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ORIGINAL ARTICLE

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The transmission efficiency of backward walking at different gradients

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Abstract The specialized design of the bipedal system towards forward locomotion has been assessed by measuring the metabolic cost and the mechanical work of both forward and backward walking on a treadmill at seven gradients from 0 to +32%. With respect to forward locomotion, backward walking implies: (1) a higher metabolic cost particularly at level gradient, while at steeper inclines the difference decreases, (2) the same mechanical internal work despite an increased stride frequency, (3) higher mechanical external work within a gradient range from 0 to +15%, (4) lower "energy recovery", i.e. the ability to save mechanical energy by moving as an inverted pendulum, mainly in level walking, and (5) as a consequence of the above results, a decrease of the efficiency of locomotion particularly at the 0% gradient. The transmission efficiency of backward walking, relative to the forward progression, was found to be about 65% in level locomotion, while at higher gradients it increased to and was maintained at a value of about 93%. The poorer economy of level backward walking could also be explained by an impaired elastic contribution in the last part of the double contact phase, while the similarity of the two gaits on higher gradients is caused by disruption of the pendulum-like paradigm due to the trajectory geometry of the body's centre of mass progressively losing its downward portion.

Keywords Backward movement · Biomechanics · Efficiency · Gradient · Locomotion

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Introduction

Automobile designers and engineers mainly consider the forward progression of a vehicle. Little attention is paid to backward motion in engine design, and none at all in the design of bodywork. As a matter of fact, air drag can increase remarkably if moving backward at comparable speeds. The presence of just one reverse gear (which limits the detrimental effect of a higher drag coefficient due to the low backward speed) also indicates the prevalence of a design strategy directed more towards manoeuvrability than independence of the direction of movement. In addition, while there is no physical reason why moving backward would be associated with greater fuel consumption (the pistons cycle in the usual way), the louder noises coming from the gearbox in reverse gear indicate that some waste of mechanical energy occurs (because of the greater number of cranks involved and their far-from "optimal wear" due to the limited use).

Turning to the biological world, evolution does not seem to deal much with retro-locomotion. Apart from notable exceptions, the low speed attainable when moving backwards reflects the lack of evolutionary pressure to obtain this specific ability. The literature so far offers different views, depending on the variables being investigated. Raibert [19] found that the motion pattern of quadrupeds limbs during a gallop is symmetrical with respect to the animal's centre in the sagittal plane. The potential presence of time-symmetrical central pattern generators that could also control backward motion has been supported by the similar activation of many limb muscles in quadrupeds [18]. However, the forward thrust [17] and the mechanical internal work [15] associated with the hind limbs exceed those associated with the fore limbs. Returning to bipeds though, the symmetry between forward and backward walking has been found in kinematic variables but not in electromyographic (EMG) recordings [8].

With such an incomplete view on symmetry in gaits, the study of backward locomotion is worthwhile because it is done by quadrupeds (e.g. to drag loads or carcasses backwards) and bipeds (for example, humans often use backward locomotion in sports). The asymmetry introduced by the erect posture in bipeds raises questions about the mechanical and metabolic advantages of using the locomotory machine to move forward rather than backward. While a couple of studies on the higher metabolic energy cost of backward walking in humans have been published (for a comprehensive list visit the web site www.backward-running-backward.com), nothing has been published so far on the mechanical work, a crucial variable in the assessment of gait efficiency.

Every muscle-driven movement is brought about by multi-stage energy degradation. The various steps can be summarized in two main categories: the energy loss occurring within the muscle and that occurring outside of it. The related efficiency cannot exceed 25–35% for the transformation of metabolic substrates into muscle contraction (eff_M, muscle efficiency), and ranges from 0 to 100% for the transmission of the generated force to the external environment and the production of mechanical work (eff_T, transmission efficiency). In the last step the friction and the geometry associated with the joints and non-muscular biological tissues involved play a major role. The global efficiency (eff_G) of muscle-driven movements is the product of eff_M and eff_T.

Walking backward is an intriguing experimental model because the same musculo-skeletal system is used to perform the task as walking forward, but working in reverse mode. As with cars, whose aerodynamics are mainly designed for forward progression, it is conceivable that the human machinery performs less efficiently during retro-locomotion at a comparable mechanical level with respect to forward locomotion.

The aim of this work is to metabolically and mechanically compare forward (FW) and backward (BW) walking, in order to assess the transmission efficiency change between the two gaits. We present data for measurements from subjects walking on a level surface and at different gradients. This is because it was observed that when walking uphill on mountain paths some relief is given by temporarily walking backward. However, it was difficult to subjectively evaluate whether the overall mechanics of walking on gradients was maintained or whether BW was different from FW.

Materials and methods

Six healthy male and four female subjects [age 34.7±5.1 (M) and 20.5±0.6 (F) years, mass 71.3±4.9 (M) and 54.5±6.1 (F) kg, stature 1.76±0.03 (M) and 1.57±0.05 (F) m], after having given their informed consent to participate in the study, walked forward and backward on a treadmill (Ergo ELG2, Woodway, Germany) at seven gradients (0, +5, +10, +15, +20, +26, +32.8%). At each gradient the speed was set to be the most comfortable and least metabolically expensive for FW (1.08, 0.95, 0.80, 0.73, 0.67, 0.61, 0.51 m/s [8]). Metabolic (net energy cost, n=6) and mechanical measurements (n=10) were both made.

Oxygen uptake was measured by an automatic gas analyser system (Sensor Medics Vmax, USA) during the last minute of 5-min exercise period. Standing metabolism was subtracted from the steady-state value obtained in each trial, and the result was divided by the progression speed in order to evaluate the metabolic cost of walking (C, J per kg of body mass and per metre travelled, by using the equivalence 1 ml O_2=20.1 J).

The 3D position of 12 body segments was digitized (100 Hz) by an ELITE (B.T.S., Milan, Italy) Motion Analyser (four CCD cameras). For each trial 5 s was sampled and the representative stride was extracted after visually checking for the regularity of the spatial coordinates. The derived trajectory of the body's centre of mass enabled us to calculate its potential and kinetic energies as well as the kinetic energy of segments relative to the speed of the body's centre of mass. The positive external mechanical work [W_{ext}, J/(kg·m)], necessary to accelerate and raise the body's centre of mass within the environment, and the internal mechanical work [W_{int}, J/(kg·m)], needed to accelerate the body segments with respect to the body's centre of mass, were computed according to Cavagna and Kaneko [2]. The "percent recovery" is a parameter introduced by Cavagna et al. [3] to estimate the ability of the centre of mass in a multi-link system to save mechanical energy by continuously exchanging potential and kinetic energy. This parameter and the stride frequency, obtained by analysing the periodicity in the 5-s captured data, were also calculated by a custom program (written in LabView, National Instrument, USA, and running on an Apple PowerBook 3400 computer).

Statistical differences between BW and FW progression were assessed for each gradient using the Wilcoxon sign-rank test.

Results

The metabolic cost of BW was significantly greater than that for FW, with the difference decreasing with the gradient (see Fig. 1). Figure 2A shows that BW stride frequency is significantly higher than in FW at all gradients investigated. W_{int} was the same in the two conditions and was independent of the gradient (Fig. 2B). W_{ext}, shown in Fig. 3A, was higher in BW than in FW at gradients between 0% and +10%, with the difference only significant at 0%. The partitioning between the positive and negative total mechanical work (=internal+external, Fig. 3B) is higher than expected in FW at gradients between +5% to +20%, with a significant difference at +10%. The mechanical energy recovery (Fig. 3C) is lower in BW than FW at the 0% gradient (P<0.01). The ratio

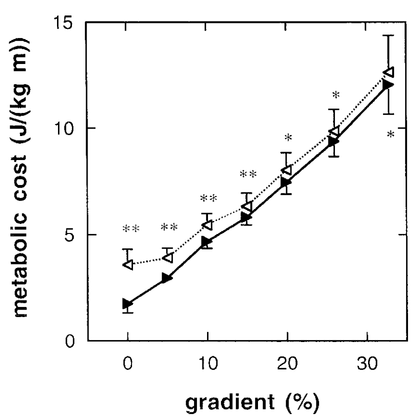

Fig. 1 Bioenergetics. Metabolic cost as a function of the gradient of forward and backward walking (*filled* and *open triangles*, respectively). The *vertical bars* represent SD. The probability of statistical significance was set at 0.05 (*) and 0.01 (**) levels

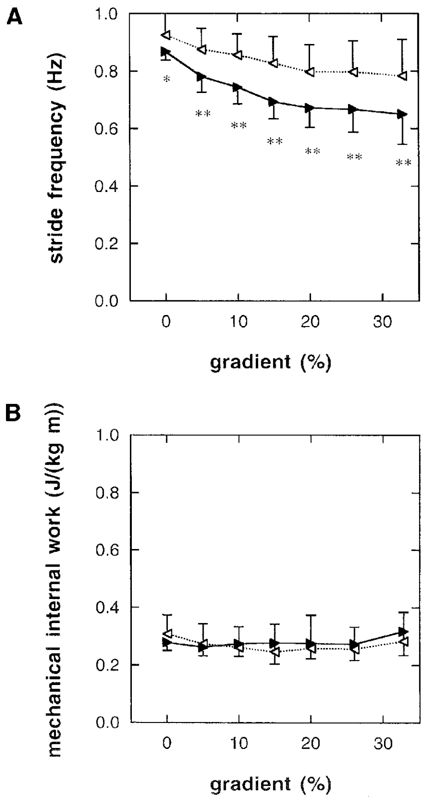

Fig. 2A, B Limbs mechanics. Stride frequency (**A**) and mechanical internal work (**B**) of forward walking (*FW*) and backward walking (*BW*) at different gradients. *Symbols* and statistics as in Fig. 1

between BW and FW for selected parameters is shown in Fig. 4A. It is apparent that many of the differences tend to disappear at gradients steeper than +10%. Also, at 0% gradient, the more than twofold increase in metabolic cost is not matched by a parallel increase in the total or external mechanical work. The positive work efficiency of FW and BW is reported as a function of gradient in Fig. 4B.

Discussion

The first result of this study is that BW has a greater metabolic cost than FW. While this has been previously reported for a 0% gradient [4, 6, 16, 22], extending the investigation to steep gradients reveals that the metabolic disadvantage reduces from about 100% (0% gradient) to about 5–8% when walking at inclines of 15–32% (Fig. 4A).

To the authors' knowledge, no paper has yet comprehensively analysed the mechanical determinants of the increased metabolic demand in BW. To date, only EMG [20], kinematic analysis [5] and motor patterns [8] have been investigated. Kinetics data are reported in abstract form only [13, 21].

Since our results show an increase (range +6.5 to +20.6%) in stride frequency in BW, a concomitant increase of W_{int} would be expected [12]. However, since this did not occur (Fig. 2B) and the overall inertia parameters of the limbs did not change, the only possible explanation is that the duty factor (the proportion of the stride for which the foot contacts the ground) approached 50% in BW [12], thus reducing the double-contact time (a crucial phase for mechanical energy conservation in the system, see below).

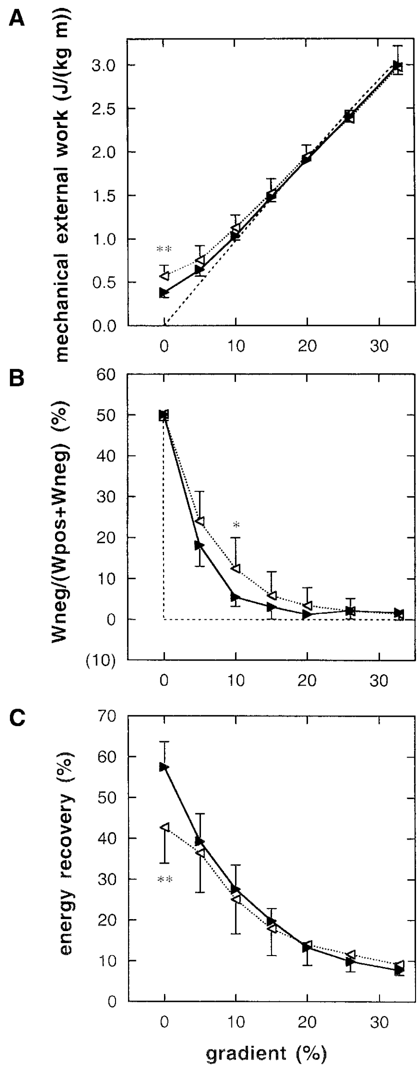

Fig. 3A–C The mechanics of the body's centre of mass. **A** The mechanical external work is shown for FW and BW. The *dashed line* represents the minimum external work that has to be done at each gradient, calculated by the increase of potential energy of the body's centre of mass. **B** The proportion of negative work in the overall external mechanical work (=positive+negative). The *dashed line* illustrates the boundary of this variable: it has to be 50% in level walking and the minimum value on gradients could be 0%. **C** The energy recovery, the percentage of the energy oscillations of the body's centre of mass that is expected to be saved by a pendulum-like mechanism, has its boundaries at 100% (ideal pendulum) and 0% (bouncing ball)

W_{ext}, regarded as a major determinant of the metabolic cost of gradient walking [14], was found to be +48.5% to +9.3% higher in BW at gradients 0–15%. In addition, the

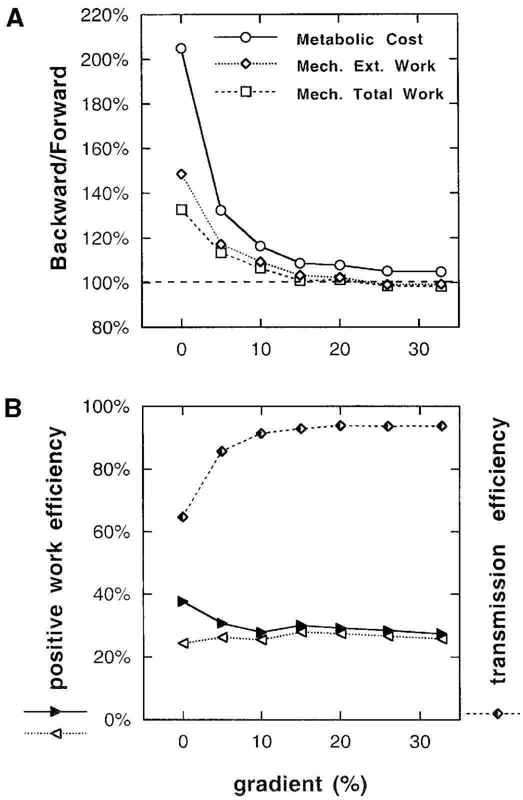

Fig. 4A, B The efficiency of backward walking. **A** The ratio between BW and FW parameters as a function of gradient. **B** The efficiency of the positive work in FW and BW is shown together with the BW/FW ratio, which corresponds to the transmission efficiency of BW (see text)

amount of negative work done was greater for BW than FW. However, this effect is confined to a narrow range of gradients (10–15%) and its metabolic significance is reduced by the high efficiency of the negative work [1].

The percentage of energy recovery decreases for both FW and BW at increasing gradients, highlighting the reduced capacity of the locomotor system to use the pendulum-like mechanism to save energy when walking uphill. This is mainly caused by the tendency of both gaits towards a monotonic trajectory of the centre of mass imposed by the uphill path [14]. Differently, in BW on the level the ability to exchange potential and kinetic energy is remarkably impaired (–25.7%), indicating an alteration of the normal movement pattern [14].

Increasing attention is being paid to the possibility of storing and releasing elastic energy at no metabolic cost in walking [7, 9], a process that mainly occurs during the double-support phase [7]. In this respect, the hypothesized lower duty factor (at increased stride frequency) in BW would limit the time-window during which elastic energy is stored/released. In addition, the observed decreases of energy recovery imply that the oscillations in the total mechanical energy curve increase and, possibly, that less energy is available at the beginning of the double-support phase to enter the elastic storage/release cycle. Also, the limb geometry reversal in BW and particularly the presentation of the foot during the contact phase impair the arch of the foot compression. Another observation that supports this line of reasoning is that, despite the generalized increase in EMG activity in lower limb muscles, the gastrocnemius muscle was activated less in BW than in FW (thus the tension developed in the Achilles tendon was also less) and mainly at the very end of the contact phase rather than in the second half of it [8, 20]. These last two effects could undermine the fundamental requisites for elastic storage and release during walking.

The global mechanical efficiency of BW (eff_G), as plotted in Fig. 4, is lower than in FW mainly at 0% incline and is almost independent of the gradient. With the exception of level walking, BW efficiency is always lower than FW efficiency by about –2.4% (26.6±1.0% versus 29.0±1.3%). When walking uphill, this difference is mostly accounted for by the higher denominator of the efficiency equation, namely the increased BW metabolic cost probably because of co-contractions. However, the noticeably lower efficiency when walking on the flat seems to be because the pendulum-like mechanism works less well when walking backwards, and it is more difficult to smooth the transition between successive steps by allowing some elastic energy storage and release.

In order to estimate the relative transmission efficiency associated with BW at different gradients we can assume from

$$eff\,\frac{\mathrm{FW}}{\mathrm{G}} = eff\,\frac{\mathrm{FW}}{\mathrm{M}} \cdot eff\,\frac{\mathrm{FW}}{\mathrm{T}}$$

and

$$eff\,\frac{\mathrm{BW}}{\mathrm{G}} = eff\,\frac{\mathrm{BW}}{\mathrm{M}} \cdot eff\,\frac{\mathrm{BW}}{\mathrm{T}}$$

that $eff^{\mathrm{FW}}{}_{\mathrm{M}}=eff^{\mathrm{BW}}{}_{\mathrm{M}}$, i.e. that muscular efficiency is the same in the two gaits. Thus, rearranging the previous equations, we obtain

$$\frac{eff\,\frac{\mathrm{BW}}{\mathrm{T}}}{eff\,\frac{\mathrm{FW}}{\mathrm{T}}} = \frac{eff\,\frac{\mathrm{BW}}{\mathrm{G}}}{eff\,\frac{\mathrm{FW}}{\mathrm{G}}}$$

whose values are also plotted in Fig. 4B. The relative transmission efficiency of BW is about 65% at 0% gradient and increases to about 93% for a gradient range 10–32%.

Thus, the main message is that when monotonic mechanical energy time courses are involved, as in walking up a hill, our legged machine does not suffer from its specialized, asymmetrical design when walking backward. In contrast, if the musculo-skeletal system is performing on a level surface, the bipedally evolved pendulum-like mechanism is partially impaired when walking backward. This, together with increased co-contractions, contributes to the lower efficiency of backward walking. In addition, it is likely that the elastic structures devoted to providing some energy relief during normal walking, namely the arch of the foot and the Achilles tendon, do not work fully when walking backward.

Walking backward has been used here as an intriguing model to investigate how the transmission efficiency, a concept also called “effectiveness” [10], helps to evaluate the costs, in terms of versatility, associated with a bipedal limb architecture and muscle control evolved for forward locomotion. The results show the determinants of this effect, particularly when walking on the level.

A limitation of the present study is that we only investigated one walking speed at each gradient, and in particular a comfortable and optimal [11] speed for FW. This was done to evaluate the effects of reverting the motion pattern at the speeds chosen by the subjects to walk forward. Preliminary measurements on one subject at the same gradient (0%) and different speeds (range 2–6 km/h) showed that BW is always metabolically more expensive than FW (average +141%), while the situation for higher gradients could not be deduced directly. Future studies should investigate the effects of changing speed on the energetics and mechanics of BW, both on the flat and at two or three gradients.

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