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RESEARCH ARTICLE

The mechanics of head-supported load carriage by Nepalese porters

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ABSTRACT

In the Everest valley of Nepal, because of the rugged mountain terrain, 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 mass, over long distances up and down the steep mountain footpaths. In Africa, women transport their loads economically thanks to an energy-saving gait adaptation. We hypothesized that the Nepalese porters may have developed a corresponding mechanism. To investigate this proposition, we measured the mechanical work done during level walking in Nepalese porters while carrying different loads at several speeds. Our results show that the Nepalese porters do not use an equivalent mechanism as the African women to reduce work. In contrast, the Nepalese porters develop an equal amount of total mechanical work as Western control subjects while carrying loads of 0 to 120% of their body mass at all speeds measured (0.5–1.7 m s^{-1}), making even more impressive their ability to carry loads without any apparent mechanically determined tricks. Nevertheless, our results show that the Nepalese porters have a higher efficiency, at least at slow speeds and high loads.

KEY WORDS: Load carrying, Locomotion, Walking, Muscular work, Efficiency, Mechanics

INTRODUCTION

Fit European or North American adults can comfortably carry a backpack load weighing approximately one-quarter of their body mass over an entire day's trek (Bastien et al., 2005b). However, a load greater than 60% of body mass (M_b) cannot be carried for more than about an hour, and loads exceeding 100% M_b can only be moved with great difficulty. Meanwhile, many other populations carry much heavier loads for hours, sometimes for days, 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 that 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., 1976). In other words, they have developed a strategy to limit the muscular work required to carry a load by becoming a 'better pendulum'. More recently, Cavagna et al. (2002) have increased our understanding of this strategy and identified in which part of the walking step the increased energy saving occurred.

Whether other populations have adapted the strategy developed by the African women to carry loads remains an open question. Nepalese porters routinely carry head-supported loads that are two times heavier than the maximum loads carried by the African women (Bastien et al., 2005a). In the Everest valley, where no roads exist, load carriage is a daily task that everyone experiences from early childhood. Malville (1999) reported that young Nepalese commercial porters, only 11 years old and weighing 29.9 kg, carry loads up to 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 that the average load of male porters was 89% M_b, with 20% of the men carrying more than 125% M_b (Basnyat and Schepens, 2001). The average female Nepalese porter's load was 70% M_b, i.e. 10% M_b, greater than the maximum load carried by the African women. Malville (1999) measured the loads carried by 635 porters and reported an average load for adult males of 146±30% M_b at the start of the trek to Namche.

With the studies on African women in mind, we set out to determine whether the Nepalese 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; Minetti et al., 2006). Here, we compare the gait mechanics of the Nepalese porters with those of the African women and Western control subjects with an analysis of the mechanical work and efficiency during walking under different loading and speed conditions.

MATERIALS AND METHODS

The total positive mechanical work required to walk on the level at a constant average speed while carrying a load 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 acting upon the centre of mass of the whole system (COM), which includes the body mass (M_b) plus any load the subject may be carrying. 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: 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 (DC) phase in walking ($W_{int,dc}$), plus the work that is not directly measurable (the work done during antagonistic co-contractions, by internal friction, etc.),

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List of symbols and abbreviations

COM	centre of mass of the whole system (body plus load)
DC	double contact (phase of walking)
E_{ext}	energy of the COM relative to the surroundings
E_{int}^{ll}	internal energy of the lower limbs ($E_{int,k}^{ll}$+$W_{int,dc}$)
$E_{int,k}^{ll}$	kinetic energy change of the lower limbs relative to the COM
$E_{int,k}^{lo}$	kinetic energy change of the load relative to the COM
$E_{int,k}^{tr}$	kinetic energy change of the trunk relative to the COM
$E_{int,k}^{ul}$	kinetic energy change of the upper limbs relative to the COM
E_{kf}	forward kinetic energy of the COM relative to the surroundings
E_{kv}	vertical kinetic energy of the COM relative to the surroundings
E_p	gravitational potential energy of the COM relative to the surroundings
f_s	step frequency
M_b	body mass
M_{tot}	total mass (M_b+load)
R	recovery of energy due to the pendulum-like transfer of energy of the COM
W_{back}	work done by the back leg during double contact
W_{ext}	work done to raise and accelerate the COM relative to the surroundings
W_{front}	work done by the front leg during double contact
W_{int}	work done to accelerate the body segments relative to the COM
$W_{int,dc}$	work done by one leg against the other during double contact
$W_{int,k}$	work done to accelerate the body segments relative to the COM
$W_{int,k}^{ll}$	work done due to the movements of the lower limbs relative to the COM
$W_{int,k}^{lo}$	work done due to the movements of the load relative to the COM
$W_{int,k}^{tr}$	work done due to the movements of the trunk relative to the COM
$W_{int,k}^{ul}$	work done due to the movements of the upper limbs relative to the COM
W_{kf}	work done to accelerate forward the COM relative to the surroundings
W_{tot}	total positive muscle-tendon work done to maintain locomotion
W_v	work done to raise the COM relative to the surroundings
θ	maximal knee flexion during weight acceptance

plus any work that is not directly related to locomotion (respiration, circulation, etc.). The first part, $W_{int,k}$, has previously been referred to simply as W_{int} and can be measured using a cinematographic system (Cavagna and Kaneko, 1977; Willems et al., 1995). The second part, $W_{int,dc}$, involves individual force recordings for each foot on separate force plates (Donelan et al., 2002; Bastien et al., 2003). During unloaded walking, $W_{int,k}$ represents up to ∼55% and $W_{int,dc}$ up to ∼17% of the total mechanical work done (Schepens et al., 2004).

Positive external work

W_{ext} was calculated as the sum of the increments in the energy–time curve of the COM (E_{ext}). The methods used to compute the external work are described in detail in Cavagna (1975) and Willems et al. (1995) and will only be summarized here.

The mechanical energy changes of the COM due to its motion in the sagittal plane during a walking stride were determined from the vertical and horizontal components of the ground reaction forces. The mechanical energy changes due to the lateral movements of the COM are small in adults (Cavagna et al., 1963; Tesio et al., 1998) and were neglected here.

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 250 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±s.d., n=1651) of the average walking speed during the stride, and the mean vertical force during the selected stride differed from M_b plus any load the subject may be carrying by 0.1±0.8%.

The integration of the vertical and forward components of the force/mass ratio yields the vertical and forward velocity changes of the COM, from which the kinetic energy (E_{kv} and E_{kf}) can be calculated after evaluation of the integration constants (Cavagna, 1975; Willems et al., 1995). Integration of the vertical velocity yields the vertical displacement of the COM, from which the gravitational-potential energy (E_p) can be calculated.

The total mechanical energy of the COM at any instant (E_{ext}) is the sum of E_p+E_{kv} and E_{kf} (Fig. 1). The sum of the increments in the E_{ext} curve represents the positive W_{ext} done to maintain the movements of the COM relative to the surroundings. Similarly, the positive work done to accelerate the COM forwards (W_{kf}) is the sum of the increments in the E_{kf} versus time curve, and the positive work done to move the COM against gravity (W_v) is the sum of the increments in the E_p+E_{kv} versus time 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.

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). The energy recovered through the pendulum-like mechanism (R) is calculated as:

$$R = 100\,\frac{W_{kf} + W_v - W_{ext}}{W_{kf} + W_v}, \quad (1)$$

where W_{kf} is the positive work due to the velocity changes of the COM in the fore–aft direction, W_v is the positive work due to its vertical movements and W_{ext} is the positive external work.

Positive kinetic internal work

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 is similar to the one used in Willems et al. (1995), which was derived from Cavagna and Kaneko (1977). Consequently, the method is only described briefly here.

$W_{int,k}$ was computed from the movements of the body segments by cinematography. The body was divided into 10 rigid segments: head/neck/trunk, load, two thighs, two ‘shank+foot’ segments, two upper arms and two ‘forearm+hand’ segments. Each segment of the right side of the subject is delimited by markers placed at the chin–neck intersection, 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

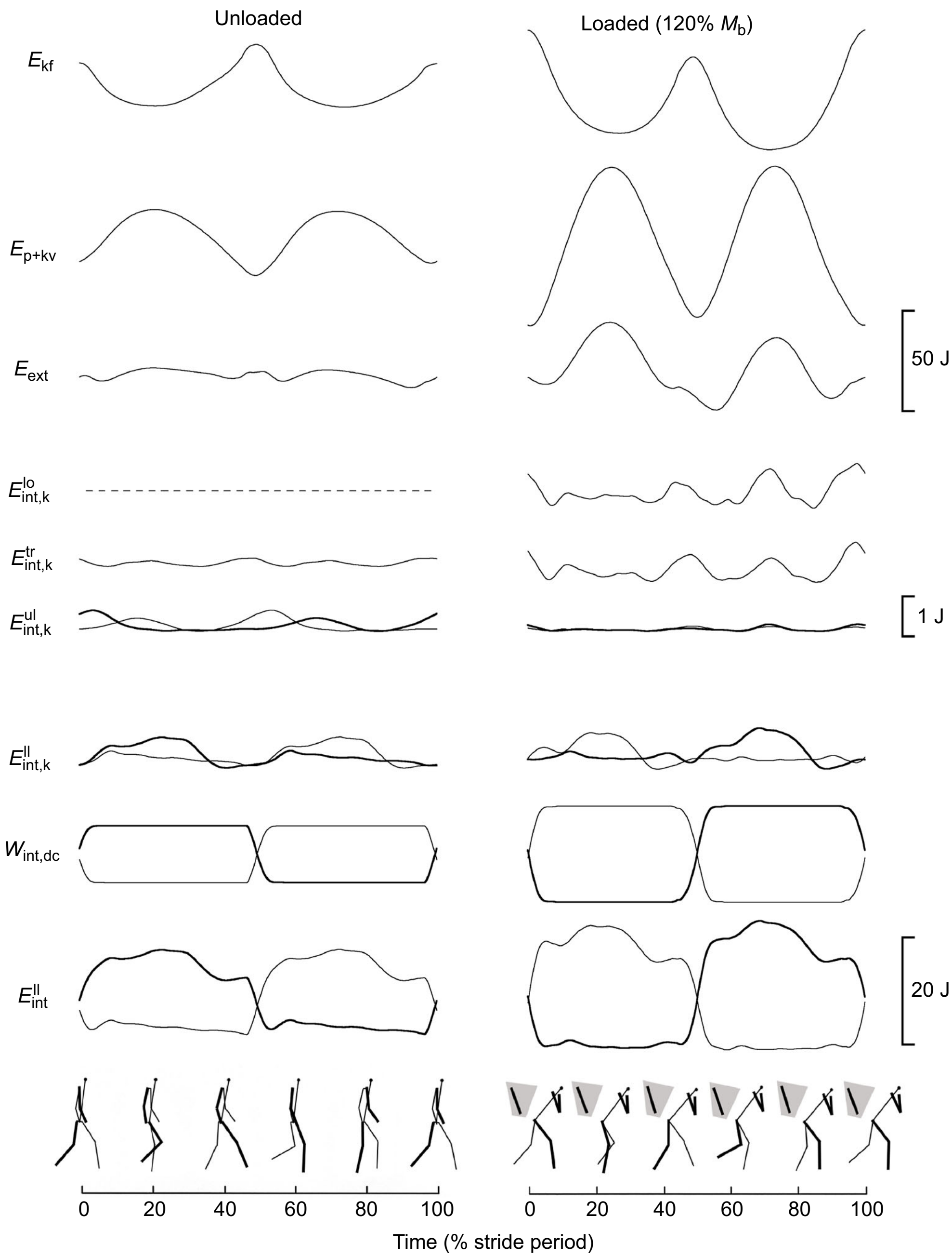

Fig. 1. Typical traces of mechanical work in load carrying. The fluctuations in the external and internal mechanical energy are presented as a function of time for an unloaded and loaded (120% M_b) walking stride at approximately the optimal speed. Both trials lasted 1.3 s. The three upper traces present the mechanical energy changes of the centre of mass of the body plus load (COM): E_{kf}, E_p+E_{kv} and E_{ext}. The following four traces are the kinetic energy changes of the load ($E^{lo}_{int,k}$), trunk ($E^{tr}_{int,k}$), upper limbs ($E^{ul}_{int,k}$) and lower limbs ($E^{ll}_{int,k}$) due to their velocity relative to the COM. The eighth trace presents the internal work ($W_{int,dc}$) made by one leg against the other. The bottom trace, the internal energy curve of the lower limb E^{ll}_{int}, is the sum of the $E^{ll}_{int,k}$ and $W_{int,dc}$ curves (see Materials and methods). The 'stick man' figures show 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. The curves are from a 26-year-old male Nepalese porter (body mass 67.0 kg) walking unloaded at 1.06 m s^{-1} and loaded at 1.08 m s^{-1}.

subjects were filmed by a single video camera (PAL, 50 Hz), 6 m lateral and normal to the axis of progression on the force platform. The 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.

A 'stick man' of the right side of the body was constructed numerically each frame. The left side of the body was reconstructed from the right side data on the assumption that the movements of the segments of left side were equal and 180 deg out of phase with the measurements of the right 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.

The angular velocity of each segment and the translational velocity of its centre of mass relative to the COM were calculated from the derivative of their position versus time relationship in order to compute the kinetic energy of each segment, i.e. the load $E^{lo}_{int,k}$, the trunk $E^{tr}_{int,k}$, the upper limbs $E^{ul}_{int,k}$ and the lower limbs $E^{ll}_{int,k}$ (Fig. 1).

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. This process was used to compute the internal work of the load $W^{lo}_{int,k}$, the trunk $W^{tr}_{int,k}$, the upper limbs $W^{ul}_{int,k}$ and the lower limbs $W^{ll}_{int,k}$. Then $W_{int,k}$ was computed as the sum of $W^{lo}_{int,k}$, $W^{tr}_{int,k}$, $W^{ul}_{int,k}$ and $W^{ll}_{int,k}$. 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

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

In walking, during the DC phase 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 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 energy transfers, as explained in detail in Bastien et al. (2003). In order to count only the work that is not already measured in W_{ext}, the positive muscular work realized by one leg against the other ($W_{int,dc}$) during the DC phase (Fig. 1) was evaluated by:

$$W_{int,dc} = W_{back} + W_{front} - W_{ext}. \qquad (2)$$

$W_{int,dc}$ was measured on a single DC phase of the stride and the results obtained were doubled to obtain the $W_{int,dc}$ for the whole stride (Bastien et al., 2003).

Total positive muscular work

The total work done (W_{tot}) 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. W_{tot} is best evaluated when no transfers of energy are allowed between the energy of the COM and the kinetic energy of each segment (Willems et al., 1995). Schepens et al. (2004) discussed the possible energy transfers between $E^{ll}_{int,k}$ and $W_{int,dc}$ and concluded that both curves should be added instant-by-instant. The sum of the increments of the resulting curve E^{ll}_{int} (Fig. 1) represents the internal work done on a lower limb (W^{ll}_{int}).

Consequently W_{tot} was computed as:

$$W_{tot} = W_{ext} + W_{int} = W_{ext} + W^{ll}_{int} + W^{ul}_{int,k} + W^{tr}_{int,k} + W^{lo}_{int,k}. \qquad (3)$$

Calculation of the muscular efficiency

The muscular efficiency was calculated as the ratio of the mechanical power to the net metabolic power. More precisely, the equations for efficiency were computed from the equations of mass-specific total average power (computed as the total mass-specific work done each stride divided by the stride period, in W kg^{-1}) and the net mass-specific energy consumption rate (in W kg^{-1}) measured on the same subjects (Bastien et al., 2005a).

Subjects and experimental procedure

Experiments were conducted at Phakding (altitude 2800 m in the Mt Everest valley), in the Solo-Khumbu region of Nepal. Experiments were carried out on 21 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 (Bastien et al., 2005a). All control subjects carried loads in typical trekker's backpacks with shoulder and 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 Research Council in Kathmandu, and the Commission d'éthique Hospitalo-Facultaire de l'Université catholique de Louvain). Informed written consent was obtained for all subjects.

The kinetic internal work was measured simultaneously with the external work in the 11 Nepalese porters and three European adults at speeds ranging from 0.38 to 2.02 m s^{-1} with loads ranging from 0 up to 127% M_b. A total of 1620 strides were analyzed. An additional 10 porters were also included in the external work measurements while walking slowly or fast, unloaded or carrying their own load (114% M_b on average). Table 1 summarizes the subject groups and their physical characteristics.

The control data collected in the present study (three subjects) are in 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. (1995) are more restrained and different from those used in the present study, the control data from both studies could not be satisfactorily combined.

Statistics

Statistical analyses were performed using SuperAnova (v1.11, Abacus Concepts). The type of statistical tests and results are given in the text as needed.

RESULTS

External mechanical work

The recovery of mechanical energy (R) and the mass-specific external work per unit distance (W_{ext}, in 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 approximately 65% at a speed of 1.1 m s^{-1} for the Nepalese porters and 1.4 m s^{-1} for the control subjects. At high speeds (≥1.4 m s^{-1}), the average R is ~30% smaller in the Nepalese porters carrying heavy loads (≥100% M_b) than in the control subjects. Although there is no evident explanation for the reduction in the average R in the Western subjects, the smaller average R in Nepalese porters is due to a drastic decrease in R for a few Nepalese subjects who clearly show a modification of their walking gait at this extreme load–speed combination. These few porters no longer use a classic walking gait; however, their gait can not be classified

Table 1. Subject characteristics

	Total n (F)	Age (years)	Body mass (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	n.d.	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 for age, body mass and height are means±s.d. F indicates female subjects. Extra porters are Nepalese porters measured only for external work while unloaded and with their own load. n.d., not determined.

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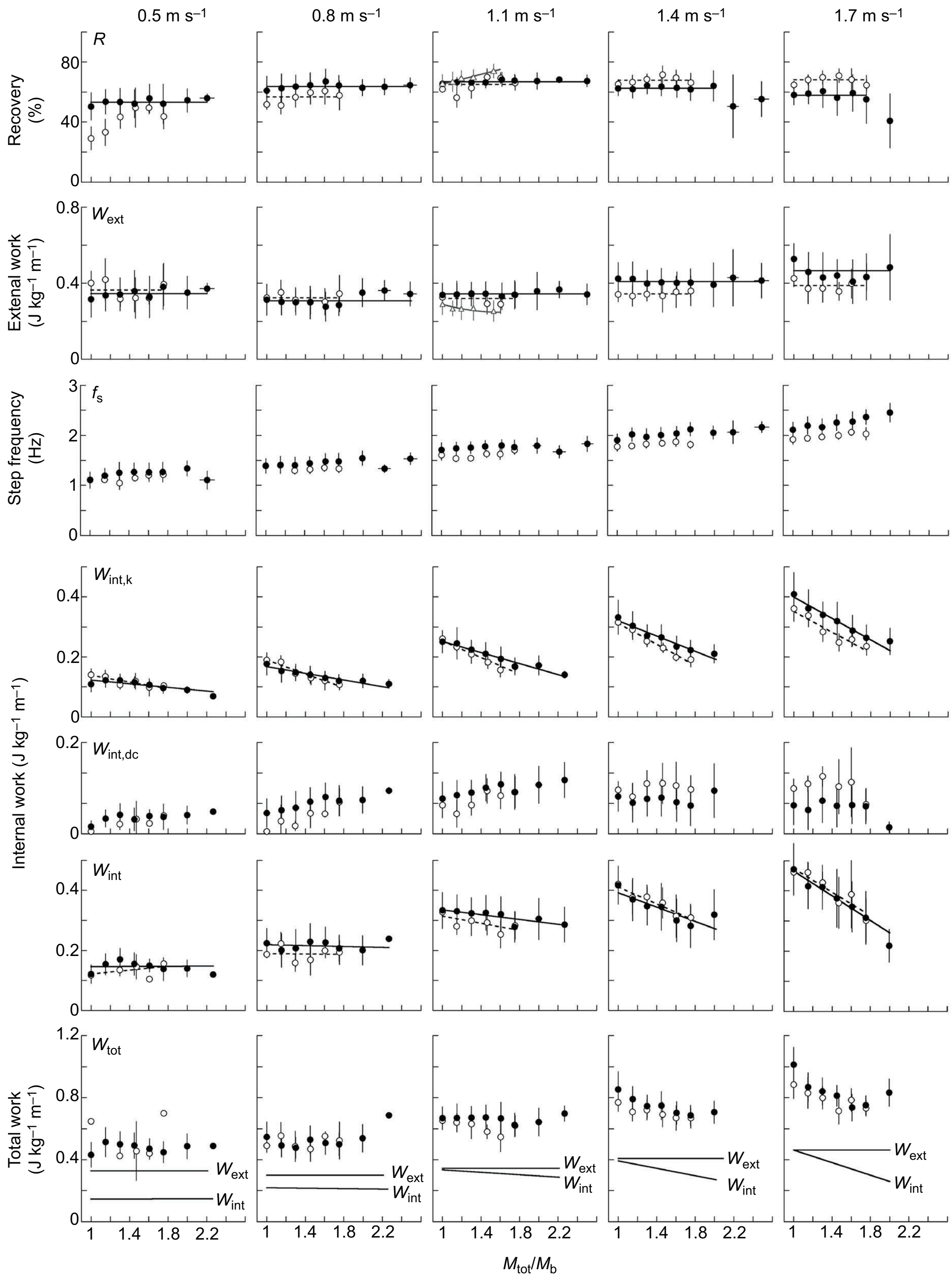

Fig. 2. Effects of load and speed on the mechanical work. Recovery (R, in %), mass-specific external work (W_{ext}, in J kg^{-1} m^{-1}), step frequency (f_s, in Hz), mass-specific internal work and its sub-components ($W_{int,k}$, $W_{int,dc}$ and W_{int}, in J kg^{-1} m^{-1}) and mass-specific total work (W_{tot}, in 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 speeds indicated at the top of each column are ±0.15 m s^{-1} in each speed class. Solid symbols are mean values for Nepalese porters (n=11, except for f_s and W_{ext}, where n=21) and open symbols are mean values for control subjects (n=3, except for f_s, where n=15). The vertical and horizontal bars indicate the standard deviations when their length exceeds the size of the symbol. The horizontal solid and dashed lines are either the mean values (first two rows) or the linear fits (Kaleidagraph®) through the data (fourth and sixth rows) for the Nepalese porters and control subjects, respectively. The solid lines of the seventh row are copied from the second and sixth rows. Data from African women (from Heglund et al. 1995) have been added in the middle panels of the first two rows (open triangles). The continuous grey line is the linear fit through the data for the first row (R) and the polynomial fit for the second row (W_{ext}).

as running, as R is >10% and there is no aerial phase (Cavagna et al., 1991). In contrast, at low speed (0.5 m s^{-1}), the average R is smaller in the control subjects carrying light loads than in Nepalese porters.

The mass-specific external work per unit distance W_{ext} is independent of load at any given speed in both the Nepalese and control subjects (Fig. 2). This is to be expected because both E_p+E_{kv} and E_{kf} are proportional to the total 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). Whatever the load carried, W_{ext} is at a minimum at 0.8 m s^{-1} for the Nepali porters and at 1.1 m s^{-1} for control subjects. At lower and higher speeds, W_{ext} increases (Fig. 2).

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 DC phase of walking. The mass-specific internal work done per unit distance to move the segments relative to the COM ($W_{int,k}$, in J kg^{-1} m^{-1}) is shown in Fig. 2. The kinetic internal work of the trunk, load and upper limbs segments represents less than 0.05 J kg^{-1} m^{-1} at any speed and load because their rotational and translational movements relative to the COM are small. On the contrary, the kinetic internal work due to the lower limbs accounts for almost all the total kinetic internal work. $W_{int,k}$ increases rapidly with 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 increases 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 increases from 0 to 100% M_b.

At all speed–load combinations, Nepalese porters and control subjects do not show major differences in kinetic internal work. However, the mean $W_{int,k}$ values for the Nepalese 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 Nepalese porters (Fig. 2). Furthermore, in the control subjects, the step frequency is nearly independent of load at all speeds while, for the Nepalese porters, it tends to increase very smoothly as a function of the load at each walking speed. This results in $W_{int,k}$ for the Nepalese 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 DC phase ($W_{int,dc}$, J kg^{-1} m^{-1}) is close to zero at low speed during unloaded walking, increasing to its maximum at intermediate speed and decreasing again at higher speeds (Fig. 2). Furthermore, for speeds <1.4 m s^{-1}, $W_{int,dc}$ increases as a function of load whereas at higher speeds it is relatively independent of load. At low speeds, Nepalese porters present a higher $W_{int,dc}$ as compared with control subjects. Above 1.1 m s^{-1}, it decreases more rapidly with speed for the Nepalese porters, thus ending up with lower $W_{int,dc}$ values than control subjects at high walking speeds (Fig. 2).

As explained in detail in Schepens et al. (2004), energy transfers can occur between $W_{int,dc}$ and $W^{ll}_{int,k}$, 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 total internal work (up to ∼52% in Nepalese porters) at intermediate walking speeds while carrying heavy loads (see comparison between W_{int} and $W_{int,k}$ in Fig. 2). 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 DC phase ($W_{int,dc}$), then our results (Fig. 2) show that in load carrying: (1) the mass-specific internal work (W_{int}) is approximately equivalent for the Nepalese porters and the control subjects; and (2) W_{int} increases with increasing walking speed but differently according to the loading condition because (3) W_{int} is independent of load for walking speeds up to 1.1 m s^{-1} but (4) W_{int} decreases markedly as a function of the load at higher speeds.

Total mechanical work

The mass-specific total work per unit distance W_{tot} (J kg^{-1} m^{-1}) is the sum of the external and internal work. 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 (Fig. 2). 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. 2). The differences observed between the external or internal work of Nepalese porters and of control subjects 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.

Muscular efficiency of load carrying

For the Nepalese porters, the muscular efficiency is nearly independent of load, showing a slight increase with speed (Fig. 3). This efficiency tends to increase slightly with speed also in the control subjects, although it decreases asymptotically with load. Consequently, the Nepalese porters tend to have a lower efficiency than the control subjects when carrying light loads, and a higher efficiency when carrying heavy loads. For example at 0.8 m s^{-1}, the controls are more efficient with loads <35% M_b, but the Nepalese porters are more efficient with heavier loads. The Nepalese porters, within the limits of the speeds/loads studied, show

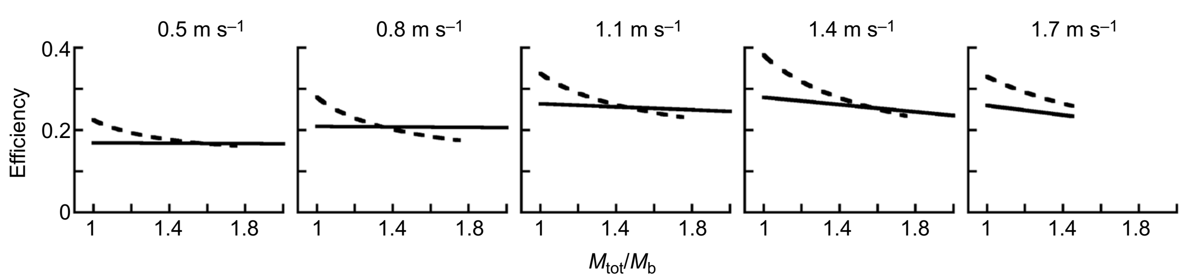

Fig. 3. Efficiency of load carrying. The efficiency of load carrying is presented as a function of the total mass (expressed as the ratio of the total mass over body mass, M_{tot}/M_b) for different walking speeds. The solid lines are for the Nepalese porters and the dashed lines for the control subjects.

a muscular efficiency between 0.15 and 0.3 and the control subjects between 0.15 and 0.4.

DISCUSSION

This study was intended to test the hypothesis that the same mechanical energy saving strategy is used during load carrying in Nepalese porters as was found in African women by Heglund et al. (1995). To test this hypothesis, mechanical work was measured during different loading conditions in Nepalese 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 work (W_{ext}), the kinetic internal work ($W_{int,k}$) and the DC phase internal work ($W_{int,dc}$). In addition, these biomechanical measurements were done in parallel with the metabolic measurements published by Bastien et al. (2005a), under the same loading and walking speed conditions. Combining both data sets allows the calculation of the efficiency of load carrying.

It was shown previously 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 W_{ext} was decreasing as the load increased (Heglund et al., 1995). The African women could reduce their muscular work because loading improved their recovery (R) during walking; specifically, the energy transduction between E_p+E_{kv} and E_{kf} within a stride was significantly increased during the descent of the COM (Cavagna et al., 2002). On the contrary, no adaptation of the pendulum-like mechanism to load carriage was found in the Western control subjects.

Although Nepalese porters and Kenyan Kikuyu women use a similar 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, R in the Nepalese porters does not increase with increasing load (Fig. 2), and as a consequence they have approximately equivalent R as compared with the control subjects. At best, R reaches 65% regardless of the loading condition. As a result, at any given walking speed W_{ext} is constant regardless of the load carried, just as in control subjects. For example, during level walking at 1.1 m s^{-1}, the positive work required to maintain the displacements of the COM over 1 m is 0.34 J for each kilogram of mass, whether it is body or load. Consequently, 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. For instance, walking at 1.1 m s^{-1} gives the Nepalese their best percent of energy recovery for loads up to 150% M_b. This cannot be compared with the African women because the effect of speed was not studied in the African women (Heglund et al., 1995).

Perhaps it is not too surprising that the Nepalese porters are unable to exploit the same energy-saving gait mechanism as the African women (Fig. 2). 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 (Minetti et al., 2006). 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 R from 64.4±2.4% to 36.9±8.6% (mean±s.d., n=12) at ∼1.35 m s^{-1}. Nepalese porters only rarely have the opportunity to achieve the full R=65% energy savings. It remains unknown whether the Nepalese porters and control subjects have identical energy recovery (R) on a gradient.

Although the Nepalese porters have not developed the ‘African’ energy-saving mechanism, they may well have developed other strategies to limit the total muscular work that is due to load carriage. For instance, they could have minimized the internal work done during load carrying.

A few opportunities to limit or reduce the internal work can be identified. First, the internal work required to move the body segments or the load relative to the COM ($W_{int,k}$). It could be minimized by reducing the movements of upper and lower limbs via changes in the step rate or step length, or reducing the movements of the load and trunk relative to the COM. Second, the internal work done during the DC phase of walking ($W_{int,dc}$) that is 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 (Bastien et al., 2003). In load carrying, the ground reaction forces acting under each foot 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 because of loading. However, this work could also be minimized by shortening the DC period, or by changing the phase between pushing and braking forces during this period of the step.

Kinetic internal work in load carrying

When carrying a load, the kinetic internal work ($W_{int,k}$) could be modified by changes in the step frequency and/or the trajectory of the limb segments. 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 load. The authors assumed, therefore, that the energy requirements for moving the legs and arms relative to the COM would remain the same in unloaded and loaded walking. The factors that influence $W_{int,k}$ during load carrying are discussed below.

Step frequency

Compared with controls at the same load and speed, Nepalese porters show higher step frequencies, most likely because of their small stature and shorter legs (Table 1). Our data show that the step frequency increases with load at a given walking speed for both control subjects and Nepalese porters (respectively, P<0.001, F=7.89 and P<0.001, F=24.21, two-way ANOVA), even though this increase is small compared with unloaded walking (e.g. at 1.1 m s^{-1}, +6% with a 75% M_b load for controls, and +7% with a 150% M_b load for Nepalese porters; Fig. 2). These results are in agreement with the studies of Martin and Nelson (1986) and LaFiandra et al. (2003).

In unloaded walking, the pelvis and the shoulders counter-rotate in the horizontal plane, particularly at high walking speed. However, in load carrying, the moment of inertia of the upper body 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). Because decreasing pelvic rotation decreases step length, it is not surprising to find a slight increase in step frequency at a given speed with increasing load.

The differences in step frequency observed between Nepalese porters and controls could explain the differences in the kinetic internal work between the two groups. At speeds above 1.1 m s^{-1}, Nepalese porters and controls have equivalent $W_{int,k}$ values when no load is carried, but as load increases the $W_{int,k}$ diverges between the groups because of a more pronounced increase in step frequency due to loading in Nepalese porters (Fig. 2).

Trunk inclination and movement

When carrying loads, the trunk inclination changes in order to keep the COM over the centre of support on the ground. In our control subjects, the trunk inclination increases up to ∼45 deg for 75% M_b loads. To a lesser extent, this was also observed in backpack load carriage by Martin and Nelson (1986) and Kinoshita (1985). Nepalese porters also increase the trunk inclination, reaching a plateau of ∼40 deg for loads greater than 75% M_b.

The rotational movement of the trunk in the sagittal plane during the walking stride does not change significantly with load and is equivalent for controls and Nepalese porters (3.50±1.05 and 3.56±1.15 deg for the two groups, respectively). Therefore, the work required to move the trunk ($W^{tr}_{int,k}$) 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, $W^{tr}_{int,k}$ represents less than 4% of the kinetic internal work in Nepalese 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 decrease in knee angle during the initial weight-bearing phase due to loads as small as 20% M_b, although no angle values were reported in the study. On the contrary, Ghori and Luckwill (1985) and Holt et al. (2003) did not report any change in knee flexion during the stance phase while carrying loads up to 50% M_b.

Because modifications of the walking gait pattern may result in an increase or decrease in mechanical work performed, the knee flexion as a function of both speed and load was evaluated using the present data. The maximal knee flexion during weight acceptance (θ) was measured as the difference between the knee angle at heel strike and at the moment of maximal flexion at mid-stance. We found that, under any loading condition, θ clearly increases with speed by approximately 15 deg over the 0.5–1.7 m s^{-1} speed range studied (P<0.0001, F=86.82 and P<0.0001, F=29.61; two-way ANOVA for the Nepalese porters and controls, respectively). For example, in the unloaded condition, θ is approximately 5 deg at the slowest walking speeds and 20–25 deg at the fastest speeds. Furthermore, for a given walking speed, θ increases significantly with load (P<0.0001, F=5.61 and P<0.0001, F=6.77; two-way ANOVA for the Nepalese porters and controls, respectively). However, for any load–speed combination, θ is always less than 30 deg, and the extra knee flexion due to load is less than 10 deg. The knee flexion at weight acceptance due to increased loading has, in fact, no clear effect on the lower limb kinetic internal work ($W^{ll}_{int,k}$) and thus on $W_{int,k}$, because the flexion is modest and occurs when the displacement of the lower limb relative to the COM is slow.

The upper limb and load movements

During unloaded walking, $W^{ul}_{int,k}$ 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, Nepalese 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, $W^{ul}_{int,k}$ is nearly zero (∼1% of $W_{int,k}$) at any walking speed.

The internal work done to move the load relative to the COM ($W^{lo}_{int,k}$, in J kg^{-1} m^{-1}) is similar in the porters and the control subjects at the same load and speed. For example, $W^{lo}_{int,k}$ represents on average ∼5% of $W_{int,k}$ for controls and ∼6% for Nepalese porters when they carry a load of 75% M_b.

Internal work during double contact

The internal work done during the DC phase ($W_{int,dc}$) was 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 (Fig. 2). In such conditions and even though all energy transfers are taken into consideration (as explained in the Materials and methods), $W_{int,dc}$ accounts for up to 50% of the total internal work and up to 25% of the total mechanical work done. During load carrying 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 load, the work done by one foot against the other during the DC phase can be expected to be proportional to the load and thus to be independent of load when normalized per unit mass (J kg^{-1}). Nevertheless, the mass-specific $W_{int,dc}$ per unit distance (J kg^{-1} m^{-1}) tends to slightly increase with increasing load at speeds <1.4 m s^{-1}, whereas it is independent of load at the highest speeds. The slight increase in $W_{int,dc}$ 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 phase duration remains unchanged.

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 the forward component of the ground reaction force acting upon the back leg. For instance, that peak 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 may affect $W_{int,dc}$. It is worth noting that when $W_{int,dc}$ is taken into account, W_{int} (in 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 clearly increases in proportion to the load (Fig. 2). So, the idea that the Nepalese porters might be able to limit this futile work done during the DC phase in order to 'save' some mechanical work during load carrying is not supported.

Total mechanical work

As discussed previously, our results do not show any mechanical work saving strategy during load carrying in Nepalese porters. As for control subjects, they are unable to minimize either external work or internal work at any speed between 0.5 and 1.7 m s^{-1}. Consequently, at a given load and speed, the total mechanical work (W_{tot}) is equivalent for Nepalese porters and control subjects. As in unloaded walking, W_{tot} (in 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 increase again 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 1 kg of body mass or load mass over 1 m 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, thus W_{tot} also decreases with load, meaning that at these speeds more mechanical work is done to move 1 kg of body mass over 1 m than to move 1 kg of load.

Muscular efficiency

At all walking speeds, the muscular efficiency of load carrying is independent of load in the Nepalese porters and decreases with load in the control subjects (Fig. 3). Consequently, for small loads, control subjects are more efficient, whereas for loads ≥35% M_b, Nepalese porters tend to be more efficient. This is due to the fact that (1) the total mechanical work (in J kg^{-1} m^{-1}) in loaded walking is similar for both groups, and (2) the Nepalese porters have a smaller metabolic cost of carrying 1 kg of load over a distance of 1 m (see fig. 1B in Bastien et al., 2005a).

Our results have been echoed by the on-field load-carrying measurements of Minetti et al. (2006) in the Khumbu valley in Nepal. They highlighted the higher efficiency of the Nepalese porters compared with trained Caucasian mountaineers during both uphill and downhill loaded walking. Our measurements suggest that Nepalese porters are particularly optimized (i.e. the most efficient) when walking slowly with heavy loads; and in fact this speed–load combination is the only one they use. For example, when porters were behind schedule for arriving at the market place, they would consistently walk for longer times, often into the middle of the night, but never at higher speeds.

In conclusion, Nepalese porters accomplish their impressive load carrying without any apparent mechanically determined tricks. Hauling loads roughly equivalent to body mass up 8000 m and down 6300 m in about a week is, by Western standards, an unimaginable feat. The Nepalese porters do the same amount of total mechanical work as control Western subjects when walking at 0.5–1.7 m s^{-1} while carrying loads ranging from 0 to 120% of body mass. Owing to our experimental design, we can conclude that the Nepalese porters' better economy during load carrying is not related to a reduction in the work to displace the COM, nor in the work to displace the body segments including the trunk and the load, nor in the work done during the DC phase. It seems that the Nepalese porters are optimized for walking slowly with heavy loads. At that speed–load combination, their muscular efficiency is higher than that of the control subjects because they perform approximately the same mechanical work but at a lower net metabolic cost. One of the remaining explanations is that Nepalese porters have developed a skill in minimizing co-contractions to reduce the metabolic cost, without mentioning their high metabolic capacity, thanks to their training, anatomy and adaptation to high altitude. Moreover, the strategy of short intense exercise periods followed by frequent rest periods allows them to work at a high intensity level, spread out over many hours each day.

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Competing interests
The authors declare no competing or financial interests.

Author contributions
Conceptualization: P.A.W., N.C.H.; Methodology: G.J.B., B.S., P.A.W., N.C.H.; Software: G.J.B.; Formal analysis: G.J.B.; Investigation: G.J.B., B.S., P.A.W., N.C.H.; Resources: B.S., P.A.W., N.C.H.; Data Curation: G.J.B.; Writing – original draft preparation: G.J.B., N.C.H.; Writing – review and editing: G.J.B., B.S., P.A.W., N.C.H.; Visualization: G.J.B., N.C.H.; Supervision: P.A.W., N.C.H.; Project administration: P.A.W., N.C.H.; Funding acquisition: P.A.W., N.C.H.

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