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Human locomotion on snow: determinants of economy and speed of skiing across the ages

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We explore here the evolution of skiing locomotion in the last few thousand years by investigating how humans adapted to move effectively in lands where a cover of snow, for several months every year, prevented them from travelling as on dry ground. Following historical research, we identified the sets of skis corresponding to the 'milestones' of skiing evolution in terms of ingenuity and technology, built replicas of them and measured the metabolic energy associated to their use in a climate-controlled ski tunnel.

Six sets of skis were tested, covering a span from 542 AD to date. Our results show that: (i) the history of skiing is associated with a progressive decrease in the metabolic cost of transport, (ii) it is possible today to travel at twice the speed of ancient times using the same amount of metabolic power and (iii) the cost of transport is speed-independent for each ski model, as during running. By combining this finding with the relationship between time of exhaustion and the sustainable fraction of metabolic power, a prediction of the maximum skiing speed according to the distance travelled is provided for all past epochs, including two legendary historical journeys (1206 and 1520 AD) on snow. Our research shows that the performances in races originating from them (Birkebeiner and Vasaloppet) and those of other modern competitions (skating versus classical techniques) are well predicted by the evolution of skiing economy. Mechanical determinants of the measured progression in economy are also discussed in the paper.

Keywords: skiing history; metabolic power; mechanics; cost of locomotion

1. INTRODUCTION

Well before becoming a leisure and sport activity for the industrial societies of temperate latitudes, cross-country skiing constituted the compulsory means of transport for most of the ethnic groups living north of the Arctic Polar Circle for millennia. As figure 1 shows, in that geographical area, daily activities such as hunting, herding and foraging still rely on skis, while the first evidence of skis, in the form of cave engravings, dates back to about 2000 BC (Clifford 1992). The very harsh environment, particularly during the long freezing winters, forced many Arctic dwellers to adopt a nomadic lifestyle to maximize the energy they can extract from prey and food and to minimize any energy waste (Freuchen 1935). From this perspective, the cost of locomotion could represent a substantial portion of the energy balance and potentially limit migration time, hunting performance and, ultimately, survival chances.

As with bicycles (Minetti *et al.* 2001) and wheelchairs (Ardigò *et al.* 2005), the evolution of skiing is testimony to the continuous quest to overcome, by using passive man-made tools, the limits to locomotion imposed by the environment and our musculo-skeletal system. The study of the physiological and mechanical aspects of such evolution, apart from shedding light on the progressive adaptation of the same actuator (muscle) to new technological advancements, helps to better understand the characteristics of modern versions of those forms of locomotion and predict their further development. Such knowledge would also contribute to a physiological evaluation of historical feats and facts regarding transport on snow, and assist interpreting ancient and modern lifestyles of the Arctic peoples.

There is no quantitative data, at present, on the relevance of ingenuity and technology in the design evolution of skis and on their improved economy (Street 1992). In addition, past research investigated the energy cost of modern skiing in outdoor conditions only. Mainly due to the (suddenly) changeable temperature and humidity, the variability in the snow crystals (Inuit use about 100 different terms for 'snow') made measurements obtained in similar general conditions very difficult to compare. Since the core of our work was the comparison among skis and their associated techniques, we needed to eliminate the environmental interference. For this reason we managed to arrange for all of our experiments to be carried out in an air-conditioned ski tunnel in Finland.

2. MATERIALS AND METHODS

(a) *Subjects*

Five healthy non-professional skiers took part in the experiments (mean ± s.d.: age 33.8 ± 11.8 years, stature 176.0 ± 2.8 cm and body mass 73.0 ± 4.8 kg). All participants were informed about the methods and aim of the study, signed written consent to the experimental procedure and were given a whole day to familiarize themselves with the skis. We chose not to test elite skiers because of their highly specialized knowledge of modern skis, a factor which could bias the results.

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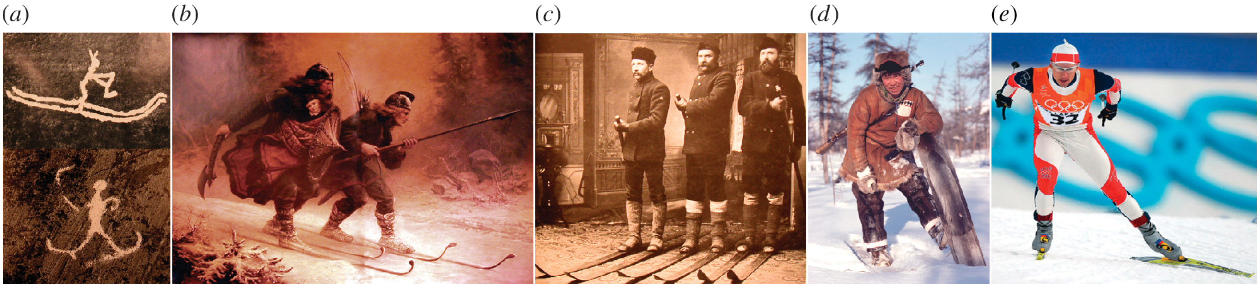

Figure 1. (*a*) Cave graffiti representing early 'skiers'; (*b*) a painting representing the Birkebeiners' feat in 1207 AD; (*c*) late nineteenth-century photograph of Finnish skiers; (*d*) a Chukchi hunter who is representative of the hundreds of thousands of people in the Arctic (the Inuit/Eskimo in Alaska, northern Canada and Greenland; the Saami/Lapps in upper Scandinavia; the Nenet and Evenk in northern Russia; the Chukchi in northeastern Siberia) who still use skis as a means of transport for hunting, herding and foraging; (*e*) a modern athlete while skating.

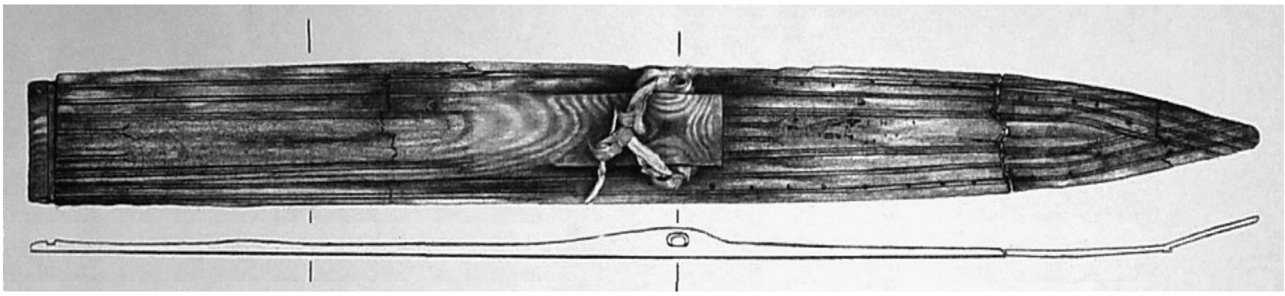

Figure 2. The first ski is shown as it was found; the remaining band that passed around the heel is only partially visible (drawing, National Board of Antiquities, Helsinki, Finland).

Table 1. The table lists the characteristics of the six ski pairs investigated.

date	model	material	length (mm)	width (mm)	underside	pole(s)	mass[a] (kg)	dynamic $\mu \pm$s.d.	metabolic cost ± s.d. (J kg^{-1} m^{-1})
542 AD	'Mantta'[b], (figure 2)	pine	1680	149	badger fur	1	5.0	0.151±0.036	4.285±0.643
1300 AD	asymmetric								
	(long)[b]	birch	3000	97	none	1	5.0	0.085±0.006	3.883±0.554
	(short)[b]	birch	2000	89	seal skin	—	—	—	—
1890 AD	end 1800[b]	birch	2870	78	tar	2	6.7	0.054±0.005	3.170±0.225
1970 AD	last wood	hickory	2000	47	wax	2	2.6	0.020±0.006	2.340±0.195
2004 AD	modern (DS)[c]	carbon fibre	2010	46	wax	2	2.2	0.013±0.004	2.106±0.210
2004 AD	modern (SK)[d]	carbon fibre	1840	43	wax	2	2.0	—	1.917±0.181

[a] Includes skis, bindings, boots and pole(s).
[b] Replicas of archaeological specimens.
[c] Diagonal stride.
[d] Skating.

(b) *The skis: technical and historical data*

Original archaeological specimens could not be used for the present study, so accurate reproductions of the originals were made (Department of Design and Technology, Manchester Metropolitan University, Cheshire). An original set of skis representative of the last wooden skis (1970s) was used as well as modern sets of skis, both for the classical and skating technique. Particular care was taken to link each pair of skis with the original bindings, boots and pole(s) and to prepare them with waxes when the treatment was appropriate. In the graphs, data from skis are named according to the year each set of skis dates back to. Their technical characteristics are reported in table 1. The three oldest sets of skis were associated with one single pole, used mainly for balancing, braking and turning purposes; when skiing with more recent models, participants used two poles that, while helping balance, gave a conspicuous contribution to forward propulsion.

(i) *The Salla ski*

It has been debated whether this object, the oldest found, was the first ski used by humankind; therefore, we did not include it in the table and its results are reported in figure 4 only. The opinion of historians is not yet clear; the ski-like specimen found in Salla, Finland, and now on show at the National Museum of Helsinki, was dated as far back as 3200 BC (with the ^{14}C technique by the National Board of Antiquities, like the next considered historic ski), but some museologists do not agree about its use and report that it is part of a broken sledge. However, considering that the Salla ski does not have significantly different features from other ancient specimens (e.g. Riihimaki, *circa* 1500 BC), in our study it is considered indicative of a very old type of ski and the cost of skiing associated with this model will be presented for comparison with the other models. The pole and the skis were made of pine (*Pinus sylvestris*, density 520 kg m^{-3}); the skis were flat on the upper side and had five parallel grooves on the underside. No evidence of animal skin along the underside or nearby the specimen has been found. Bindings were simply made by a leather strap that wrapped the anterior part of the foot and passed through a hole pierced horizontally through the ski under the footplate. Boots associated with these skis were simply made with animal skin wrapped around the foot.

(ii) *The Mantta ski*

The oldest ski about which a complete and detailed documentation has been written is the specimen found in Mantta, Finland, now the property of the National Museum of Helsinki. Vilkuna (1984) gave an accurate description of this finding dated about 542 AD, which was found in excellent condition in a bog where the absence of oxygen preserved the specimen for about 1500 years. Like previous models, the Mantta skis and the pole used with them were also made of pine but, in contrast to previous models, showed animal fur oriented backward on the underside (front half) to obtain a better grip during the ‘kick’ phase (when the foot is in firm contact with the ground, as opposed to the gliding phase) and on uphill terrain. The front part was engraved on the upper side so that the structure of the wood got weaker, making the front end of the ski point up; this particular detail was important to enable the ski to float on the snow instead of penetrating it. Further developments can be observed at the binding level: despite the boots still being made of simple animal skin, the ski was thicker under the foot so that it was more resistant to the deformation induced by the skier’s weight and thrust. Moreover, bindings were made with two leather straps: one wrapping the foot tight to the ski and passing through a horizontal hole pierced under the raised footplate, and one going around the heel to get better control of the ski (see figure 2).

(iii) *The asymmetrical skis*

For many centuries the asymmetrical skis represented a stable and interesting solution; a model that was chronologically and physically between the Mantta ski and the skis used at the end of the nineteenth-century. The short ski, with animal skin on the underside, was mainly used to kick and the long ski was mainly used to glide. A difference between these skis and previous ones is the material they were made of. Since a milder climate allowed birch (*Betula pendula*, density 670 kg m^{-3}) to grow at latitudes where people skied, ski makers chose to use this wood instead of pine; the new wood used for skis was stronger and more flexible, resulting in better gliding and a more reliable means of transport. The underside of the short ski was flat and animal skin was generally fixed on its middle third while the longer ski had one single groove to maintain better control of the ski while gliding. At this stage, bindings did not show any difference from previous models, being quite similar to those used with the Mantta ski, but were used with proper boots rather than animal skin.

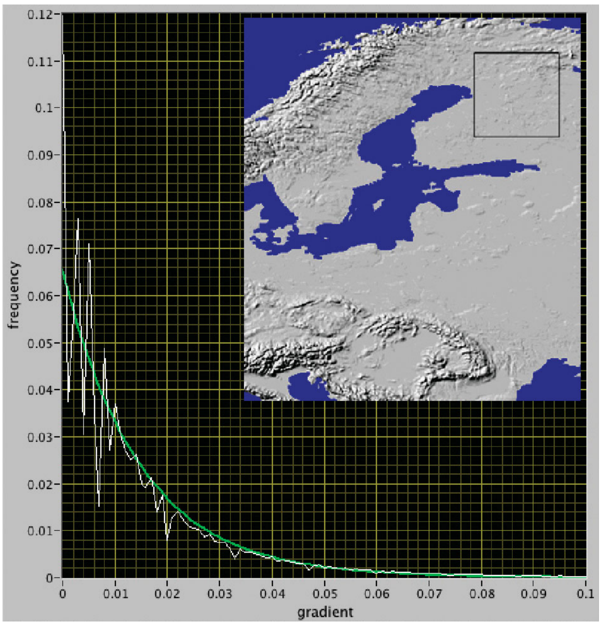

Figure 3. We used a digital elevation model of the Scandinavian area (E020N90, edcdaac.usgs.gov/main.asp) providing the altitude (m a.s.l.) every 941 m of latitude and every 340–430 m of longitude. We sampled a (700 by 700 points) subarea of about 177 520 km^2 mainly located in central and northern Finland (square inset) and wrote a custom programme (LabView, National Instruments, USA) to measure 977 202 gradients in the area and work out their frequency distribution. The result was a quasi-exponential distribution (mean = 0.0148, mode = 0.0050, s.d. = 0.0187, Skewness = 3.038, Kurtosis = 18.331) whose cumulative function showed that 95% of the gradients were within the range of 0–5%. The typical uplands, with lots of lakes and bogs, were paradoxically more easily travelled during winter when most of the soft ground was frozen.

(iv) *The skis used at the end of the nineteenth-century*

The next significant step in the development of cross-country skiing equipment was very long skis treated with tar on the underside that were commonly used at the end of the nineteenth-century, both to accomplish daily activities and for leisure. A thin layer of tar limited the friction between the wood (birch) and the snow and prevented water from penetrating the ski which could consequently be lighter and was less likely to break. Light bamboo poles took the place of the heavier pine pole. The binding was again made of one single leather strap that passed under the footplate, but a piece of rubber was normally nailed or glued over the footplate in order to increase the friction between the ski and the boot. This was purpose-made with leather for the first time in history and had an elevated point that allowed ‘hooking’ of the leather strap during the kick phase and keeping the ski coherent with the foot.

(v) *The last wooden skis*

With the first Olympic Winter Games, held in 1924 in Chamonix, cross-country skiing became a sport, spread rapidly all over the world and its evolution was much faster than in past times. A major development was brought about by snow processing and tracks that allowed the skis to be thinner, shorter and consequently lighter than previously used models. The last wooden skis were made with hickory (*Carya serraefolia*, density 820 kg m^{-3}), a highly flexible wood used to make skis from about 1940 to 1970; their undersides presented one single groove and were treated with grip waxes. Furthermore, metal bindings were introduced and fixed the ski boot to the ski by means of a large clasp; despite the fact that the heel was still quite free to move laterally, ski boots had a flat, plastic point that was securely closed in a strong clasp, a change that significantly helped control the skis.

(vi) *Modern classical technique skis*

Nowadays skis and poles are made with very light carbon fibre and graphite and their undersides are waxed both with gliding wax on the front and on the back ends, and with grip wax under the middle third. A thinner clasp substituted the large metal one: ski boots have a small metal bar under their front end that is fastened to a narrow and tight clasp. Corresponding to an underside tunnel, the upper side of the ski longitudinally and centrally raises between the boot and binding to prevent the heel of the boot from moving laterally.

(vii) *Modern skating technique skis*

The different forms of classical technique used for millennia, called ‘diagonal stride’ and its variations, consisting of ‘herringbone’, ‘kick-double-pole’ and ‘double-pole’, have recently been overtaken by new skating techniques (1976, Innsbruck Olympic Winter Games) that have been made possible by harder packed snow. The actual skis do not show significant differences from modern classical technique (Cl) skis but the ski boots and bindings are specifically designed to improve performance using the skating technique. When skating, the feet do not stop at any step and the ankle movement is limited if compared with the classical technique, so skating ski boots are taller and more rigid. Bindings are slightly different from those used to ski with the classical technique: an elastic release system helps to secure the ski boots to the skis. Finally, these skis do not need a grip wax so they are prepared with gliding waxes only.

(c) ***Experimental procedure***

The experiments were performed at the Vuokatti ski tunnel (Finland), where participants skied the length of the tunnel (1250 m) back and forth twice with each pair of skis, in random order. They were requested to adopt subjectively chosen ‘migration’ and ‘hunting’ speeds, the former defined as sustainable for a day trip (7–8 h) and the latter defined as sustainable for just 3–4 h. When skiing using classical and skating techniques with the 2004 models, participants travelled at two additional, faster speeds; the first defined as slightly faster than the ‘hunting’ speed, the second as requiring about 80% of their maximum heart rate (continuously monitored with an alarm set at 90%). The time needed to ski the whole tunnel back and forth was recorded and the average speed was calculated.

(i) *Environmental parameters*

Kept at a constant temperature (air -5.2 ± 1.1, snow $-4.5\pm0.5\,^{\circ}\mathrm{C}$, $n=115$) and humidity ($83.6\pm1.4\%$, $n=115$) throughout the year by means of a computer controlled air-conditioning system, the Vuokatti ski tunnel was chosen because it has standard snow conditions, hence reducing the environmental variability. Moreover, as shown in figure 3, the gradient range present in the tunnel ($\pm5.9\%$) reflects the geo-morphological characteristics of central and northern Finland where most of the specimens were found.

(ii) *Bioenergetic measurements*

Participants were equipped with a portable metabograph (Cosmed K4 b^2; Rome, Italy) that measured their heart rate (HR; $b\ \mathrm{min}^{-1}$), carbon dioxide output ($\dot{V}_{\mathrm{CO}_2}$; $\mathrm{l\ min}^{-1}$) and oxygen uptake ($\dot{V}_{\mathrm{O}_2}$; $\mathrm{l\ min}^{-1}$) on a breath-by-breath basis. Oxygen uptake at rest was measured while the participants were standing quietly inside the ski tunnel before each experimental session and was used to calculate the net oxygen consumption for skiing with each set of skis. Metabolic energy was converted into equivalent units (J) according to the measured respiratory quotient coefficient (di Prampero 1986). The metabolic cost of skiing ($\mathrm{J\ kg}^{-1}\ \mathrm{m}^{-1}$) was calculated by integrating the net oxygen consumption over each trial duration and dividing it by the length of the track (2.5 km) and mass (body + equipment).

(iii) *Biomechanical measurements*

We recorded skiers’ lower limb kinematics by means of inertial sensors (MT9, Xsens, The Netherlands) placed on the skiers’ right leg and thigh. A stride has been defined as the distance/time between the ends of two successive kicks performed by the same leg. Time courses of Euler angles from the data recorded on the legs were used to calculate the stride frequency (Hz) and estimate the internal work (see appendix A). Given the low speeds analysed, aerodynamic drag was considered negligible.

(iv) *Ski friction measurements*

Ski friction was measured for all the pairs of skis by means of two inertial sensors MT9. The sensors were accurately fastened to a sledge, which was secured to and coherent with the pair of skis to be tested. After an initial push, the deceleration (a, $\mathrm{m\ s}^{-2}$) of the sledge (over which one of the experimenters was sitting) was measured to calculate the coefficient of dynamic friction (μ) according to $\mu=a\ \mathrm{g}^{-1}$. The procedure was repeated 4–5 times per ski model; results are reported in table 1.

3. RESULTS

(a) ***Bioenergetic results***

Figure 4 shows the evolution of skiing economy across the different models and, therefore, eras. For each new ski there was a benefit in terms of less fuel needed to cover the same distance. Also, skiing was more expensive than running (on firm terrain) until 1890 AD. It is remarkable how skiers spontaneously selected speeds corresponding to almost the same metabolic power levels (curves labelled 7 and 9 $\mathrm{W\ kg}^{-1}$, for ‘migration’ and ‘hunting’ simulations, respectively) despite the diversity of skis and the little time to get used to them. Even the faster two speeds for both modern classical and skating techniques were (involuntarily) chosen to correspond to about 10 and 11 $\mathrm{W\ kg}^{-1}$, respectively. The main messages from this graph are that: (i) with respect to the year 542 AD (and previously), humans can nowadays ski 2.6 times faster for the same metabolic power (hence at less then half the cost), (ii) the cost of transport seems to be speed-independent (as in running) for all skis, this being particularly evident when four speeds have been investigated (2004 AD, two techniques) and (iii) the evolution of skiing has reduced the cost of modern skiing (per unit distance, regardless of speed) to the same as optimum walking and allows us to move at double the speed of brisk walking for the same metabolic power.

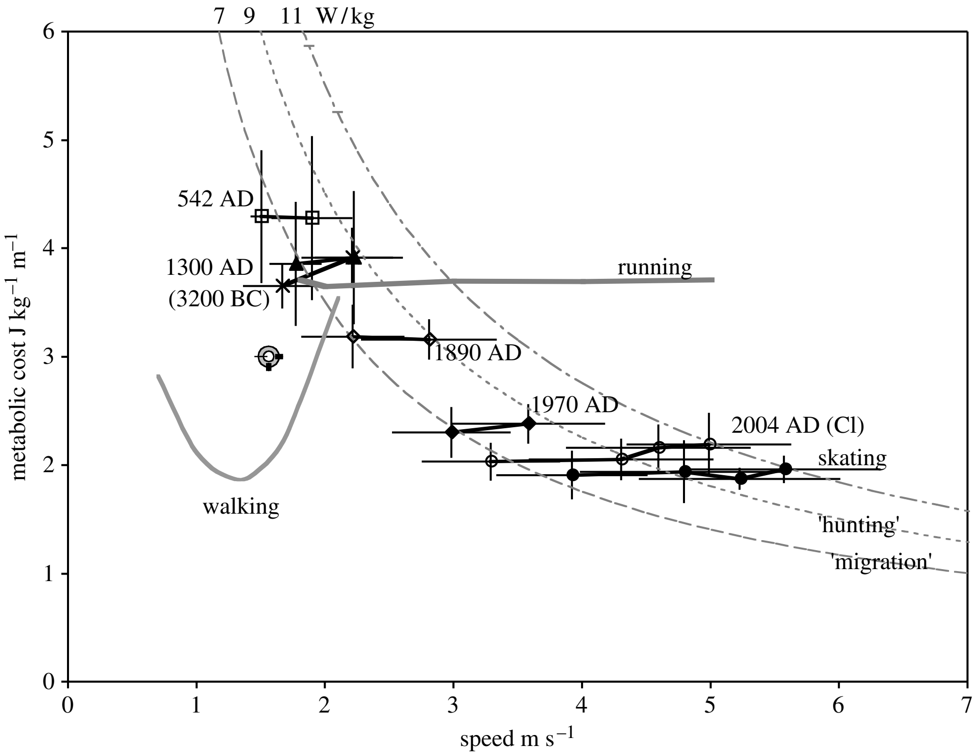

Figure 4. The metabolic cost of transport (means with standard deviations) is plotted against the speed for all the investigated skis (the one marked 3200 BC refers to the replica of 'Salla', a debated ski-like specimen under which no fur was found in the archaeological site). The units have been changed from ml O_2 to J according to the breath-by-breath measured respiratory exchange ratio. Walking and running costs on firm terrain (grey curves) are reported for the sake of comparison (Cavagna & Kaneko 1977). The double circle symbol refers to walking on snow in the tunnel. The slowest point for each ski relates to the 'migration' speed. The three hyperbolae represent different iso-metabolic power curves (cost × speed = constant). While the metabolic cost is the analogous of fuel consumption (per unit distance travelled), the hyperbolae show cost/speed combination at which the effort (approximately proportional to the heart rate) is the same. Bars show s.d.

(b) *Biomechanical results*

With all the investigated skis (except the 2004 skating skis), the footfall sequence resembles one of running (one pole) or trotting (the quadrupedal analogue of running), if we consider the two poles as appendices to the fore limbs. This similarity partly explains the independence of the metabolic cost from speed for each ski model.

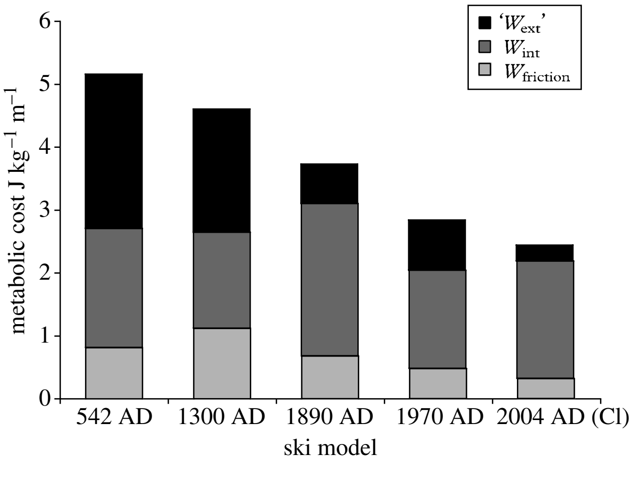

Figure 5. The metabolic cost for each ski model is here shown as partitioned in its main mechanical components equivalent: the external work (W_{ext}, black, obtained from $C - W_{int/eff} - W_{friction/eff}$), the internal work ($W_{int}$, dark grey) and the work performed against friction ($W_{friction}$, light grey). While the work against friction has to be considered part of the external work, here we keep on using W_{ext} to represent the mechanical work done to raise and accelerate the body centre of mass only.

Apart from the number of propulsive limbs, the other difference with respect to running is the extra distance obtained by sliding with respect to the ground, which was found to increase from 14.0 to 60.5% of the total stride length in the chronological ski sequence (those estimates were obtained by calculating the stride length and comparing it to the distance travelled with two non-sliding steps). Despite a highly significant ($p < 0.001$) linear regression between the cost and friction coefficients obtained from the present data, the increase in stride length and its sliding portion makes the exertion required to counter friction (and the associated metabolic cost) stay almost constant for the first three ski models, while in the last two it decreases by about 62.3% (figure 5). The other determinants of the decrease in metabolic cost need to be looked for in other components of the total mechanical work: the work to raise and accelerate the body centre of mass (external work) and to accelerate the limbs with respect to it (internal work). The internal work can be estimated using a mathematical model (Minetti 1998) from the stride frequency, the duty factor (the fraction of the stride duration at which a single limb is in contact with the ground) and the inertial characteristics of the oscillating limbs, which have been recalculated to account for the added mass of skis and poles (further details in appendix A). Due to the opposite change of those variables, the model predicts almost the same internal exertion for all the skis. We did not directly measure the external mechanical exertion but it is expected to decrease

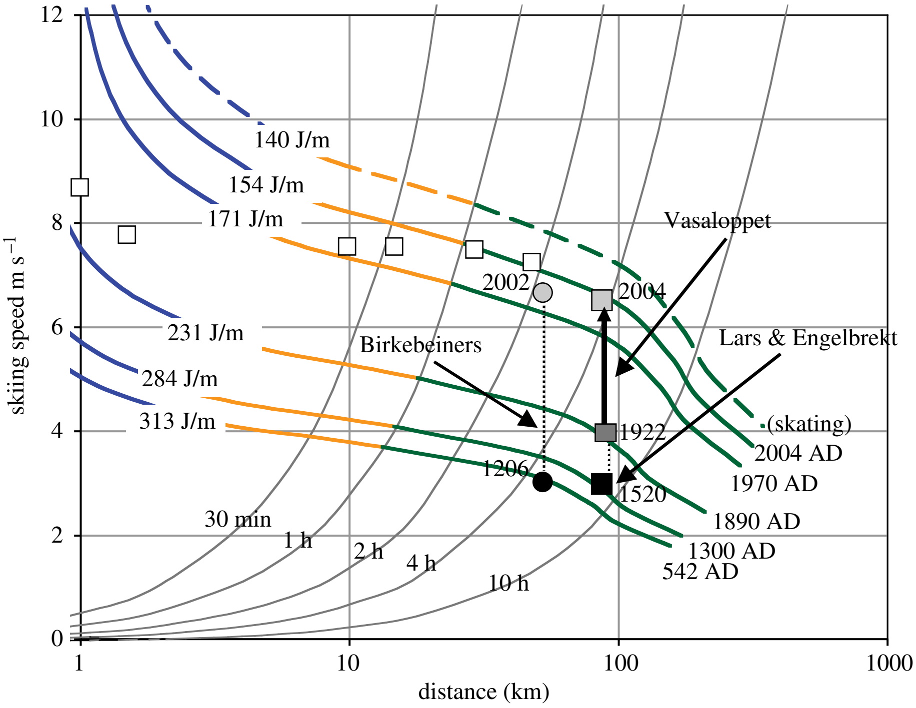

Figure 6. The three-colour curves represent the maximum speed/distance relationships for constant metabolic cost, each of which refers to a different ski. They have been obtained by combining the relationships between the time to exhaustion and the available fraction of the metabolic power used, as suggested by Wilkie, Saltin and Davies for different exercise duration ranges (blue: 40 s–10 min; light orange: 10 min–1 h; green: 1 –24 h, respectively). In this computational frame, 20.3 W kg^{-1} has been assumed as the maximum metabolic power available. In the graph, the grey curves show iso-duration speed/distance pairs and the open square symbols represent recent records in cross-country skiing, from sprint events to endurance races. Grey and black symbols are explained in the text. For further details refer to the text and to appendix B.

along skiing history since the increase in the sliding length will allow distributing the raise of the body centre of mass across a longer distance (thus less work per unit distance). This was confirmed (−86.8%) when we calculated an 'estimated version' of the mechanical external exertion ('guessed' W_{ext} in figure 5) by subtracting the metabolic equivalent of the exertion against friction and the internal exertion from the measured cost.

In summary, the technological evolution of skiing, with the decrease of ski friction and overall equipment mass, has allowed a progressive increase in the sliding distance of a running-like gait and an increase in the progression speed by decreasing two of the three components of the total mechanical exertion.

4. DISCUSSION

Recent literature about the energy cost of cross-country skiing shows a remarkable variability due to the different environmental conditions (temperature, humidity and wind) during the experiments. When the main goal is to compare different materials (such as skis) external interference should be kept to the minimum. From this perspective, the ski tunnel allows the standardization of skiing measurements (to a particular environmental condition). The gradient range of the tunnel is limited (±5.9%), when compared with modern cross-country ski racing tracks, but reflects the terrain characteristic of central and northern Finland (figure 3) where such locomotion types originated and where most of the archaeological ski specimens were found.

To make the present results useful to anthropologists and historians for interpreting ancient travel feats on skis, we need: (i) to assume that the metabolic cost remains speed-independent at speeds slightly outside the investigated range and (ii) to consider that the fraction of the metabolic power available, from which to calculate the progression speed, is inversely related to the time to exhaustion. In fact, a speed-independent metabolic cost allows estimation of the maximum speed by dividing it by the available metabolic power, which depends on the journey duration. Figure 6 shows speed versus distance curves where these effects are taken into account. For each metabolic cost, corresponding to a given ski model, the curve has been obtained by combining the equations by Wilkie (1980; from 40 s to 10 min duration), Saltin (1973; from 10 min to 1 h) and Davies (1981; from 1 to 24 h); an approach recently introduced by Minetti (2004; further details in appendix B).

Figure 6 predicts, for each historical ski, the maximum sustainable performance in terms of speed and distance (i.e. each iso-cost curve delimits the upper speed value for that ski model). The predictive ability of the graph is confirmed by the location, close to the band formed by the iso-cost curves of the two most modern skis, of some recent cross-country records (the accuracy of the positioning is challenged both by the difference between the gradient distribution of each race and the one of the Vuokatti tunnel, and by the potentially different weather and snow conditions).

With this framework we tried to get insights into historical feats that are the origin of two of the most popular ski races today.

The Birkebeiner (Birchlegs) in Norway is a 54 km ski race from Lillehammer to Rena (classic technique) commemorating the feat in 1206 AD of two Birchleg warriors who saved the two year old prince Håkon Håkonsson from his pursuers by carrying him in a dramatic flight over the snowy mountains (figure 1*b*). Today more than 6000 skiers compete annually, each with a 3.5 kg backpack (to symbolize—by largely underestimating it—the child mass). The latest speed-record available online (2002) is plotted in figure 6 as a grey circle. The estimated speed in 1206 can be obtained by moving downward from it (i.e. by keeping the distance constant) and stopping at the level of the lowest iso-cost curve. The newly created point (the filled circle) corresponds to a journey of about 5 h, in comparison with the modern 2 h and 38 min, which constitutes a challenge to the child too.

The Vasaloppet in Sweden is a 90 km ski race from Mora to Sälen commemorating the feat in 1520 of Lars and Engelbrekt who were sent in hot pursuit of Gustav Eriksson Vasa, a 24 year old nobleman from Uppsala and the future King of Sweden, in order to convince him to lead the fight for independence from the Danes. Today the Vasaloppet, which was inaugurated as a race in 1922, is the biggest ski competition in the world. From 1922 to 2004 the average speed-records changed from 3.75 to 6.56 m s^{-1} (www.vasaloppet.se), as represented by the line between the grey squares in figure 6. While other variables (such as technique refinements and enhancements of aerobic training) could also play a role, the vertical span covered by those records (from 1890 skis—which was the actual technology in 1922—to the modern ones) confirms the predictive ability of the metabolic costs measured in this study, both in relative and absolute terms. While the modern record time for the Vasaloppet is 3 h and 48 min, 8 h and 10 min can be estimated (by using the iso-cost curve of the year 1300 ski) for the Lars and Engelbrekt feat in 1520 AD (solid square in the graph).

These two examples illustrate how to use the results from this investigation when one variable among metabolic cost, maximum metabolic power (here assumed to be constant across epochs), speed, distance (or duration) or date of journeys on skis, is unknown. While the main aim was to quantify and mechanically explain the evolution of economy for the locomotion on skis, we need to consider, as briefly mentioned, that thousands of circumpolar dwellers still rely on ‘ancient’ skis (e.g. the Chukchi hunter in figure 1*d*), with the related implications for their cost of transport. Another potential use of figure 6 and current results is the estimation of speed, range or cost for past and future polar explorations on skis.

Our final considerations are about the ‘recent’ introduction of the skating technique (figure 1*e*).

From the present data it is possible to infer the advantage, in terms of maximum sustainable speed, of skating with respect to classical techniques. Whenever the metabolic cost is speed-independent, as also occurs in running and mono-fin swimming (Minetti 2004), the maximum speed ($\dot{s}_{\max}$) can be predicted by knowing the sustainable fraction of the maximum oxygen uptake ($\hat{\dot{V}}O_{2.\mathrm{fract}}$) and the cost of transport (C) and calculating (di Prampero 1986):

$$\dot{s}_{\max} = \frac{\hat{\dot{V}}O_{2\ \mathrm{fract}}}{C}.$$

By applying this equation to the most commonly used classical technique, the diagonal stride (DS) and the skating (SK) technique:

$$\dot{s}_{\max\ \mathrm{DS}} = \frac{\hat{\dot{V}}\mathrm{O}_{2\ \mathrm{fract}}}{C_{\mathrm{DS}}} \quad \text{and} \quad \dot{s}_{\max\ \mathrm{SK}} = \frac{\hat{\dot{V}}\mathrm{O}_{2\ \mathrm{fract}}}{C_{\mathrm{SK}}}$$

$$\text{thus} \quad \frac{\dot{s}_{\max\ \mathrm{SK}}}{\dot{s}_{\max\ \mathrm{DS}}} = \frac{C_{\mathrm{DS}}}{C_{\mathrm{SK}}}$$

(this only applies to comparably long races). The speed gain in skating, as reported in races (e.g. the KönigLudwiglauf, 50 km, and the American Birkebeiner, 55 km) where both techniques are used, is +9.96% (±7.44% s.d., $n=24$), while our prediction (from metabolic costs) is +9.86%. Such a speed gain is (obviously) maintained for all distances, as shown by the two upper curves in figure 6. It is important to remark that the novelty for skating is not confined to the new motion pattern and ski equipment, the processing of the snow track being a fundamental component of it.

The transition from the classic to the skating technique is equivalent to the introduction of gears (or the transition between the ‘Hobby Horse’ and the ‘Bone Shaker’) in cycling (Minetti *et al.* 2001). In fact, the pushing phase of the diagonal stride forces the foot to stop with respect to the ground, thus making the lower limb extend backward, with respect to the body centre of mass, at the same speed of travel, whose increase due to the evolution of skiing causes muscles to contract in a progressively inefficient region of the force/velocity diagram. Pushing sideways at a slower speed while continuously sliding, as in the skating technique, is the solution to an evolutionary dead end, in analogy with cycling. The next step could be to prevent even upper limbs (with the poles) from stopping with respect to the ground.

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APPENDIX A

The following paragraphs further elaborate upon concepts expressed by Minetti (1998); applied here to the estimation of internal exertion, as affected by the extra load (skis and poles). The work necessary to accelerate the limbs with respect to the body centre of mass during locomotion is a concept introduced by Fenn (1930) and successively formalized as mechanical internal exertion (W_{INT}, Cavagna & Kaneko 1977). In a different way to the external mechanical exertion (W_{EXT}), which accounts for the changes in potential and kinetic energies of the body centre of mass with respect to the environment, W_{INT} takes into account the acceleration of body segments, whose movement does not directly result in a change in the centre of mass position. This is particularly the case in terrestrial locomotion, where limbs are moved quasi-reciprocally with respect to the centre of mass.

The mechanical internal work, expressed as J kg^{-1} of body mass and per metre travelled, can be modelled as:

$$W_{\mathrm{int}} = f\bar{s}\left(1 + \left(\frac{d}{1-d}\right)^2\right)q,$$

where f is the stride frequency (Hz), $\bar{s}$ is the average progression speed (m s^{-1}), d is the 'duty factor' (i.e. the fraction of the stride duration at which a single limb is in contact with the ground) and q summarizes the inertial characteristics of the limbs, according to the equation:

$$q = \frac{\pi^2}{4}[(a^2 + r^2)(m_{\mathrm{L}}^* + b^2 m_{\mathrm{U}}^*)].$$

Here, a and r represent the average proximal distance of the limb centre of mass and the radius of gyration about it (both as a fraction of limb length), m_{L}^* and m_{U}^* refer to the fractional mass of the lower and upper limbs, respectively, and b is the upper limb length (as a fraction of the lower one). For humans with fully extended limbs, $q = 0.155$, while its average value for walking and running is 0.1 (Minetti 1998).

The duty factor (d) in the diagonal stride reflects the pushing phase (as a fraction of the stride) of a single lower limb. In this study, we estimated it by

$$d = \frac{1 - Sl_{\mathrm{fract}}}{2},$$

where the slide fraction (Sl_{fract}) is

$$Sl_{\mathrm{fract}} = \frac{l_{\mathrm{stride}} - 1.8}{l_{\mathrm{stride}}},$$

with the stride length (l_{stride}, m):

$$l_{\mathrm{stride}} = \frac{\bar{s}}{f}.$$

The value 1.8 m represents the maximum distance travelled by two steps when no sliding occurs.

Apart from the term b, all the other components of q are affected by the use of skis and poles. The above equations could help us to quantify the increase in the internal work as caused by distal limb loading, after updating the relevant parameters according to the total added mass (L, kg). Coefficient a needs to be changed into:

$$a \rightarrow a + (1 - a)\frac{0.5L}{m_{\mathrm{L}} + 0.5L}.$$

While, for the fractional mass of the lower and upper limbs:

$$m_{\mathrm{L}}^* \rightarrow \frac{m_{\mathrm{L}} + (3/4)0.5L}{m + L} \quad \text{and} \quad m_{\mathrm{U}}^* \rightarrow \frac{m_{\mathrm{U}} + (1/4)0.5L}{m + L},$$

where the total added mass has been unevenly partitioned (three quarters in lower limbs and one-quarter in upper limbs) to consider the different mass of skis and poles.

Coefficient r needs to be the average of the new upper and lower limb radii of gyration:

$$r_{\mathrm{L}} \rightarrow \sqrt{\frac{(m_{\mathrm{L}}/2)(-r_{\mathrm{L}})^2 + (m_{\mathrm{L}}/2)(r_{\mathrm{L}})^2 + (3L/8)(1-a)^2}{m_{\mathrm{L}} + (3L/8)}},$$

and

$$r_{\mathrm{U}} \rightarrow \sqrt{\frac{(m_{\mathrm{U}}/2)(-r_{\mathrm{U}})^2 + (m_{\mathrm{U}}/2)(r_{\mathrm{U}})^2 + (L/8)(1-a)^2}{m_{\mathrm{U}} + (L/8)}}.$$

The present model is applied to all ski models, except for the 2004 AD with skating technique because the motion pattern of that gait is very different from the diagonal stride (and from the running-like limbs oscillation) that is the prerequisite of this model.

The equations above have been used, together with the average stride frequency measured by the inertial sensor and the skis + poles mass as in table 1, to estimate the increase in W_{INT} for each ski model.

APPENDIX B

The following paragraphs further elaborate upon concepts already expressed by Minetti (2004). The speed values in figure 6 were obtained by estimating, for each duration (t, s), the maximum sustainable mechanical effort (Wilkie 1980) as:

$$\dot{W}_{\mathrm{mech}} = A + \frac{B}{t} - \frac{A\tau(1 - \mathrm{e}^{-(t/\tau)})}{t},$$

where A is the maximum long-term mechanical work rate (W), B is the mechanical equivalent of the available energy from anaerobic sources (J) and τ is the time constant (s) describing the inertia of the system. As developed by Wilkie, this equation is accurate for durations ranging from 40 s to 10 min. To take into account the decay of the sustainable maximum oxygen consumption for longer exercise period durations (10 min$<t<$1 h), term A has been multiplied by:

$$\frac{\dot{V}_{\mathrm{O}_2}}{\dot{V}_{\mathrm{O}_2\,\mathrm{max}}} = \frac{940 - t/60}{1000},$$

where the first ratio represents the sustainable proportion of the total metabolic power (Saltin 1973).

We assume here that the efficiency is independent from the exercise duration. To extend it further we used data published by Davies (1981), who reported an available fraction of $\dot{V}_{\mathrm{O}_2\,\mathrm{max}}$of 66 and 47% for an 8 and 24 h exercise, respectively. From his data the new multiplier for term A is:

$$\frac{\dot{V}_{\mathrm{O}_2}}{\dot{V}_{\mathrm{O}_2\,\mathrm{max}}} = \frac{0.085(t/3600)^2 - 3.908(t/3600) + 91.82}{100}.$$

With this inclusion the duration range for accurate speed predictions extends from 40 s to 24 h.

To calculate iso-cost curves the following equation was used:

$$\dot{s} = \frac{3.6}{C}\left(\frac{\dot{W}_{\mathrm{mech}}}{\mathrm{eff}} - \dot{W}_{\mathrm{basmet}}\right),$$

where $\dot{s}$ (km h^{-1}) is the progression speed, eff is the efficiency of muscle contraction (0.25; Woledge *et al.* 1985), $\dot{W}_{\mathrm{basmet}}$ is the basal metabolic power (W) and C is expressed as J m^{-1}. For the final calculations we assumed that $A = 350$ W, $B = 21$ kJ, $\tau = 10$ s and $\dot{W}_{\mathrm{basmet}} = 80$ W to approximate very well conditioned subjects ($\dot{V}_{\mathrm{O}_2\,\mathrm{max}}$of about 65 $\mathrm{mlO_2\,kg^{-1}\,min^{-1}}$). While the first two (or the first and the third) equations are always operating simultaneously, the curves have been coloured to represent the main influencing effect: blue (Wilkie 1980) for 40 s$<t<$10 min, light orange (Saltin 1973) for 10 min$<$ $t<$1 h and green (Davies 1981) for 1 h$>t>$24 h.

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