picture 11: Heavily loaded Nepalese porter (120% of his body weight) measured on the force platforms for mechanical work output while walking at constant speed. The markers on the subject are for the cinematographic analysis done simultaneously to the ground reaction forces measurements.

Chapter 3
Head-supported load carriage by Nepalese porters I: mechanics.

Abstract

In the Everest valley of Nepal, because of the rugged mountain terrain, the roads are nothing more than dirt paths and all material must be conveyed on foot. The Nepalese porters routinely carry head-supported loads, which often exceed their body weight, over long distances up and down the steep mountain footpaths. This is the first of two companion papers reporting the biomechanics (this paper) and energetics (the following chapter) of load-carrying by the Nepalese porters. We expected to find that the Nepalese porters had developed a mechanical energy-saving strategy that would allow them to carry economically their very heavy loads, since such a mechanism has been shown previously in African women carrying head-supported loads. To test this hypothesis, the mechanical work done during level walking was measured under different loading and speed conditions in the Nepali porters, and compared to the African women and Western control subjects. Our results show that the Nepalese porters do not seem to have any biomechanical advantage in load carrying compared to control subjects at same load-speed combinations. The Nepali porters do the same amount of total mechanical work as Western control subjects when walking at 0.5-1.7 m s^{-1} while carrying loads ranging from 0 to 120% of their body weight.

Keywords

Load carrying • Locomotion • Mechanics • Walking • Work

Published as:

Bastien, G. J., Willems, P. A., Schepens, B. and Heglund, N. C. Head-supported load carriage by Nepalese porters I: mechanics. *J. Exp. Biol*. submitted.

Introduction

Fit European or North American adults can comfortably carry a backpack load weighing about a quarter of their body weight over an entire day's trek (Bastien et al., 2005*b*, Chapter 1). However a load greater than 60% of the body weight (M_b) cannot be carried for more than about an hour, and loads exceeding 100% M_b can be just barely moved. At the same time, many other populations carry much heavier loads for hours and sometimes for days at a time, because no other means of transport is available. Among these populations, African women have shown a striking adaptation for load carriage. In 1986, Maloiy et al. showed than Kenyan women carry loads much more economically than Western subjects. In a subsequent study, Heglund et al. (1995) showed that, while carrying head-supported loads, these women increase their pendulum-like transfer of energy, which is characteristic of the walking gait (Cavagna et al., 1963). In other words, they have developed a strategy to limit the muscular work required to carry a load by becoming 'better pendulums'. More recently, Cavagna et al. (2002) have increased our understanding of this strategy and identified in which part of the walking stride the increased energy saving occurred. These authors have shown that, for the African women, loading significantly improves the transduction of E_p to E_k during the descent of the *COM* in the walking step.

Whether other populations have adapted the strategy developed by the African women to carry loads remains an open question. For instance, Nepali porters routinely carry head-supported loads that are two times heavier than the loads carried by the African women (Bastien et al., 2005*a*, Chapter 2). In the Everest valley where no roads exist, load carriage is a daily task that everyone experiences since early childhood. Malville (1999) reported that young Nepali commercial porters, only 11 years old and weighing 29.9 kg, carry loads of 36.5 kg or 123% M_b . Not surprisingly, this population has developed a renowned ability for load carrying. Full-time professional porters convey food and material from Jiri (the end of the road heading towards Mt. Everest from Kathmandu) to Namche, the principal marketplace for the region. This 7-9 day trip on dirt footpaths covers a horizontal distance of ~100 km with >8000 m of total ascents and >6300 m of total descents. We measured 113 porters on the last day of this trip and found their average load was 89% M_b , with 20% of the men carrying more than 125% M_b (Chapter 2). We found that the average female Nepali porter's load was 10% M_b greater than the maximum load carried by the African women. Similarly, Malville (1999) measured the loads carried by 635 porters involved in long-distance portage on the route to Namche, and reported an average load for adult males of 146±30% M_b .

With the African women studies in mind, we set out to determine whether the Nepali porters could also use an energy-saving strategy that would allow them to carry economically their very heavy loads over long distances. Few studies on the energy consumption and biomechanics of people carrying loads have been published (Heglund et al., 1995; Laursen et al., 2000; Griffin et al., 2003). In this paper we compare the gait mechanics of the Nepali porters to the African women and Western control subjects with an analysis of the mechanical work during walking under different loading and speed conditions. The energy consumption rate in the same Nepali porters population during walking under identical loading and speed conditions is reported in the Chapter 4.

Subjects and Methods

The total positive mechanical work required to maintain constant-speed walking on a level surface while carrying a head-supported load was measured in Nepalese porters and control subjects. This mechanical work falls naturally into two categories: the external work and the internal work. External work (W_{ext}) derives from the resultant of all the external forces (*e.g.* the ground reaction forces and the force required to overcome wind resistance—this is measured as a ground reaction force) acting upon the centre of mass (*COM*); in this study the *COM* refers to the centre of the total mass (M_{tot}) which includes the body mass (M_b) plus any load the subject may be carrying (M_{load}). Positive external work results in an increase in the energy of the *COM* plus environment; negative external work results in a decrease in the energy of the *COM* plus environment. Negative external work was not measured in this study, but since walking on a level hard surface results in little work (positive or negative) being done on the environment (*e.g.* the air), it is about equal to the positive external work done.

Internal work is the result of internal forces (*i.e.* forces that do not result in a displacement of the *COM*), and can be divided into several sub-categories: for example the work performed to accelerate the segments relative to the *COM* ($W_{int,k}$), the work done by one leg against the other during the double contact phase in walking ($W_{int,dc}$), the work done by one muscle on another during antagonistic co-contractions, plus any work that is not directly related to locomotion (respiration, circulation, etc.). The first part, $W_{\text{int,k}}$, has previously been referred to simply as W_{int} and is measured using cinematographic analysis (Cavagna and Kaneko, 1977; Willems et al., 1995). $W_{\text{int,k}}$ can be up to ~55% of the total ($W_{\text{tot}} = W_{\text{ext}} + W_{\text{int,k}} + W_{\text{int,dc}}$) mechanical work of unloaded walking at high walking speeds (Schepens et al., 2004). The second part, $W_{\text{int,dc}}$, quantified for the first time only recently (Donelan et al., 2002*a*; Bastien et al., 2003), involves individual force recordings for each foot on separate force plates. $W_{\text{int,dc}}$ can be up to ~17% of the total mechanical work of unloaded walking at intermediate walking speeds (Schepens et al., 2004). The other categories of internal work of walking were not considered here.

Positive external work

The external work (W_{ext}) is calculated here as the sum of the increments in the energy fluctuations of the *COM* (E_{ext}) as a function of time during a walking cycle. The methods used to compute the external work are the same as those of Willems et al. (1995), which are derived from Cavagna (1975); therefore the methods will only be summarized here.

The mechanical energy changes of the *COM* due to its motion in the sagital plane during a walking stride were determined from the vertical and horizontal components of the ground reaction forces (Cavagna, 1975). The mechanical energy changes due to the lateral movements of the *COM* are small in adults (Tesio et al., 1998) and were neglected in this study.

The ground reaction forces were measured by means of a force platform (3 m long and 0.4 m wide) mounted at ground level. The force platform comprised five separate plates, conceptually similar to those described by Heglund (1981). The plates were sensitive to forces in the fore-aft and vertical directions, and had a natural frequency of 180 Hz and a linear response to within 1% of the measured value for forces up to 3000 N. The individual signals from the four bi-axial transducers in each of the plates were digitalized by a 12-bit analog-to-digital converter every 5 ms and processed by means of a personal computer.

A complete stride was selected for analysis only when the subject walked at a relatively constant average height and speed. Specifically, the sum of the increments in both the forward and vertical velocity of the *COM* could not differ by more than 25% from the sum of the decrements (Cavagna et al., 1977). According to these criteria, the average difference in the forward velocity of the *COM* at the beginning and at the end of the selected stride was 0.2±4.0% (mean ±SD, n=1651) of $\bar{\mathbf{V}}_f$ (the average walking speed during the stride), and the mean vertical force during the selected stride differed from M_{tot} by 0.1±0.8%.

The integration of the vertical and forward components of the force/mass ratio yields the velocity changes of the *COM*, from which the kinetic energy (E_k) can be calculated after evaluation of the integration constants (Cavagna, 1975; Willems et al., 1995). The kinetic energy of the *COM* is equal to $E_k = \frac{1}{2} M_{tot}(\mathbf{V}_f^2 + \mathbf{V}_v^2)$, where M_{tot} is the mass and $\mathbf{V}_f$ and $\mathbf{V}_v$ are respectively the forward and vertical components of the velocity of the *COM*. Integration of the vertical velocity yielded the vertical displacement ($\mathbf{S}_v$) of the *COM*, from which the gravitational-potential energy can be calculated. Potential energy of the *COM* is equal to $E_p = M_{tot}\boldsymbol{g}\mathbf{S}_v$, where $\boldsymbol{g}$ is the gravitational constant.

The total mechanical energy of the *COM* at any instant in time (E_{ext}) is the sum of E_k and E_p (Fig. 1); by making the instant-by-instant sum of these two curves, all possible energy transfers between the two are allowed, as will be discussed in the next section. The sum of the increments in the E_{ext} curve during a stride is equal to the minimum positive external work (W_{ext}) that must have been done to maintain the oscillations in energy of the *COM*. Similarly, the positive work done during a stride to maintain the velocity changes of the *COM* (W_k) is equal to the sum of the increments of the E_k curve, and the positive work done against gravity (W_p) is equal to the sum of the increments in the E_p curve. In order to reduce the effect of noise, the increments in mechanical energy were considered to represent positive work actually done by the muscles and tendons only if the time between two successive maxima was greater than 20 ms.

Measurement of energy transfer

The purpose of these measurements is to determine the work that must have been done by the muscles and tendons, excluding any part of the work that is done without the need of muscular intervention. For instance, walking can be compared to an inverted pendulum in which the potential energy of the *COM* is transformed into kinetic energy and vice versa (Cavagna et al., 1976). During the single contact phase of walking, when the subject's *COM* is in front of the point of contact, the *COM* falls down and accelerates forwards, *i.e.* the potential energy of the *COM* (E_p) is used to accelerate it forwards (E_k). In a subsequent phase of the step, when the subject's *COM* is behind the point of contact, the body rides up onto the stance leg, as the *COM* is decelerated and lifted at the same time, *i.e.* kinetic energy of the *COM* (E_k) is converted into potential energy (E_p). In walking, the E_k and E_p curves are out of phase, thus allowing energy transfers. If these two energy curves were exactly 180° out of phase and of same amplitude and shape, then the transfer would be complete and no positive external work would be required to maintain the movements of the *COM*, *i.e.* walking would be a perfect energy-saving pendulum system. On the contrary, if the energy curves were in phase, no pendular transfer of energy would be possible and all the work required to lift and to accelerate the *COM* would have to be done by the muscles. In human walking, some external work is required to maintain movement of the *COM* but a large quantity of energy is saved through this energy transfer. A relative measure of the amount of energy transferred due to this pendular mechanism is called the percent recovery (R) and is calculated as:

$$R = 100 \frac{W_k + W_p - W_{ext}}{W_k + W_p} . \tag{1}$$

Positive kinetic internal work ($W_{int,k}$)

The kinetic internal work ($W_{int,k}$) is the positive work done to sustain the translational and rotational kinetic energy changes of the body and load segments due to their movements relative to the *COM*. The method used here to compute the internal work due to the movements of the body segments relative to the *COM* is the same as the one used in Willems et al. (1995), which was derived from Cavagna and Kaneko (1977). Consequently the method is only summarized here.

$W_{int,k}$ was computed from the movements of the body segments by cinematography. The body was divided into ten rigid segments: head/neck/trunk, load, two thighs, two shank/feet, two upper arms, and two fore-arm/hand segments. Each segment is delimited by markers placed at the side of the neck at the height of the chin (chin–neck intersect), the great trochanter, the lateral condyle of the femur, the lateral malleolus, the glenohumeral joint, the lateral condyle of the humerus, the dorsal wrist and on the load. The subjects were filmed by a single analog video camera (PAL, 25 Hz), 6 m lateral and normal to the centre of the force-platform. Each image was digitalized by means of a VCR and a frame grabber (PCI-1407, National Instruments©). The odd and even fields of each interlaced image were extracted and reshaped to the original image size by bi-linear interpolation in order to obtain a 50 Hz frame rate and less subject motion-blur. The camera images were synchronized to the stride selected for the W_{ext} measurements by superimposing the heel strike on the force records to the corresponding frame of the film. As a result of the different sampling rates (50 Hz *versus* 200 Hz), the kinetic internal work can be shifted up to ±15 ms relative to the external work. The co-ordinates of the markers in the sagital plane were then digitalized every frame during the selected stride. The angle versus time curve of each segment was smoothed and resampled with a cubic spline function to match the acquisition frequency of the force platform.

A 'stick man' of the position of each segment relative to the head/neck/trunk segment was constructed numerically each frame. The side of the subject opposite to the camera was reconstructed from the camera side data on the assumption that the movements of the segments of one side were equal and 180° out of phase with the measurements of the other side. The position of the centre of mass and the moment of inertia of the body segments were calculated using the anthropometric tables of Dempster and Gaughran (1967).

The position of the centre of mass and the moment of inertia of the 'load segment' were calculated by assimilating the load into a cone frustum and assuming that the load in the backpack / basket was homogeneously distributed. The dimensions of the frustum, the load mass and the moment of inertia were calculated for each individual load. A sensitivity analysis of our assumptions in assimilating the load into a frustum of cone in which the mass is homogeneously distributed has been evaluated for a load equal to the body weight (100% M_b) and for walking between 0.5 and 1.7 m s^{-1}. First, if the moment of inertia of the load segment were underestimated by 100%, then $W_{int,k}$ would be increased by only 1.35±1.13%. Second, if the load mass were not evenly distributed but instead was concentrated in the upper one third of the frustum of cone, then its centre of mass would be higher and the moment of inertia would be reduced, and the resulting $W_{int,k}$ would be decreased by only 0.46±0.46%. Thus, any errors made by our assumptions about the shape and distribution of the load mass cannot lead to a significant error in the calculation of the kinetic internal work, and would have an even smaller effect on the total mechanical work measurement.

The angular velocity of each segment and the translational velocity of its centre of mass relative to the *COM* of the body plus load were calculated from the derivative of their position *versus* time relationship. The kinetic energy ($E_{\mathrm{int,k}}$) of each segment due to its displacement relative to the *COM* of the body plus load and to its rotation was then calculated as the sum of its translational and rotational energy (Fig. 1):

$$E_{\mathrm{int,k},i}=1/2\cdot m_i\cdot(V_{\mathrm{f},i}^2+V_{\mathrm{v},i}^2+K_i^2\cdot\omega_i^2) \quad (2)$$

Distance and angle distortions are two sources of error inherent to image analysis. These distortions are minimized when the observer to subject distance is much greater than the field width or height dimensions. In our case, the video camera was 6 m away from the 3 m wide by 2 m high field of measurement (the force-platform), resulting in a theoretical maximum absolute angle error of 3.9% for an angle measured in the centre of the platform path (centre of image field) compared to that measured at the extremes of the platform path (on the sides of the image field). However, since only the relative segment angles in two successive images is used to compute the segment velocity relative to the *COM*, this error is greatly attenuated and is neglected.

Measurement of energy transfer

The kinetic energy versus time curves of the segments within a limb were summed. The positive internal work due to the movements of the limb was then calculated by adding the positive increments in its kinetic energy versus time curve. In order to minimize errors due to noise, the increments in kinetic energy were considered to represent positive work actually done only if the time between two successive maxima was greater than 10-80 ms, depending upon the walking speed. The same procedure was used with the kinetic energy versus time curves of the upper limbs $W_{\mathrm{int,k}}^{\mathrm{u}}$, the lower limbs $W_{\mathrm{int,k}}^{\mathrm{l}}$, the trunk, $W_{\mathrm{int,k}}^{\mathrm{t}}$ and the load, $W_{\mathrm{int,k}}^{\mathrm{c}}$ to compute the internal work due to their movements. $W_{\mathrm{int,k}}$ was then computed as the sum of $W_{\mathrm{int,k}}^{\mathrm{u}}$, $W_{\mathrm{int,k}}^{\mathrm{l}}$, $W_{\mathrm{int,k}}^{\mathrm{t}}$ and $W_{\mathrm{int,k}}^{\mathrm{c}}$. This procedure allowed energy transfers to occur between the segments of the same limb, but disallowed any energy transfers between the different limbs or the trunk or the load (Willems et al., 1995; Schepens et al., 2004).

Positive internal work done by one leg against the other ($W_{\text{int,dc}}$)

The methods used to compute the internal work done by one leg against the other during the period of double contact ($W_{\text{int,dc}}$) are the same as in Bastien et al. (2003), and are presented here only briefly[a].

In walking, during the double contact phase (DC) when both feet are on the ground, positive work is done by the back leg pushing forwards while negative work is done by the front leg pushing backwards. The power generated against the external forces exerted by the front and back legs was calculated from the product of the vertical and horizontal components of the ground reaction forces acting under each leg ($\mathbf{F}_{\text{v,back}}$, $\mathbf{F}_{\text{v,front}}$, $\mathbf{F}_{\text{f,back}}$ and $\mathbf{F}_{\text{f,front}}$) multiplied respectively by the vertical and horizontal velocity ($\mathbf{V}_{\text{v}}$ and $\mathbf{V}_{\text{f}}$) of the *COM* (Bastien et al., 2003).

$$\begin{aligned} W_{\text{f,back}} &= \int_{t_1}^{t_2} (\mathbf{F}_{\text{f,back}} \cdot \mathbf{V}_{\text{f}}) \cdot \mathrm{d}t & \quad W_{\text{v,back}} &= \int_{t_1}^{t_2} (\mathbf{F}_{\text{v,back}} \cdot \mathbf{V}_{\text{v}}) \cdot \mathrm{d}t \\ W_{\text{f,front}} &= \int_{t_1}^{t_2} (\mathbf{F}_{\text{f,front}} \cdot \mathbf{V}_{\text{f}}) \cdot \mathrm{d}t & \quad W_{\text{v,front}} &= \int_{t_1}^{t_2} (\mathbf{F}_{\text{v,front}} \cdot \mathbf{V}_{\text{v}}) \cdot \mathrm{d}t \end{aligned} \tag{3}$$

where t1, t2 are the beginning and end of a complete stride. $W_{\text{f,back}}$, $W_{\text{v,back}}$, $W_{\text{f,front}}$, $W_{\text{v,front}}$ are the work done on the *COM* as a function of time resulting from the forward and vertical components of the forces acting upon the back and front leg.

The positive work done by the ground reaction forces was calculated independently for the back (W_{back}) and the front (W_{front}) limb from the time–integral of the power curves taking into account any energy transfers. Specifically, transfers between W_{v} and $W_{\text{f,back}}$ and between W_{v} and $W_{\text{f,front}}$ can occur and must be taken into account to compute correctly W_{back} and W_{front} (as explained in detail in Bastien et al., 2003). The external work is then subtracted from the net positive muscular work done by each leg in order to count only the work that is not already measured by the W_{ext}. Thus, the positive muscular work realized by one leg against the other during double contact $W_{\text{int,dc}}$ (Fig. 1) was evaluated by:

$$W_{\text{int,dc}} = W_{\text{back}} + W_{\text{front}} - W_{\text{ext}} \,. \tag{4}$$

[a] See Appendix 3 for details on the methods to compute $W_{\text{int,dc}}$

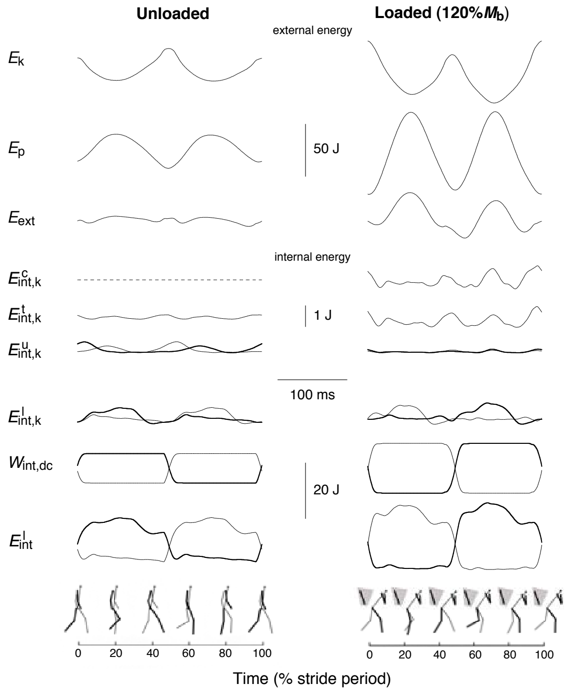

Fig. 1: Typical traces of mechanical work in load carrying. The fluctuations in the external and internal mechanical energy are presented for an unloaded and loaded (120% M_b) walking stride at about the optimal speed. The three upper traces present the mechanical energy changes of the centre of mass of the body (*COM*): E_k is the kinetic energy due to its velocity relative to the surroundings, E_p is the potential energy and E_{ext} is the external energy which is the sum of the E_k and E_p curves. Due to loading, the variations of the E_k , E_p and E_{ext} curves increase because the total mass is increased. The following four traces are the kinetic energy changes of the load ($E^c_{int,k}$), trunk ($E^t_{int,k}$), upper ($E^u_{int,k}$) and lower ($E^l_{int,k}$) limbs due to their velocity relative to the *COM*. The energy fluctuations for the load, trunk and upper limbs are small when walking either unloaded or loaded. The energy fluctuations for the lower limbs are much greater, but they are also unaffected by loading. The eighth trace presents the internal work ($W_{int,dc}$) made by one leg against the other as a function of time: the positive work done by the back leg during one double contact phase is equal to the negative work absorbed simultaneously in the front leg. The bottom trace, the internal energy curve of the lower limb (E^l_{int}), is the sum of the $E^l_{int,k}$ and $W_{int,dc}$ curves. This summation assumes that the internal positive work done by the back leg during a double contact phase ($W_{int,dc}$) increases passively the backward velocity of the front leg relative to the *COM* (see Methods). The energy fluctuations in E^l_{int} are increased with loading because it depends on $W_{int,dc}$ which, in turn, has greater variations with increased total mass. The 'stick-man' at the bottom of the figure shows the position of the limb segments each 20% of the stride. Thick lines refer to the segments on the right side (camera side) of the body, thin lines refer to the segments of the left side of the body that were reconstructed on the assumption that the movements of the left segments during one half-stride were equal to the movements of the right segments during the other half-stride. The curves are from a 26 year-old male Nepalese porter (body weight 67.0 kg) walking unloaded at 1.06 m s^{-1}.and loaded at 1.08 m s^{-1}.

Total positive muscular work

The total work done during walking is the sum of the external and internal work. However some energy transfers must be taken into account in order to avoid counting the same work twice, as explained below.

Measurement of energy transfer

In order to compute the total positive muscular work done (W_{tot}), it is necessary to account for the possible energy transfers between W_{ext}, $W_{int,k}$ and $W_{int,dc}$. Willems et al. (1995) showed that W_{tot} was best evaluated when no transfers of energy were allowed between W_{ext} and $W_{int,k}$. Bastien et al. (2003) assessed which part of the positive mechanical work done by the legs can be attributed to external muscular work (W_{ext}) and to internal muscular work ($W_{int,dc}$)[a]. Schepens et al. (2004) discussed the possible energy transfers between $W_{int,k}$ and $W_{int,dc}$ and concluded that the $E^{l}_{int,k}$ and $E_{int,dc}$ curves of each leg should be added instant-by-instant[b]. The sum of the increments of the resulting curve, E^{l}_{int} (Fig. 1), is the internal work done on a lower limb (W^{l}_{int}).

Therefore, the total positive work done by the muscles during walking, after allowing reasonable energy-saving transfers is:

$$W_{tot} = W_{ext} + W_{int} = W_{ext} + W^{l}_{int} + W^{u}_{int,k} + W^{t}_{int,k} + W^{c}_{int,k} \ . \tag{5}$$

Subjects and experimental procedure

Experiments were conducted at Phakding (alt. 2800 m), in the Solo-Khumbu region of Nepal (the Mt. Everest valley). In total, experiments were carried out on twenty-one Nepalese porters (from the Rai, Sherpa or Tamang ethnic groups) and three European control subjects. All Nepalese subjects carried loads in a wicker basket (*doko*) supported only by a strap (*naamlo*) looped over their head. All control subjects carried loads in typical trekker's backpacks with hip support. The experiments involved little discomfort, were performed according to the Declaration of Helsinki, and were approved by the local ethics committees (the Nepal Health

---

[a] See Appendix 3 for details on the methods to compute $W_{int,dc}$

[b] See Appendix 4 for details on the methods to compute W_{int} and W_{tot} including $W_{int,dc}$

Research Council in Kathmandu, and the Comité Ethique de la Faculté de Médecine in U.C.L.).

The mechanical work measurements (W_{ext}, $W_{int,k}$ and $W_{int,dc}$) were made on 11 Nepali porters and 3 European controls at speeds ranging from 0.38 to 2.02 m s^{-1} with loads ranging from 0 up to 127% M_b. For the external work measurements only, an additional ten porters were studied while walking slowly or fast while unloaded or carrying their own load. These porters were in general heavily loaded (114 % M_b on average). Table 1 summarizes the subject groups and their physical characteristics.

Table 1. Subjects characteristics

	n total (women)	Age† (yr)	Body weight† (kg)	Height† (m)	Speed range (m s^{-1})	Load range (% M_b)
Nepalese Porters	11 (3)	30.4±8.9	57.5±6.6	1.60±0.06	0.38 - 2.02	0 - 127
Extra porters*	10 (0)	24.9±7.9	50.3±4.0	**	0.56 - 1.83	0 - 154
Controls	3 (1)	28.0±6.1	68.8±10.9	1.82±0.10	0.43 - 1.85	0 - 75

†Values are mean±SD

* Nepalese porters measured only for external work while unloaded and with their own load

** Parameters not measured

For external work measurements, subjects walked across the force platform at speeds ranging from 0.38 to 2.02 m s^{-1} with loads ranging from 0 up to 154% M_b. The average forward speed during the measurements, which comprised between 1.4 and 3.4 strides, was determined by two photocells placed at the level of the subject's neck and set 2.35 m apart. A total of 1651 external work measurements are reported in this study.

The control data collected in the present study (3 subjects) are in excellent agreement with previously published external work data (Heglund et al., 1995) on 12 European adults carrying backpack loads (P=0.528, F= 0.398, three-way ANOVA, with W_{ext} in J kg^{-1} m^{-1} as the dependent variable, over a speed range of 1.0–1.5 m s^{-1} and a load range of 0–45 % M_b). Unfortunately, because the load and speed ranges/classes used in Heglund et al. are more restrained and different from those used in this study, the control data from both studies cannot be satisfactorily combined.

The kinetic internal work was measured simultaneously with the external work in the 11 Nepali porters and 3 European adults over the full speed range of 0.38 to 2.02 m s^{-1}. A total of 1620 strides were analyzed.

Although $W_{int,dc}$ was determined in the same subjects as explained above, since $W_{int,dc}$ required the two feet to be on different plates during the double contact phase, it could not be determined on consecutive double contact phases. For this reason, $W_{int,dc}$ was measured on a single double contact phase of the stride and the results obtained was doubled to obtain the $W_{int,dc}$ for the whole stride (Schepens et al., 2004).

Statistics

All statistical analysis were performed using SuperAnova (v1.11, Abacus concepts, inc.). Indications on statistical tests are given in the text as needed.

Results

External mechanical work

The recovery of mechanical energy (R) and the mass-specific external work (W_{ext}, J kg^{-1} m^{-1}) during walking at different speeds under different loading conditions are shown in Fig. 2. R is independent of load for all subjects, and attains a maximum of about 65% at a speed of 1.14 m s^{-1} for the Nepali porters, and a speed of 1.48 m s^{-1} for the control subjects, decreasing at lower and higher walking speeds (Fig. 3). However, the average R was smaller (~30%) in the Nepali porters walking fast (≥ 1.4 m s^{-1}) with heavy loads (≥100% M_b) and the control subjects walking slowly (0.5 m s^{-1}) with light loads. Although there is no evident explanation for the latter observation, the former is due to a drastic decrease of R for a few Nepali subjects who clearly showed a modification of their walking gait at this extreme load-speed combination. Although they no longer used a classic walking gait, their gait could neither be classified as running, since R was >10% and there was no aerial phase (Cavagna et al., 1991).

The mass-specific external work per unit distance (W_{ext}, J kg^{-1} m^{-1}) is independent of load at any given speed in both the Nepali and control subjects (Fig. 2). This is to be expected since both E_k and E_p are proportional to mass and R does not change with load. The external work in J m^{-1} must therefore increase in proportion to the added mass, and, when normalized per unit of total mass, W_{ext} must be independent of load at any speed (Fig. 2).

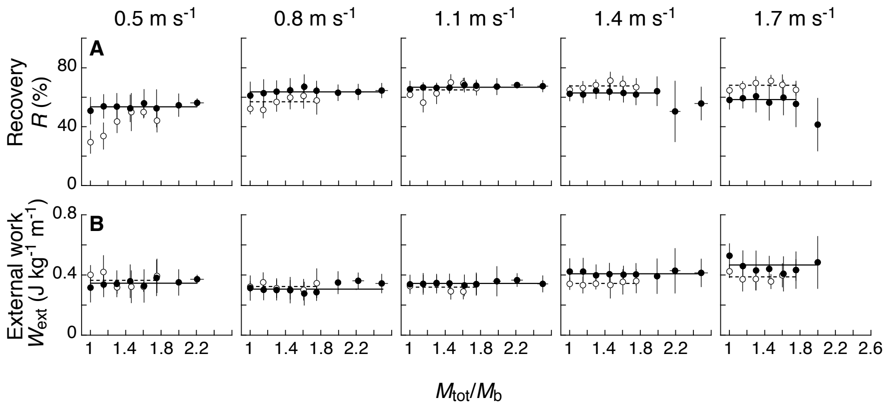

Fig. 2: Effects of load and speed on the recovery and external work. (**A**) The recovery (*R, %*) and (**B**) the mass-specific external work (W_{ext} , J kg^{-1} m^{-1}) are presented as a function of the total mass (expressed as the ratio of the total mass over body mass, M_{tot} / M_b) for different walking speeds (m s^{-1}). The recovery (*R*) is the percentage of energy transferred between the kinetic and potential energy through the pendulum-like mechanism in walking. W_{ext} is the positive work done to accelerate and raise the *COM* during walking, normalized per unit distance and unit of total mass (body plus load). Solid symbols are the mean values for Nepali porters (*n*=21) and open symbols are the mean values for the control subjects (*n*=3). The horizontal continuous and interrupted lines are the mean values of the data, as indicated by their extent, for the Nepalese and control subjects respectively. The speeds indicated on top of each column are ±0.15 m s^{-1} in each speed class. The vertical and horizontal bars indicate the standard deviations when their length exceeds the size of the symbol.

Whatever the load carried, W_{ext} is minimal at a speed slightly lower than the speed where *R* is maximal (Fig. 3). This is due to the fact that the sum $W_k + W_p$ increases more than W_{ext} increases at speeds above the speed where W_{ext} is minimum (Cavagna et al., 2000), which results in a slight additional increase in *R* (see Eq. 1 in methods). W_{ext} is minimum at 0.78 m s^{-1} for the Nepali porters and at 1.05 m s^{-1} for control subjects. At lower and higher speeds, W_{ext} increases (Fig. 3).

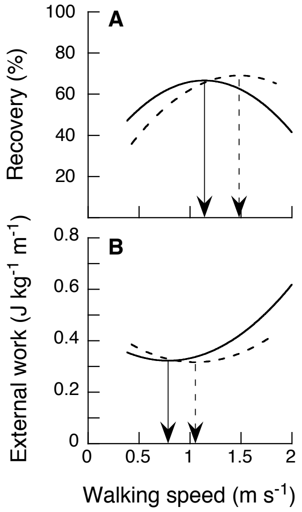

Fig. 3: Optimal walking speed for the external work and recovery. (**A**) The recovery (*R, %*) and (**B**) the mass-specific external work (W_{ext} , J kg^{-1} m^{-1}) are presented as a function of the walking speed (m s^{-1}) for loads ranging from 0 to 150% of the body mass (M_b). The continuous and interrupted lines are the second-order polynomial fits (Kaleidagraph®) through the data points for any loading condition for the Nepali porters and control subjects respectively. The arrows show the optimal speed for any loading condition where W_{ext} is minimum or R maximum for Nepali porters (plain arrows) and control subjects (interrupted arrows).

Internal mechanical work

The internal work as measured in this study includes the work done to accelerate the body and load segments relative to the *COM* and the work done by one leg against the other during the double contact phase of walking. The mass-specific internal work done to displace the segments relative to the *COM* ($W_{int,k}$, J kg^{-1} m^{-1}) and its sub-components ($W^{t}_{int,k}$, $W^{c}_{int,k}$, $W^{u}_{int,k}$, $W^{l}_{int,k}$) are shown in Fig. 4. The trunk, load and upper limbs mass-specific kinetic internal work are small (<0.05 J kg^{-1} m^{-1}) at any speed and load because their rotational and translational movements are small relative to the *COM*. On the contrary, the mass-specific kinetic internal work due to the lower limbs accounts for almost all the total kinetic internal work. $W_{int,k}$ increases rapidly with the walking speed, but at any given speed decreases with increasing load. For example, when walking unloaded in both subject groups, $W_{int,k}$ increases from 0.1 to 0.4 J kg^{-1} m^{-1} when speed goes from 0.5 to 1.7 m s^{-1}. However, when walking at 1.4 m s^{-1} $W_{int,k}$ decreases from 0.3 to 0.2 J kg^{-1} m^{-1} when load goes from 0 to 100% M_b .

At all speed-load combinations, Nepali porters and control subjects do not show major differences in kinetic internal work. However, the mean $W_{int,k}$ values for the Nepali porters tend to be slightly above those of control subjects, particularly at the highest speeds. The latter can be explained by a somewhat higher step frequency at all speeds (particularly the highest speeds) in the Nepali porters. Furthermore, in the control subjects, the step frequency is nearly independent of load at all speeds while, for the Nepali porters, it tends to increase very smoothly as a function of the load at each walking speed (Fig. 4). This results in $W_{int,k}$ for the Nepali porters being clearly above those of control subjects for heavy loads and high walking speeds.

The work done by one leg against the other during the double contact phase ($W_{int,dc}$, J kg^{-1} m^{-1}) is nearly zero at low speed in unloaded walking, increasing to its maximum at intermediate speed and decreasing again at higher speeds (Fig. 4). Furthermore, for speeds < 1.4 m s^{-1}, $W_{int,dc}$ increases as a function of the load whereas, at higher speeds, $W_{int,dc}$ is relatively independent of the load. At low speeds, Nepali porters present a higher $W_{int,dc}$ compared to control subjects, but above 1.1 m s^{-1} $W_{int,dc}$ decreases more rapidly with speed for the Nepali porters, thus ending up with lower $W_{int,dc}$ values than control subjects at high walking speeds (Fig. 4).

As explained in detail in Schepens et al. (2004), energy transfers can occur between $W_{int,dc}$ and $W^{1}_{int,k}$, meaning that the internal work is not simply the sum of $W_{int,k}$ and $W_{int,dc}$. Nevertheless, $W_{int,dc}$ can represent a large fraction of the internal work (up to ~52% in Nepali porters) particularly at the intermediate walking speeds while carrying heavy loads (see comparison between W_{int} and $W_{int,k}$ in Fig. 4). When the calculation of internal work accounts for the positive work done to accelerate the segments relative to the *COM* ($W_{int,k}$) and for the positive work done by the back leg against the front leg during the double contact phase ($W_{int,dc}$) then our results (Fig. 4) show that in load carrying: a) the mass-specific internal work (W_{int}, J kg^{-1} m^{-1}) is about equivalent for the Nepali porters and the control subjects; b) W_{int} increases with increasing walking speed but differently according to the loading condition because c) W_{int} is independent of load for walking speeds up to 1.1 m s^{-1} but d) W_{int} decreases markedly as a function of the load at higher speeds.

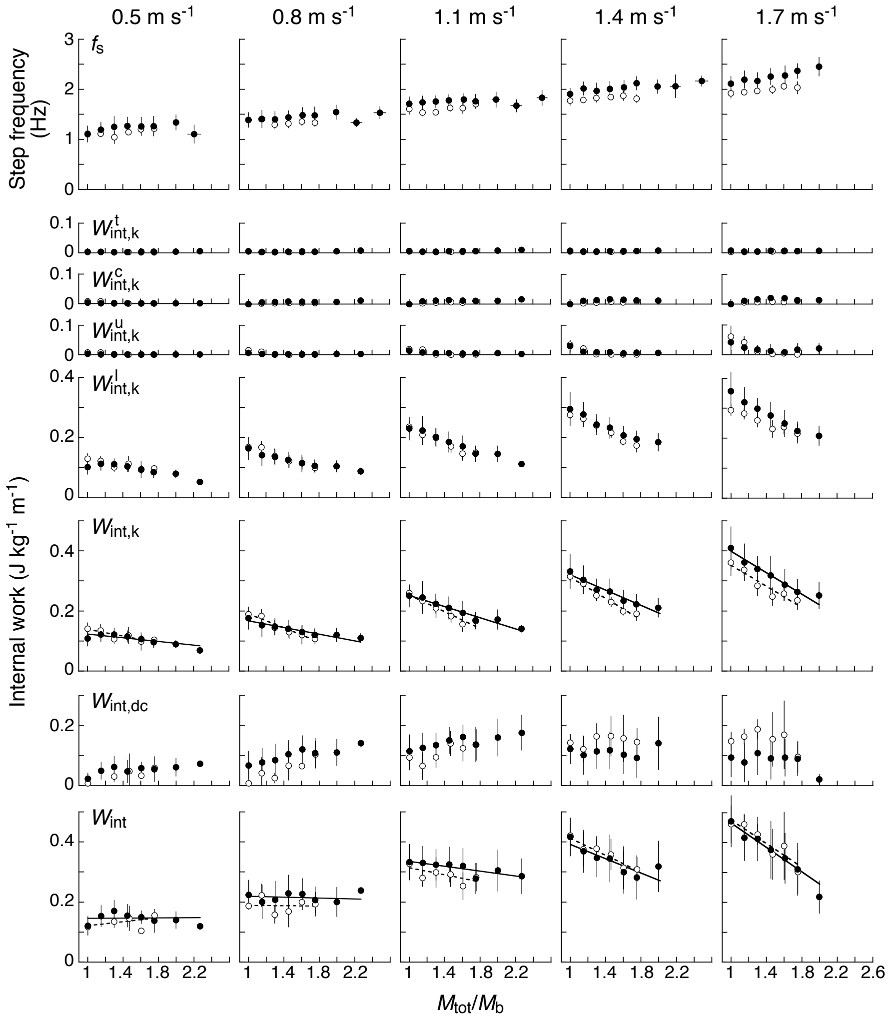

Fig. 4: Effects of load and speed on the step frequency and internal work. From top to bottom, the step frequency (Hz), the mass-specific sub-components of the internal work and the internal work (J kg^{-1} m^{-1}) are presented as a function of the total mass (expressed as the ratio of the total mass over body mass, $M_{\mathrm{tot}} / M_{\mathrm{b}}$) for different walking speeds (m s^{-1}). The mass-specific kinetic internal work for the trunk ($W^{\mathrm{t}}_{\mathrm{int,k}}$), load ($W^{\mathrm{c}}_{\mathrm{int,k}}$), upper limbs ($W^{\mathrm{u}}_{\mathrm{int,k}}$) and lower limbs ($W^{\mathrm{l}}_{\mathrm{int,k}}$) segments are summed to obtain the positive work done to accelerate the segments relative to the *COM* during walking ($W_{\mathrm{int,k}}$). $W_{\mathrm{int,dc}}$ is the internal work done by one leg against the other during the double contact phase of walking. The total internal work, W_{int} (bottom trace), is computed by allowing energy transfer between $W_{\mathrm{int,dc}}$ and $W^{\mathrm{l}}_{\mathrm{int,k}}$. Solid symbols are mean values for Nepali porters (n=11, except for f_{s} where n=21) and open symbols are mean values for control subjects (n=3, except for f_{s} where n=15). The continuous and the interrupted lines are the linear fits (Kaleidagraph®) through the data points for the Nepali porters and control subjects respectively. Other indications are as in Fig. 2.

Total mechanical work

The mass-specific total work, W_{tot}, is the sum of the external and internal work. It has been shown in Figs. 2 & 4 that both W_{ext} and W_{int} are independent of load at speeds up to 1.1 m s^{-1}, therefore W_{tot} is also independent of the increasing total mass at these walking speeds. On the contrary, at speeds ≥ 1.1 m s^{-1} although W_{ext} remains constant, W_{int} decreases with increasing load; therefore W_{tot} also decreases with the increasing total mass at these walking speeds (Fig. 5). The differences observed in Nepali porters and control subjects' external or internal work tend to cancel when both W_{ext} and W_{int} are summed; the total mechanical work during load carrying, W_{tot}, is equivalent for all subjects at any load-speed combination.

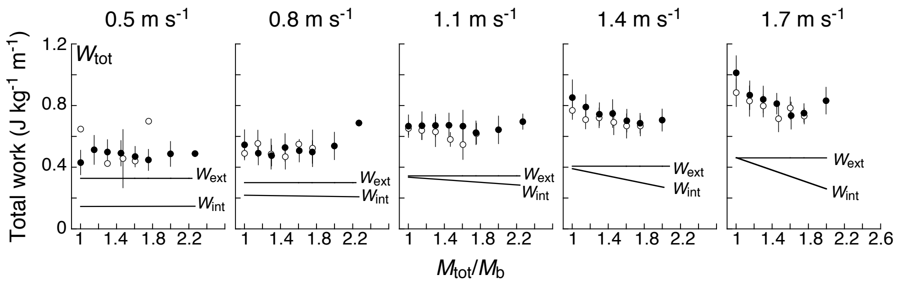

Fig. 5: Effects of load and speed on the total work. The mass-specific total work (W_{tot}, J kg^{-1} m^{-1}) is presented as a function of the total mass (expressed as the ratio of the total mass over body mass, M_{tot} / M_b) for different walking speeds (m s^{-1}). W_{tot} is the sum of the external work (W_{ext}, Fig. 2) and the internal work (W_{int}, Fig. 4); the solid symbols are the mean values for the Nepali porters (n=11) and the open symbols are the mean values for the control subjects (n=3). The continuous lines are either the linear fits (Kaleidagraph®) through the W_{int} data that are used to compute W_{tot}, or the mean values of the W_{ext} data that are used to compute W_{tot}, for the Nepali porters (these lines are very close to the corresponding lines in Figs. 2 and 4, but calculated on a reduced number of points, as explained in the Methods). Other indications are as in Fig. 2.

Discussion

This study was intended to test the hypothesis that the same mechanical energy saving strategy is used during load carrying in Nepali porters as was found in the African women by Heglund et al. (1995). To test this hypothesis, the mechanical work was measured during different loading conditions in Nepali porters and control subjects. This study also presents for the first time the total mechanical work done during walking with a load, where the total work includes the external (W_{ext}), the kinetic internal ($W_{int,k}$) and the double contact internal work ($W_{int,dc}$). In addition, this is the first of two companion papers studying the physiology of load carrying in Nepali porters in which biomechanical and metabolic measurements were done in parallel on the same subjects, under different loading conditions and as a function of the walking speed.

It was shown in a previous study that African women could carry loads up to 20% M_b without any significant increase in their energy consumption (Maloiy et al., 1986). For greater loads, their gross metabolic power increased in proportion to the added mass but the first 'free' 20% was conserved. This was possible because the positive mechanical work done to move the *COM* (the mass-specific external work, J kg^{-1} m^{-1}) was decreasing as the load increased (Heglund et al., 1995). The African women could reduce their muscular work because loading improved their percent recovery (*R*) during walking; specifically, the transduction of E_p to E_k was significantly increased during the descent of the *COM* during the stride (Cavagna et al., 2002). On the contrary, no adaptation to load carriage was found in the Caucasian control subjects.

Although Nepalese porters and Kenyan Kikuyu women use an identical type of head-supported load carriage, using a strap looped over the forehead that supports the load, the similarities seem to stop there. In particular, the recovery, *R*, for the Nepali porters does not increase with increasing load (Fig. 2), and as a consequence the Nepali porters have about equivalent *R* compared to the controls subjects. At best, *R* reaches 65% whatever the loading condition. As a result, W_{ext} (the external work normalized per unit of total mass) is a constant at any walking speed, once again just as in the control subjects. Thus, for example, during level walking at a constant 1.1 m s^{-1}, the positive mechanical work required to maintain the displacements of the *COM* over one meter is 0.34 Joules for each kilogram of the total mass, whether it is composed of body or load. This also means that the speed at which W_{ext} is minimal and the speed at which *R* is maximal are not different whether the subjects walked unloaded or loaded (Fig. 3). For instance, walking at 1.1 m s^{-1} gives the Nepalese porters their best percent of energy recovery for loads up to 150% M_b . However, this cannot be compared to the African women since the effect of speed was not studied in the African women (Heglund et al., 1995).

Perhaps it is not too surprising that the Nepali porters are unable to exploit the same energy saving gait mechanism as the African women (Fig. 6). With the exception of the porters in the low flatlands, the Nepalese typically walk on very hilly terrain where there are hardly ever two steps taken at the same level. In preliminary experiments in our laboratory, we have found that a change in height within one step of only 0.09 m (equivalent to a grade of ~10%) is sufficient to decrease the energy transfer from 64.4% ±2.4% (mean ±SD, n=12) to 36.9% ±8.6% (n=12) at a constant average walking speed of ~1.35 m s^{-1}. Most likely the Himalayan porters only rarely achieve the full 65% energy savings potentially available through the pendular mechanism during walking on the flat. It remains unknown if the Nepali porters and controls have identical energy recovery (*R*) on a gradient.

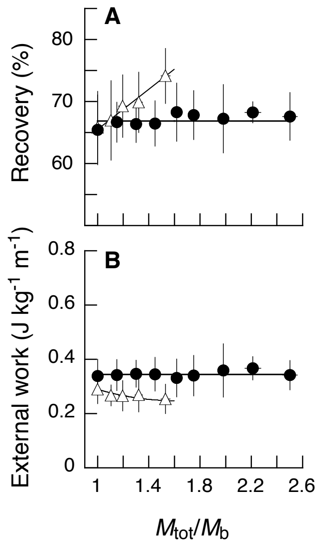

Fig. 6: Recovery and external work comparison to African women. (**A**) The recovery (*R, %*) and (**B**) the mass-specific external work (W_{ext} , J kg^{-1} m^{-1}) are presented as a function of the total mass (expressed as the ratio of the total mass over body mass, M_{tot} / M_b) for walking at 1.1 m s^{-1} for the Nepalese porters (solid symbols, *n*=21) and the African women (open symbols, *n*=8; data are from Heglund et al., 1995). The lines drawn through the Nepali data are the mean values in the 1.1 m s^{-1} speed class for the corresponding load ranges. The lines drawn through the African women data are the linear and polynomial fit (Kaleidagraph®) through the recovery and external work data points respectively. Other indications are as in Fig. 2.

Although the Nepali porters have not developed the 'African' energy-saving mechanism, they may well have developed another strategy to limit the total muscular work due to load carriage. For instance, they could have minimized the internal work done during load carrying.

Three opportunities to limit or reduce the internal work can be identified. First, the internal work required to move the body segments relative to the *COM* could be minimized by reducing movements of the arms, trunk, lower limbs via changes in the step rate or step length. Second, in load carrying, the internal work to move the load relative to the *COM* could be minimized by limiting the movements of the load relative to the trunk. Third, the internal work done during the double contact phase of walking ($W_{int,dc}$) due to one leg pushing against the other could be reduced. It has been shown that this work was non-negligible in level unloaded walking at intermediate walking speeds, whereas it is null at the lowest and highest speeds (Bastien et al., 2003). In load carrying the ground reaction forces acting under each leg increase in proportion to the total mass, and as a consequence the work done by each leg against the other is thought to increase at a given speed due to loading. However this work could also be minimized by shortening the DC period, or by changing the phase between pushing and braking forces during the DC period of the step.

Kinetic internal work in load carrying

The kinetic internal work is the positive muscle and tendon work done to accelerate the body segments relative to the *COM*. It is, therefore, dependent on the gait pattern. For example, the step frequency, the step length, the trajectory of the foot during the swing phase could change with load. The most interesting changes that influence the kinetic internal work during load carrying are discussed below.

Step frequency

On one hand, the study on African women (Maloiy et al., 1986) showed that, for walking between 0.8 to 1.7 m s^{-1}, the step frequency was unaffected by loading. The authors assumed, therefore, that the energy requirements for moving the legs and arms relative to the centre of mass would remain the same in unloaded and loaded walking. The latter assumption was also made in Heglund et al. (1995) where, for any loading condition, $W_{\mathrm{int,k}}$, the internal work to move the segments relative to the *COM* was thought to represent 54% of the unloaded total mechanical work in walking. On the other hand, some previous studies (Martin and Nelson, 1986; LaFiandra et al., 2003) have found that particularly at high speed, in response to loading, subjects tend to decrease their step length and increase the step frequency, even though these changes are small. Our data show that the step frequency significantly increases with load at a given walking speed for the control subjects (P<0.001, F= 7.89, two-way ANOVA), even though this increase is small (*e.g.* +6.1% at 1.1 m s^{-1} for a 75% M_{b} load compared to unloaded walking). Nepali porters do not show any advantage over control subjects concerning step frequency. Compared to controls at the same load and speed, Nepali porters show even higher step rates, most likely because of their small stature and shorter legs (Table 1), but they also present a significant increase in step frequency as loading increases (P<0.001, F= 24.21, two-way ANOVA), even though this increase is small (*e.g.* +6.8% at 1.1 m s^{-1} for a 150% M_{b} load compared to unloaded walking).

Trunk inclination and movement

In unloaded walking, the trunk is in a nearly upright position: at any speed the trunk angle relative to the vertical in the sagital plane is about 5 degrees on average. When carrying loads the trunk inclination changes considerably in order to keep the *COM* over the centre of support on the ground. To a lesser extent, this was also observed previously by Martin and Nelson (1986) and Kinoshita (1985) in backpack load carriage. In our control subjects, the trunk inclination increases steeply: for 75% M_b loads, the trunk inclination is up to ~45 degrees. For Nepali porters, the trunk inclination also clearly increases, but less steeply, and it reaches a plateau at ~40 degrees for all loads greater than 75% M_b. However, the rotational movement of the trunk in the sagital plane during the walking stride does not change significantly with loading and is equivalent for controls and Nepali porters (3.50±1.05 and 3.56±1.15 degrees for the two groups respectively). Therefore, the work required to move the trunk ($W_{\mathrm{int,k}}^{\mathrm{t}}$) relative to the *COM* is small in load carrying as well as in unloaded walking. For example, at 1.1 m s^{-1}, with loads of 0-75% M_b, $W_{\mathrm{int,k}}^{\mathrm{t}}$ represents less than 4% of the kinetic internal work in Nepali porters as well as in controls.

Lower limb movements

During the initial weight-bearing phase of the walking stride, the knee joint flexes, absorbing the shock during heel strike. In unloaded walking, it has been shown that this flexion increases with walking speed (Perry et al., 1977: Holt et al., 2003). In load carrying, Kinoshita (1985) reported a significant decrease in knee angle during the initial weight-bearing phase due to loadings as low as 20% M_b, although no values were reported in the study. On the contrary, Ghori and Luckwill (1985) found no change in the peak knee angle measured during stance phase, even though backpack loading was up to 50% M_b. These authors report a constant knee flexion of ~18 degrees independent of the load at a freely chosen walking speed ranging from 0.97 to 1.27 m s^{-1}. Similarly, Holt et al. (2003) compared one backpack load condition (40% M_b) to unloaded walking at various walking speeds; these authors also did not find any effect of loading on the knee flexion during the stance phase.

Because modifications of the walking gait pattern may result in increases or decreases in mechanical work performed, the knee flexion as a function of both speed and load was evaluated using the present data. The thigh-leg angle at heel strike was compared to the smallest thigh-leg angle observed during the following stance phase. We found that, under any loading condition, knee flexion clearly increases with speed by about 15 degrees over the speed range studied (P<0.0001, F= 86.82 and P<0.0001, F= 29.61; two-way ANOVA for the Nepali porters and controls respectively). For example, in the unloaded condition, the knee flexes by about 5 degrees at the slowest walking speeds and by 20-25 degrees at the fastest speeds. Furthermore, for a given walking speed, the knee flexes significantly more with increasing mass (P<0.0001, F= 5.61 and P<0.0001, F= 6.77; two-way ANOVA for the Nepali porters and controls respectively). However, for any load-speed combination the knee flexion is always less than 30 degrees, and the extra knee flexion due to loading is in any case less than 10 degrees. The knee flexion due to increased loading has, in fact, no clear effect on the lower limb kinetic internal work ($W^{l}_{int,k}$), and thus, no clear effect on $W_{int,k}$ because the flexion is modest and occurs when the displacement of the lower limb relative to the *COM* is slow.

It is worth noting, however, that an effect of knee flexion due to loading could be observed elsewhere. For instance, the measured increase in knee flexion would lead to an increase in the vertical displacement of the *COM* by up to 0.01 m, which in turn results in an increase of the positive mechanical work done to lift the *COM* (W_p) by up to 0.15 J kg^{-1} m^{-1}. As shown in the Results, this is not a significant increase in W_{ext}.

The upper limb movements

During unloaded walking, $W^{u}_{int,k}$ tends to increase with the speed of progression, and accounts for up to ~18% of $W_{int,k}$ at the highest walking speed. However, when carrying loads above 15% M_b, Nepali porters and control subjects generally have little arm movement relative to the *COM* because they usually grasp straps attached to the load, and as a consequence, $W^{u}_{int,k}$ is nearly zero (~1% of $W_{int,k}$) at any walking speed. When the arms are swung, then $W^{u}_{int,k}$ can represent up to 14% of $W_{int,k}$ at 1.1 m s^{-1} with a 100% M_b load, for example.

Pelvic and thoracic counter-rotation

In unloaded walking, the upper and lower body counter-rotate allowing an increase in step length, particularly at high walking speed. However, in load carrying, the moment of inertia of the upper body in the transverse plane is increased by the load, as suggested by Lafiandra et al. (2003). Probably to avoid excessive torques and unbalance, subjects clearly decrease both pelvic and thoracic rotations when carrying loads (Lafiandra et al., 2002). For example, in all of our subjects (controls and Nepali) walking at 1.1 m s^{-1}, the transverse rotation of the shoulders decreases in average from 6 to 2 degrees with increasing loads. The concomitant decrease in transverse pelvic rotation with increasing load is also clearly observed in our data and our values are in agreement with those of Lafiandra et al. (2003).

At a given walking speed, the reduced pelvic rotation implies smaller step lengths, which in turn can be compensated by increasing the step frequency and/or the hip angular excursion. Using our data at 1.1 m s^{-1}, transverse pelvic rotation is decreased on average from about 8 to 3 degrees in the control group. At that walking speed, for a subject 1.71 m tall, the consequence would be a ~4% decrease of the step length. In order to maintain the 1.1 m s^{-1} walking speed, the same subject would have to increase step frequency by 4% (meaning an increase of 0.07 Hz) or increase hip angular excursion by 4% (meaning an increase of 1.6 degrees) or any combination of the two. So it is not surprising to find a very slight increase of the step frequency with increasing load at a given walking speed (Fig. 4). Moreover it is not surprising that the increase in step frequency due to loading is the most pronounced at the highest walking speed since the reduction of the transverse pelvic rotation is the greatest at these speeds, and hip angular excursion is at its maximum and only an increase in step frequency can compensate for the decreased pelvic rotation.

Finally Nepali porters clearly show larger increase in step frequency due to loading compared to controls, particularly at high speeds. Again, the latter can be explained by a greater reduction in pelvic rotation for the Nepali porters. Indeed at 1.7 m s^{-1}, the transverse pelvic rotation is decreased in average by 9.8 degrees for the Nepali porters (from 13.8 to 4.0 degrees for unloaded *vs* 75% M_b load) whereas it is decreased by 6.8 degrees for controls (from 11.4 to 4.6 degrees for unloaded *vs* 75% M_b load). The differences in step frequency observed between Nepali porters and controls largely explain the differences in the kinetic internal work between the two groups. Clearly, for each speed above 1.1 m s^{-1}, Nepali porters and controls have equivalent $W_{int,k}$ values when no load is carried, but as load increases $W_{int,k}$ diverges between groups. The Nepali porters show higher $W_{int,k}$ values compared to controls when heavily loaded because of a more pronounced increase in step frequency due to loading; the effect being more pronounced at the highest walking speeds (Fig. 4).

Load movements relative to the COM

The internal work done to move the load relative to the *COM* ($W^{c}_{int,k}$, in J kg m^{-1}) increases with speed and is independent of load, and is about equal or greater for the porters compared to controls at the same load and speed (Fig. 4). $W^{c}_{int,k}$ represents on average ~5% of $W_{int,k}$ for controls and ~6% of $W_{int,k}$ for Nepali porters when they carry a load of 75% M_b. This ratio is up to ~12% for a 120% M_b load in the Nepali porters.

Internal work during double contact

The internal work done during the double contact phase (DC) of walking ($W_{int,dc}$) due to one leg pushing against the other is measured during load carrying for the first time in the present study. Clearly $W_{int,dc}$ is not negligible particularly at intermediate walking speeds with heavy loads carried (Fig. 4). In such conditions and even though all energy transfers are taken into consideration (as explained in the Methods), $W_{int,dc}$ accounts for up to 50% of the total internal work and for up to 25% of the total mechanical work done during load carrying. During loaded walking at constant speed the forward component of the ground reaction forces under each foot increases simply because the total mass increases. As a consequence, if no other influencing factor changes with loading, the work done by one foot against the other during DC expressed in Joules can be expected to increase with the load and thus to be independent of load when normalized per unit of total mass (J kg^{-1}). Nevertheless, $W_{int,dc}$ (J kg^{-1} m^{-1}) tends to slightly increase with increasing load at speeds < 1.4 m s^{-1} whereas it is rather independent of load at the highest speeds. The slight increase in $W_{int,dc}$ (J kg^{-1} m^{-1}) with load can be explained at least partially by the increase in step frequency (compensating the decrease in step length as explained previously) while the DC duration remains unchanged with loading. As mentioned by Bastien et al. (2003), other factors may also lead to more work being done by one leg against the other, as for example the timing of the peak of $\mathbf{F}_{f,back}$ (the forward component of the ground reaction force acting upon the back leg). For instance, we observed that the peak of $\mathbf{F}_{f,back}$ is delayed with increasing load, thereby increasing the opportunity to do more $W_{int,dc}$. Also, the inclined posture accompanying the backpack load carriage may result in more forward oriented ground reaction force vectors under each foot as suggested by Kinoshita (1985) and thereby increase $W_{int,dc}$. It is worth noting that when $W_{int,dc}$ is taken into account, W_{int} (J kg^{-1} m^{-1}) is independent of load for speeds up to 1.1 m s^{-1}; meaning that at low walking speeds, the internal mechanical work done during walking clearly increases in proportion to the added mass (Fig. 4). So, the idea that the Nepali porters might be able to limit this futile work done during the double contact phase in order to 'save' some mechanical work during load carrying is not supported.

As discussed previously, our results do not show any mechanical work saving strategy in load carrying for the Nepali porters. As for control subjects, they are unable to minimize neither external work nor internal work at any speed between 0.5 and 1.7 m s^{-1}. Consequently, the total mechanical work (W_{tot}) is equivalent for Nepali porters and control subjects compared at same load and speed. As in unloaded walking, W_{tot} (J kg^{-1} m^{-1}) in load carrying increases with the speed almost linearly within the 0.8-1.7 m s^{-1} range but also tends to re-increase at the very lowest speeds. For speeds < 1.4 m s^{-1} W_{ext} and W_{int} are independent of load, thereby W_{tot} is also independent of load, meaning that the total mechanical work done to move one kilogram of body or load one meter is the same whatever the load carried. For speeds ≥ 1.4 m s^{-1} W_{ext} is independent of load but W_{int} decreases with speed, thereby W_{tot} also decreases with load, meaning that at these speeds more mechanical work is done to move one kilogram of body one meter than to move one kilogram of load.

In conclusion, Nepali porters do not show any 'mechanical' advantage in load carrying compared to control subjects measured at same load-speed combinations. The Nepali porters do the same amount of total mechanical work as Western control subjects when walking at 0.5-1.7 m s^{-1} while carrying loads ranging from 0 to 120% of the body weight. In the following chapter we compare the metabolic consequences of carrying loads in Nepalese porters and control subjects.