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Himalayan porter's specialization: metabolic power, economy, efficiency and skill

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Carrying heavy loads in the Himalayan region is a real challenge. Porters face extreme ranges in terrain condition, path steepness, altitude hypoxia and climate for 6–8 h a day, many months a year, since they were boys. It has been previously shown that, when carrying loads on level terrain, porters' metabolic economy is higher than in Caucasians but the reasons are still unknown. We monitored Nepalese porters both during 90 km trekking in Khumbu Valley and at two different altitudes (3490 and 5050 m above sea-level), where they were compared to Caucasian mountaineers during (22%) gradient walking. Both subject groups carried a load of up to 90% body mass. The remarkably higher performance of porters during uphill locomotion (+60% in speed, +39% mechanical power) is only partly explained by the lower cost of loaded walking (−20%), being also the result of a better cardio-circulatory adaptation to altitude, which generates a higher mass-specific metabolic power (+30%). Consequently, Nepalese porters show higher efficiency, both during uphill and downhill loaded walking. Their higher economy on steep paths cannot be ascribed to a better exchange between potential and kinetic energy, as in our experiments the body centre of mass travelled monotonically uphill (or downhill). A different oscillation pattern of the loaded head–trunk segment, together with the analysis of the different components of the mechanical work during load carrying, suggests that achieved motor skills in balancing the loaded body segment above the hip could play a role in determining the better economy of porters.

Keywords: Nepalese porters; metabolic power; economy; efficiency; gradient walking; altitude

1. INTRODUCTION

Human-powered load carrying, in geographical areas where wheel-based tools are precluded by economical, technological or environmental limitations, has always been a challenge. In order to circumvent the low carrying effectiveness of upper limbs, different strategies to walk with heavy loads evolved. Particularly famous are the women of the Luo and Kikuyu tribes in East Africa for carrying loads equivalent to 70% of their body mass balanced on their heads or using forehead supporting straps (Maloiy *et al.* 1986), similar to Nepalese porters. In addition, porters from the Himalayan region simultaneously cope with unusually heavy loads (about 80–90% of their body mass, up to 200%), rough terrain, steep paths (up to 50% gradient) and extreme altitude hypoxia. The feats of these ethnic groups have been studied, in terms of economy of transport, in the past. During loaded walking on a flat terrain, both Nepalese porters (Bastien *et al.* 2005) and East African women (Maloiy *et al.* 1986) use remarkably less metabolic energy than Caucasian control subjects. Mechanical measurements of loaded walking on a flat surface (Heglund *et al.* 1995) suggested that the higher economy of African women was explained by a better exchange of potential and kinetic energies of the body centre of mass during the pendulum-like oscillation. In the case of Nepalese porters, the reason for their economy on a flat surface is still a mystery and the metabolic cost of transport on steep paths, which better represents their occupational environment, has never been assessed. For the mechanical energy exchange to take place, and save metabolic energy, both potential and kinetic energy curves need to oscillate out-of-phase. This ceases to occur during walking at gradients steeper than 15% (Minetti *et al.* 1993), where the time course of potential energy becomes a monotonically ascending (uphill) or descending (downhill) curve. Thus, energy recovery is supposed to play a very minor role in uphill walking economy.

While economy of loaded walking on a flat terrain was the principal investigated parameter in East African women (Maloiy *et al.* 1986), the metabolic power available is the additional, crucial variable in Nepalese porters. During uphill walking, the external mechanical work necessary to raise the heavy load and the body mass at every step greatly increases, and this requires a very high metabolic effort. Other environmental aspects potentially affect the porters' working capacity. In fact, it is known that only a fraction of the maximum metabolic power measured at sea-level is available at high altitude in Caucasian (e.g. 61% at 5600 m a.s.l.; Cerretelli 1976) whereas walking on rough terrain requires a higher

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metabolic cost (Soule & Goldman 1972). When considering that carrying performance, in terms of load mass and walking speed, is economically rewarded in this region, it turns out that metabolic cost of transport is not the only concern and probably needs to be complemented by the ability to maintain a high aerobic power for a long time or carry extra load. This combination, together with a careful management of resources, could help both to travel faster and reduce the risks of fatigue, exhaustion and muscle/joint pain or instability.

Moved by the interest in load carrying when multiple burdens limit the locomotor performance, and aware that the only hypothesis available at present to explain loaded walking economy cannot hold for gradient locomotion, we decided to study Nepalese porters during trekking in the Khumbu valley (Himalayan region) with the aim of measuring their economy and metabolic power on gradients.

2. MATERIAL AND METHODS

Nepalese porters (most of ethnicity Rai, Tamang, Magar and Gurung) use peculiar equipment for load carrying (see porters' photographs in the electronic supplementary material): a tumpline (namlo) links the forehead to a basket (doko), which leans along the bent back and is periodically rested on a T-shaped stick (tokma), also used as an alpenstock. Males and females become porters early in their life (Kumar *et al.* 2001) and walk fully loaded in very simple, non-technical shoes (sometimes even barefoot).

We spent three weeks in the Khumbu Valley where we monitored, during about 90 km trekking from Lukla to Lobuche and back, the heart rate (Polar, Finland), walking speed and gradient (GPSMap 76CS, Garmin, USA) in two of our five porters (mass 54.0 ± 4.8 kg, stature 1.59 ± 0.04 m, age 25.8 ± 8.1 years) carrying about 45 kg (83% of body mass) load. In addition, we carried out experiments on all the porters and on five Caucasian subjects in the vicinity of Namche Bazar (3490 m a.s.l.) and of the Italian Research Pyramid (5050 m a.s.l.; 360 degree panarama of the location in the electronic supplementary material) on selected path sections (mentioned later). A series of custom programs (LabView v. 7.1, National Instruments, Austin, TX, USA) was designed to process the GPS data and provide reliable speeds and path gradients. Owing to the inherent lack of precision in GPS position output, originally sampled at 1 Hz, an automatic routine progressively re-sampled the data at lower frequencies until the stabilization of the overall distance travelled was reached, resulting in a final sampling rate of 0.1–0.2 Hz.

The experiments in Namche and at the Research Pyramid were designed to investigate more detailed (metabolic and mechanical) aspects of the porters' performance. Five porters and five Caucasians (71.2 ± 11.1 kg, 1.73 ± 0.05 m, 31.2 ± 5.8 years, four of which were professional/expert mountaineers) were asked to ascend and descend 22% steep paths (482 and 325 m long, respectively, in the two locations) loaded with 25, 45 and 60 kg in their doko/rucksack, at a speed they could maintain for several hours. The paths were chosen in order to make sure that the trajectory of the body centre of mass was monotonically increasing or decreasing and no pendulum-like strategy could be adopted within the step (Minetti *et al.* 1993). In this way, the mechanical power is prevalently determined by the rate of change of potential energy (see §1). The experimental set-up included a portable metabograph

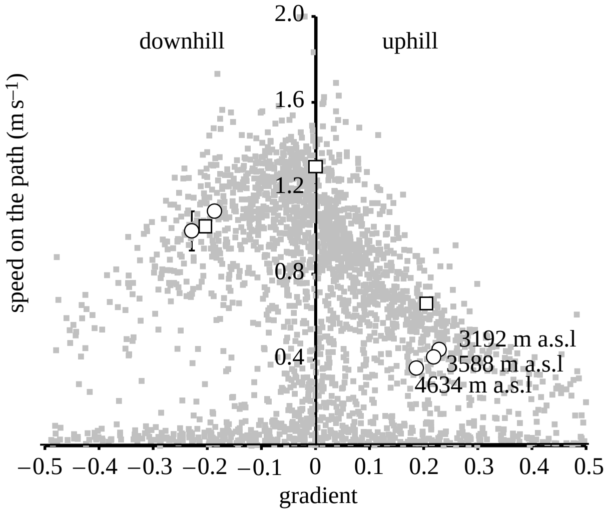

Figure 1. Walking speed along paths as a function of gradient: grey squares, Nepalese porters measured during loaded (45 kg) trekking in the Khumbu Valley (about 93 km total, 5 days uphill, 3 days downhill, altitude range 2650–5050 m a.s.l.); open circles, the porters' speed during ascending and descending the steepest/longest sections of the trekking (near Namche Bazar, Tengboche, Lobuche; some standard deviation bars are smaller than the symbol); and open squares, average spontaneous speed at three gradients for an unloaded Caucasian mountaineer walking on irregular paths in the Dolomites (120 km), average altitude 1800 m a.s.l. (unpublished observations). The cluster of low-speed values of porters refers to the periodical stops for resting.

(K4b^2, Cosmed, Rome, Italy), a magnetometer/inertial sensor system (MT9+Xbus, Xsens, Enschede, The Netherlands) measuring the angular/linear acceleration and the absolute orientation (resolution 0.05° r.m.s.) of the trunk at 100 Hz and a pocket GPS (GPSMap 76CS). At the end of each uphill and downhill walk, blood lactate concentration was assessed (Accutrend, Roche Diagnostic, Basel, Switzerland) to exclude the use of anaerobic energy sources. The metabolic cost of walking was calculated from the integral of oxygen consumption versus time data series, after having removed the value measured during rest (i.e. quiet standing while appropriately loaded for the session), and by dividing the results by the overall distance travelled (obtained by means of GPS technology).

The Ethical Committees and Research Review Boards of the National Research Council (C.N.R., Milan, Italy) and of the Royal Nepal Academy of Science and Technology (RONAST, Kathmandu, Nepal) approved this investigation.

3. RESULTS

(a) *Lukla–Lobuche trekking, two porters*

Figure 1 shows porters' freely chosen speed (light grey squares) of loaded walking on the path during the 5-day trekking, as a function of gradient (uphill and downhill). A 35 min subset of heart rate recording (HR, b.p.m.) during one of the steepest portions of the trekking path, shown in figure 2, illustrates how porters frequently stop to rest, with the heart frequency dropping the first 40 b.p.m. at the linear rate of about 1 b.p.m. s^{-1}. The relationship between the heart rate and the vertical speed ($\dot{s}_{vert}$, m_{vert} s^{-1}) in the uphill portion of the trekking was very linear ($HR = 125.7 + 239.3\ \dot{s}_{vert}$, $R^2 = 0.773$, $p < 0.001$).

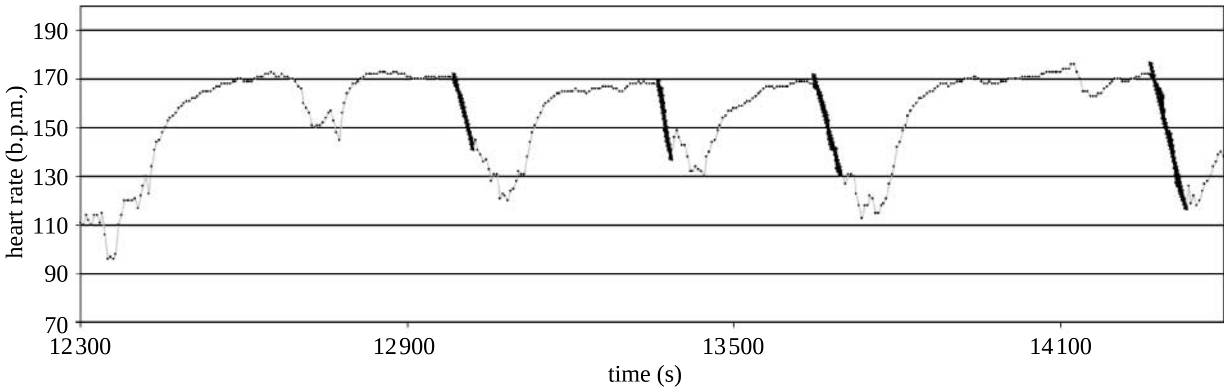

Figure 2. Time course of heart beat frequency of a 45 kg-loaded Nepalese porter during uphill walking in one of the steepest and highest portion of the trekking. The temporal interval between consecutive horizontal ticks corresponds to 10 min. The shown frequent stops for resting were used to evaluate Nepalese porters' attitude to quickly reset their heart rate after the end of exercise (the start of the thick vertical lines was suggested by GPS data).

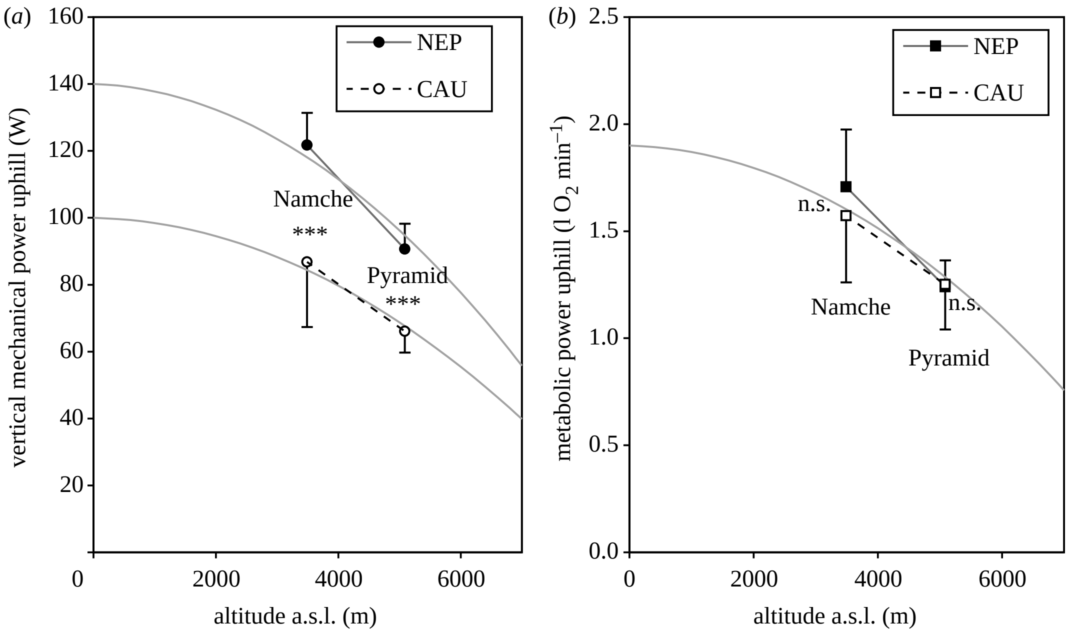

Figure 3. (*a*) The mechanical vertical power and (*b*) the metabolic power of Nepalese porters (NEP) and Caucasian mountaineers (CAU) are plotted against altitude and expressed in absolute units. All the different loads have been pooled. Descending curves represent the expected decay of performance due to hypoxia (Cerretelli 1976), with value at zero altitude set as to fit the experimental data. Asterisks denote significant differences: $^{***}p<0.001$; n.s., not significant.

(b) *At Namche and at the Research Pyramid, porters versus mountaineers*

Nepalese porters were +61.1% faster in the uphill leg compared with Caucasian mountaineers (no difference was found with mountaineers in the downhill part, although porters walked at −41.2% metabolic power) resulting in 38.7% higher vertical mechanical power (figure 3*a*). This was calculated as the ratio between the difference in potential energy ($\Delta PE = m_{tot}\, g\, \Delta h$, where m_{tot} is the total mass raised (body+load), g is the gravitational acceleration and Δh is the altitude difference) and the ascension duration in the controlled paths. Both the subject groups used the same absolute metabolic power (and almost the same heart rates) both in Namche and at the Research Pyramid (figure 3*b*). Altitude affected both groups by limiting metabolic (−23.9%) and mechanical (−24.7%) performances at the Research Pyramid.

In figure 4, the experimental metabolic cost per kilogram of mass raised or lowered 1 m (C_{vert}, $J(kg_{tot}\, m_{vert})^{-1}$) is plotted against the extra load imposed and compared to the minimum cost necessary to do the same job (horizontal grey bands, see figure 4). This 'unavoidable' vertical cost has been calculated according to physics ($\Delta PE = 9.81\ J(kg_{tot}\, m_{vert})^{-1}$) and physiology (efficiency of muscle work ranges 0.25–0.30 (positive, uphill) and 1.0–1.2 (negative, downhill)). During uphill walking, porters' economy is higher than in mountaineers, C_{vert} being 20.7% lower. During downhill walking, their lower C_{vert} is very close to the theoretically unsurpassable minimum. In both cases, the vertical cost of transport seems load independent (particularly for extra mass up to 45 kg).

By combining mechanical and metabolic results from figure 3, positive (uphill) and negative (downhill) efficiencies of loaded walking can be obtained for the two subject groups. Nepalese porters outperform Caucasian mountaineers in both cases, as shown in figure 5.

Trunk oscillation during the ascent (uphill) and descent (downhill) is summarized in figure 6 by means of frequency spectra. The magnetometer/inertial sensor

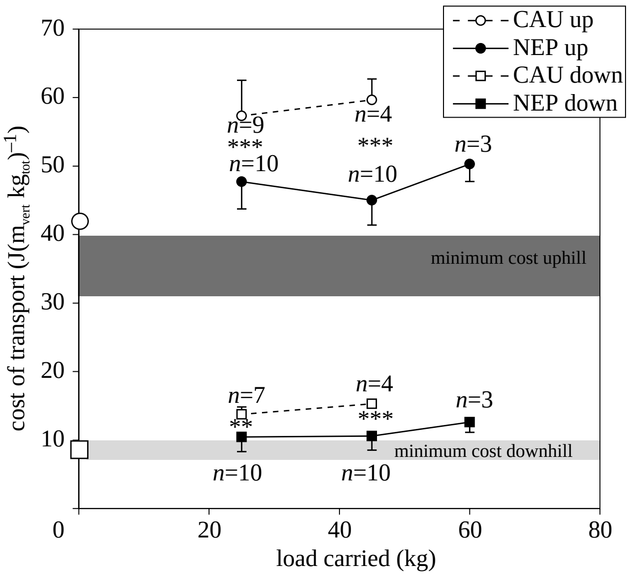

Figure 4. The metabolic cost to raise/lower 1 kg of (body or load) mass 1 m (vertical) during uphill (circles) and downhill (squares) walking is shown as a function of the added mass for Nepalese porters (NEP; filled symbols) and Caucasian mountaineers (CAU; open symbols). No mountaineers and only a few porters were able to carry 60 kg loads, as indicated by the sample size (Namche and Pyramid data pooled). Values for zero load have been taken from the literature (experiments on a treadmill at sea-level; Margaria 1938). The two shaded areas represent the range of the minimum costs (constituting the downward limits), estimated by dividing the mass-specific potential energy change by the positive and negative efficiency ranges (0.25–0.30 and 1.00–1.20, respectively) of muscle work (Woledge *et al.* 1985) and gradient walking (Margaria 1938). Asterisks indicate significant differences: $^{**}p<0.01$; $^{***}p<0.001$.

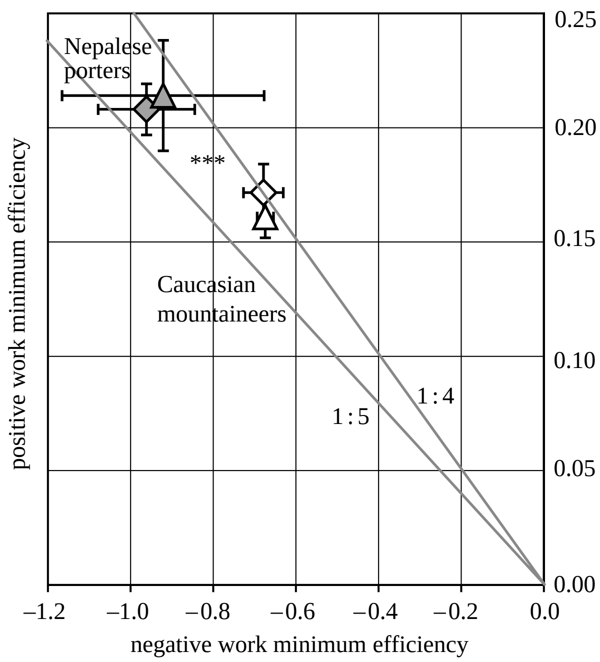

Figure 5. The minimum efficiency of loaded walking the uphill and downhill portions of the paths, was obtained by dividing the mechanical vertical (positive or negative) power by the associated metabolic power. Diamond and triangle symbols refer to experiments in Namche (3490 m a.s.l.) and at the Research Pyramid (5050 m a.s.l.), respectively ($^{***}p<0.001$). Grey lines represent given (absolute) ratios between the positive and negative efficiencies.

system measured the roll, pitch and yaw of the trunk segment at 100 Hz. A period of 80 s was sampled in similar uphill and downhill portions of each controlled experiment and a 400 harmonics Fourier analysis was performed on the (3×8000) data points. The frequency spectra, obtained by combining the harmonic coefficients of the three axes of rotation, were standardized for the subjects' step frequency and averaged intra-group (figure 6). Oscillation in Nepalese porters seems to occur with lower amplitude (in harmonics different from the stride frequency) and more consistent pattern (lower variability in most of the harmonics), as emerging from the comparison between standard deviations (see figure 6).

4. DISCUSSION

Data from the entire trekking (figure 1) show that porters' speed is rather high at all gradients (uphill and downhill), particularly when compared with unloaded walking on 120 km long irregular paths in the Dolomites at a lower altitude measured by using the same GPS technique (A. E. Minetti *et al.* 2002, unpublished observations). It is interesting to note that the maximum speed for porters vertically mirrors the shape of metabolic cost versus gradient curve for unloaded walking at optimal speeds measured earlier (Margaria 1938; Minetti *et al.* 2002), confirming the general inverse relationship between speed and cost (mentioned later). The maximum loaded speed seems to have occurred at a gradient close to −10%, which also corresponds to the optimum gradient when walking unloaded.

Furthermore, we calculated that 81.5% of all gradients measured during the trekking was within ±0.28, supporting a theory about the optimum gradient range of mountain paths (Minetti 1995). Heart rate measurements revealed that porters, differently from trained Caucasians who experience at high altitude an 18% drop from their maximum value (Marconi *et al.* 2004), still reach and maintain very high frequencies (160–170 b.p.m., see figure 2), almost irrespective of the altitude.

Nepalese porters walked uphill much faster than Caucasian mountaineers, thus developing a much higher vertical mechanical power (figure 3*a*). The sustainable vertical speed of walking depends on the sustainable maximum metabolic power available (net $\dot{E}$, W or W kg^{-1}) and the metabolic cost of loaded walking at that speed (C_{vert}, J m_{vert}^{-1} or J (kg m_{vert})$^{-1}$), according to $\dot{s}_{vert} \propto \dot{E}/C_{vert}$. This means that a higher speed of loaded walking can be obtained by increasing $\dot{E}$ or by reducing C_{vert} or by a combination of the two changes. The latter is the synergy allowing porters to achieve their performance. They use the same absolute metabolic power as mountaineers (figure 3*b*), corresponding to a 29.2% higher mass-specific $\dot{E}$ (W kg^{-1}) and a 20.7% lower C_{vert} (figure 4). This last result is in line with a recent paper (Bastien *et al.* 2005) on the energetics of loaded Nepalese porters on a flat terrain (C 19.6% lower). By using the above relationship, we can summarize that a +60% speed has been obtained by the combination of a +30% metabolic power and a −20% metabolic cost of loaded uphill walking (i.e. 161.1%≈129.2%/79.3% where, for instance, 161.1% corresponds to the reported gain of

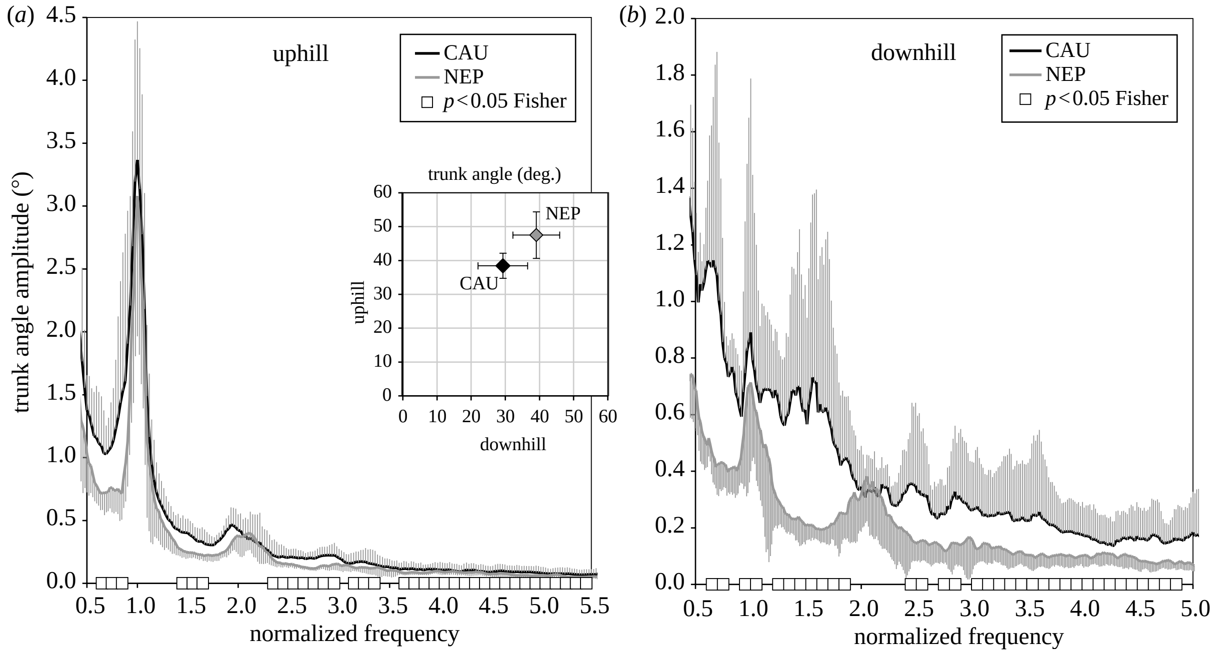

Figure 6. The frequency spectra of trunk oscillation during (*a*) uphill and (*b*) downhill walking are plotted against normalized frequency (1.0 means the prevalent oscillation frequency, corresponding to the step cadence of 0.525 Hz in the mountaineers and 0.650 Hz in the Nepalese porters). Data for the different loads and locations were pooled. Vertical error bars represent positive (CAU) and negative (NEP) amplitude standard deviations. Oscillation variability, compared using Fisher's tests for the same normalized frequency ranges (0.1 intervals), was found to be significantly greater in mountaineers (CAU) for most of the investigated range (open squares). The inset graph shows the different average trunk angles (uphill versus downhill) associated with the two groups/carrying tools (0° means vertical trunk).

61.1% in speed and 79.3% is the −20.7% decrease of C_{vert} in porters). This is a much greater gain with respect to the improvement in economy alone.

The reasons for the higher metabolic power of porters can be found in training, anatomy and adaptation. Porters start carrying about 35 kg at the age of about 12 years old (Kumar *et al.* 2001) and stop at the age of about 40–45 years old (population mode 25–30 years old), working for 6–8 h d^{-1} for many months a year (Sacareau 1994). They have less body fat and larger chest width (Sloan & Masali 1978), leading to higher spirometric values (Havryk *et al.* 2002). In addition, their maximum heart rate and oxygen consumption are maintained (Marconi *et al.* 2004), and convective and diffusive muscle O_2 flow is facilitated (Kayser *et al.* 1991), in chronic hypoxia. While most of the quoted literature investigated Sherpas, other ethnic groups permanently resident at high altitude in Himalaya seem to share the same adaptations, possibly through genetics (Gelfi *et al.* 2004).

To check the first determinant, we measured the on- and off-transients of the $\dot{V}_{O_2}$ kinetics at the beginning and end of the uphill and the downhill parts of the controlled experiments. $\dot{V}_{O_2}$ kinetics were simplified by partitioning every transient situation into a pre-transition-plateau, transition and post-transition-plateau phases. The breaking points between adjacent phases, each of them considered as linear, were obtained from an iterative statistical procedure (Jones & Molitoris 1984). Then the average rate of $\dot{V}_{O_2}$ change (ml O_2 min^{-1} s^{-1}) of the metabolic transient was determined by the ratio between the average $\dot{V}_{O_2}$ difference (absolute values of post-transition plateaus minus pre-transition plateaus) and the duration of the transition phase. On- and off-phases were pooled together and the results were 18.5±2.6 ml O_2 min^{-1} s^{-1} for porters and 12.4±2.7 ml O_2 min^{-1} s^{-1} for mountaineers. Thus, $\dot{V}_{O_2}$ kinetics was 49.5% faster in Nepalese porters ($p<0.005$) suggesting a level of athletic conditioning (Hagberg *et al.* 1978) that Caucasian mountaineers cannot afford at these altitudes.

Nevertheless, both subject groups experienced the same decrease (about −24%) of their metabolic and mechanical performances at the highest investigated altitude (5050 m a.s.l., figure 3), a result that confirms previous observations on the effects of hypoxia on exercise capacity (Cerretelli 1976).

The gain in positive and negative (minimum) efficiencies (figure 5) of porters summarizes their superiority as load carriers. Their values are closer to the maximum reported for concentric and eccentric muscle contraction (Woledge *et al.* 1985). This is a remarkable finding because (i) we know that the usual energy-saving mechanisms of locomotion, i.e. the storage/release of mechanical elastic energy, and the exchange of potential and kinetic energy of the body centre of mass are probably not involved in steep uphill walking (Minetti *et al.* 1993) and (ii) only the work against gravity has been included in the calculation of efficiency (thus the term 'minimum' efficiency).

The present results, and the ones published earlier (Bastien *et al.* 2005), pose a question about the determinants of the much lower cost of locomotion in porters (figure 4). It is apparent how porters' costs are much closer to the minimum ones (and, incidentally, correspond to an unloaded Caucasian walking at the same speed on a 22% inclined treadmill at sea-level—open circles and squares in figure 4; Margaria 1938), implying the minimization of any other waste of energy from rough terrain, heavy load, high altitude and unnecessary muscle contractions.

The cost of walking is expected to be proportional to the mechanical work done (through muscle efficiency), isometric muscle contractions (which produce no work) and other dissipative activities. The first component is partitioned as: (W1) the external work, necessary to lift and accelerate the body centre of mass at each step; (W2) the internal work, needed to linearly/rotationally accelerate body segments (head–trunk and limbs) with respect to the body centre of mass and to overcome the internal friction; and (W3) accessory mechanical work, such as the respiratory work and others related to the adopted carrying tools or to the environment.

W1 has to be similar in both subject groups: they walked on the same path at the same gradient, carrying the same loads (vertical costs in figure 4 have been expressed in (total) mass-specific units to standardize for the differences in body mass). As mentioned earlier, the trajectory of the centre of mass is monotonically ascending (or descending) at that steepness (Minetti *et al.* 1993). Thus, potential energy change is the predominant component of the external work and is likely to be the same in both groups. The internal work (W2) of limbs is predicted (Minetti 1998) to be similar in both groups since the smaller size of porters (−24.2% body mass) is compensated by a higher step frequency (+23.8%) than Caucasian mountaineers. Rather, W2 could be reduced in porters by more firmly controlling the movement of the heavily loaded head–trunk segment. A higher balancing ability, by minimizing the continuous adjustment of antagonist pairs of stabilizing muscles, could reduce the internal rotational work of the segment and prevent useless co-contractions. From the frequency spectra of trunk oscillation (figure 6), it is apparent that Nepalese porters show narrower harmonic content and lower variability than Caucasian mountaineers, with a remarkably different pattern in the downhill graph (this last finding, not being associated with a further gain in economy with respect to uphill walking, would deserve further investigations). While the amplitude differences are not large enough to explain the remarkable reduction of metabolic cost in porters (a simulation showed that the extra internal work due to the rotational pattern is rather small), the distinct spectra and their variability suggest different motor patterns of the trunk in both the groups. Similar to the skill of balancing a broom on our fingertip, which potentially reduces the metabolic cost, the ability to maintain a narrower and more consistent oscillation of the heavy trunk might imply reduced co-contractions and be the major determinant of the observed higher economy of porters. In addition, the association between spine stability and average bending angle of the trunk, which is higher in Nepalese porters (inset in figure 6), has been reported in load-carrying experiments (Granata & Marras 2000).

Finally, the different carrying tools could have influenced the cost of loaded walking (and the trunk oscillation pattern). The rucksack straps, for example, could cause extra respiratory work (higher breathing frequency), particularly in an impaired respiratory system, as in non-chronically acclimatized subjects at high altitude (Lundby *et al.* 2004). To check this hypothesis, we tested six Caucasian subjects (88.7±11.0 kg, 1.852±0.057 m, 26.5±3.1 years) in our laboratory (Alsager, UK) during uphill walking (+22% gradient) at a constant speed ($0.44\ \mathrm{m\ s^{-1}}$) on a treadmill with a 25 kg load alternatively supported by both carrying tools. While a significantly smaller ($p<0.019$) tidal volume (thus a higher breathing frequency) was associated with the use of a rucksack, pulmonary ventilation and the cost of loaded walking were not different ($p<0.358$) for the both carrying techniques.

In conclusion, the remarkable performance of Nepalese porters is determined by a more powerful 'engine' in a smaller body and by a lower cost of loaded walking. The long-lasting and specific training in hypoxia led to a surprisingly specialized adaptation of this ethnic group to the challenging environment. Owing to the experimental design, we can exclude that porters' better economy of loaded walking on gradients is related to a better exchange between potential and kinetic energy of the body centre of mass. We suggest that the cost of balancing the loaded head–trunk segment is a promising candidate and deserves further investigations.

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