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PHYSIOLOGIE ET BIOMÉCANIQUE DU SKI-ALPINISME

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UNIL | Université de Lausanne
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Table of contents

Abstract

Introduction: Ski mountaineering is an increasingly popular winter sport and leisure activity. Elite athletes practice this sport with a high level of professionalism, but so far little scientific evidence was available to support their approach. The main aim of this work was to develop a specific knowledge about ski mountaineering, allowing providing specific recommendations for the practice.

Methods: First we investigated energy cost (EC) and vertical energy cost (EC_v). These two parameters were estimated with oxygen uptake, at different gradients (7 to 33%) and different speeds (2 to 7 $km \cdot h^{-1}$) on treadmill with roller skis and on snow with ski mountaineering gear. Then we assessed energy expenditure (EE) during a long duration ski mountaineering event by measuring heart rate and altitude all along the race and associating them with an EE. The EE was compared with the energy intake during the race. Hydration level was estimated by comparing body weight immediately before and after the race. The energy intake during the 4 days preceding the race was estimated with food diaries and compared with the guidelines.

Results/discussion: EC and EC_v of ski mountaineering were very high and varied with gradient and speed. EC_v decreased between 7 and 33% and with increasing speed at steep gradients. For a 5 h 51 ± 53 min race, the mean EE was 22.6 ± 2.6 MJ. The energy intake covered 20 ± 7% of the EE and was about 14% lower than the recommendations. No significant dehydration was observed. For the longest (53 km) race, we can extrapolate the EE as about 40 MJ. Before the race the energy intake and especially the carbohydrate intake were far under the guidelines (83 ± 17% and 46 ± 13% of the recommendations).

Conclusions: EC and EE of ski mountaineering are very high. To minimize the EE to reach the top of a mountain and optimize the performance, the skier should choose a steep gradient and combine this steep gradient with a fast speed. The CHO intake should be increased during but, also before the race while the fluid intake seemed to be adequate.

Résumé

Introduction : Le ski-alpinisme est un sport d'hiver qui s'est particulièrement développé durant les dernières décennies : de plus en plus de personnes pratiquent cette activité dans un cadre de loisirs et de plus en plus d'athlètes d'élite prennent part à des compétitions qu'ils préparent avec un haut degré de professionnalisme. Cependant, les connaissances scientifiques restent limitées et les athlètes ne disposent pas de recommandations précises et spécifiques. Le but principal de ce travail est donc de développer un savoir spécifique sur le ski-alpinisme, ce qui devrait permettre d'établir des recommandations pour la pratique.

Méthode : Le coût énergétique (CE) et le coût énergétique vertical (CE_v) du ski-alpinisme ont été calculés en mesurant la consommation d'oxygène à différentes pentes (7 à 33%) et vitesses (2 à 6.8 $km \cdot h^{-1}$) sur tapis roulant avec des skis à roulettes et sur le terrain avec des skis de randonnée. Ensuite, la dépense énergétique (DE) d'une course de ski-alpinisme de longue durée a été évaluée en mesurant la fréquence cardiaque et l'altitude en continu. La DE a été comparée à l'énergie consommée par les ravitaillements. Des carnets alimentaires ont permis d'estimer la consommation d'énergie (boissons et nourriture) pendant les 4 jours précédant la course.

Résultats/discussion : Le CE du ski-alpinisme est très élevé. Le CE_v diminue entre 2 et 6 $km \cdot h^{-1}$ et entre 7 et 33%. Pour une course de 5 h 51 ± 53 min (26 km), la DE était de 22.6 ± 2.6 MJ, alors que, pour le grand parcours de la Patrouille des Glaciers (53 km), elle serait d'environ 40 MJ. La consommation d'énergie, pendant le parcours de 26 km, couvrait 20 ± 7% de la DE et était inférieure de 14% aux recommandations, alors qu'aucune déshydratation significative n'était constatée. Les jours précédant la course, la consommation d'énergie et surtout d'hydrates de carbone était bien inférieure aux quantités recommandées (83 ± 17% et 46 ± 13% des recommandations).

Conclusion : Le CE et la DE étaient très élevés. Pour minimiser la dépense lors d'une ascension, il faut combiner pente et vitesse élevées. La consommation d'hydrates de carbone devrait être massivement augmentée avant et pendant la course, alors que l'hydratation semble adéquate.

Abbreviations

ACSM: American College of Sports Medicine

ATP: adenosine triphosphate

CHO: carbohydrate

EC: energy cost of locomotion

EC_v: vertical energy cost of locomotion

HR: heart rate

HR_{max}: maximum heart rate

PDG: Patrouille des Glaciers

MET: metabolic equivalent of task

MET_{max}: maximal metabolic equivalent of task

m_{vert}: vertical meter

PAL: physical activity level

Race A: shorter race route of the Patrouille des Glaciers, from Arolla to Verbier

Race Z: longer race route of the Patrouille des Glaciers, from Zermatt to Verbier

SD: standard deviation

$\dot{V}O_{2max}$: maximal oxygen uptake or maximal oxygen consumption

vt1: first ventilatory threshold

vt2: second ventilarory threshold

$\%\dot{V}O_{2max}$: percentage of maximal oxygen uptake

1. Introduction

1.1 Endurance performance

Endurance exercise can be defined as cardiovascular exercise and/or locomotion that is performed for an extended period of time (1). Endurance exercise involves complex integration of multiple physiological systems but despite its multifactorial nature, this type of exercise is characterized by one simple requirement: the ability to sustain repeated muscle contractions over a long period of time. The aim of endurance training is to increase the level of power output that can be sustained during a prolonged period of time.

Popular endurance activities like running, cycling, cross-country skiing, or swimming during a prolonged period of time have been thoroughly investigated. Indeed, many scientific studies were performed on these activities and the athletes can rely on considerable scientific knowledge. However one of these endurance activities, ski mountaineering (for a description see appendices 1 and 2), was poorly investigated so far. The basic principles and the main determinants of performance are the same for all endurance sports. However it is of interest to have specific information about each type of exercise, because of its particularities. This is especially the case for ski mountaineering as it has some special characteristics, which are different from other endurance activities: 1) the cold and snowy environment of mountains in winter, 2) hypoxia induced by high altitude, 3) the fact that the races include different types of locomotion (skiing uphill, skiing downhill, running, walking, steep climbing, cross-country like skiing) and 4) the fact that ski mountaineering races are often team events.

1.2 Main determinants of endurance performance

The maximal (peak) oxygen uptake ($\dot{V}O_{2max}$), the fractional utilization of $\dot{V}O_{2max}$ (linked with the concept of lactate threshold) and the exercise economy are often regarded as the major determinants of endurance and ultra-endurance (2) performance (Figure 1). Other factors like the fuel provision, the core temperature, the hydration and psychological and tactical parameters should also be taken into account.

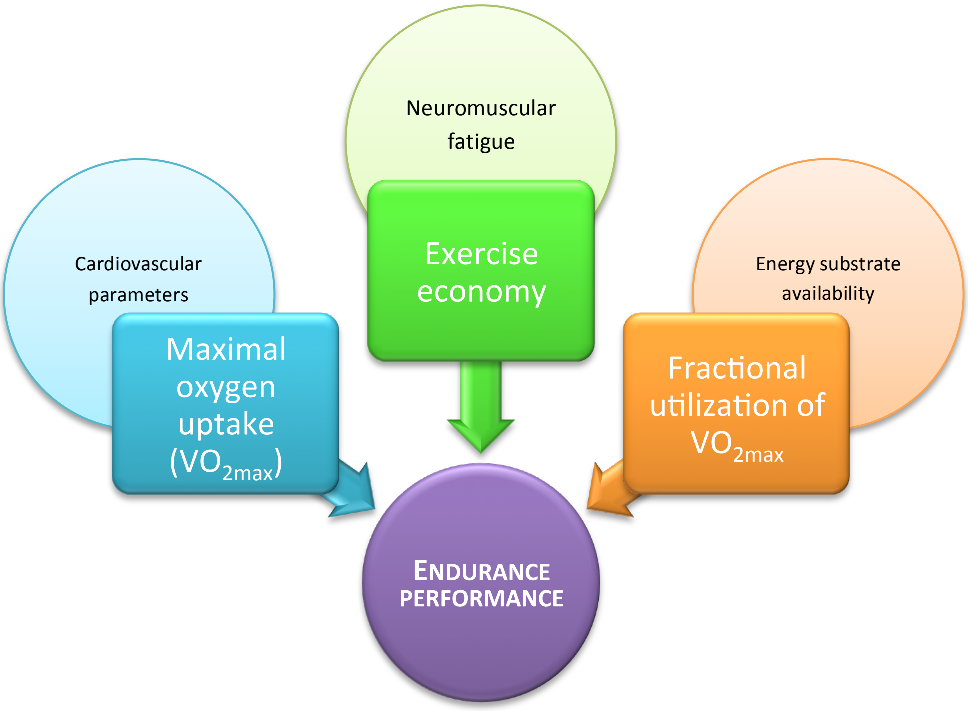


Figure 1: The main physiological determinants of endurance performance. Traditionally, $\dot{V}O_{2max}$, exercise economy and fractional utilization of $\dot{V}O_{2max}$ are considered as the main determinants of endurance performance. These three main determinants are influenced by cardiovascular parameters (mainly $\dot{V}O_{2max}$), neuromuscular fatigue (mainly exercise economy) and energy substrate availability (mainly fractional utilization of $\dot{V}O_{2max}$).

1.2.1 Maximal oxygen uptake

$\dot{V}O_{2max}$ refers to the highest rate at which the body can take up and consume oxygen during intense exercise (3). $\dot{V}O_{2max}$ can be expressed either as an absolute rate (in $l{\cdot}min^{-1}$) or as a relative rate (in $ml{\cdot}kg^{-1}{\cdot}min^{-1}$). For weight-bearing sports such as walking, running or ski mountaineering, relative rates are usually used since it describes the metabolic power available for transporting body mass. By dividing the relative $\dot{V}O_{2max}$ by 3.5, the maximal metabolic equivalent (MET_{max}) can be determined, rendering the description of metabolic scope independent of body mass (4).

To produce repeated muscle contractions over a prolonged period of time, it is necessary to sustain energy delivery. Energy is made available for muscles through adenosine triphosphate (ATP) that is hydrolysed to release the energy necessary for cross-bridge cycling and other cellular activity. The limited stores of ATP must be rapidly replenished (5). To achieve that, three metabolic pathways are available: the phosphagen system (i.e. phosphocreatine), anaerobic glycolysis and mitochondrial respiration. The first two can release energy with high rates but only for short periods (6). So for ATP regeneration and energy release during prolonged periods of time, mitochondrial respiration is predominant. This pathway is aerobic as it requires continuous oxygen availability. So enhanced oxygen delivery during exercise improves mitochondrial respiration and thus the capacity for endurance exercise (6).

$\dot{V}O_{2max}$ is determined by the cardiac output and by the oxygen extraction that is defined as the arterio-venous oxygen difference, like expressed in Fick's equation: $\dot{V}O_{2max} = \dot{Q} \cdot (C_aO_2 - C_vO_2)$, where $\dot{Q}$ is the cardiac output, C_aO_2 the arterial oxygen content, C_vO_2, the mixed venous oxygen content and $C_aO_2 - C_vO_2$, the oxygen extraction. There are numerous limiting factors of $\dot{V}O_{2max.}$ As already said cardiac output is, in conditions of normoxia, the major determinant. However alveolar ventilation, pulmonary diffusion, blood volume and haematocrit, muscle diffusion capacity, capillary density and mitochondrial enzyme levels also influence the $\dot{V}O_{2max}$ (3).

The best elite athletes involved in endurance sport can exhibit $\dot{V}O_{2max}$ higher than 6 $l \cdot min^{-1}$ (7), while one of the highest relative value ever reported is the 96 $ml \cdot kg^{-1} \cdot min^{-1}$ from the cross-country skier Bjørn Dæhlie. Women have lower $\dot{V}O_{2max}$ than men (8-10), because of their greater fat stores, lower haemoglobin levels and lower cardiac output; $\dot{V}O_{2max}$ tends to decrease with age (9) and decreases at high altitude (11).

$\dot{V}O_{2max}$ can be improved through training but remains mainly genetically determined. Average sedentary people can improve their $\dot{V}O_{2max}$ by 15-20% through training (9) and in highly trained athletes, the $\dot{V}O_{2max}$ cannot be much improved (12). Bouchard et al. (1999) showed, in a study on 483 sedentary people, that after 20 weeks of endurance training, the improvement was limited to 0.4 ± 0.2 $l \cdot min^{-1}$: 7% of subjects showed a gain of 0.1 $l \cdot min^{-1}$ or less (low responders) while 8% of subjects improved by 0.7 $l \cdot min^{-1}$ or more (13). So the trainability of $\dot{V}O_{2max}$ is limited and varies a lot from one individual to another and is also genetically determined (13).

Already in the 70s, Costill et al., found a strong correlation between $\dot{V}O_{2max}$ and 10-mile run times (14). Similarly, Maughan (1983) et al. showed a strong correlation between $\dot{V}O_{2max}$ and marathon performance (15). Similar results were pointed out for triathlon (16), cross-country skiing (17) and mountain biking (18). Duc et al. (2011) showed that $\dot{V}O_{2max}$ was also significantly correlated with the performance during a middle long duration (1 h 41 min ± 11 min) ski mountaineering race (19).

$\dot{V}O_{2max}$ is often used to compare endurance athletes. This is partly justified, but $\dot{V}O_{2max}$ is not sufficient to determine the performance level of an athlete. In other words, a high $\dot{V}O_{2max}$ is necessary for optimal endurance performances but it is not sufficient and two athletes with the same $\dot{V}O_{2max}$ can perform at very different levels (Figure 2, comparison Athletes A and B).

1.2.2 Exercise economy

The exercise economy is the energy (or oxygen consumption) required to perform a given workload or power output (20). As illustrated in the figure 2: depending on their economy of movement, two athletes with similar $\dot{V}O_{2max}$ (Athletes A and B) can have different endurance performances (e.g. running speed) and, athletes with different $\dot{V}O_{2max}$ can have similar performances in terms of workload (or time, during a race) (Athletes A and C). The energy expenditure of a more economical athlete will be lower for the same performance, or for the same energy expenditure, he will get a better performance. In highly trained runners with comparable high $\dot{V}O_{2max}$ values, 65% of the variation observed in race performance (over 10 km) can be explained by variation in running economy (21). The inter-individual variation is less important in cycling, but it remains a predictor of the performance (22).

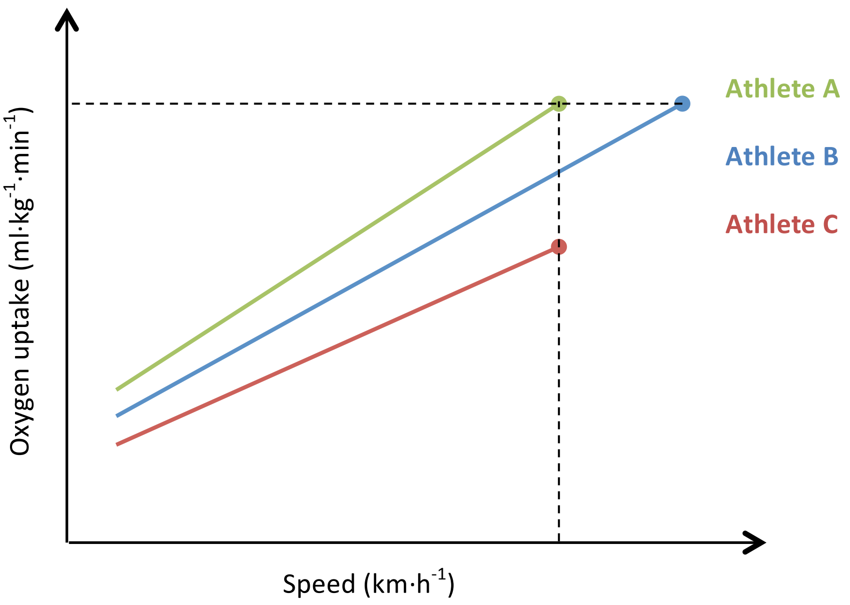


Figure 2*:* Speed vs. oxygen uptake relationship for three different athletes during a maximal running test on motorized treadmill. For submaximal intensities, oxygen uptake increases linearly with increasing speed up to a plateau and/or a maximal value ($\dot{V}O_{2max}$). Athlete A and Athlete B have the same $\dot{V}O_{2max}$ but different maximal speeds: Athlete B is able to run faster than athlete A, her/his locomotion is more economical and (s)he needs less energy for the same workload. Athlete A and Athlete C have the same maximal speed, but Athlete C has a lower $\dot{V}O_{2max}$. The locomotion of Athlete C is more economical than the locomotion of Athlete A. Athlete C consumes less oxygen for the same (maximal) speed. These two comparisons show that $\dot{V}O_{2max}$ is not sufficient to determine the endurance performance of an athlete.

To express the economy of a given type of locomotion, the most frequently used variable is the energy cost (23, 24). The energy cost of locomotion is the amount of energy required to cover a given distance (EC, generally expressed in $J \cdot kg^{-1} \cdot m^{-1}$) or, in the case of vertical energy cost, to gain 1 m of altitude (m_{vert}) (EC_{vert} generally expressed in $J \cdot kg^{-1} \cdot m_{vert}^{-1}$). EC and EC_{vert} allow quantifying how economical a given locomotion is and comparing different types of locomotion or different individuals. When studying vertical displacements like in ski mountaineering a third important parameter is mechanical efficiency, which quantifies the effectiveness in transforming metabolic energy in vertical displacement (24, 25). In case of locomotion along an upward gradient the EC_{vert} and mechanical efficiency are more representative of the overall economy of the locomotion than EC, because the main goal is to reach a place located at higher altitude and not to cover a given distance (26).

Energy cost is influenced by several factors including: biomechanical predispositions (e.g. moment arm and Young's modulus of the Achilles tendon for economy of running (27, 28)), neuromuscular recruitment of muscles or muscle fibres (29, 30), training (type, history, frequency, etc. (24, 31, 32)) and cardiorespiratory parameters like blood flow or mitochondrial efficiency (33-35). The figure 3 summarizes the factors that may influence the exercise economy with the example of running.

For long duration exercise, it should also be noted that the energy cost at a specific speed increases during exercise and is substantially increased at the end of long-distance running (36) and triathlon events (37) due to neuromuscular fatigue. However Vernillo et al. (2014) showed that despite the neuromuscular fatigue at the end of a long duration mountain ultra-marathon (330 km with 24,000 m positive and negative elevation change) (38), the uphill-running pattern of runners was changed after the race for a more economical one (39) while the EC of downhill running had increased (40).

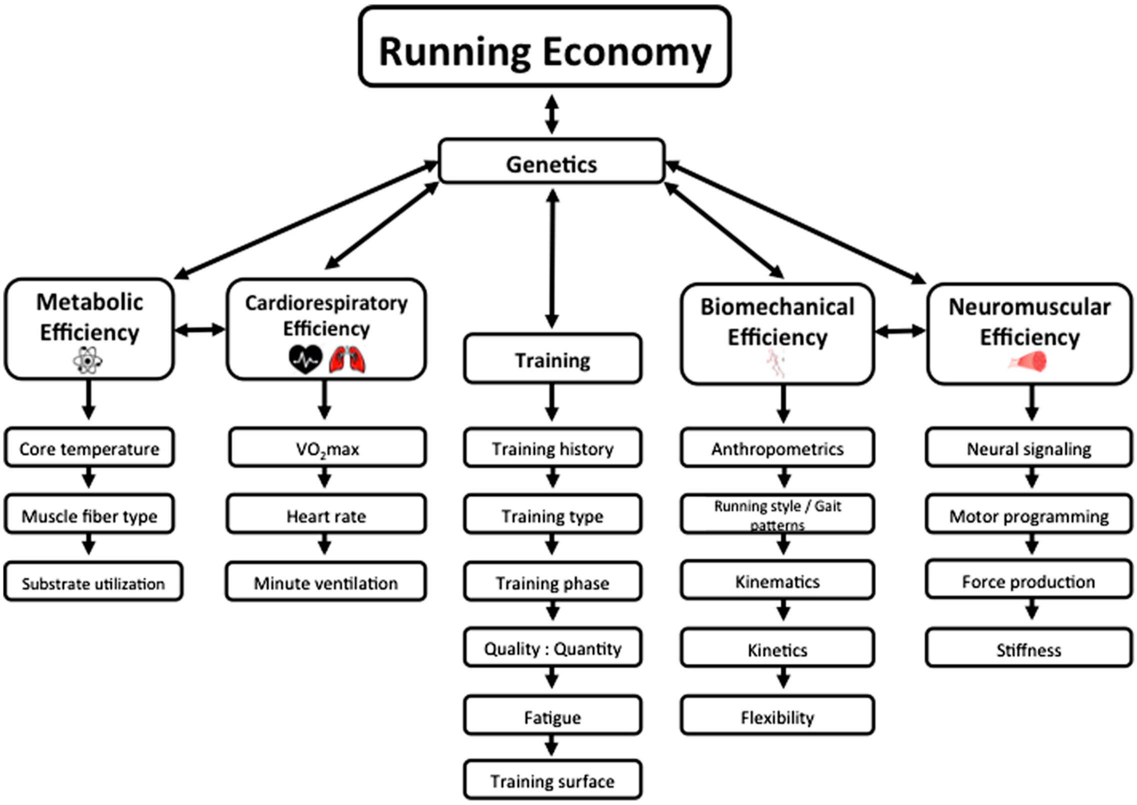


Figure 3: Factors affecting running economy according to Barnes et al. (41).

Exercise economy and EC of locomotion have been extensively studied for many types of human locomotion (walking, running, cycling, skating, rowing, swimming, cross country skiing, etc.) (23, 42-45). Tosi et al. (2009 and 2010) worked on the EC of ski mountaineering and gave the first quantitative description of EC for this type of sport. First, in a field study (46) on packed snow and at a slope of 21%, they observed the changes of EC with speed (at preferred speed, at lower pace than preferred speed and at higher pace than preferred speed) and with ankle loads (0, 0.5, 1 and 2 kg). The mean EC at the preferred speed was 10.6 ± 0.4 $J \cdot m^{-1} \cdot kg^{-1}$, higher than EC for walking or snowshoeing at the same speed and slope gradient. They found that EC increases with speed and with ankle load, but it appeared that the effect of ankle load would be negligible for recreational skiers (much weaker effect than for walking), while it should be taken into account for elite skiers. 1 kg added to an 80 kg subject resulted in an increment of about 2% in EC. Then, in a laboratory study (47) with roller skis on a motorized treadmill, they tested different speeds (between 1.4 and 6 $km \cdot h^{-1}$)

at a slope gradient of 21%. They found a minimum EC (10.6 ± 0.2 $J \cdot m^{-1} \cdot kg^{-1}$) at about 3.5 $km \cdot h^{-1}$ and a maximum mechanical efficiency (about 0.25) at about 4.5 $km \cdot h^{-1}$. These data were similar to what they found on snow and suggested that the preferred speed on snow minimizes the EC and maximizes the mechanical efficiency. In addition, they observed that the taller athletes were more economical than the shorter athletes; probably because each step is energy demanding and taller subjects needed fewer steps to cover the same distance.

1.2.3 Fractional utilization of $\dot{V}O_{2max}$ (lactate threshold)

An exercise at the intensity of $\dot{V}O_{2max}$ can be sustained during 6 to 10 min (48). So during endurance exercise lasting more than 10 min the oxygen uptake is lower than $\dot{V}O_{2max}$ and the sustainable exercise intensity can be expressed in percentage of $\dot{V}O_{2max}$ (%$\dot{V}O_{2max}$). Therefore it is important to know how long an athlete can perform at a given %$\dot{V}O_{2max}$ or at which %$\dot{V}O_{2max}$ he can perform for a given exercise duration to predict the performance. The capacity to maintain a high workload (high fractional utilization of $\dot{V}O_{2max}$) for extended periods is therefore an important prerequisite for endurance performance (Figure 4).

To support ATP regeneration and energy release, the body depends on lipids and carbohydrate (CHO) (blood glucose and glycogen) as energy substrates. The substrate used varies with exercise intensity (49): with increasing intensity, there is a shift from more lipids to more CHO utilization. Indeed, CHO show higher rates of ATP production than lipids, which means that more energy is available per unit of time. Substrate utilization is also determined by exercise duration (50), fitness level (51), CHO stores (52) and nutrition before and during the race (amount, composition and timing) (52-54).

Traditionally, lactate is considered as the by-product of glucose utilization by muscle cells and blood lactate accumulation indicates that glucose is the main fuel oxidized. However it is known today that lactate can also be used as a gluconeogenic precursor or as substrate for oxidation in muscles, brain, heart or liver (Lactate Shuttle concept) (55). The lactate threshold is the maximum steady state exercise intensity that can be maintained without blood lactate accumulation. Glycogen (store of glucose) is stored in muscles and liver, but its amount is limited (56) and after 1 to 2 h of steady-state exercise over the intensity of lactate threshold, glycogen stores are depleted. The athletes have to slow down or even to stop exercising. One of the aims of endurance training is to spare glycogen by increasing the reliance on lipids at workload of same intensity. It means that the exercise intensity at the lactate threshold should become closer to the $\dot{V}O_{2max}$ intensity and that for the same intensity, the athlete uses more lipids and less CHO than before training and that with the same CHO consumption, (s)he will be able to perform a higher workload.

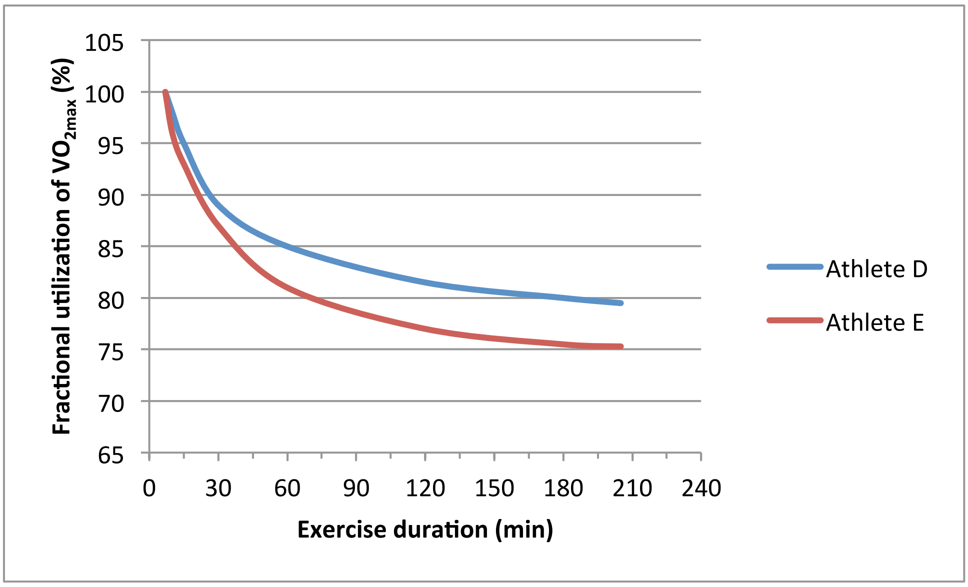


Figure 4: Exercise duration vs. maximum sustainable exercise intensity (in %$\dot{V}O_{2max}$) for two athletes with different capacities to sustain high fractions of $\dot{V}O_{2max}$ for extended periods of time. For duration of about 7 min, the maximum sustainable exercise intensity is about 100% of $\dot{V}O_{2max}$. The maximum sustainable exercise intensity decreases with increasing duration. Athlete D is able to sustain a higher fraction of $\dot{V}O_{2max}$ than Athlete E for each duration. So even if they have similar $\dot{V}O_{2max}$ and exercise economy, the endurance performance of Athlete D will be better.

The concept of lactate threshold is closely linked to other thresholds that are measured with gas exchange: the first and second ventilatory thresholds (vt1 and vt2) that allow determining critical exercise intensities and comparing athletes before and after training and also with each other. The thresholds are useful because they allow to assess the 'metabolic state' of the body at different exercise intensities and to estimate how long the athlete can sustain an exercise at a given intensity.

The concept of critical power should also be mentioned, it represents the maximum power that can be sustained during a prolonged period of time (e.g. 60 min) without fatigue and is therefore an index of the capacity to perform work over a long period of time (57)

Intensity at lactate threshold was shown to be correlated with the performance in cycling time trial (58), in marathon running (59) or in 5 km to 10 miles running (60). Duc et al. (2011) (19) showed that in addition to $\dot{V}O_{2max}$, race performance in ski mountaineering is significantly correlated with oxygen uptake at vt1 and vt2.

1.2.4 Adequate fuel provision

1.2.4.1 Energy expenditure for multi-hour events

Energy expenditure can be considered as the product of EC and distance or as a function of exercise intensity and duration. Energy expenditure is of major interest for endurance or ultra-endurance events, because the long distances and durations imply high energy expenditure.

Additionally to the energy expenditure, the metabolic cost of an activity can be estimated in METs (metabolic equivalent of task) that express the energy cost of physical activities as a multiple of the resting metabolic rate (4), and as physical activity level (PAL), defined as daily total energy expenditure divided by basal metabolic rate. In the general population, the maximal limit for a sustainable lifestyles is a PAL of 2.0-2.5 (61), while elite endurance athletes, during multi-day events such as the Tour de France may reach values up to 4-5 (62)

Kimber et al. (2002) and Barrero et al. (2015) showed that the average energy expenditure for a triathlon ironman (3.8 km swimming, 180 km cycling and 42 km running) is between 40 (63) and 46

MJ (64), while Saris et al. (1989) found that cyclists who participate in the Tour de France have a mean daily energy expenditure of 25 MJ and reach 33 MJ on mountain stages (65). Cross-country skiers expend between 13 and 15 MJ for a 50 km race (66).

The environment of the latter sport is more similar to the environment of ski mountaineering racing than cycling or triathlon, but the duration is shorter than most of the more famous team races (for more details about ski mountaineering races, see Appendix 3 and 4). Duc et al. (2011) (19) measured heart rate (HR) and speed during a 1 h 41 min ± 11 min ski mountaineering race. The exercise intensity was estimated with HR zones determined during a maximal field test. They observed that the intensity in a middle long individual race is high, with a large fraction of time spent around the vt2 and an average HR of 93 ± 2% of maximum HR (HR_{max}). Similarly, Schenk et al. (2011) (67) measured the HR of athletes during a 2 h 42 min ± 23 min ski mountaineering race. Their conclusions were very close to what was shown by Duc et al.: a large fraction of time was spent around vt2 at an average HR of 87 ± 2% of HR_{max}. Thus, ski mountaineering racing can be considered as very strenuous. These high exercise intensities combined with the long duration of ski mountaineering team races should imply very high energy expenditure, but up to now this was not quantified.

1.2.4.2 Energy intake

For endurance activities with high levels of energy expenditure, energy intake is an important variable to be considered when devising strategies for optimizing performance. High exercise intensities over prolonged periods imply high CHO and also lipid oxidation rates. CHO and lipids availability are thus important determinants of energy expenditure. Therefore it is paramount that athletes use optimal nutritional strategies, not only to manage intake during exercise, but also before exercise, to optimize storage, and after exercise, to optimize refuelling. If the lipid stores are almost unlimited and sufficient for lipid supply for energy production during exercise lasting several hours, the stored CHO (glycogen) is limited and requires frequent refuelling to maintain high exercise intensity during a long duration effort and to avoid hypoglycaemia (68). Low muscle glycogen stores, with dropping blood glucose levels can cause performance decreases, subjective feelings of low levels of energy, sensation of heavy legs, excess fatigue, loss of concentration, irritability, dizziness and fainting (69, 70). Therefore it is important to ensure glycogen store fuelling and refuelling and it is better to start a race with full stores, especially since the capacity to eat and process food during a race is limited.

There is a plethora of literature on sports nutrition, and several scientific and sports organizations such as the American Dietetic Association (ADA), the Dieticians of Canada (DC) and the American College of Sports Medicine (ACSM) (71, 72), the International Olympic Committee (IOC) (73) and the International Society for Sport Nutrition (ISSN) (74, 75) have published recommendations and guidelines on energy intake before, during and after exercise (76). The main nutritional guidelines for endurance activities are always about CHO intake before, during and after exercise: high CHO intake is recommended (69). Among athletes, actual nutritional behaviour does not always comply with the official recommendations, because of a lack of knowledge (77), mistaken beliefs, lack of interest or motivation, practical problems, or perhaps intuition (78).

Additionally to the energy function, macro and micro nutrients from food have different functions in the body and deficits should be avoided. For instance, Diaz et al. (2010) (79) considered a 2 days ski mountaineering race and noted the great importance of the nutrition (energy intake, macronutrients, vitamins A and B, Na, Zn and Fe) to optimize performance and avoid injuries by increasing the antioxidant status and decreasing muscle damage.

1.2.5 Core temperature

During exercise, muscle contractions produce excess body heat and maintaining normal body temperature becomes a priority to maintain health (80, 81) and optimize performance (82). Body temperature over 40°C may result in heatstroke (81). Different mechanisms exist to eliminate excess heat: conduction, which refers to heat that flows from a warmer to a cooler object by direct contact (e.g. skin in contact with the ground); convection, which involves heat transfer via air (or water) circulation at the body surface; radiation, which arises through the transmission of infrared waves, and evaporation, which occurs via liquid (e.g sweat) at the skin surface. When exercising at low or moderate intensity in cool and dry environments, heat loss occurs mainly through conduction, convection and radiation. As environmental heat stress and exercise intensity increase, evaporation of sweat becomes the predominant mechanism for body heat dissipation (81).

Several factors affect heat balance in terms of both heat production and efficiency of heat loss mechanisms: exercise intensity (higher energy production induces higher heat production), wind, environmental temperatures, cloud cover, clothing, heat acclimatization and hydration (83, 84).

In winter sports like ski mountaineering, it is more likely that the athletes encounter extreme cold than extreme warm conditions and overheating. In cold conditions the main danger is that the rate of heat loss from the body exceeds the rate of body heat production, causing the body temperature to fall and possibly ending in hypothermia (85). But as ski mountaineering is a very strenuous and intense activity (19, 67), the important heat production should balance the heat loss and hypo- and hyperthermia should be limited.

1.2.6 Hydration

High sweat rates imply loss of water and electrolytes from the body and if it is not associated with sufficient fluid refuelling by drinking, it may result in dehydration. Adequate fluid ingestion is important for performance but also to maintain a proper fluid homeostasis and to guarantee good health during endurance events (64, 86). Already a 1% reduction of body weight because of fluid loss can be associated with a core body temperature increase of 0.25°C and a HR elevation of 1 to 10 beats per min (87-89). Core temperature and HR increased proportionally with dehydration while stroke volume decreased also proportionally, resulting in a performance decrease (90, 91). In endurance sports with races lasting several hours there is a risk for excessive dehydration that can imply, in extreme cases, life-threatening complications (92).

The guidelines of the ACSM indicate that endurance athletes should limit body mass losses from sweating to 2-3% of body mass (68, 93). So it is important to start races in euhydration and to drink enough and frequently during races (71).

On the other hand, Zouhal et al. (2011) (78) showed that the fastest runners were also those who lost more weight during the race, while Beis et al. (2012) (94) showed that the most successful marathon runners loose more than 2-3% of body weight during a marathon: that goes against the finding that a 2% body weight loss during exercise impairs athletic performance and contradicts the usual recommendations. Noakes et al. (2002 and 2003) even demonstrated that overhydration during a race can cause hyponatremia leading to severe and potentially life-threatening health problems (95, 96).

Another point is that dehydration is one of the main causes of gastrointestinal distress during endurance activity (97).

For ski mountaineering races that take place during winter, the low temperatures and air dryness bring the sweat loss down compared to other events of same duration in warmer and more humid conditions. However in altitude diuresis is increased and thirst impaired (66, 98). Furthermore, respiratory water loss is greater in altitude than at sea level due to increased ventilation and low air humidity. Respiratory water loss can be as high as 1.90 $l \cdot day^{-1}$ for men (99) and 0.85 $l \cdot day^{-1}$ for women (100).

1.2.7 Other factors

Other non-physiological factors influence the performance in endurance e.g. psychological factors like mental or attitudinal skills and characteristics of the athlete, for instance confidence, goal-setting, the use of self-talk or anxiety (101, 102) or tactical factors like pacing, but we will not go into detail about these non-physiological factors.

1.3 Aims and structure

1.3.1 Aims

Ski mountaineering is an increasingly popular winter sport and leisure activity, especially in the European Alps. Increasing numbers of people practice this activity for leisure, and also competitive ski mountaineering has gained in popularity. There are now many regional, national and international events, including European and World Championships. Elite athletes practice this sport with a high level of professionalism, but as yet without much scientific evidence to support their approach, as illustrated by a scant literature on this particular mode of locomotion.

So the knowledge about ski mountaineering is progressively expanding, but there are still a lot of unknowns and the recommendations for the good practice and the optimization of performance has to be found in papers or guidelines about other endurance sports, like cycling, long distance cross-country skiing, trail running or ultra-marathon running. Those guidelines stay unspecific and neglect some important features like altitude, environment or locomotion types. This thesis will try to enlarge the knowledge about ski mountaineering such as to allow formulating ski mountaineering specific practical recommendations.

Project	Aims
Optimal slopes and speeds in ski mountaineering – a laboratory study	• Calculation of EC, EC_v and mechanical efficiency at different speeds and slope gradients • Determination of the effect of speed and of slope gradient on EC, EC_v and mechanical efficiency • Determination of optimal speed and slope gradient, if they exist • Determination of the effect of speed and of slope gradient on biomechanical parameters (stride length and frequency, relative thrust phase duration)
Optimal slopes and speeds in ski mountaineering – a field study	• Calculation of EC, EC_v and mechanical efficiency at different speeds and slope gradients (including a slope gradient >24%) • Comparison with roller skiing • Determination of the effect of speed and of slope gradient on EC, EC_v and mechanical efficiency • Determination of optimal speed and slope gradient, if they exist • Determination of the effect of speed and of slope gradient on biomechanical parameters (stride length and frequency, thrust phase duration and relative thrust phase duration)
Energy expenditure of extreme competitive mountaineering skiing	• Description of a long duration ski mountaineering race • Estimation of the energy expenditure of a long duration ski mountaineering race • Calculation of the EC during a long duration ski mountaineering race • Measurement of the exercise intensity during a long duration ski mountaineering race • Estimation of the energy intake and energy balance during a long duration ski mountaineering race • Estimation of the hydration status after a long duration ski mountaineering race • Determination of the main determinants of the performance in a long duration ski mountaineering race
Nutritional behaviour and beliefs of ski mountaineers – a semi-quantitative and qualitative study	• Monitoring of the pre-competition nutritional practice • Determination of the main beliefs and knowledge about pre-race nutrition • Comparison of the practice with the beliefs and knowledge and with the recommendations • Comparison of the food behaviour between participants in longer and shorter races

Table 1: Aims of the different protocols

1.3.2 Structure

Four different studies were performed for this thesis (Figure 5).

Two of them were about the EC and biomechanical aspects of ski mountaineering. The specific introductions and the extensive methods, results and discussions can be found in the appendices at the end of the thesis (Appendices 5 and 6).

The two other studies were observational studies, which looked at different aspects of a ski mountaineering event: the race itself and its energy aspects, and the nutrition before the race. Again the specific introductions and the extensive methods, results and discussions can be found in the appendices at the end of the thesis (Appendices 7 and 8).

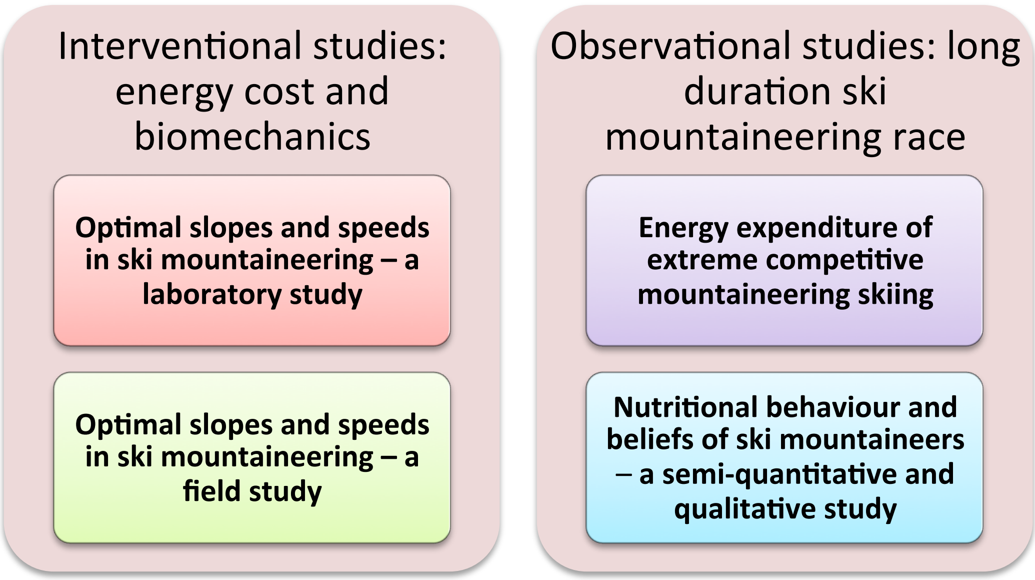


Figure 5: Structure of the thesis

In the main part of the thesis the results of all the four studies will be discussed in common, while each study is presented individually in the appendices.

2. Results

2.1 Optimal slopes and speeds in ski mountaineering – a laboratory study

Introduction: The purpose of this study was to estimate EC, EC_v and mechanical efficiency and the main stride parameters during simulated ski mountaineering at different speeds and slope gradients. We finally aimed to identify an optimal speed and slope gradient that maximizes performance.

Methods: 12 subjects were tested with roller skis on a motorized treadmill at three different slope gradients (10, 17 and 24%) each time at three different speeds which represent about 70, 80 and 85% of estimated HR_{max}. Energy expenditure was calculated by indirect calorimetry, while biomechanical parameters (stride length, stride frequency, relative thrust phase duration) were measured with an inertial sensor-based system.

Results/discussion: At 10% there was no significant change in EC, EC_v and mechanical efficiency no matter the speed. At 17 and 24% the fastest speed was significantly more economical. There was a significant effect of slope gradient on EC, EC_v and mechanical efficiency. The most economical slope gradient was the steepest one. There was a significant increase of stride frequency with speed. Relative thrust phase duration decreased significantly with speed at steep slope gradients only, while stride length increased significantly with speed also only at steep slope gradients. There was a significant effect of slope gradient on stride length (decrease with steepness) and relative thrust phase duration (increase with steepness).

Conclusion: A combination of a decreased relative thrust phase duration with increased stride length and frequency decreases EC_v in ski mountaineering. To minimize the energy expenditure to reach the top of a mountain and to optimize performance, ski mountaineers should therefore choose a steep slope gradient (at least 24%) and, provided they possess sufficient metabolic scope, combine this steep slope gradient with a fast speed (at least 6 $km \cdot h^{-1}$).

For more details, see Appendix 5.

2.2 Optimal slopes and speeds in ski mountaineering – a field study

Introduction: The main objective of this study was to verify previous results obtained during simulated ski mountaineering on a treadmill, by testing different speeds and slope gradients during actual ski mountaineering on snow. We aimed to describe the effects of speed and slope gradient on energy expenditure and to relate any changes to changes in stride characteristics. The last purpose was to determine an optimal slope gradient and speed allowing minimization of energy expenditure and optimization of performance.

Methods: 11 subjects were tested using their ski mountaineering gear at three different slope gradients (7, 11 and 33%) at 80% of HR_{max}, and at 11% at three different speeds at 80, 90 and 100% of HR_{max}. Energy expenditure was calculated by indirect calorimetry to derive EC, EC_{vert} and mechanical efficiency of vertical displacement, while biomechanical parameters (stride length, stride frequency, relative and absolute thrust phase duration) were measured with an inertial sensor-based system.

Results/discussion: At 11% there was no significant change with speed in EC, EC_{vert} and mechanical efficiency, while stride length and frequency increased and absolute thrust phase duration decreased. There was a significant effect of slope gradient on EC, EC_{vert} and mechanical efficiency, while speed, stride length and stride frequency decreased and absolute and relative thrust phase duration increased. The most economical slope gradient (lowest EC_{vert} and highest efficiency) was the steepest one.

Conclusion: During ski mountaineering uphill at shallow slope gradients (11%) EC, EC_{vert} and mechanical efficiency do not vary with speed, while at steeper slope gradients (33%) speed improves economy. It follows that to minimize the energy expenditure and optimize performance to reach a place located at a higher altitude in ski mountaineering, an athlete should choose a steep slope gradient, if he/she is able to maintain a sufficient speed.

For more details, see Appendix 6.

2.3 Energy Expenditure of Extreme Competitive Mountaineering Skiing

Introduction: Ski mountaineering is a popular leisure activity and competitive sport. Little is known about the physiology of ski mountaineering events. The hypotheses of this study were that during multi-hour ski mountaineering races energy expenditure is very high and only partly covered by the energy intake. The intake may be below official recommendations and athletes may develop significant dehydration. Determinants of performance were also investigated.

Methods: 28 athletes on the '*Patrouille des Glaciers*' (PDG) race-courses (17 on course Z, 27 km, +2113m; 11 on course A, 26 km, +1881m) volunteered. Pre-race measurements included body mass, stature, $\dot{V}O_{2max}$, and HR vs. oxygen uptake at simulated altitude During the race HR, altitude, incline, location (race Z and A), and food and drink intake (only race A) have been assessed. Energy expenditure was calculated from altitude corrected HR derived oxygen uptake. Dehydration status was estimated by weighting the athletes immediately before and after the race according to the guideline of ACSM.

Results/discussion: Race time was 5 h 7 min ± 44 min (Z) and 5 h 51 min ± 53 min (A). During the race, subjects spent 19.2 ± 3.2 MJ (Z), and 22.6 ± 2.9 MJ (A) respectively. Energy deficit was 15.5 ± 3.9 MJ (A); intake covered 20 ± 7% of the energy expenditure (A). Overall EC of the race was 9.9 ± 1.3 $J \cdot m^{-1} \cdot kg^{-1}$ (Z) and 8.0 ± 1.0 $J \cdot m^{-1} \cdot kg^{-1}$ (A). Uphill EC was 11.7 ± 1.7 $J \cdot m^{-1} \cdot kg^{-1}$ (Z, mean slope gradient: 13%) and 15.7 ± 2.3 $J \cdot m^{-1} \cdot kg^{-1}$ (A, mean slope gradient: 19%). The subjects of the race A lost 1.5 ± 1.1 kg during the race, indicating near euhydration. Age, body mass, gear mass, $\dot{V}O_{2max}$ and EC were significantly correlated with performance; energy deficit was not.

Conclusion: Energy expenditure and energy deficit of a multi-hour ski mountaineering race are very high comparable to other endurance activities e.g. road cycling or ultra-endurance triathlon. The energy intake is above recommendations. Hydration during the race seems to be adequate.

For more details, see Appendix 7.

2.4 Nutritional behaviour and beliefs of ski mountaineers – a semi-quantitative and qualitative study

Introduction: Endurance athletes are advised to optimize nutrition prior to races. Little is known about actual athletes' beliefs, knowledge and nutritional behaviour. We monitored nutritional behaviour of amateur ski mountaineering athletes during 4 days prior to a major competition in order to compare it with official recommendations and with the athletes' beliefs.

Methods: Participants to the two routes of the PDG were recruited. Dietary intake diaries of 40 athletes (21 A, 19 Z) were analysed for energy, CHO, fat, protein and liquid; ten athletes were interviewed about their pre-race nutritional beliefs and behaviour.

Results/discussion: Despite a strong belief that pre-race CHO, energy and fluid intake should be increased, energy consumption was 2416 ± 696 $kcal \cdot day^{-1}$, which represent 83 ± 17% of recommended intake. CHO intake covered only 46 ± 13% of minimal recommended (10 $g \cdot kg^{-1} \cdot day^{-1}$) and fluid intake was 2.7 ± 1.0 $l \cdot day^{-1}$ (no quantitative recommendations available).

Conclusion: Our sample of endurance athletes did not comply with pre-race nutritional recommendations despite elementary knowledge and beliefs. In these athletes a clear and reflective nutritional strategy was lacking. This suggests a potential for improving knowledge and compliance with recommendations. However the recommended amount is very high and remains very difficult to reach.

For more details, see Appendix 8.

3. Discussion

3.1 Ski mountaineering as endurance performance

Ski touring or ski mountaineering racing is often a multi-hour activity, i.e. for the athletes that we observed during the PDG (for a description of the race, see appendix 4), the main duration of the race was 5 h 07 min ± 44 min for the modified race Z (and 5 h 51 min ± 53 min for the race A (26 km)). Because of avalanche risk race Z was shortened to 27 km instead of the originally intended 53 km. In its initial conformation the duration of race Z would therefore have even been more than twice so long. Even if the elite teams reach the finish line in about 6 h, it may take more that 20h for some amateur teams to cross the line.

In addition to the long duration, the exercise intensity was generally high. The participants in the race A spent 13 ± 20% of the total race time above vt2, while the participants in the race Z, who started out and paced their race expecting to complete the originally scheduled route, spent 17 ± 23% of the total race time above vt2. The mean percentages of HR_{max} were respectively 82 ± 4 and 81 ± 2% and 77 ± 7 and 82 ± 5% for the uphill sections that were separately analysed. So the intensities were very similar between the uphill and downhill sections. The average exercise intensity was slightly lower than what was found by Duc et al. (2011) (19) and Schenk et al. (2011) (67), but this can be explained by the shorter duration of the races they looked at. The distribution of HR in the intensity zones was similar for race A and Z (Figure 6).

This result was expected since the two routes were quite similar: 26 km for race A, 27 km for race Z, with altitude differences of +1,881 m and -2,341 m for race A, and of +2,113 m and -1,749 m for race Z. However the subjects of race Z started out expecting to complete the originally scheduled route, 53 km long and the double of positive and negative altitude differences. The pace and intensity they chose were therefore likely those they felt appropriate for a race twice as long. If we consider that the skiers who chose to participate in race Z, the longer and generally considered elite race, were better trained and experienced skiers, it may be speculated that they would have kept this intensity for the second part of the race if it had taken place. On the other hand, HR may decrease with exercise duration and fatigue (103), so if the subjects of the race Z had known from the start that they would race for only 27 km, their HR might have been clearly higher because of the higher intensity of a faster pace.

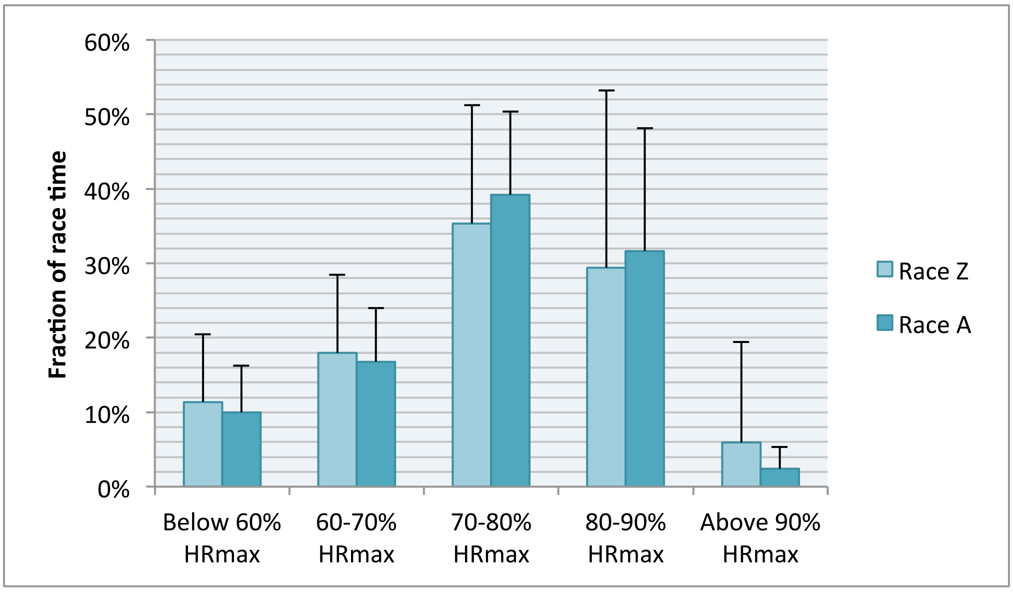


Figure 6: Fraction of race time (% of race time) in each intensity zones for the race Z (light) and A (dark) (mean and SD): the distribution of the intensity zones was similar for both races but the subjects of race Z started out expecting to complete a 53 km route ant not only 27. Therefore they paced their race for a twice as long race as the race they finally did. The SDs are rather wide, likely indicating the important variation from one athlete to another in the teams.

In the present study the distribution of time spent in the HR zones, below and above vt2 was quite heterogeneous: some athletes spent no time above the vt2 whereas others spent three quarters of the race time above this value. The likely reason is that PDG is a team event and that the three athletes of the same team must stay together. If a team is made up of athletes of different performance capacities it will lead invariably to intra-team differences for HR and exercise intensity (Figure 7). This makes inter-individual comparisons difficult but reflects the reality of most multi-hour ski mountaineering races, which generally are team events.

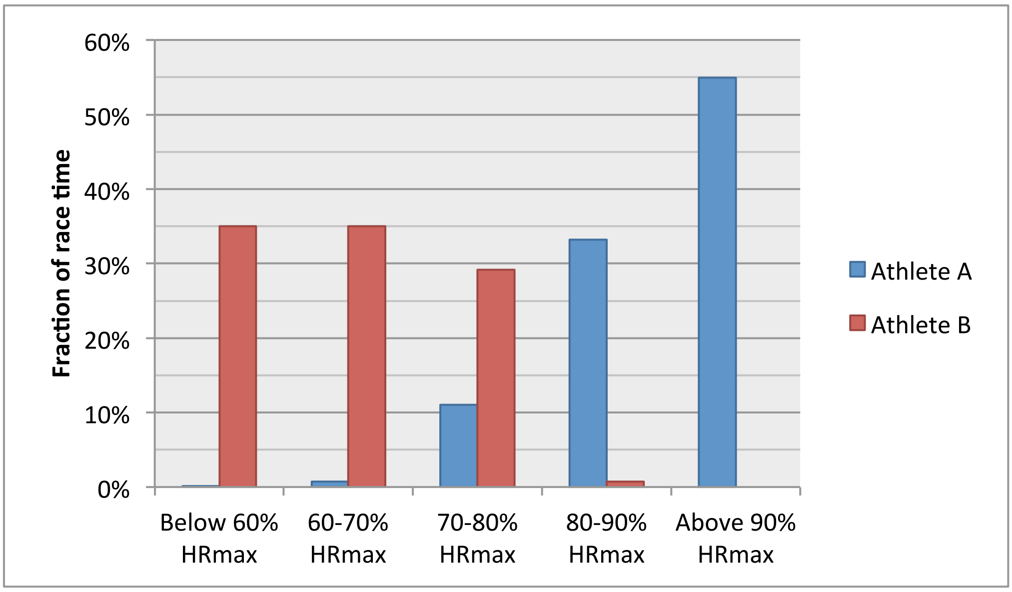


Figure 7: Extreme example of 'team effect'. Athlete A and Athlete B are members of a same team, but have different aerobic capacity levels. For a given team speed, the exercise intensity was high for the Athlete A and low for the Athlete B. It illustrates the importance of matching of aerobic capacity between members of teams.

3.2 Main determinants of endurance performance in ski mountaineering

3.2.1 Maximal oxygen uptake

Absolute $\dot{V}O_{2max}$ was negatively correlated with race time for the considered participants in the PDG (multivariate analysis for performance, Appendix 7). Its influence on performance can be considered as modest compared to that reported for other endurance activities, but again, the presence of a 'team effect' in our particular sample of amateur teams may also partly explain that result.

PRACTICAL CONSEQUENCES:

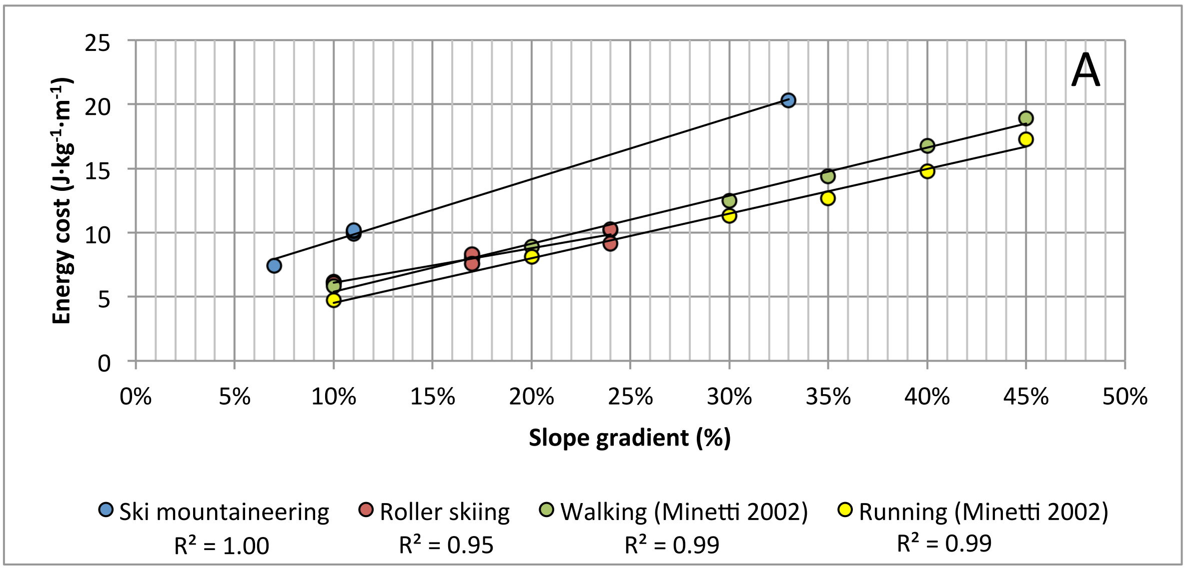
- To optimize performance, $\dot{V}O_{2max}$ intensity should be trained (short interval-training), although the sustainable exercise intensity during the race is lower.

3.2.2 Exercise economy

3.2.2.1 Energy cost, vertical energy cost and mechanical efficiency

According to the same multivariate analysis (Appendix 7), EC was positively correlated with race time of the PDG: the participants who were more economical performed better.

EC, EC_v and mechanical efficiency were calculated at different slope gradients and speeds on a motorized treadmill with roller skis as well as on snow with ski mountaineering gear. The EC measured on snow showed that ski mountaineering is a very strenuous activity: EC and EC_v of ski mountaineering were very high compared to roller skiing, running or walking (104) at the same slope gradients (Figure 8), while mechanical efficiency was lower. Unlike actual ski mountaineering EC, EC_v and mechanical efficiency of roller skiing were close to EC, EC_v and mechanical efficiency of walking and running. Two possible explanations for the much higher energy expenditure of ski mountaineering compared to other types of locomotion were identified: higher friction forces, due to the fact that the great surface of the skis is always in contact with the snow and the equipment that represents a further load to the lower limbs, especially compared to walking and running, which might influence the EC.



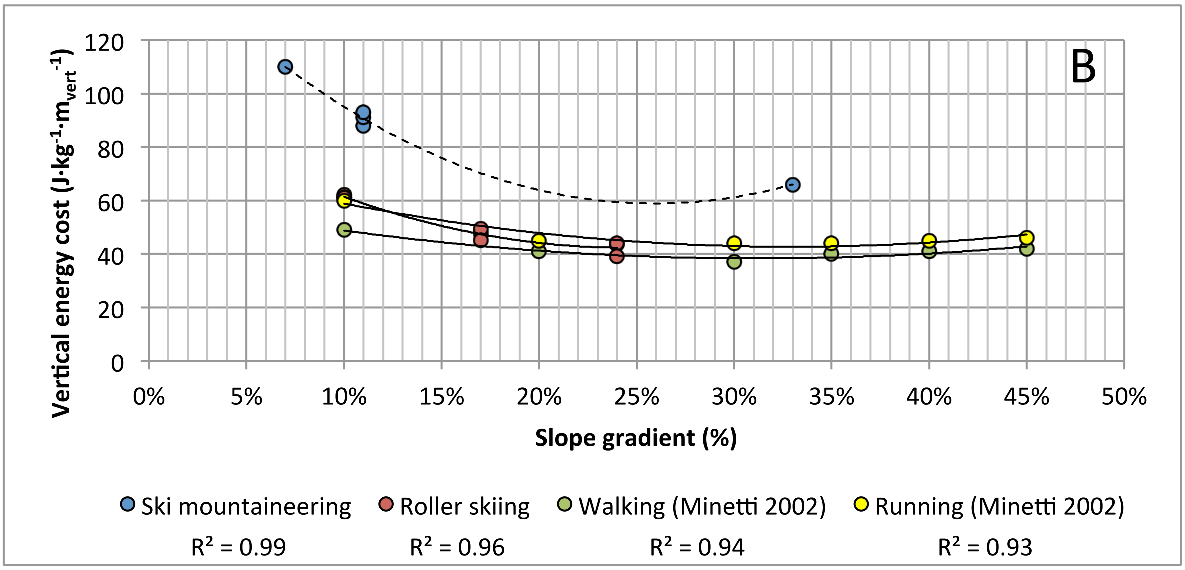
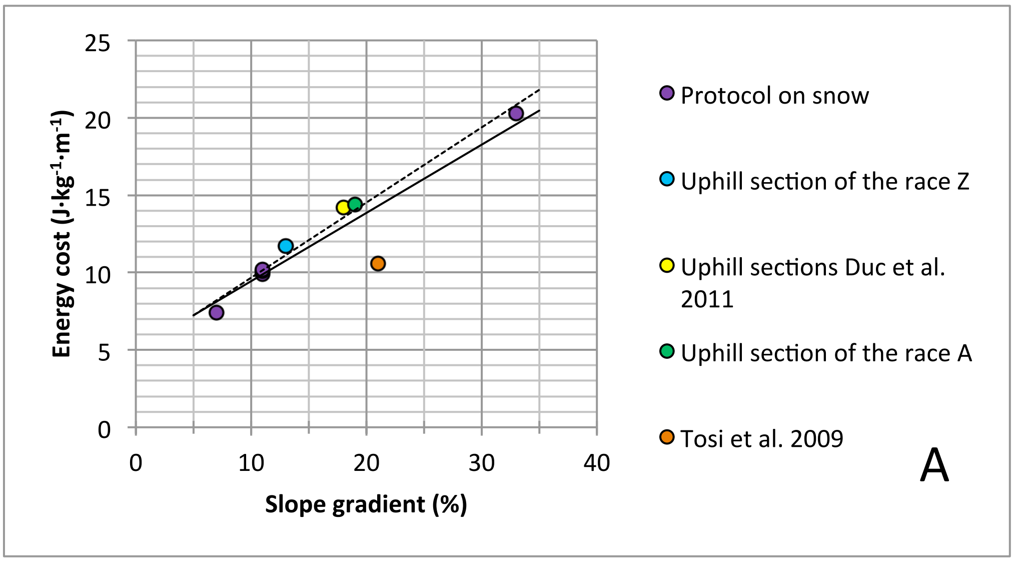


Figure 8A: EC of ski mountaineering, roller skiing, walking and running at different slope gradients. Linear regressions were tested and the respective correlation coefficients are indicated under the figure. These coefficients are very close to 1, showing that the increase of EC with speed is probably linear between 10 and 45%. **Figure 8B:** EC_v of ski mountaineering, roller skiing, walking and running at different slope gradients. Second order polynomial regressions were tested and the respective correlation coefficients are indicated under the figure. These regressions indicate that, between 10 and 45%, the EC_v of roller skiing, walking and running decreased up to an optimum. On this figure, a similar evolution for EC_v of ski mountaineering is supposed and a second order polynomial regression was also tested, without knowing, with only three points if it is adequate. For these two figures, effect of speed was neglected.

From a metabolic point of view, roller skiing thus seems not a perfect model for ski mountaineering. The EC and EC_v are higher in ski mountaineering (Figure 8), but the evolution of energy expenditure as function of speed and slope gradient seems to be similar. Therefore it remains relevant to consider the metabolic data from roller skiing.

According to our observations, in both cases, EC, EC_v and mechanical efficiency varied with the slope gradient, while they changed with the speed only if the slope gradient was higher than 11%. EC and mechanical efficiency increased linearly with slope gradient, while EC_v decreased (between, 7, 11 and 33% on snow and 10, 17 and 24% on treadmill). But, at least with roller skis on a treadmill, the relationship between slope gradient and EC_v did not seem to be linear, but rather to reach an optimum. It allowed us to suppose that there probably is an optimal slope gradient, which minimizes the energy expenditure to reach a goal located at higher altitude. As far as we could see this optimal slope gradient should be steep (>24%) and it can be supposed that it may be between 25 and 30% as previously demonstrated for walking or running (26). Different speeds were tested at 10, 17 and 24% of gradient on a treadmill and at 11% on snow. At 'steeper' slope gradients (>11%) the highest speed (5 km·h^{-1} at 17%, 4 km·h^{-1} at 24%) was the most economical (EC_v lower), showing the highest mechanical efficiency. No variation was observed with speed at 'flat slope gradients' (10 and 11%).

EC was also calculated during the PDG. EC was calculated for the whole race (9.9 ± 1.3 J·m^{-1}·kg^{-1} (Z), 8.0 ± 1.0 J·m^{-1}·kg^{-1} (A)) and, in this case, involved several types of locomotion like running, walking, ascent on skis with skins applied, alpine skiing in descent, or cross-country skating like skiing. This implies that the overall EC is very dependent of the route of the particular race and differs between races, according to the fraction of the race spent in the different types of locomotion. As consequence results obtained in the present study cannot be applied to another race. That is why EC was also separately estimated for the ski mountaineering uphill sections during the PDG. The EC of our uphill sections can be compared with the results of other studies and to our estimations of EC at different slope gradients on snow (Figure 9). Our results are congruent with each other and with the results of Duc et al. (2011). But both EC and EC_v are much higher than the EC and EC_v found by Tosi et al. (2009) and the mechanical efficiency is much lower. These differences might be explained by differences in material (measuring devices and ski mountaineering gear), snow conditions, speeds, carried loads and fatigue.



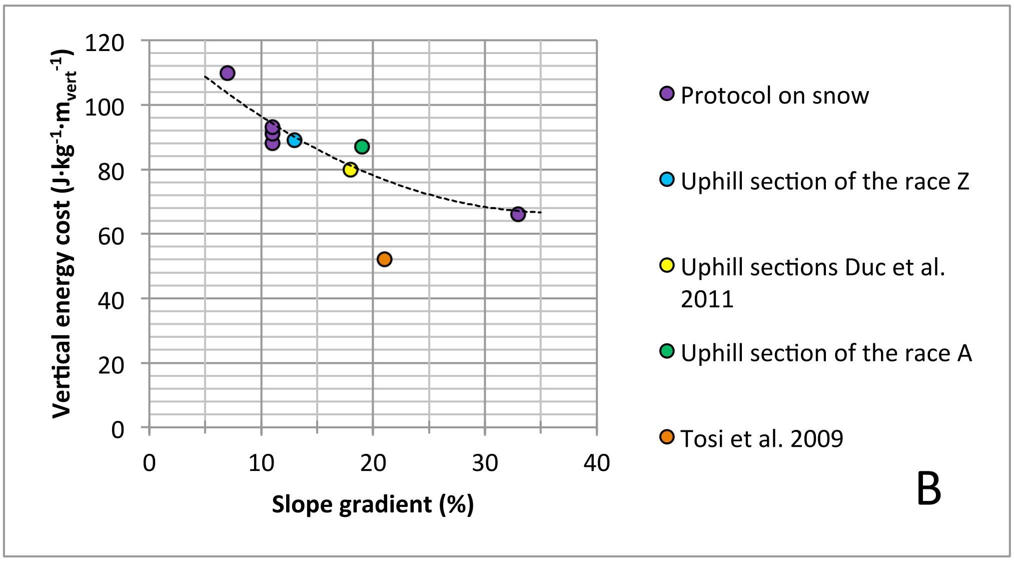


Figure 9A: EC as function of slope gradient: EC calculated by us (PDG and on snow), by Tosi et al. (field study) and by Duc et al. during a ski mountaineering race ('Trace Catalane'). Data from Tosi (orange) are below all the others. There seems to be a linear positive relationship between slope gradient and EC (solid line), with R^2= 0.84 and EC = 0.44 · slope gradient + 5. If we exclude Tosi et al. (dotted line), the R^2 increases up to 0.98 and the equation is EC = 0.49 · slope gradient + 4.8. **Figure 9B:** EC_v as function of slope gradient: EC_v calculated by us (PDG and on snow), by Tosi et al. (field study) and by Duc et al. during a ski mountaineering race ('Trace Catalane'). Data from Tosi are below all the others. If we exclude Tosi et al., there seems to be a polynomial negative relationship between slope gradient and EC_v (dotted line), with R^2= 0.86 and EC_v = 0.04 · slope gradient^2 – 3.1 · slope gradient + 123.2. These relationships do not take into account the differences of speed, of carried load and the effect of fatigue.

3.2.2.2 Biomechanical parameters

The next question is whether the energy expenditure changes with speed and slope gradient may be explained by biomechanical changes (i.e. stride characteristics). The biomechanical changes with speed and slope gradient looked similar to what happens for walking or running (105). With increasing slope gradient, speed decreased, stride length and stride frequency decreased and thrust phase duration (absolute and relative) also decreased. With increasing speed, stride length and frequency increased, absolute thrust phase duration decreased and relative thrust phase duration did not change (results on snow, for the results on treadmill, see appendix 5). The fact that the metabolic variables were constant with speed at 11%, while the biomechanical variables changed indicates that the biomechanical changes of the strides are probably not the main reason for the metabolic changes.

From a biomechanical perspective, ski mountaineering and roller skiing appeared to be quite similar with no significant difference for stride frequency, stride length and relative thrust phase duration between the two activities (Table 2, Appendices 5 and 6). It suggests that if roller skiing is not a perfect metabolic model for ski mountaineering, it seems an adequate model for its biomechanics as far as stride characteristics are concerned, indicating that the use of roller skis in summer to train for ski mountaineering seems to be quite appropriate, because the movement is quite similar with comparable biomechanical variables.

Study	Slope gradient	Speed ($km \cdot h^{-1}$)	Stride frequency ($stride \cdot min^{-1}$)	Relative thrust phase duration (% of cycle duration)	Stride length (m)
Treadmill	10%	4.0	38	38	1.88
Snow	11%	4.7	42	40	1.89
Treadmill	10%	5.0	43	33	2.09
Snow	11%	5.8	48	41	1.99
Treadmill	10%	6.0	47	35	1.99
Snow	11%	6.8	54	40	2.11

Table 2: Biomechanical parameters at 10 and 11% on treadmill with roller skis and on snow. By using the best linear mixed model that predicts the different data from speed, slope gradient and activity, the activity (ski mountaineering or roller skiing) had no significant effect on stride length, stride frequency and relative thrust phase duration.

PRACTICAL CONSEQUENCES:

- To minimize energy expenditure and optimize the performance to reach a place located at a higher altitude, ski mountaineers should choose a steep slope gradient (>24%) and combine it with a fast speed.

3.2.3 Fractional utilization of $\dot{V}O_{2max}$ (lactate threshold)

The correlation between the lactate threshold or the average fraction $\dot{V}O_{2max}$ sustained during the race and the performance were not directly investigated. However it is reasonable to assume that the intensity at lactate threshold or the fraction of $\dot{V}O_{2max}$ that can be sustained during the race are determinants of the performance in a race like the PDG. The participants in the race Z and A spent respectively 17 ± 23% and 13 ± 20% of the total race time above vt2, so the intensity was submaximal but high and likely in vicinity of the lactate threshold. If the fraction of $\dot{V}O_{2max}$ that can be sustained during the race were higher, the athletes would have been faster with the same substrate utilization and perceived exertion and thus their performances would have been better.

PRACTICAL CONSEQUENCES:

- Besides low intensity endurance and $\dot{V}O_{2max}$ intensity training, which are important for long duration races like the PDG, it is also important that the athletes focus on training around vt2 intensity and shift vt2 closer to the $\dot{V}O_{2max}$.

3.2.4 Adequate fuel provision

3.2.4.1 Energy expenditure for multi-hour ski mountaineering events

Subjects spent 19.2 ± 3.2 MJ (modified race Z), respectively 22.6 ± 2.9 MJ (race A) during the race. If the race Z had taken place normally, the duration would have been about twice as long and the energy expenditure twice as high, or about 40 MJ. Therefore the energy expenditure of the complete race Z is about as high as the energy expenditure of a triathlon ironman (63, 64), or more than a mountain stage of the Tour de France in cycling (65). The estimated energy expenditures of the race A and of the modified race Z are close to the energy expenditure of an average stage of the Tour de France (65) and more than 50% higher than a 50 km in cross-country skiing (106). It represents for the race Z and A respectively average intensities of 13 ± 2 and 12 ± 1 METs. It is the equivalent of cycling at 26 to 31 km·h^{-1} or running at 14.5 km·h^{-1} or in cross-country skiing, skating at competitive speed (107). Calculated over 24 h, race day energy expenditure can be estimated as 24.6 ± 3.9 MJ for the participants of the race Z and 28.9 ± 2.9 MJ for the participants of the race A, supposing that the athletes did not engage in significant other additional physical activity except participating to the race. The PAL on race day thus amounted to 2.4 ± 0.4 for participants doing race Z and 3.0 ± 0.5 doing race A. The general population has a natural limit of sustainable daily energy turnover at a PAL of 2 to 2.5 that can be maintained over several days (62). The high PAL values for non-elite athletes found for race A suggest that those subjects would probably not be able to maintain energy balance over time, as suggested also by the important energy deficit reached during the race. Multi-hour ski mountaineering events therefore belong to the category of extreme activities and can be considered as very strenuous and energy demanding.

3.2.4.2 Energy intake

Energy intake before the race

Energy and macronutrients

Current recommendations for CHO storage before an endurance race range from 10-12 g·kg^{-1}·day^{-1}, starting 36 to 48 h prior to the race (73, 74). The surveyed and interviewed athletes seemed to be aware of the importance of CHO storage: all the subjects mentioned that it is good to eat a lot of pasta during the days preceding the race. Given this belief, the finding that the CHO intake of the studied population was less than half (46 ± 13%) of the recommended levels and that not even a single participant reached them is quite surprising. It could be due to a lack of understanding of the concept of pre-race CHO loading (although it seems to go against the statement that a lot of pasta should be eaten). On the other hand, it may also reflect difficulties in reaching the recommended CHO amounts just by varying the quantities and proportions of the usual dietary components, without using additional specific CHO-rich sports food. To reach the minimum value of the guidelines, a 80 kg athlete should consume at least 800 g CHO·day^{-1}, that represents about 5 kg cooked pasta. These observations lead us to ask the question whether today's guidelines are adequate for practical use. The observed average CHO consumption in our sample was far from the recommendations. It suggests that it might have been too difficult for our participants to reach the recommendations by consuming twice as much CHO as they did, even if that was only during the last 24 to 36 h.

Sports food consumption and in particular CHO-rich food and drinks is common in our population (58% of the participants). CHO-rich food is especially interesting to increase the far too low CHO intake. Participants in the race Z consumed significantly more CHO-rich sports food than participants in the race A, but their total CHO intake was not significantly higher. That means that while they consumed more sports food, their CHO intake through traditional food was lower. A combination of high CHO intake through traditional food and through sports food is necessary to reach the recommended amount.

For fat and protein intake, there are no specific pre-race guidelines, but the recommended levels for athletes in daily life were reached by the subjects.

<u>Other nutritional concerns</u>

Although several studies showed that vitamin and/or mineral supplementation does not improve performance during endurance (108, 109) or ultra-endurance (110) exercises, if the daily diet is adequate (111), supplement intake remains widespread among athletes. It is recommended to be careful and to estimate the safety, the efficacy, the potency and the legality of a supplement before taking it (71-74). In our population, a third of the participants took one or more supplements. The most widespread supplement was magnesium (25% of the participants), which is taken to avoid muscle cramps, although it has been shown that magnesium supplementation has no effect on muscle cramping during exercise if there is no deficiency (rare in athletes with a sufficient and balanced diet) (112, 113).

Digestive comfort is another key variable during endurance events such as multi-hour ski mountaineering races. Digestive discomfort and gastrointestinal distress like cramps, nausea, vomiting, bloating, and diarrhoea are frequently reported during ultra-endurance activities, particularly during ultra-marathon running (97, 114, 115). To avoid gastrointestinal distress during racing, athletes are advised to avoid dehydration, high-fibre food intake, and hypertonic beverages and to practice their planned race nutrition strategies before the actual race (97, 115, 116). It is difficult to say from the food diaries which food items were specifically avoided during these 4 days, because we do not know the habitual diet of the participants, but from the interviews it seemed that mostly red meat and other fatty food items were avoided.

In general, the athletes seemed to be well aware of the importance of pre-race nutrition for performance. In spite of this declared importance of adequate nutrition in preparation of an endurance event, the knowledge on this topic was approximate. Any misunderstandings were detected (e.g. supplement vs. sports food) and it seemed to be difficult for the athletes to explain why they choose some food items and avoided others. The overall impression was that it rather reflected beliefs than knowledge (117) and that the athletes did not follow a clear nutritional strategy based on solid knowledge. This lack of a clear knowledge and strategy can be a reason for the far too low energy and CHO consumption.

Energy intake during the race

Like already said, the energy expenditure of ski mountaineering racing is very high, resulting in a huge energy deficit. To minimize this deficit and partly balance the energy expenditure, it is important to optimize the energy supply during the race. The deficit cannot be avoided because the access to and the capacity to eat and process food is limited during the race (118). Apart from the practical difficulties of eating while being engaged in sports, a physiological limiting step is the capacity of absorption of the small intestine. The sodium dependant transporters of glucose (SGLT1) become saturated at a CHO intake around 7 $g \cdot kg^{-1} \cdot h^{-1}$, the rate recommended by the ACSM.

During the race A of the PDG, the food intake covered 20 ± 7% of the energy expenditure. The intake was 14% lower than the recommendation of the ACSM (Figure 10).

Like before the race, the energy and especially CHO intake during the race were too low. The food and drink supply should be completed with CHO-rich food items (traditional food items rich in CHO, CHO-rich drinks and sports food). In our population, the athletes mainly drank water during the race: if this water intake was partly replaced by CHO-rich drinks, the energy intake would be increased quite easily.

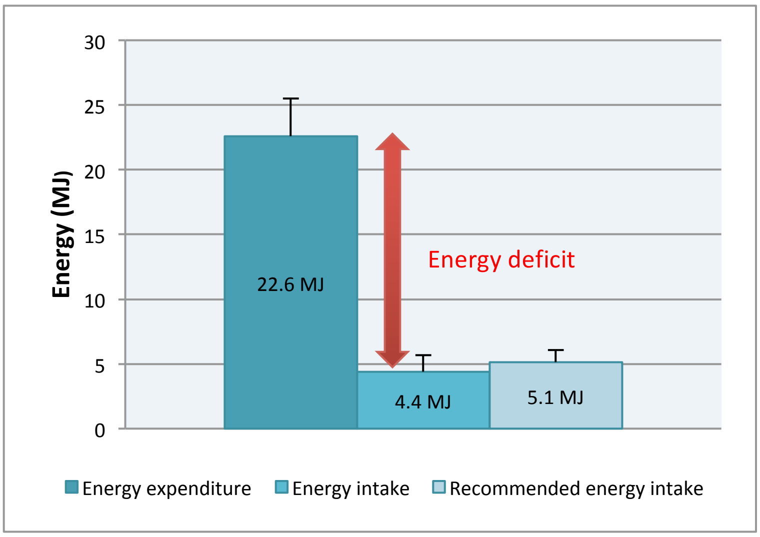


Figure 10: Comparison between energy expenditure, energy intake and recommended energy intake (ACSM) for the finishers of the race A (mean and SD). The energy intake reached 20 ± 7% of the energy expenditure and was 14% below the recommended amount.

PRACTICAL CONSEQUENCES:

- The athletes should be better informed about nutrition to allow them developing an evidence-based conscious and reflective feeding strategy.
- A high priority should be given to CHO intake. The amount should be increased with traditional food (pasta, rice, bread, etc.), completed with CHO-rich sports food and drinks before and during the race (e.g. to replace water by CHO-rich sports drinks).

- The chosen nutritional strategy should be experimented prior to the actual race (e.g. before and during a hard training session or a less important competition) to ensure that it does not cause gastrointestinal distress.

3.2.5 Core temperature

Core temperature was not specifically investigated. We can only say that no problem related to hyper- or hypothermia was reported by any of the subjects.

3.2.6 Hydration

Hydration before the race

To our knowledge there is no specific quantitative recommendation for liquid intake before a long duration race. The ACSM only recommends to start hydration several hours before exercise (71). One of the main representations of the athletes (9/10 interviewed subjects mentioned it) was that the water intake should be increased during the days preceding the race and the mean liquid intake was 2.7 ± 1.0 $l \cdot day^{-1}$ during the 4 days preceding the race. Since we only have information about pre-race and no data on habitual fluid intake of our subjects, we do not know if, according to the recommendation, they increased their fluid intake prior to the race.

Hydration during the race

During the race A, the fluid intake was 1.8 ± 0.7 l (3 ± 1 $dl \cdot h^{-1}$) mainly water but also CHO-rich sports drinks, soft drinks or broth. The guidelines (70, 72) recommend that endurance athletes should attempt to minimize dehydration by limiting body mass loss through sweating to no more than 2 to 3% of body mass. During the race A of the PDG, the finishers lost 1.5 ± 1.1 kg, i.e., 2 ± 1% of their body mass (part water and part energy substrate), so it can be concluded that they were not much dehydrated.

For a winter mountain race like the PDG, the low temperatures and air dryness bring the sweat loss down compared to other events of similar duration in warmer and more humid conditions. This can explain the limited dehydration during the PDG compared to other endurance competitions (119). We do not know what would have happened if the race Z could have been held normally: with a twice as long duration the dehydration may have been more important.

PRACTICAL CONSEQUENCES: Hydration seems to be adequate in our population and the athletes should continue like this, before and during the race. For this kind of winter sport dehydration does not seem to constitute a major problem.

4. Conclusions and perspectives

The main results of our work are the following:

1) Besides the fact that a wide variety of technical skills should be trained due to the different types of locomotion and the transitions between them, the physiological determinants of performance that should be trained in ski mountaineering are also multiple. The exercise intensity varies along the race: therefore, very high ($\dot{V}O_{2max}$), high (around vt2) and moderate (lower than vt2) exercise intensities should be trained.
2) To minimize the energy expenditure (EC_v) to reach a goal located at a higher altitude, ski mountaineers should choose a steep slope gradient (>24%) and combine it with a fast speed, assuming that they possess the necessary aerobic metabolic capacity necessary.
3) The very high energy expenditure during a long duration ski mountaineering event implies a very high energy requirement. However the average energy and CHO intake before and during the race are under the recommended amounts, and ski mountaineers should be advised to increase CHO intake before and during racing.
4) No significant dehydration was observed after a multi-hour ski mountaineering event and ski mountaineers seem to have appropriate hydration behaviour.

These results constitute an overview of some determinants of ski mountaineering performance and thus allow formulating some practical and specific recommendations for ski mountaineering practice.

But it also raises few new questions:

- Regarding EC, it would be interesting to investigate more accurately slope gradients between 24 and 33% to determine if there is an optimal slope gradient in between. Different speeds at steep slope gradients should also be tested on snow to verify if the economy of the locomotion is influenced by speed at steep slope gradient, as for roller skiing. It would further be of interest to quantify the friction coefficient of roller skis on a treadmill and of skis with skins on various snow types.

- The protocol about the PDG was disturbed due to the race cancellations and the change of distance for the race Z. Of course, it would be interesting to have all the data from the race Z to calculate the energy expenditure of the original route, to estimate the energy deficit and dehydration after this race and to investigate the influence of different variables (age, gender, anthropometric features, aerobic capacity, energy intake, nutrition, hydration, pacing, altitude, training, tolerance to high altitude) on performance. To achieve this goal, it would also be interesting to analyse an individual race, to eliminate the 'team effect'.

- About nutrition: it would be interesting to investigate if elite athletes are closer to the guidelines than the considered non-elite athletes, regarding energy and CHO intake, to verify if the recommendations are reachable or not in this kind of elite population. It would also be of interest to verify if there is a correlation between energy and CHO intake, especially prior to the event, and the race performance, to find out if a pre-race CHO intake as high as currently recommended is really useful and necessary.

- It would also be interesting to look at the training habits of ski mountaineers (type of activities (only ski mountaineering or other endurance activities), intensity, duration, altitude acclimatization, fatigue) with the aim of determining the best training strategy.

All of these points would allow further enhancing the knowledge about ski mountaineering and helping the athletes and trainers to improve their approach of training and competitions.

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Appendices

Appendix 1: Ski mountaineering

Ski mountaineering or ski touring is a winter mountain endurance sport and leisure activity. As competitive sport it is called ski mountaineering and, when referring to the leisure activity, the term ski touring is preferably used. In this work, the term ski mountaineering is mostly used to refer to both of them.

Ski mountaineering is a form of skiing, which consists in covering distances in a snowy mountain environment, on skis. The route usually involves downhill, but also uphill sections and is typically off-piste.

When skiing downhill the heel is fixed on the ski and the athletes slide down like alpine skiers. When climbing the ski binding is modified and the heel is free allowing foot rotation around the toes while adhesive skins are attached under the skis, preventing sliding backward. The locomotion is between walking (sometimes running) and cross-country skiing. Specifically, the use of ski poles requires arm work, which looks more like cross-country skiing than walking or running. In addition to skiing downhill and uphill, a ski tour may involve some other locomotion forms: walking, running or steep climbing with the skis fastened on the backpack or a cross-country skate skiing-like movement on flat snowy sections. So ski mountaineering requires a wide variety of athletic and technical skills.

Appendix 2: Ski mountaineering gear

The ski mountaineering equipment is mainly composed of the following items:

- The skis: are very similar to alpine skis, usually with a lighter structure (Figure 11A).
- The ski bindings: allow the heel to be clipped down when skiing downhill, and allow it to be released and to pivot at the toes, when skiing uphill (Figure 11B).
- The ski boots: look like alpine ski boots, usually lighter. They are more flexible and allow a flexion behind the heel (Figure 11C).
- The skins: adhesive artificial skins, which allow the ski to glide forward, but not to slip backward; they are put under the skis during the uphill sections and are removed for the downhill sections. Skins were originally made from seal skin, but are now made from nylon or mohair (Figure 11D).
- The ski poles: look like alpine ski poles, but often longer and lighter.
- The heel elevators (optional): allow raising the heel when steep climbing.
- Others: sports clothes for winter, security material and in particular avalanche rescue equipment, sometimes mountaineering gear: harness, crampons, ice axe, helmet, rope, etc..

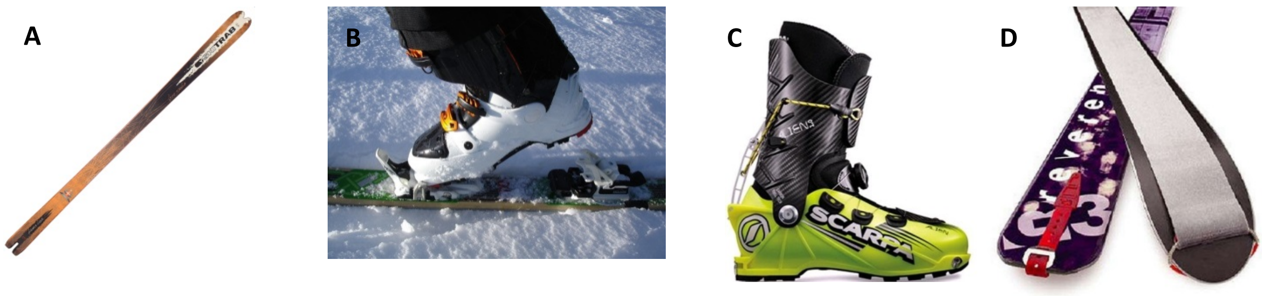

Figure 11: Ski mountaineering gear: A: ski, B: ski binding, C: ski boot and D: adhesive skins.

During summer, the athletes train sometimes with roller skis (Figure 12) on roads. These skis are shorter and narrower than normal skis and equipped with two wheels that can only roll in the forward direction and usually classic style cross-country ski bindings. The skiing technique used is very similar to the technique used in classic cross-country skiing.

Figure 12: Roller skis (in this case mounted with cross country bindings for cross country boots).

Appendix 3: Ski mountaineering races

Types of races

Five types of races are recognized by the International Ski Mountaineering Federation (ISMF) and are organized as world cup events or during continental and world championships (120):

- Sprint: varied, short course with ascent, descent and a walking part with skis attached to rucksack, which will take place in qualifying phases (quarter-finals, semi-finals and final). The total duration is about 3 min 30 s for the best elite athletes.

- Vertical race: single ascent on skis, for individual racers. No part takes place on foot with skis on backpack. Vertical race is possible off-piste, but only along a sheltered track with a minimum width of 2 m. The positive ascent should be between 500 and 700 m.

- Individual race: minimum three ascents/descents on mountain slopes. The longest ascent must not exceed 50% of the total positive difference in height. At least 85% must be raced with skis on feet, at most 5% on feet and at most 10% should be technical sections raced carrying skis on the rucksack (ridges, couloirs, etc.). The positive ascent should be between 1,600 and 1,900 m for men and 1,300 and 1,500 m for women and the duration between 1 h 30 min and 2 h for men.

- Team race: Team race features look like individual race but in team of two or three. The positive ascent should be over 2,100 m for men and over 1,800 m for women.

- Relay: in team of four competitors for men and three competitors for women. Each relay leg must include two distinct ascents and descents raced by each member of the relay team, with a foot part in the second ascent. The total positive ascent should be between 150 and 180 m and the total duration above 15 min.

Sprint, relay and individual races are generally dedicated to elite athletes and almost only team races and vertical races are organized for non-elite athletes.

Main races

Besides the continental and world championships, three races are considered as the most prestigious ski mountaineering events: the Italian Trofeo Mezzalama, the Swiss Patrouille des Glaciers (PDG) and the French Pierra Menta (Figure 13).

Figure 13: The three main ski mountaineering races: the Trofeo Mezzalama (Italy), the Pierra Menta (France) and the Patrouille des Glaciers (Switzerland).

That is three team events in teams of two (Pierra Menta) or three athletes (Mezzalama and PDG). They are high altitude and long distance ski mountaineering competitions.

Since 2011, together with the Adamello Ski Raid (Italy), the Altitoy-Ternua (France) and the Tour du Rutor (Italy), they are related in a circuit with an overall ranking: the Grande Course.

Appendix 4: The Patrouille des glaciers

The PDG (http://www.pdg.ch (121)) is the most famous and popular ski mountaineering race in Switzerland.

The PDG has its origin in World War II: its aim was for the troops to prove their operational capability in the context of a team competition in a mountain environment. The first race was held in April 1943 and 18 patrols took part. Sadly, the third race in 1949 was marred by the death of three participants and the race remained banned for more than 30 years. In 1984, the event was organized again. 190 teams started the race. Since then, the popularity and the media interest for the race have progressively increased. In 2014, 1800 teams were selected, while 1200 were not admitted after the multistage enrolment procedure for lack of capacity.

The PDG is organized every 2 years by the Swiss Armed Forces. Military and civilian teams, the world best ski mountaineering athletes, like hundreds of recreational athletes compete simultaneously. Each team is composed of three skiers that must stay grouped at all time of the race. There are two official race routes: one from Zermatt to Verbier (Race Z) and one from Arolla to Verbier (Race A) (Figure 14, Table 3) and two race days for each race route.

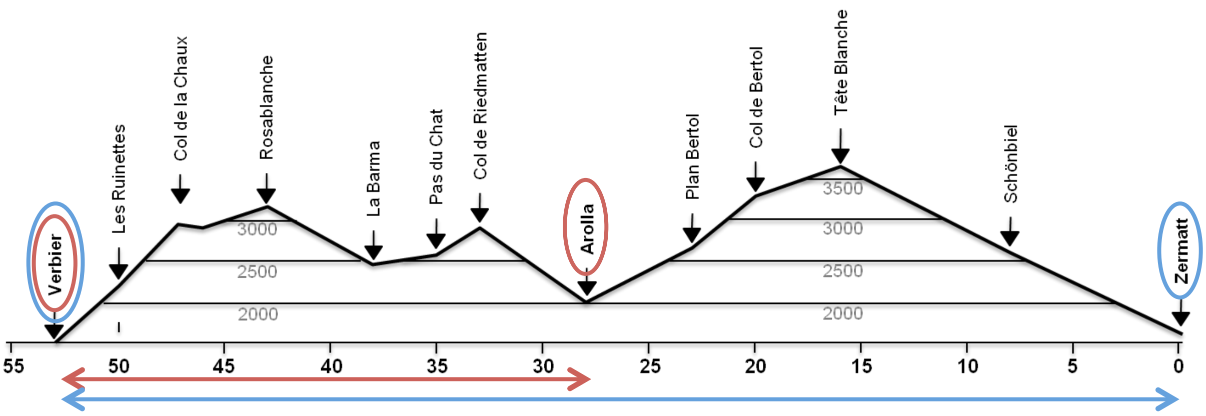

Figure 14: Racetracks of the PDG: in blue, race Z, from Zermatt to Verbier (53 km), in red, race A, from Arolla to Verbier (26 km).

The race consists of different types of locomotion: running, walking and steep climbing on foot, ascent on skis with adhesive skins applied, alpine skiing style descent and cross-country-like skiing on flatter snowy sections.

	Distance	Positive altitude difference	Negative altitude difference	Maximum altitude
Race Z	53 km	+3,994 m	-4,090 m	3,650 m
Race A	26 km	+1,881 m	-2,341 m	3,160 m

Table 3: The two official race routes of the PDG: distance, altitude difference and maximum altitude.

The PDG 2012

In 2012, when the study occurred, the race was held on 25, 26, 27 and 28 April. Due to high avalanche danger, one start of each race route was cancelled. Half the participants of race A could race normally and half the participants of race Z could race, but were stopped after 27 km (instead of 53) (Tab. 2). This change of racetrack was not known at the start of the race: participants were only informed when stopped.

	Distance	Positive altitude difference	Negative altitude difference	Maximal altitude
Modified race Z	27 km (50% of the expected distance)	+2,113 m (53%)	-1,749 m (43%)	3,650 m (no change)

Table 4: The modified race route of the race Z: distance, altitude difference and maximal altitude

Appendix 5: Optimal slopes and speeds in ski mountaineering – a laboratory study (submitted)

Optimal slopes and speeds in ski mountaineering – a laboratory study

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Abstract

Purpose: The purpose of this study was to estimate the energy cost of linear (EC) and vertical displacement (EC_{vert}), mechanical efficiency and main stride parameters during simulated ski mountaineering at different speeds and gradients, to identify an optimal speed and gradient that maximizes performance.

Methods: 12 subjects were tested with roller skis on a motorized treadmill at three different gradients (10, 17 and 24%) each time at three different speeds at about 70, 80 and 85% of estimated peak heart rate. Energy expenditure was calculated by indirect calorimetry, while biomechanical parameters were measured with an inertial sensor-based system.

Results: At 10% there was no significant change with speed in EC, EC_{vert} and mechanical efficiency. At 17 and 24% the fastest speed was significantly more economical. There was a significant effect of gradient on EC, EC_{vert} and mechanical efficiency. The most economical gradient was the steepest one. There was a significant increase of stride frequency with speed. At steep gradients only, relative thrust phase duration decreased significantly, while stride length increased significantly with speed. There was a significant effect of gradient on stride length (decrease with steepness) and relative thrust phase duration (increase with steepness).

Conclusion: A combination of a decreased relative thrust phase duration with increased stride length and frequency decreases EC_{vert}. To minimize the energy expenditure to reach the top of a mountain and to optimize performance, ski-mountaineers should choose a steep gradient (>24%) and, provided they possess sufficient metabolic scope, combine it with a fast speed (>6 $km \cdot h^{-1}$).

Keywords:

endurance, skiing, energy expenditure, biomechanics

Abbreviations:

ANOVA: analysis of variance

HR_{max}: maximum heart rate

HR_{mean}: mean heart rate

HR: heart rate

$\dot{V}O_2$: oxygen uptake

$\dot{V}O_{2max}$: maximal oxygen uptake

Introduction

In the European Alps ski mountaineering is a popular winter endurance sport and leisure activity. Exercise duration typically lasts for several hours while exercise intensity is high, in competition often around the respiratory compensatory threshold (Duc et al. 2011; Schenk et al. 2011). Consequently, energy expenditure is high and in previous work we reported values up to 40 MJ for a multi-hour ski mountaineering race (Praz et al. 2014). Since energy expenditure is function of the energy cost of locomotion, the latter is of interest for performance optimization.

The energy cost of locomotion corresponds to the energy expenditure to cover a given distance and was extensively studied for walking and running (Saibene and Minetti 2003). The energy cost of walking and of running varies with the slope angle (Minetti 1995; Minetti et al. 2002). For uphill sections, a steeper slope angle is associated with a higher energy cost. These variations are due to the change of proportion of positive and negative external work (shift from concentric and eccentric contractions to mainly concentric contractions from level to uphill locomotion). Along steeper slope angles, the difference of efficiency between these two types of work, combined with the work done to raise the centre of mass against gravity, leads to an increase of total mechanical work for a given distance covered. On the level, proportions of positive and negative work are equal, but the proportion of positive mechanical work increases when the slope angle becomes positive. From +15% onward for walking (Minetti et al. 1993) and 30% for running (Minetti et al. 1994), the trajectory of the centre of mass increases monotonically and the mechanical work becomes positive only (Saibene and Minetti 2003).

Since the energy costs of walking (Saibene and Minetti 2003) and, to a lesser extent of running (Steudel-Numbers and Wall-Scheffler 2009), vary non-linearly with speed, there is an optimal speed where energy cost is lowest. For ski mountaineering it was shown that the energy cost varies with speed, with an optimal speed of 3.5 km·h^{-1} at a single tested slope angle of 21% (Tosi et al. 2009; Tosi et al. 2010). The effect on energy cost of added ankle loads (0.5, 1, 2 kg) was also investigated and found to be negligible for recreational skiers, but relevant for elite competitive skiers (Tosi et al. 2009).

Several studies investigated the energy cost of ski mountaineering in more or less standardized conditions: on snow over short distances (Tosi et al. 2009), on a treadmill (Tosi et al. 2010) or during actual races (Duc et al. 2011; Praz et al. 2014). The speeds, the slope angles, the carried loads, the durations and the level of exertion were different in all these studies and make comparisons and conclusions difficult to establish. Knowing how energy cost is influenced by different parameters, like speed, slope angle or carried load, would allow estimating the energy expenditure for a given route, carried load and speed, and would allow minimizing the energy expenditure for a given route.

For activities in which altitude differences play an important role, the energy cost for vertical displacement is important and can be defined as the energy expenditure for covering a distance with a corresponding vertical displacement of 1 m. Typically for ski mountaineering uphill, the goal is to reach a place located at a higher altitude than the starting point as fast as possible. The vertical energy cost is therefore especially important and should be taken into account when choosing the best trajectory to reach the place of arrival as quickly as possible, while preventing excessive fatigue.

For walking and running, vertical energy cost decreases with the slope angle to reach a minimum value between 20% and 30% and then increases for steeper slope angles (Minetti 1995; Minetti et al. 2002). It would be especially interesting for ski mountaineering, in which quickly overcoming altitude differences is so important, to know if such an optimal slope angle exists. Furthermore, it would be of interest to see if speed and slope angle influence biomechanical parameters such as stride characteristics, potentially affecting energy cost. Several studies on walking and running reported that stride length, frequency and stance phase duration change with speed (increase of stride length and frequency and decrease of thrust phase duration) (Bertram and Ruina 2001) and with slope angle (decrease of stride length and frequency and increase of thrust phase duration)(Kawamura et al. 1991; Padulo et al. 2012; Padulo et al. 2013).

The main aims of this work were therefore 1) to measure, for ski mountaineering, the energy cost for a given distance covered and the associated vertical energy cost; 2) to investigate how these vary with speed and slope angle; and 3) to assess associations between changes in stride length, frequency and relative thrust phase duration and variations of energy cost for different slope angles and speeds.

Methods

The protocol of the study was approved by the Valais research ethics committee (CCVEM 033/11). Each participant gave informed written consent prior to participating to the study.

Subjects

12 subjects were recruited (10 men and 2 women, 27 ± 5 years, 178 ± 6 cm, 72 ± 10 kg body mass and 6.0 ± 0.7 kg for the carried material). They were all trained (8 ± 4 $h \cdot week^{-1}$) and experienced (4 ± 1 years) ski mountaineers.

Experimental design

The subjects came twice, on different days, to the laboratory: a first time for a familiarization session and a second time for the measurement session. Except the order of the stages and that no measurements were realized during the familiarization session, the protocol was exactly the same for the two sessions. The familiarization session was necessary because the participants were trained for ski mountaineering on snow with normal ski mountaineering gear and not for roller skis on a treadmill, the investigated activity. The time period between the two sessions was between 1 day and 1 week.

Measurement session

The subjects first filled out a questionnaire about their ski mountaineering practice (frequency, duration, etc.). Body weight (with shorts, shirt and socks but without equipment) and height were measured. Subjects used their own ski mountaineering boots and were provided classical cross-country roller skis (1.2 kg per ski, including ski mountaineering bindings: Dynafit, tlt speed superlight, Italy) and ski poles. A fixed 2.7 cm heel-elevator was used in all conditions. The experiments were performed on a treadmill with 250 cm x 100 cm belt size (Saturn 250/100, h/p/cosmos, Germany). Compared to ski mountaineering skis, roller skis are shorter and narrower. The wheels allow rolling forward only; a stopping system on the back wheel axis prevents rolling backward. Roller ski technique is quite similar to ski mountaineering technique, but we cannot exclude some differences due to the length difference of the skis and to the different friction coefficients (between the synthetic hairy skins that are put under the skis and the snow vs. between the wheels and the treadmill). Previous research showed that changes of resistance induced some metabolic changes for submaximal exercise but had no or little effect on biomechanical variables (Hoffman et al. 1998).

After a 5 min warm-up nine conditions were tested: three slope angles (10, 17 and 24%) and three speeds per slope angle: a slow, medium and fast, adapted for each slope angle in randomized order (Table 1). Each stage lasted 4 min to reach metabolic steady state during the last 30 s of the stage, which were considered for the analysis.

Measurement systems

Gas exchange and breathing variables were measured breath-by-breath with a metabolic measurement system (CPX, Medgraphics, USA) and heart rate (HR) beat-by-beat with a portable HR monitor (Polar S610, Finland). The metabolic system was calibrated prior to each session with a 3 l syringe and gases of known composition.

A lightweight inertial sensor (36 g) with three-dimensional accelerometers (±11 g) and three-dimensional gyroscopes (±1200°·s^{-1}) (Physilog® 3, Gait Up, Switzerland) was attached to each ski, just in front of the binding. The sampling frequency was set at 500 Hz. The sensors were synchronized with each other before starting data acquisition. Stride frequency, stride length and relative thrust phase duration (% of the total stride duration) were computed using the algorithm from Fasel et al. (Fasel et al. 2015) adapted for ski mountaineering. Thrust phase duration is defined as the time period during which the ski was still (Pellegrini et al. 2014). A validation study compared the adapted algorithm against an optoelectronic reference system (mean and standard error for stride frequency 0.001 ± 0.025 strides·min^{-1}, for stride length -0.025 ± 0.005 m·cycle^{-1} and for relative thrust duration 0.61 ± 0.28%). These errors were below the differences observed between trials, thus, the system could be considered valid for measuring temporal and spatial parameters of ski mountaineering on a treadmill.

Condition	Slope angle	Speed	Vertical speed
Flat slope, slow speed	10%	4 km·h^{-1}	398 m_{vert}·h^{-1}
Flat slope, medium speed	10%	5 km·h^{-1}	498 m_{vert}·h^{-1}
Flat slope, fast speed	10%	6 km·h^{-1}	597 m_{vert}·h^{-1}
Medium slope, slow speed	17%	3 km·h^{-1}	503 m_{vert}·h^{-1}
Medium slope, medium speed	17%	4 km·h^{-1}	670 m_{vert}·h^{-1}
Medium slope, fast speed	17%	5 km·h^{-1}	838 m_{vert}·h^{-1}
Steep slope, slow speed	24%	2 km·h^{-1}	467 m_{vert}·h^{-1}
Steep slope, medium speed	24%	3 km·h^{-1}	700 m_{vert}·h^{-1}
Steep slope, fast speed	24%	4 km·h^{-1}	933 m_{vert}·h^{-1}

Table 1: Speeds and slope angles of the nine different stages on treadmill and corresponding vertical speed (vertical m climbed per h).

Calculations

The rate of metabolic energy expenditure was calculated from the oxygen uptake ($\dot{V}O_2$) values assuming an energy equivalent of 20.9 kJ·l^{-1} O_2 (corresponding to a respiratory exchange ratio of

0.96) minus the energy expenditure at rest, determined before the beginning of the measurement session on treadmill while standing motionless. Relative energy cost of linear displacement ($J \cdot kg^{-1} \cdot m^{-1}$) was calculated by dividing the rate of metabolic energy expenditure by the speed and the body mass. Relative vertical displacement energy cost ($J \cdot kg^{-1} \cdot m_{vert}^{-1}$) was obtained by dividing the rate of metabolic energy expenditure by the vertical speed and the body mass. We calculated net mechanical efficiency of uphill ski mountaineering using Margaria's equation for uphill running:

$$\textit{net mechanical efficiency} = \textit{vertical mechanical power}/\textit{net metabolic rate} \quad (1)$$

where vertical mechanical power, i.e. the rate of work done to raise the body mass against gravity, is:

$$\textit{vertical mechanical power} = m \cdot g \cdot \sin(\arctan(\theta)) \cdot v \quad (2),$$

where m is the body mass (kg), g the gravity acceleration ($9.81\ m \cdot s^{-2}$), θ the slope angle and v the speed ($m \cdot s^{-1}$) (Margaria 1968; Margaria et al. 1963). Maximal HR (HR_{max}) was estimated using the formula $HR_{max} = 220 - age$ and exercise intensity of each stage with the mean HR (HR_{mean}) during the last 30 s of the trail in percentage of estimated HR_{max} ($HR_{mean}/HR_{max} \cdot 100$).

Statistical analysis

Data analysis was performed with Matlab (The Mathworks, USA) and Excel (Microsoft, USA). Statistical analysis was done with Stata (StataCorp, USA). Normal distribution was checked graphically and ANOVAs associated with post-hoc t-tests were used to test the associations between speed and energy cost, vertical energy cost, mechanical efficiency, stride length, stride frequency and relative thrust phase duration and associations between slope angle and energy cost, vertical energy cost, mechanical efficiency, stride length, stride frequency and relative thrust phase duration. Then linear mixed models were applied to test a possible interaction between speed and slope angle assuming linear effects of speed and slope. The significance level was set at 0.05. Linearity of the relationships between parameters was assessed graphically.

Results

Due to technical problems with the metabolic system, the data of eight subjects could be taken into account for the metabolic analysis and eleven for the biomechanical analysis

HR_{mean} and exercise intensity (percentage of estimated HR_{max}) of each stage are indicated in Table 2: ANOVAs showed that the intensity was different between the three speeds at each slope angle, but similar for the slow, middle and fast speeds at each slope angle, respectively.

Effect of speed on energy cost, vertical energy cost and mechanical efficiency

For the flattest slope angle (10%), energy cost, vertical energy cost and mechanical efficiency did not change significantly with speed. For the steeper slope angles (17 and 24%) significant changes were only observed between medium and high speeds: energy cost and vertical energy cost decreased and mechanical efficiency increased at high speeds (Figures 1-3, Table 2).

Slope angle	Speed ($km \cdot h^{-1}$)	HR_{mean} (bpm)		Percentage of HR_{max}		Energy cost ($J \cdot kg^{-1} \cdot m^{-1}$)		Vertical energy cost ($J \cdot kg^{-1} \cdot m_{vert}^{-1}$)		Mechanical efficiency	
10%	4	136 ± 19		71 ± 9		6.2 ± 1.0		62 ± 10		0.16 ± 0.03	
10%	5	146 ± 17	*	76 ± 9	*	6.1 ± 0.6		61 ± 6		0.16 ± 0.01	
10%	6	160 ± 17		84 ± 8		6.1 ± 0.4		61 ± 4		0.16 ± 0.01	
17%	3	133 ± 16		69 ± 8		8.0 ± 0.7		48 ± 4		0.21 ± 0.02	
17%	4	151 ± 15	*	79 ± 8	*	8.3 ± 0.5	*	49 ± 4	*	0.20 ± 0.01	*
17%	5	165 ± 14		86 ± 7		7.5 ± 0.6		45 ± 4		0.22 ± 0.02	
24%	2	130 ± 20		67 ± 10		10.2 ± 0.8		44 ± 4		0.23 ± 0.02	
24%	3	149 ± 21	*	77 ± 11	*	10.3 ± 0.7	*	44 ± 3	*	0.22 ± 0.02	*
24%	4	164 ± 18		86 ± 10		9.1 ± 0.9		39 ± 4		0.25 ± 0.03	

Table 2: Effect of speed: energy cost, vertical energy cost and mechanical efficiency for each slope angle and speed and significant results of the ANOVA which tested the effect of speed on energy cost, vertical energy cost and mechanical efficiency. The exercise intensity of each stage is indicated with HR_{mean}. The * indicate significant global effect of speed, ($p<0.05$).

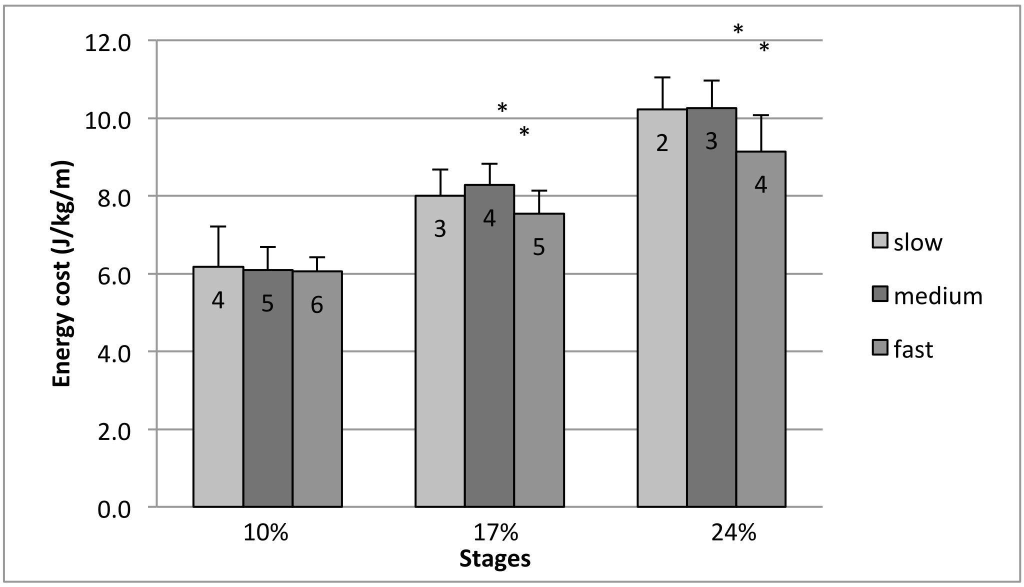

Figure 1: Effect of speed on energy cost: average energy cost for all the speeds at 10, 17 and 24% (mean and SD). With a 'flat' slope angle (10%), there was no significant change of energy cost with speed. With steeper slope angles (17 and 24%), the energy cost was significantly lower at the fastest speed compared to the slow and medium speeds. The numbers on the columns indicate the speed in km·h^{-1} and the * indicate significant differences.

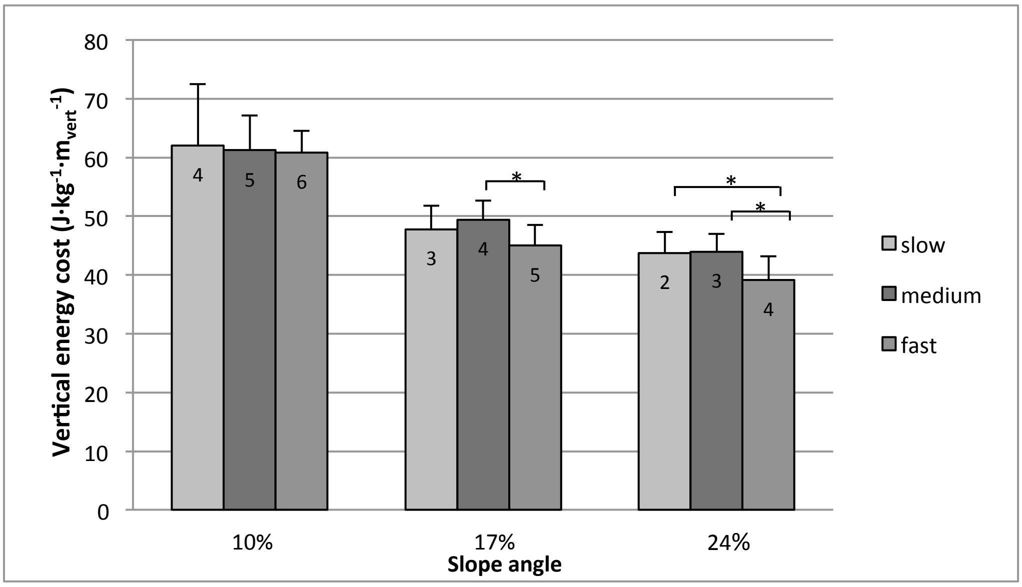

Figure 2: Effect of speed on vertical energy cost: average vertical energy cost at 10, 17 and 24% (mean and SD). With a 'flat' slope angle (10%), there was no significant change of vertical energy cost with speed. With steeper slope angles (17 and 24%), the vertical energy cost was significantly lower at the fastest speed compared to the slow and medium speeds. The numbers on the columns indicate the speed in km·h^{-1} and the * indicate significant differences.

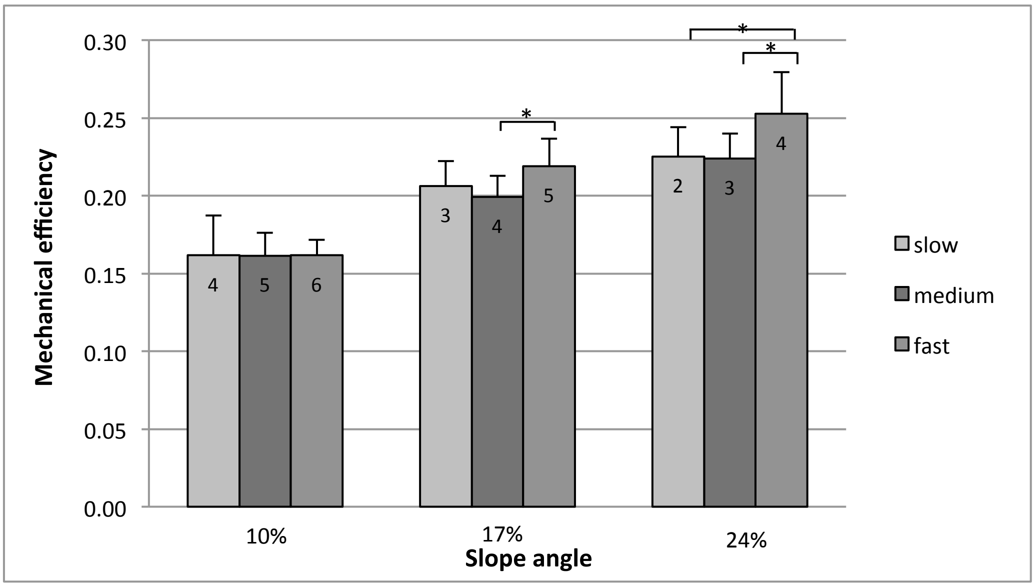

Figure 3: Effect of speed on mechanical efficiency: average mechanical efficiency at 10, 17 and 24% (mean and SD). With a 'flat' slope angle (10%), there was no significant change of mechanical efficiency with speed. With steeper slope angles (17 and 24%), the mechanical efficiency was significantly better at the fastest speed compared to the slow and medium speeds. The numbers on the columns indicate the speed in km·h^{-1} and the * indicate significant differences.

Effect of slope angle on energy cost, vertical energy cost and mechanical efficiency

At 4 km·h^{-1}, all slope angles (10, 17 and 24%) were tested (Table 3): slope angle had a significant effect on energy cost, vertical energy cost and mechanical efficiency. Energy cost increased with slope angle (Figure 4), while vertical energy cost decreased with slope angle (Figure 5) and mechanical efficiency was increased with steeper slope angle (Figure 6).

Gradient	Speed (km·h^{-1})	Energy cost (J·kg^{-1}·m^{-1})		Vertical energy cost (J·kg^{-1}·m_{vert}^{-1})		Mechanical efficiency	
10%	4	6.2 ± 1.0		62 ± 10		0.16 ± 0.03	
17%	4	8.3 ± 0.5	*	49 ± 4	*	0.20 ± 0.01	*
24%	4	9.1 ± 0.9		39 ± 4		0.25 ± 0.03	

Table 3: Effect of slope angle: energy cost, vertical energy cost and mechanical efficiency at 4 km·h^{-1} and 10, 17 and 24% and significant results of the ANOVA, which tested the effect of slope angle on energy cost, vertical energy cost and mechanical efficiency. The * indicate a significant global effect of slope angle ($p<0.05$).

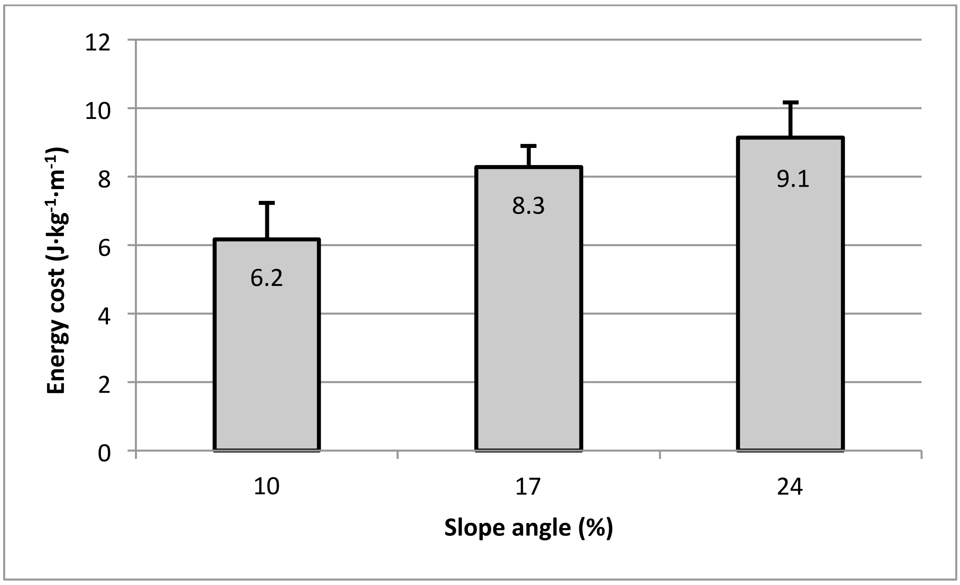

Figure 4: Effect of slope angle: energy cost at 10, 17 and 24% at 4 km·h^{-1} (mean and SD). Energy cost increased with the slope angle. Numbers on the columns indicate the mean. All the differences were significant and the relationship seemed to be linear.

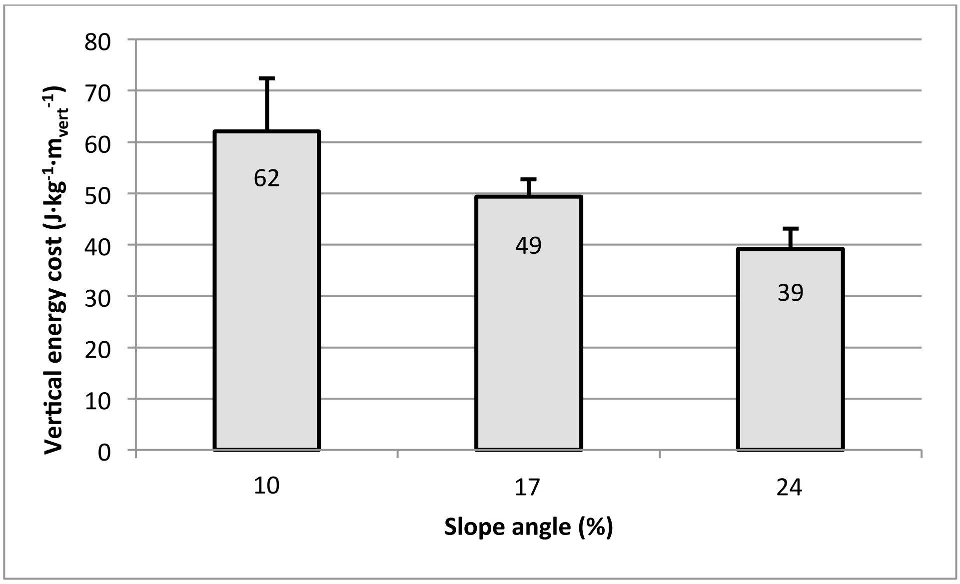

Figure 5: Effect of slope angle: vertical energy cost at 10, 17 and 24% at 4 km·h^{-1} (mean and SD). Vertical energy cost decreases with the slope angle. Numbers on the columns indicate the mean. All the differences were significant but the relationship seemed to not be linear, the difference is bigger between 10 and 17% than between 17 and 24%.

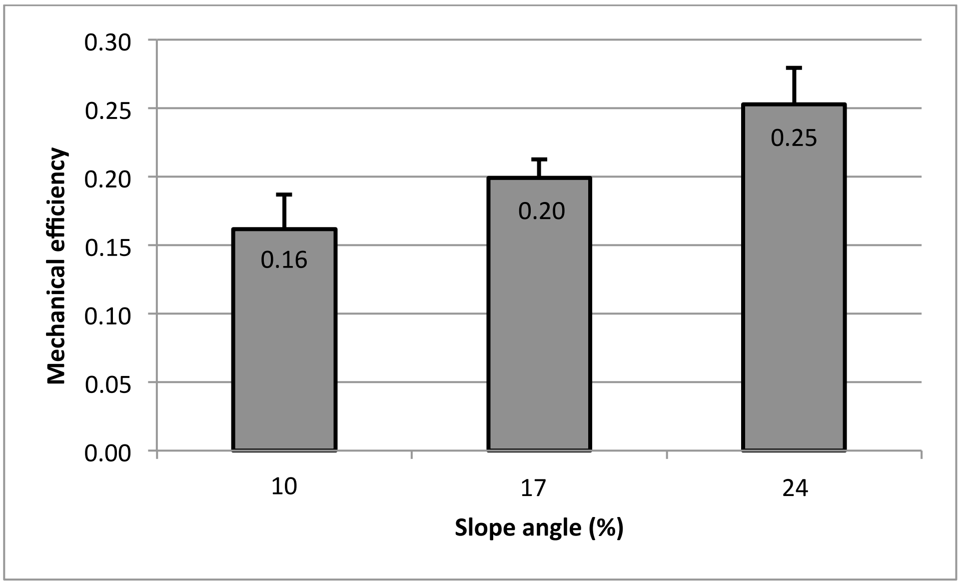

Figure 6: Effect of slope angle: mechanical efficiency at 10, 17 and 24% at 4 km·h^{-1} (mean and SD). Mechanical efficiency increased with slope angle. Numbers on the columns indicate the mean. All the differences were significant and the relationship seemed to be linear.

The relationships slope angle vs. vertical energy cost and slope angle vs. mechanical efficiency appeared to be linear.

A linear mixed model showed a significant interaction between speed and slope angle for all the three measured metabolic variables. Energy could be predicted from speed and slope angle as:

Energy cost = 0.17·speed + 34.30·slope angle - 2.65·speed·slope angle + 3.2 (R^2=0.82)

The slope angle was positively associated with the energy cost ($p<0.001$), but when the speed increased, the effect of slope angle became weaker ($p=0.04$) and there was no significant effect of speed on energy cost at 10% ($p=0.46$), but when the slope angle increased, the effect of speed on energy cost became negative ($p=0.04$).

Mechanical efficiency could be predicted with speed and slope angle:

Mechanical efficiency = -0.01·speed + 0.17·slope angle + 0.12·speed·slope angle + 0.15 (R^2=0.74)

For higher speeds, the effect of slope angle was higher and for the steeper slope angle, the effect of speed was higher ($p<0.01$).

Vertical energy cost could also be predicted from speed and slope angle:

Vertical energy cost = 3.5·speed - 43.5·slope angle - 29.5·speed·slope angle + 62.09 (R^2=0.71)

Inversely, the interaction between speed and slope angle was negative, so when the speed was increased, the effect of slope angle decreased; meanwhile, when the slope angle was increased, the effect of speed decreased (p<0.01).

Effect of speed and slope angle on biomechanical variables

Stride frequency

There was a significant effect of speed on stride frequency irrespective of the considered slope angle (Table 4). The faster the speed, the higher the frequency, but the relationship did not appear linear. The stride frequency increased more between the two slowest speeds than between the two fastest speeds. The effect of slope angle on stride frequency was not significant but with p=0.06 a tendency appeared (Table 5). The difference was more important between the flattest slopes (10 and 17%), than between the steepest slopes (17 and 24%).

Stride length

The effect of speed on stride length was more pronounced when the slope angle was steeper (p=0.16 at 10%, p=0.08 at 17% and p<0.01 at 24%) (Table 4). The stride length increase appeared non-linear. Again, the difference was bigger between the slowest speeds than between the fastest. There was a significant effect of slope angle on stride length (Table 5): the relationship did not seem linear, but rather to decrease toward a plateau or optimum. Even if we assume linearity, the linear mixed model showed no interaction between speed and slope (p=0.74).

Relative thrust phase duration

The effect of speed on relative thrust phase duration was more pronounced when the slope angle was steeper (p=0.17 at 10%, p=0.09 at 17% and p<0.01 at 24%) (Table 4). The relative thrust phase duration decrease did not appear linear; it decreased between the slowest speeds and then tended to stabilize. There was a significant effect of slope angle on thrust phase duration (Table 5), but it did not seem linear but rather to increase toward a plateau or optimum (Table 5). Even if we suppose linearity, the linear mixed model showed no interaction between speed and slope (p=0.11).

Slope angle	**Speed (km·h^{-1})**	**Stride frequency (stride·min^{-1})**		**Relative thrust phase duration (% of cycle duration)**		**Stride length (m)**	
10%	4	38 ± 5		38 ± 3		1.88 ± 0.29	
10%	5	43 ± 6	*	33 ± 4		2.09 ± 0.37	
10%	6	47 ± 8		35 ± 7		1.99 ± 0.31	
17%	3	36 ± 5		48 ± 4		1.54 ± 0.24	
17%	4	41 ± 4	*	44 ± 4		1.77 ± 0.27	
17%	5	44 ± 9		45 ± 6		1.70 ± 0.27	
24%	2	29 ± 4		58 ± 5		1.30 ± 0.26	
24%	3	37 ± 4	*	53 ± 4	*	1.48 ± 0.22	*
24%	4	41 ± 4		47 ± 5		1.65 ± 0.16	

Table 4: Effect of speed: stride frequency, relative thrust phase duration and stride length for each stage and significant results of the ANOVA, which tested the effect of slope angle on stride frequency, relative thrust phase duration and stride length. The * indicate a significant global effect of slope angle (p<0.05).

Slope angle	**Speed (km·h^{-1})**	**Stride frequency (stride·min^{-1})**	**Relative thrust phase duration (% of cycle duration)**		**Stride length (m)**	
10%	4	38 ± 5	38 ± 3		1.88 ± 0.29	
17%	4	41 ± 4	44 ± 4	*	1.77 ± 0.27	*
24%	4	41 ± 4	47 ± 5		1.65 ± 0.16	

Table 5: Effect of slope angle: stride frequency, relative thrust phase duration and stride length at 4 km·h^{-1} and 10, 17 and 24% and significant results of the ANOVA, which tested the effect of slope angle on stride frequency, relative thrust phase duration and stride length. The * indicate a significant global effect of slope angle (p<0.05).

Discussion

On the uphill sections of ski mountaineering competition routes the goal is to reach a place located at a higher altitude in the shortest possible time. A combination of high metabolic scope (i.e. the sustainable fraction of $\dot{V}O_{2max}$ for the duration of the effort (Peterson et al. 1990)) with a low energy cost of locomotion is therefore key. The former is a function of genetic make-up and training while the latter is function of body and gear weight, the biomechanics of the particular movement and the trade-off between speed, slope angle, efficiency and metabolic scope. The main finding of our study was that, provided there is sufficient metabolic scope, a combination of a steep slope angle and a high speed is accompanied by a lower vertical energy cost and a higher mechanical efficiency, suggesting that it is more economical to choose a steeper route at lower speed while skiing uphill (Figure 7, green hatched area of the plane).

In this work, three main energetic parameters of the locomotion were analysed: the energy cost of linear displacement along a slope angle, the vertical energy cost and the mechanical efficiency. The latter two can be considered as more essential with regard to the energy cost of ski mountaineering, in which efficient vertical displacement is the main goal (Minetti 1995). At flatter slope angles, speed had no significant effect on energy cost, vertical energy cost or mechanical efficiency. By contrast, at steeper slope angles, the fastest speed was more economical (lowest energy cost and vertical energy cost, and higher mechanical efficiency). Simultaneously, mechanical efficiency increased with the slope angle while vertical energy cost decreased with an increasing slope angle, suggesting that a steeper slope angle is more economical. These results suggest that if an athlete possesses the required aerobic capacity, he/she should choose a combination of steep slope angle and fast speed to minimize his energy expenditure and optimize his/her performance.

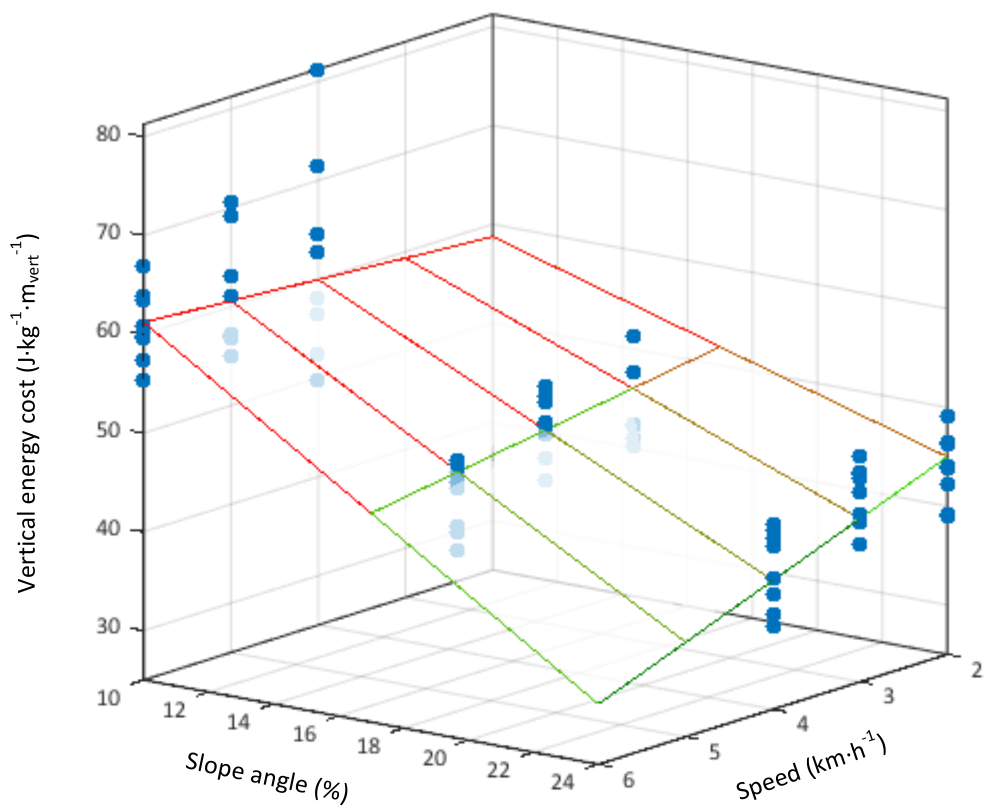

Figure 7: Vertical energy cost (J·kg^{-1}·m$_{vert}$$^{-1}$) as a function of slope angle (%) and speed (km·h^{-1}) (linear mixed model). In order for a ski mountaineering athlete to optimize performance, i.e. overcoming an altitude difference as fast as possible, sufficient aerobic capacity should be available in order to be able to combine a high speed with a steep slope angle (green area of the inclined plane).

Energy cost

The energy cost values we found (between 6.1 and 10.3 J·kg^{-1}·m^{-1} according to the stages) were slightly lower than the energy cost found by Tosi et al. on snow (Tosi et al. 2009) (10.6 ± 0.4 J·kg^{-1}·m^{-1}) and on treadmill (Tosi et al. 2010) (10.6 ± 0.2 J·kg^{-1}·m^{-1}) at 21% slope angle. Several factors could explain these differences, like differences in the friction coefficients, in the protocol (distance, slope angle, fatigue, etc.) or in the subjects (size, etc.)…

This study's findings confirm that energy cost depends on speed, as pointed out by Tosi et al. for ski mountaineering (Tosi et al. 2009; Tosi et al. 2010) and by Blessey et al. for walking (Blessey et al. 1976). The energy cost of walking changes non-linearly with speed, as it does for running, even if the variation is less important than for walking (Steudel-Numbers and Wall-Scheffler 2009). The study's results suggest that the same is true for ski mountaineering, since larger energy expenditure differences were observed between the intermediate and faster speeds than between the slower and intermediate speeds.

Even though only three slope angles were tested, graphical inspection of the results would suggest that the relationship between slope angle and energy cost was linear. It is possible that the relationship between slope angle and energy cost for higher resolution of tested slope angles would have been non-linear as reported for walking and running (Minetti et al. 2002; Saibene and Minetti 2003). Minetti et al. showed that above 15% the energy cost of running and walking were directly proportional to the slope angle, but that below 15% the energy cost decreased non-linearly. But this part of the curve is less interesting in the case of ski mountaineering, because such flat slope angles are less common in this mountain activity and when such flat slopes are encountered ski mountaineering athletes remove the skins from under the skis and generally revert to a cross-country skating as locomotor pattern.

Mechanical efficiency

The principle of mechanical efficiency, like introduced by Margaria et al. for walking (Margaria 1968) considers the energy expenditure only as a gain/loss of potential energy, disregarding the kinetic energy. Margaria et al. further assumed that beyond a given slope angle the rise of the centre of mass is the prevailing contributor to the mechanical external work (Minetti et al. 2002). For walking, it has been found that the negative work from the cyclic downward movements of the centre of mass disappears at around 15-20%. Thus, there is only positive work and it has been shown that the efficiency of walking at steep slope angles approaches 0.25, close to that of concentric contractions (Woledge et al. 1985). Indeed, beyond this angle, negative eccentric work regresses to nil and only positive concentric work remains because body mass is almost exclusively accelerated against gravity and not anymore slowed down (Minetti et al. 1993). In the present study, the flattest tested slope angle (10%) was flatter than 15%, so it is less obvious that the kinetic energy can be neglected for this slope angle and the mechanical efficiency calculation is therefore less accurate for this slope angle.

Nevertheless, the present results are similar to those reported for the effect of slope angle during running and walking (Minetti et al. 2002). The mechanical efficiency close or equal to 0.25 found for the steepest slope angle represents the efficiency of mainly concentric muscle contractions (Woledge et al. 1985) and suggests that during ski mountaineering at 24% all mechanical work done can be considered as positive.

Mechanical efficiency increased with increasing slope angle and the graphical inspection of the results suggested that the relationship between slope angle and mechanical efficiency was linear. The results are also in concordance with the results from Tosi et al. (Tosi et al. 2010) who reported that the mechanical efficiency is dependent on speed. But this was only the case for the intermediate and steep slope angles. At 10%, there was no significant change of mechanical efficiency with speed.

Vertical energy cost

Vertical energy cost was the lowest at the steepest slope angle combined with the fastest speed, indicating that this condition was the most economical. Nevertheless, it remains possible that at even steeper slope angles (>24%), the vertical energy cost may even be lower than the values that we observed, on the condition that the athlete would have the required aerobic capacity to maintain a sufficiently fast speed. In fact, 4 $km \cdot h^{-1}$ at 24% was not an all-out effort (86 ± 10% of estimated HR_{max}) for many of the subjects and it cannot be excluded that in several of them at a faster speed, the vertical energy cost could have decreased even further. By using the link between the vertical energy cost, the vertical speed, the $\dot{V}O_2$, the $\dot{V}O_2$ was estimated at 6 $km \cdot h^{-1}$ and 24% (minimum value for vertical energy cost in figure 7) and it would be about 45 $mlO_2 \cdot kg^{-1} \cdot min^{-1}$. Such oxygen consumption would be submaximal for well-trained elite endurance athletes with high $\dot{V}O_{2max}$ (Schneider 2013).

Steeper slope angles should therefore be tested in a further study, if possible with elite athletes who possess high aerobic metabolic scope.

By calculating the vertical energy cost we could estimate the optimal slope angle for ski mountaineering tracks, similarly to what was done for walking on mountain trails (Minetti 1995). For walking and running, like for ski mountaineering, vertical energy cost decreased with increasing slope angle, while the covered distance decreased. By multiplying the vertical energy cost (per unit distance) by the path length (distance in the incline), the total energy expenditure can be estimated. For walking and running the existence of an optimal slope angle minimizing energy expenditure has been demonstrated and the optimum slope angle for mountain trails to minimize the energy expenditure was reported to lie between 25 and 28% (Minetti 1995). We found that for ski mountaineering the vertical energy cost decreased from 10, to 17 and to 24%. It would thus seem likely that the minimum vertical energy cost might be found above 24%, close to the optimal slope angle reported for walking, but our treadmill did not allow testing steeper slopes. Also, we only tested our subjects while breathing ambient air, i.e. with an inspired oxygen tension corresponding to low altitude (Lausanne University, 395m). Altitude comes with a drop in inspired oxygen tension, which leads to a decrease in aerobic capacity (Cerretelli 1976). Consequently, the fraction of $\dot{V}O_{2max}$ sustainable for a prolonged period of time is lower at higher altitude, so the athletes should choose flatter slope angles than at lower altitude. It follows, as for mountain trails, that ski mountaineering routes' slope angles should be adapted to the effect of altitude on metabolic scope (Minetti 1995).

Stride parameters

In support to previous studies on running and walking, the stride parameters changed with speed and slope angle. These relationships are in accordance with the relationships found for running and walking (Bertram and Ruina 2001; Kawamura et al. 1991; Padulo et al. 2013): an increase of the speed is associated with stride length and frequency increases and a decrease of the relative thrust phase duration, while an increase of the slope angle is associated with stride frequency and relative thrust phase duration increases and a decrease of the stride length. These relationships seem to be curvilinear with a plateau or an optimum at intermediate speeds, possibly indicating biomechanical limitations. No previous study investigated stride length, stride frequency and thrust phase duration in ski mountaineering and this study provides some first reference values. Further studies on snow are necessary to verify if these data obtained with roller skis on treadmill are confirmed during actual ski mountaineering.

Conclusions

A combination of a decreased relative thrust phase duration with increased stride length and frequency decreases vertical energy cost in ski mountaineering. To minimize the energy expenditure to reach the top of a mountain and to optimize performance, ski-mountaineers should therefore choose a steep slope angle (at least 24%) and, provided they possess sufficient metabolic scope, combine this steep slope angle with a fast speed (at least 6 $km \cdot h^{-1}$).

Acknowledgements

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Competing interests

There are no competing interests.

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Appendix 6: Optimal slopes and speeds in ski mountaineering – a field study

Optimal slopes and speeds in ski mountaineering – a field study (in preparation)

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Abstract

Introduction: The objectives of this study were to verify earlier results obtained during simulated ski mountaineering on a treadmill, by testing different speeds and slope gradients during actual ski mountaineering on snow, to describe the effects of speed and slope gradient on energy expenditure, to relate any changes to changes in stride characteristics, and to determine an optimal slope gradient and speed allowing minimization of energy expenditure and optimization of performance.

Methods: 11 subjects were tested using their ski mountaineering gear at three different slope gradients (7, 11 and 33%) at 80% of maximum heart rate, and at 11% at three different speeds at 80, 90 and 100% of maximum heart rate. Energy expenditure was calculated by indirect calorimetry to derive energy cost of locomotion (EC), vertical energy cost (ECv) and mechanical efficiency of vertical displacement, while biomechanical parameters (stride length, stride frequency, relative and absolute thrust phase duration) were measured with an inertial sensor-based system.

Results/discussion: At 11% there was no significant change with speed in EC, EC_v and mechanical efficiency, while stride length and frequency increased and absolute thrust phase duration decreased. There was a significant effect of slope gradient on EC, EC_v and mechanical efficiency, while speed, stride length and stride frequency decreased and absolute and relative thrust phase duration increased. The most economical slope angle (lowest EC_v and highest efficiency) was the steepest one.

Conclusion: During ski mountaineering uphill at shallow slope gradients (11%) EC, EC_{vert} and mechanical efficiency do not vary with speed, while at steeper slope gradients (33%) speed improves economy. It follows that to minimize the energy expenditure and optimize performance to reach a place located at a higher altitude in ski mountaineering, an athlete should choose a steep slope gradient, if he/she is able to maintain a sufficient speed.

Keywords:

endurance, skiing, energy expenditure, biomechanics, climbing

Abbreviations:

ANOVA: analysis of variance

EC: energy cost of locomotion

EC_{vert}: vertical energy cost

HR_{max}: maximum heart rate

HR: heart rate

m_{vert}: vertical meter

$\dot{V}O_2$: oxygen uptake

$\dot{V}O_{2max}$: maximal oxygen uptake

Introduction

Energy expenditure and energy cost of locomotion have been extensively studied for many types of human locomotion (walking, running, cycling, skating, rowing, swimming, cross country skiing, etc.) [1-5]. The energy cost of locomotion is the amount of energy required to cover a given distance (EC, generally expressed in $J \cdot kg^{-1} \cdot m^{-1}$) or, in the case of vertical energy cost, to gain 1 m of altitude (m_{vert}) (EC_{vert} generally expressed in $J \cdot kg^{-1} \cdot m_{vert}^{-1}$). EC and EC_{vert} allow quantifying how economical a given locomotion is and comparing different types of locomotion. When studying vertical displacements a third important parameter is mechanical efficiency, which quantifies the effectiveness in transforming metabolic energy in vertical displacement. In case of locomotion along a slope gradient the EC_{vert} and mechanical efficiency are more representative of the overall economy of the locomotion than EC, because the main goal is to reach a place located at higher altitude and not to cover a given distance [6].

Ski mountaineering is an increasingly popular winter sport and leisure activity, especially in the European Alps. Increasing numbers of people practice this activity for leisure, and also competitive ski mountaineering has gained in popularity. There are now many regional, national and international events, including European and World Championships. Elite athletes practice this sport with a high level of professionalism, but as yet without much scientific evidence to support their approach, as illustrated by the scant literature on this particular mode of locomotion.

Tosi et al. [7] reported that the EC of ski mountaineering is higher than the EC of walking or snowshoeing, and also quantified the effect of ankle loading on EC. They concluded that ankle loading has a negligible effect for recreational skiers, but should be taken into account by elite skiers to optimize performance. In another study [8], simulating ski mountaineering with roller skis on a treadmill, similar EC values as found on snow were reported ($10.6 \pm 0.4\ J \cdot kg^{-1} \cdot m^{-1}$ at 21% and 3.9

$km \cdot h^{-1}$ on snow versus 10.6 ± 0.2 $J \cdot kg^{-1} \cdot m^{-1}$ at 21% and 3.5 $km \cdot h^{-1}$ on treadmill). They also found that athletes self-selected a speed around 3.5 $km \cdot h^{-1}$ which minimized the EC, and that the mechanical efficiency increased with speed up to a maximum at around 4.5 $km \cdot h^{-1}$.

However, these studies neglected an important factor in ski mountaineering: the slope gradient. For ski mountaineering uphill, the goal is reaching a place located at a higher altitude than the starting point in the shortest time possible. The EC_{vert} is therefore especially important and should be taken into account when choosing the best trajectory to reach the place of arrival as quickly as possible, while preventing excessive exertion. Furthermore, because of the constraints imposed by the terrain the slope gradients can be expected to vary along a given route.

For walking and running the EC_{vert} depends on the slope gradient. Less energy is expended climbing 1 m at steeper slope gradients, up to an optimum slope gradient (between 25 and 30%), while beyond it climbing again becomes more costly [6, 9]. It can be reasonably expected that the same would apply for ski mountaineering. If an optimal slope gradient with minimum energy expenditure could be defined it would help the ski mountaineer in choosing the most appropriate path to reach a destination at a higher altitude. As speed may also influence EC [7, 8], it would be especially interesting to test different combinations of speeds and slope gradients.

In a previous study (Praz et al., submitted) we tested different combinations of slope gradients and speeds in a laboratory setting using roller skis on a motorized treadmill. The main finding was that, provided the athlete had sufficient metabolic scope (i.e. high $\dot{V}O_2max$), a combination of a steep slope gradient and a high speed was accompanied by a lower EC_{vert} and a higher mechanical efficiency, suggesting that it was more economical to choose a steeper route while ski mountaineering uphill. The slope gradient had a significant effect on energy expenditure (energy expenditure was higher with steeper slope gradient) while the effect of speed on energy expenditure was significant only when the slope gradient was steep (the fastest speed was the most economical). In addition, it was found that an increased speed was accompanied by a significant and non-linear increase of stride frequency (irrespective of the considered slope gradient), of relative thrust phase duration and of stride length (if the slope gradient was steep). Moreover, an increased slope gradient implied an increased relative thrust phase duration, an increased stride frequency and a decreased stride length. Due to technical limitations of the treadmill, the upper range of tested slope gradients was limited to 24%. Since we found that the steepest tested slope gradient (24%) was the most economical, it would be of interest to test steeper slope gradients to see if the energy expenditure might be even lower at these slope gradients. The controlled laboratory conditions of our former study allowed standardization, but roller skiing on a motorized treadmill differs from actual ski mountaineering on snow: compared to regular skis, the roller skis we used on the treadmill were shorter and narrower, and depending on snow conditions, the friction coefficients might be different [10, 11].

The main goal of this work was therefore to verify the results found during simulated ski mountaineering on a treadmill by testing different speeds and slope gradients during actual ski mountaineering on snow, including at a steeper slope gradient than 24%, to describe the effects of speed and slope gradient on energy expenditure (EC, EC_{vert}, mechanical efficiency) and to relate any changes to changes in biomechanical parameters (stride frequency, stride length, relative and absolute thrust phase duration). The main objective was to determine if it is possible to minimize the energy expenditure and to optimize the performance by modifying the slope gradient and the speed.

Methods

The protocol of the study was approved by the Valais research ethics committee (CCVEM 033/11). Each participant gave informed written consent prior to participating to the study.

Subjects

11 male ski mountaineers were recruited (34 ± 8 years, 176 ± 5 cm, 69 ± 9 kg body mass and 8 ± 2 kg carried material (clothes, boots, skis, poles, gear, backpack), 14 ± 7% of fat mass and $\dot{V}O_{2max}$: 61 ± 7 $ml \cdot kg^{-1} \cdot min^{-1}$). They were all well trained and experienced in ski mountaineering.

Experimental design

The athletes were first seen in the laboratory for anthropometric and aerobic fitness measurements and then took part to the field test. The time period between the two sessions was between 1 and 4 weeks.

Laboratory test

The protocol of the laboratory test consisted of anthropometric measurements: weight, height and body composition (rod, balance, air displacement plethysmography (Bodpod, Cosmed, Italy)) and a maximal running test on a treadmill (HP Cosmos Pulsar, Germany). With this test, maximal oxygen expenditure ($\dot{V}O_{2max}$) and maximal heart rate (HR_{max}) were determined. After a 3 min warm-up at 5.4 $km \cdot h^{-1}$, speed was gradually increased every 3 min from a first stage at 7.2 $km \cdot h^{-1}$, up to voluntary exhaustion.

Gas exchange and breathing variables were measured breath-by-breath with a metabolic measurement system (Metalyzer, Cortex, Germany), heart rate (HR) beat-by-beat with a portable HR monitor (Suunto t6d, Finland) and blood lactate concentration was measured at each stage on a finger capillary sample (Lactate Pro LT-1710, Arkray, Japan). The metabolic system was calibrated prior to each session with a 3 l syringe and gases of known composition.

Field test

The athletes first skied uphill on three different sections (lasting between 5 and 10 min each), at low intensity (aiming at a HR between 70 and 80% of HR_{max}). Intensity was controlled with feedback provided by a portable HR monitor (Suunto Ambit, Finland). The mean slope gradients of the different sections were 7% ('flat gradient'), 11% ('middle gradient') and 33% ('steep gradient') and the distances were 765, 500 and 595 m, respectively. The goal of this part of the protocol was to look at the effect of slope gradient on EC and biomechanical parameters. Then the athletes repeated the middle gradient twice: first at high (between 80 and 90% of HR_{max}) and then at maximum intensity, to look at the influence of exercise intensity (in other words, of speed) on EC and biomechanical parameters.

The athletes climbed from the start to the marked finish lines without making any sharp turns. The starting line was at an altitude of 1,733 m, the finish lines were at 1,787, 1,802 and 1,891 m, respectively. The three sections led sequentially along a large marked path ('flat' and 'middle slope gradients') and an alpine ski slope ('steep slope gradient'). The sections were selected such as to keep the slope gradients constant. The order of the trials was always the same: 'flat slope gradient', 'steep slope gradient', 'middle slope gradient', 'middle slope gradient high intensity', 'middle gradient slope maximum intensity'. This order was chosen to minimize the effects of fatigue.
During the test, athletes were equipped with their personal ski mountaineering gear (skis, boots, and poles). Gas exchange and breathing variables were measured breath-by-breath with a portable metabolic measurement system (Metamax, Cortex, Germany). The procedure for the calibration of the metabolic system was the same as for the measurements in laboratory.

A lightweight inertial sensor (36 g) with three-dimensional accelerometers (± 11 G) and three-dimensional gyroscopes (± 1200°$\cdot s^{-1}$) (Physilog 3, Gait Up, Switzerland) was attached to each ski, just in front of the binding. Their sampling frequency was set at 500 Hz. The two sensors were synchronized with each other using an electronical trigger and then synchronized with the HR monitor and the metabolic system at the beginning of the measurements. Stride frequency, stride length, absolute and relative thrust phase duration (% of the total stride duration) were computed using the algorithm from Fasel et al. [12] adapted for ski mountaineering (Praz et al., submitted). Four biomechanical parameters were analysed: the stride frequency (stride·min^{-1}), the stride length (m), the thrust phase duration (time period during which the ski was still) (s) and the relative thrust phase duration (% of the total stride duration). The slope gradient was also estimated with the inertial sensor during each thrust phase duration.

The last minute of each stage was considered for the metabolic analysis and the last 2 minutes for the biomechanical analysis.

Calculations

The rate of metabolic energy expenditure was calculated from the oxygen uptake ($\dot{V}O_2$) values assuming an energy equivalent of 20.9 kJ·l^{-1} O_2 (corresponding to a respiratory exchange ratio of 0.96) minus the energy expenditure at rest, determined before the beginning of the measurement session on the treadmill while standing motionless. Relative EC of linear displacement (J·kg^{-1}·m^{-1}) was calculated by dividing the rate of metabolic energy expenditure by the speed and the body mass. Relative vertical displacement energy cost (J·kg^{-1}·m_{vert}^{-1}) was calculated by dividing the rate of metabolic energy expenditure by the vertical speed and the body mass. Net mechanical efficiency of uphill ski mountaineering was calculated using Margaria's definitions for uphill running:

$$net\ mechanical\ efficiency = \frac{vertical\ mechanical\ power}{net\ metabolic\ rate}$$

vertical mechanical power, i.e. the rate of work done to raise the body mass against gravity:

$$vertical\ mechanical\ power = m \cdot g \cdot sin(arctan(\theta)) \cdot v,$$

where m is the body mass (kg), g the gravity acceleration (9.81 $m \cdot s^{-2}$), θ the slope gradient and v the speed ($m \cdot s^{-1}$) [13, 14].

Statistical analysis

Statistical analysis was done with Stata (StataCorp, USA). ANOVAs associated with post-hoc t-tests were used to analyse the effect of speed and slope gradient on the different variables. Normality was graphically checked (insufficient data for formal verification). The significance level was set at 0.05. Linearity of relationships between parameters was assessed graphically. A linear mixed model adjusted for speed and slope gradient was used to evaluate the effect of the activity (ski mountaineering or roller skiing) on the different variables.

Results

Exercise intensity and speeds

The average intensities, slope gradients, speeds and vertical speed of each trial are given in table 1. No significant differences were found for the maximal HR and $\dot{V}O_2$ measured during the maximal running test in laboratory and during the trial at maximal intensity in the field (Table 1).

There was no significant difference for the exercise intensity (%$\dot{V}O_{2max}$ (p=0.45) and %FC_{max} (p=0.11)) between the first three trials (7, 11 and 33% at low intensity); but for the same exercise intensity the speed decreased significantly with increasing slope gradient (all differences significant), while the vertical speed was significantly higher for steeper slope gradients (all differences significant) (Table 1).

Between the last three trials at a slope gradient of 11%, the intensity increased significantly (p<0.0001), as did the speed and vertical speed (p<0.0001). All differences were significant.

Slope Gradient	Target exercise intensity (%HR_{max})	Exercise intensity (%HR_{max})	Exercise intensity (%$\dot{V}O_{2max}$)	Speed ($km{\cdot}h^{-1}$)	Vertical speed ($m{\cdot}h^{-1}$)
7%	Between 70 and 80	75 ± 6	67 ± 10	6.1 ± 0.7	412 ± 65
33%	Between 70 and 80	80 ± 3	69 ± 8	2.2 ± 0.4	687 ± 93
11%	Between 70 and 80	79 ± 3	70 ± 8	4.7 ± 0.7	528 ± 77
11%	90	90 ± 2	84 ± 13	5.8 ± 0.7	634 ± 68
11%	100	99 ± 3	99 ± 11	6.8 ± 0.7	738 ± 74

Table 1: Slope gradients, exercise intensities and speeds for the five trials in chronological order. The values reported are mean ± SD.

Effect of slope gradient

Slope gradient had a significant effect on stride frequency and length and on relative and absolute thrust phase duration. The stride frequency and the stride length decreased significantly with increasing slope gradient, resulting in a slowdown, while thrust phase duration (absolute and relative) increased significantly (Table 2). All the differences between all the trials were significant.

Gradient	Exercise intensity (%$\dot{V}O_{2max}$)	Stride frequency ($stride{\cdot}min^{-1}$)		Stride length (m)		Thrust phase duration (s)		Relative thrust phase duration (% cycle duration)	
7%	67 ± 10	43 ± 8		2.37 ± 0.34		0.40 ± 0.04		29 ± 7	
11%	70 ± 8	42 ± 7	*	1.89 ± 0.24	*	0.57 ± 0.06	*	40 ± 8	*
33%	69 ± 8	28 ± 3		1.33 ± 0.15		1.26 ± 0.16		59 ± 8	

Table 2: Effect of slope gradient on stride frequency, stride length, absolute thrust phase duration and relative thrust phase duration (mean ± SD). The significant results of the ANOVAs (p<0.05) are indicated with a *. All the differences were significant.

Slope gradient had a significant effect on speed, EC, EC_{vert} and mechanical efficiency. The EC increased significantly with increasing slope gradient, while EC_{vert} decreased significantly and mechanical efficiency increased significantly (Table 3). All the differences were significant.

Slope gradient	Exercise intensity (% $\dot{V}O_{2max}$)	Speed ($km \cdot h^{-1}$)		EC ($J \cdot kg^{-1} \cdot m^{-1}$)		EC_{vert} ($J \cdot kg^{-1} \cdot m_{vert}^{-1}$)		Mechanical efficiency	
7%	67 ± 10	6.1 ± 0.7		7.4 ± 0.7		110 ± 21		0.09 ± 0.02	
11%	70 ± 8	4.7 ± 0.7	*	9.9 ± 1.1	*	88 ± 10	*	0.11 ± 0.01	*
33%	69 ± 8	2.2 ± 0.4		20.3 ± 1.2		66 ± 5		0.15 ± 0.01	

Table 3: Effect of slope gradient on EC, EC_{vert} and mechanical efficiency at low exercise intensity (mean ± SD). The significant overall results of the ANOVAs ($p<0.05$) are indicated with a *. All post-hoc (t-test) pairwise comparisons (EC, EC_{vert} and mechanical efficiency) were also significant).

Effect of exercise intensity at a slope gradient of 11%

The stride frequency and the stride length both increased significantly with increasing exercise intensity, resulting in a speed increase, all the trials were significantly different from each other. The absolute thrust phase duration decreased significantly with the total cycle duration (increase of the frequency), while no significant change of the relative thrust phase duration was detected ($p=0.93$) (no significant differences between the three trials) (Table 4).

Exercise intensity (% $\dot{V}O_{2max}$)	Stride frequency ($stride \cdot min^{-1}$)		Stride length (m)		Thrust phase duration (s)		Relative thrust phase duration (% cycle duration)
70 ± 8	42 ± 7		1.89 ± 0.24		0.57 ± 0.06		40 ± 8
84 ± 13	48 ± 6	*	1.99 ± 0.22	*	0.51 ± 0.08	*	41 ± 7
99 ± 11	54 ± 8		2.11 ± 0.15		0.46 ± 0.10		40 ± 5

Table 4: Effect of exercise intensity on stride frequency, stride length, thrust phase duration and relative thrust phase duration (mean ± SD). The significant results of the ANOVAs ($p<0.05$) are indicated with a *: exercise intensity had a significant effect on stride length and frequency and on absolute thrust phase duration.

There was no significant effect of exercise intensity (or speed) on the metabolic variables: EC ($p=0.85$), EC_{vert} ($p=0.46$) and mechanical efficiency ($p=0.74$) at 11% (Table 5).

Exercise intensity (%$\dot{V}O_{2max}$)	Speed ($km \cdot h^{-1}$)		EC ($J \cdot kg^{-1} \cdot m^{-1}$)	EC_{vert} ($J \cdot kg^{-1} \cdot m_{vert}^{-1}$)	Mechanical efficiency
70 ± 8	4.7 ± 0.7		9.9 ± 1.1	88 ± 10	0.11 ± 0.01
84 ± 13	5.8 ± 0.7	*	10.1 ± 1.5	91 ± 13	0.11 ± 0.02
99 ± 11	6.8 ± 0.7		10.2 ± 1.5	93 ± 14	0.11 ± 0.02

Table 5: Effect of exercise intensity on speed, EC, EC_{vert} and mechanical efficiency at 11% (mean ± SD). The significant results of the ANOVAs ($p<0.05$) are indicated with a *: exercise intensity had a significant effect on speed, but not on EC, EC_{vert} and mechanical efficiency.

Discussion

The main goals of this study were to describe the effects of speed and slope gradient on energy expenditure and to relate any changes to changes in biomechanical parameters, to compare these results to those found during simulated ski mountaineering on a treadmill and to determine if it is possible to minimize the energy expenditure and to optimize the performance by modifying the slope gradient and the speed. The EC_{vert} and the mechanical efficiency changes indicated that for vertical displacements a steeper slope gradient is more economical. This finding is similar to what was found in laboratory settings where we found that the steepest slope gradient (24%) was more advantageous (Praz et al., submitted). Additionally, in the current study slope gradients up to 33% were measured. The present study confirmed the laboratory results that at lower slope gradients (e.g. 11%), EC, EC_{vert} and mechanical efficiency were independent from speed (Praz et al., submitted).

More specifically, a steeper slope gradient was associated with a significantly higher EC, but lower EC_{vert} and higher mechanical efficiency, indicating that to reach the top of a mountain, it is more economical to choose a trail with a steeper slope gradient. Simultaneously, the stride length and frequency decreased (leading to the reduction in speed), while the thrust phase duration (absolute and relative) increased, showing that the motionless phase of each step became longer. These changes were similar to what is happening with speed and slope gradient changes in walking [15, 16].

As only three slope gradients were tested it is difficult to characterize the relationship between slope gradient and EC_{vert}. It remains possible that EC_{vert} would further decrease at slope gradients steeper than 33%. Figure 1B however, suggests that the relationship would be non-linear and would be similar to the relationship of slope gradient vs. EC_{vert} as described for running and walking. For running and walking, the slope gradient vs. EC_{vert} relationship is not linear, reaching a minimum between 25 and 30% [6, 9, 17, 18]. It cannot be excluded that it is also the case for ski mountaineering, considering that no slope gradients between 25 and 33% were tested. Based on our earlier laboratory results and the present findings it nevertheless appears likely that the slope gradient vs. EC_{vert} relationship is non-linear and that an optimum gradient probably exists. The latter might be located between 25 and 33%, like for running or walking, but it is not excluded that it is at an even steeper slope gradient. Further measurements at gradients between 25 and 33% and at slope gradients steeper than 33% would be useful to more conclusively determine an optimum slope gradient.

At the slope gradient of 11%, speed had no significant effect on the metabolic variables (EC, EC_{vert} and efficiency), while most of the biomechanical variables changed with speed: with increasing speed, the stride frequency and length increased and the absolute thrust phase duration decreased. The relative thrust phase duration was the only biomechanical variable that was not influenced by the speed at 11%. The finding that at 11% the metabolic variables remained constant, while the biomechanical variables changed indicates that the biomechanical changes of the strides are probably not the main reason for the energy expenditure changes at steeper slope gradients.

In our previous laboratory study we investigated the EC, EC_{vert}, mechanical efficiency and biomechanical variations with speed and slope gradient, using roller skis on a treadmill (Table 6) (Praz et al., submitted). Roller skis are short skis equipped with wheels that athletes use during summer to train on roads in preparation for the ski mountaineering season. From a metabolic perspective, roller skiing, like walking and running [9], was found to be more economical than actual ski mountaineering on snow (see also Figure 1). A linear mixed model analysis including activity (snow or treadmill), speed and slope gradient, confirmed the effect of activity on EC, EC_{vert} and efficiency ($p<0.0001$). The EC of roller skiing (between 6.1 and 10.3 $J \cdot kg^{-1} \cdot m^{-1}$) was lower than the EC of ski mountaineering (between 7.4 and 20.3 $J \cdot kg^{-1} \cdot m^{-1}$), but the evolution with speed and slope gradient was similar (Figure 1): EC was dependent on slope gradient but independent from speed when the slope gradient was shallow. It was the same for EC_{vert}: ski mountaineering on snow (between 66 and 110 $J \cdot kg^{-1} \cdot m_{vert}^{-1}$) seemed to be much less economical than roller skiing on a treadmill (between 39 and 62 $J \cdot kg^{-1} \cdot m_{vert}^{-1}$). But, again, the changes with speed and slope gradient were quite similar for both studies, with an influence of the slope gradient on EC_{vert} and no change with speed at a slope gradient of 10-11%. The mechanical efficiency was much lower on snow (between 0.09 and 0.15) than on the treadmill (between 0.16 and 0.25). In both cases, the mechanical efficiency was better for the steepest slope gradient and was independent of speed for low slope gradients (10-11%). A possible explanation for the higher EC of actual ski mountaineering might be higher friction forces between the skis and the snow and the higher carried load (on average 2 kg heavier). Thus, from a metabolic point of view, roller skiing seems not a perfect model for ski mountaineering. In comparison to actual ski mountaineering, the EC and EC_v are lower and the mechanical efficiency higher, but the evolution of energy expenditure as a function of speed and slope gradient seems to be similar.

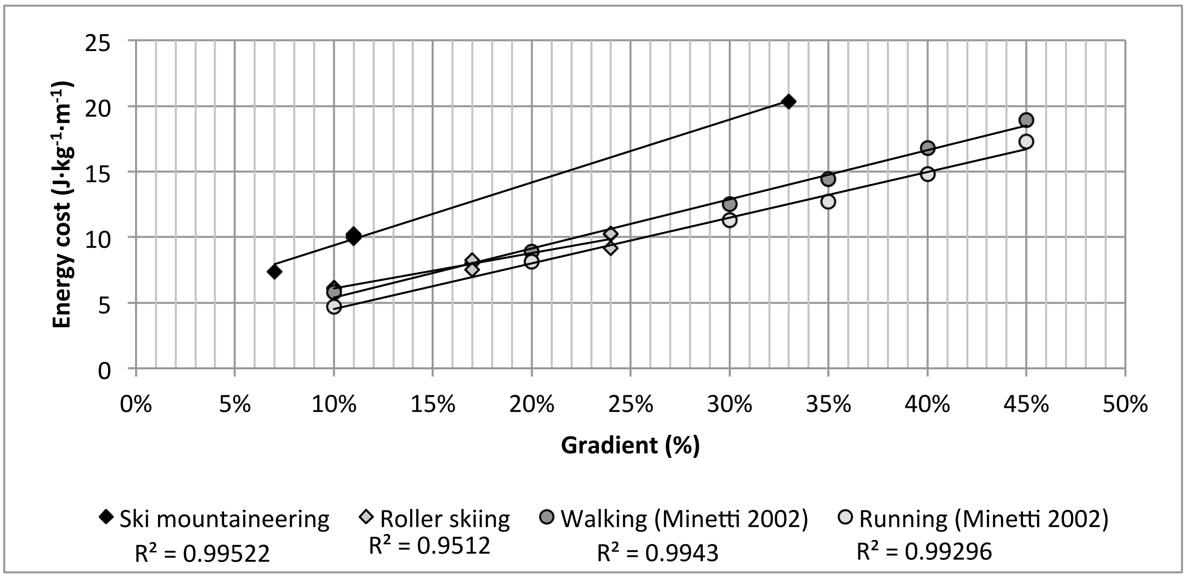
Even though roller skiing and ski mountaineering are different from a metabolic point of view, the stride characteristics seem rather similar. Comparing the trials at 10 and 11%, respectively, on treadmill and on snow, stride length, stride frequency and relative thrust phase duration were very similar (table 6): using a linear mixed model that predicts the different data from speed, slope gradient and activity, the activity (ski mountaineering or roller skiing) had no effect on stride length ($p=0.38$), stride frequency ($p=0.69$) and relative thrust phase duration ($p=0.54$). It should be noted that the stride frequency decreased with slope gradient for ski mountaineering, but not with roller skis. As the speed was constant for all the slope gradients in the roller skiing study and decreases with increasing slope gradient in the ski mountaineering study, it suggests that the increases with slope is rather due to the speed decrease at steep gradient, than due to the steep slope gradient itself.

Study	Slope Gradient	Speed ($km \cdot h^{-1}$)	EC ($J \cdot kg^{-1} \cdot m^{-1}$)	EC_{vert} ($J \cdot kg^{-1} \cdot m_{vert}^{-1}$)	Mechanical efficiency	Stride frequency ($stride \cdot min^{-1}$)	Relative thrust phase duration (% of cycle duration)	Stride length (m)
snow	7%	6.1	7.4	110	0.09	43	29	2.37
Treadmill	10%	4	6.2	62	0.16	38	38	1.88
Snow	11%	4.7	9.9	88	0.11	42	40	1.89
Treadmill	10%	5	6.1	61	0.16	43	33	2.09
Snow	11%	5.8	10.1	91	0.11	48	41	1.99
Treadmill	10%	6	6.1	61	0.16	47	35	1.99
Snow	11%	6.8	10.2	93	0.11	54	40	2.11
Treadmill	17%	3	8.0	48	0.21	36	48	1.54
Treadmill	17%	4	8.3	49	0.20	41	44	1.77
Treadmill	17%	5	7.5	45	0.22	44	45	1.70
Treadmill	24%	2	10.2	44	0.23	29	58	1.30
Treadmill	24%	3	10.3	44	0.22	37	53	1.48
Treadmill	24%	4	9.1	39	0.25	41	47	1.65
Snow	33%	2.2	20.3	66	0.15	28	59	1.33

Table 6: Measures for all the parameters and all the trials of the two studies, on motorized treadmill with roller ski (Treadmill, in white) and on snow with ski mountaineering gear (Snow, in grey) (mean values for all the subjects (n=12 on treadmill and n=11 on snow).

Thus, comparison between the present study and the study on the treadmill would suggest that roller skiing on a treadmill is a good model for ski mountaineering from a biomechanical (i.e. stride characteristics) perspective, but is quite different from ski mountaineering when we consider the metabolic aspects. Therefore, for future metabolic studies on ski mountaineering, it does not seem adequate to use roller skis, even if it allows having more standardized conditions. On the other hand, the use of roller skis to train for ski mountaineering in summer seems to be quite appropriate, because the movement is quite similar with comparable biomechanical variables.

B



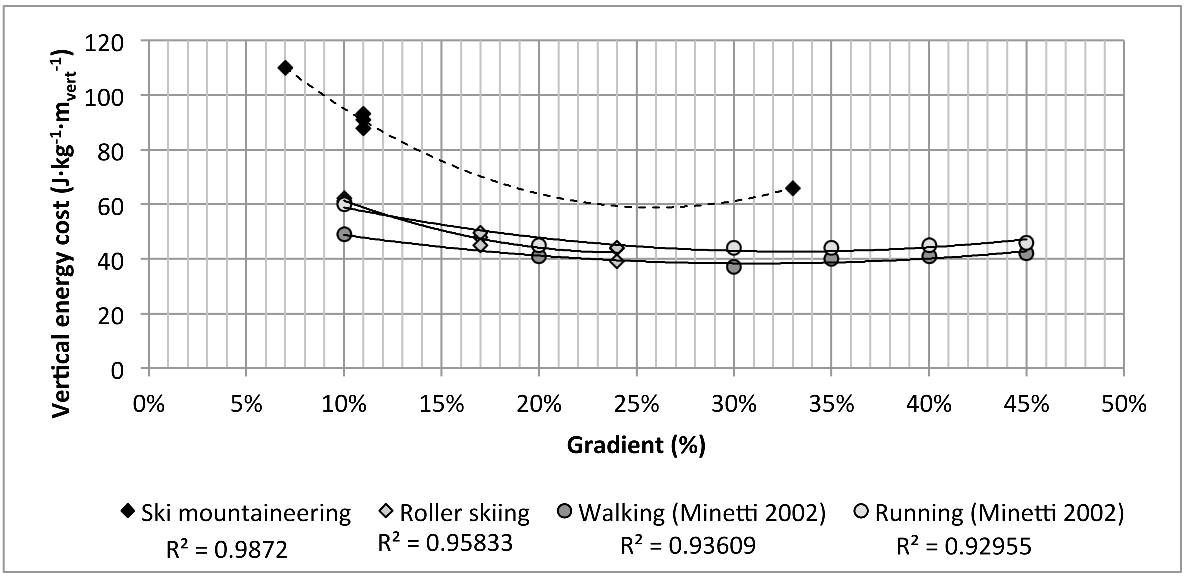


Figure 1A: EC of ski mountaineering (current study), roller skiing (Praz et al., submitted), walking and running [9] at different slope gradients. Linear regressions were tested and the respective correlation coefficients are indicated under the figure. These coefficients are very close to 1, showing that the increase of EC with speed is probably linear between 10 and 45%. **Figure 1B:** EC_v of ski mountaineering, roller skiing, walking and running at different slope gradients. Second order polynomial regressions were tested and the respective correlation coefficients are indicated under the figure. These regressions indicate that, between 10 and 45%, the EC_v of roller skiing, walking and running decreased down to a minimum. On this figure, we supposed a similar evolution for vertical ski mountaineering and a second order polynomial regression was also tested, without knowing, with only three points if it is adequate. For these two figures, effect of speed was neglected.

It would be of interest to look at a larger range of slope gradients and several speeds per slope gradient, to fit regression lines and identify a model, which would predict the evolution of the different parameters with speed and slope gradient. The treadmill study suggested that if a steeper slope gradient had been chosen to test the effect of speed on energy expenditure, a further effect of speed on energy expenditure might have been found. So, in a future work, it would be interesting to test different speeds at slope gradients higher than 11%.

Two limitations in the calculation of the metabolic parameters should be highlighted. Firstly, the calculation of the mechanical efficiency, as introduced by Margaria et al. for walking [14], considers the energy expenditure only as potential energy, disregarding the kinetic energy, with the assumption that beyond a given slope gradient the increasingly monotonic rise of the centre of mass is the prevailing contributor to the mechanical external work [9]. This slope gradient should be about 15%, because above this gradient, there is no more negative work and only positive work. The flattest tested slope gradients in our studies were flatter than 15%, so it is less obvious that the kinetic energy can be neglected for these slope gradients and the mechanical efficiency calculation is therefore less accurate for these slope gradients. Secondly, by taking always the same energy equivalent (20.9 $kJ \cdot l^{-1} O_2$) corresponding to a respiratory exchange ratio of 0.96, the anaerobic part of the energy production is neglected for the fastest trials and the energy expenditure was likely slightly underestimated.

In conclusion, the locomotion of ski mountaineering is more economical at steeper slope gradients and faster speeds, while at shallow slope gradients there is no variation in the energy cost of locomotion with speed. It follows that to minimize the energy expenditure and optimize performance to reach a place located at a higher altitude in ski mountaineering, an athlete should choose a steep slope gradient and, if he/she possesses the necessary aerobic scope, choose a faster speed.

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Appendix 7: Energy expenditure of extreme competitive mountaineering skiing

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ORIGINAL ARTICLE

Energy expenditure of extreme competitive mountaineering skiing

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Abstract

Purpose Multi-hour ski mountaineering energy balance may be negative and intake below recommendations.

Methods Athletes on the '*Patrouille des Glaciers*' race-courses (17 on course Z, 27 km, +2,113 m; 11 on course A, 26 km, +1,881 m) volunteered. Pre-race measurements included body mass, stature, VO_{2max}, and heart rate (HR) vs VO_2 at simulated altitude; race measurements HR, altitude, incline, location, and food and drink intake (A). Energy expenditure (EE) was calculated from altitude corrected HR derived VO_2.

Results Race time was 5 h 7 min ± 44 min (mean ± SD, Z) and 5 h 51 min ± 53 min (A). Subjects spent 19.2 ± 3.2 MJ (Z), respectively, 22.6 ± 2.9 MJ (A) during the race. Energy deficit was −15.5 ± 3.9 MJ (A); intake covered 20 ± 7 % (A). Overall energy cost of locomotion (EC) was 9.9 ± 1.3 J m^{-1} kg^{-1} (Z), 8.0 ± 1.0 J m^{-1} kg^{-1} (A). Uphill EC was 11.7 ± 1 J m^{-1} kg^{-1} (Z, 13 % slope) and 15.7 ± 2.3 J m^{-1} kg^{-1} (A, 19 % slope). Race A subjects lost −1.5 ± 1.1 kg, indicating near euhydration. Age, body mass, gear mass, VO_{2max} and EC were significantly correlated with performance; energy deficit was not.

Conclusions Energy expenditure and energy deficit of a multi-hour ski mountaineering race are very high and energy intake is below recommendations.

Keywords Endurance · Energy balance · Altitude · Skiing

Abbreviations

ACSM	American College of Sport Medicine
EC	Energy cost
EE	Energy expenditure
HR	Heart rate
HR_{max}	Maximal heart rate
HR_{mod}	Modified heart rate
HR_{res}	Heart rate reserve
MET	Metabolic equivalent of task
m_{vert}	Vertical meter
s_1	Speed 1
s_2	Speed 2
s_3	Speed 3
SD	Standard deviation
VO_2	Oxygen consumption
VO_{2max}	Maximal oxygen consumption
vt_2	Ventilatory threshold 2

Introduction

Ski mountaineering for leisure and competition has become popular in alpine countries over the past decades. It consists of ascending snow-covered slopes on skis with special bindings that allow pivoting at the toe, letting the heel free when climbing, and fixing it when skiing down hill. For climbing, adhesive nylon or mohair skins are attached under the skis, preventing sliding backward.

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There are several types of ski mountaineering races: individual, team (team members must stay together), relay (team members relay each other), vertical (uphill only), sprint and long distance races. The main differences are the total vertical and horizontal distances covered and the distribution of downhill and uphill sections. Team events alternate several steep ascents with downhill sections (ISMF 2012–2013, http://www.ismf-ski.org). During transitions skins are quickly removed or applied, and the bindings changed to the uphill or downhill position, respectively. Downhill sections are mostly 'off-piste', where the snow is not groomed, while uphill sections are usually prepared with two parallel trails to allow overtaking. In addition to uphill and downhill sections on skis, there can be running, walking and steep climbing sections, with skis fastened on the backpack, and flat sections where the athlete adopts a cross-country skate skiing-like movement. Team races are often several hours long. Most of the time, two or three participants make up a team. Athletes must carry most of their liquid and solid food on them, as there generally are few if any food and drink stations along the racetrack.

Few studies have been carried out on ski mountaineering. Tosi et al. (2009) estimated the energy cost (EC) of ski mountaineering on packed snow (slope 21 %) and described EC variations with speed and ankle load. They also reported that the effect of ankle load on EC is negligible for recreational skiers but relevant for elite skiers, explaining the on-going quest for lighter ski boots and skis in competition. In a second study they measured EC on a motorized treadmill using roller skis (Tosi et al. 2010) and showed that locomotor efficiency depends on speed, with the skiers self-selecting a speed minimizing EC. Duc et al. (2011) studied the physiological demand during an actual ski mountaineering race. They chose an individual race, shorter than most team races, with a series of uphill and downhill sections (mean duration 1 h 40 min ± 11 min). They showed that such type of ski mountaineering race is very strenuous, due to the large fraction of time spent around the respiratory compensation threshold. Diaz et al. (2010) reported a negative energy balance during a 2-day ski mountaineering competition accompanied by signs of increased oxidative stress, but did not actually measure energy expenditure.

To infer more about long duration ski mountaineering races we must refer to events of similar duration in other endurance sports like ultra-marathon and trail running, cycling or cross-country skiing. For team ski-mountaineering races, like for other types of endurance sports of long duration, EE is expected to be very high and energy intake low. This would imply a large energy deficit and the guidelines of the ACSM (Rodriguez et al. 2009) for endurance sports, 0.7 g carbohydrates kg^{-1} h^{-1}, might not be met (Diaz et al. 2010) although carbohydrate ingestion during exercise is known to improve performance during endurance events (Jeukendrup 2011). In endurance sports with races lasting several hours there is also risk for excessive dehydration. The guidelines of the ACSM indicate that endurance athletes should limit body mass losses from sweating to 2–3 % of body mass (Rodriguez et al. 2009; Jeukendrup 2011). Kruseman et al. (2005) found a weight loss of 4.5 ± 1.5 kg in runners after participating in a mountain marathon lasting 7 h, mostly from loss of water. We expected that a multi-hour ski mountaineering race would also lead to significant dehydration.

In order to better describe the physiological demand of ski-mountaineering and predictors of race results we therefore set out to measure EC and EE in participants to a competitive extreme ski mountaineering race in the Swiss Alps, '*La Patrouille des Glaciers*', combining laboratory indirect calorimetry test results with HR monitoring during the race. We tested the following hypotheses: (1) athletes' EE is very high and only partly covered by energy intake; (2) athletes develop significant dehydration (>3 % body mass); (3) race performance is function of age (Lara et al. 2014), low altitude aerobic capacity, fractional use of HR reserve (HR_{res}), body and racing gear weight (Tosi et al. 2009) and technical competences for uphill and down-hill skiing [linked to EC (Tartaruga et al. 2013)].

Methods

The protocol of the study was approved by the Valais research ethics committee (CCVEM 033/11). Each participant gave informed written consent prior to participate to the study.

The race

The study was conducted during the '*Patrouille des Glaciers*' (http://www.pdg.ch) held on 25, 26, 27 and 28 April 2012. The '*Patrouille des Glaciers*' is the most famous and popular ski mountaineering race in Switzerland with 1,450 selected teams of three skiers each that must stay grouped at all times. The worlds best ski mountaineering athletes participate in the race. The race consists of different types of locomotion: running, walking, and steep climbing on foot, ascent on skis with adhesive skins applied, alpine skiing style descents, and cross-country skating-like skiing.

There are two official race routes, one from Zermatt to Verbier (race Z; distance 53 km; altitude differences +3,994 and −4,090 m; maximal altitude 3,650 m) and one from Arolla to Verbier (race A, distance 26 km; altitude differences +1,881 and −2,341 m; maximal altitude 3,160 m) (Fig. 1) and two races on separate days for each race route. In 2012 due to high avalanche danger one start of each race

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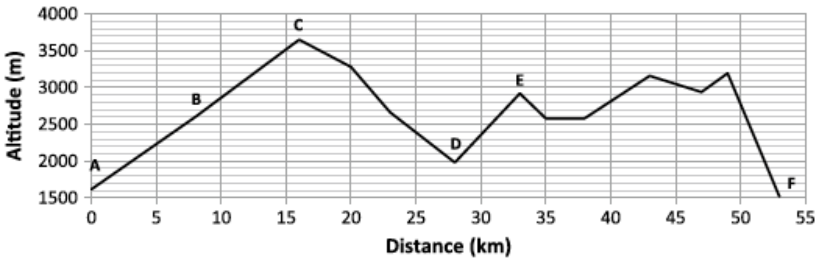

Fig. 1 Racetrack of the *Patrouille des Glaciers*: *A* start of race Z, *B* start of the separately analysed ski mountaineering uphill section of race Z, *C* finish of the separately analysed ski mountaineering uphill section of race Z, *D* finish of race Z after racetrack modification, start of race A and start of the separately analysed ski mountaineering uphill section of race A, *E* finish of the separately analysed ski mountaineering uphill section of race A and *F* scheduled finish of race Z and finish of race A

route was cancelled. Half the participants of the race A could race normally and half the participants of the race Z could race but were stopped after 27 km (instead of 53) and 2,113 m ascent and 1,749 m descent. This change of racetrack Z was not known at the start of the race; participants were only informed when stopped in Arolla.

The modified route of the race Z consisted of a 16 km uphill section followed by an 11 km downhill section. The first part of the uphill section was covered walking or running with the skis attached to the backpack. Then the participants put their skis with adhesive skins on and walked up on skis. We analysed separately this uphill section where the athletes used their skis mounted with skins (distance 8 km, mean slope 13 %). The route of the race A began with an ascent section (distance 5 km, mean slope 19 %) that we also analysed separately. Then there were an uphill section, a flat section, an uphill section and the final downhill. The athletes walked, ran, climbed on skis with skins applied, and skied downhill during the race.

The weather conditions at the start sites were: minimal temperature: 3 °C for the first race day and 10° for the second race day, maximal temperature: 14 and 19 °C; mean air humidity was 37 and 20 % and maximal wind speed 35 and 50 km h^{-1}, respectively, while at 3,500 m, for the two race days, minimal temperature, maximal temperature, air humidity and maximal wind speed were, respectively: −3 and 0 °C, −8 and −6 °C, 66 and 61 % and 70 and 59 km h^{-1}.

Subjects

Seventy subjects were recruited (40 for the race Z and 30 for the race A); 28 subjects could be taken into account due to the cancellation of several races. They were all healthy and trained skiers. 17 (14 men, 3 women) took part in race Z and 11 (11 men) in race A. Their mean ± SD age, height, body mass, body fat percentage and maximal oxygen consumption (VO_{2max}) were, respectively, 41 ± 6 years, 177 ± 6 cm, 69 ± 9 kg, 12 ± 5 %, 60 ± 5 ml kg^{-1} min^{-1} for the race Z subjects and 30 ± 10 years, 178 ± 7 cm, 74 ± 8 kg, 15 ± 5 %, 54 ± 5 ml kg^{-1} min^{-1} for the race A subjects. There were no significant differences between groups.

Research design

The experimental protocol consisted of two visits to the laboratory prior to the race and measurements on race day. The aim of the first laboratory visit was to characterize the participants [anthropometry and aerobic fitness level (VO_{2max})]. The second visit allowed creating individual HR-altitude-VO_2 equations, which were then used to estimate EE from HR and altitude measured during the race.

Anthropometry and maximal test

Between 2 and 3 months prior to the race, anthropometric features, body composition, VO_{2max} and maximal HR (HR_{max}) were determined. Body fat percentage was measured by air displacement plethysmography (BodPod, Cosmed, Italy). The subjects performed a maximal running test on a motorized treadmill (HP Cosmos Pulsar, Germany) to determine VO_{2max} and HR_{max}. Running was chosen because maximum exercise testing while walking/running uphill on skis with skins applied (uphill ski mountaineering) in the laboratory was technically too difficult for most athletes. Running on a treadmill was assumed to involve a sufficiently similar muscle mass volume as ski mountaineering and most athletes used running for base training. After warm-up (3 min at 5.4 km h^{-1}), speed was set at 7.2 km h^{-1} and increased by 1.8 km h^{-1} every 3 min without breaks between stages up to voluntary exhaustion under strong verbal encouragement. The inclination of the treadmill was 0 %. Gas exchange and breathing variables were measured breath-by-breath throughout with a metabolic measurement system (Metalyser, Cortex, Germany) and HR with a portable HR monitor

(Suunto t6d, Finland). The data obtained during the last 30 s of each step were considered for the analysis. The metabolic system was calibrated prior to each experimental session with a 3 l syringe and gases of known composition. The HR results were analysed according to five exercise intensity zones to describe the intensity profile during the race: <60 % of the HR_{res}, between 60 and 70 % HR_{res}, between 70 and 80 % HR_{res}, between 80 and 90 % HR_{res} and >90 % HR_{res}, with HR_{res} defined as the difference between resting HR and HR_{max} (Achten and Jeukendrup 2003; Gatterer et al. 2013; Haddad et al. 2014; Vernillo et al. 2012). Resting HR was measured with the athlete standing quietly on the treadmill before the start of the VO_{2max} test. As a second means for the quantification of exercise intensity we determined the ventilatory threshold 2 (vt_2) with the V-slope method (Wasserman and McIlroy 1964).

Individual altitude corrected HR-VO_2 relationships

Between 2 and 4 weeks before the race, each subject performed a trial by ascending on skis on a motorized treadmill with a slope set at 19 % (Cosmed Venus, Italy). There were 12 stages at different speeds and simulated altitudes. The subjects were equipped with their own racing gear including clothes, skis, skins, boots, poles, helmet, backpack, avalanche probe, snow shovel, avalanche transceiver, head lamp, food, drink, etc. (11.4 ± 2.6 kg). The purpose was to obtain individual altitude corrected HR-VO_2 relationships for each participant in order to interpret the HRs recorded during the race as metabolic rates. Since altitude exposure during the race is acute we exposed the subjects to acute simulated altitude, having the subjects breathe N_2-enriched air through a mask from a mixing bag continuously monitored for partial pressure of oxygen, equivalent to the desired altitude (AltiTrainer, SMTec, Switzerland). At each altitude (500, 2,500, 3,500 m) the participants performed four 3 min stages: rest, speed 1 (s_1), speed 2 (s_2, estimated race pace) and speed 3 (s_3). S_2 was self-selected by each subject s_1 was 0.5 km h^{-1} slower than s_2 and s_3 0.5 km h^{-1} faster than s_2. The total duration was 36 min for the 12 stages. Between s_1, s_2 and s_3 there was no break and the order of the stages was always the same for all the subjects. VO_2 and HR were measured and recorded in the same way as for the maximal test except that a portable indirect calorimetry system (Metamax, Cortex, Germany) was used. These measurements allowed us to draw up relationships with individual coefficients between HR, altitude and VO_2 for each subject.

Since HR varied non-linearly with speed and simulated altitude, the data were fitted with exponential functions (1) in order to derive correction factors, which allowed calculating an equivalent low altitude HR (HR_{mod}) from HR measured at any altitude during the race (Richalet 2012):

$$HR_{mod} = HR - a^{(-altitude/b)} + y_0 \quad (1)$$

with y_0 the y axis intercept, i.e., the HR found at that given speed at 500 m and a and b determined individually for each subject.

Then HR_{mod} was then linked to a VO_2 (2).

$$VO_2 = c \cdot HR_{mod} + d \quad (2)$$

with c and d determined individually for each subject (Keytel et al. 2005; Wicks et al. 2011).

In addition, body fat percentage and mass were measured again on this day to have values close to the race day.

Day −4 to race day measurements

From day 4 before the race till pre-race meal, the participants noted every food item or drink they consumed. On race day, 1 to 2 h prior to the departure, after voiding, the subjects were weighed with a scale (precision 100 g, Mio Star Body Balance, Melectronic, Migros, Switzerland), once in underwear only and once carrying complete race equipment, skis, boots and poles included (12.9 ± 3.0, 1.5 kg more than during the treadmill test).

Race HR was recorded beat-by-beat (t6d or Memory Belt, Suunto, Finland). For each team altitude was also continuously measured (t6d, Suunto, Finland). Each subject collected the wrappings of all food items consumed during the race. Any liquid or food intake on the way other than that carried was noted.

The 11 subjects of six teams that reached their scheduled finish (race A) were weighed again with and without racing gear immediately upon arrival before they ate or drank anything. One athlete gave up because of injury, one was disqualified because his team was too slow and two could not be taken into account because their watch did not record HR. The 15 others could not race because their start was cancelled. Upon arrival any food or drink items consumed during the race from other sources than the supplies carried were recorded by checking and discussing the notes of the participants and crosschecking the answers with the other team members. The subjects of the race Z were not taken into account for weight measurement and food intake because they did not reach the scheduled finish line and could not be weighted again and asked about eating and drinking.

Individual calibration equations relating HR and altitude to VO_2 obtained during simulated uphill skiing on the treadmill were used to calculate VO_2 at any time point during the race (Achten and Jeukendrup 2003). We estimated EE using a conversion factor of 20 kJ L O_2^{-1} assuming an average metabolic respiratory quotient of 0.8 representing a mixed energy substrate including use of fat mass energy reserves. EC (J m^{-1} kg^{-1}) was calculated with the estimated EE (J) per mass unit (body mass+equipment mass) (kg) divided by the absolute distance covered (m). EC per vertical meter (m_{vert}) was measured with the estimated EE (J) per mass unit (body mass+equipment mass) (kg) divided by the altitude difference (m). We estimated metabolic equivalent of task (MET), a measure expressing the energy cost of physical activities in multiples of 4.184 kJ kg^{-1} h^{-1}. The energy intake during the race was calculated from the nutritive values indicated on the wrappings of the consumed food items (bars, gels, etc.) and using standard food tables. Liquid intake was calculated as the watery part of all ingested food and drink.

Dehydration status was estimated according to the guidelines of ACSM that indicate that body mass losses from sweating should be limited to 2–3 % of body mass (Rodriguez et al. 2009; Jeukendrup 2011).

Statistical analysis

For each group mean and standard deviation (SD) values were calculated for each variable. Linear regressions were performed to verify the association between each variable and race performance (time). To assess the relative importance of each variable a multiple linear regression was then performed including those variables that were significantly associated with performance in individual linear regressions. Differences were considered significant at an alpha level of 0.05 or smaller.

Results

Race Z

Absolute best time of the Z race was 2 h 55 min. For the experimental subjects who participated in race Z mean race time was 5 h 7 min ± 44 min (175 ± 25 % of the best time). Best female time was 3 h 31 min and our female subjects (1 patrol) took 4 h 9 min (118 %). The subjects spent 76 ± 1 % of race time going uphill and 24 ± 1 % downhill. Mean HR was 156 ± 7 bpm, i.e., 75 ± 7 % of HR_{res}. Going uphill HR was 76 ± 7 % of HR_{res}. Figure 2 shows the average (±SD) distribution of time spent in the five intensity zones. The athletes spend 17 ± 23 % of the total time above vt_2. The mean total EE was 19.2 ± 3.2 MJ (3.4 ± 5 MJ h^{-1}). The EC (EE/distance) for the whole race was 9.3 ± 1.2 J kg^{-1} m^{-1} and the EC for the 8 km long 13 % uphill section was 11.7 ± 1.7 J kg^{-1} m^{-1} or 89.4 ± 12.6 J kg^{-1} m_{vert}^{-1}, taking into account the 11.6 ± 2.4 kg racing gear. The climbing speed for this section was 584 ± 76 m_{vert} h^{-1} and the athletes spent about 3.3 ± 0.5 MJ h^{-1} (12 ± 1 METs). The uphill section analysed consisted almost exclusively of ascent on skis equipped with skins, but all the types of locomotion are included in the energy values reported for the complete race.

Race A

Absolute best race time was 3 h 32 min. The mean race time of the study subjects in race A was 5 h 51 min ± 53 min (166 ± 25 % of best time). Mean HR was 153 ± 8 bpm, i.e., 71 ± 4 % of HR_{res}. During the uphill section HR was 82 ± 5 % of HR_{res}. The average (±SD) distribution of time spent in the five intensity zones is shown in Fig. 2. The athletes spend 13 ± 20 % of the total time above vt_2. The mean total EE was 22.6 ± 2.9 MJ (3.5 ± 0.4 MJ h^{-1}). The EC for the whole race was 8.0 ± 1.0 J kg^{-1} m^{-1} and the EC for the 5 km and 19 % uphill section was 15.7 ± 2.3 J kg^{-1} m^{-1} or 86.5 ± 10.0 J kg^{-1} m_{vert}^{-1}, taking into account the 14.8 ± 2.7 kg equipment. The climbing speed for this section was 632 ± 104 m_{vert} h^{-1} and the athletes spent 3.8 ± 0.5 MJ h^{-1} (13 ± 2 METs). Participants

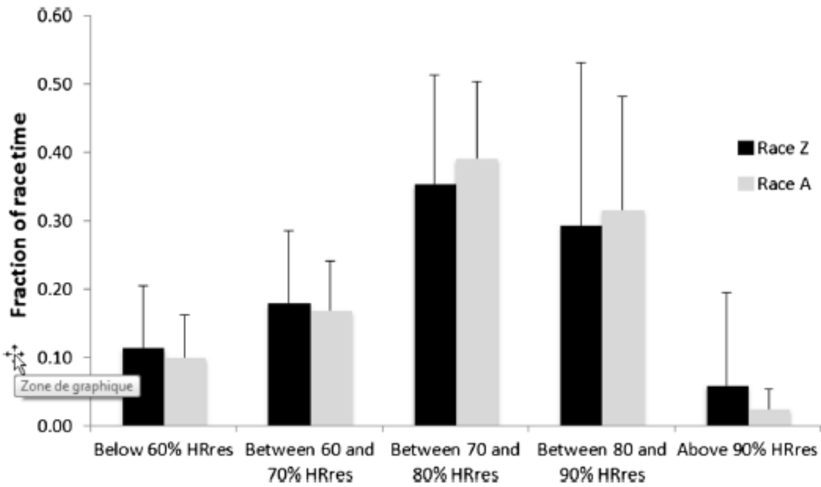

Fig. 2 Exercise intensity fraction of race time (in % of race time) in each intensity zone for race A and race Z: the distribution of the intensity zones was similar for both races but the subjects of race Z started out expecting to complete a 53 km route and not only 27 km, therefore they paced their race for a twice as long race as the race they finally did

Table 1 Results of multivariate analysis for performance

	Race Z					Race A				
	Coefficient	CI (95 %)	*p* value	Adjusted coefficient	CI (95 %)	Coefficient	CI (95 %)	*p* value	Adjusted coefficient	CI (95 %)
Age (years)	0.07	(0.02; 0.11)	0.01	0.45	(0.07; 0.82)	0.03	(−0.02; 0.07)	0.18	0.32	(−0.23; 0.87)
Sex	−1.00	(−1.94; −0.06)	0.04	−0.55	(−1.03; −0.07)					
Mass (body+gear) (kg)	0.02	(−0.3; −0.07)	0.35	0.30	(−0.29; −0.89)	0.08	(0.02; 0.15)	0.02	0.92	(0.26; 1.58)
VO_{2max} ($l \times min^{-1}$)	−0.49	(−1.02; −0.04)	0.07	−0.50	(−10.95; −0.04)	−1.49	(−2.87; −0.11)	0.04	−0.71	(−1.31; −0.11)
EC ($J\ kg^{-1}\ m^{-1}$)	0.09	(−0.15; 0.33)	0.43	0.20	(−0.11; 0.52)	0.32	(−0.11; 0.76)	0.12	0.51	(−0.11; 1.13)
Constant	2.21	(−1.46; 5.89)	0.21	-9.3×10^{-10}	(−0.27; 0.27)	0.51	(−7.42; 8.45)	0.87	(7.9×10^{-9} 7.74)	(−0.47; 0.47)

Best predictors of race time (multiple linear regression): age, mass and EC are positively related with race time, while VO_{2max} was negatively correlated with race time

There were not enough women to consider the sex performance relationship for race A

CI confidence interval

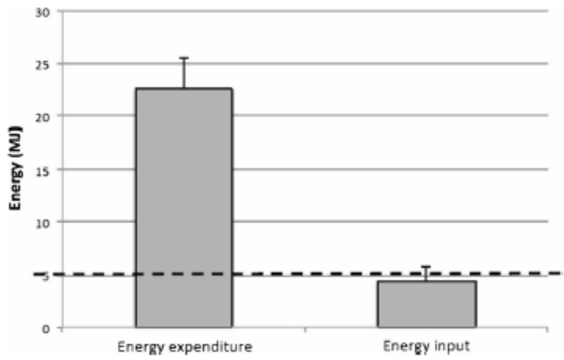

Fig. 3 Energy expenditure and energy intake comparison between energy expenditure, energy intake and recommended energy intake (*dotted line*) for the 26 km race A. The total energy intake reached 20 ± 7 % of the EE

ate and drank during the race for a total energy intake of 4.4 ± 1.3 MJ reaching 20 ± 7 % of the EE (Fig. 3) and a fluid intake of 1.8 ± 0.7 l. The mean weight loss was 1.5 ± 1.1 kg (2 ± 1 % of body mass). The energy intake of the pre-race breakfast was 3,056 ± 1,059 kJ. Total energy intake (pre-race meal+intake during the race) thus reached 35 ± 12 % of race EE. During the 4 days before the race, they ate 10.6 ± 2.3 MJ day^{-1} ($n = 9$).

Correlates of performance

Multivariate analysis showed positive associations between body mass, racing gear mass, body fat percentage, average EC for the whole race, EC of the uphill section, with race time, and a negative association between VO_{2max} with race time (Table 1).

Discussion

The main findings were that participants of an extreme competitive ski mountaineering race, '*La Patrouille des Glaciers*', (1) developed an important energy deficit, which was only partly covered by energy intake *en route* (race A), (2) showed no significant dehydration despite 4–7 h of endurance effort at 12–13 ± 2 METs and the need to dispose of up to 3 MJ of heat h^{-1} (climbing sections), and (3) had a race performance which correlated to age, sex, body and gear mass, aerobic capacity and locomotor efficiency but not to liquid and energy intakes.

Energy expenditure

The energy requirement for a multi-hour ski mountaineering race is very high with a mean EE in our study of

11–26 MJ for exercise durations of 5–6 h. If the race Z had taken place normally, the duration would have been about twice so long and the EE twice as high, or about 35 MJ. A pilot study in 2010 on six men, of which three completed the whole race Z yielded 43.1 ± 0.6 MJ. In comparison, Kimber et al. (2002) showed that the EE for a triathlon ironman is 42.0 ± 3.9 MJ for men and 35.9 ± 4.2 MJ for women for durations similar to the scheduled duration of the race Z of our study, without the mid-race stop. Saris et al. (1989) found that cyclists who participate in the Tour de France have a mean daily EE of 25.4 MJ and reach 32.7 MJ on mountain days, again values similar to that of the modified race Z and of race A. Cross-country skiers expend between 13 and 15 MJ for a 50 km race (Meyer et al. 2011). The environment of the latter sport is more similar to the environment of ski-mountaineering racing than cycling or triathlon, but the duration is shorter. A multi-hour ski mountaineering event therefore belongs to the category of extreme activities and can be considered as very strenuous and energy-demanding, with even higher intensities reached for races of shorter duration (Duc et al. 2011).

Calculated over 24 h, race day energy expenditure can be estimated as 24.6 ± 3.9 MJ for the participants of the race Z and 28.9 ± 2.9 MJ for the participants of the race A, supposing that the athletes did not engage in significant other additional physical activity except participating to the race. This total daily expenditure was calculated by summing calculated basal metabolic rate considering sex, weight, stature and age [Black formula (Black et al. 1996)], physical activity induced energy expenditure and 10 % of total energy expenditure to take into account the thermic effect of food (Black et al. 1996). The physical activity level (PAL), defined as daily energy expenditure divided by basal metabolic rate, on race day thus amounted to 2.4 ± 0.4 for participants doing race Z and 3.0 ± 0.5 doing race A. The general population has a natural limit of sustainable daily energy turnover at a PAL of 2–2.5 that can be maintained over several days (Westerterp et al. 1992). The high PAL values for non-elite athletes found for race A suggest that those subjects would probably not be able to maintain energy balance with time, as suggested also by the important energy deficit attained during the race.

The large muscle mass involved in this particular type of locomotion is a major reason why the EE is so high. Altitude also influences the EE. Since maximum aerobic capacity decreases with altitude, the absolute EE decreases, as athletes choose to exercise at similar relative intensity levels. In acclimatizing subjects basal metabolic rate was found higher compared to sea level (Meyer et al. 2011): at 4,300 m basal metabolic rate had increased by 10–17 % compared to sea level, presumably because of increased sympathetic activity (Mawson et al. 2000). Altitude was lower for our race (between 1,520 and 3,650 m) and exposure short, but it is conceivable that basal metabolic rate was somewhat increased. Furthermore, cold exposure linked to the alpine environment in winter also increases EE (Meyer et al. 2011).

Energy cost of locomotion

In general the energy cost of locomotion (EC) is a prime determinant of performance for endurance type sports (di Prampero 1986) that can make the difference between two athletes with the same VO_{2max}. The combination of a high aerobic capacity, a low EC and the ability to maintain a high fraction of aerobic capacity will allow better performance. In extreme ski mountaineering, global EC involves several types of locomotion like running, walking, ascent on skis with skins applied, alpine skiing in descent, or cross-country skating-like skiing. This implies that the overall EC is very dependent on the route of the particular race and differs between races according to the fraction of the race spent in the different types of locomotion. Most of the time is generally spent climbing uphill on skis equipped with adhesive skins applied and the bindings in

Table 2 Comparison between studies

	Uphill section of the race Z	Uphill section of the race A	Tosi et al. (2009)	Uphill sections (addition of 2) Duc et al. (2011)
Length (m)	8,000	5,000	500	7,070
Altitude difference (m)	1,050	933	105	1,315
Mean gradient (%)	13	19	21	18
Mean duration (h)	1.95 ± 0.26	1.51 ± 0.23	0.13 ± 0.01	1.4 ± 0.2
Load (kg)	11.6 ± 2.4	14.8 ± 2.7	7 ± 1	~4.5
Mean speed (km h^{-1})	4.2 ± 0.6	3.4 ± 0.6	3.9 ± 0.2	4.8 ± 0.9
Mean vertical speed (m h^{-1})	584 ± 76	632 ± 104	808 ± 48	896 ± 96
EC (J kg^{-1} m^{-1})	11.7 ± 1.7	15.7 ± 2.3	10.6 ± 0.4	14.2 ± 2.5
EC (J kg^{-1} m_{vert}^{-1})	89.4 ± 12.6	86.5 ± 10.0	50.6 ± 1.9	78.9 ± 13.9

EC in (J kg^{-1} m^{-1}) of ski-mountaineering comparison between the values of the present study (race A and race Z) and the results of previous studies: EC calculated for race A is the highest because of the steep gradient and the heavier load carried

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open mode so that minimizing EC in that particular mode has an important impact on overall energy cost. The EC of the uphill sections we found can be compared with the results of other studies (Table 2). The lowest EC (Tosi et al. 2009) was described for a short section lasting only 8 min while that of races lasting 1–2 h (Duc et al. 2011) up to 6 h 45 (this study) are higher. The EC of the uphill section of race A had the highest EC (15.7 ± 2.3 J kg^{-1} m^{-1}); but the load that the athletes carried was also the heaviest for this race, and the movement is likely less efficient while carrying heavier backpacks. Effect of mass is even more important on EC per m_{vert} as on EC per m distance covered. The lower mean slope of the uphill section of the race Z thus probably also partly explains the lower EC. Our subjects were slower than the subjects of Duc et al. (2011) probably because our race was much longer. The highest speed and vertical speed were reported by Duc et al. (2011) because they studied an actual race situation that was shorter than '*La Patrouille des Glaciers*'. Like for walking there likely is an optimal gradient of path regarding EC. The 13 % gradient of race Z is the less economical of the already tested gradients and the 21 % gradient of Tosi et al. (2009) the most economical. These results suggest that the most economical gradient may be close to the optimal gradient for walking (25 %) (Minetti 1995). Variations of EC of ski mountaineering with speed, slope, snow conditions (type and temperature of snow) are not known yet. The EC that we calculated is only for a definite speed, load and gradient and cannot be generalized for all ski-mountaineering races. To assess the EC of a given race it would be useful to know how the EC changes with those factors.

Exercise intensity

The distribution of HR in the intensity zones was similar for race A and Z (see Fig. 2). This was expected since the 2 routes were quite similar: 26 km for race A, 27 km for race Z, with altitude differences of +1,881 and −2,341 m for race A, and of +2,113 and −1,749 m for race Z. However, the subjects of race Z started out expecting to complete the originally scheduled route, 53 km long and double positive and negative altitude differences. The pace and intensity they chose were those they felt appropriate for a race twice as long as they finally completed. If we consider that the skiers who chose to participate in race Z, the longer and generally considered elite race, were well trained and experienced skiers (their VO_{2max} was 60.1 ± 7.5, 10 % higher as those participating in race A), we may speculate that they would have kept this intensity for the second part of the race if it had taken place. On the other hand, HR may decrease with exercise duration and fatigue (Esteve-Lanao et al. 2008), so if the subjects of the race Z had known from the departure that they would race for only 27 km, their HR might have been somewhat higher because of the higher intensity of a faster pace.

In an individual and shorter ski mountaineering race, the '*Trace catalane*', Duc et al. (2011) found a mean percentage of HR_{max} of 93 ± 2 % but they used percentage of HR_{max} and not percentage of HR_{res}. In the present study the average percentage of HR_{max} amounted to 81 ± 2 % (race Z) and to 82 ± 4 % (race A). This is less than that reported by Duc et al. (2011). The difference is likely due to the race being much shorter (mean time of the '*Trace Catalane*': 1 h 41 min ± 11 min).

In our study the distribution of time spent in the HR zones, below and above vt_2 was quite heterogeneous: some athletes spent more than half of race time above 90 % of HR_{res} whereas others spent more than 2/3 of race time below 70 % of HR_{res}; some athletes spent no time above the ventilatory threshold whereas other spent three quarters of the race time above this value. The likely reason is that '*La Patrouille des Glaciers*' is a team event and that the three athletes of a patrol must stay together. If a team is made up of athletes of different performance capacity this will lead to intra-team differences for HR. This makes inter-individual comparisons difficult but reflects the reality of most multi-hour ski mountaineering races that generally are team events. This team effect may also at least partly explain our finding of a modest influence of VO_{2max} upon race performance.

Food and drink supply

The high EE we found should be associated with important food and drink intake during the race to at least partly balance it. That is even truer in altitude where substrate utilization is modified. More blood glucose is used at rest and during exercise (Brooks et al. 1992). The high blood glucose utilization has no sparing effect on muscle glycogen; consequently, carbohydrate need is increased and exogenous carbohydrate consumption during the race is likely of great importance.

The mean energy intake during race A from food and liquids was only 4.4 ± 1.3 or 7.1 ± 1.8 MJ with pre-race breakfast included. This implied an average energy deficit at the finish of the race of 18.2 ± 2.9 MJ, respectively, 13.4 ± 3.6 MJ. The recommendations of the ACSM for endurance sports are 0.7 g carbohydrates·kg^{-1} h^{-1}, which in our study amounted to an average value of 5.1 ± 0.9 kJ, and the recommendations were therefore not met by 14 %. But an energy deficit cannot be avoided during such races because the access to and capacity to eat and process food is limited (Diamond 1991). Apart from the practical difficulties of eating while being engaged in sports, a physiological limiting step is the capacity of absorption of the small intestine. The sodium dependant transporters of glucose (SGLT1) become saturated at a carbohydrate intake around 7 g $\times$ kg^{-1} h^{-1}, the rate recommended by the ACSM. Nevertheless, even if all athletes had followed the recommendation, the deficit would have been 15.8 MJ (12.4 MJ, pre-race breakfast included) (Rodriguez et al. 2009).

The subjects who finished the race A lost 1.5 $\pm$ 1.1 kg, i.e., 2 $\pm$ 1 % of their body mass. The guidelines (Jeukendrup 2011) recommend that endurance athletes should attempt to minimize dehydration by limiting body mass loss through sweating to not more than 2–3 % of body mass. Thus, our athletes followed the recommendations for rehydration. Knechtle et al. (2012) reported similar weight loss, 1.9 $\pm$ 1.4 kg, during a 100 km ultra-marathon. Kruseman et al. (2005) reported a weight loss of 4.5 $\pm$ 1.5 kg during a 7 h 3 min $\pm$ 1 h 17 min mountain running marathon. The longer duration and the fact that the race took place in summer with higher temperatures can explain the higher losses than observed in our study.

The sweat loss and water need depend on the evaporation required to maintain heat balance at any given core temperature and on the maximal evaporative capacity of the environment. The first depends on skin and core temperature and metabolic rate, and the second on clothing, environmental temperature, wind and humidity (Gonzalez et al. 2009). For a winter mountain race like '*La Patrouille des Glaciers*' the low temperatures and air dryness bring the sweat loss down compared to other events of same duration in warmer and more humid conditions. On race day, the air was dry and there was a lot of wind at altitude. In altitude diuresis is increased and thirst impaired (Kayser 1994; Meyer et al. 2011). Furthermore, respiratory water loss is greater in altitude than at sea level due to increased ventilation and low air humidity. Respiratory water loss can be as high as 1.90 L day^{-1} for men (Butterfield et al. 1992) and 0.85 L day^{-1} for women (Mawson et al. 2000).

For races of such long duration, loss of body mass is not only function of dehydration but also due to use of energy substrate. At the end of a long race like '*La Patrouille des Glaciers*', glycogen stores are mostly depleted, whereas they are generally full at the start since most athletes use nutritional strategies stocking up on glycogen reserve prior to major competitions. Given that glycogen is stored with 3–4 parts of water per glucose unit, the oxidation of 500 g of glycogen (8,368 kJ) would have involved >1.5 kg weight loss. So it seems that our athletes were not much dehydrated and it follows that their drinking habits can be considered appropriate.

Correlates of performance

Like for other endurance sports, we found that age (Lara et al. 2014), body and gear mass (Tosi et al. 2009), VO_{2max} and EC correlated with performance in multi-hour ski mountaineering racing. That was expected, and confirms that the great importance given by athletes to reduce the mass of their equipment is at least partly justified. However, body mass cannot be neglected. Mass is especially important for sports with ascensions, like ski mountaineering, because a great part of the energy consumption is used to overcome gravity (Ardigo et al. 2003; Saibene and Minetti 2003). The part of total energy consumption used against gravity (Potential energy/EE) were, respectively, 22 $\pm$ 3 and 18 $\pm$ 3 % for race Z and A.

The influence of the EC showed that it is important to optimize ski mountaineering technique by specifically training this type of locomotion. Training and experience influence EC (Beneke and Hutler 2005). The more the athlete trains for a sport, the more economical he may become.

The fraction of the time that the athletes spent for the way up and for the way down of the Z race was calculated. There was no correlation between the fraction of the time spent for the way up and performance. In fact, this fraction did not vary much from one person to another and shows that skiers who perform better on the way up also do better on the way down.

Limitations

Sea level aerobic capacity was measured 8–12 weeks before the race and changes in that period cannot be excluded. However, the individual altitude corrected HR-VO_2 relationships were obtained more close (2–4 weeks) to the start of the race. Since there were similar HR-VO_2 relationships between the two tests at submaximal stages, we are confident about the use of the HR-VO_2 relationship to transform HR on race day into VO_2.

Calorimetry would have been the most accurate method to measure EE and EC. Nevertheless the use of calorimetry for field activity is unfeasible. For indirect calorimetry, VO_2 must be measured, which implies that participants wear a mask and a bulky metabolic testing system. To limit interference with performance it is more practical to measure HR with a thoracic belt and a watch, associating it with laboratory measured individual HR-VO_2 relationships, taking into account the effect of altitude, since HR-VO_2 relationships shift with increasing altitude. This method seemed to give us similar values compared with other studies.

The HR-altitude-VO_2 relationship was determined on a motorized treadmill with skis, skins, poles, etc., to be then used to interpret HR collected on snow, assuming that this relationship is similar on treadmill and on snow. This seems a reasonable assumption since Tosi et al. (2010) found similar EC values on a treadmill and on snow (2009). The main difference is that Tosi et al. used roller skis while normal skis with skins were used in the present study. With roller skis on a treadmill the friction is perhaps lower than with skins on snow whereas with skis and skins on treadmill the friction may be higher than on snow.

Several factors might have influenced HR during the race independently from oxygen consumption, such as the excitement of the race. In addition, cardiac drift (Esteve-Lanao et al. 2008) during long-duration exercise may also have influenced HR during the race. For a same intensity or speed HR increases with time. So an increasing HR does not always means an increasing speed, like a constant HR does not always means a constant speed or intensity. The drift already begins after 10 min and is especially important for multi-hour exercises. We can estimate that the drift can increase HR by about 10 bpm for a given intensity between start and finish of the race (about 5 h) (Gimenez et al. 2013). The limited dehydration in our subjects and the relatively low air temperature probably limited the extent of cardiovascular drift (Montain and Coyle 1992). During the downhill sections eccentric muscular activity may also have lead to an exaggerated HR response (Turnbull et al. 2009).

The race cancellations are clearly the most important limitation of this study. We lost more than half of the subjects. In addition, the remaining subjects became, by chance, less representative of the general population of participants. Almost all women could not start; the majority of our youngest and oldest subjects were also eliminated. But overall as many slow as fast subjects were lost. The effect of sex could thus not be evaluated for race A because there were no women who reached the finish, while the effect of sex in race Z is influenced by the fact that there was only one women's patrol and this team was very fast. Moreover, age was not any more evenly distributed for race A and the correlation between age and performance is therefore difficult to evaluate. Finally, the interruption of the race Z halfway made calculation of energy expenditure for the full race Z impossible and we could therefore only estimate it, while the exercise intensity chosen by the participants was likely lower than if the participants had known about the interruption.

Perspectives and conclusions

Multi-hour ski mountaineering racing requires a lot of energy (about 20 MJ for 5 h 30 min on average). This very high requirement is not balanced by energy intake in parallel, and the majority of the athletes do not fulfil the recommendations of ACSM for energy intake during endurance sports. On the other hand, dehydration may not be a major problem for this type of race since weight loss remains limited. The dry and cold high mountain environment in winter conditions likely contributes to this. Exercise intensity is high, but heterogeneous because performance capacity between members in a team can vary. Age, low body and racing gear mass, high VO_{2max} and low energy cost are significantly correlated with performance. Accordingly, ski mountaineering athletes should be advised to increase food intake during racing, adapt exercise intensity during training according to expected race intensity and beware of the importance of body and gear mass for performance.

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Conflict of interest There are no conflicts of interests.

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Appendix 8: Nutritional behaviour and beliefs of ski mountaineers – a semi-quantitative and qualitative study

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RESEARCH ARTICLE Open Access

Nutritional behaviour and beliefs of ski-mountaineers: a semi-quantitative and qualitative study

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Abstract

Background: Endurance athletes are advised to optimize nutrition prior to races. Little is known about actual athletes' beliefs, knowledge and nutritional behaviour. We monitored nutritional behaviour of amateur ski-mountaineering athletes during 4 days prior to a major competition to compare it with official recommendations and with the athletes' beliefs.

Methods: Participants to the two routes of the 'Patrouille des Glaciers' were recruited (A, 26 km, ascent 1881 m, descent 2341 m, max altitude 3160 m; Z, 53 km, ascent 3994 m, descent 4090 m, max altitude 3650 m). Dietary intake diaries of 40 athletes (21 A, 19 Z) were analysed for energy, carbohydrate, fat, protein and liquid; ten were interviewed about their pre-race nutritional beliefs and behaviour.

Results: Despite belief that pre-race carbohydrate, energy and fluid intake should be increased, energy consumption was 2416 ± 696 (mean ± SD) kcal · day^{-1}, 83 ± 17 % of recommended intake, carbohydrate intake was only 46 ± 13 % of minimal recommended (10 g · kg^{-1} · day^{-1}) and fluid intake only 2.7 ± 1.0 l · day^{-1}.

Conclusions: Our sample of endurance athletes did not comply with pre-race nutritional recommendations despite elementary knowledge and belief to be compliant. In these athletes a clear and reflective nutritional strategy was lacking. This suggests a potential for improving knowledge and compliance with recommendations. Alternatively, some recommendations may be unrealistic.

Keywords: Endurance activity, Food behaviour, Food beliefs, Pre-race nutrition, Energy intake, Ski-mountaineering

Background

For endurance activities with high levels of energy expenditure, energy intake is an important variable to be considered when devising strategies for optimizing performance [1–3]. High exercise intensities over prolonged periods imply high carbohydrate (CHO) and also fat oxidation rates [4]. CHO and fat availability are thus important determinants of energy expenditure and it is paramount that athletes use optimal nutritional strategies, not only to manage intake during races, but also before races, to optimize storage, and after races, to optimize refuelling [2, 3, 5–7]. There exists a plethora of literature on sports nutrition, and several scientific and sports organizations such as the American Dietetic Association (ADA), the Dieticians of Canada (DC) and the American College of Sport Medicine (ACSM) [2, 8], the International Olympic Committee (IOC) [9] and the International Society for Sport Nutrition (ISSN) [10, 11] have published recommendations and guidelines on energy intake before, during and after exercise [3]. Paradoxically, there is relative paucity of literature reporting actual athlete nutritional behaviour [12]. Among athletes, actual nutritional behaviour does not always comply with the official recommendations, because of a lack of knowledge [13], mistaken beliefs, lack of interest or motivation, practical problems, or perhaps intuition [14]. Nutrition knowledge and beliefs can influence food behaviour [15], even if the relationship is not necessarily obvious. Improved nutritional knowledge plays a role in the adoption of healthier food habits [16, 17] and this is

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likely also the case for sport nutrition. Better insight into actual athlete behaviour and its determinants is of importance for adapting guidelines in view of improving compliance [18, 19].

A particular type endurance sport is ski-mountaineering racing, consisting of climbing uphill on alpine skis with the heals unlocked in special pivoting bindings and adhesive skins applied to the gliding surface, alternated by skiing downhill with the skins removed and the bindings in the locked position. What makes this sport particular is that it combines very strenuous activity in different locomotion modes with exposure to altitude hypoxia and temperature extremes. Especially uphill the exercise intensity is high with a large fraction of time spend around the respiratory compensation threshold [20–22]. The most popular and famous ski-mountaineering races are generally team races that can last from 4 to more than 12 h. We previously quantified energy expenditure during a famous Swiss ski-mountaineering race ('Patrouille des Glaciers') and found that it was very high: more than 20 MJ (4,800 kcal) for the shorter race route (distance: 26 km; altitude differences: +1881 m and −2341 m; maximal altitude: 3160 m) and more than 35 MJ (8,400 kcal) for the longer one (distance: 53 km; altitude differences: +3994 m and−4090 m; maximal altitude: 3650 m) [22].

The goal of the present study was to get a global perspective on pre-race nutritional habits among amateur ski-mountaineers during the 4 days preceding this major multi-hour ski-mountaineering race. Four different aspects were investigated: 1) pre-competition nutritional practice; 2) comparison between practice and recommendations; 3) comparison of food behaviour between participants in longer and shorter races; and 4) knowledge and beliefs about pre-race nutrition.

Methods

Seventy participants in two multi-hour ski-mountaineering races were recruited for a study about ski-mountaineering racing (Fig. 1). They were healthy and trained skiers, who took part in one of the two racecourses of the 'Patrouille des Glaciers' 2012 [22]. The nutritional part of the study was optional for participants. The Valais cantonal research ethics committee approved the protocol of the study (CCVEM 033/11) and each participant gave informed written consent prior to participation.

Laboratory measurements

Between 2 and 3 months prior to the race, the subjects came to the laboratory, where anthropometric features, body composition and maximal oxygen uptake (VO_{2max}) were determined. Body fat percentage was measured by air displacement plethysmography (BodPod, Cosmed, Italy). The subjects performed a maximal running test on a motorized treadmill (HP Cosmos Pulsar, Germany) to determine VO_{2max}. After warm-up (3 min at 5.4 km · h^{-1}), speed was set at 7.2 km · h^{-1} and increased by 1.8 km · h^{-1} every 3 min without breaks between stages up to voluntary exhaustion under strong verbal encouragement. The inclination of the treadmill was 0 %. Gas exchange and breathing variables were measured breath-by-breath throughout with a metabolic measurement system (Metalyser, Cortex, Germany). The data obtained during the last 30 s of each step were considered for the analysis. The metabolic system was calibrated prior to each experimental session with a 3 l syringe and gases of known composition.

The races

The 'Patrouille des Glaciers' is the most famous and popular ski-mountaineering race in Switzerland. It is a long duration high altitude team race (teams of three) and consists of two different race routes: race Z from Zermatt to Verbier (distance: 53 km; altitude differences: +3994 m and−4090 m; maximal altitude: 3650 m) and race A from Arolla to Verbier (distance: 26 km; altitude differences: +1881 m and−2341 m; maximal altitude: 3160 m).

Food intake

We asked the subjects to complete food diaries during the 4 days preceding the race. They had to write down everything they ate or drank with as much detail as possible about the quality and quantity of food items consumed. The subjects received detailed instructions and examples to help them to appropriately complete their diaries. The

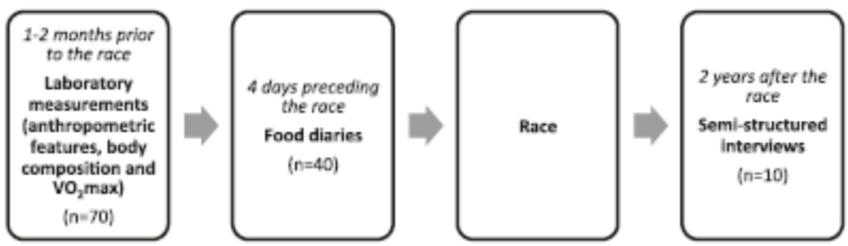

Fig. 1 Study flowchart

data were analysed with a nutrient analysis software package (Prodi 5.3, Nutri-Science GmbH, Germany).

Fifty-three journals were collected: 13 were eliminated from analysis, because they were incomplete, unclear or unreadable. 40 journals were analysed: 19 were journals of subjects of race Z (4 women and 15 men, 30 ± 10 years, 176 ± 7 cm, 70 ± 9 kg, 15 ± 5 % of fat mass, VO_{2max}: 50 ± 8 $ml \cdot kg^{-1} \cdot min^{-1}$ and 21 of race A (6 women and 15 men, 40 ± 7 years, 176 ± 7 cm, 72 ± 10 kg, 18 ± 8 % fat mass, VO_{2max}: 58 ± 8 $ml \cdot kg^{-1} \cdot min^{-1}$). Energy, macronutrients (CHO, fat and proteins) and liquid intakes were analysed.

Beliefs

Using the diaries, individual semi-structured interviews were held two years later with a pool of 10 subjects of those with a complete diary. These interviews focused on the beliefs about feeding before the race. There were six main questions: 1) tell me more about the importance that you assigned to nutrition during the preparation for the race; 2) what was your food behaviour during the 4 days preceding the race; 3) tell me more about your liquid intake during the 4 days preceding the race; 4) if you were used to consume food supplements, what importance did you assign to these during the 4 days preceding the race; 5) if you were used to consume sports food, which importance did you assign to these during the 4 days preceding the race; and 6) where did you get your information about the nutrition and food strategies you applied? Based on the initial answers to these questions the interviewers asked the participants further questions, to develop and explore details about points that seemed to be especially interesting or needed clarification. Five subjects for each race route were interviewed. We purposely handpicked a diversified sample: three women and seven men, 22 to 56 years, 5 to 37 % of fat mass, VO_2max from 32 to 67 ml $kg^{-1} \cdot min^{-1}$ (40 ± 10 years, 175 ± 6 cm, 70 ± 11 kg, 16 ± 9 % of fat mass, VO_2max: 53 ± 10 $ml \cdot kg^{-1} \cdot min^{-1}$).

Statistical analysis

An ANOVA was used to test whether the four analysed days were similar and to see if pooled mean values could be used for further analysis. For each nutrient the mean and standard deviation values were calculated for the whole population and for the participants in the race Z and the race A separately. T-tests were performed to verify if there were differences between the participants in the shorter and the longer race. Linear regressions were performed to verify associations between sex, body composition or VO_2max and aspects of nutritional behaviour. Data were analysed with the software Stata (StataCorp, USA). A p-value <0.05 was considered significant.

Results

Food intake and recommendations

There was no significant difference concerning the main analysed variables (energy, CHO and drinking intake) between the four analysed days, so the data were pooled and the mean values of the 4 days were used for further analysis. The mean energy consumption was 2416 ± 696 $kcal \cdot day^{-1}$. 54 ± 8 % of the daily energy intake was from CHO, 28 ± 6 % from fat and 18 ± 5 % from protein (Table 1, Fig. 1). CHO intake was 46 ± 13 % below the recommended intake levels (10–12 $g \cdot$ body weight (BW) $\cdot day^{-1}$) (Fig. 1). Consequently energy consumption was low too (83 ± 17 % of recommended intake (Harris and Benedict · 1.8 (low exercise intensity, corresponding to a pre-race tapering period) [2]), but the deficit was limited because fat and protein intake partly compensated the lack of CHO intake (Fig. 2). The energy intake through fat was 29 ± 6 % (Fig. 3) of the total daily energy intake (recommendations: between 15 and 30 %) while protein intake was 100 ± 28 % of the minimal recommended intake for athletes in daily life (1.3 $g \cdot kg^{-1}$ BW $\cdot day^{-1}$). The mean liquid intake was 2.7 ± 1.0 $l \cdot day^{-1}$ (slightly above recommendations, 1 $ml \cdot kcal^{-1} \cdot day^{-1}$ in daily life, 2.4 $l \cdot day^{-1}$), partly compliant with the guidelines to already increase the liquid intake before the beginning of a race, without giving a specific amount [23].

One third of the participants took mineral or vitamin supplements. Magnesium was the most commonly used mineral (25 % of the participants) while vitamin supplement intake was also frequent (20 % of the participants). 23 participants (58 %) consumed CHO-rich sports food or drinks, of which 20 % took maltodextrin to increase CHO intake.

There were few differences between the nutritional behaviour of men and women: men consumed more energy from fat (p = 0.049) and tended to consume less energy from CHO (p = 0.061) than women. A higher body fat percentage was negatively associated with

Table 1 Macronutrients: recommendations and declared pre-race consumption by the participants in races Z and A

	Energy intake ($kcal \cdot day^{-1}$)	Recommended energy intake ($kcal \cdot day^{-1}$)	Protein intake ($g \cdot day^{-1}$)	Recommended protein intake ($g \cdot day^{-1}$)	CHO intake ($g \cdot day^{-1}$)	Recommended CHO intake ($g \cdot day^{-1}$)	Percentage of the total daily energy from fat	Recommended percentage of the total daily energy from fat	Liquid intake ($l \cdot day^{-1}$)
Race Z	2390 ± 569	2892 ± 280	86 ± 22	90 ± 11	315 ± 88	694 ± 86	29 ± 5 %	15-30 %	3.2 ± 1.0
Race A	2428 ± 314	2948 ± 494	96 ± 6	94 ± 15	329 ± 28	721 ± 113	28 ± 7 %	15-30 %	2.3 ± 0.9

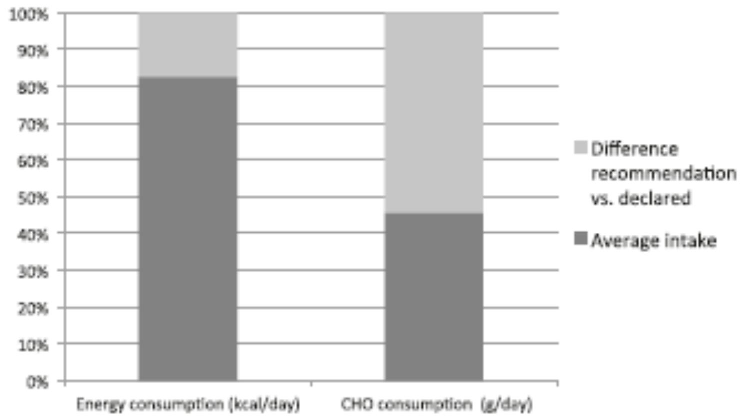

Fig. 2 Average percentage of the daily energy intake from CHO, fat and protein. ACSM guidelines for athletes recommend that CHO should represent 50 to 70 % of the total daily energy intake, protein between 10 and 35 % and fat between 20 and 35 % [41]

energy intake ($R^2 = 0.18$, $p = 0.007$), CHO intake ($R^2 = 0.29$, $p = 0.001$) and liquid intake ($R^2 = 0.19$, $p = 0.010$) (adjusted for gender) and positively associated with the percentage of the daily energy intake form fat ($R^2 = 0.14$, $p = 0.043$). A higher VO_{2max} ($l \cdot min^{-1}$) was negatively associated with the lipid intake ($R^2 = 0.11$, $p = 0.044$).

Comparison of the food intake of the participants in the shorter and the longer race

No significant differences were noted between macronutrient (CHO, fat and protein) intake of the participants of races A and Z; only liquid intake was higher for the participants in race Z (3.2 ± 1.0 vs. 2.3 ± 0.9 $l \cdot day^{-1}$, $p = 0.005$ (*t*-test, intake adjusted for body mass) (Table 2).

Ten of the 19 (53 %) participants in the race Z used vitamin and/or mineral supplements and 16 (84 %) consumed sports food. Only one person (5 %) used none. For the participants in the race A, three of the 21 (14 %) consumed minerals and/or vitamin supplements and eight (38 %) sports food. Twelve of the 21 participants (57 %) in the race A took neither supplements nor sports food.

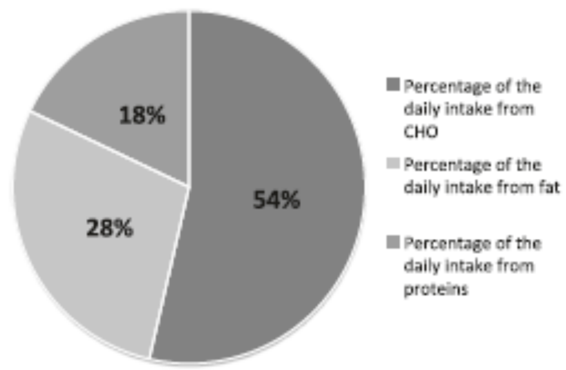

Fig. 3 Comparison recommendation-reality for energy and CHO consumption. The entire column represents the recommendation (100 %) and the black part the average declared intake for all 40 subjects (in percentage of the recommendation)

Knowledge and beliefs

All the interviewed subjects indicated that nutrition during the 4 days preceding a long duration ski-mountaineering race is relevant for performance. Six of the 10 interviewed subjects found it important or very important while four found it of little or moderate importance. Three common representations could be highlighted in the interviews: 1) during the 4 days before such a race it is good to eat (lots of) pasta to fill up energy stores (all interviewed subjects); 2) during these days water intake has to be increased (9/10); and 3) it is better to eat white meat than red meat (5/10).

For the comparison of beliefs with practice, as estimated with the food diaries, we found, on the basis of eight main meals over the 4 days analysed for each subject: 1) On average 4.9 ± 1.2 of them included pasta (55 % of meals); these values were 4.4 ± 1.2 meals and 61 %, respectively, for all 40 subjects; 2) The subjects drank 2.2 ± 1.4 $l \cdot day^{-1}$ (2.7 ± 1.0 $l \cdot day^{-1}$ for all 40 participants); 3) For the participants in the race Z, who had dinner just before the race (the participants in the race A started in the morning and had breakfast as the last meal before the race): two of the five interviewed subjects ate white meat during the last dinner (8 of the 19 participants (42 %) who completed the food journal).

In order to enhance performance and to ensure digestive comfort, some other food items were avoided: four athletes avoided or decreased fat food intake (in particular cheese), three athletes spoke about alcohol avoidance, one of the ten took care not to eat too much and one avoided vegetables and salads.

Table 2 Supplementation and sports food consumption for each subject from the two race routes

Race Z			Race A		
Subject	Supplementation	Sports food	Subject	Supplementation	Sports food
1	Vitamin C Magnesium	-	20	-	Maltodextrin
2	Magnesium Iron (and vitamins) supplement	MaltodextrinCHO-rich sports drink CHO-rich sports cakeProtein shake	21	Magnesium + vitamin C + L-Carnitin	CHO-rich sports drink
3	Homeopathic minerals tablets	MaltodextrinCHO-rich sports drink	22	-	-
4	Magnesium Calcium	CHO and protein-rich sports drink CHO-rich sports drink	23	-	Maltodextrin
5	-	-	24	-	-
6	Multivitamin	CHO-rich sports drink CHO-rich sports cake	25	-	CHO-rich sports drink
7	-	-	26	-	-
8	-	CHO-rich sports drink	27	-	-
9	Multivitamin	Maltodextrin CHO-rich sports drink	28	-	-
10	-	CHO-rich sports cake	29	Magnesium	Maltodextin
11	-	CHO-rich sports drink	30	Rhodiola rosea[a] Magnesium	-
12	-	CHO-rich isotonic sports drink	31	-	-
13	-	CHO-rich sports drink	32	-	-
14	Mutivitamin (+zinc, calcium, magnesium and guarana)	Maltodextrin CHO-rich sports cake	33	-	-
15	2 Multivitamin and minerals (+caffeine, taurine and guarana) supplement Magnesium	3 Protein shakes Protein bar 2 CHO-rich sports drinks CHO-rich bar	34	-	-
16	Amino acids (aspartate and glutamate) Omega 3	-	35	-	-
17	Vitamin C	Grape sugar	36	-	CHO-rich sports drink
18	-	CHO-rich sports cake	37	-	Maltodextrin CHO-rich sports bar
19	-	2 CHO-rich sports drinks CHO-rich sports cake	38	-	-
			39	-	-
			40	-	2 CHO-rich sports drinks

[a]Rodiola rosea is a medicinal herb containing amino acids, vitamins and minerals

Most of the subjects spoke about food supplements (6/10). Four athletes took magnesium (against muscle cramps (3) or to improve blood flow (1)); one athlete took calcium (also against muscle cramps), one of them spoke about caffeine and one about vitamins. Six indicated that they took sports foods, mostly CHO drinks (4/10), CHO-rich cake (2/10) and maltodextrine (2/10), and protein bars and shakes to preserve muscle mass (1/10).

The most often quoted sources of information about pre-race nutrition were friends and family (4/10), and personal experience and educational background (3/10). Some people got their knowledge from reading (2/10), sports coaches (2/10), sales representatives of sports food brands (2/10), physicians (1/10) or pharmacists (1/10).

The food journals revealed that vitamin and mineral supplement intake, and sports food consumption was higher than what the interviewed subjects said and remembered (Table 2).

Discussion

Our intention was to explore 4-day pre-race nutritional habits and beliefs among amateur athletes participating to a major multi-hour ski-mountaineering race. The main findings were that 1) the energy and CHO intake was below recommended amounts, while protein and fat intake were close to the recommended intake; 2) the main difference between the participants in the shorter and longer races were liquid, supplement and sports food intakes; and 3) that knowledge and beliefs about pre-race nutrition among these amateur athletes participating to extreme endurance events are insufficient or incorrect.

It is generally believed that high CHO intake to optimize glycogen storage is the most specific and important recommendation for endurance activity to ensure an appropriate energy supply all along a multi hour endurance race [5]. The CHO stores (muscle and liver glycogen) are limited and need to be regularly refuelled. CHO ingestion is thus thought to be very important, whether it is to increase glycogen storage before a workout, during a race to avoid hypoglycaemia and to protect muscle and liver glycogen stores, or after a race to ensure recovery and optimal glycogen resynthesis [6, 7]. Low muscle glycogen stores during exercise, when accompanied by dropping blood glucose levels can cause performance decreases, subjective feelings of low levels of energy, sensation of heavy legs, excess fatigue, loss of concentration, irritability, dizziness and fainting [7, 24]. So it is important to ensure glycogen store fuelling and refuelling and it is better to start a race with full stores [6, 7], especially since the capacity to eat and process food during a race is limited [25]. Current recommendations for CHO storage before an endurance race are 10 to 12 $g \cdot kg\ BW^{-1} \cdot day^{-1}$, starting 36 to 48 h prior to the race [2, 9, 10].

The average CHO consumption in our population was less than half (46 ± 13 %) of these recommended levels and in fact not even a single participant to our study reached them. Given the belief of the interviewed athletes, that high CHO intake is important prior to such endurance events, this finding is surprising and possibly suggests lack of understanding of the concept of pre-race CHO loading. On the other hand, it may also reflect difficulties in reaching the recommended CHO amounts just by varying the quantities and proportions of the usual dietary components, without using additional specific CHO-rich sports food to allow the athletes reaching CHO and total energy-intake values closer to the guidelines. Our observations lead us to ask the question whether today's guidelines are adequate for practical use. The observed average CHO consumption in our sample was so far from the recommendations that it suggests that it might have been too difficult for our participants to reach the recommendations by consuming twice as much CHO as they did, even if it were only during the last 24 to 36 h and not during the full 4 days we looked at.

For the other macronutrients: fat and proteins, there are no specific pre-race recommendations for endurance activities, but there are guidelines for athletes in daily life. Endurance athletes are advised to consume between 1.2 and 1.8 $g \cdot kg\ BW^{-1} \cdot day^{-1}$ of protein [8, 9] and daily fat intake should amount to 20 to 35 % of total energy intake [2, 8–10]. For these nutrients the intakes of the subjects complied with the guidelines.

Fluid and electrolyte intake are thought to be important for performance because dehydration, when exceeding 2-3 % of body mass, may cause performance impairment [2], even though there is on-going debate on this topic [26]. So it is important to start races in euhydration and to drink enough and frequently during races [8]. Since we only have information about pre-race behaviour and have no data on habitual fluid intake in our subjects we do not know if, according to the recommendations, they increased their fluid intake prior to the race. Intake was on average 2.7 $l \cdot day^{-1}$, which is slightly above the recommendations for habitual daily intake (2.4 $l \cdot day^{-1}$) [23]. Also in this case the beliefs of the interviewed athletes contrast with their behaviour since 9 out of 10 mentioned the importance of increasing liquid intake in the last days prior to a major race but only drank an average 2.2 $l \cdot day^{-1}$.

Although several studies showed that vitamin and/or mineral supplementation does not improve performance during anaerobic [27], strength [28], endurance [28, 29] or ultra-endurance [30] exercise, if the daily diet is adequate [31], supplement intake remains widespread among athletes [30, 32, 33]. In our population, a third of the participants took such supplements. The recommendation is to abstain from vitamin or mineral supplementation if the athlete eats enough and a wide variety of food and in the absence of a known deficit [3]. Additionally, it is important to be careful and to estimate the safety, the efficacy, the potency and the legality of a supplement before taking it [2, 8–10]. Besides supplements, special sports food consumption was also widespread. Endurance athletes mostly consume special CHO drinks, gels or bars, which can help reaching the recommendations for energy and CHO intake [18, 34]. But in spite of 58 % of the 40 participants using CHO-rich sports food or drinks, their CHO intake remained far below the recommendations.

Digestive comfort is another key variable during endurance events such as multi-hour ski-mountaineering races [35, 36]. Digestive discomfort and gastrointestinal distress like cramps, nausea, vomiting, bloating, and diarrhoea are frequently reported during ultra-endurance activities, particularly during ultra-marathon running [35–37]. To avoid gastrointestinal distress during racing, athletes are advised to avoid dehydration, high-fibre food intake, and hypertonic beverages, and to practice their planned race nutrition strategies before the actual race [36–38]. It is difficult to say from the food diaries which food items were specifically avoided during these 4 days, because we do not know the habitual diet of the participants, but from the interviews it seemed that mostly red meat and other fatty food items were avoided.

In general, the athletes seemed to be well aware of the importance of pre-race nutrition for performance. The participants in the longer race Z placed a more particular emphasis on this topic than the participants to the shorter race A. They also trained more, used lighter racing gear (12.4 ± 2.5 kg vs. 15.4 ± 3.2 kg) and their supplement and sports food intake was higher. The participants in the longer Z race were likely more ambitious and experienced athletes, who tried noticeably harder to optimize everything for the race. Our finding of lower lipid consumption by participants with a higher VO_2max and/or lower body fat percentage, as well as the higher energy, CHO and liquid consumption of participants with lower body fat percentage also seem in accordance with this contention.

In spite of the declared importance of adequate nutrition in preparation of an endurance event, the knowledge on this topic was approximate. Half of the interviewed participants confused supplementation with sports food; all the participants believed that it is good for them to eat a lot of pasta during the 4 days preceding the race, but rarely spoke about CHO and other CHO sources. Moreover, it seemed to be difficult for them to explain why they choose some food items and avoided others. The overall impression was that it rather reflected beliefs than knowledge [15].

The finding in the interviewed athletes that they underestimated their sports food and supplement intake compared to the intake reported in the food journals is probably partly due to the long period of time between the real intake and the interviews. But another important reason for this difference is probably the fact that the athletes did not follow a clear strategy based on solid knowledge. This lack of a clear knowledge and strategy can be a reason for the far too low energy and CHO consumption.

Limitations

Our results should be interpreted taking into account some study limitations. Despite participation of 70 subjects to the study we obtained only 40 complete food intake diaries that could be analysed of which 25 % was discussed in detail during the face-to-face semi-structured interviews. The number of observations is therefore limited and not necessarily representative for all amateur athletes participating to the 'Patrouille des Glaciers' and similar extreme endurance events. Also, the interviews were performed two years after the race and obviously some detail may have been lost. However, it is unlikely that the major individual beliefs changed over these two years [39]. The overall strategy, grounded in the personal beliefs was probably close to that of race day. Finally, food diaries are known to be unreliable with frequent under and ill reporting of intake [40], so that our results should be interpreted as semi-quantitative.

Conclusions

This study about pre-competition nutritional habits and beliefs of amateur athletes before a long duration ski-mountaineering race showed that: although most of the athletes seemed aware of the importance of nutrition for endurance sports and specifically before a major race, their knowledge was approximate and a clear sound nutritional strategy was missing. Their average CHO intake represented less than half of the recommended intake, while energy intake was on average 17 % too low. There was no significant difference in the energy and macronutrient intake of the participants in the longer and the shorter race, but participants in the longer race drank significantly more, used more mineral and vitamin supplements and more sports food and drinks.

Taking into consideration all of these issues, some recommendations can be formulated for pre-race nutrition:

1) The athletes should be better informed about nutrition to allow them developing an evidence-based conscious and reflective feeding strategy.
2) A high priority should be given to CHO intake. The amount should be increased with traditional food (pasta, rice, bread, etc.), completed with CHO-rich sports food and drinks.
3) The chosen pre-race nutritional strategy should be experimented before that prior to the actual race (e.g. before a hard training period or a less important competition) to ensure that it does not cause gastrointestinal distress.

Competing interest

We have no conflict of interest to declare.

Authors' contributions

CP participated in study design, data collection (food diaries and interviews) and analysis, and drafted the manuscript. MG and CB participated in study design, the interviews and data analysis. BK participated in study design, data analysis and writing. All authors read and approved the final manuscript.

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