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Pendular energy transduction within the step in human walking

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Summary

During walking, the centre of mass of the body moves like that of a 'square wheel': with each step cycle, some of its kinetic energy, E_k, is converted into gravitational potential energy, E_p, and then back into kinetic energy. To move the centre of mass, the locomotory muscles must supply only the power required to overcome the losses occurring during this energy transduction. African women carry loads of up to 20% of their body weight on the head without increasing their energy expenditure. This occurs as a result of an unexplained, more effective energy transduction between E_k and E_p than that of Europeans. In this study we measured the value of the E_k to E_p transduction at each instant in time during the step in African women and European subjects during level walking at 3.5–5.5 km h^{-1}, both unloaded and carrying loads spanning 20–30% of their body weight. A simulation of the changes in E_k and E_p during the step by sinusoidal curves was used for comparison. It was found that loading improves the transduction of E_p to E_k during the descent of the centre of mass. The improvement is not significant in European subjects, whereas it is highly significant in African women.

Key words: locomotion, walking, recovery, energy expenditure, human.

Introduction

During each step of walking, the gravitational potential energy E_p and the kinetic energy E_k of the centre of mass of the body oscillate between a maximum and a minimum value. *A priori*, active movements of an organism are assumed to be powered by muscles: positive muscle work to increase potential energy and kinetic energy, and negative muscle work to absorb potential energy and kinetic energy. Both positive and negative muscular work require the expenditure of chemical energy. During walking, both the positive and the negative work actually done by the muscles to sustain the mechanical energy changes of the centre of mass (positive and negative external work) are reduced by the pendular transduction of potential energy to kinetic energy and *vice versa* (Cavagna et al., 1963).

The fraction of mechanical energy recovered due to this transduction, R_{step} , has been defined as:

$$R_{step} = (W^+_v + W^+_f - W^+_{ext})/(W^+_v + W^+_f) = 1 - W^+_{ext}/(W^+_v + W^+_f)\,, \quad (1)$$

where W^+_v represents the positive work calculated from the sum, over one step, of the positive increments undergone by the gravitational potential energy, $E_p=Mgh$ (where M is the mass of the body and h is the height of the centre of mass), W^+_f is the positive work calculated from the sum, over one step, of the positive increments undergone by the kinetic energy of forward motion E_{kf}. $E_{kf}=0.5MV_f^2$ (where V_f is the instantaneous forward velocity of the centre of mass), and W^+_{ext} is the positive external work calculated from the sum over one step of the positive increments undergone by the total mechanical energy of the centre of mass, $E_{cg}=E_p+E_{kf}+E_{kv}$ (Cavagna et al., 1976). The kinetic energy of vertical motion, $E_{kv}=0.5MV_v^2$ (where V_v is the instantaneous vertical velocity of the centre of mass), has not been taken into account when obtaining R_{step} from W^+_v and W^+_f. E_{kv} has no effect on W^+_v because the vertical velocity is zero at the top/bottom endpoints of the E_p curve. As will be shown below, using W^+_k, measured from the total kinetic energy curve $E_k=E_{kv}+E_{kf}$, instead of W^+_f, measured from the E_{kf} curve, has a negligible effect on R_{step} (see Fig. 8).

R_{step}, as defined in Equation 1, represents the fraction of the maximum positive energy increments possibly undergone by the centre of mass (measured assuming no energy transduction) that is recovered by the pendular mechanism over the whole step cycle: it does not give information about the time course of this transduction within the step. Factors that are expected to affect R_{step} are: (i) the relative amplitude of the potential and kinetic energy curves, (ii) their shape and (iii) their relative phase. In a frictionless pendulum, energy recovery, R, equals unity because the changes in potential energy mirror the changes in kinetic energy. During walking, R_{step} attains a maximum at an intermediate speed when the difference in amplitude of the potential and kinetic energy curves approaches zero and the phase difference between the potential and kinetic energy curves approaches 180° (Cavagna et al., 1976, 1983; Griffin and Kram, 2000).

More information about the pendular mechanism of walking may be obtained by analyzing how the pendular transduction of the mechanical energy occurs during the step cycle. The factors affecting the pendular transduction of mechanical energy within the step are not known. The aim of this study is to define these factors by following the transduction between potential and kinetic energy at each instant of time during the step.

We applied this new approach to the great skill of African women carrying loads (Maloiy et al., 1986): African women carry loads more economically than Europeans as a result of their greater R_{step} (Heglund et al., 1995); however, it is not known how this greater R_{step} is attained. The within-step analysis of the potential kinetic energy transduction demonstrates the phases of the step in which the difference between African women and European subjects is most apparent.

Materials and methods

Subjects and experimental procedure

In this study, we analyzed the changes in E_k, E_p and E_k+E_p of the centre of mass of the body during one step of level walking at a constant speed with and without a load being carried by the subject (loaded and unloaded walking steps). Data were obtained for 11 Europeans (five male and six female, 65.6±7.1 kg, mean ± S.D.) and four African women (three Luo and one Kikuyu, 73.9±14.4 kg, mean ± S.D.) previously described by Heglund et al. (1995). The steps analyzed were recorded during walking at 3.5–5.5 km h^{-1}, both for unloaded subjects and for subjects carrying loads spanning 20–30% of their body weight. The speed range corresponds to freely chosen walking speeds. The load range was chosen because it results in the maximum difference between R_{step} measured in the European subjects and R_{step} measured in the African subjects (see fig. 2 in Heglund et al., 1995). Data collected within these speed and load ranges were averaged (see Table 1) neglecting any effect of the speed and load change, because the scatter of the data was too large to define a trend within such a narrow speed and load range. Loads were head-supported by the African women and shoulder-supported by the Europeans. The Kikuyu woman carried the loads on her back supported solely by a strap over their head. Two of the Luo women carried the loads on top of her head, and the other Luo woman carried the loads both ways. A step was considered to be suitable for analysis when the sum of the increments of E_p and E_k over the step cycle did not differ by more than 10% from the sum of the decrements due to variability between successive steps of the subject. All the usable steps (N=32) of the African women during walking with loads were analyzed. An equal number of steps was randomly chosen for analysis from a larger pool of data for African women during unloaded walking and for European subjects during both unloaded and loaded walking. The five European males walked both loaded (18 steps analyzed) and unloaded (15 steps analyzed) whereas, of the six European females, four walked loaded and unloaded, one walked unloaded only and one walked loaded only, giving a total of 14 loaded steps and 17 unloaded steps analyzed.

The subjects walked across a force platform sensitive to the vertical and horizontal (fore–aft) components of the force exerted by the feet on the ground. The lateral component of the force was neglected (Cavagna et al., 1963). The force platform had a natural frequency greater than 180 Hz in both directions and was mounted at ground level in the middle of a walkway. The dimensions of the platform were 1.8 m×0.4 m in the case of the African women and 6.0 m×0.4 m in the case of the Europeans. The mean walking speed was measured by means of photocells placed 1.2 m apart (Africans) and 1.9–3.6 m apart (Europeans) alongside the platform.

The platform signals were collected by a microcomputer for analysis using a sampling rate of 500 Hz for the African subjects and 100 Hz for the European subjects. The changes in E_k, E_p and E_k+E_p of the centre of mass of the body were determined from the platform signals using the procedure described in detail by Cavagna (1975). In short, integration of the horizontal force and of the vertical force minus the body weight, both divided by the body mass, yielded the velocity changes of the centre of mass. The instantaneous velocity in the forward direction was obtained using the mean walking speed, measured from the photocell signal, to determine the integration constant. A first integration was made in the vertical direction on the assumption that the initial and final velocities of the step cycle were equal.

Contrary to our previous studies, in which the kinetic energy of forward and vertical motion were calculated separately, the kinetic energy of both forward and vertical motion, E_k, was calculated from the velocity of the centre of mass in the sagittal plane. W_k is the work necessary to sustain the kinetic energy changes (positive when E_k increases, negative when E_k decreases).

A second integration of the vertical velocity yields the vertical displacement of the centre of mass. This integration assumes that the net vertical displacement over the whole step cycle was zero. The oscillations of the gravitational potential energy E_p were calculated from the vertical displacement. W_v is the work necessary to sustain the gravitational potential energy changes (positive when E_p increases, negative when E_p decreases). The total energy of the centre of mass, E_{cg}, due to its motion in the sagittal plane, is the algebraic sum at each instant of E_p and E_k. W_{ext} is the sum of the changes in E_{cg} during one step (the sum of the positive increments corresponds to the external positive work done by the muscular force, the sum of the negative increments corresponds to the external negative work done by the muscular force).

During walking, the negative work done by external friction is small and was neglected: a maximum error of 10% due to this assumption was measured in sprint running (Cavagna et al., 1971). During level walking at a constant speed, the net changes in mechanical energy of the centre of mass of the body are zero over the whole step cycle. It follows that the external positive work done by the muscular force equals the external negative work (neglecting the negative work done by friction outside the muscles), i.e. during each step, the muscles and elastic structures deliver and absorb an equal amount of mechanical energy and the net work (positive + negative) is zero. As mentioned above, chemical energy is expended to perform positive work and also, to a lesser extent, to perform negative work. To reduce energy expenditure, the mechanical energy changes of the centre of mass (both positive and negative) should be reduced to a minimum.

Within-step analysis of the potential–kinetic energy transduction

The mechanisms resulting in the measured value of R_{step} (Equation 1) were analyzed in this study by measuring the fraction of mechanical energy recovered due to the transduction between E_p and E_k at each instant in time during the step. The step period, τ, was divided into equal time intervals (2 ms for the Africans and 10 ms for the Europeans), and the recovery, $r(t)$, was calculated from the absolute value of the changes, both positive and negative increments, in E_p, E_k and E_{cg} during each time interval:

$$r(t) = 1 - |\Delta E_{cg}(t)|/[|\Delta E_p(t)| + |\Delta E_k(t)|] = 1 - |W_{ext}(t)|/[|W_v(t)| + |W_k(t)|]\,, \quad (2)$$

where t is time. The signal-to-noise ratio in $r(t)$ decreased when the changes in energy during a particular time interval approached zero (see Fig. 7).

Simulation of the energy transduction within the step

To examine the trend of $r(t)$ within the step (Equation 2), the changes in E_p and E_k taking place during a walking step were simulated by two sinusoidal curves. This simulation is not meant to represent a model of the complex walking mechanics but offers a useful background within which to interpret the experimental recording of $r(t)$ and to distinguish different phases within the step. In addition, it allows us to define the relationship between the mean pendular energy transduction derived from the present analysis and R_{step}, previously used in the literature (see below).

Since, during walking, E_p and E_k of the centre of mass change roughly out of phase, we assumed in the simulation that E_p=–sin$x$ and E_k=sin(x–α), where the phase shift α=0° when the E_p and E_k curves are exactly 180° out of phase. In previous studies (Cavagna et al., 1983; Griffin et al., 1999), this phase shift was defined as $\alpha=360°\Delta t/\tau$, where Δt is the difference between the time at which E_{kf} is at a maximum and the time at which E_p was at a minimum and τ is the step period. At low and intermediate walking speeds, such as those considered in the present study, $\alpha>0°$; at high walking speeds (>6 km h^{-1}), $\alpha<0°$ (Cavagna et al., 1983). For most walking speeds, $45°>\alpha>-45°$.

The total mechanical energy of the centre of mass E_{cg} was calculated as the algebraic sum of the curves for E_p and E_k:

$$E_{cg} = -\sin x + \sin(x - \alpha)\,. \quad (3)$$

The effect of a change in the phase shift α is shown in Fig. 1. E_{cg} attains a maximum or a minimum when its derivative is zero, i.e. when cos$x$=cos(x–α). In contrast, cos$x$=cos(2π–x)=cos(–x), so the angle for a maximum of E_{cg} will be (π+α/2) and the angle for a minimum of E_{cg} will be α/2 (Fig. 1). Substituting these angles into Equation 3, one obtains the maximum and minimum values of the total mechanical energy in the simulation, i.e. $E_{cg,max}$=2sin(α/2) and $E_{cg,min}$=–2sin(α/2). The changes in R_{step} in the simulation with the phase shift α (Fig. 2, dotted line) can then be defined as:

$$R_{step} = 1 - W^{+}_{ext}/(W^{+}_{v} + W^{+}_{f}) = 1 - [2|2\sin(\alpha/2)|/(2 + 2)] = 1 - |\sin(\alpha/2)|\,. \quad (4)$$

The recovery of mechanical energy at each instant during one cycle, $r(x)$, was calculated in the simulation according to Equation 2 by substituting $|\Delta E_p(t)|$, $|\Delta E_k(t)|$ and $|\Delta E_{cg}(t)|$ with the absolute value of the derivative of the functions: –sin$x$, sin(x–α) and –sin$x$+sin(x–α), for x=0–360° in increments of 1° (Fig. 1, upper panels, thick lines):

$$r(x) = 1 - [|-\cos x + \cos(x - \alpha)|]/[|-\cos x| + |\cos(x - \alpha)|]\,. \quad (5)$$

The calculated value of $r(x)$ for sinusoidal curves was equal to that measured on the same sinusoidal curves with the procedure used to determine $r(t)$ on the experimental tracings.

If the two sinusoidal curves, representing E_p and E_k, are exactly out of phase (α=0°) and have the same amplitude, E_{cg} is constant, $W^{+}_{ext}(x)$ is zero and $r(x)$=1 over the whole cycle. If the two sinusoidal curves are exactly out of phase (α=0°) but have different amplitudes, $E_{cg}(x)$ oscillates in phase with the curve of larger amplitude, $W_{ext}(x)\neq0$, and $r(x)$ decreases below unity, maintaining a constant value over the cycle. For example, if the amplitude of E_p is half that of E_k, $r(x)$=1–(1/3)=0.66 (Equation 2).

If the two energy curves have the same amplitude, but are not exactly out of phase ($\alpha\neq0°$), $r(x)$ changes as described in Fig. 1 for α =10° and 20°. In each cycle, there are two periods when $r(x)$=0: the changes in potential energy and in kinetic energy have the same sign and, as a consequence, $|\Delta E_{cg}(x)|=|\Delta E_p(x)|+|\Delta E_k(x)|$ (see Equation 2). During one of these periods, henceforth called t_{pk+}, lasting from the minimum of E_p to the maximum of E_k, positive external work is done to increase E_p and E_k simultaneously. During the other, t_{pk-}, lasting from the maximum of E_p to the minimum of E_k, negative external work is done to absorb E_p and E_k simultaneously. The phase shift between E_p and E_k was calculated both as $\alpha=360°t_{pk+}/\tau$ and as $\beta=360°t_{pk-}/\tau$ (Table 1).

The two periods when $r(x)$ is zero are separated by two time intervals when $r(x)$ increases to unity and then decreases to zero following a bell-shaped curve: one period after t_{pk+} during most of the lift phase (increment of the E_p curve in Fig. 1), the other after t_{pk-} during most of the lowering phase (decrement of the E_p curve in Fig. 1). According to equation 2, $r(x)$=1 is

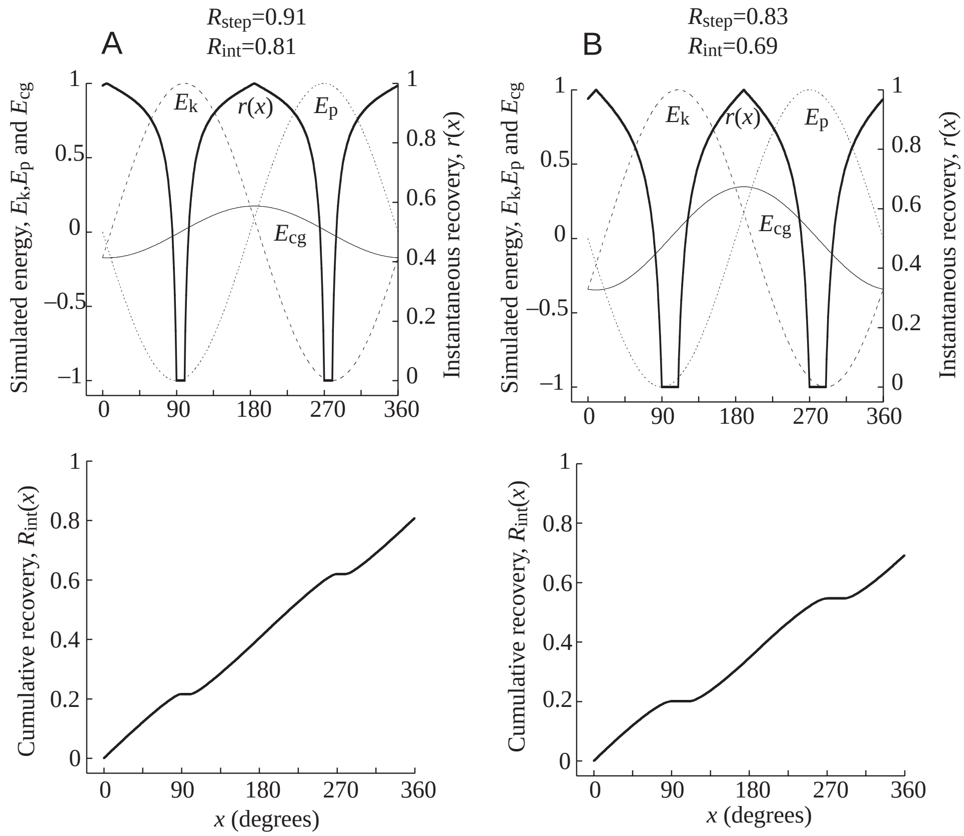

Fig. 1. Simulation of the transduction between kinetic and potential energy of the centre of mass when the maximum in kinetic energy is set to lag behind the minimum in potential energy by a value of α=10° (A) and α=20° (B), which covers the range of mean experimental values measured in this study during walking (see values of α in Table 1). α is the phase shift between the maximum of the kinetic energy E_k and the minimum of the potential energy E_p. Upper panels: the total energy of the centre of mass of the body (E_{cg}, thin continuous line) is simulated as the sum of two sine waves representing its potential energy (E_p=–sin$x$; dotted lines) and kinetic energy [E_k=sin(x–10°) in A, and E_k=sin(x–20°) in B: broken lines) during a step cycle, expressed in degrees. The fraction of the mechanical energy recovered at each instant by the pendular transduction within the cycle, $r(x)$ (thick lines and right-hand ordinates), is calculated according to Equation 5 from the relative changes in the E_k, E_p and E_{cg} curves. $r(x)$ is zero when the changes in the E_k and E_p curves have the same sign, and attains unity when the E_{cg} curve is at a maximum or at a minimum. Lower panels: the area under the $r(x)$ curve divided by 360°, defined as $R_{int}(x)=[\int_0^x r(u)du]/360°$, attains the value $R_{int}(360°)=R_{int}$ at the end of each cycle. Time-averaged R_{int} is less than R_{step}, calculated according to Equation 1 from the total amplitude reached by the E_p, E_k and E_{cg} curves during the cycle. The relationship between R_{int} and R_{step} for different values of α is shown in Fig. 2.

attained when $\Delta E_{cg}(x)$ is zero (i.e. E_{cg} attains a maximum or a minimum and E_p=E_k).

The mean value of r over the whole step cycle was calculated, both for the simulation, $r(x)$, and for the experimental tracings, $r(t)$, as the time integral divided by the period: $R_{int}=[\int_0^z r(u)du]/z$ where z=360° for the simulation and z=τ for the experimental tracings. In the case of two sinusoidal curves of different amplitude and exactly out of phase (α=0°), R_{int}=R_{step} (R_{step} is defined as in Equation 1). In the case of two sinusoidal curves of the same amplitude but with a phase shift α between the time at which E_k is at a maximum and the time at which E_p is at a minimum, the relationship between R_{int} and α (Fig. 2, continuous line) is given by:

$$R_{int} = 1 - (1/\pi)\{|\alpha| - 2tg(|\alpha|/2)\log_e[\sin(|\alpha|/2)]\}\,, \qquad (6)$$

where α is expressed in rad. Equation 6 is obtained by integrating $r(x)$, as defined in Equation 5, and dividing the result by 2π. In the simulation, R_{int} is not equal to R_{step} except when the curves are exactly out of phase (α=0°) or exactly in phase (α=180°), or when α=±96.3° (Fig. 2). When the phase

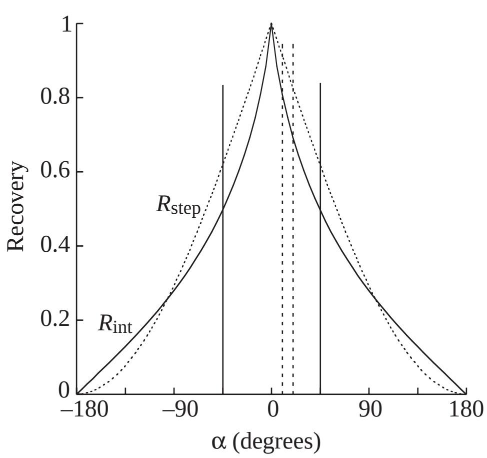

Fig. 2. Simulation: effect of the phase shift α. The fraction of the mechanical energy recovered through the pendular transduction in the simulation, calculated as R_{step} (dotted line, Equation 4) or as R_{int} (solid line, Equation 6) is plotted as a function of the phase shift α between the curves E_p=–sin$x$ and E_k=sin(x–α) illustrated in Fig. 1. The two vertical continuous lines encompass the values of α attained during all speeds of walking; α decreases from approximately 45° at the lowest speeds to approximately –45° at highest speeds (Cavagna et al., 1983). The two vertical broken lines encompass the values of α (10°–20°) observed in this study (Table 1). Note that R_{step}≥R_{int} over the entire range of α measured during walking.

Table 1. *Experimental values of the parameters of the walking step*

	t_{pk+} (ms)	$t_{tr,up}$ (ms)	t_{pk-} (ms)	$t_{tr,down}$ (ms)	τ (ms)	α (degrees)	β (degrees)	R_{step}	R_{int}
European									
Unloaded	18.1±14	265±23.6	18.8±20.4	255±20.9	557±46.3	11.5±8.8	11.9±12.1	0.67±0.04	0.61±0.04
Loaded	15.6±13.2	259±20.6	10.9±10.3	258±17.4	544±29	10.3±8.4	7.2±6.7	0.65±0.04	0.61±0.04
P	0.465	0.313	0.058	0.439	0.212	0.584	0.057	0.058	0.731
African									
Unloaded	32.3±15.6	246±26	21.9±25.7	240±32.1	540±52.9	21.5±9.3	14.4±15.2	0.66±0.06	0.62±0.06
Loaded	21.4±10.6	246±19	7.9±8.6	248±23.5	524±33.4	14.7±7.2	5.5±5.8	0.71±0.05	0.67±0.05
P	0.002	0.913	0.005	0.252	0.148	0.002	0.003	0	0

t_{pk+}, period when E_k and E_p increase simultaneously; $t_{tr,up}$, period of E_k-E_p transduction during the lift of the centre of mass; t_{pk-}, period when E_k and E_p decrease simultaneously; $t_{tr,down}$, period of E_k–E_p transduction during the descent of the centre of mass; τ, step period; α, phase shift between the maximum of E_k and the minimum of E_p; β, phase shift between the minimum of E_k and the maximum of E_p; R_{step}, recovery of mechanical energy calculated from the sum of the positive increments over the whole step of E_k, E_p and E_{cg}; R_{int}, recovery of mechanical energy calculated from the increments of kinetic energy E_k, gravitational potential energy E_p and total mechanical energy at the centre of mass E_{cg}, at each instant during the step.

Values are means ± S.D. (N=32).

Comparisons between groups were made using a single-factor analysis of variance (ANOVA) (Excel v8.0).

shift varies in the simulation as in human walking (45°>α>–45°), $R_{int} \leq R_{step}$ and both decrease with |α|.

Average recordings

To compare the energy transduction within the step in different subjects, the step cycle was divided into four periods: the two periods with $r(t)$=0 (t_{pk+} and t_{pk-}) and the two with $r(t)\neq0$ (Fig. 1). The mean values for the four periods are given in Table 1 for each experimental condition. The abscissa of each of the two phases with $r(t)\neq0$ was normalized from zero to one, and an average of $r(t)$ was calculated at discrete intervals along the normalized abscissa (0.01). The mean step cycle was then reconstructed using on the abscissa, the mean values of the four time intervals (Table 1, Figs 4, 6).

In some recordings, t_{pk+} and/or t_{pk-} were zero, and the separation between the two periods with $r(t)\neq0$ was made using the minimum of $r(t)$ or, when oscillations where present (see Fig. 7), the maximum and/or the minimum of E_p and E_k. Often $r(t)$ failed to attain unity in spite of the fact that E_{cg} attained a maximum or a minimum (i.e. $|\Delta E_{cg}(t)|$=0) because of the discrete time periods used to calculate $|\Delta E_{cg}(t)|$ and/or the averaging of the curves (see Figs 3–7).

Results

Time course of energy recovery within the step of unloaded subjects

Typical recordings showing $r(t)$ during an unloaded step together with the simultaneous changes in E_p, E_k and E_{cg} are given in Fig. 3A for a European subject and in Fig. 3B for an African subject. Similar to the trend shown by the simulation (Fig. 1), $r(t)$=0 during two periods. The first period, t_{pk+}, occurs at the beginning of the lift of the centre of mass, when both E_p and E_k increase simultaneously as a result of positive work done by the muscular force. The second period, t_{pk-}, occurs just after the maximum of E_p, when both E_p and E_k decrease simultaneously as a result of negative work done by the muscular force. The succession of events, both in the simulation and during the walking step, is therefore: (i) t_{pk+} to begin the upward displacement and complete the acceleration forwards; (ii) some transduction from E_k to E_p taking place up to the end of the lift of the centre of mass, during a period henceforth referred to as $t_{tr,up}$; (iii) t_{pk-} to begin the downward displacement of the centre of mass and complete the deceleration forwards; (iv) some transduction from E_p to E_k taking place up to the end of the descent, during a period henceforth referred to as $t_{tr,down}$. Both t_{pk+} and t_{pk-} start at the extremes of the vertical oscillation of the centre of mass of the body.

A comparison of Figs 1 and 3 shows that, in contrast to the simulation, the changes in $r(t)$ during $t_{tr,up}$ and $t_{tr,down}$ are not symmetrical. During $t_{tr,up}$, when the body rides upwards on the front leg and the point of application of force moves forward from heel towards the toe of the supporting foot (Elftman, 1939), $r(t)$ increases steeply to a plateau and then falls abruptly to zero. Three peaks are usually observed on the plateau corresponding to a more or less pronounced oscillation of E_{cg}. During $t_{tr,down}$, when the body ‘falls forwards’, $r(t)$ changes in a manner more similar to the simulation, reaching a single peak and forming a bell-shaped curve.

In the simulation, E_{cg} attains one maximum (during the lift) and one minimum (during the fall). During the walking step, in contrast, E_{cg} usually attains two peaks: the first at the beginning of the lift, the second at the end of the lift. The first peak of E_{cg} occurs near the maximum of E_k, which coincides with the end of t_{pk+}; the second peak of E_{cg} occurs near the maximum of E_p, which coincides with the beginning of t_{pk-}. The positive increment in E_{cg} to the first peak (increment *a*) corresponds to external positive work done by the muscular force mainly to increase the kinetic energy of the centre of

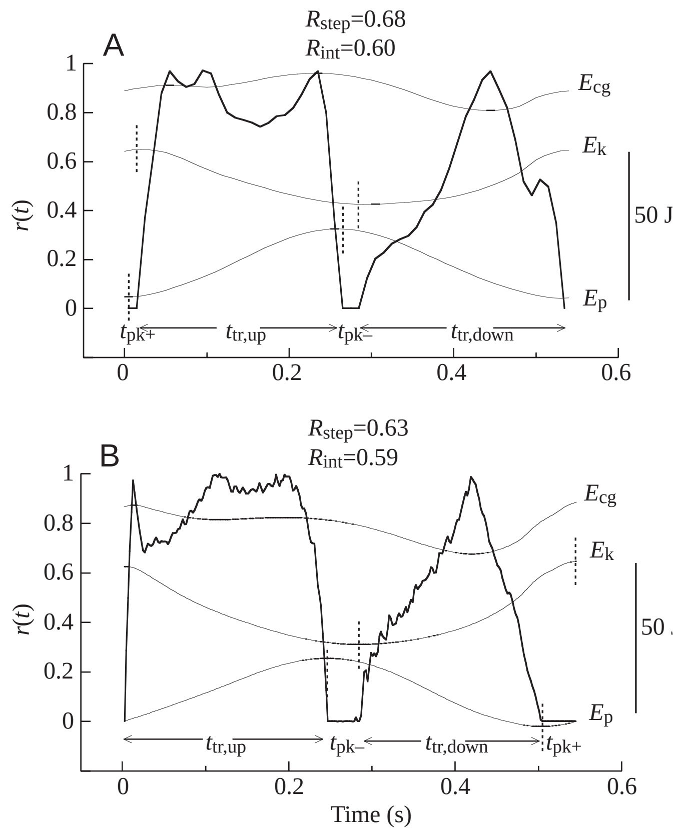

Fig. 3. Typical experimental recordings of unloaded walking. The fraction of the mechanical energy recovered during unloaded walking at each instant of the step cycle [$r(t)$, thick lines] is superimposed on the mechanical energy changes of the centre of mass (E_p, gravitational potential energy; E_k, kinetic energy; and $E_{cg}=E_p+E_k$, where E_{cg} is the total mechanical energy of the centre of mass, thin lines). Typical record obtained from (A) a European subject (male, 66.2 kg, 4.86 km h^{-1}) and (B) an African woman (Kikuyu, 83.3 kg, 4.85 km h^{-1}). The vertical broken lines on the E_k and E_p curves delimit the periods when the instantaneous recovery of mechanical energy $r(t)$ is zero, indicated on the figure as t_{pk+} when E_p and E_k increase simultaneously, and as t_{pk-} when E_p and E_k decrease simultaneously. The periods during which energy transduction between E_p and E_k occurs are indicated as $t_{tr,up}$ during the lift of the centre of mass and $t_{tr,down}$ during the descent of the centre of mass. As in the simulation, R_{step} is greater than R_{int} but, in contrast to the simulation, the $r(t)$ curves recorded during the rise and fall of the centre of mass during walking are not symmetrical see (Fig. 1).

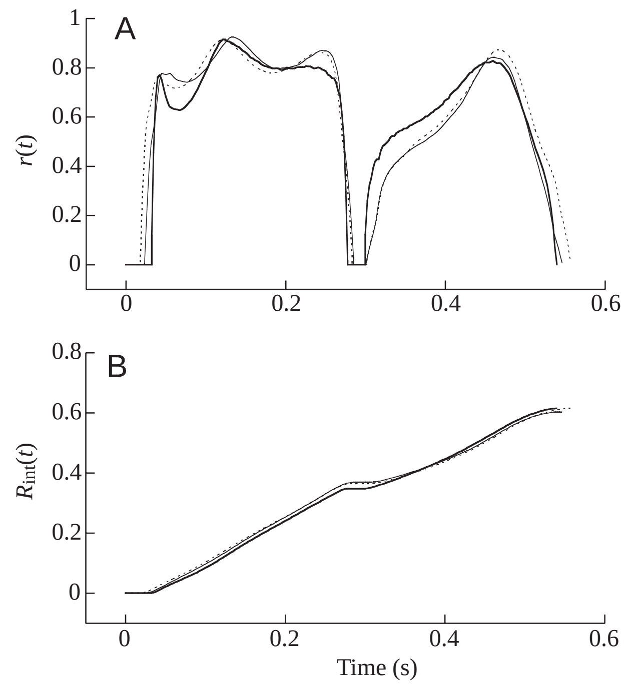

Fig. 4. Unloaded walking. (A) Average curves of the instantaneous recovery of mechanical energy $r(t)$ for the African women (thick continuous line, mean of 32 steps by four subjects), the European women (thin continuous line, mean of 17 steps by five subjects) and all European subjects (males and females, broken line, average of 32 steps on ten subjects). The time-average of the standard deviation of the mean was less than 25% of $r(t)$ during the lift of the centre of mass ($t_{tr,up}$ in Fig. 3) and less than 35% during its descent ($t_{tr,down}$). (B) The area under the average $r(t)$ curve divided by the step period $\{R_{int}(t)=[\int_0^{\tau} r(u)du]/\tau\}$ attains a value of $R_{int}(\tau)=R_{int}$ at the end of the step which is equal for all groups of subjects. The corresponding mean values of the parameters for all European subjects and for the African women are given in Table 1 (unloaded).

mass beyond the level attained as a result of the decrement in potential energy. The end of increment a occurs during the time of double contact, t_{dc}. The positive increment in E_{cg} to the second peak (increment b) corresponds to positive work done to complete the lift of the centre of mass to a level greater than that attained as a result of the decrement in kinetic energy. Increment b occurs during the time of single contact, t_{sc}. The sum of these two positive increments of E_{cg} (a+b) represents the positive external work done at each step to translate the centre of mass of the body in the sagittal plane (Cavagna et al., 1963; Cavagna and Margaria, 1966).

Average $r(t)$ recordings, constructed as described in Materials and methods, are given in Fig. 4A for unloaded European subjects (broken line), for unloaded European women (thin continuous line) and for unloaded African women (thick line). The area below the average $r(t)$ recordings, divided by the mean step period, is given by the curves in Fig. 4B (to be compared with the bottom graphs of Fig. 1). These curves show that: (i) the relative amount of energy recovered during $t_{tr,up}$ is on average larger than that recovered during $t_{tr,down}$ in both European and African subjects; (ii) this asymmetry is smaller in African women than in the European subjects as a result of less complete pendular transduction during $t_{tr,up}$ and more complete transduction during $t_{tr,down}$, which is a consequence of the more pronounced ‘shoulder’ on the $r(t)$ recording at the beginning of the descent of the centre of mass; (iii) the recovery at the end of the step period, R_{int}, is equal in African women and in European subjects; and (iv) no appreciable difference was found between all European subjects (male and female) and the European women.

The mean values of R_{int} and R_{step} (Equation 1) are given in Table 1. It can be seen that $R_{int}<R_{step}$ as predicted by the simulation, both in the Europeans and in the African women. However, both R_{int} and R_{step} measured during the walking step are smaller than those predicted by the simulation (Fig. 2).

Effect of loading

Typical recordings showing $r(t)$ within a step of walking with a load, together with the simultaneous changes in E_p, E_k and E_{cg}, are given in Fig. 5A for a European subject and in Fig. 5B for an African subject. The average $r(t)$ recordings in Fig. 6 compare the load-carrying skills of African women and European subjects.

In all subjects, loading tends to decrease the duration of t_{pk-} and, to a lesser extent, the duration of t_{pk+}: the reductions are, however, not significant in Europeans subjects whereas they are significant in African women, for whom t_{pk-} decreases by approximately two-thirds (Table 1). Since the step period τ is not significantly decreased by loading (by only 2–3%, see Table 1), the phase shifts $\alpha=360°t_{pk+}/\tau$ and $\beta=360°t_{pk-}/\tau$ change in a manner similar to t_{pk+} and t_{pk-}. Loading therefore tends to increase the transduction between potential and kinetic energy by making the two curves more exactly out of phase, particularly during the swing phase (single-contact phase) of the step. As mentioned above, the effect is significant in African women and not in European subjects.

Another effect of loading results from a change in the shape of the potential and kinetic energy curves. This is shown by a more pronounced ‘shoulder’ of the $r(t)$ record during the first part of the descent of the centre of mass. This effect is also more pronounced in the African women than in the European subjects (Fig. 6).

Both these effects of loading tend to increase the fraction of the total mechanical energy changes of the centre of mass that is recovered by the pendular mechanism in the African women. This results in an increase in R_{int} by the end of the step cycle compared with the European subjects (Fig. 6). The increase in R_{int} in the African women during load-carrying is approximately equal to the increase in R_{step} (Table 1). It should be stressed that the effect of load-carrying occurs mainly during the swing phase of the step, when (more

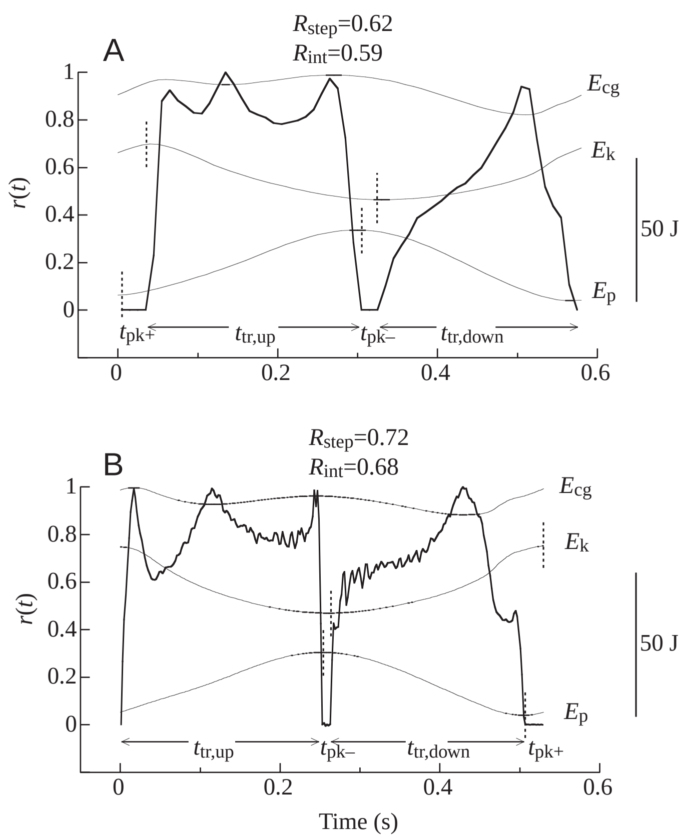

Fig. 5. Typical experimental recordings of loaded walking for (A) a European subject (male, 65.6 kg, 3.71 km h^{-1}, loaded with 19.3 kg) and (B) an African woman (Luo, 83.5 kg, 3.95 km h^{-1}, loaded with 19.5 kg). For further details, see legend to Fig. 3. Note that in the African subject, loading results in a reduction in t_{pk-} and in an increase in $r(t)$ at the beginning of the descent of the centre of mass ($t_{tr,down}$).

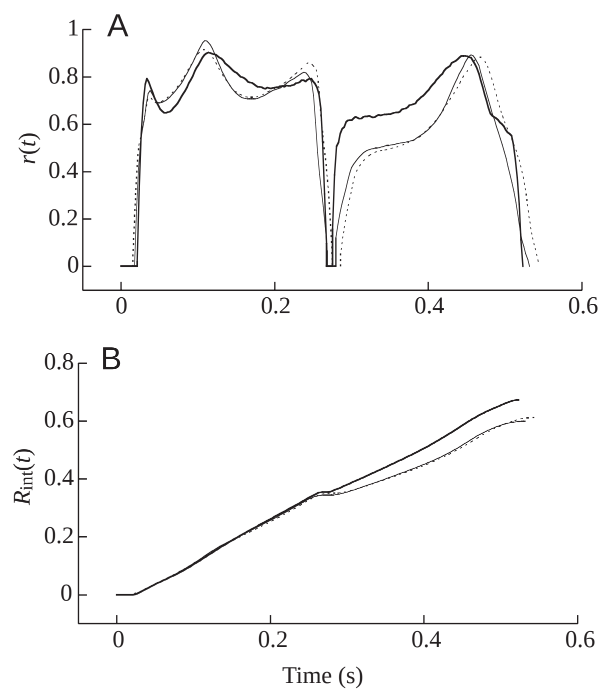

Fig. 6. Loaded walking. (A) Average curves of the instantaneous recovery of mechanical energy $r(t)$ for the African women (thick continuous line, mean of 32 steps by four subjects), the European women (thin continuous line, mean of 14 steps by five subjects) and all European subjects (males and females, dotted line, mean of 32 steps by ten subjects). A comparison with Fig. 4 shows that, in all subjects, loading decreases t_{pk-} and increases $r(t)$ at the beginning of the descent of the centre of mass ($t_{tr,down}$), but that this results in a net increase in R_{int} in the African women only (final value attained by the thick line at the end of the step in B). The corresponding mean values of the parameters for all European subjects and the African women are given in Table 1 (loaded). For further details, see legend to Fig. 4.

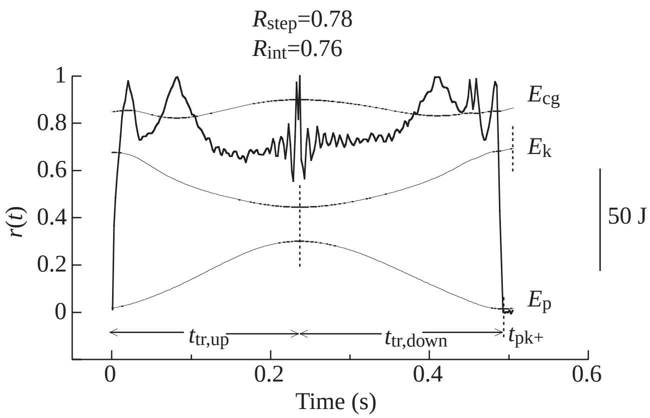

Fig. 7. Recordings such as those depicted in Fig. 5, showing an extreme case in which loading results in t_{pk-} being reduced to zero and in an increase in the instantaneous recovery of mechanical energy $r(t)$ during the descent of the centre of mass to a level equal to that attained during the lift. This leads to very high values of pendular recovery during the step (African woman, Luo, 88.9 kg, 4.5 km h^{-1}, loaded with 19.1 kg). For further details, see legend to Fig. 5.

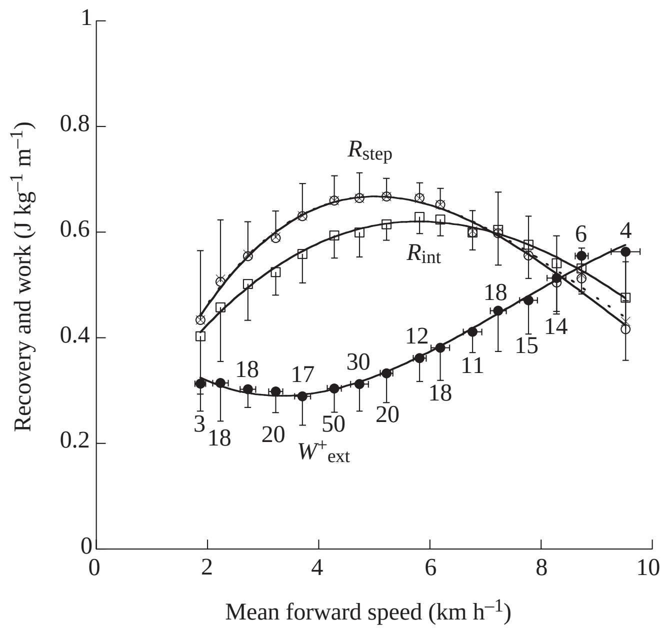

Fig. 8. The pendular recovery of mechanical energy, defined by equation 1 (R_{step}, open circles) and by equation 6 (R_{int}, open squares), and the external work done per unit distance (W^+_{ext}, filled circles) plotted as a function of speed during unloaded walking for the 11 European subjects of this study. Values are means ± S.D. (N is given by the numbers near the filled circles) for data grouped into the following intervals along the abscissa: <2, 2 to <2.5,…., 8.5 to <9, >9 km h^{-1}. Lines are fitted using a third-order polynomial fit (r^2=0.98, KaleidaGraph 3.5). The crosses and the dotted line show how R_{step} changes when the kinetic energy of vertical motion of the centre of mass, E_{kv}, is taken into account in the calculation of W^+_v and W^+_k (see text). Note that W_{ext} attains a minimum at a speed lower than the speed at which the pendular recovery attains a maximum.

frequently in African women) loading sometimes results in a t_{pk-} value of zero with a continuous high levels of transduction between potential and kinetic energy of the centre of mass (Fig. 7).

Discussion

Normal walking

The present study provides (i) a new parameter, R_{int}, which summarizes the transduction between E_p and E_k over the whole step cycle and (ii) the possibility of a continuous analysis of such transduction during a walking step.

The time-average R_{int} is related but not equal to R_{step}, previously determined from the total changes in E_p, E_{kf} and E_{cg} (see equation 1 in Cavagna et al., 1976). As shown by the simulation, R_{int} and R_{step} are affected in different ways by a phase shift between sinusoidal curves representing E_p and E_k (Fig. 2). By contrast, the experiments analyzed in the present study suggest that R_{int} and R_{step} change in a similar manner when a load is applied to the trunk during walking (Table 1).

R_{int}, R_{step} and W^+_{ext} were calculated for the 11 European subjects of the present study during unloaded walking at different speeds (Fig. 8). On average, R_{int} is less than R_{step} up to approximately 7 km h^{-1}, after which the trend is reversed, probably as a result of a relative change in the amplitude and shape of the E_p and E_k curves with the speed of walking. Both R_{int} and R_{step} attain a maximum at intermediate speeds: approximately 5 km h^{-1} for R_{step} and 6 km h^{-1} for R_{int}, whereas W^+_{ext} attains a minimum at approximately 4 km h^{-1}. This result confirms that maximal pendular transduction takes place at a speed higher than the most economical speed of walking, as has become progressively more evident as more data are collected (Willems et al., 1995). The speed difference between the minimum of W^+_{ext} and the maximum of R_{step} is due to the fact that, when the speed increases above 4 km h^{-1}, the increase in W^+_{ext} from its minimum is smaller than the continuous increase in W^+_v+W^+_f; as a consequence, the ratio W^+_{ext}/(W^+_v+W^+_f) decreases and R_{step} increases (Equation 1). The same argument is probably valid for R_{int} which, however, does not have a simple relationship with R_{step}, not only for the reasons explained by the simulation (Fig. 2), but also because of the changes in amplitude and shape of the E_p and E_k curves with speed. In general, both R_{step} and R_{int} represent an index of the ability of the pendular mechanism to minimize the impact of W^+_v+W^+_f on W^+_{ext}. The result is that the minimum of W^+_{ext} is attained at a lower speed, when and because W^+_v+W^+_f is smaller, in spite of the fact that the pendular mechanism works better at a higher speed, when W^+_v+W^+_f is larger.

Our within-step analysis of pendular energy transduction shows that muscular intervention may be divided into two components: (i) when the transduction between E_p and E_k is zero (i.e. during t_{pk+}, to increase both E_p and E_k and during

t_{pk-}, to decrease both E_p and E_k), and (ii) during the transduction between E_p and E_k, when the muscles both release and absorb energy (during $t_{tr,up}$ and $t_{tr,down}$). The first component is due to a shift between the E_p and E_k curves away from being exactly out of phase (180°), whereas the second component is due to a difference in the amplitude and shape of the two curves. It is now possible to assess how energy recovery through pendular transduction is affected by the phase shift between the E_p and E_k curves and how it is affected by the difference in shape/amplitude of the two curves. An example is discussed below for loaded compared with unloaded walking.

An obvious reason for failure to recover energy using the pendular mechanism is a phase shift of other than 180° between the potential and kinetic energy curves. Why is the value of 180° not maintained? Although a net input of energy during t_{pk+} to increase both E_p and E_k is to be expected, to overcome the energy lost by friction in the pendular motion, the necessity of a net absorption of both E_p and E_k during t_{pk-} is less clear. t_{pk+} occurs mostly during the period of double contact and corresponds to the forward and upward push of the back foot as it is about to leave the ground (Cavagna and Margaria, 1966). Mochon and McMahon (1980) showed that the action of muscles during the double-support phase establishes the initial conditions for the succeeding mainly ballistic phase of the step, which takes place during the single contact. t_{pk-} on the other hand occurs during the single-contact phase and corresponds to an unexplained waste of energy due to the fact that the maximum of E_p is attained before the minimum of E_k.

During the periods when energy transduction does occur between E_p and E_k, the failure of $r(t)$ to attain a value of unity implies that negative and positive work is done by the muscular force to absorb or deliver energy because the E_p and E_k curves are not mirror images. During normal, unloaded walking, this failure is smaller during $t_{tr,up}$, corresponding to the lift of the centre of mass, than during $t_{tr,down}$, corresponding to the descent of the centre of mass. This is unexpected because, as mentioned above, the lift is initiated by the double-support phase of the step, whereas the descent is initiated with the whole body pole-vaulting over the supporting leg in the ballistic single-contact phase of the step, i.e. when the inverted pendulum model should apply. The ‘square’ shape of $r(t)$ rising abruptly to a plateau during $t_{tr,up}$, results in an increase of approximately 60% in the total fractional energy recovered (R_{int}). The less effective ‘triangular’ shape of $r(t)$ during $t_{tr,down}$ is due to a slower rise to unity, during which the gravitational potential energy actively absorbed by the muscles and elastic structures is greater than the simultaneous increase in kinetic energy. The contrary is true for the shorter period after the peak of $r(t)$: energy must now be added to increase E_k beyond the level attained due to the decrease in E_p (Fig. 3).

Walking with loads

One effect of loading is to improve the pendular transduction between potential and kinetic energy of the centre of mass by making the changes in E_p and E_k more exactly out of phase. This is shown by the reduction in both t_{pk+} and t_{pk-}, which is significant in the African women only (Table 1). The reduction is relatively larger for t_{pk-} than t_{pk+}, suggesting that the period during which both E_p and E_k decrease as a result of negative work being done by the muscular force is more easily reduced than the period during which energy is added to the system. In fact, under some conditions, t_{pk-}, but not t_{pk+}, can disappear (Fig. 7).

Of the two periods when an energy transduction occurs between E_p and E_k, loading affects mainly $t_{tr,down}$, when the body ‘falls forwards’ on the supporting leg (Figs 5, 6). Loading favors the transduction of E_p to E_k, so that a smaller amount of E_p has to be absorbed by the muscles (compare the negative slopes of the E_{cg} curves during $t_{tr,down}$ in Figs 3 and 5). This is shown by a faster increase in $r(t)$ at the beginning of the descent of the centre of mass, which is particularly evident in the African women (Fig. 6). In the extreme case illustrated in Fig. 7, loading results both in the disappearance of t_{pk-} (discussed above), and in a transduction between E_p and E_k during the descent of the centre of mass similar to that attained during the lift, resulting in a plateau at a high value of $r(t)$. It is quite possible that the differences described between European subjects and African women in the present study may derive in part from the location of the mass support: head-supported in the African women and shoulder-supported in the European subjects.

Concluding remarks

The present study throws more light on pendular energy transduction during walking because it offers the possibility of investigating this energy transduction at different phases of the gait cycle. One of the first outcomes of this new analysis is a demonstration of the asymmetry between the upward and downward phases of the pendular oscillation of the centre of mass. The new index R_{int}, designed to quantify pendular energy transduction, confirms and extends the information given by the previously used index, R_{step}. An application of this new approach is the analysis of the effect of loading on the mechanics of walking: the phases of the step mainly affected by loading can now be determined, even though the mechanism of the observed changes is still unknown. Loading improves the pendular transduction between E_p and E_k, particularly during the single-contact ballistic phase of the step. The improved pendular transduction is achieved because the E_p and E_k curves become more exactly out of phase because of a change in their relative shape, particularly at the beginning of the descent of the centre of mass. Even if this mechanism occurs at least to some extent in the European subjects, it is exploited fully by the African women, with the result that the increase in the fraction of energy recovered by pendular transduction over the whole step cycle in response to loading is significant in the African women only.

List of symbols

E_{cg} total mechanical energy of the centre of mass: $E_{cg}=E_k+E_p$
E_k kinetic energy of the centre of mass: $E_k= E_{kf}+E_{kv}$
E_{kf} kinetic energy of forward motion of the centre of mass: $E_{kf}=0.5MV_f^2$
E_{kv} kinetic energy of vertical motion of the centre of mass: $E_{kv}=0.5MV_v^2$
E_p gravitational potential energy of the centre of mass
$\boldsymbol{g}$ acceleration due to gravity
M body mass
$r(t)$ instantaneous recovery of mechanical energy calculated from the absolute value of the increments, both positive and negative, of E_p, E_k and E_{cg} during the step (Equation 2)
$r(x)$ instantaneous recovery of mechanical energy calculated from the absolute value of the derivative of the functions simulating E_p, E_k and E_{cg} during a cycle (Equation 5)
R recovery
R_{int} mean value over one period of $r(x)$ (simulation) or $r(t)$ (experimental data); for the simulation: $R_{int}(x)=[\int_0^x r(u)du]/360°$ and $R_{int}(360°)=R_{int}$; for the experimental data: $R_{int}(t)=[\int_0^\tau r(u)du]/\tau$ and $R_{int}(\tau)=R_{int}$
R_{step} recovery of mechanical energy calculated from the sum over one step of the positive increments of E_p, E_k and E_{cg} (Equation 1)
t time
t_{dc} fraction of the step period τ during which both feet are in contact with the ground (double contact)
t_{pk+} difference between the time at which E_k is maximum and the time at which E_p is minimum. E_k and E_p increase simultaneously during t_{pk+}
t_{pk-} difference between the time at which E_k is minimum and the time at which E_p is maximum. E_k and E_p decrease simultaneously during t_{pk-}
t_{sc} fraction of the period τ during which one foot only contacts the ground (single contact)
$t_{tr,down}$ time of E_k–E_p transduction during the descent of the centre of mass
$t_{tr,up}$ time of E_k–E_p transduction during the lift of the centre of mass
V_f instantaneous velocity of forward motion of the centre of mass
V_v instantaneous velocity of vertical motion of the centre of mass
W_{ext} external work done during each step calculated from the changes in mechanical energy of the centre of mass, $E_{cg}=E_p+E_{kf}+E_{kv}$. W^+_{ext} is the sum of the positive increments of E_{cg} during τ
W_f work calculated from the forward speed changes of the centre of mass during each step. W^+_f is the sum of the positive increments of E_{kf} during τ
W_k work calculated from the kinetic energy changes of the centre of mass during each step. W^+_k is the sum of the positive increments of E_k during τ
W_v work calculated from the potential energy changes of the centre of mass during each step. W^+_v is the sum of the positive increments of E_p during τ
α phase shift between the maximum of E_k and the minimum of E_p; $\alpha=360°t_{pk+}/\tau$, where t_{pk+} is the difference between the time at which E_k is a maximum and the time at which E_p is a minimum
β phase shift between the minimum of E_k and the maximum of E_p; $\beta=360°t_{pk-}/\tau$, where t_{pk-} is the difference between the time at which E_k is a minimum and the time at which E_p is a maximum
τ step period, i.e. period of repeating change in the motion of the centre of mass: $\tau=t_{sc}+t_{dc}$

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