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ORIGINAL ARTICLE

Mountaineering experience decreases the net oxygen cost of climbing Mont Blanc (4,808 m)

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Abstract The purpose of this study was to test the hypothesis that mountaineering experience decreases the net oxygen cost of uphill walking (OCw) on steep mountain trails and in ice and snow conditions. OCw was measured during an ascent of Mont Blanc in eight experienced alpinists and eight non-alpinists who were matched for sex (4 + 4) and low-altitude aerobic power ($\dot{V}O_{2max}$ 50–55 ml kg^{-1} min^{-1}). Subjects carried a breath-by-breath gas exchange analyzer and a GPS. $\dot{V}O_{2max}$ at altitude was estimated from measured low-altitude $\dot{V}O_{2max}$ using Bassett's equation to calculate fractional use of $\dot{V}O_{2max}$ during the ascent (F$\dot{V}O_{2max}$). OCw was calculated as the difference between $\dot{V}O_2$ while climbing minus resting $\dot{V}O_2$. At all elevations, Alpinists exhibited a lower OCw ($P < 0.01$). In all subjects, OCw increased when encountering ice and snow conditions. F$\dot{V}O_{2max}$ remained stable around 75% at all elevations independent of experience or sex. In conclusion, the OCw is lower in experienced mountaineers compared to non-experienced subjects, and increases when going from steep rocky mountain terrain to ice and snow conditions, independent of mountaineering experience or sex.

Keywords Hypoxia · Altitude · Oxygen · Walking · Pace · Endurance · Females

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Introduction

There is an ever increasing number of people who climb at an altitude of 5,000 m during trekking trips proposed by commercial tour operators (Ainslie et al. 2005). These high-altitude ascents represent a major challenge for the majority of these subjects, as many are not acclimatized or accustomed to walking on icy and steep paths. In Europe, one of the most popular summits is Mont Blanc (4,808 m), with approximately 20,000 climbers each year.

The oxygen cost of climbing increases as the ground becomes icier and steeper (Haisman and Goldman 1974; Minetti et al. 2002; Saha 1958; Soule and Goldman 1972), although alpine experience minimizes the OCw on steep mountain paths (Bastien et al. 2005; Saha 1958). More than 50 years ago, Saha et al. (1958) compared OCw in Tensing Norgay (the first man to climb Mount Everest) with sedentary subjects and reported that the difference in OCw could also be due to individual $\dot{V}O_{2max}$ values and altitude acclimatization. However, these researchers collected expired gas only over a 5-min period at 2,300 m on dry paths. Exercise of longer duration has been reported to increase the oxygen cost of running (di Prampero et al. 1986). The Mont

Blanc ascent lasts 10 h interspersed by a short rest and a night spent in a mountain hut at 3,817 m. Therefore, OCw could increase substantially after 3,000 m due to the combined effects of environmental conditions and fatigue. In addition, $\dot{V}O_{2max}$ decreases in relation to altitude, dropping to approximately 70% of the sea level $\dot{V}O_{2max}$ at 5,000 m (Bassett et al. 1999; Péronnet et al. 1989; Mazzeo 2008).

An increase in OCw may also decrease $\dot{V}O_2$ reserve, causing a higher fractional use of $\dot{V}O_{2max}$, especially in the final ascent phase. The increased OCw in high mountain conditions may be important, especially above altitudes of 3,000 m, at which a significant drop in $\dot{V}O_{2max}$ is accompanied by an increase in slope and the appearance of snow and ice.

The purpose of this study was to compare the OCw during a 5,000 m ascent without acclimatization between experienced alpinists (A) and non-alpinists (NA). It was hypothesized that, for both sexes, alpine experience limits the increase in OCw when walking on snow and ice and therefore prevents an increase in $F\dot{V}O_{2max}$ (i.e., the $\dot{V}O_2$ reserve decrease) during the Mont Blanc ascent in acute hypoxia conditions.

Materials and methods

Subjects

Eight experienced A and eight NA participated in this study. None of the subjects were acclimatized to altitude. The subjects were matched for $\dot{V}O_{2max}$ (maximum oxygen consumption: 53.8 ± 4.3 vs. 54.1 ± 2.8 ml kg^{-1} min^{-1} for A and NA, respectively; $P = 0.84$), age (40.3 ± 3.7 vs. 39.3 ± 4.9 years, respectively; $P = 0.24$) and sex (equal number of male and female participants) (Table 1). The NA group did not have any previous mountain climbing experience. Neither group had been exposed to altitude in the 2 months prior to the study.

Before participation, all subjects were informed of the risks and stresses associated with the protocol, and gave their written voluntary informed consent. The present study conformed to the standards set by the *Declaration of Helsinki* and its procedures were approved by the local ethics committee of the Hospital Saint Louis of Paris.

Table 1 Physical characteristics of the subjects (Mean ± SD)

	Non-alpinists (NA)	Alpinists(A)	*P*
Age (year)	40 ± 11	44 ± 5	0.35
Weight (kg)	63.2 ± 8.7	68.0 ± 6.7	0.25
Height (m)	170 ± 9	174 ± 5	0.27
BMI (kg/m^2)	21.8 ± 2.2	22.4 ± 1.6	0.59
$\dot{V}O_{2max}$ at sea level (ml kg^{-1} min^{-1})	54.1 ± 2.8	53.8 ± 4.3	0.84

Verification of the sensitivity of oxygen analyzer K4b$_2$ cells up to altitude

The K4b$_2$ had been previously tested in the Italian Royal Air Force's hypobaric chamber to determine the sensitivity of the K4b$_2$ O_2 cells up to an altitude of 9,000 m. The experimental personnel verified that FIO_2 remained at 20.9% until 8,000 m. The flow calibration was not tested during this test because it required manual intervention inside the hypobaric chamber by a subject previously acclimatized to these extreme altitudes. However, the flow calibration was verified at the Gouter Hut before starting the final ascent to the summit on Sunday. The Cosmed K4b$_2$ allows the introduction of actual barometric pressure values and then to change air density, allowing appropriate usage in hypobaric conditions. Furthermore, when the K4b$_2$ is used in conditions in which barometric pressure is constantly changing (as during mountain climbing), the system measures both analyzer pressure and ambient temperature and pressure in real-time and the standard temperature pressure dry (STPD) correction (K4b^2, Cosmed, software, Roma) was applied. The environmental and route conditions did not change during the study and the barometric pressure at sea level remained at 765 mmHg during the entire ascent.

Determination of $\dot{V}O_{2max}$ at sea level

Two weeks before the ascent, all subjects performed an incremental test at sea level on a cycle ergometer with 2-min stages to determine individual $\dot{V}O_{2max}$ After a low-intensity warm-up (10 min at 40 and 50 W for males and females, respectively), the work load was increased by 40 W (males) and 50 W (females) every 2 min. A fingertip capillary blood sample was collected immediately after the test and $\dot{V}O_{2max}$ was defined as the highest 30-s oxygen uptake value reached with a respiratory exchange ratio ($RER = \dot{V}CO_2/\dot{V}O_2$) greater than 1.05, blood lactate concentration of greater than 8 mM, and a peak heart rate of at least 90% of the age-predicted maximum. The breath-by-breath data were smoothed using a three-step average filter to enhance the underlying characteristics (Data management software, Cosmed, Rome, Italy) and then averaged every 30 s.

Estimation of $\dot{V}O_{2max}$ at altitude

The $\dot{V}O_{2max}$ for each subject was corrected for each of six 500 m stages from 2,000 to 5,000 m according to the equation described by Bassett (1999):

$$y = -0.178 \times x^3 - 1.43 \times x^2 - 4.07 \times x + 100, \quad (1)$$

where y is the percentage of $\dot{V}O_{2max}$ ($F\dot{V}O_{2max}$) at sea level and x is the elevation (km) above sea level. $\dot{V}O_{2max}$ was estimated using Eq. 1 at six elevations: 2,000–2,500 m (stage 1), 2,500–3,000 m (stage 2), 3,000–3,500 m (stage 3), 3,500–4,000 m (stage 4), 4,000–4,500 m (stage 5), and 4,500–4,807 m (stage 6). $\dot{V}O_{2max}$ was estimated to be equal to 83.7, 79.7, 75.9, 72.2, 68.9, and 67.2% of sea level $\dot{V}O_{2max}$ at 2,000, 2,500, 3,000, 3,500, 4,000, 4,500 and 4,807 m, respectively.

Determination of the oxygen cost and $F\dot{V}O_{2max}$ during the entire Mont Blanc ascent

Subjects were paired within A and NA groups according to individual alpine experience and $\dot{V}O_{2max}$ and were assigned a personal mountain climbing guide who was asked not to influence the rate of the ascent. Subjects were free to choose their own pace. Every 2 h of climbing included a 25 and 15-min rest break. When the conditions turned to snow and ice (3,200 m), the subjects roped up and were again instructed to walk at their own pace. Both subjects and the guides were provided with instructions on how to place the mask of the $K4b^2$ and carried walkie-talkies to communicate with the experimental personnel. The subjects were allowed to remove their masks for drinking and eating during rest stops.

All subjects wore the same equipment and clothing (Millet, Annecy, France). Each subject carried a rucksack weighing 7 kg (males) and 5 kg (females) in addition to the gas exchange analyzer (800 g $K4b_2$ Cosmed, Roma). The gas exchange analyzers were calibrated each morning before starting the ascent according to the manufacturer's instructions ($K4b^2$, Cosmed, Roma) (Doyon et al. 2001). Breath-by-breath data were later reduced to 30-s averages. Data on heart rate and gas exchange ($\dot{V}O_2$; VCO_2; breathing frequency, Fr; and tidal volume, Vt) were collected for each subject from the start of the Mont Blanc ascent (2,372 m) at 11 a.m. on Saturday, until arrival at the mountain hut (3,817 m) at 5 p.m. on Saturday. Data collection continued on Sunday, commencing at 3 a.m. and finishing at 8 a.m. when the subjects attained the summit (4,807 m). Individual baseline data were registered over a period of 5 min. The oxygen pulse ($mlO_2\ bt^{-1}$) was calculated as the ratio between the oxygen uptake (ml min^{-1}) and the heart rate (bt min^{-1}) and the ventilatory equivalent for oxygen was calculated as the ratio between VE and $\dot{V}O_2$.

Both altitude and vertical speed were measured using an altimeter, which also acts as a heart rate monitor (AXN700, Polar, Finland) and a GPS (Garmin, USA) receiver (12 satellites) into the $K4b^2$. The Garmin GPS equipment computes vertical displacements from pressure changes detected with an incorporated altimeter. We verified that the two altimeters provided the same altitude. Vertical speed was calculated as the time spent to cover the 500 m separating the different stages.

Oxygen saturation (SaO_2) was estimated by an ear oximeter (Nonin, 8000Q, Plymouth, Minn, USA) at sea level and at an altitude of 3,900 m after 10 min of quiet sitting (Cymerman et al. 1989; Woorons et al. 2005). For technical reasons, SaO_2 was not measured at the summit.

Oxygen cost of the ascent

The net OCw is defined as the volume of oxygen required above non-walking resting conditions to transport the subject's body over one unit of vertical distance. The resting non-walking $\dot{V}O_2$ did not present a higher inter- and intra-individual variability during the ascent and was similar to data in resting conditions reported in the scientific literature (Medbo and Tabata 1989). The non-walking resting $\dot{V}O_2$ ($\dot{V}O_{2rest}$) was measured during during the 15-min pauses at each altitude stage (every 500 m). The excess post-exercise oxygen uptake (EPOC) was determined for each altitude stage during the pauses to determine the actual oxygen uptake at rest to obtain the net OCw.

OCw was expressed in milliliter of oxygen for one vertical meter by dividing net oxygen uptake by the speed of the ascent:

$$\mathrm{OCw} = \left(\dot{V}O_2 - \dot{V}O_{2rest}\right)/\mathrm{Av}, \quad (2)$$

where OCw is the oxygen cost of walking in ml O_2 kg^{-1} vertical m^{-1} and is estimated by the oxygen uptake along the entire ascent. $\dot{V}O_2$ is the average oxygen uptake expressed in ml kg^{-1} min^{-1} and $\dot{V}O_{2rest}$ is the $\dot{V}O_2$ measured at rest during the pauses; Av is the mean vertical speed (m min^{-1}) and is the result of the horizontal + vertical displacement of the walkers, the respective component depending on the slope of the path. We calculated OCw both with and without the weight of the backpack. Individual body mass was obtained after weighing each participant in his or her T-shirt and shorts.

Statistics

Statistical analysis was performed using 13 subjects, as three subjects in the NA group did not complete the ascent. Data were analyzed with a two-factor ANOVA (altitude and sex) after determining the normality of the distribution and the equality of the variance using commercially available software (SigmaStat, Jandel, Chicago, IL, USA). If normality was not acceptable, a

Mann–Whitney test was used. Statistical significance was set at $P < 0.05$.

Results

Mean data for stage 6 (4,500–4,807 m) for the 8 A and 5 NA subjects are listed in Tables 1 and 2. None of the subjects showed signs of acute mountain sickness nor required medication to prevent its occurrence.

Effect of alpine experience and sex on OCw

During the entire ascent, resting $\dot{V}O_2$, measured at the end of each 15-min pause, was not significantly different between A and NA (mean ± SD vs. mean ± SD ml kg^{-1} min^{-1}). Therefore, the net OCw was not altered by the oxygen cost at rest. Neither alpine experience ($P = 0.80$) nor sex ($P = 0.68$) influenced oxygen uptake during the pauses ($\dot{V}O_{2pause}$) at each altitude stage.

At each altitude stage, the A group demonstrated a faster ascent speed than the NA group for the same $\dot{V}O_2$ (Table 2). Indeed, the A group had a lower OCw than the NA group (Table 2), which was independent of sex (Table 3). When subjects encountered ice and snow above 3,000 m, OCw significantly increased independent of both alpine experience and sex.

Despite an increase in OCw with altitude and a decrease in $\dot{V}O_{2max}$, $F\dot{V}O_{2max}$ was maintained at 75% $\dot{V}O_{2max}$ during the entire ascent since the subjects decreased their ascent pace with increasing altitude.

Effect of alpine experience on $F\dot{V}O_{2max}$, O_2 pulse, and VE/$\dot{V}O_2$

Above 3,000 m, the vertical speed decreased significantly ($P < 0.01$), independent of alpine experience ($P = 0.95$). The decrease in speed, combined with the increase in OCw with increasing altitude, resulted in a similar $F\dot{V}O_{2max}$ in both groups ($P = 0.15$) (Table 2). For example, at 4,000 m, $F\dot{V}O_{2max}$ was equal to 76.7 ± 7.9 and 78.9 ± 7.0% $\dot{V}O_{2max}$ in the NA and A groups, respectively.

Heart rate (HR) decreased after 4,000 m in proportion to the decrease in $\dot{V}O_2$ ($P = 0.015$) (Table 2). Consequently, O_2 pulse did not change during the ascent but, at each altitude, the A group demonstrated a lower HR and a higher O_2 pulse (Table 2). O_2 pulse was the only variable influenced by sex, with females exhibiting a lower O_2 pulse at each altitude stage (Table 3). VE did not increase across the altitude stages, and remained below 100 L min^{-1} in both groups (Table 2). Neither Rf nor Vt were influenced by altitude ($P = 0.10$ and 0.14 for Rf and Vt, respectively). The A group exhibited a higher VE (L kg^{-1}) compared to the NA group ($P = 0.03$). However, this difference disappeared when VE was normalized by speed (L kg^{-1} m^{-1}). Neither VE/VO_2 nor R changed with altitude in either group (Table 2).

The effect of alpine experience on SaO_2

In both groups, subjects exhibited hypoxemia on arrival at the Gouter Hut (3,817 m) (97.4 ± 1.0 vs. 84.3 ± 3.7% at 400 and 4,808 m, respectively; $P = 0.001$), with no difference in SaO_2 between groups ($P = 0.52$).

Discussion

To our knowledge, this is the first study to measure gas exchange during a mountain climb up to an altitude of nearly 5,000 m. The main findings of this study were (1) climbing experience decreases the net OCw in icy and snowy conditions but does not prevent its increase throughout the ascent, (2) independent of alpine experience, the progressive decrease in climbing speed allowed subjects to maintain $F\dot{V}O_{2max}$ at a steady state of 75% $\dot{V}O_{2max}$ and (3) subjects' sex had no effect on the OCw.

Climbing experience decreases the net OCw in icy and snowy conditions but does not prevent its increase throughout the ascent

Our results are in agreement with previous findings (Haisman and Goldman 1974; Minetti et al. 2002; Ramaswamy et al. 1966; Saha 1958; Soule and Goldman 1972). Pugh (1958), whose study included similar altitude and terrain as that of the present study, reported similar values for $\dot{V}O_2$ and speed (25–35 ml kg^{-1} min^{-1} and 300–400 m h^{-1}, respectively). This suggests that the combined use of crampons when roping up on the glacier and the steepness of the rocky path led to an increase in OCw in both groups. Therefore, it is likely that the increase in the oxygen cost of locomotion with altitude is the result of a change in locomotor pattern due to the path conditions (steepness, ice, and crampon use). Despite the characteristics of the walking path, the alpinists demonstrated a lower OCw than the NA. The OCw of the vertical meter reported in the present study (4–6 mlO_2 m^{-1}) is in agreement with data reported in several other studies that used a treadmill with a similar slope (Minetti 1995; Minetti et al. 2002), natural outdoor conditions using a self-selected climbing speed (300–500 m h^{-1}) and low altitude (1,000 m) (Durnin 1955), and during exercise on a treadmill at an altitude of 4,300 m (Cymerman et al. 1981). Pugh (1958) reported a lower OCw value of 3.5–4 mlO_2 kg^{-1} m^{-1} (i.e., a $\dot{V}O_2$ equal to 26 ml kg^{-1} min^{-1}

Table 2 Mountaineering experience effect on physiological responses during the Mont Blanc ascent for experienced alpinists (A) and non-experienced subjects (NA)

	2,000–2,500 m NA A	2,500–3,000 m NA A	3,000–3,500 m NA A	3,500–4,000 m NA A	4,000–4,500 m NA A	4,500–4,800 m NA A	Asc M Asc × M
Vertical speed (m h^{-1})	416 ± 58	360 ± 50	326 ± 92	289 ± 57	281 ± 19	259 ± 43	<0.0001
	440 ± 96	455 ± 104	369 ± 66	327 ± 52	346 ± 115	329 ± 103	0.00216
							0.93
% Speed at 2,000 m	100	87 ± 23	79 ± 22	71 ± 18	67 ± 7	62 ± 13	0.0001
	100	103 ± 11	84 ± 10	75 ± 4	78 ± 17	75 ± 42	0.022
							0.68
$\dot{V}O_2$ (ml kg^{-1} min^{-1})	33.5 ± 4.2	32.1 ± 2.7	31.6 ± 2.9	29.7 ± 2.8	26.8 ± 2.9	27.2 ± 2.1	0.0005
	33.5 ± 4.2	33.8 ± 3.6	36.7 ± 2.7	30.7 ± 3.9	30.6 ± 4.7	28.8 ± 5.9	0.20
							0.81
%$\dot{V}O_2$ at 2,000 m (ml kg^{-1} min^{-1})	100	95 ± 6	94 ± 9	87 ± 8	81 ± 12	81 ± 9	0.0001
	100	101 ± 6	101 ± 9	92 ± 7	91 ± 8.0	85 ± 11	0.0032
							0.53
$F\dot{V}O_{2max}$ altitude (%$\dot{V}O_{2max}$)	75 ± 6	75 ± 8	77 ± 9	77 ± 8	72 ± 9	74 ± 7	0.62
	75 ± 9	79 ± 6	83 ± 9	79 ± 7	82 ± 9	78 ± 12	0.02
							0.70
HR (bpm)	162 ± 18	159 ± 13	155 ± 10	156 ± 8	144 ± 14	144 ± 15	0.0015
	147 ± 11	147 ± 10	146 ± 15	145 ± 13	137 ± 15	138 ± 15	0.0011
							0.89
$\dot{V}O_2$/HR (mlO_2 kg^{-1} bt^{-1})	0.21 ± 0.02	0.21 ± 0.02	0.20 ± 0.02	0.20 ± 0.02	0.19 ± 0.03	0.20 ± 0.03	0.64
	0.23 ± 0.03	0.23 ± 0.03	0.23 ± 0.02	0.21 ± 0.04	0.23 ± 0.04	0.22 ± 0.06	0.0012
							0.97
VE (L min^{-1})	60.8 ± 12.2	60.3 ± 15.0	57.0 ± 13.5	54.3 ± 17.1	57.4 ± 23.5	53.7 ± 16.6	0.98
	60.0 ± 12.3	64.4 ± 12.7	66.1 ± 13.3	67.5 ± 9.2	69.0 ± 17.3	68.2 ± 11.5	0.07
							0.67
Rf (rate min^{-1})	39 ± 7	36 ± 6	41 ± 8	40 ± 6	39 ± 2	42 ± 5	0.16
	34 ± 6	37 ± 8	42 ± 12	44 ± 11	44 ± 14	47 ± 13	0.41
							0.7
VE/$\dot{V}O_2$	28.4 ± 4.0	29.7 ± 5.9	28.4 ± 4.5	27.9 ± 5.8	30.9 ± 9.6	28.8 ± 5.0	0.108
	26.2 ± 3.9	28.0 ± 3.9	28.8 ± 3.5	32.9 ± 6.2	33.5 ± 7.2	36.1 ± 5.2	0.09
							0.16
VE/$\dot{V}CO_2$	36.1 ± 6.5	36.3 ± 8.5	35.6 ± 6.8	34.9 ± 8.3	39.8 ± 12.7	36.7 ± 5.8	0.07
	30.9 ± 4.2	33.6 ± 5.1	34.1 ± 4.1	38.3 ± 8.0	41.7 ± 10.3	44.7 ± 8.0	0.62
							0.28
OCw (ml kg^{-1} m^{-1})	4.9 ± 0.4	5.7 ± 1.6	6.1 ± 1.1	6.4 ± 1.3	–	–	0.002
	4.6 ± 0.5	4.6 ± 0.7	5.6 ± 1.0	5.7 ± 0.9	–	–	0.012
							0.69

Asc Ascent effect, *M* mountaineering experience effect, $F\dot{V}O_{2max}$ percentage of the $\dot{V}O_{2max}$ corrected for altitude according to Eq. 1, *OCw* the oxygen cost of walking (see "Materials and methods"), *NA* non-alpinists, *A* alpinists, *Asc* ascent effect, *M* mountaineering experience effect

* $P < 0.05$

at a rate of climbing of 494 m h^{-1}). However, Pugh (1958) considered the subjects' total weight, including the alpine material, which decreases the OCw when expressed per kilogram of body mass (Bastien et al. 2005; di Prampero et al. 1986; Westerterp et al. 1992).

The higher OCw observed in NA subjects could be partly due to the higher VE measured at each altitude in NA versus A subjects. However, this difference between the two groups disappeared when VE was normalized by the speed (to obtain the ventilatory cost in L m^{-1}) since

Table 3 Effect of sex on the physiological responses during the Mont Blanc ascent

	2,000–2,500 m Males Females	2,500–3,000 m Males Females	3,000–3,500 m Males Females	3,500–4,000 m Males Females	4,000–4,500 m Males Females	4,500–4,800 m Males Females	Asc S Asc × S
Vertical speed (m h^{-1})	430 ± 67	395 ± 119	327 ± 65	315 ± 60	324 ± 95	318 ± 96	<0.01
	426 ± 52	420 ± 96	368 ± 93	301 ± 55	317 ± 102	290 ± 89	0.70
							0.89
% Speed at 2,000 m	100	91.4 ± 21.9	76.9 ± 15.2	74.6 ± 16.3	74.5 ± 16.9	72.5 ± 23.1	<0.0001
	100	98.3 ± 16.4	86.2 ± 17.8	70.7 ± 9.2	73.0 ± 15.4	64.7 ± 14.0	0.49
							0.67
$\dot{V}O_2$ (ml kg^{-1} min^{-1})	34.2 ± 3.0	33.0 ± 3.3	31.9 ± 2.8	31.0 ± 3.4	30.3 ± 4.8	28.9 ± 5.3	<0.002
	33.1 ± 3.8	32.9 ± 3.3	33.4 ± 2.8	29.3 ± 3.4	27.9 ± 3.9	26.6 ± 3.6	0.42
							0.67
%$\dot{V}O_2$ at 2,000 m (ml kg^{-1} min^{-1})	100	96.8 ± 7.1	93.6 ± 7.4	90.9 ± 8.6	87.8 ± 12.2	83.6 ± 12.6	<0.001
	100	99.6 ± 6.6	101.7 ± 10.7	89.7 ± 6.2	86.8 ± 8.7	82.9 ± 6.4	0.28
							0.56
$F\dot{V}O_{2max}$ altitude (%)	73 ± 4	74 ± 6	75 ± 6	77 ± 7	78 ± 11	76 ± 12	<0.0008
	76 ± 9	79 ± 8	75 ± 10	79 ± 8	79 ± 11	77 ± 10	0.13
							0.61
HR (bpm)	152 ± 21	148 ± 13	150 ± 16	147 ± 15	137 ± 16	135 ± 18	0.162
	157 ± 11	158 ± 10	151 ± 10	153 ± 9	142 ± 13	143 ± 9	0.4
							0.96
$\dot{V}O_2$/HR (mlO_2 kg^{-1} bt^{-1})	0.23 ± 0.03	0.23 ± 0.03	0.21 ± 0.03	0.21 ± 0.04	0.23 ± 0.04	0.22 ± 0.05	0.60
	0.21 ± 0.03	0.21 ± 0.03	0.22 ± 0.02	0.19 ± 0.02	0.20 ± 0.02	0.19 ± 0.03	0.03
							0.68
VE (L kg^{-1})	0.91 ± 0.13	0.94 ± 0.21	0.95 ± 0.14	0.91 ± 0.17	0.96 ± 0.22	0.91 ± 0.17	0.99
	0.93 ± 0.19	0.97 ± 0.17	0.92 ± 0.18	0.93 ± 0.23	0.95 ± 0.33	0.93 ± 0.27	0.88
							0.99
Rf (rate min^{-1})	37.5 ± 9.6	34.8 ± 8.2	43.1 ± 10.9	42.2 ± 8.8	40.9 ± 14.1	46.9 ± 10.3	0.08
	35.6 ± 4.1	38.0 ± 6.0	40.1 ± 9.3	41.9 ± 9.5	44.2 ± 9.7	43.8 ± 11.0	0.73
							0.89
VE/$\dot{V}O_2$	26.6 ± 3.5	28.3 ± 5.9	29.0 ± 3.8	29.4 ± 3.7	31.8 ± 6.2	31.6 ± 3.0	0.037
	28.0 ± 4.5	29.5 ± 4.1	27.3 ± 3.7	32.0 ± 8.6	33.7 ± 10.1	35.0 ± 8.8	0.62
							0.76
VE/$\dot{V}CO_2$	32.5 ± 6.2	34.1 ± 9.2	35.8 ± 6.8	35.2 ± 6.7	40.1 ± 10.4	38.6 ± 3.6	0.015
	34.4 ± 5.9	35.8 ± 4.1	33.9 ± 3.8	38.6 ± 9.5	42.3 ± 10.1	45.5 ± 10.3	0.29
							0.754
OCw (ml kg^{-1} m^{-1})	4.8 ± 0.4	5.4 ± 1.4	5.9 ± 0.8	6.1 ± 1.2	6.1 ± 1.4	5.5 ± 1.9	0.004
	4.7 ± 0.6	4.9 ± 1.3	5.7 ± 1.3	6.1 ± 1.3	5.6 ± 1.1	5.8 ± 1.0	0.43
							0.94

$F\dot{V}O_{2max}$ percentage of the $\dot{V}O_{2max}$ corrected for altitude according to Eq. 1, *OCw* oxygen cost of walking (see "Materials and methods"), *Asc* ascent effect, *S* effect of sex, *S* × *Asc* sex × ascent effect

* $P < 0.05$

this variable is correlated with the difference in vertical speed (Sharma and Brown 2007). For a given ventilation, the oxygen cost of breathing at altitude is lower because of the decreased air density. The increase in OCw with increasing altitude cannot be due to the ventilatory cost given that neither VE, Fr, nor Vt increased with altitude.

Independent of alpine experience, the progressive decrease in climbing speed allowed subjects to maintain $F\dot{V}O_{2max}$ at a steady state of 75% $\dot{V}O_{2max}$

The decrease in ascent speed observed above 3,000 m was associated with a decrease in $\dot{V}O_2$, allowing subjects to maintain $F\dot{V}O_{2\,max}$ at 75% despite continued increases in altitude (Ainslie et al. 2002; Pugh 1967; Weller et al. 1997). The three subjects (all in the NA group) who were forced to cease their ascent at 4,000 m used 60, 75 and 83% of their respective $\dot{V}O_{2max}$ Our data are in agreement with those of Saha (1958), who reported values of 55% $\dot{V}O_{2max}$ in experienced middle-aged mountain walkers and 70% $\dot{V}O_{2max}$ in inexperienced subjects. Our relatively high value of $\dot{V}O_{2max}$ may reflect the good endurance capacity of our middle-aged subjects. However, it must be noted that $\dot{V}O_{2max}$ in the present study at low altitude was obtained on a cycle ergometer, which typically yields lower values than those obtained during treadmill running or walking with increases in grade. Therefore, the fractional use of $\dot{V}O_{2max}$ found in the present study may be slightly overestimated. Since the aim of this study was to test the alpine experience on the energetics of the ascent, $\dot{V}O_2$ was normalized by body mass, ignoring the weight of the backpack, clothing, rope, and crampons.

Subjects' sex had no effect on the OCw

In contrast to the findings on alpine experience, the sex of subjects did not affect the energetics of the Mont Blanc ascent. The absence of a sex effect is in agreement with other studies that examined the influence of acute hypoxia on cardiorespiratory responses and performance (Elliot and Atterbom 1978; Muza et al. 2001; Wagner et al. 1979). As shown by Olfert et al. (Olfert et al. 2004), physical fitness level is more important than sex per se in determining whether or not pulmonary gas exchange impairments occur during exercise. Therefore, despite that no specific physiological profile has been reported to be associated with successful altitude ascensions (Oelz et al. 1986; Pugh 1972), we recommend a $\dot{V}O_{2max}$ of >45 ml kg^{-1} min^{-1} to ensure the aerobic suitability of aspiring walkers when climbing summits greater than 4,500 m, especially when performed in acute hypoxic conditions encountered on the Mont Blanc and Kilimanjaro mountains (Kenya) or on Pikes Peak (USA).

Perspectives

This study showed that previous alpine experience allows climbers to benefit from a lower OCw during a 5,000 m ascent in acute hypoxic conditions. This lower OCw is likely due to the experienced alpinists' greater skill when walking in icy conditions with crampons and on steep slopes. However, despite the increase in OCw with increasing altitude, the fractional use of $\dot{V}O_{2max}$ remained stable at 75% $\dot{V}O_{2max}$ during the entire ascent due to the decrease in walking speed. As observed when running a marathon (di Prampero et al. 1986; Foster and Lucia 2007; Morgan and Craib 1992), the oxygen cost of locomotion may be a decisive factor in whether or not non-experienced walkers are successful in climbing high summits (Tsianos et al. 2006).

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