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Human locomotion on ice: the evolution of ice-skating energetics through history

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Summary

More than 3000 years ago, peoples living in the cold North European regions started developing tools such as ice skates that allowed them to travel on frozen lakes. We show here which technical and technological changes determined the main steps in the evolution of ice-skating performance over its long history. An in-depth historical research helped identify the skates displaying significantly different features from previous models and that could consequently determine a better performance in terms of speed and energy demand. Five pairs of ice skates were tested, from the bone-skates, dated about 1800 BC, to modern ones.

This paper provides evidence for the fact that the metabolic cost of locomotion on ice decreased dramatically through history, the metabolic cost of modern ice-skating being 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, gives the opportunity to estimate the maximum skating speed according to the distance travelled.

Ice skates were probably the first human powered locomotion tools to take the maximum advantage from the biomechanical properties of the muscular system: even when travelling at relatively high speeds, the skating movement pattern required muscles to shorten slowly so that they could also develop a considerable amount of force.

Key words: energy cost of locomotion, bioenergetics, biomechanics, ice skate.

Introduction

The energy-saving principle is one of the strongest factors leading the evolution of the different movement strategies adopted in the animal world: human locomotion, as well as the locomotion of many animals, evolved in order to travel more conveniently in terms of time and/or energetic demand to reach a destination. This is true almost regardless of the media in which locomotion takes place, whether it is on land, water or air, and consequently it is independent of the particular characteristics of an animal species. In most species, evolution forced animals to develop peculiar anatomical structures and extremely specialized and ingenious forms of locomotion, sometimes requiring fast contracting muscles or muscles that exert great forces.

Within this framework, our study focuses on the development of human locomotion on ice. Particularly, we tried to understand how much the metabolic cost of transport changed through history and what the longest distances people could travel were. We hypothesized that changes brought to subsequent models of ice skates decreased the cost of transport, and we show here to what extent this happened.

Ice skates, nowadays mainly used for sport, art or leisure, first developed as a means of locomotion at least 3000 years ago (Luik, 2000). Ancient Scandinavian sagas suggest that the first ice skates were small wooden plates, but no archaeological finding can support this perspective at present. On the other hand, many findings show evidence of animal bones used as ice skates in large European areas and in some of the Russian northern regions since the Bronze Age (Brown, 1959; Muhonen, 2005). Originally, bone skates were used while pulling sledges transporting goods and to go fishing in times and regions where freezing winters did not allow fishing from the shore, as was possible during the mild season. It seems that the oldest remains were found in Scandinavian countries, but ice-skating mainly developed in The Netherlands, where it has been the most popular means of winter transport for centuries. The presence of heavier and lighter snowfalls could have determined the development of cross-country skiing and ice-skating, respectively, in Scandinavia and in The Netherlands. Dutch people were the very early pioneers since, as far back as the 13th century, they could maintain communication by skating for miles from village to village along frozen rivers and canals (Heathcote et al., 1892), keeping the ice free from snow and filling up cracks. From its very conception, skating on ice was a form of human-powered locomotion that was simple and effective, very cheap (and thus accessible to a large part of the population) and allowed people to reach more distant destinations than they could do by walking or running. In fact, unless more expensive means of transport such as horses or (later) trains were used, ice skates were probably the most convenient locomotion tool until bicycles were built (Minetti et al., 2001), the latter probably not being very safe on slippery roads in winter. It is interesting from this point of view to observe that the countries where ice-skating began are those where bicycles are most used now, possibly because of the flatness of the territory, combined with the widespread presence of waterways (CIA, 2005).

Despite the fact that research has widely explored the bioenergetics of modern ice-skating (di Prampero et al., 1976), there is no evidence to support how the metabolic cost associated to its development changed over time. Previous studies showed how humans created different passive tools and invented strategies to enhance their performance through history. The evolution of these tools, for example bicycles (Minetti et al., 2001), wheelchairs (Ardigò et al., 2005) and skis (Formenti et al., 2005), clearly shows that the achievement of high speeds, for the same metabolic effort, has always been a primary target. In the current paper, we point out which limiting factors humans empirically understood to be the most important in determining their travelling performance on ice, since their first attempt. Moreover, an estimation of the highest sustainable ice-skating speed over a range of given distances is proposed. Presenting many similarities with cross-country skiing, ice-skating performance evolved both in terms of speed and metabolic cost.

Materials and methods

Participants

Five healthy ex-professional short-track skaters took part in the experiments (mean ± s.d.; age 22.0±3.7 years, stature 172.2±4.9 cm and body mass 66.0±5.1 kg). This kind of participant was chosen in order to (1) optimize the time needed to familiarize with historical models and (2) take advantage of their ability to avoid the ankle plantarflexion movement, a technique typically adopted by modern long-distance skaters (de Koning et al., 2000). This type of movement is of peculiar importance since with conventional and historical skates, ankle plantarflexions should be avoided (Houdijk et al., 2000b). Participants were informed about the aims, procedures and details of the study and signed an informed consent form to take part in the experiments. Ethics approval was given by the Dept of Exercise and Sport Science Ethics Committee (Manchester Metropolitan University) before beginning the experiments. On the first day, the opportunity to try the different skates was given and, at the end of this familiarization session, participants declared that they felt comfortable with all the five models needed for the tests.

The skates

Five pairs of ice skates were chosen as representative of the main steps in technological development and possibly as good candidates to show how metabolic cost changed between subsequent models. Archaeological specimens of the two oldest models could not be used, so a pair of horse metatarsal bones was prepared by the authors, and an accurate replica of the 5th century model was made by the Department of Design and Technology (Manchester Metropolitan University, Cheshire, UK). The two oldest pairs of skates were normally associated with leather bindings. Nevertheless, for health and safety reasons, we made sure that the skates were securely fastened to the participants' feet, assuming that safety has always been a priority. Consistent with this principle, participants wore walking boots during the tests on the historical skates, while ice-skating boots were used when skating with the modern models. Fig. 1 shows the skate models employed for the experiments; technical information about them can be found in Table 1. The following paragraphs describe the ice skates in more detail.

Table 1. *Characteristics of the five pairs of skates used during the experiments*

Date	Material	Blade length (mm)	Blade width (mm)	Foot height (mm)	Mass (pair) (g)	Dynamic μ	Metabolic cost (J kg^{-1} m^{-1})
1800 BC	Animal bone	210	14	36	1450*	0.0103±0.0022	4.62±0.91
1200 AD	Ash and iron	230	6	59	1300	0.0147±0.0011	2.46±0.75
1400 AD	Ash and iron	250	6	45	900	0.0112±0.0007	2.01±0.35
1700 AD	Birch and steel	410	1.3	50	950	0.0084±0.0010	1.78±0.28
2004 AD	Fibreglass, carbon fibre, Kevlar®, steel	460	1	62	930	0.0058±0.0004	1.32±0.27

*Includes pole.

The mean values and standard deviation of the dynamic coefficient of friction (μ) measured is reported, as well as the metabolic cost (averaged between the speeds considered). Since the bone skates did not have a blade, measurements reported here show the dimensions of the underside of the bone, the part that was in contact with the ice while skating.

The bone skates

Apart from ancient Scandinavian sagas telling about small wooden plates used as a means of travelling on ice and hard snow, the oldest detailed written references to ice skates can be found in Heathcote et al. (Heathcote et al., 1892) and Munro (Munro, 1893). Apparently, animal bones were the first step in the development of ice skates. Most of the 211 findings considered by Jacobi (Jacobi, 1976) are horse bones (66%), while the remaining 34% come from cow bones. Amongst the horse bones, metatarsi represented 45% of the findings, while about 39% were metacarpi and 16% radii; similar proportions are found among cow bones. It seems that the bones were chosen to match the size of the skater's feet.

Numerous bone skates show holes pierced horizontally, perpendicular to the main axis of the bone, through which leather straps could pass and fasten the foot to the bone skate. Following this information, authors personally prepared the horse metatarsal bones needed for the experiments, taking particular care not to warm up the bone during the piercing process and thus alter the mechanical properties of the bone structure. It was noticed that the hole at the back was found approximately under the ankle, while the one at the front was always pierced very close to the front end of the bone, in the condyle. By means of PQCT (peripheral quantitative computed tomography) scans, authors observed that the trabecular area represented 45% of the sections at the front and at the back of the bones. While the cortical density was similar in the two sections considered, the front section showed a much higher trabecular density (+70%) than the section at the back. This finding shows that piercing the hole very close to the condyle was probably more difficult than doing it slightly further at the back, but it seems reasonable to expect that this particular section was chosen for its higher strength and resistance to usage.

Bones did not have an edge that allowed the typical skating movement pattern, so the forward propulsion was given by the upper limbs: a stick was pushed backwards between the legs while the legs were kept almost straight.

Fig. 1. (A) The skates used in the present study, from the left: the bone skates, the first wooden skates with a metal blade, the skates used in the 15th and 18th century, and the modern conventional ice skates. Details can be found in the text. (B) 'Winter landscape with iceskaters' 1608, a painting by Hendrick Avercamp (1585–1634). Reproduced with permission from The Rijksmuseum, Amsterdam, The Netherlands.

Finally, it is surprising how bone skates were still in use in the 18th century "*in Iceland, Gotland and in parts of Hungary and Germany*", as reported by Roes (Roes, 1963).

The first wooden skates with a blade

It was not until approximately the 13th century that a few skates began to be made in wood with a metal blade fixed on the underside, and by the 14th century, these were generally the most used ice skates in The Netherlands: wood was easy to work and metal lasted for a long time. The model used in the present study was the oldest one that authors could find a detailed description of (Goubitz, 2000); a replica is kept at the National Service for Archaeological Heritage in Amersfoort (The Netherlands). Surprisingly, the dynamic coefficient of friction (μ) measured for these skates was higher than that recorded for the bone skates (Table 1). Nevertheless, the use of these materials allowed the skater to propel him/herself with their more-powerful lower limbs. Ice-skating in its modern form began with a model similar to this.

Skates used from the 15th to 18th centuries

Although still made from the same materials, ice skates used between the 15th and the 18th centuries were much lighter, by about 30%, than their predecessors. Authors chose to include this model among those considered for the study because of its reduced mass, which could reduce the cost of skating by limiting the mechanical internal work. On the other hand, if compared with more recent models, the blades of these skates were still quite short, a factor that could make it more difficult to control balance. Nevertheless, it was with models similar to this that a massive production of skates began in this epoch, particularly in The Netherlands, where ice-skating rapidly spread, becoming the most popular means of locomotion and transport in winter. Even before this time, the shallow waters surrounding The Netherlands froze easily, but the greatest incentive for a further increase in ice-skating popularity in the 15th century is due to the building of windmills used to remove excess water from the low-lying districts. The largest network of canals in the world was set up and, associated with the numerous freezing winters recorded during the Little Ice Age, this probably determined the success of ice-skating. This popularity is confirmed and was appreciated by the Dutch and English artists of that time (an example is reported in Fig. 1): hundreds of ice-skating scenes on canals, rivers and lakes were recorded on painters' drawings, now on show at the most prestigious museums and art galleries in The Netherlands and in England.

The 18th century ice skates

Longer blades could possibly allow an easier balance control during ice-skating and could consequently be associated with a benefit in terms of economy. At the same time, from a mechanical perspective, only the edge of the blade is in contact with the ice for most of the time while skating, particularly during the pushing phases. About three centuries ago, skaters empirically understood that, at a given temperature and for a given force, the pressure exerted by the blade on the ice would be lower if the contact area between ice and blade could be larger. As a direct consequence, at each stride, the blade would not be pressed as much into the ice, and a lower resistance to progression would be encountered. The implications of such geometrical variation brought the authors to include this skate model in the study.

Modern ice skates

It is only since the 19th century that purpose-made boots were screwed onto the metal frame of the skates, a change that increased the control of the skates further, allowing for easier and safer travelling. This factor potentially allows the skater to take fewer strides over a given distance. Technology, materials and skills in skate-making allowed the development of lighter skates, with longer and thinner blades, which showed a very small dynamic coefficient of friction (Kobayashi, 1973; de Koning et al., 1992). The combination of the two above-mentioned elements poses a good basis for hypothesising a decrease in the internal work required to sustain a given speed: lower limbs could move at slower speeds and had a lighter mass to lift at each stride. By moving more slowly, muscles are recruited for more efficient contractions, lying closer to the maximum power peak in the speed–power curve. On the other hand, the bent position of the knee and the high knee joint torque characterizing the long gliding phases (Houdijk et al., 2000b) restrict muscle blood flow, especially in the vastus lateralis muscle (Foster et al., 1999). Finally, at each given speed and depending on the value of the knee angle, there should be an optimum stride frequency/length, possibly determined by the need to balance, by properties such as force–length and power–velocity relationships typical of the skeletal muscle as well as a specific ratio between limiting the internal work while maintaining a sufficient muscle blood flow.

In modern long-distance competitions, a recently developed model is used: originally patented in 1891, it was not used in competitions until the mid-1990s. Scientists initially named it 'slapskate' (van Ingen Schenau et al., 1996), which was later changed to 'klapskate' (van Ingen Schenau, 1998). It differs from the model considered in the present study because of a hinge located on the frame of the skate, between boot and blade. Since klapskates have been used, performance has increased, resulting in 3–5% higher speeds. Several previous studies (van Ingen Schenau et al., 1996; van Ingen Schenau, 1998; de Koning et al., 2000; Houdijk et al., 2000b; Houdijk et al., 2000a; Houdijk et al., 2001) have explored the mechanical determinants of the increased performance and its effects on physiological variables such as oxygen uptake and heart rate. Despite no difference being observed in heart rate and in the resistance opposed by air friction (van Ingen Schenau, 1982), an increased power output was calculated ($\approx$10%). Finally, for speeds not statistically different, oxygen uptake was lower when using klapskates than when skating on conventional skates (de Koning et al., 2000). Because these extensive measurements are reported in detail in the above-mentioned literature, we have chosen not to replicate them here.

Experimental procedure

Experiments were performed in an indoor ice rink in Bormio (Italy). The ice was properly prepared before the beginning of each recording session by means of traditional ice-rink machines, which polish the surface of the ice, leaving an extremely thin layer of water on the top of it. Temperature on the ice surface was –4.5°C and relative humidity was 80%. Each participant was asked to skate with each of the five skate models at two different, constant speeds: the first speed was defined as sustainable for 8 h (low speed; L), simulating quite a long journey, while the second as sustainable for 4 h (high speed; H). Bone skates could only be tested at the low speed because participants declared that they would not feel safe at a higher speed. Two faster speeds were tested for modern ice skates; participants were asked to travel at speeds corresponding to approximately 60% and 75% of their maximum theoretical heart rate, continuously monitored by means of a heart rate monitor transmitting real-time data to a portable PC. Time needed to cover each lap was recorded; mean values and their standard deviation for the last three minutes of activity were calculated.

Bioenergetic measurements

Skate models were randomly tested for 7 min each at every speed, and the metabolic energy associated with their use was calculated over the last three minutes of each trial. Participants were equipped with a portable telemetric metabograph sampling on a breath-by-breath basis (Cosmed K4 *b*^{2}; Rome, Italy) (Hausswirth et al., 1997). The K4 system includes a portable unit worn by the participant and a base station for recording the data. The portable unit weighs 1.5 kg and consists of a silicon mask with a flow-rate turbine fixed on the participant's face, a processing unit containing O_2 and CO_2 analyzers placed on the participant's chest and a transmitter/battery pack placed on the back of the participant. Before each recording session, the turbine was calibrated with a 3-l syringe, and a two-point calibration of the O_2 and CO_2 analyzers was carried out using ambient air and a standard calibration gas mixture (5% CO_2, 16% O_2, 79% N_2). Data considered for further calculations were oxygen uptake ($\dot{V}_{O_2}$; $l\,min^{-1}$), carbon dioxide output ($\dot{V}_{CO_2}$; $l\,min^{-1}$), respiratory quotient (RQ) and heart rate (*f*H; beats min^{-1}). Oxygen uptake at rest was measured while participants were standing quietly on the ice rink before each experimental session and was used to calculate the net oxygen consumption for skating with each set of ice skates. Metabolic energy was converted into equivalent units (J) according to the measured respiratory quotient coefficient (di Prampero, 1986). The energy cost of skating ($J\,kg^{-1}\,m^{-1}$) was obtained from the ratio between steady-state net oxygen uptake ($J\,kg^{-1}\,s^{-1}$) and mean speed ($m\,s^{-1}$).

Stride frequency and length measurements

Authors recorded the kinematics of the right leg and the trunk of three participants by means of two inertial sensors (Xsens MT9; Enschede, The Netherlands). The duration of a stride was defined as the time between two successive kicks performed by the same leg. For the bone skates tests, as legs were approximately still, data coming from the sensor placed on the trunk were considered and the duration of a 'stride' was defined as the time between two successive pushes, visible through trunk oscillations. Time courses of values recorded from the gyroscopes during the last three minutes of each trial were used to calculate stride frequency and, by knowing the mean speed of progression, stride length. At low speeds, air resistance could be considered negligible, whilst for the fastest speed adopted with the modern skates ($9.2\,m\,s^{-1}$), it was calculated that air resistance could contribute up to 70% of frictional losses, according to van Ingen Schenau (van Ingen Schenau, 1982).

Skate friction measurements

Skate friction was calculated on the basis of videos recorded by means of a digital camera (25 Hz). One participant took part

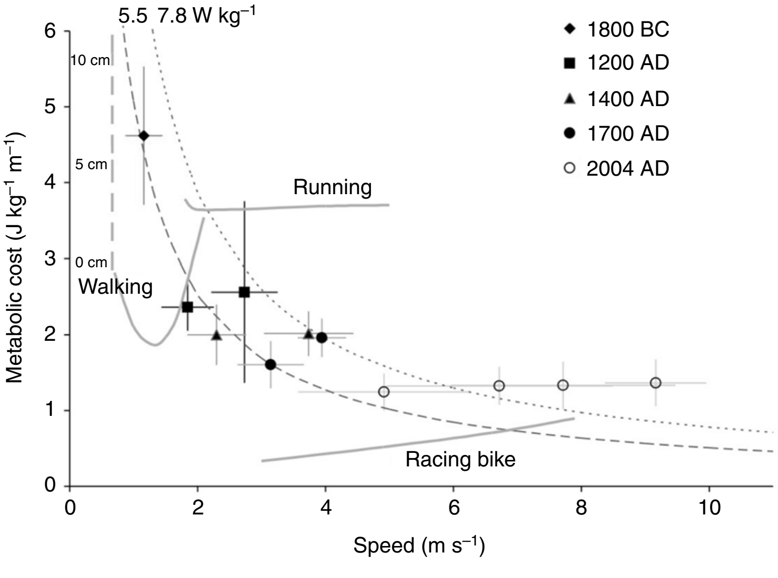

Fig. 2. Mean ± s.d. of the metabolic cost of transport is shown as a function of speed of progression for all the ice skates used in the present study. Units of measure were converted from ml O_2 to J, according to the respiratory exchange ratio (see text for further details). Iso-metabolic power curves (cost *X* speed=constant) are represented by the two hyperbolae. Data referring to walking, running and riding a racing bicycle on firm terrain are shown for the sake of comparison and were taken from previous publications (Cavagna and Kaneko, 1977; Capelli et al., 1998). The cost of walking on snow at $0.67\,m\,s^{-1}$ is also shown in respect to the footprint depth, reported in cm, as measured by Pandolf et al. (Pandolf et al., 1976). In relatively recent competitions, the introduction of klapskates has allowed 5% faster speeds for energy cost values similar to those reported here for modern ice skates.

Table 2. *Speed, stride frequency and stride length associated with the use of different skates for low and high speeds*

	Low speed			High speed		
Date	Speed (m s^{-1})	Stride frequency (strides s^{-1})	Stride length (m)	Speed (m s^{-1})	Stride frequency (strides s^{-1})	Stride length (m)
1800 BC	1.13±0.40	0.50±0.01	2.68±0.52	–	–	–
1200 AD	1.80±0.12	0.63±0.09	2.94±0.44	2.75±0.73	0.90±0.19	3.16±1.01
1400 AD	2.55±0.16	0.54±0.12	4.87±0.92	4.06±0.59	0.65±0.2	6.44±0.93
1700 AD	2.87±0.51	0.57±0.15	5.17±0.53	3.96±0.32	0.68±0.12	5.97±1.71
2004 AD	5.09±1.85	0.40±0.05	13.31±6.09	6.70±2.39	0.45±0.09	15.24±5.55
$F_{(3,8)}$	6.43	2.39	6.61	4.95	4.25	9.21
P	0.02	0.14	0.01	0.03	0.05	0.00

Values are averaged for the three participants who were equipped with the inertial sensors (mean ± s.d.). An analysis of variance (ANOVA) was used to determine differences between subsequent skates models; *F* values and levels of significance are reported. More details can be found in the text.

in these tests; he was initially pushed by the experimenter and then glided while standing still, with his trunk slightly flexed. Fifteen black markers were placed in a straight line at 2 m intervals on the ice surface, and the time when the skates crossed each marker was recorded. Deceleration (a; m s^{-2}) was calculated as the mean value of speed decay. This procedure was repeated five times for each skate model, and the mean value of deceleration was used to calculate the coefficient of dynamic friction (μ), according to $\mu=a\,\boldsymbol{g}^{-1}$, where $\boldsymbol{g}$ is the acceleration of gravity (9.81 m s^{-2}).

Results

Bioenergetic results

The energy cost of locomotion on ice with the skates investigated is shown as a function of progression speed in Fig. 2. Bone skate speeds appear to lay in quite a limited range and, in terms of metabolic cost, skating on them was about twice as demanding as walking on firm terrain; nevertheless, skating on bones might have been safer than walking on ice. A paired Student's *t*-test showed that, for a given skate model, the metabolic cost measured was not significantly different between the low (L) and high (H) speeds (mean values for all skates models tested at both speeds; cost L=1.80± 0.52 J kg^{-1} m^{-1}; cost H=1.96±0.74 J kg^{-1} m^{-1}; P=0.24). The independence between cost and speed is also graphically clear when looking at the points representing the cost of modern ice-skating, within the four speeds tested. By comparing results referring to bone skates and modern skates, it can be seen that for a similar mass-specific metabolic input (5.5 W kg^{-1}), humans can now skate at 25% of the cost and, consequently, four times faster.

Stride frequency and length results

Differences between the two speeds considered

Student's paired *t*-statistic showed that the low speed and the high speed, subjectively chosen by the participants, were significantly different (L=3.05±1.40 m s^{-1}; H=4.28± 1.77 m s^{-1}; $P<0.001$). Showing low values at both speeds, mean stride frequencies (f) were also significantly different (f at L=0.53±0.12 Hz; f at H=0.65±0.22 Hz; P=0.03). The length of the strides (l) was also significantly greater at the high speed (l at L=6.58±4.93 m; l at H=7.83±5.32 m; P=0.03).

Differences between the skate models

Stride frequencies and lengths are summarized in Table 2, which also gives the level of significance for differences between skates models and, hence, historical periods. For a given mass-specific metabolic power, faster speeds are achieved on more recent skates by means of longer strides performed at low frequency. When comparing variables relative to the skate models, a positive relationship between stride length (l) and speed resulted from a linear regression analysis (r^2=0.85, intercept set=0, N=23).

Table 1 shows the coefficient of dynamic friction (μ) associated with the skates considered in the study. For these measurements, authors did not take air resistance into account, which might have played a partial role in the first part of our trials (when the highest speed recorded for the skater was almost 3 m s^{-1}). It seems clear how the development of ice skates has aimed at reducing the resistance opposed by the ice, taking advantage of more suitable materials and shapes.

Discussion

The present study provided evidence for the energetic demand of skating on ice in different eras. The main limitation of this research is probably the choice of performing the experiments in an ice rink, where participants had to make turns. This necessity might have partly affected the locomotion pattern, determining a slightly higher metabolic energy cost and stride frequency than could be measured on a straight path. On the other hand, this could be partially compensated by the lower resistance to progression offered by prepared ice rather than by natural ice. Moreover, for the purpose of this study, environmental parameters such as ice temperature, wind speed and direction needed to be kept strictly constant so that observed differences related only to the different sets of skates used. In this perspective, performing the experiments outdoor could have non-systematically biased the results, making it difficult to understand how much of the observed differences were associated with the skate models or environmental elements.

Pandolf et al. measured the energy cost of locomotion on snow and reported it as a function of footprint depth (Pandolf et al., 1976) (Fig. 2). A comparison of Pandolf's results and those presented in the present study shows that, on average, when travelling by a frozen lake or river, skating on bones was more convenient than walking on snow, as long as the snow was more than six or seven centimetres deep. It has also been shown that for a given speed and gradient the cost of human walking is directly related to the transport of the mass carried (Bastien et al., 2005). It can probably be speculated that while travelling on skates the cost of pulling a sledge with an extra given load would not be linearly related to the mass of the load to be transported on the ice. The widespread presence of water, and thus the numerous frozen lakes in winter, together with the advantage given by pulling a load while skating rather than carrying it by foot, seems to explain why humans first began skating on ice. As soon as technology evolved, in approximately the 13th century, ice skates also enabled humans to travel at speeds that could not be achieved by walking, and at lower metabolic costs. Nowadays, ice-skating is about one-third cheaper than running on firm terrain, and for a given metabolic power much higher speeds can be sustained; only cycling on modern racing bicycles allows for faster travelling.

On the basis of our results, it would be interesting to calculate approximately how far humans could skate in the past and the maximum speed that they could sustain over a given distance; in order to do this, two fundamental assumptions need to be taken into account. It was shown here that the metabolic cost of ice-skating is speed independent; the first assumption to be considered is that this relationship remains unchanged for speeds slightly outside of the investigated range and still relying on an aerobic metabolism. This assumption is supported by evidence reported in a paper by de Koning et al. (de Koning et al., 2000): they studied speeds of approximately 10 and 12 m s^{-1} and measured metabolic cost values similar to those recorded in our experiments. Moreover, all the participants taking part in this study subjectively chose an upright posture when travelling at the slowest speeds while leaning slightly forward at high speeds. This is determined by the need to keep the body centre of mass further ahead (leaning forward) when higher accelerations are expected from the power generated by the lower limbs, and at the same time it is clearly a consequence of the mechanical power required to overcome the aerodynamic drag. Air does not determine a strong resistance to the forward motion when travelling slowly but becomes the most limiting factor for performance as speed increases (di Prampero, 1985). This can explain in part the independence of cost and speed in the present study and could support the hypothesis that cost would not increase for slightly higher speeds, when naturally a more aerodynamic position would further decrease the proportion of power required to overcome air resistance. Unfortunately, at present, literature does not exactly provide strong evidence from this perspective because of the different methods and conditions in which the cost of ice-skating has been measured (Houdijk et al., 2000a; Nobes et al., 2003). Measuring the partitioning of the energy needed to move and to balance is a difficult task in studies

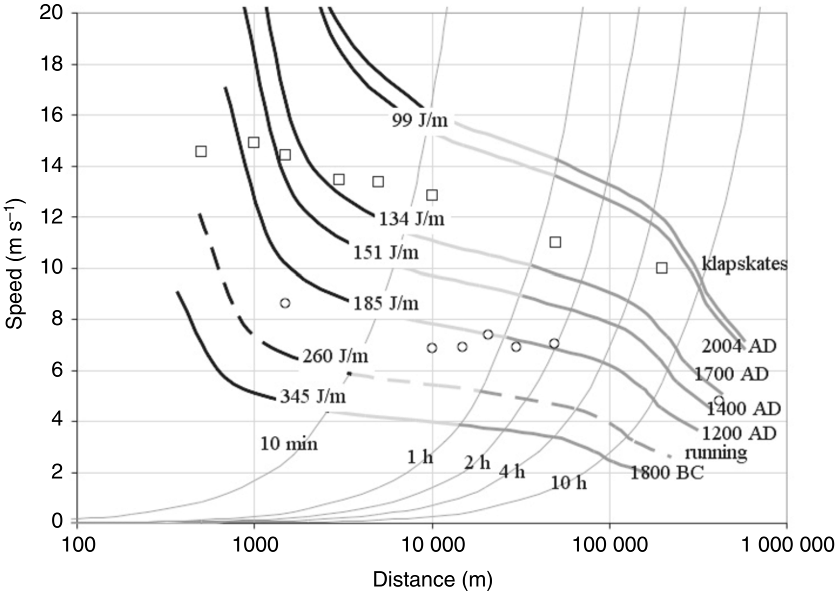

Fig. 3. The three-colour (black, light grey, dark grey) curves represent the maximum speed/distance relationships calculated for constant metabolic cost for each skate model. Data for klapskates were calculated assuming 5% faster speeds. The broken line reports values for running and is shown as a comparison to the ice-skating data. Obtained from equations provided by Wilkie (Wilkie, 1980), Saltin (Saltin, 1973) and Davies (Davies, 1981), the three-colour curves are based on the assumption that the available fraction of the metabolic power used for a physical activity is inversely related to the time to exhaustion (from the left; black, 40 s–10 min; light grey, 10 min–1 h; dark grey, 1–24 h). For the calculations, the maximum metabolic power available has been set at 21.3 W kg^{-1}. The light grey curves are iso-duration speed/distance pairs; the open squares represent the actual records in ice-skating and the open circles show records for cross-country skiing, reported as a means of comparison. Example: the energy cost of skating on bones (1800 BC) is indicated by the thick 345 J m^{-1} iso-cost line. 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 skater could cover a distance of 2638 m at an average speed of 4.4 m s^{-1} before exhaustion. 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. Consequently, in 10 min, a distance of almost 10 km can be travelled at an average speed of ~16 m s^{-1} before exhaustion, as indicated by the intersection between the 99 J m^{-1} iso-cost curve and the 10 min iso-time line.

about animal locomotion: when travelling at slow speeds on skates (or by bike), a great portion of the energy used is needed to balance; proportionally, balancing becomes more economical at faster speeds. This could also contribute to the determination of the cost of modern ice-skating recorded in the present experiments and may support the assumption that it might keep on being unvaried at higher speeds than those studied here.

The second assumption to be considered is that the fraction of the metabolic power available for physical activity, necessary for calculating the speed, should be inversely related to the time of exhaustion. Further details on this method can be found in our previous studies (Minetti, 2004; Formenti et al., 2005). A prediction of the maximum sustainable speed as a function of the distance travelled is shown in Fig. 3. The validity of the model used is supported by the points representing the highest average speeds achieved in recent competitions (the slowest records lie almost parallel to the iso-cost lines). Differences between the prediction and the actual records may be related to the different conditions in which the competitions took place (particularly when the accelerative phase at the start is a substantial contributor of the total cost), wind and temperature being important determinants of ice-skating performance.

It might be interesting to notice that, as mentioned above, quite strong winds must also have characterized the flat Dutch lands in past centuries. This is confirmed by the high number of windmills and by the peculiar technique of skating in a queue while holding a long stick, which has been recorded by numerous artists. Not only could the skaters at the back benefit from the aerodynamic protection offered by the skater at the front, but the skater at the front could also take advantage of the push coming from skaters behind. It is important to remember that speeds were generally not as fast as in modern competitions, so the posture adopted was almost upright in respect to the ground and even when travelling at low speeds, the queue strategy might reveal an efficient saving mechanism if going opposite to the wind direction. On the contrary, when going with the wind direction, skaters held the stick while skating side by side in a row, being partially pulled by the wind.

In terms of speed and energy demand, the advent of ice skates and skis meant that, for centuries, travelling on ice was more convenient than moving on snow or firm terrain: until bicycles were invented. The mechanical reasons for this lie particularly in the different friction, the different progression techniques and the different weights of the tools. At the same time, from a biomechanical and physiological perspective, a crucial role was clearly played by the practical implication of the force–speed relationship characterizing muscular contraction (Marsh, 1999). This can be easily noticed especially when travelling fast: in contrast to walking, running and classical cross-country skiing, the skating locomotion pattern allows muscles to shorten slowly, at speeds probably close to those at which they can develop their maximum mechanical power. In the same way that gear ratios improved cycling performance by making the pedalling frequency independent of speed, subsequent models of ice skates allowed faster speeds for similar stride frequencies. Stride frequency is an important parameter because, for a given movement pattern, and thus a muscular strain trajectory, stride frequency is strictly related to the speed at which the propulsive muscles shorten and consequently influences the power that the muscle can develop while contracting. According to this principle, it seems clear that when trying to achieve high power outputs, stride frequency needs to be restrained to a limited range.

The use of klapskates employed nowadays implies a movement which, in terms of push-off mechanics, is slightly different from that of jumping (or running). In fact, 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 it in these structures' elastic recoil (Hick's windlass effect), possibly playing a role in determining performance. In the future, we think that it would be interesting to see the effect of 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.

Nowadays, the most interesting advances in human locomotion often result from sports competitions. From this perspective, the major limiting factor for future developments could be represented by the regulations governing sporting events, unless they are reviewed. Regulations changed in the past, allowing, for example, the use of mono-fins for swimming competitions. Performance on racing bicycles could benefit from a laying position and an aerodynamic shield; record times of cross-country skiing and ice-skating could improve if the skis and blades were kept lubricated while travelling. At present, these solutions are not allowed in official competitions. To a certain extent, rules still limit the evolution of performance in cycling, swimming, skiing and ice-skating in both a specific context and, generally speaking, the development of human-powered vehicles.

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