picture 13: A heavily loaded Nepalese porter making slow progress on the route between the Kathmandu valley and Namche Bazaar in the Mt Everest valley.

Conclusion and perspectives

This study was intended to study the physiology of the most renowned head-supported load-carrying people: the porters of Nepal. They carry during days loads that most western subjects would not even be able to lift; we observed that, on the average, the loads were more or less equivalent to body weight and sometimes twice as big. To carry so heavy loads, the Nepalese porters generally walk slowly and make very frequent rest stops. We tested the hypothesis that porters in Nepal would be economical in terms of energy consumption during load carriage due to an adaptation of the walking gait to loading.

A laboratory was set in Phakding (Everest valley) at an altitude of 2800 m (see Appendix 5). We measured mechanical work production and energy consumption during load-carrying at different walking speeds and different loads in Nepalese porters.

This work and its hypothesis follow the studies that started twenty years ago on African women. These women could routinely carry heavy head-supported loads at a lower metabolic cost than Western control subjects. One of the most interesting results was that these African women could carry loads up to 20% of their body weight without increasing their energy consumption (Maloiy et al., 1986). Subsequent studies have shown that the ‘trick’ of the African women was a mechanical energy-saving strategy (Heglund et al., 1995). The African women can improve their walking gait when loaded and reduce the mechanical work production to limit the cost of carriage. With the exception of the studies on African women (Maloiy et al., 1986; Heglund et al., 1995; Cavagna et al., 2002; Jones et al., 1987), little was known about the energetic cost and gait mechanics of carrying head-supported load. To our knowledge, our study is the first to measure simultaneously the mechanics and the energetics in load-carriage for a large range of speed-load combinations in Nepali porters, the world-specialists in portage, but also in Caucasian subjects.

Indeed for comparison to the Nepalese porters, we made the same measurements in Western subjects carrying loads in backpacks and investigated in details the effects of load and speed on the energy cost for these control subjects. We show that their energy consumption per unit distance during load-carrying is minimal for walking at 4 km h^{-1}. However, even at that optimal speed, their gross metabolic rate increases in direct proportion to the load. As a result, fit European or North American adults can comfortably carry a backpack load weighting ‘only’ a quarter of their body weight over long distances.

Nepalese porters routinely carry much heavier loads than Western subjects. As mentioned earlier, they carry on average about their body weight during several days but many male porters carry much more, between 4 to 8 times the recommended maximal load for Western subjects and between 2 to 3 times the heaviest loads carried by the African women. Our results confirm that the Nepalese porters are the experts in load carriage. We have shown that they carry loads much more economically than the African women, who in turn are more economical than Western subjects. Such metabolic economy is achieved by a 20% ‘free ride’ (no increase in the energy consumption for loads up to 20% of their body weight) and by a metabolic cost per kilogram of additional load that is lower than for any other population. For example, the Nepalese porters can carry loads twice those of Western subjects for the same energy cost.

Even though the Nepalese porters carry loads at lower cost, they do the same amount of mechanical work than Western subjects during load-carrying. As a matter of fact, our mechanical study of load carriage failed to find out how the Nepalese porters could reduce the cost of carriage. This, however, shows that the mechanical adaptation to load carriage developed in the African women is not ‘universal’; the Nepalese porters also adapt to load-carrying, even better than the African women, but the exact mechanisms by which they save energy are still unknown.

Throughout chapters of this study we tried to give the most complete picture of the energetics, mechanics and kinematics effects of load on walking both in Nepali porters and in Western control subjects. This had never been done before.

However, many aspects should be studied further on in the future. For example, in order to be able to compare our results with other works, all our measurements were done in standard ‘laboratory conditions’ (*i.e.* on the level at constant walking speeds). In real life, the Nepalese porters almost never walk that way. They carry their burdens on difficult footpaths up and down steep mountains, making very frequent pauses and walking slowly. It can be calculated for instance that the heavily loaded porters walk only 10 to 15 km on a 12 hours day, giving an average walking speed of about 1 km h^{-1}. In fact, it would be of great interest to measure the porters on the road as they practice their intermittent walking pace. Notably, we could design a completely autonomous and portable system that would be carried on the road by the porters. Such a system could be aimed to measure the walking speed between two pauses, the slope of the terrain, the walk-rest durations and ratio, the breath by breath measure of $\dot{V}O_2$ on long distances and other environment parameters. Actually, two anthropologists (Malville and Panter-Brick) measured oxygen consumption of Nepalese porters carrying their burdens at their own pace as they progressed on the mountain paths. Unfortunately, these data are not usable in the frame of a physiological study because of major flaws in the measurements. In particular, the walking speed, the load, the gradients and the RER (respiratory exchange ratio) are not strictly controlled during their free walking experiments (Malville et al., 2001; Panter-Brick, 1992). In fact, in the end, due to the errors in their metabolic measurements mentioned above, Malville et al. came to exactly the wrong conclusion concerning the energetic cost of carrying head-supported loads. They assert that "greater economy of load-carrying is not a factor contributing to the ability of Nepali porters to carry loads", while in Chapter 2 and 4 we show that the Nepalese porters are the most economical porters ever measured. In the self-paced experiments of Panter-Brick, the speed, load and incline are all unknown, misleading her to the incredible assertion that there is no relation between energy consumption rate and load weight. Nevertheless, both anthropologists emphasized on the importance of the self-pacing and intermittent walking strategy used by the Nepalese porters. As discussed in the Chapter 4, such a strategy coupled with their economic carriage is most probably a major determinant of their ability to transport so heavy loads. Future experiments on the field, if correctly done, could identify the trade-off between load, speed, gradient, oxygen consumption and walk/rest ratio that these porters adopt and evaluate how important are the benefits of such a strategy.

The duration of the energy consumption measurements can also be a point of concern. Indeed, our metabolic measurements were maintained at steady state only for a few minutes. As the duration of the exercise is increased, fatigue may induce further increase in energy demand. This, for example, was suggested by Epstein et al. (1988) for load carrying exercises eliciting more than 50% $\dot{V}O_2max$ and by Patton et al. (1991), who found that the energy consumption rate during load-carrying activities was increasing over time even though the oxygen consumption was as low as 26.5% $\dot{V}O_2max$. In addition, the long distance experiments of Shoenfeld et al. (1977) performed at free walking speed led the authors to the conclusion that the absolute load weight rather than the percentage of body weight was a determinant of the fatigue. Further research could sharpen the definition of the optimal load-speed combination for long walks. Preliminary experiments are actually conducted in our laboratory to test the hypothesis of a slow component of $\dot{V}O_2$ during load-carrying and its relation to the $\dot{V}O_2max$ of the subjects. The latter experiments in Western subjects will also focus on the relation between the maximal load and the sustainable duration of exercise.

On the basis of these forthcoming results, future research could also orientate on the interest of intermittent walking pace in load carrying. Indeed, in our countries, hikers walk during long periods between rests (30 minutes or even more) whereas Nepalese porters are organized to rest every few minutes (or even less) using their T-stick or stone-platforms built for this purpose along the paths. The factors limiting the bouts duration in load-carrying are not clear to date. Some aspects like the $\dot{V}O_2$ (the effort intensity), the load position, the pain due to the backpack's pressure, the muscular volume activated, the load distribution and its effect on the body equilibrium, the increase in inner temperature could be taken into account or controlled simultaneously in a new large study on load-carrying. For example, it has been shown that the Nepalese have higher pain thresholds compared to Occidentals subjects (Clark and Clark, 1980). This, maybe is one of the element that allows them to carry heavier loads.

Although the analysis of the gait mechanics presented in this study is as complete as possible, some of the sources of energy expenses are actually not measured. For instance, the co-contractions and isometric contractions are not included in our internal work measurement but they have a metabolic cost. Recently, some studies have developed a force-production based approach to evaluate the metabolic cost of individual mechanical tasks in walking or running (Kram and Taylor, 1990; Gottschall et al., 2003; Griffin et al., 2003; Grabowski et al., 2005; Pontzer, 2005). These studies suggests that the net metabolic rate depends upon the active muscle volume required to generate force on the ground during locomotion, the time to generate it and a cost coefficient (expressed in $J\ N^{-1}$ or in $J\ cm^{-3}$). Such approach accounts for isometric contractions and could thus provide additional information on the mechanics of load-carrying in Nepalese porters. Nevertheless, this approach also fails in measuring the co-contractions. Yet, it can be reasonably hypothesized that these types of muscular contractions are increased under an external constraint such as loading and part of the great load-carrying economy in the Nepalese porters could be due to less futile muscular contractions being done when loaded compared to Western subjects.

The African women save energy because of a 'mechanical strategy'; they do less mechanical work than Caucasians without modification of their metabolic efficiency. On the contrary, the Nepalese porters save energy because of a 'metabolic strategy'; they do as much mechanical work as Caucasians with a higher metabolic efficiency. At the level of the muscles, this can be achieved, among others, by a 'functional' modification (*i.e.* change in ATP production/use processes) or by a 'structural' modification (*i.e.* change in muscular structure).

There are some evidences for functional modifications. Morpurgo et al. (1976) report that Sherpas living permanently at 4000 m above sea level have a higher affinity of blood for oxygen as compared with acclimatized Caucasians. Sloan and Masali (1978) made anthropometric measurements in male Sherpas and report that their long legs and large calf muscles may be a racial adaptation to the load-carrying. The works of Hochachka are certainly very instructive concerning possible metabolic adaptations in specific populations. For instance, Hochachka et al. (1991) have shown that Queshua natives from the Andes, living at high altitude, present two to three times less lactate accumulation than lowlanders during an incremental exercise to fatigue. This low lactate accumulation in hypobaric hypoxia was called the 'lactate paradox' and, for the Queshua, was due to a metabolic organization that maximizes the amount of ATP per mole of carbon substrate catabolized. In other terms, the Queshua have developed a metabolic adaptation to their environment; they take advantage of aerobic metabolism (high ATP yield per mole of substrate compared to anaerobic metabolism) and, in addition, they preferentially use carbohydrates, which again yields more ATP compared to lipids. As a result, the Queshua people are more efficient at submaximal rates of exercise because of higher energetic efficiency of muscles; they work more or longer on a given amount of O_2. The authors also postulated that the higher efficiency of Queshua people is due to the occurrence of more CA^{2+} ATPase and/or myosin ATPase isoforms in muscles of the Andean natives adapted to the altitude. Closer to our sample of subjects, Hochachka et al. (1996) have shown that Sherpas, living and working at high altitudes, also presented metabolism adaptation to their environment (hypobaric hypoxia). Briefly, the authors found higher ADP (free adenosine diphosphate) concentrations in Sherpas heart and interpreted it to reflect elevated carbohydrate contributions to heart energy needs. Again, according to the authors, such metabolic organization is advantageous because the ATP yield per O_2 molecule is 25-60% higher with glucose than with free fatty acids (the usual fuels utilized in the human heart in postfasting conditions). It should be noted that all these parameters were studied in the context of the adaptation to high altitude and not in the context of heavy load-carrying at mid altitude (1500-4000 m).

The higher metabolic efficiency of the Nepalese porters could also be due to a structural change of the muscle. It is well known that exercise training changes the structure of the muscles: muscle mass, muscle cross-sectional area, type-I and –II fibre area, proportions of fibre types, angle of pinnation, amount of myosin heavy chain isoforms, mitochondrial capacity, capillary density etc. (Brooks et al., 2005). However, the specificity of this training (strength or endurance) will change the muscular structure in different manners. As the porters walk many hours a day alternating very short bouts at high intensity and rest periods, it is not clear if such exercise would generate changes towards strength or endurance adaptation. In addition, these structural modifications may take place not only in the muscles but also in the respiratory and cardiovascular systems.

If we accept the numerous assumptions made by Griffin et al. (2003, *i.e.* the force production based approach already discussed in Chapter 4), our results in Nepalese porters would suggest either a smaller active muscle volume or a smaller cost coefficient (*i.e.* a smaller cost per Newton of force exerted on the ground) compared to the Western subjects. This, in fact, means more efficient muscles due to functional or structural adaptations developed either genetically or with training.

Finally, we'll turn to comparative physiology and body scaling. It's a fact that ants can carry several times their own body weight, a man can carry another man, a horse cannot carry another horse and an elephant can carry only a small fraction of its own body weight. This is related to body scaling. Big animals are in fact more fragile and less strong than small animals because strength $\propto$ (weight)$^{2/3}$. Indeed, the weight depends on the volume which depends on R^3 (where R is the length or size) and the strength depends on the bone and muscle sections which depend on R^2. As the size of an organism increases, its mass increases at a much greater rate than the cross-sectional area of its muscles and bones, so those muscles have proportionately more mass to lift and the bones more mass to support (larger stresses). From a mechanical point of view, this explains why small animals can carry relatively heavier loads. This also could partially explain how the Nepalese porters carry heavier loads than our Western control subjects, given their lighter weight and smaller stature.

At long last, it could be that there is not one single energy-saving mechanism but a combination of several mechanisms that would explain the economy of the Nepalese porters. Further investigations in load-carrying could orientate in all the directions cited above to reveal the 'knack' of the Nepalese porters.