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ORIGINAL ARTICLE

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Effect of load and speed on the energetic cost of human walking

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Abstract It is well established that the energy cost per unit distance traveled is minimal at an intermediate walking speed in humans, defining an energetically optimal walking speed. However, little is known about the optimal walking speed while carrying a load. In this work, we studied the effect of speed and load on the energy expenditure of walking. The O_2 consumption and CO_2 production were measured in ten subjects while standing or walking at different speeds from 0.5 to 1.7 m s^{-1} with loads from 0 to 75% of their body mass (M_b). The loads were carried in typical trekker's backpacks with hip support. Our results show that the mass-specific gross metabolic power increases curvilinearly with speed and is directly proportional to the load at any speed. For all loading conditions, the gross metabolic energy cost (J kg^{-1} m^{-1}) presents a U-shaped curve with a minimum at around 1.3 m s^{-1}. At that optimal speed, a load up to 1/4 M_b seems appropriate for long-distance walks. In addition, the optimal speed for net cost minimization is around 1.06 m s^{-1} and is independent of load.

Keywords Altitude · Energy cost · Load carrying · Optimal speed · Walking

Introduction

Backpacks are commonly used in military or recreational activities to carry loads over long distances, sometimes for many hours a day. Previous studies of the energy cost of different methods of load carriage have shown that the most economic techniques keep the load as close to the trunk as possible (Abe et al. 2004; Balogun 1986; Das and Saha 1966; Datta and Ramanathan 1971; Holewijn 1990; Kram 1991; Legg 1985; Legg and Mahanty 1985; Legg et al. 1992; Lloyd and Cooke 2000; Soule and Goldman 1969). In particular, the backpack remains one of the most convenient and economical ways of carrying a load, especially when a hip belt redistributes part of the load from the shoulders to the pelvis. Other studies have shown that while walking unloaded, there is an optimal speed where the energy cost per unit distance traveled is minimized (Cotes and Meade 1960; Margaria 1938; Ralston 1958; Zarrugh et al. 1974). The effect of backpack load-carrying on the optimal speed and energetic cost of walking has, to our knowledge, only been studied once previously (Falola et al. 2000) at only one load (10% of body mass, M_b).

The present study answers three questions that are of interest to anyone studying or practicing load carrying. First, how does the energy cost change as a function of speed and load? Second, is there an optimal speed and does it change with load? Third, since trekking is done frequently in mountainous regions, does the energy cost increase between low and mid-altitude? In order to answer these questions, we measured the energy cost of walking at 130 m and at 2,800 m over a wide walking speed range (0.5–1.7 m s^{-1}) and a large range of loads carried in a backpack (0–75% of M_b).

Previous studies have attempted to define the optimal or maximum acceptable load to be carried (Cathcart et al. 1923 cited in Pimental and Pandolf 1979; Hughes and Goldman 1970; Pierrynowski et al. 1981); however, since both walking speed and load influence the energy expenditure, this study will discuss for the first time the load-speed combinations that are most suitable for long walks.

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Methods

In this study we measured the energy cost of carrying loads during constant-speed, level walking. All subjects carried loads in typical trekker's backpacks with hip support. The experiments involved no discomfort, were performed according to the Declaration of Helsinki, and were approved by the local ethics committee.

Measurement of energy cost

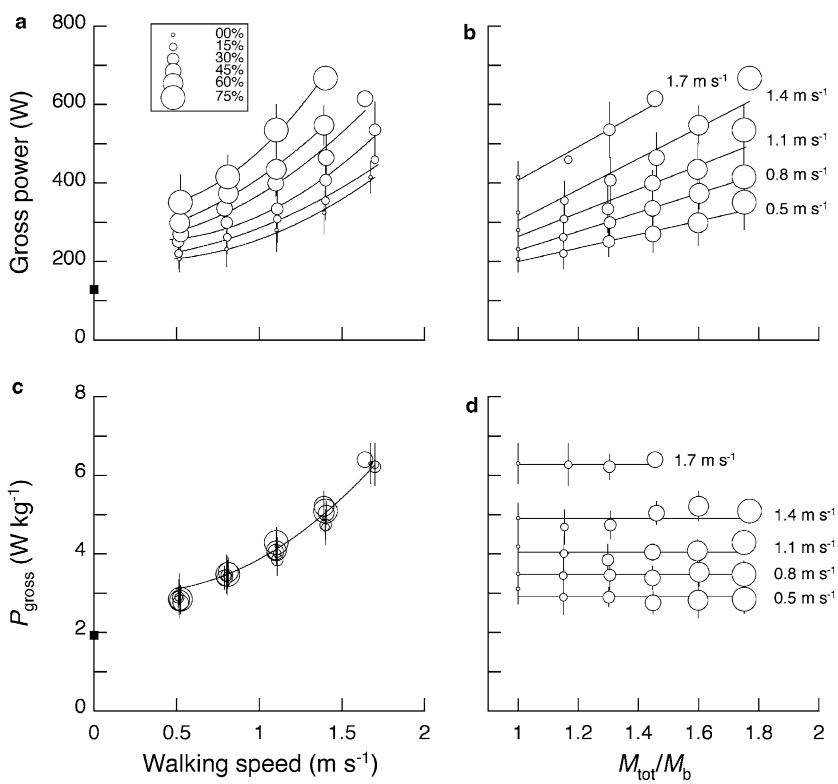
The energy cost was estimated from O_2 consumption and CO_2 production measured with a portable K4 telemetric system (Cosmed, Italy) (Hausswirth et al. 1997). The K4 system includes a portable unit worn by the subject and a base station for recording the data. The portable unit weighs 1.5 kg and consists of a silicon mask containing a flow-rate turbine which is fixed on the subject's face, a processing unit containing the O_2 and CO_2 analyzers which is placed on the subject's chest, and a transmitter/battery pack which is placed in the subject's backpack. Every day, the turbine was calibrated with a 3-l syringe, and a two-point calibration of the O_2 and CO_2 analyzers was carried out using ambient air and a standard calibration gas mixture (5% CO_2, 16% O_2, 79% N_2).

The mass-specific gross energy consumption rate (P_{gross} in W kg^{-1}) was obtained from the total O_2 consumption rate using an energetic equivalent of oxygen, taking into account the measured respiratory exchange ratio (RER) (Schmidt and Thews 1983). Only trials with a RER ≤ 1 were recorded and analyzed. The mass-specific gross cost of transport (C_{gross} in J kg^{-1} m^{-1}) was calculated by dividing P_{gross} by the walking speed in m s^{-1}. The mass-specific net energy consumption rate (P_{net} in W kg^{-1}) was calculated from the energy consumption that can be attributed to the walking and load-carrying per se, i.e., the energy consumption rate while walking minus energy consumption rate while standing unloaded. The mass-specific net cost of transport (C_{net} in J kg^{-1} m^{-1}) was calculated from the P_{net} divided by the speed in m s^{-1}. All data are converted to standard conditions (STPD). Data are given as mean (SD) unless otherwise stated.

Subjects and experimental procedure

Two groups of subjects were used in this study. A first group of six subjects (five males, one female) was mea-

Fig. 1a–d Effects of load and speed on the gross metabolic power. **a**, **c** Gross power of locomotion (W) and mass-specific gross energy consumption rate (P_{gross}; W kg^{-1}), respectively, as a function of the walking speed (m s^{-1}) for loads ranging from 0 to 75% of body mass (M_b). The *symbol size* increases with the backpack load: the *smallest empty circle* is for unloaded walking, the *largest symbol* is for a 75% M_b load. Symbols are mean values; the vertical bars indicate the standard deviation when their size exceeds the size of the symbol. The *continuous lines* are the second-order polynomial fit (Kaleidagraph) through the data points for each loading condition in **a** and for unloaded walking only in **c**. From low to high speed, n is for 0% M_b load: 10,10,9,9,3; for 15% M_b: 10,10,9,9,2; for 30% M_b: 10,10,10,9,3; for 45% M_b: 4,4,4,2,1; for 60% M_b: 10,10,10,9; for 75% M_b: 3,4,3,1. The gross power for zero speed (*plain squares*) is the mean metabolic power measured during standing unloaded. **b** and **d** present the gross power of locomotion and P_{gross}, respectively, 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 *lines* are the linear fit (**b**) or the mean values (**d**) of the data points for each speed



sured at sea level (altitude 130 m) and a second group of four subjects (two males, two females) was measured at 2,800 m altitude. All subjects were physically fit young Caucasian adults with an average age of 23.7 (4.2) years, height 1.76 (0.09) m, M_b 66.6 (9.1) kg.

Subjects were asked to carry loads ranging from 0 to 75% of their M_b while walking on a 1-m wide nearly circular level track at different speeds ranging from 0.5 to 1.7 m s^{-1}. The first group used a 40-m-long indoor track, and the second group used a 51-m-long outdoor track; all other conditions and materials are identical. The walking speed was measured by ten photocells placed at the level of the neck and evenly spaced along the track. Subjects were given verbal commands in order to maintain their actual speed close to the desired speed. For all tests, the speed measured by every photocell was within 0.15 m s^{-1} of the desired speed. The maximal standard deviation of the lap speed, within any test, was 0.04 m s^{-1}.

For each speed tested (0.5, 0.8, 1.1, 1.4 and 1.7 m s^{-1}), the experiment began and ended with measurement of the unloaded standing O_2 consumption rate. This phase was maintained as long as necessary to obtain a steady O_2 consumption rate for at least 3 min. A maximum of seven different loads (0, 15, 30, 45, 60 and 75% M_b) were then imposed for each speed. The 45% and 75% M_b loads and the 1.7 m s^{-1} speed were measured only in the group tested at altitude. The order of the speeds and loads was systematically rotated to eliminate any possible sequence effects. As in the standing measurements, data recording during walking were maintained as long as necessary to obtain a steady-state period of at least 3 min. When a subject was unable to support the load, maintain the imposed speed, or the RER exceeded 1.0, the trial was stopped, the data were not recorded and the experiment was resumed at a lower speed or a lower load.

Results

For most of the speeds studied, P_{gross} was slightly higher for the subjects walking at altitude compared to the subjects doing the same exercise at sea level. However, a three-way ANOVA with repeated measures performed on the mass-specific gross power showed no significant difference between the groups for subjects compared at the same load and speed ($F=0.88$; $P>0.37$). The same statistical analysis also showed no sex related difference in our subjects group ($F=1.21$; $P>0.30$). As a result, all data from both groups were merged into one group ($n=10$) in order to study the effect of speed and load on that population.

The gross power when walking unloaded or with a backpack load increases curvilinearly with walking speed, and carrying a load costs more energy compared to unloaded walking at all speeds (Fig. 1a). The gross power increases proportionally to the load and the faster the walk the steeper the increase (Fig. 1b). Normalizing the gross power by the total mass (body mass + load mass) yields P_{gross}, the mass-specific gross power (W kg^{-1}). As shown by Fig. 1c, when walking unloaded P_{gross} increases curvilinearly with walking speed. It is around 3 W kg^{-1} at the lowest speed (0.5 m s^{-1}) and reaches ~7 W kg^{-1} at the highest speed studied (1.7 m s^{-1}). When carrying a load in a backpack, P_{gross} increases curvilinearly as a function of speed the same way as when subjects walk unloaded (Fig. 1c). Moreover, at each walking speed, P_{gross} is independent of load for loads up to 75% M_b (Fig. 1d). For example, P_{gross} is around 4 W kg^{-1} when walking at 1.1 m s^{-1} with or without an extra backpack load.

The gross power and the mass-specific gross power during standing unloaded, P_{stand} (W kg^{-1}) are shown in Fig. 1a, c at a speed of zero. P_{stand} was not different between the subjects measured at altitude (2,800 m) and those measured at sea level (t-test, $t=0.84$, $P>0.40$).

The mass-specific gross power divided by the walking speed yields the mass-specific gross cost (C_{gross} in J kg^{-1} m^{-1}). C_{gross} is the total energy spent while moving one unit of mass (either body or load) one unit of distance. C_{gross} is presented as a function of walking speed for all loading conditions in Fig. 2; not surprisingly, at each walking speed C_{gross} remains constant for all loads.

Loaded or unloaded, C_{gross} decreases as walking speed increases, up to an optimal speed where C_{gross} is minimal, and then increases again at higher speeds. The optimal speed for all loads is 1.30 (0.05) m s^{-1} ($n=6$), calculated as the minimum of the polynomial fit line through the C_{gross} data points for each loading condition.

The net power is the energy above the unloaded standing energy consumed per unit of time to move the

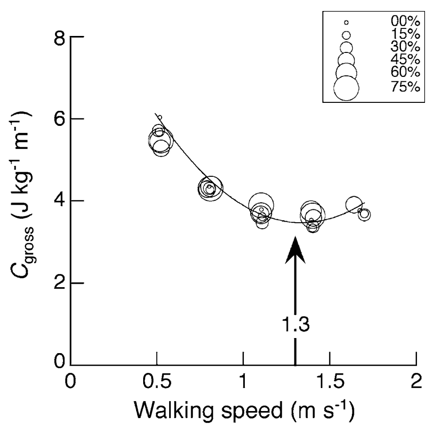


Fig. 2 Effects of load and speed on the mass-specific gross cost (J kg^{-1} m^{-1}). The mass-specific gross cost of locomotion (C_{gross}; J kg^{-1} m^{-1}) is presented as a function of the walking speed (m s^{-1}) for loads ranging from 0 to 75% M_b. C_{gross} is calculated as the mass-specific gross power divided by the walking speed. The *continuous line* is the second-order polynomial fit through the data points for unloaded walking. The *arrow* shows the optimal speed for all loading conditions from 0 to 75% M_b. Other indications as in Fig. 1

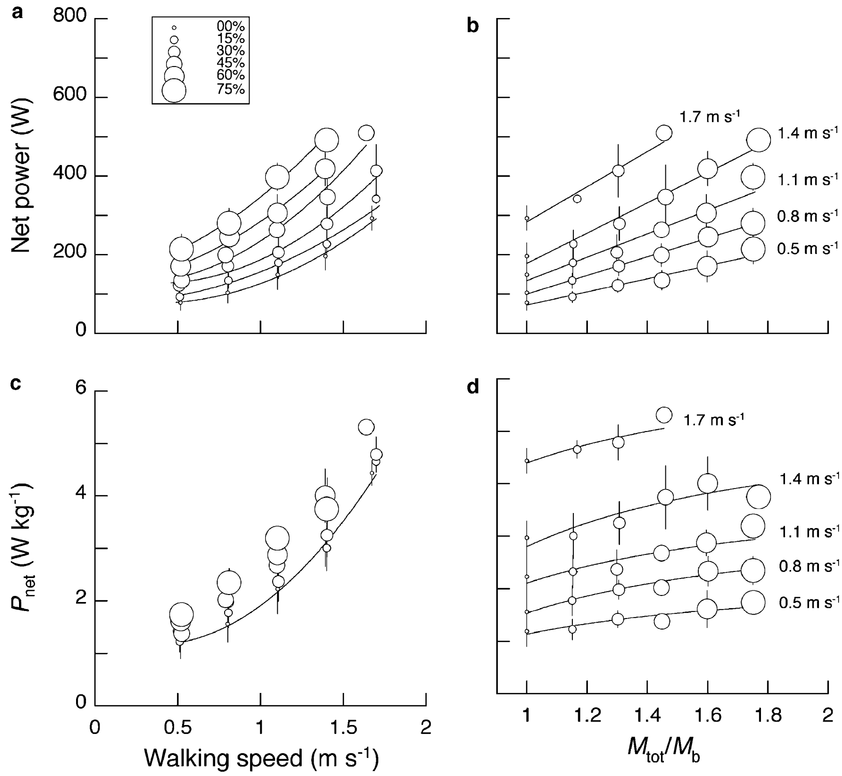


Fig. 3a–d Effects of load and speed on net metabolic power. **a**, **c** Net power of locomotion (W) and mass-specific net energy consumption rate (P_{net}; W kg^{-1}), respectively, as a function of the walking speed (m s^{-1}) for loads ranging from 0 to 75% M_{b}. **b**, **d** Net power of locomotion and P_{net}, respectively, as a function of the total mass for different walking speeds. In **d** the lines are best-fit nonlinear $y=m-b/x$ lines through all of the data points for each speed. Other indications as in Fig. 1

total mass (body and load). The net power and the mass-specific net power (P_{net} in W kg^{-1}) are presented in Fig. 3 as a function of walking speed and load. The net power increases curvilinearly as a function of speed at any load, and increases linearly as a function of load at any speed, the same way as the gross power, but all values are shifted down by a constant value equal to the standing power (Fig. 3a, b). P_{net} increases curvilinearly with walking speed but also increases slightly with increasing load at all walking speeds (Fig. 3c, d). For example, when walking at 1.1 m s^{-1}, P_{net} is approximately 2.1 W kg^{-1} when no load is carried, increasing to 2.7 W kg^{-1} for a load of 45% M_{b} and reaching 3.0 W kg^{-1} for a load of 75% M_{b} (Fig. 3d).

When walking unloaded, the mass-specific net cost (C_{net} in J kg^{-1} m^{-1}) presents a U-shaped curve with speed (Margaria 1938); it is high at slow and fast speeds and is low at intermediate speeds. The optimal speed, defined as the speed at which C_{net} is minimal, is around 1.0 m s^{-1} for unloaded walking (Fig. 4).

When walking loaded, the C_{net} curve still shows an optimal speed. For loads up to 75% M_{b}, the optimal speed remains close to the one found in the unloaded condition, and is always between 0.9 and 1.2 m s^{-1} (Fig. 4).

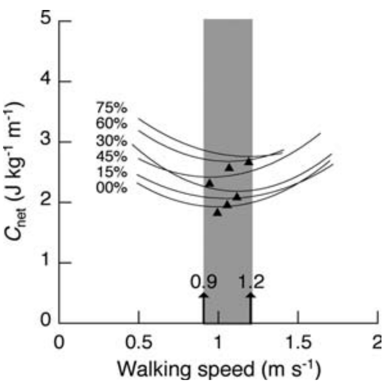


Fig. 4 Optimal speed as a function of walking speed and load. The mass-specific net cost of locomotion (C_{net}; J kg^{-1} m^{-1}) is presented as a function of the walking speed and load. Lines are the second-order polynomial fit (Kaleidagraph) through all of the data points for each loading condition, as noted in the figure. *Upward triangles* indicate the optimal speed for each loading condition; the *gray area* shows the speed range in which the optimal speed is included for all loading conditions from 0 to 75% M_{b}

Discussion

The mass-specific gross metabolic power (P_{gross}, in W kg^{-1}) increases curvilinearly with walking speed while either unloaded or loaded (Fig. 1c). Our data show that P_{gross} more than doubles when the unloaded walking speed increases from 0.5 to 1.7 m s^{-1}; this is in agreement with many previous studies (Bobbert 1960; DeJaeger et al. 2001; Givoni and Goldman 1971; Pandolf et al. 1977; Passmore and Durnin 1955; Soule et al. 1978; Workman and Armstrong 1963; Zarrugh and Radcliff 1978). At each speed, as the load is increased within the range of 0 to 75% M_{b}, P_{gross} (W kg^{-1}) is independent of load (Fig. 1d) because at a given speed the gross power (W) is directly proportional to the total mass. For example, at a speed of 1.1 m s^{-1}, carrying a load of 60% M_b increases the gross metabolic power by 60%, and the P_{gross} remains constant at 4 W kg^{-1} (Fig. 1b, d).

Some previous studies in which the load was kept close to the trunk confirm the latter result (Goldman and Iampetro 1962; Soule et al. 1978), but other studies describe the mass-specific gross power versus load relationship as curvilinear, showing a minimum at an 'optimum' load for a given speed (Cathcart et al. 1923, cited in Pimental and Pandolf 1979; Holewijn 1990; Hughes and Goldman 1970; Pierrynowski et al. 1981). However, fitting our P_{gross} versus load data at each speed to a polynomial curve results in only small differences between the lowest and highest power, and no clear minimum at most speeds. Furthermore, a two-way ANOVA with repeated measures shows no significant influence of load on the mass specific gross power ($F = 2.18$; $P > 0.08$). It is therefore concluded that the P_{gross} versus load relationship is best described as constant over the load range studied for each walking speed (Fig. 1d). In other words, the total metabolic power required to move one unit of body mass is about the same as the power required to move one unit of load mass, but in either case the power increases rapidly with walking speed (Fig. 1c).

At any given speed, the total cost of transporting a load, C_{gross}, is independent of load (Fig. 2) since it is simply P_{gross}, which is independent of load (Fig. 1), divided by the walking speed. C_{gross} decreases with increasing walking speed up to about 1.3 m s^{-1} and then tends to increase again at higher speeds (Fig. 2). The initial decrease is due to the fact that the zero speed cost, including standing, becomes a successively smaller fraction of P_{gross} as speed increases. The increase in C_{gross} at high walking speeds is due to the fact that P_{gross} increases curvilinearly with speed and becomes relatively important at the high speeds. The optimal speed of C_{gross} corresponds to the 'self-selected speed' for level unloaded walking (1.39 m s^{-1}) found by Minetti et al. (2003).

Although Pandolf et al. (1977) found that supporting loads increases metabolism during standing, more recent studies (Griffin et al. 2003; Holewijn 1990; Maloiy et al. 1986; Pierrynowski et al. 1981), including a subsequent study by Pimental and Pandolf (1979), have found no increase in standing gross power while supporting loads up to 60% M_b. In this case, either the loads are supported by non-metabolizing tissues, or the resulting increase in metabolism is too small to resolve. The P_{stand} measured in this study [1.99 (0.36) and 1.88 (0.41) W kg^{-1} for the altitude and sea level groups, respectively] is equivalent to the P_{stand} measured in previously published studies on adults (DeJaeger et al. 2001; Passmore and Durnin 1955). Subtracting the unloaded standing metabolic rate from the loaded walking metabolic rate yields the increase in the metabolic rate due to moving while supporting a load (P_{net}).

In contrast to the P_{gross}, the mass-specific net power (P_{net}) at a given speed is not independent of load (Fig. 3d). At each speed the P_{net} increases with load, for example, at 1.1 m s^{-1} P_{net} increases by nearly 50% over the load range studied (Fig. 3d). At that same speed, when $M_{tot}/M_b = 1$ (unloaded walking), P_{net} equals 2.10 W kg^{-1}, meaning that each kilogram of body mass costs 2.10 W to move and support; this is in agreement with previously published data (DeJaeger et al. 2001). For the load, on the other hand, our results show that the net power increases linearly as a function of the load, i.e., the increase in net power is proportional to the load for a given speed (Fig. 3b). For example, at the same 1.1 m s^{-1} speed, the increase in the net power (i.e., the slope of the line) is 3.91 W per kg of added mass, meaning that each kilogram of load costs 3.91 W to move and support, whatever the load. Thus the net power for carrying one unit of body mass is less than the net power for carrying one unit of load, but both are independent of load at a given walking speed. Since total mass is the sum of body and load mass, each with a different net energetic cost rate, then P_{net} increases nonlinearly as a function of the load, approaching the load cost asymptotically at high loads.

The metabolic rate increase required for just carrying a load is simply equal to the gross power while walking at a given speed loaded minus the gross power while walking at the same speed unloaded. Figure 5 shows that the resulting load power passes through zero, increases in proportion to the load mass, and increases more rapidly at higher walking speeds. The slope of the lines in Fig. 5 represents the mass-specific load power, P_{load} (W kg^{-1}), that can be attributed to the load-carrying per se. P_{load} is independent of load and increases with walking speed. For example, at 1.1 m s^{-1} the load

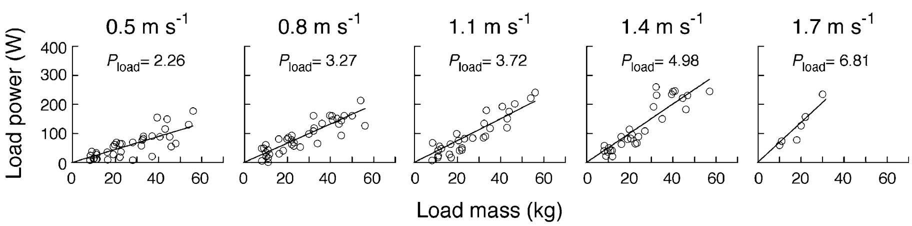


Fig. 5 Effects of load and speed on the load metabolic power. The load metabolic rate is presented as a function of the load mass for each walking speed. The load metabolic rate is calculated by subtracting the metabolic rate while walking unloaded from the metabolic rate while walking at that same speed with a load. The symbols show the data points; the lines are the linear fit (Kaleidagraph) of the data points and forced through zero. For each walking speed, the slope of the linear fit line is indicated above the corresponding data and represents P_{load} (W kg^{-1}), the mass-specific load metabolic rate

power is 3.72 W kg^{-1} of load for all loads, while at 1.7 m s^{-1} it is 6.81 W kg^{-1} of load. P_{load} is in fact the same as the slopes of the gross and net power versus total mass relationships shown in Figs. 1b and 3b, the small numerical differences being due to inter-individual variations.

That the metabolic cost of carrying a kilogram of load is independent of load at a given speed clearly disagrees with a previous study (Holewijn 1990) in which a partial differentiation of the Pandolf equation (Pandolf et al. 1977) shows that the extra metabolic rate per kilogram of added mass increases with total load. This discrepancy is due to the fact that here we take P_{stand} to be independent of load (see above) while the Pandolf equation assumes it increases with load (the M_2 component of the Pandolf equation).

Both C_{gross} and the C_{net} show a U-shaped curve as a function of speed, with a minimal cost at an intermediate optimal speed (Cotes and Meade 1960; Margaria 1938; Ralston 1958; Wickler et al. 2001; Zarrugh et al. 1974). The optimal speed for unloaded walking is 1.3 m s^{-1} for C_{gross} (Fig. 2) and about 1.0 m s^{-1} for C_{net} (Fig. 4); these values are identical or close to values found during unloaded walking in other studies (Ardigo et al. 2003; Bobbert 1960; Cotes and Meade 1960; DeJaeger et al. 2001; di Prampero 1986; Zarrugh et al. 1974). The difference between the two optimal speeds can be explained by looking at how they are calculated. As shown by many authors (Bobbert 1960; Cotes and Meade 1960; DeJaeger et al. 2001; Pandolf et al. 1977; Zarrugh et al. 1974), the relation between metabolic power (P in W kg^{-1}) and walking speed (V in m s^{-1}) is best described by a second-order polynomial function:

$$P = aV^2 + bV + c \tag{1}$$

The cost (C in J kg^{-1} m^{-1}) is the power divided by the walking speed, thus from Eqn. 1:

$$C = aV + b + \frac{c}{V} \tag{2}$$

The speed derivative of C is null when the cost is minimal, thus the theoretical optimal speed is (Cotes and Meade 1960; Zarrugh et al. 1974):

$$V_{opt} = \sqrt{c/a} \tag{3}$$

The optimal speed depends upon c (the intercept of the power versus speed relationship) and the coefficient a. Since the net power is calculated by subtracting a constant (the standing power) from the gross power, the intercept c for the net power is smaller than the one for gross power while the coefficient a is unchanged. Therefore, the optimal speed found for the net cost relationship is slower than the optimal speed for the gross cost. Clearly, the walking speed at which the cost is minimal depends upon how it is calculated (Workman and Armstrong 1986). For example, if the resting metabolic rate were subtracted from the gross power rather than standing rate, then the optimal speed would be between that for C_{net} and C_{gross}.

During load carrying an optimal speed, calculated either on the gross or net cost, still exists, and furthermore it remains at the same speed. To our knowledge, this study is the first to show an optimal walking speed in human load carrying for a large range of loads. For loads up to 75% of the body mass, the optimal speed for minimal gross cost is 1.30 (0.05) m s^{-1} and the optimal speed for minimal net cost is 1.06 (0.09) m s^{-1}. It can be seen in Fig. 4 that for all loads studied, the optimal speed for minimal net cost is always between 0.9 and 1.2 m s^{-1} and there is no load-related trend. One previous study on horses (Wickler et al. 2001) observed that the gross cost shows a minimum at a lower speed if horses carry a load of 19% M_b compared to no load. However, this study normalized results to body mass and not to total mass. As acknowledged by the authors, if the gross cost were expressed per unit of total mass, it would be the same when loaded or unloaded, occurring at one optimal speed (Wickler et al. 2001).

It is interesting to note that the minimum C_{gross} occurs at the same speed as the minimal mechanical work performed by muscles to move the center of mass (the external work) in unloaded walking in adults (Cavagna et al. 1976; Willems et al. 1995) as well as in children (DeJaeger et al. 2001). It has been shown also that the mass-specific external work (J kg^{-1} m^{-1}) does not significantly change with backpack loads (Heglund et al. 1995). This suggests that the speed at which the efficiency of walking is maximal is about the same whether walking unloaded or loaded.

Many studies have compared the energy cost of different methods of load carriage (Abe et al. 2004; Balogun 1986; Das and Saha 1966; Datta and Ramanathan 1971; Holewijn 1990; Kram 1991; Legg 1985; Legg and Mahanty 1985; Legg et al. 1992; Lloyd and Cooke 2000; Soule and Goldman 1969). It has been shown that when a load is carried close to the trunk (different kinds of backpacks, double packs, trunk jackets), the gross metabolic rate is directly proportional to the load (Goldman and Iampetro 1962; Legg and Mahanty 1985; Soule et al. 1978) as was found in this study. However if the load is carried either using smaller muscular groups (arms) or at the extremities (hands, feet), then the gross metabolic rate is greater at any given load and speed (Datta and Ramanathan 1971; Legg 1985; Soule and Goldman 1969). The question of whether an optimal speed exists and whether it remains unchanged for other load carriage techniques is open. If, for a given load, the gross metabolic rate is multiplied by a same factor at all walking speeds, then the optimal speed would remain the same because the intercept c and coefficient a in Eq. 3 would be both multiplied by that factor.

In our experiments, energy expenditure was measured at steady state with a RER ≤ 1, which supposes that the exercise could be maintained over time. However, it is possible that the energy cost may increase due to muscular fatigue (Epstein et al. 1988). According to other studies (Astrand and Rodhal 1977; Epstein et al. 1988) work intensities $< 50\%$ $\dot{V}O_{2\ max}$ can be sustained for about an hour at a time. The $\dot{V}O_{2\ max}$ was not measured for our subjects; however, they were all young fit adults and it can be conservatively assumed that their $\dot{V}O_{2\ max}$ was at least 45 ml kg^{-1} min^{-1} (Wilmore and Costill 1994). In this case the metabolic rate would be $< 50\%$ of $\dot{V}O_{2\ max}$ for loads up to 60% M_b when walking at 1.3 m s^{-1}.

As walking speed increases, the maximal load that can be carried at $< 50\%$ $\dot{V}O_{2\ max}$ decreases sharply (Soule et al. 1978); for example, at 1.7 m s^{-1}, only loads $< 30\%$ M_b can be carried at $< 50\%$ $\dot{V}O_{2\ max}$. Similarly, self-pacing studies showed that men and women tend to limit their rate of energy consumption to around 45% $\dot{V}O_{2\ max}$ for walks lasting 1–3.5 h, regardless of the terrain and load carried (Evans et al. 1980; Hughes and Goldman 1970; Levine et al. 1982; Myles and Saunders 1979). Using our data, this would correspond to loads of 60% M_b at 1.1 m s^{-1}; 45% M_b at 1.4 m s^{-1} and 15% M_b at 1.7 m s^{-1}. These load/speed values are in agreement with an early publication (Cathcart et al. 1923, cited in Hughes and Goldman 1970) stating that at a walking speed of 1.4–1.7 m s^{-1} the most economical load is equal to 40% of M_b, although the authors came to that conclusion using a completely different approach.

As the duration of the exercise is increased beyond 3 h, self-pacing studies show that individuals further limit their energy expenditures (Levine et al. 1982; Myles et al. 1979; Saha et al. 1979). For example, for exercises lasting longer than 6 h, the energy expenditure is limited to 35% of $\dot{V}O_{2\ max}$. Using our data, this latter value corresponds to a load of approximately 25% M_b at the optimal walking speed of 1.3 m s^{-1}. Not surprisingly, this load falls into the comfortable range for fit hikers (Gordon et al. 1983) and is the load most commonly adopted by recreational trekkers. Clearly, if heavier loads are carried, then the walking speed is decreased, not because the optimal speed has changed, but because the energy expenditure rate is limited. Finally, since $\dot{V}O_{2\ max}$ decreases with age, the acceptable load to be carried for long duration walks would also decrease consistently with age (Holewijn 1990; Samanta et al. 1987).

We found no difference in the energy expenditure of the subjects walking at sea level or at a 2,800 m altitude. This is not surprising since previous load carrying experiments performed at 3,660 m (Nag et al. 1978) and 4,300 m (Cymerman et al. 1981) showed close agreement with the Pandolf equation (Pandolf et al. 1977), which was determined at sea level.

The results reported in this study apply to level walking only. However, previous studies have shown that: (1) for a given unloaded walking speed, the metabolic rate increases exponentially with increasing positive gradient (Ardigo et al. 2003; Bobbert 1960; Margaria 1938); and (2) the energy expenditure per unit of total mass is a constant for a given positive gradient and speed (Goldman and Iampetro 1962). Thus, in uphill walking, the optimal speed should be the same with or without a load, but should decrease with increasing positive gradient. For example, using published data (Bobbert 1960; Margaria 1938), the optimal speed for gross cost minimization would be reduced to about 1.0 m s^{-1} for walking up a +10% gradient. The downhill energy cost is rather independent of speed and no precise optimal speed can be detected (Ardigo et al. 2003; Margaria 1938). Note that the Pandolf equation (Pandolf et al. 1977) leads to a fixed optimal speed whatever the positive gradient for any fixed load, suggesting that this predictive equation is limited in its use and interpretation vis-a-vis the effect of grade on the energy cost.

In conclusion, this study shows that the optimal speed for minimum gross cost (J kg^{-1} m^{-1}) is around 1.3 m s^{-1} for walking unloaded or with backpack loads up to 75% M_b. Our results confirm that gross energy cost is proportional to the load carried in a backpack; however, the extra cost induced by extra load increases with the walking speed. And finally, at the optimal speed, a load equivalent to 25% of M_b can be carried at steady state over an entire day trek by reasonably fit hikers.

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