

Energetics and Optimization of Human Walking and Running: The 2000 Raymond Pearl Memorial Lecture

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ABSTRACT Humans seem to adjust their walking and running gaits to minimise the metabolic energy cost of locomotion. The walking speed that we tend to prefer is the one that minimises energy cost per unit distance, though faster speeds might seem preferable when time is valuable. At speeds up to 2 m/s, walking requires less energy than running, and we walk. At higher speeds, running is more economical, and we run. At each speed we use the stride length that minimises energy costs. A computer model that predicts metabolic rates for all conceivable gaits of a simple biped helps to understand these and other features of human gait. The energy cost of walking is increased on uphill slopes and also on soft ground. Consequently, zigzag paths should be preferred to straight ones, up hills of more than a critical gradient. Also, it may be more economical to divert a path around a hill than to travel along a straight line. Simple theories of optimum diversions are presented, both for hilly ground and for ground interrupted by marshy patches, on which costs of walking are increased. Energy costs are also increased by heavy loads, though it seems possible in some circumstances to carry moderate loads without measurable extra cost. *Am. J. Hum. Biol.* 14:641–648, 2002.

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The energy cost of locomotion is a major item in human energy budgets. For example, Passmore and Durnin (1955) calculated that walking accounted for 20% of the weekly energy expenditure of a clerk who walked for 9 hours each week, and 27% of the much greater energy expenditure of a coal miner who walked for 21 hours each week. The ways of life of these examples were of course very different from those of early humans, but locomotion must also be a major cost in the energy budgets of hunter-gatherer populations such as the !Kung San (Bushmen) of Botswana, who walk about 2,400 km per year (Lee, 1979). At a likely speed of 5 km/h, this would require an average of 9 hours walking per week. It seems likely that locomotion was important also in the energy budgets of early humans. It therefore seems reasonable to suppose that human evolution may have been strongly influenced by selection for structures and patterns of movement that reduce the energy cost of locomotion. Further, it seems that each of us has learned energy-saving behaviours and patterns of movement by trial and error. We do not always behave in energy-saving ways (indeed, many of us deliberately take exercise), but we have learned how to save energy when we wish to do so. This article is about the energy costs of human walking and running, about how our gaits seem to

be adapted to minimise energy costs, and about how we should plan journeys to keep energy costs as low as possible.

ENERGY COSTS OF WALKING AND RUNNING

The energy cost of human locomotion is commonly calculated from measurements of oxygen consumption. Speed can be controlled, if desired, by having the subjects walk on a treadmill, matching their speed to the speed of the belt. Figure 1a shows data obtained in this way for walking and fairly slow running; fast running requires anaerobic metabolism, so its energy cost cannot be calculated simply from oxygen consumption. Notice in Figure 1a that the lines for walking and running cross at a speed of about 2 m/s. Below this speed, walking requires less energy than running but above 2 m/s running uses less energy than walking. Participants in this experiment were instructed to walk or to run, but when adult humans are free to choose their gait they are found to change from walking to running at about 2

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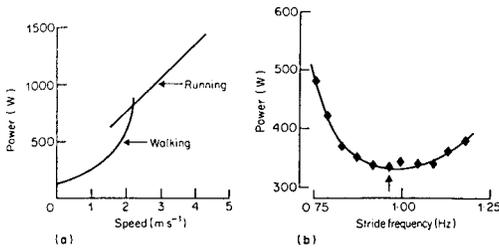


Fig. 1. a: A graph showing the metabolic power used by adult men, walking and running at different speeds. Based on the data of Margaria (1996). b: A graph of metabolic power against stride frequency for adult men walking at 1.5 m/s, from the data of Zarrugh and Radcliffe (1978). Reprinted from Alexander (1996).

m/s (Thorstensson and Roberthson, 1987); we choose whichever gait requires less energy. Normal walking remains possible at speeds up to about 3 m/s and athletes making the peculiar pelvic movements of race walking attain walking speeds exceeding 4 m/s, but such fast walking is very expensive of energy. An athlete needs 30% more energy to walk at 3.5 m/s than to run at the same speed (di Prampero, 1986).

Any particular speed can be achieved either by taking short strides at high frequency, or by taking longer strides at lower frequency. Figure 1b shows results of an experiment in which subjects' oxygen consumption was measured while they walked on a treadmill, matching their stride frequency to the beat of a metronome. These particular results were obtained at a moderate walking speed of 1.5 m/s. They show that the energy cost of walking at this speed was least when the stride frequency was about 0.95 Hz. When the metronome was not used, the subjects walked with about this stride frequency. Experiments at other speeds showed that the optimum (energy minimising) stride frequency increased as speed increased and that the preferred frequency at each speed was close to the optimum.

The experiments illustrated in Figure 1 show that people choose their gait and adjust their stride frequency in such a way as to minimise metabolic energy costs at their chosen speed of travel. We will ask in the next section whether the same principle applies to other details of human locomotion.

FORCE PATTERNS

There are marked differences in the patterns of force that people exert on the

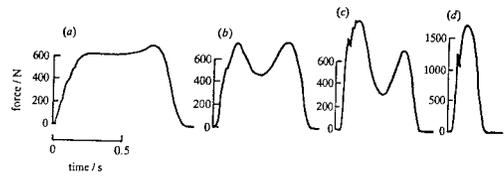


Fig. 2. Records of the vertical components of force exerted on the ground by one foot of a man walking at (a) 0.9 m/s, (b) 1.5 m/s, and (c) 2.1 m/s; and running (d) at 3.6 m/s. From Alexander (1992).

ground when walking at different speeds or running. In describing them, I will refer only to the vertical components of force. The magnitudes of the horizontal components are adjusted to keep the resultant force on the foot always more or less in line with the hip (Alexander and Jayes, 1980). Therefore, any given pattern of vertical force implies a particular pattern of horizontal force.

In walking (Fig. 2a,b,c), each foot is on the ground for more than half the time, so there are stages of the stride at which both feet are on the ground simultaneously. In running (Fig. 2d), each foot is on the ground for less than half the time, so there are stages at which both are off the ground. In slow walking (Fig. 2a), the force exerted by a foot rises, plateaus, and then falls. As speed increases (Fig. 2b,c), the force pattern becomes more and more markedly two-peaked. However, in running (Fig. 2d) the pattern becomes bell-shaped, with only one major peak. (In counting force peaks, the small, high frequency disturbance that occurs both in walking and running immediately following impact of the foot with the ground was ignored).

These changes in force pattern can be described by two parameters. The first is the duty factor, β , the fraction of the duration of a stride for which each foot remains on the ground. In principle, it can take any value between 0 and 1. It is about 0.6 for walking and falls abruptly to about 0.35 at the onset of running (Alexander, 1989).

The other parameter is the shape factor, q , that describes the shape of the record of the force exerted by one foot. It is obtained by fitting to the force record half a cycle of the function $F(t) = A[\cos(Bt) - q\cos(3Bt)]$, where A and B are constants and t is time (Alexander and Jayes, 1980). A shape factor of zero describes a half cycle of a cosine curve, shape factors greater than 0.15

describe two-peaked curves, and negative shape factors describe bell-shaped curves. Shape factors can in principle have any value between -0.33 and $+1.00$. Values outside this range would imply a negative ground force at some stage of the step. The shape factor is about 0.2 in slow walking, rises gradually to about 0.7 as walking speed increases, and then falls abruptly to a small negative value at the onset of running (Alexander, 1989).

These observations raise the question whether the changes of duty factor and shape factor that accompany changes of speed have the effect of minimising energy costs? There is no obvious way of investigating this empirically. It does not seem practicable to train subjects to vary duty factor and shape factor on command, comparable to the variation of stride frequency that was controlled with the aid of a metronome. Mathematical modelling is the only approach to the problem that at present seems feasible (Minetti and Alexander, 1997).

MUSCLE AND TENDON PROPERTIES

To calculate energy costs of movement for a mathematical model we need information about the physiological properties of muscle and the elastic properties of tendons. Figure 3 summarises the relevant physiological properties of muscle, as determined in experiments with small bundles of living muscle fibres taken from various vertebrates (Woledge et al., 1975; Ma and Zahalak, 1991). Figure 3a shows how the force that a fully activated muscle can exert depends on the velocity of shortening (v). When it is shortening at zero rate (pulling against an immovable object), it exerts its isometric force (F_{iso}). When shortening at increasing rates, it exerts progressively less force until at its maximum shortening speed (v_{max}) it exerts no force at all. When it is forcibly stretched (negative shortening speeds), it exerts forces up to about $1.8 F_{iso}$. Figure 3b shows how the metabolic rate of a fully activated muscle depends on the rate of shortening. The metabolic rate is higher when the muscle is shortening, doing work, than when it is contracting isometrically. It is lower when the muscle is being forcibly stretched and so is acting like a brake, unless the rate of stretching is very high. The maximum rate of shortening (v_{max}) is high

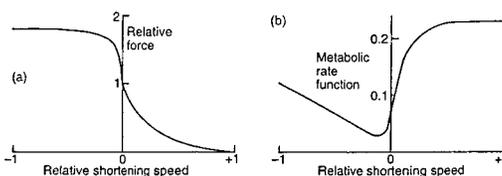


Fig. 3. Physiological properties of vertebrate striated muscle. Relative force means $(\text{force})/F_{iso}$; relative shortening speed means $(\text{shortening speed})/v_{max}$; and metabolic rate function means $(\text{metabolic rate})/F_{iso}v_{max}$. From Alexander (1999).

for fast muscles and low for slow ones (Woledge et al., 1975). It varies both between and within muscle fibre types.

In other experiments, lengths of tendon have been stretched and allowed to recoil in a dynamic testing machine of the kind used for investigating the strength and elasticity of metals and plastics. Such tests have shown that tendon has nonlinear elastic properties. It can be stretched to about 110% of its unloaded length before it breaks. Graphs of stress against strain seem to be more or less identical for all mammalian tendons and all have very good elastic properties, returning in their elastic recoil 93% of the work done to stretch them (Bennett et al., 1986). The ligaments of the arch of the foot have similar elastic properties. Ker et al. (1987) squeezed amputated feet in a dynamic testing machine in experiments designed to imitate the pattern of forces that would have acted on the foot in running. We found that the foot behaves like a spring, giving about 78% energy return in its elastic recoil. We estimated that about 35% of the (kinetic plus gravitational potential) energy that the body loses and regains in each running footfall is stored and returned by elastic stretching and recoil of the Achilles tendon and about 17% is stored and returned by the spring-like action of the arch of the foot. Thus, the elastic properties of tendons and ligaments are highly important for the energetics of running.

Similar conclusions have been reached in experiments on kangaroos (Biewener et al., 1998). In these experiments, tendon buckles were fitted to the gastrocnemius and plantaris tendons of living animals to measure the forces that the muscles exerted in hopping and sonomicrometry crystals were implanted in the muscles to record the

length changes of muscle fibre bundles. The surgical procedures might perhaps have been acceptable on humans if willing volunteers could have been found, but it would not have been possible to kill the subjects afterwards for calibration of the tendon buckles, as was done for the kangaroos. It was found that, while the kangaroo's foot is on the ground, the muscle fibres of the gastrocnemius and plantaris remain almost constant in length, while the tendons stretch and recoil (though the plantaris muscle is rudimentary in humans, it is substantial in kangaroos and most other mammals).

This knowledge of the properties of muscles and tendons can be used as follows to estimate the metabolic energy cost of movements (Alexander, 1997). Suppose that we know or can estimate the maximum shortening speed (v_{\max}) of a muscle and the elastic compliance of its tendon. We also know the force exerted by the muscle/tendon complex and the rate at which its length is changing at every stage of the movement. Then for each stage of the movement we can use the rate of change of force to calculate the rate at which the tendon is being stretched. We can subtract this from the rate of change of length of the muscle/tendon complex to obtain the rate of change of length of the muscle fascicles. Knowing this we can use Figure 3a to find out how much of the muscle must be activated to exert the current force; more specifically, this gives us the force that the activated muscle would exert if contracting isometrically. We now have enough information to obtain the metabolic rate from Figure 3b. The procedure is repeated for successive stages of the movement and the energy cost of the whole movement is obtained by integration.

The method has a serious fault. The data for Figure 3 were obtained in experiments in which bundles of muscle fibres made a single contraction at constant speed. In locomotion, muscles make repeated cycles of lengthening and shortening at constantly changing speeds. More relevant physiological data have been obtained from "work loop" experiments, in which bundles of muscle fibres are stretched and allowed to shorten repeatedly, with stimulation at appropriate stages of the cycle. These have shown that the force exerted by a muscle at some stages of a cycle may differ substan-

tially from the force predicted by Figure 3a for its current rate of shortening (Askew and Marsh, 1998). However, our understanding of the results of work loop experiments is not yet sufficiently good to enable us to use them to predict the metabolic costs of arbitrary cycles of movement. For the present, the method outlined in the preceding paragraph seems to be the best available for use in mathematical models.

MODEL OF BIPEDAL LOCOMOTION

Minetti and Alexander (1997) devised a very simple computer model of a biped. Its only joints, at the hip and knee, are operated by muscles with properties as shown in Figure 3. The maximum shortening speeds v_{\max} of the muscles were selected to be realistic for humans and the knee muscles were given tendons with elastic properties designed to give realistic compliance to the leg as a whole. The model can be made to walk or run at any chosen speed, with any combination of stride length, duty factor, and shape factor. The energy cost of a stride is calculated as described above.

Some results are shown in Figure 4. Each graph refers to a different speed, with a stride length selected to be realistic for that speed. The horizontal axis of each graph represents duty factor, showing almost the whole range of theoretically possible duty factors. The vertical axis shows the whole range of theoretically possible shape factors. The contours show the energy costs of walking or running with each combination of duty factor and shape factor.

Figure 4a represents a very slow walking speed. The contours show a local minimum of energy cost (hollow star) with a duty factor of 0.2 and a shape factor of 0.1 and a global minimum (filled star) with a duty factor of 0.55 and a shape factor of 0.4. Figure 4b represents a faster walking speed. The global optimum is again a walk (the duty factor is greater than 0.5), but the shape factor is greater than the optimum for the slow walk. Figure 4c represents the speed (2 m/s) at which adult humans break into a run. There are still two minima, but the global minimum (by a small margin) is now the run, with a duty factor of 0.25. Finally, Figure 4d represents a typical jogging speed. The walking minimum has disappeared and the optimum gait is clearly a run.

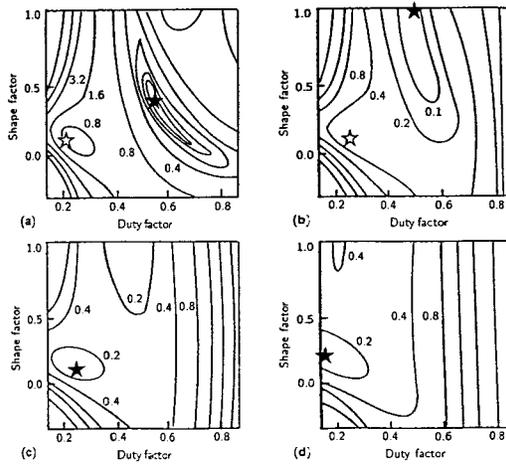


Fig. 4. Predicted metabolic energy costs of different gaits for a simple model of human locomotion at (a) 0.4 m/s; (b) 1.2 m/s; (c) 2.0 m/s; and (d) 3.2 m/s (Minetti and Alexander, 1997). The contours show energy cost in joules per metre, per kilogramme body mass. Reproduced from Alexander (1996).

Thus, the model predicts that a biped aiming to minimise energy costs should modify its gait as it increased speed, much as humans are observed to do (Fig. 2). At low speeds it should walk, increasing the shape factor as speed increased until at a critical speed it should switch abruptly to running. The critical speed and (in further calculations) the optimum stride length for each speed are quite accurately predicted. The predicted duty factors are lower and the predicted shape factors are higher than those observed for normal human locomotion. Good quantitative predictions could not be expected from so simple a model, but the qualitative agreement between the predicted and observed changes of gait parameters with speed is consistent with the hypothesis that our gaits are adapted to minimise energy costs.

JOURNEY PLANNING

If Figure 1a were replotted to show energy cost per unit distance, instead of per unit time, it would show that a given distance can be travelled at least energy cost by walking at 1.4 m/s. This may be the optimum speed for some journeys, but if time is a consideration as well as energy the optimum speed will be faster (see, for example, Alexander, 1998). Wirtz and Ries (1992) observed that young adults walk in city streets at a mean speed of 1.5 m/s.

The shortest distance between two points is a straight line, so the straight path should be the most economical of energy for journeys over firm level ground. However, real landscapes include hills and patches of soft or rough ground that it may be better to avoid by making a detour.

The energy cost of walking is much higher on soft level surfaces than on firm ones. For example, Zamparo et al. (1992) found that the cost of walking on dry sand was up to 2.5 times as high as on concrete. Pandolf et al. (1996) found that the cost of walking in deep snow was up to 5 times as high as on a treadmill. Alexander (2000) sought to establish principles for route planning over ground that included soft patches, by considering the very simple landscape shown in Figure 5a. **BKE** represents a triangular area of soft ground, where the energy cost of walking unit distance (C_{marsh}) is higher than the cost of walking unit distance on firm ground (C_{firm}). The angle at the apex of the triangular area is 2ϕ . A walker who wishes to travel from **A** to **F** can save energy by diverting to some extent from the straight path **ABEF**. The symmetry of this idealised landscape tells us that the path that requires least metabolic energy must be of the form **AGJF**. Mathematical analysis shows that for given values of $C_{\text{marsh}}/C_{\text{firm}}$ and ϕ , a walker should be prepared to deviate from the direct path by angles up to the angle θ

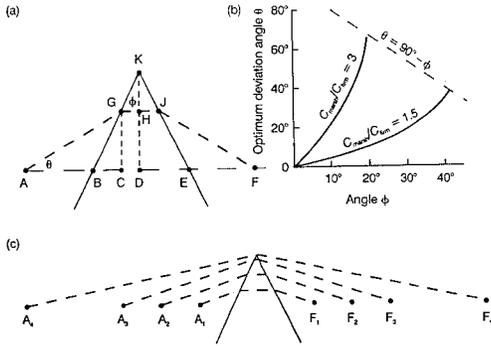


Fig. 5. Diagrams illustrating a discussion of the optimal route across firm ground interrupted by a triangular soft patch. **a:** Plan of the landscape, explained in the text, **b:** Optimum deviation angles θ for different angles ϕ at the apex of the patch of soft ground, when walking on the soft ground requires 1.5 or 3 times as much energy as walking the same distance on the firm ground. Angles beyond the broken line can never be advantageous, **c:** Examples of optimal routes. From Alexander (2000).

shown in Figure 5b. This figure includes graphs for two different ratios of energy costs ($C_{\text{marsh}}/C_{\text{firm}}$). The optimum diversion angle is the angle given by the graph, or the smallest angle required to avoid the soft ground altogether (which is never beyond the broken line), whichever is smaller. Figure 5c shows some optimum paths for a cost ratio of 1.5 and an apical angle of 30° . The walker should be prepared, in this case, to divert by up to 18° , but for the journey from A_4 to F_4 a smaller angular diversion is sufficient to avoid the soft ground altogether. I have no empirical data to test the predictions of this model, but they seem to correspond reasonably well with the manner in which I choose my routes, when walking across level open country.

Measurements of the oxygen consumption of people walking on sloping treadmills show that the energy cost of walking equal distances up a slope and then down a slope of the same gradient is always greater than the cost of walking the same total distance on the flat (data in Margaria, 1975). For example, if the gradient is 0.2 it is 2.5 times the cost of walking on the flat. Alexander (2000) used Margaria's empirical data to calculate the paths of least energy cost across the shoulders of idealised pyramidal hills such as the one shown as a contour map in Figure 6a. In this diagram, the walker is required to travel from **A** to **C**.

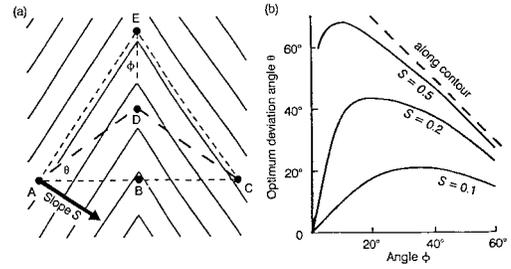


Fig. 6. Diagrams illustrating the discussion of optimal routes across the shoulder of a hill. **a:** Contour map, explained in the text. **b:** Optimum deviation angles θ plotted against the angle ϕ , for hills of three different slopes. From Alexander (2000).

The shortest path, **ABC**, involves a climb followed by a descent. The path parallel to the contours, **AEC**, involves no climbing but is longer. The simple geometry of this landscape ensures that the optimum path will be of the form shown by the line **ADC**, which diverges at an angle θ from the shortest path. Figure 6b shows optimum values of this angle for hills of different slopes and with different values of the angle ϕ at which the contours meet the plane of symmetry of the hill. The steeper the slope, the larger is the optimum angle θ , and the more nearly does the optimum path follow the contours. Again, I have no empirical data to test the predictions of the model. However the routes of old footpaths through mountain country, for example, the Brandy Pad through the Mourne Mountains in Northern Ireland, seem generally to run between the shortest path and the path along the contours, as the model predicts.

Minetti (1995) considered a different problem regarding walking in hilly country. If it is required to climb a slope, is it more economical of energy to walk straight up the slope or to zig-zag? His calculations led to the conclusion that, for gradients of 0.25 or less, the direct route is best. On steeper hillsides the optimum path is a zig-zag, with each straight section of the path rising with a gradient of 0.25. Minetti found that footpaths in the Alps and Himalayas conformed reasonably well to these predictions.

LOAD CARRYING

The last question that I will ask, is whether there is a manner of carrying loads that minimises the energy cost. Maloij et al.

(1986) found that African women carry loads on their heads much more economically than soldiers carry loads in back packs. The women could carry loads up to 20% of body weight, without any increase in metabolic rate; but similar loads increased the metabolic rates of the soldiers by 20%. In further experiments with African women carrying head loads, Jones et al. (1987) found that fat women carried loads less economically than thin ones. More specifically, the weight of body fat had to be set against the 20% of body weight that could be carried without energy cost. Heglund et al. (1995) reminded us that energy is saved in walking by the principle of the pendulum, by transferring energy back and forth between the kinetic and gravitational potential forms. They found that this transfer was more effective when head loads were being carried than in unloaded walking, due to the kinetic and potential energy changes being more fully complementary. However, they did not discover why they are more fully complementary, so we still do not fully understand why head loads can be carried so economically.

Kram (1991) noted that in Asia loads are often carried on the ends of a bamboo pole, balanced on the porter's shoulder. He wondered whether this might save energy, in similar fashion to the African habit of carrying loads on the head. He found that the energy cost of walking carrying loads in this way is proportional to the total weight of body plus load, as also found for soldiers carrying back packs. However, his experimental subjects were American students with no previous experience of carrying loads on poles. It is possible that experienced Asian porters carry their loads more economically. Alternatively, it seems possible that both the soldiers who carried loads in back packs and the students who carried loads on poles had too much body fat to benefit from the unexplained mechanism that enables lean African women to carry loads economically on their heads.

African women carry head loads up to 70% of body weight. In contrast (male) Nepalese porters carry loads averaging 146% of body weight on their backs (Malville, 1999). They stop every 2 or 3 minutes, resting the load on a T-headed walking stick or on pathside platforms. The energy cost of this work does not seem to have been measured, so we do not know whether it is more

economical to carry these enormous loads, or to carry larger numbers of smaller loads. It seems possible that the advantage may lie in saving time, rather than in saving energy.

In conclusion, humans seem to have a strong tendency to walk in ways that minimise metabolic energy costs. We walk at low speeds and run to go faster, using the gait that is the more economical at our chosen speed. At any particular speed we seem to choose our stride length, duty factor, and shape factor to minimise energy costs. We prefer to walk at speeds close to the speed (about 1.4 m/s) at which the energy cost per unit distance is least. Simple models of route selection over soft ground and over hills suggest that we may plan our routes to minimise energy costs. African women seem to save energy by carrying loads on their heads, but the mechanism is not fully understood.

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