Biomechanical and physiological determinants of skiing locomotion development

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INTRODUCTION

How far could man travel on snow five thousand years ago? What did man empirically understand to be the limiting factors for his skiing performance, from its very beginning to date? Very little research focused on the biomechanics and physiology of the development of cross-country skiing [1]. In the present study the evolution of skiing locomotion from 3000 BC to date is explored by investigating how humans adapted to move effectively in lands where a cover of snow, for several months every year, prevented from travelling as effectively as on dry ground. Following historical research, a few sets of skis were identified as the 'milestones' of skiing evolution in terms of ingenuity and technology. Their replicas were built and the metabolic energy associated to their use was measured in a climatic-controlled tunnel.

METHODS

Seven sets of skis were tested, covering a span of about five thousand years. Original archaeological specimens could not be used for the present study, so accurate reproductions of the originals were made (Department of Design and Technology – MMU, Cheshire). Experiments took place at the Vuokatti ski tunnel, Finland, where temperature (mean±s.d., air –5.2±1.1 °C, snow -4.5±0.5 °C, n=115) and humidity (83.6±1.4 %, n=115) are monitored and controlled 24 hours a day by a computer controlled air conditioning system. Five healthy adult non-professional skiers took part in the experiments (age 33.8±11.8 years, stature 176±2.8 cm and body mass 73.0±4.8 kg). Participants were requested to adopt two subjectively chosen speeds, the former defined as sustainable for 7 to 8 hours ('migration'), the latter for just 3 to 4 hours ('hunting'). When skiing with the 2004 AD models (classical and skating techniques) participants travelled at two additional faster speeds, the fastest being 70% of their maximum speed. Participants were equipped with a portable metabograph (Cosmed K4b2) that measured their heart rate (HR) (b min^{-1}), carbon dioxide output (VCO2) (l min^{-1}) and oxygen uptake (VO2) (l min^{-1}) on a breath-by-breath basis. Oxygen uptake at rest was measured and was used to calculate the net oxygen consumption for skiing with each set of skis. VO2 measurements (mlO_2) were converted into equivalent units (J) according to the obtained respiratory quotient coefficient [2]. The metabolic cost of skiing (J/(kg m)) 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 by the (body) mass. Kinematic variables relative to the skiers' movement were recorded by means of inertial sensors (MT9, Xsens) placed on the skiers' right thigh and shank. A stride has been defined as the distance/time between the ends of two successive kicks performed by the same leg. Euler angles from the data recorded on the legs were used to calculate the stride frequency (Hz) and estimate the internal work [3]. Ski friction was measured for all the pairs of skis by means of two inertial sensors during passive deceleration manoeuvres.

RESULTS AND DISCUSSION

The decision to perform the experiments in the ski tunnel allowed recording data in standard conditions, hence reducing to a minimum the variability due to temperature changes.

Results from the present study show that: a) for the same amount of metabolic power today it is possible to travel at twice the speed of ancient times (Figure 1) and b) the cost of transport is speed-independent for each ski model. By combining this finding with the physiological relationship between time of exhaustion and the fraction of sustainable metabolic power [4], a prediction of the maximum skiing speed according to the distance travelled is provided for all past epochs and can predict with a good precision modern competitions.

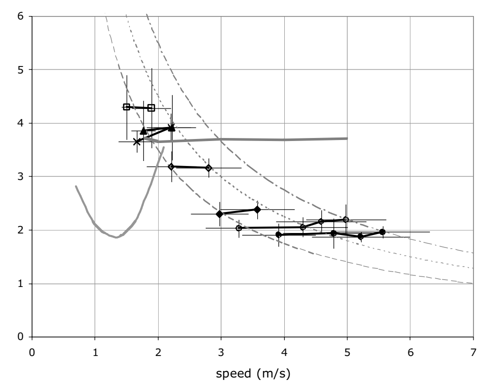

Figure 1: the metabolic cost (J/kg m) of skiing is here plotted against the speed for all the investigated skis. For sake of comparison, lines reporting walking and running costs are shown (walking in the tunnel is represented by the grey circle). Iso-power curves show the power chosen by participants.

Total stride length increased from 14.0% to 60.5% in the chronological ski sequence. We did not directly measure the 'body centre of mass' part of the external mechanical work, but it is expected to decrease 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. This was confirmed (-86.8%) when we calculated an 'estimated version' of it by subtracting from the measured cost the metabolic equivalent of both the work against friction and the internal work.

CONCLUSIONS

Results from the present study will help historians to understand the times needed and distances covered during migrations in cold regions in the past. Our research shows that the performances of two legendary historical journeys (1206 and 1520 AD) on snow, the performances of races originating from them (Birkebeiner and Vasaloppet) and those of other modern competitions (skating vs. classical techniques) are well predicted by the evolution of skiing economy.

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