, Hollander et al. 1987, van Ingen Schenau, de Boer et al. 1989, Smith and Roberts 1990, de Koning, de Groot et al. 1992, Allinger and Van den Bogert 1997, Rundell, Nioka et al. 1997, Foster, Rundell et al. 1999, Houdijk, Heijnsdijk et al. 2000). Fewer studies explored the origins and the development of this ingenious form of human powered locomotion (Heathcote, Tebbutt et al. 1892, Munro 1893, Brown 1959, Blauw 2001, Muhonen 2005, Formenti and Minetti 2007, Formenti and Minetti 2008).

Humans started skating on ice around the second millennium before Christ, as suggested by archaeological specimens. The first ice skates were possibly made of animal bones (Jacobi 1976), on which the skater would stand; skates were used together with a pointy stick pushed backwards on the ice surface for propulsion (Olaus 1555). No clear evidence supports any of the different hypotheses as to why bone skating started. Also, the most ancient archaeological specimens cannot be clearly ordered chronologically, so it is difficult to identify ice skates' birthplace. Archaeological evidence helps making possible connections between bone skates' qualitative features and tool making traditions in different European regions thousands of years ago. This approach still leaves a wide spectrum of candidates as for the location where bone skates might have been used first.

Most of the oldest bone skates were found in areas where water covers more than 5% of the corresponding modern country, namely Finland (with over 60 000 lakes), the Netherlands, Sweden, and Norway. The energy-saving principle was hypothesised to be a determinant factor in the birth of bone skates (Formenti and Minetti 2008). These authors created replicas of ancient bone skates, and measured velocity and metabolic energy cost of bone skating. The average velocity recorded on bone skates was about 1.2 m s^{-1}. In terms of metabolic energy cost, this velocity is similar to the optimal velocity of walking on firm ground, but the metabolic energy cost of skating on bones was 4.6 J kg^{-1} m^{-1}, about two times greater than the cost of walking. They then used the recorded metabolic energy cost values as input for computer simulations of travel in the above mentioned Northern European regions, and in Germany, where relatively many bone

skates were found. Assuming a given metabolic power (5.3 W kg^{-1}) for walking and bone skating, they calculated the energy cost and speed of travelling for a number of simulated journeys (total of 2,400 km over five countries). These journeys were simulated in two conditions: 'walking and skating', and 'walking only'. For the 'walking and skating' simulations, the distance to be travelled was constant (10 km), but the cost and velocity of locomotion varied depending on the presence and dimensions of frozen lakes on route. In contrast, for the 'walking only' simulation, the distance to be travelled varied according to the presence of lakes to be avoided: if lakes were present on the route, the authors measured the shortest path connecting the starting point to the final destination. Formenti and Minetti estimated that the greatest reduction in metabolic energy cost of transport would be observed in Finland, where using bone skates allowed saving about half the energy for the average journey considered in the study. The reduction in metabolic energy cost of transport was not as great in the other countries considered. Finally, they estimated that ancient Finnish hunters and fishermen using bone skates for winter travel could have saved almost 10 per cent of the energy needed to survive for a period of four months. On the basis of their metabolic energy measurements and computer simulations, they suggest that the use of bone skates in areas characterised by a high density of lakes allowed travelling shorter routes, hence reduced times and metabolic cost of transport. In conclusion, it is fascinating to notice that, alongside modern ice skates' models, bone skates were still in use in the 18th century *"in Iceland, Gotland and in parts of Hungary and Germany"* (Roes 1963).

Technical and materials' development supported the evolution of human locomotion on ice

Ever since the first bone skates were used, several subsequent modifications lead to the current fastest ice skate, called the klapskate. Most of these modifications were based on empirical evidence for ice friction and exercise physiology, as discussed later. Only some of these modifications originated from research studies. The first contribution to understanding the kinematics of ice skating is attributed to Tebbutt (Heathcote, Tebbutt et al. 1892). In Amsterdam, he took a series of instantaneous photographs of skaters travelling on three different skates, and consequently adopting different skating techniques. He observed that the fastest skate was the one that allowed for the longest strides and that required the smallest lateral deviation from the forward motion, indicating that little of the power generated was wasted laterally. In the 1970s van Ingen Schenau and colleagues started a most comprehensive and informative series of studies on the biomechanics and physiology of ice skating at the Vrije Universiteit in Amsterdam. They

investigated the effect of air friction on speed skating performance, showing that it accounted for about 70% of energy loss through friction at a speed of 9.2 m s^{-1} (van Ingen Schenau, 1982; previously reported by di Prampero et al. 1976). They created the first biomechanical models (van Ingen Schenau and Bakker, 1980) and investigated applied physiology of this form of locomotion implying peculiar mixed features such as isometric contractions for long periods of time during the gliding phase as well as fast powerful push-offs (de Groot et al., 1987). The adoption of klapskates at world level competitions gave a strong impulse for further research trying to explain the reasons for faster velocities on klapskates rather than on traditional skates (van Ingen Schenau et al., 1987, van Ingen Schenau, 1998, de Koning et al., 2000, Houdijk et al., 2000a, Houdijk et al., 2000b, Houdijk et al., 2001, Houdijk et al., 2003). Skating posture does not change during skating on klapskates and traditional skates, consequently no difference in air frictional losses could be measured. Lower friction between blade and ice was suggested to be a major determinant of faster velocities, because it was thought that the pressure of the tip of the blade in the ice at the end of each push-off could cause a great dissipation of power. Houdijk et al. (2000a) showed that this difference in friction determined a relatively small energy dissipation difference (only 0.84 W, compared with a 54 W dissipated by ice friction). Skating velocity increased because of a higher power output, determined by an 11 J increase in work per stroke and a higher stroke frequency (from 1.30 to 1.36 strokes s^{-1}). Moving the position of the klapskate hinge along the skate's main axis directly alters the levers' system used by the lower limb muscles. Van Horne and Stefanyshyn (2005) investigated the effects of different klapskate hinge's position, and found an intermediate optimum position in terms of lower limbs' power generation.

No study explored the biomechanics and energetics of skating on more ancient models, and their evolution through history. Formenti and Minetti hypothesised that, similarly to cross-country skiing (Formenti, Ardigò et al. 2005), ice skating developed in order to reduce energy cost and time of travel. They conducted an in-depth historical research, and identified five skates displaying significantly different features from previous models, that could consequently determine a better performance in terms of velocity and energy demand (Formenti and Minetti 2007). The models used in these experiments are shown at the top of Figure 3. Apart from the bone skates mentioned in the previous paragraph, skates used in the 13th, 15th, and 18th century, as well as modern skates were included in the study. The main technical steps in the development of ice skates were identified with the use of thinner and longer metal blades, the reduction in skates' dynamic coefficient of friction and weight, the increase in the foot height over the ice, and the use of straps

and boots that allowed a better control of the skate. The upper part of Table 1 shows the characteristics of the skates included in the study.

Table 1. Characteristics of five ice skates models, and associated kinematic and metabolic parameteres as reported in Formenti and Minetti (2007, 2008).

		Ice skate model				
		1800 BC	1200 AD	1400 AD	1700 AD	2004 AD
blade length	(mm)	210	230	250	410	460
blade width	(mm)	14	6	6	1.3	1
foot height	(mm)	36	59	45	50	62
mass (pair)	(gr)	1450*	1300	900	950	930
dynamic μ (10^{-2})		1.03 ± 0.22	1.47 ± 0.11	1.12 ± 0.07	0.84 ± 0.10	0.58 ± 0.04
low speed	(m s^{-1})	1.13 ± 0.40	1.80 ± 0.12	2.55 ± 0.16	2.87 ± 0.51	5.09 ± 1.85
stride frequency	(strides s^{-1})	0.50 ± 0.01	0.63 ± 0.09	0.54 ± 0.12	0.57 ± 0.15	0.40 ± 0.05
stride length	(m)	2.68 ± 0.52	2.94 ± 0.44	4.87 ± 0.92	5.17 ± 0.53	13.31 ± 6.09
high speed	(m s^{-1})	---	2.75 ± 0.73	4.06 ± 0.59	3.96 ± 0.32	6.70 ± 2.39
stride frequency	(strides s^{-1})	---	0.90 ± 0.19	0.65 ± 0.20	0.68 ± 0.12	0.45 ± 0.09
stride length	(m)	---	3.16 ± 1.01	6.44 ± 0.93	5.97 ± 1.71	15.24 ± 5.55
metabolic cost	(J kg^{-1} m^{-1})	4.62 ± 0.91	2.46 ± 0.75	2.01 ± 0.35	1.78 ± 0.28	1.32 ± 0.27

Table 1. Relatively longer strides on ice skates allow greater locomotor efficiency: characteristics of five innovative pairs of ice skates developed through history, and associated kinematic parameters recorded at two sub-maximal speeds.

Ice skate models are identified with the approximate time in history when they were in use. In the upper part of the table, dimensions and weight of each model are reported. Bone skates do not have a blade, so blade's measurements reported indicate the dimensions of the underside of the bone skate, the part that is relatively flat on the ice while skating; the mass reported for the bone skates also includes the stick used for propulsion. The dynamic coefficient of friction's average and standard deviation values are reported for each skate model. In the middle part of the table, speed, stride frequency, and stride length associated with the use of each skate model are reported for two speeds (i.e. low and high speed). Speed, stride frequency, and stride length average and standard deviation values shown are calculated from data recorded on the three participants who were equipped with the inertial sensors. At the bottom of the table, the metabolic cost associated

with the use of each skate model is reported; metabolic cost data shown are average and standard deviation values calculated for the speeds considered in the study. More details can be found in the text. Adapted from Formenti and Minetti (2007).

Being particularly interested in the relative metabolic energy cost associated with the use of different skates' models, Formenti and Minetti carried out their experiments on an ice rink, where ice surface, temperature and other environmental conditions remained unchanged throughout the tests. The metabolic energy cost of modern ice-skating was only 25% of that associated with the use of bone skates. Moreover, for the same metabolic power, nowadays skaters can achieve speeds four times higher than their ancestors could. In the range of speeds considered, the cost of travelling on ice was speed independent for each skate model, as for running. This latter finding, combined with the accepted relationship between time of exhaustion and the sustainable fraction of metabolic power, gave the opportunity to estimate the maximum skating speed according to the distance travelled (Figure 3).
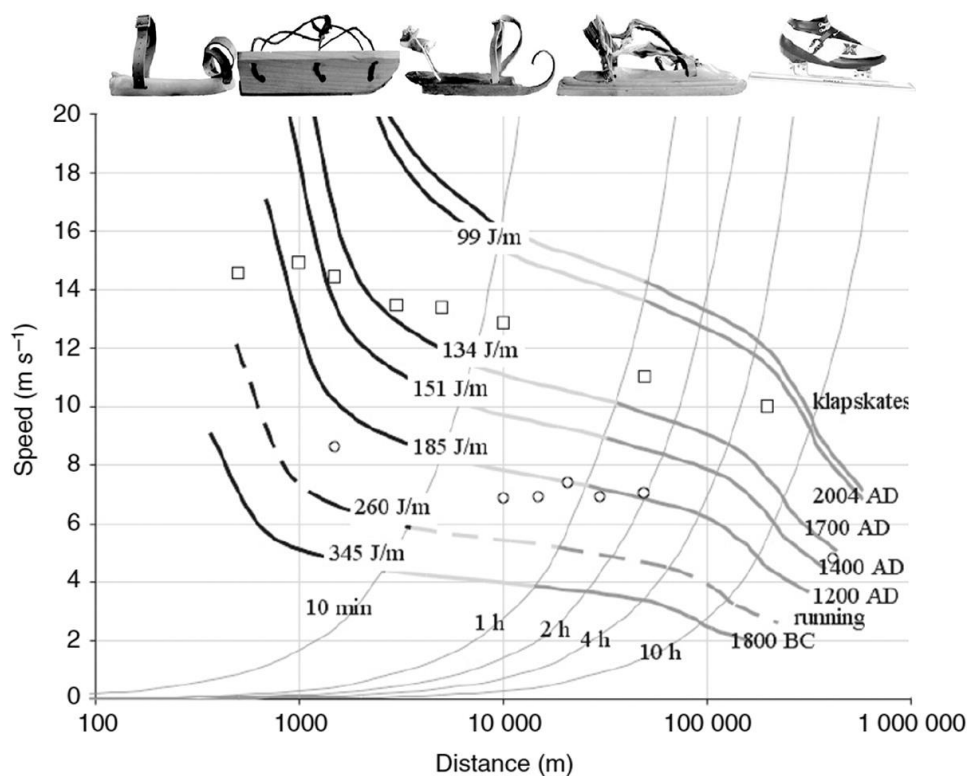

Figure 3. Innovative ice skates models improved ice skating performance through history.
At the top of the figure, from the left, replicas of the bone skates and the first wooden skates with a metal blade, examples of skates used in the 15th and 18th century, and a modern conventional ice

skate are shown. More details about the skates' models can be found in the text. In the diagram, the three-colour (black, light grey, dark grey) lines illustrate the maximum sustainable speed/distance relationships, calculated for constant metabolic cost (iso-cost lines) for each skate model, identified with the approximate time in history when they were in use. The light grey curves are iso-duration speed/distance pairs, and the respective durations are reported (10 min to 10 h). The broken line illustrates values for running, and is shown as a means of comparison with the ice-skating performance data. Also reported as a means of comparison are the ice-skating top records (open squares), and records for cross-country skiing (open circles). Adapted from Formenti and Minetti (2007).

Data shown for klapskates in Figure 3 were calculated assuming 5% faster speeds, according to Houdijk *et al.* (2000). The three-colour lines were calculated through equations provided by Wilkie (1980), Saltin (1973), and Davies (1981), and were calculated assuming that the available fraction of the metabolic power used for a given movement pattern (ice skating), is inversely related to the time to exhaustion. From the left, the black, light grey, and dark grey lines respectively illustrate the maximum sustainable speed calculated for periods of time ranging from 40 s to 10 min, from 10 min to 1 h, and from 1 to 24 h. For the calculations, the maximum metabolic power available was set at 21.3 W kg^{-1}. An example might be helpful in order to clarify the information reported in Figure 3: the energy cost of skating on bones (1800 BC) is indicated by the thick 345 J m^{-1} iso-cost line (bottom line in the diagram). The intersection between this iso-cost line and the light 10 min iso-time line shows that in 10 min, for an energy cost of 345 J m^{-1}, a person skating on bones could cover a distance of approximately 2.6 km at an average speed of 4.4 m s^{-1} (~ 16 km h^{-1}) before exhaustion. This is indicated by the intersection of the 345 J m^{-1} iso-cost and the 10 min iso-time lines in the diagram. In contrast, the energy cost of modern ice-skating is only 99 J m^{-1}, less than one-third of the energy cost associated with skating on bones. On the basis of the equations from Wilkie (1980) and Saltin (1973), it appears that a skater could cover a distance of about 9.2 km in 10 min, at an average speed of about 15.3 m s^{-1} (~ 56 km h^{-1}) before exhaustion. In the diagram this is indicated by the intersection between the 99 J m^{-1} iso-cost curve and the 10 min iso-time line. The 10 km speed skating men world record at the time of writing is 12 min and 41 s, achieved at an average speed of about 47 km h^{-1} (ISU 2012), not far from the values predicted above. The main limitation of this approach becomes evident when observing the difference between the iso-cost lines for modern skates and klapskates, and the actual records (open squares) for events shorter than 10 minutes; here, the model used largely

overestimates the maximum sustainable speed. In their study, Formenti and Minetti recorded oxygen consumption at steady state speeds up to about 10 m s^{-1}; this could explain why their model predicts long distance events better than events where the energetic demand of the initial acceleration plays a major role in determining the overall performance.

This figure can also help suggesting when people could travel faster on ice than on land, (moving at their maximum sustainable velocity). On frozen Dutch canals in the 13th century, ice skaters could cover a distance of about 26 km in an hour, a much longer distance than the 18 km that could possibly be travelled by running. This level of performance afforded by ice skates had no equal amongst other forms of human powered locomotion until the advent of bicycles centuries later (Minetti, Pinkerton et al. 2001).

Ice skates were the first passive tools for human locomotion that took advantage of skeletal muscle biomechanical properties

Contraction of skeletal muscle can generate its maximum power when it shortens at about one third of its fastest shortening speed. Even when travelling at relatively high speeds, the skating movement pattern requires muscles to shorten slowly, so they can also develop a considerable amount of force; this is the greatest advantage of skating over running. When we run, the velocity of muscle shortening is coupled to the velocity of running: the faster we run, the faster our muscles need to shorten. From a biomechanical perspective, this coupling of muscle shortening velocity and locomotion velocity is the main limiting factor for our fastest running speed. In contrast, when we skate, we can travel faster by taking longer strides, avoiding the need to shorten our muscles very rapidly, hence generating a greater power at each stride. If we compared a runner with a skater travelling at the same speed, the runner would take about six steps for every 'skating step'. For a similar heart rate, say 130 beats per minute, the skater would travel almost four times as fast as the runner. The stride frequencies and lengths recorded reported by Formenti and Minetti (2007) are presented in Table 1; these results suggest that our ancestors empirically understood the above mentioned, important biomechanical properties of skeletal muscle contraction. For example, participants were asked to skate at a low and at a high speed, defined as sustainable for 8 and 4 hours respectively, simulating the speed that might have been adopted for a journey. It is clear that the 'natural selection' of ice skates favoured models that allowed higher speeds,

associated with longer strides and low stride frequencies. Travelling fast on modern skates was associated with a metabolic energy cost which was even lower than that recorded on slow, old skates. Overall, subsequent models of ice skates dramatically improved our locomotion efficiency, allowing faster travel at lower metabolic energy cost.

Modern klapskates require a movement pattern that, in terms of push-off mechanics, is slightly different from that of jumping (or running). When travelling on klapskates, no flexion of the metatarsal joint occurs: the ankle is extended, but the foot rotates as a single element around the hinge between the boot and the blade. By contrast, when we perform a standing jump (or when we run), just before our foot loses contact with the ground, it bends at the metatarsal–phalangeal joint level. The tendons in the arch of the foot, storing some elastic energy during the extension of the metatarsal joint, normally return a substantial portion of energy during these structures' elastic recoil (Hick's windlass effect), possibly playing a role in determining performance. I expect that a block that gives the opportunity to bend the foot at the level of the metatarsal–phalangeal joint in the last stage of the pushing phase would contribute to a small, but perhaps significant increase in ice skating performance.

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