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THE MECHANICS OF WALKING IN CHILDREN

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SUMMARY

1. The work done at each step, during level walking at a constant average speed, to lift the centre of mass of the body, to accelerate it forward, and to increase the sum of both gravitational potential and kinetic energies, has been measured at various speeds on children of 2–12 years of age, with the same technique used previously for adults (Cavagna, 1975; Cavagna, Thys & Zamboni, 1976).

2. The pendulum-like transfer between potential and kinetic energies (Cavagna *et al.* 1976) reaches a maximum at the speed at which the weight-specific work to move the centre of mass a given distance is at a minimum ('optimal' speed). This speed is about 2·8 km/hr at 2 years of age and increases progressively with age up to 5 km/hr at 12 years of age and in adults. The speed freely chosen during steady walking at the different ages is similar to this 'optimal' speed.

3. At the 'optimal' speed, the time of single contact (time of swing) is in good agreement with that predicted, for the same stature, by a ballistic walking model assuming a minimum of muscular work (Mochon & McMahon, 1980).

4. Above the 'optimal' speed, the recovery of mechanical energy through the potential–kinetic energy transfer decreases. This decrease is greater the younger the subject. A reduction of this recovery implies a greater amount of work to be supplied by muscles: at 4·5 km/hr the weight-specific muscular power necessary to move the centre of mass is 2·3 times greater in a 2-year-old child than in an adult.

INTRODUCTION

The energy expenditure during locomotion is usually expressed per unit of body mass because the muscles spend energy mainly to increase the gravitational potential energy and the kinetic energy of the mass of the body or of its parts. This approach, however, does not take into account the effect on locomotion of the linear dimensions of the body. How does the reduced body size affect the mechanics of the locomotion of children compared to that of adults? The net energy expenditure per unit of body mass in walking and running at a given speed, was found to be greater in children than in adults (Piacentini & Bollettino, 1942; Åstrand, 1952; Silverman & Anderson, 1972). This could be due to: (i) a greater mechanical work done per unit mass, and/or

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(ii) a smaller efficiency of muscular contraction. A greater mechanical work could in turn be a consequence of: (a) inappropriate movements, and/or (b) the reduced dimensions of the body directly affecting the mechanics of locomotion. In this study, we have measured the potential and kinetic energy changes of the centre of mass of the body of children of different age, during walking at different speeds, in order to assess if the greater energy expenditure is accompanied by a greater amount of work done to move the body as a whole. In addition, the same measurements were used to investigate how the mechanics of walking, already described in adults (Cavagna *et al.* 1976), is modified in children.

METHODS

List of Symbols

M	Body mass.
l	Leg length, i.e. the approximate distance between the hip joint and the ground while wearing gym shoes.
a_f	Forward acceleration of the centre of mass.
a_v	Vertical acceleration of the centre of mass.
F_f	Forward component of the resultant force exerted by the feet against the ground.
F_v	Vertical component of the resultant force exerted by the feet against the ground.
V_f	Instantaneous speed of forward motion of the centre of mass.
V_v	Instantaneous speed of vertical motion of the centre of mass.
$\overline{V_f}$	Average speed of locomotion: $\overline{V_f} = L/\tau$.
o	Suffix indicates that the variables ($\overline{V_f}$, L, τ, t_{sc}, t_{dc}) is the average, within one age group, of the data obtained in an interval of speeds defined by the mean $\pm 0{\cdot}5$ km/hr of the two speeds of walking at which R is maximum and $W_{ext}/(ML)$ is minimum. For further explanation see below.
g	Acceleration of gravity.
P	Body weight: $P = Mg$.
S_v	Sum of the upward displacements of the centre of mass taking place during the period of a step: $S_v = W_v/(Mg)$.
$E_{k,f}$	Kinetic energy of forward motion of the centre of mass: $E_{k,f} = \frac{1}{2}(MV_f^2)$.
$E_{k,v}$	Kinetic energy of vertical motion of the centre of mass: $E_{k,v} = \frac{1}{2}(MV_v^2)$.
E_p	Gravitational potential energy of the centre of mass.
E_{tot}	Total mechanical energy of the centre of mass: $E_{tot} = E_{k,f} + E_p + E_{k,v}$.
W_f	Positive work done at each step to increase the forward speed of the centre of mass: W_f is the sum of the increments of $E_{k,f}$ during τ.
W_v	Positive work done at each step to lift the centre of mass: W_v is the sum of the increments of E_p during τ.
W_{ext}	Positive work done at each step to increase the mechanical energy of the centre of mass: W_{ext} is the sum of the increments of E_{tot} during τ; this is called 'external work'.
$\dot{W}$	Average mechanical power output during the step: $\dot{W} = W/\tau$. This power is smaller (about half) than the average power developed during performance of positive work. In fact not only positive work, but also negative work is done during τ.
$W/(ML)$	Positive work done per unit distance and per unit of body mass: $W/(ML) = \dot{W}/(M\overline{V_f}) = W\tau/(\tau ML)$.
R	Transfer of mechanical energy with the pendulum-like mechanism characteristic of walking: $R = ((W_f + W_v - W_{ext})/(W_f + W_v))\ 100$.
α	Phase shift between mechanical energy of forward motion and mechanical energy of vertical motion: $\alpha = 360\,°.\ \Delta t/\tau$, where Δt is the difference between the time at which $E_{k,f}$ is maximum and the time at which E_p is minimum.
τ	Step period, i.e. period of repeating change in forward and vertical velocity of the centre of mass: $\tau = t_{sc} + t_{dc}$.
t_{sc}	Fraction of the period τ during which one foot only contacts the ground (single contact).

t_{dc} Fraction of the period τ during which both feet contact the ground (double contact).
L Length of the step: $L = \overline{V}_f \tau$; $L = L_{sc} + L_{dc}$.
L_{sc} Forward displacement of the centre of mass taking place at each step of walking when one foot only is in contact with the ground: $L_{sc} = \overline{V}_f t_{sc}$. Since V_f is on the average smaller than $\overline{V}_f$ during t_{sc}, L_{sc}, as defined, is about 3% greater than real when $\overline{V}_f = \overline{V}_{f,o}$ (maximum 5% at the lowest speeds).
L_{dc} Forward displacement of the centre of mass taking place at each step of walking when both feet contact the ground: $L_{dc} = \overline{V}_f t_{dc}$. Since V_f is on the average greater than $\overline{V}_f$ during t_{dc}, L_{dc}, as defined, is about 5% smaller than real when $\overline{V}_f = \overline{V}_{f,o}$ (maximum 8·5% at the lowest speeds).

Measurements

Experiments were made with forty-two children, whose characteristics are averaged in Table 1, in six groups of different age; the total number of children in this Table is forty-three because one child was studied just after he was seven and again when he was twelve. Experiments were also made with seven normal male adults and the data obtained on them were averaged with those obtained on ten subjects of a previous study (Cavagna *et al.* 1976); once again, one of the subjects included in the recent study also participated in the previous experiments. All the subjects wore gym shoes. An average of sixteen tests was made for each subject and one to four steps were studied during each test.

TABLE 1. Average characteristics of the subjects

Age groups (yr)	No. of subjects Total (♀)	Age (years) Mean ± S.D.	Weight (kg) Mean ± S.D.	Height (m) Mean ± S.D.	Leg length (m) Mean ± S.D.
1–2	2 (1)	2·2 ± 0·4	13·3 ± 2·5	0·89 ± 0·07	0·42 ± 0·04
3–4	11 (5)	3·9 ± 0·5	17·8 ± 2·1	1·03 ± 0·06	0·49 ± 0·04
5–6	6 (2)	5·8 ± 0·6	21·9 ± 3·8	1·13 ± 0·06	0·57 ± 0·04
7–8	10 (4)	7·7 ± 0·5	27·1 ± 5·6	1·26 ± 0·08	0·63 ± 0·06
9–10	8 (3)	10·0 ± 0·6	36·3 ± 6·3	1·43 ± 0·08	0·77 ± 0·05
11–12	6 (2)	11·9 ± 0·5	41·1 ± 3·0	1·51 ± 0·07	0·82 ± 0·03
Adults	17 (0)	29·8 ± 7·2	72·6 ± 10·6	1·76 ± 0·07	0·89 ± 0·06

The subjects walked at different speeds over a strain-gauge platform (4 m long and 0·5 m wide) which was sensitive to the forward and the vertical components of the force applied to it by feet during walking; the characteristics of the platform are described by Cavagna (1975).

Disregarding the forces of friction (as shown by Cavagna, Komarek & Mazzoleni, 1971, the error involved is tolerable even in sprint running), the forward component of the force applied to the platform is:

$$F_f = Ma_f, \tag{1}$$

where M is the mass of the body and a_f the forward acceleration of the centre of mass. The vertical force is:

$$F_v = P + Ma_v, \tag{2}$$

where P is the body weight and a_v is the vertical acceleration of the centre of mass. It is possible to calculate the vertical and forward accelerations of the centre of mass, and subsequently the velocity, displacement and mechanical energy of the centre of mass, directly from the measurements of the vertical and forward forces exerted on the platform. The system used for these calculations has been described in detail elsewhere (Cavagna, 1975) and it is only briefly described here. Before each walk the subject stood quietly on the platform. The electrical output of the vertical platform (i.e. the signal corresponding to the body weight) was then set to zero by means of an offset voltage. In this way the vertical output from the platform is proportional to the vertical acceleration of the centre of mass:

$$F_v - P = Ma_v, \tag{3}$$

obtained by rearranging eqn. (2). After this procedure the subject was invited to walk at a constant speed across the platform starting a few metres away. As the subject walked across the platform,

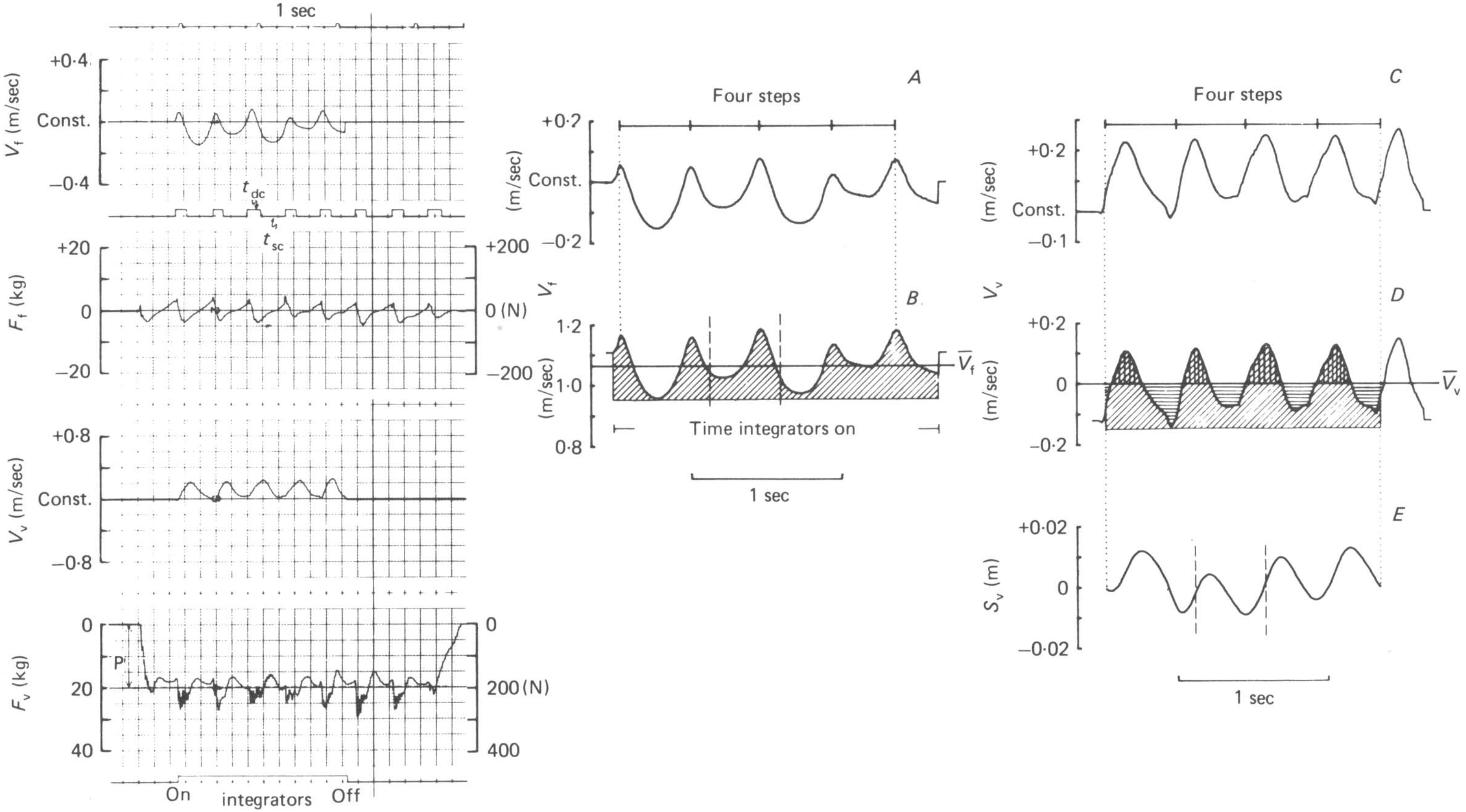

Fig. 1. Left: tracings recorded when a subject was walking at 3·8 km/hr over the force platform. F_f and F_v are, respectively, the forward and vertical components of the resultant force impressed by the feet on the platform; whereas F_f oscillates around the zero (positive values = acceleration forward of subject, i.e. backward push on platform), F_v oscillates around a force value (20 kg) equal to the subject's body weight, P. Simultaneously the forward force and the vertical force minus the body weight ($F_v - P$) are integrated electronically to determine the velocity tracings V_f and V_v; these give the forward and vertical components of the velocity of the centre of mass of the body plus an integration constant to be determined as indicated, on the right, in B and D. The time of swing, t_{sc}, and of double contact, t_{dc}, are recorded below the V_f tracing. Right: the procedure followed to determine the absolute value of the velocity in the forward (A and B) and the vertical (C and D) directions from the velocity + constant tracings. The forward velocity tracing is integrated during the time the integrators are on and the area (oblique hatching) is divided by the same time in order to locate the average velocity forward ($\overline{V}_f$) on the tracing. The vertical velocity tracing, given in D, is integrated during the interval of four complete steps (delimited by the vertical dotted lines) and the area (oblique hatching) is divided by this interval to locate the average vertical velocity ($\overline{V}_v$) which is zero. The instantaneous vertical velocity is integrated further to yield the vertical displacement upwards (vertical hatching) and downwards (horizontal hatching) of the centre of mass (S_v in E). The vertical interrupted lines indicate the step reproduced in the middle of Fig. 2. For a full explanation of symbols see Methods.

the forward and the vertical minus body weight signals from the platform were integrated analogically in order to obtain the changes in the forward (V_f) and vertical (V_v) velocity of the centre of mass:

$$\int F_f \, dt = MV_f + \text{constant}; \quad (4)$$

$$\int (F_v - P) \, dt = MV_v + \text{constant}. \quad (4a)$$

These forces and velocity changes were recorded on a strip chart recorder (Fig. 1). The integration constants must be known in order to calculate the absolute velocity. The value of the integration constants in eqn. (4) and (4*a*) is zero when the subject begins to move on the platform from the resting condition ($V = 0$). However, when the subject arrives on the platform with a velocity above zero, the values of the constants in eqn. (4) and (4*a*) are unknown and the absolute velocity cannot be measured simultaneously with the performance of excerise. The absolute forward velocity is obtained by (1) measuring the average forward velocity of the subject moving across the platform by means of two photocells: these also turn on and off the integrators while the subject is over the platform without contacting the ground before or after it (Fig. 1*A*); (2) measuring the area under the recorded velocity tracing during the time interval while the integrators are on (oblique hatching in Fig. 1*B*) and (3) dividing the area by the time required to travel the distance between the photocells to position the average velocity forward in the tracing (Fig. 1*B*). Instantaneous forward velocity can then be calculated. In this procedure it is assumed that the average speed of the trunk between photocells is equal to the average speed of the centre of mass; this is reasonable since the displacements of the centre of mass within the body and the tilting of the trunk are small in comparison with the distance between the sights.

A similar procedure is followed to determine the absolute value of the vertical component of the velocity (Fig. 1*C* and *D*); in this case however the area, *A*, below the vertical velocity tracing is measured only for an interval of time, $n\tau$, corresponding to an integral number of steps (oblique hatching in Fig. 1*D*). The ratio $A/n\tau$ gives an average vertical velocity equal to zero, on the assumption that during an integral number of cycles, the upward displacement of the centre of gravity is equal to the downward displacement (i.e. that in level walking the height of the centre of gravity on the average is constant). This assumption may not be true at the end of a single step, but it is certainly valid over a number of steps. Once the zero vertical velocity is determined, then the instantaneous vertical velocity is known.

From the instantaneous velocity in the forward and vertical directions the instantaneous kinetic energy $E_{k,f} = \frac{1}{2}(MV_f^2)$ and $E_{k,v} = \frac{1}{2}(MV_v^2)$ can be calculated; the increments of kinetic energy represent the positive work required to accelerate the centre of mass of the body.

The instantaneous potential energy $E_p = PS_v$ can be obtained by integrating the vertical velocity to determine the vertical displacement of the centre of mass (Fig. 1*E*)

$$\int V_v \, dt = S_v + \text{constant}. \quad (5)$$

Geometrically the upward displacement is represented by the upper area enclosed by the instantaneous vertical velocity tracing and the zero (vertical hatching in Fig. 1*D*). The positive work against gravity is given by the increments of the potential energy. The total mechanical energy is then obtained by adding the instantaneous potential energy and the instantaneous kinetic energies of forward and vertical motion:

$$E_{tot} = E_p + E_{k,v} + E_{k,f}. \quad (6)$$

Finally, the positive external mechanical work is obtained by adding the increments in total mechanical energy over an integral number of steps.

The upward curve of the central set of tracings in Fig. 2 indicates how the kinetic energy of forward motion of the centre of mass of the body of a 20 kg subject oscillates during one step of walking at 3·8 km/hr. This kinetic energy curve was calculated from the portion of the forward velocity curve delimited by the two vertical interrupted lines in Fig. 1*B*. The dotted curve below indicates the oscillation of the potential energy of the body and was calculated from the vertical displacement curve given in Fig. 1*E*. The continuous curve just above it is the sum of the potential energy and the kinetic energy of vertical motion (calculated from curve in Fig. 1*D*). At the top and bottom points, the two curves coincide since at these points the vertical velocity and then the kinetic energy of vertical motion are nil. The two curves below indicate the total mechanical energy (continuous curve) and, for comparison, the sum of the potential energy and the kinetic energy of forward motion (dotted curve); the total mechanical energy may differ from this sum not only for the slope of the curve, giving the rate of work production, but also for the amplitude of the oscillation of the curve which represents the external mechanical work done. The positive external mechanical work done, W_{ext}, is taken as the increments of the total mechanical energy curve during the interval of time, of one or more complete steps, in which the vertical velocity tracing was integrated to locate the average vertical velocity (Fig. 1*D*). The same is done for the curve giving the kinetic energy of forward motion to determine the work necessary to sustain the kinetic energy changes, W_f, and for the curve giving the sum of the potential energy and the kinetic energy of vertical motion to determine the work done to lift the centre of mass, W_v. All the calculations reported in Fig. 1 as well as the curves in Fig. 2 were made directly by a computer. The work involved in lateral movements and in rotating the body about its centre of mass was ignored (Cavagna, 1975).

The records of the velocity changes (Fig. 1) were used to decide, immediately after the walk, whether a particular test was acceptable for analysis of the energy changes of the centre of mass; we included only those tests where the subject moved at a constant average speed across the platform without an appreciable drift of the integrators during the period of analysis. These requirements were considered fulfilled when the sum of the increases in velocity (as measured by the integrators) did not differ more than 25% from the sum of the decreases in velocity in both the forward and vertical directions for an integral number of steps. This 25% limit amounted to a forward speed change of 7–3% of the average forward speed during walking at 2–8 km/hr in adults and of 5–3% during walking at 2–6 km/hr in 3–4-year-old children. For the tests that met these criteria, the digital values of the forward and vertical velocity changes were utilized to calculate the mechanical energy changes of the centre of mass according to the procedure described above. Oscillations were sometimes present on the energy tracings (Fig. 2); the error made by summing up the increments of these oscillations was minimized by a smoothing sub-routine.

The time during which both feet contact the ground, t_{dc}, was measured in some subjects (thirty-nine children and twelve adults) by means of electrical contacts under the soles of the feet which operated a transmitter carried at the waist of the subject (Cavagna *et al.* 1976). When both feet were on the ground, the circuit was closed through the metallic surface of the platform giving rise to a square signal which was recorded together with the force and the velocity tracings (Fig. 1).

The phase shift between kinetic energy of forward motion and gravitational potential energy, α, was measured from the time difference between the maximum of kinetic energy and the minimum of potential energy; similar results were obtained from the difference in time between the minimum of kinetic energy and the maximum of potential energy, however the scatter of the data was largely due to the blunt shape of the kinetic energy curve in this phase of the step (Fig. 2). α was measured (in forty children and seven adults) utilizing those records in which kinetic energy ad potential energy displayed only one maximum and one minimum per step. At high speeds, potential energy (sometimes also kinetic energy) may attain two maxima during the step (fig. 1 of Cavagna *et al.* 1976) since in these steps the pendulum-like transfer between potential and kinetic energies is low, we measured α only when this transfer exceeded 20%.

RESULTS

The mechanical energy changes of the centre of mass during a step, calculated per kilogram of body mass, are illustrated in Fig. 2 for subjects in three age groups. In each set of tracings the curves indicate, from top to bottom: the kinetic energy of forward motion, the gravitational potential energy plus the kinetic energy of vertical motion, the gravitational potential energy alone (dotted), the total mechanical energy of the centre of mass (disregarding lateral movements) and the sum of gravitational potential energy and of the kinetic energy of forward motion (dotted).

The three sets of tracings given for each age correspond to a walking speed near to the minimum (left), average (middle) and maximum (right) of that age. When the speed increases, the period of the step decreases and the phase shift between kinetic

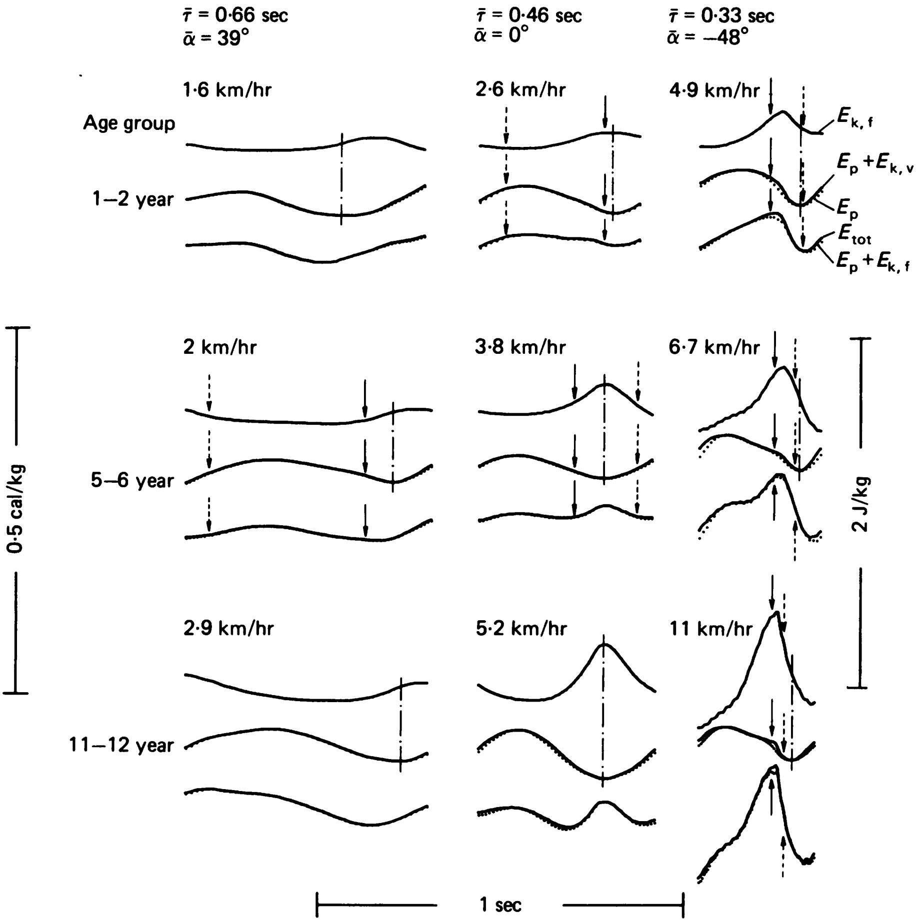

Fig. 2. Computer plots of weight specific mechanical energy changes of the centre of mass of the body in children of different ages walking at the indicated speeds. In each set of tracings the upper curve refers to the kinetic energy of forward motion, $E_{k,f}$; the middle one to the sum of the gravitational potential energy, E_p and of the kinetic energy of vertical motion, $E_{k,v}$ and the bottom one to the total energy, $E_{tot} = E_{k,f} + E_p + E_{k,v}$. Dotted lines indicate the curves E_p and $E_{k,f} + E_p$. Tracings begin when the vertical velocity of the centre of mass of the body is at a maximum. The nine sets of tracings are arranged in three columns with about the same step period, τ, and the same phase shift between $E_{k,f}$ and E_p, α, to show the similarity of the trend of the curves in each column in spite of the large differences in the speed of walking. In the left column the minimum of E_p (indicated by the dashed and dotted line) takes place before the maximum of $E_{k,f}$ ($\alpha > 0$ °); in the middle one $E_{p,min}$ and $E_{k,f,max}$ coincide ($\alpha = 0$ °), i.e. the two curves are exactly out of phase; in the right column $E_{p,min}$ follows $E_{k,f,max}$ ($\alpha < 0$ °). The arrows indicate the instant when the front foot contacts the ground (continuous) and when the back foot leaves the ground (interrupted). In the 1–2 year age group the left set of tracings refers to a 1·9-year-old female, 0·84 m tall, 11·5 kg body weight; those at the middle and at the right to a 2·5-year-old male, 0·94 m, 15 kg; in the 5–6 year age group, left: 6·2-year-old male, 1·22 m, 27·5 kg; middle: 5·2-year-old male, 1·11 m, 20·2 kg; right: 6·8-year-old male, 1·17 m, 20·6 kg; in the 11–12 year age group, left: 11·5-year-old male, 1·4 m, 41 kg; middle and right: 12·5-year-old female, 1·59 m, 41·3 kg. For a full explanation of symbols see Methods.

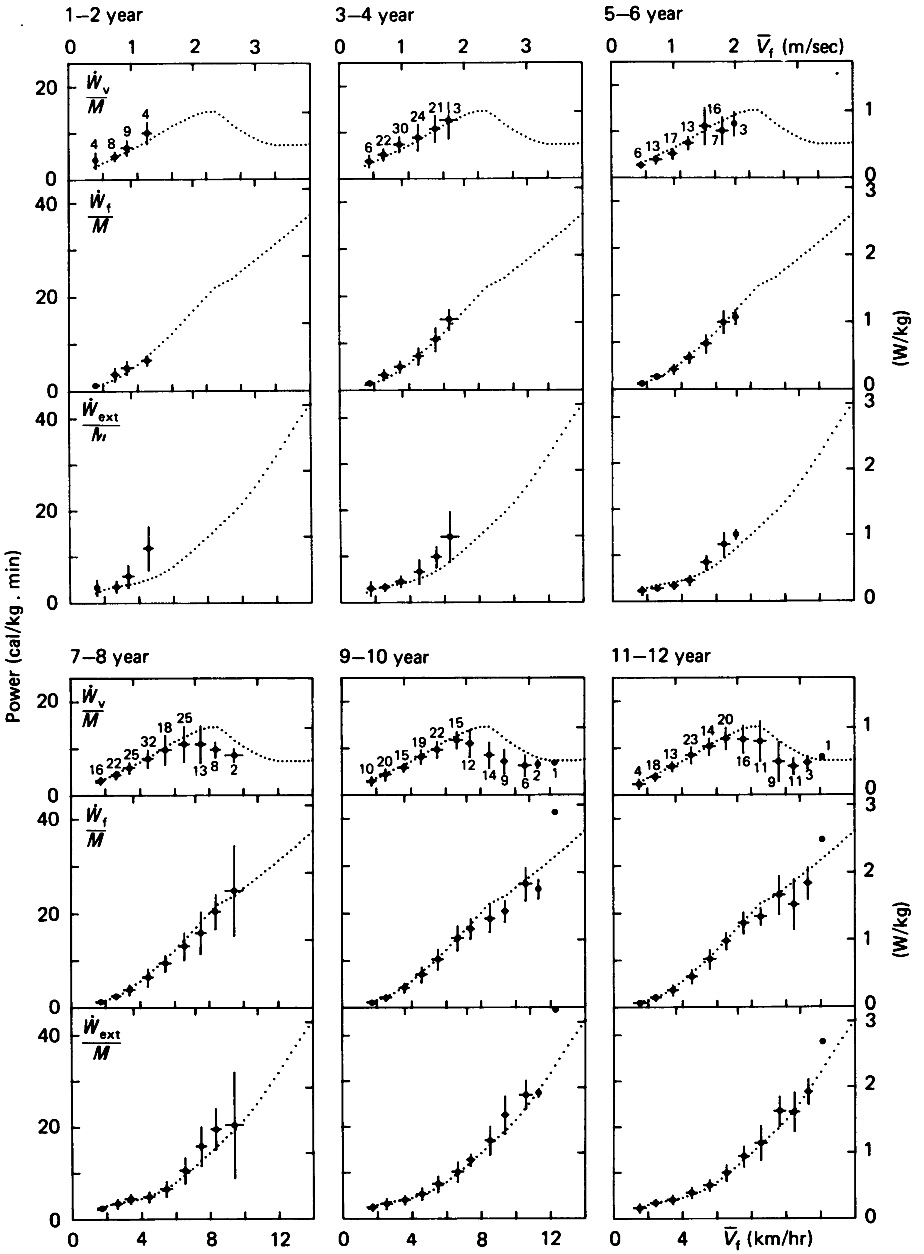

Fig. 3. The weight specific power output is given as a function of speed for different groups of age (see Table 1). $\dot{W}_v/M$ is the power spent against gravity, $\dot{W}_f/M$ is the power due to forward velocity changes and $\dot{W}_{ext}/M$ the power necessary to maintain the combined movement of the centre of mass in a saggital plane. Each point represents the average ($\pm$S.D.) of the co-ordinates of all the data within 1–2 km/hr, 2–3 km/hr, etc. The figures near each point give the number of items in the mean. Dotted lines give the trend of the data obtained in adults. For a full explanation of symbols see Methods.

and potential energy curves changes: the maximum of kinetic energy occurs after the minimum of potential energy at low speeds ($\alpha > 0$ °), coincides with the minimum at intermediate speeds ($\alpha = 0$ °) and preceeds the minimum at high speeds ($\alpha < 0$ °). The nine sets of tracings are arranged in three vertical columns, having about the same period and the same phase shift, to show the similarity of the trend of the curves in each column in spite of the large differences in the speed of walking.

The positive work done at each step, calculated from the increments of the energy curves, was multiplied by the step frequency to obtain the average power spent to lift the centre of mass $\dot{W}_v$, to accelerate it forwards, $\dot{W}_f$ and to maintain its combined movement in a saggital plane, $\dot{W}_{ext}$ (Fig. 3). It can be seen that: (1) the weight-specific power to lift and to accelerate forward the centre of mass increases with speed similarly at all ages and is about equal to that measured in adults (dotted lines), (2) the weight-specific external power spent to maintain the combined movement of the centre of mass in a sagittal plane increases with speed more steeply in children than in adults; the difference at a given speed decreases with age, (3) little difference exists between power output in the 11–12 years age group and in the adults.

It is known that in walking the work actually done to move the centre of mass, W_{ext}, is less than the sum of the absolute values of the work to lift the centre of mass, W_v, and to accelerate it forward, W_f, because of a transfer between gravitational potential energy and kinetic energy (as in a pendulum). The amount of this transfer is quantified by the percentage recovery (Cavagna *et al.* 1976):

$$R = ((W_v + W_f - W_{ext})/(W_v + W_f))\ 100. \tag{7}$$

In a frictionless pendulum the work necessary to maintain the motion, W_{ext}, is nil and, as a consequence, $R = 100$; in fact all of the potential energy is 'recovered' as kinetic energy and vice versa during a cycle. Since W_v and W_f are equal in children and in adults, the greater values of W_{ext} must be due, according to eqn. (7), to a smaller value of the percentage recovery.

The external work done per unit distance, $W_{ext}/(ML)$, and the percentage recovery are plotted as a function of the speed of walking in Fig. 4 to show how the first is affected by the second. In the children as in the adults, the external work done per unit distance reaches a minimum near the speed at which the percentage recovery is at a maximum. In addition the present data show that: (1) the minimum of the external work done per unit distance and the maximum transfer between potential and kinetic energy are attained at an 'optimal'speed which is smaller the younger the subject; these minimum and maximum values do not differ statistically from those measured in the adults; in the youngest subjects only (1–2 years) the maximum of percentage recovery is smaller than in the adults, (2) above the 'optimal' speed the percentage recovery decreases and the weight specific external work done per unit distance increases more steeply the smaller the age.

The effect of the potential-kinetic energy transfer on the external work done per unit distance is clearly shown by the data in Fig. 4. What, in turn, affects this transfer? Examination of the curves in Fig. 2 helps to understand that the total mechanical energy would be constant and, as a consequence, the external work done would be zero, if the curves giving the kinetic energy of forward motion and the potential plus the kinetic energy of vertical motion (a) had the same amplitude,

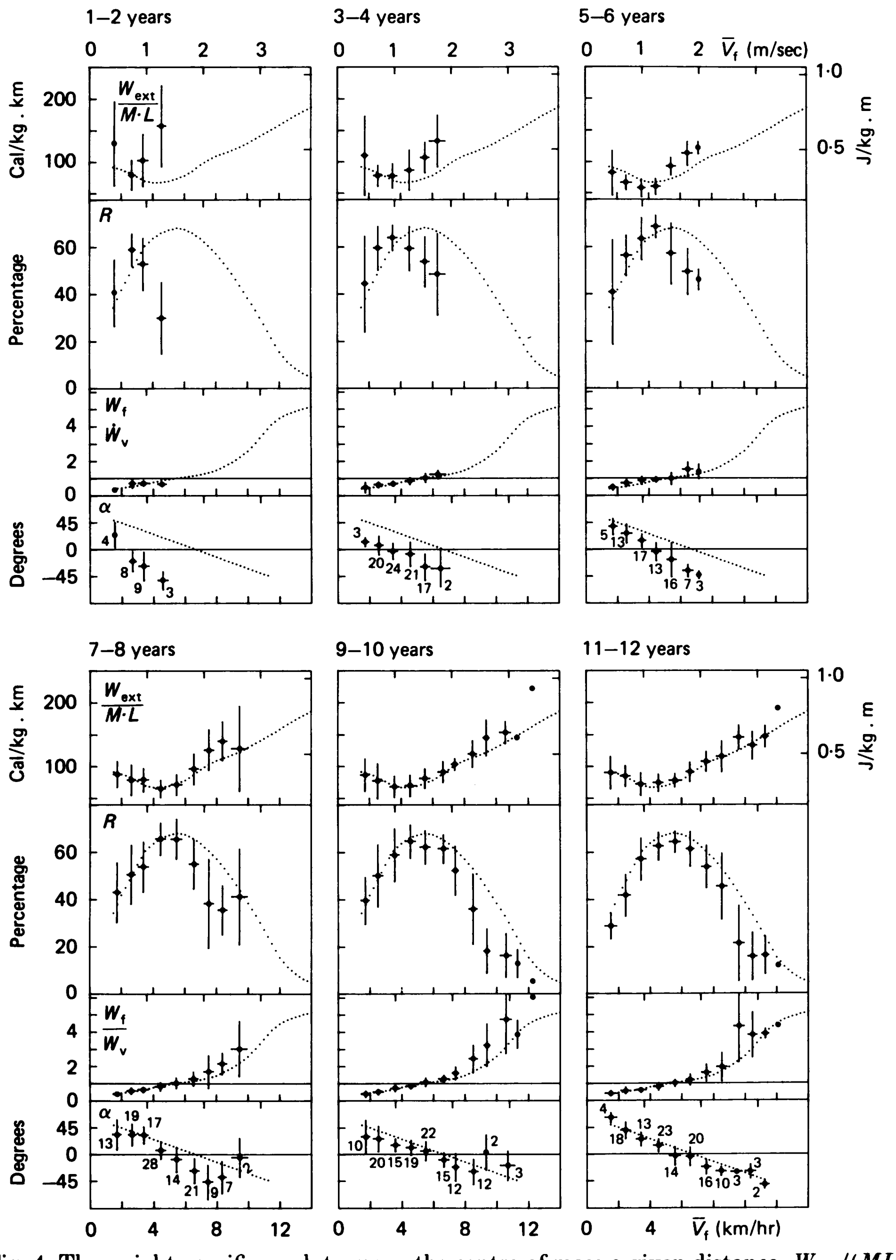

Fig. 4. The weight specific work to move the centre of mass a given distance, $W_{ext}/(ML)$, the pendulum-like recovery of mechanical energy, R, the ratio between work to accelerate forward and work against gravity, W_f/W_v and the phase shift of the curves E_p and $E_{k,f}$, α, are plotted as a function of speed for each age group. α was measured on some subjects only (see text). Other indications as in Fig. 3. For a full explanation of symbols see Methods.

(b) were in opposite phase and (c) had the same shape. Shape cannot be measured, but factors (a) and (b) were measured as the ratio W_f/W_v, and the phase angle α, respectively, and plotted in Fig. 4 below the percentage recovery. It can be seen that W_f/W_v increases with speed from below to above unity with the same trend in children and in adults: $W_f/W_v = 1$ at 5·5 km/hr independently of age. α decreases with speed from positive values (maximum of $E_{k,f}$ after the minimum of E_p, see Fig. 2) to negative values (maximum of $E_{k,f}$ before the minimum of E_p) more steeply the smaller the age and crosses the zero ($E_{k,f}$ and E_p curves completely out of phase) near to the speed of walking at which the percentage recovery is maximum.

In the youngest children, $E_{k,f}$ and E_p are exactly out of phase when the work due to the forward speed changes is smaller that the work done against gravity, whereas in the adults $E_{k,f}$ and E_p happen to be exactly out of phase when $W_f/W_v = 1$.

In conclusion, the phase shift between potential and kinetic energy, more that their relative amplitudes, appears to be important in determining the maximum transfer between them. In addition both requirements for a maximum of transfer are simultaneously fulfilled only at the adult age.

The step period, (which is the sum of the time of single contact, t_{sc}, and of double contact, t_{dc}) and the step length, L (which equals the sum of the forward displacement during single contact, L_{sc}, and during double contact, L_{dc}) are plotted as a function of the average speed of walking in Fig. 5; the vertical displacement of the centre of gravity at each step, S_v, is plotted in the same Figure because it is obviously affected by the step length. The relationship between vertical displacement and step length has been discussed in previous works (Cotes & Meade, 1960; Cavagna *et al.* 1976; Cavagna & Franzetti, 1981): the step length and the vertical displacement increase with speed up to 6–8 km/hr (first phase of walking); at greater speeds the step length continues to increase whereas the vertical displacement decreases (second phase of walking). The present results show that: (1) The second phase of walking is detectable only after the age of seven. When detectable it begins at a lower speed in children than in adults. (2) At a given speed children make a step relatively longer than adults; this is indicated by a greater ratio between length of the step and length of the leg (L/l): a greater value of L_{sc}/l leads to a greater relative vertical displacement of the trunk (Cotes & Meade, 1960; Cavagna *et al.* 1976) and this, in turn, may lead to a greater relative vertical displacement of the centre of gravity. S_v/l is in fact greater in children below 4 years of age than in adults, however above the age of four, S_v/l is similar in children and in adults in spite of the fact that L_{sc}/l remains slightly greater in children.

DISCUSSION

Walking in children

The ratio between weight specific power output to move the centre of mass during the walking of children and adults is given in Fig. 6*A* as a function of the speed.

Fig. 6*A* was constructed from the data in Fig. 3 as follows. Lines were drawn by hand through the $\dot{W}_{ext} = F(\overline{V}_f)$ points; the ratio between the values indicated by these lines and those indicated by the dotted lines (adults) was plotted as a function of $\overline{V}_f$; the curves in Fig. 6*A* were drawn by hand through the points obtained in this way.

The relatively greater load imposed on children decreased abruptly from 1–2 to 3–4 years of age and then more or less uniformily with age. At 5·5 km/hr the weight

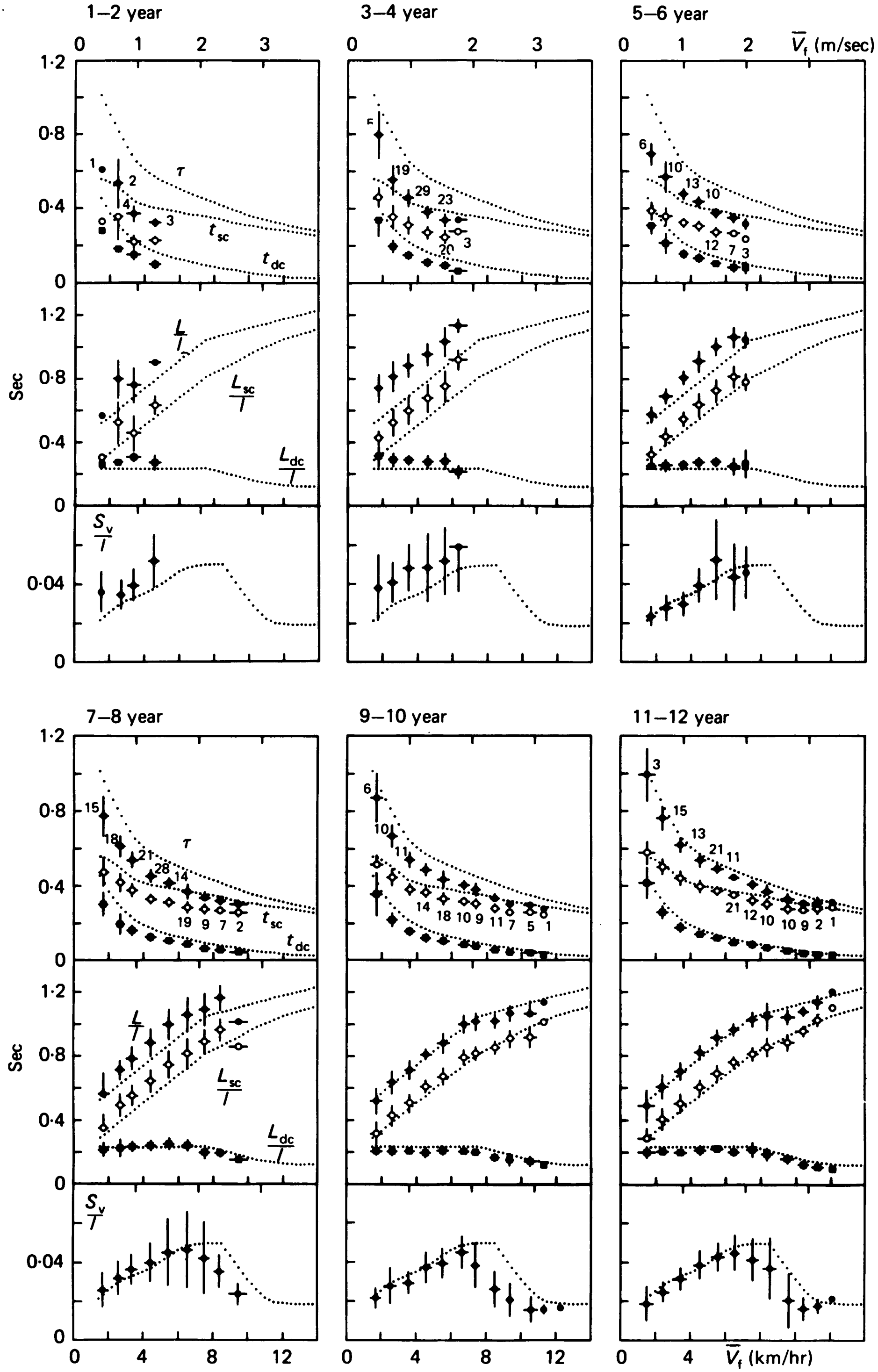

Fig. 5. The step period, τ, the relative step length, L/l, and the relative vertical displacement of the centre of mass of the body during each step, S_v/l, are given as function of speed for each age group. τ and L/l are divided into time and forward displacement during single contact, t_{sc} and L_{sc}/l (○), and during double contact, t_{dc} and L_{dc}/l (■). τ and L were measured on some subjects only (see text). Other indications as in Fig. 3. For a full explanation of symbols see Methods.

specific external power is about 40% greater at 3–4 years, 20% at 5–6 years, 5% at 7–8 years of age, whereas already at 4·5 km/hr it is 130% greater in the 1–2 years age group.

Mechanical power is necessary not only to maintain the movement of the centre of mass, but also to accelerate the limbs relatively to the centre of mass and this power also is likely to be greater in children.

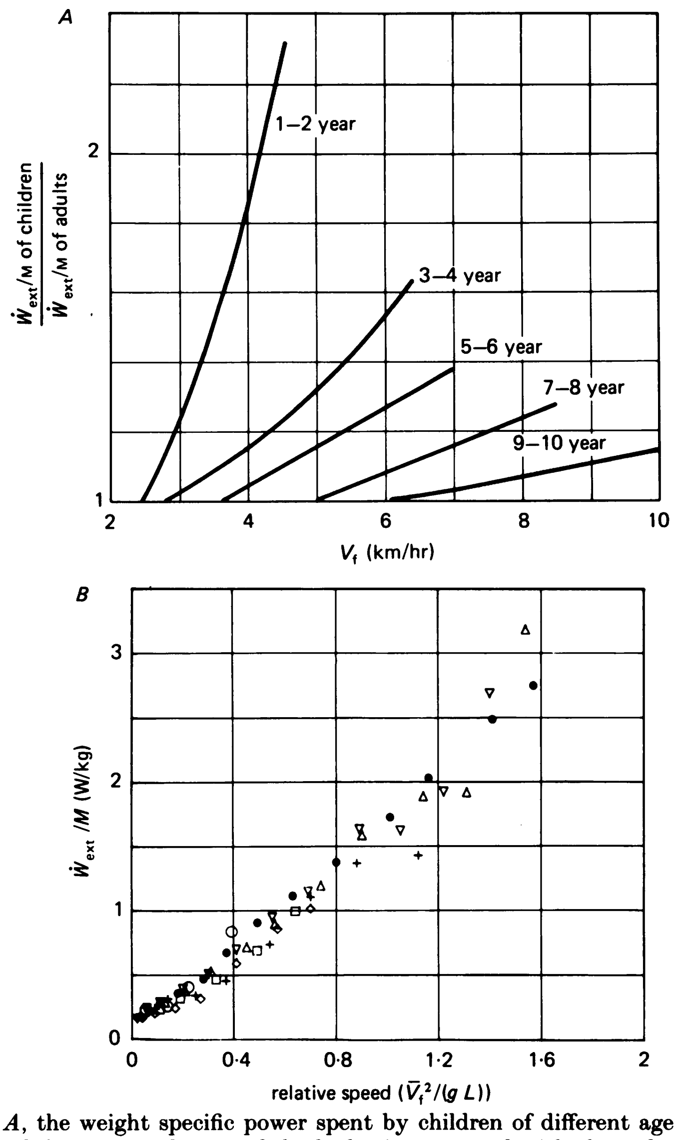

Fig. 6. *A*, the weight specific power spent by children of different age to maintain the motion of the centre of mass of the body, is compared with that of adults for various walking speeds. *B*, The weight specific power of children of differnt age and of adults is plotted as a function of the Froude number ($\bar{V}_f^2/gl$). It can be seen that subjects moving with the same Froude number spend the same weight specific power (1–2 year, ○; 3–4 year, □; 5–6 year, ◇; 7–8 year, +; 9–10 year, △; 11–12 year, ▽; adults, ●).

At a given speed, the power necessary to accelerate the limbs tends to be smaller in children because of the smaller linear dimensions of the limbs and greater because of the greater step frequency. Assuming geometric similarity between adults and children, an approximate relationship between this power and speed has been worked out for children on the basis of the data of Cavagna & Kaneko (1977) on adults (T. Fuchimoto, unpublished observation). At 5·5 km/hr the weight specific power necessary to accelerate the limbs would be 33 % greater at 3–4 years of age and 15 % greater at 11–12 years of age.

It is therefore reasonable to conclude that children do perform a greater amount of work per unit mass and per unit time to maintain a given speed of walking. This may explain, at least in part, why the weight specific oxygen consumption during walking was found to be greater in children than in adults (Piacentini & Bollettino, 1942; Silverman & Anderson, 1972). Simultaneous measurements of mechanical work and energy expenditure at the different ages would be necessary to detect a concomitant change of the efficiency of positive work production by muscles.

Fig. 6*A* shows that a given walking speed is not functionally equivalent at the different ages because it requires a different power to move the centre of mass. In order to eliminate differences with age, power is plotted in Fig. 6*B* as a function of a dimensionless parameter, the Froude number, which is particularly appropriate to compare objects of different size, but geometrically and kinematically similar, moving in situations where mainly inertia and gravity interact (Alexander, 1976); the Froude number, $\overline{V}_f^2/(gl)$, is the ratio between inertial and gravitational forces within one object and must be equal in the different objects if they are geometrically and kinematically similar. The data plotted in the Fig. 6*B* do not show appreciable difference with age suggesting that children of different age and adults, during walking, are objects geometrically and kinematically similar.

The 'optimal' speed of walking for children

Fig. 4 shows that there exists a speed of walking, $\overline{V}_{f,o}$, in children as in adults, at which the transfer between gravitational potential energy and kinetic energy is maximum and the weight specific work necessary to maintain the movement of the centre of mass for a given distance is minimum and about equal at all ages; $\overline{V}_{f,o}$ is smaller the younger the subject. How important are these facts in determining the speed freely chosen during normal walking? $\overline{V}_{f,o}$ is plotted in Fig. 7 as a function of stature and compared with the freely chosen walking speed measured in a number of children of the same stature (dashed line in Fig. 7, data by Sutherland, Olshen, Cooper & Woo, 1980).

There is not always an exact correspondence between the speed at which the percentage recovery is maximum and the speed at which the external work done per unit distance is minimum, even if the two values are usually very near (Fig. 4). An intermediate speed value was therefore determined by making the mean, within each age group, of the speeds at which R was maximum and $W_{ext}/(ML)$ was minimum. This mean speed value $\pm 0{\cdot}5$ km/hr was used to define the range of the speeds of walking considered to be 'optimal' for each age from the viewpoint of the movement of the centre of mass of the body. The variables on the ordinates of Fig. 7 are the average of the data obtained within this range.

The data in Fig. 7 indicate that $\overline{V}_{f,o}$, calculated as described above for each age group, shows a close correspondence with the walking speed freely chosen by children of the same stature. This indicates that the normal speed of walking is chosen in order to keep the transfer between potential and kinetic energy at a maximum and, as a consequence, the external work done per unit distance at a minimum; this conclusion, suggested by the data obtained previously in adults (Cavagna *et al.* 1976), is now confirmed by the finding that the coincidence between $\overline{V}_{f,o}$ and the freely chosen speed, holds over a range of speeds (2·8–5 km/hr) and body sizes (0·9–1·8 m).

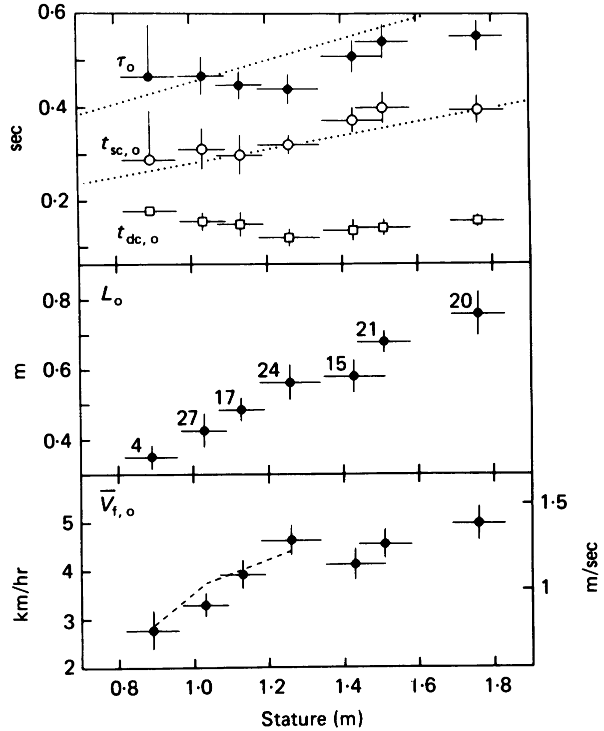

Fig. 7. The 'optimal' walking speed, $\overline{V}_{f,o}$, step length, L_o and step period, τ_o (with its fractions $t_{dc,o}$ and $t_{sc,o}$) are given as a function of the average stature of each age group (Table 1). The speed freely chosen during walking (Sutherland *et al.* 1980) is indicated by the dashed line. The dotted lines delimit a range of t_{sc} calculated according to a ballistic walking model (Mochon & McMahon, 1980).

The determinants of the 'optimal' walking speed

Fig. 7 shows that the 'optimal' speed, $\overline{V}_{f,o} = L_o/\tau_o$, increases about 80% with the increase of stature taking place from 2 years to adult age. The increase of $\overline{V}_{f,o}$ is due to an increase of the step length, L_o (of about 120%), which is only partly compensated by an increase of the step period, τ_o (of about 20%). The increase of the step length may be roughly explained by an increase of the stature (of about 100%). The step period is the sum of the time during which both feet contact the ground t_{dc}, and of the time of single contact (often called time of swing), t_{sc}. Fig. 7 shows that $t_{dc,o}$ is roughly independent of stature indicating that the forward displacement of the centre of mass during this time is proportional to $\overline{V}_{f,o}$. On the contrary $t_{sc,o}$ increases with stature (34%), with the result that it becomes a fraction of the step duration which is greater the larger the subject.

Several attempts have been made to calculate the time of single contact because it is apparent that during this period the rotation of the whole body over the leg on the ground (as an inverted pendulum) and of the swinging leg (as a compound pendulum) are strongly affected by gravity (Grieve & Gear, 1966; Alexander, 1980; Mochon & McMahon, 1980). The dotted lines in Fig. 7 delimit a range of values of time of single contact calculated according to a model coupling the inverted and the compound pendulums with the assumption of no muscular intervention during the swing phase; the upper boundary corresponds to a maximum knee flexion of the swinging leg, whereas the lower boundary corresponds to the limit where the toe of the swinging leg just clears the ground during the swing (Mochon & McMahon, 1980). The region between the two boundaries was found to encompass most of the times

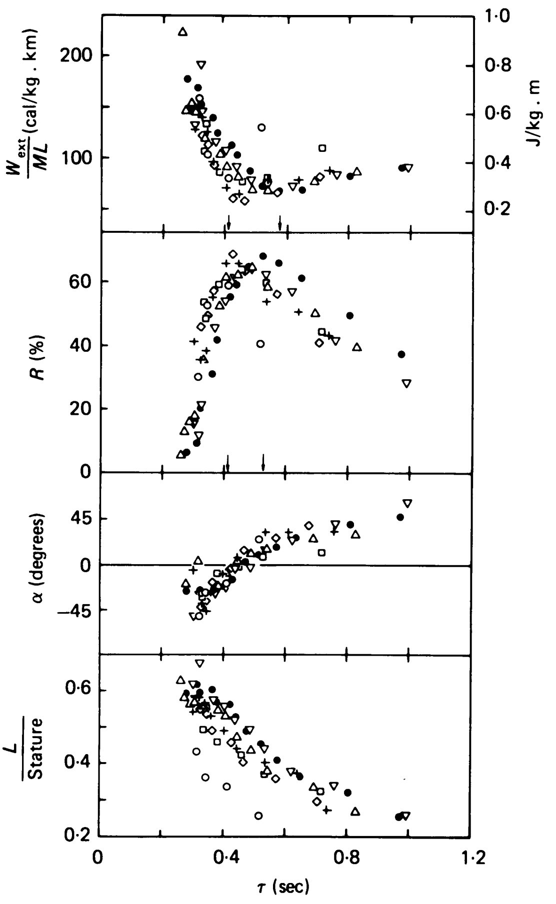

Fig. 8. The weight specific work to move the centre of mass a given distance, $W_{ext}/(ML)$, the percentage recovery, R, the phase shift, α, and the relative step length, L/Stature, are plotted as a function of the step period, τ, instead of the speed, as in Fig. 4, for the different age groups. The arrows delimit the range of periods in which a minimum of $W_{ext}/(ML)$ and a maximum of R are attained (left arrows: 1–2 year; right: adults). This range is much narrower than the corresponding range of speeds (Fig. 4). Lack of a complete control and balance may give reason for the relatively shorter steps in the 1–2 year age group (Sutherland *et al.* 1980). Symbols as in Fig. 6.

of swing measured during walking at different speeds by Grieve & Gear (1966) with the exception of those subjects less than about 1·2 m in height. In Fig. 7 we did not plot a range of times of swing, but only the value corresponding to the 'optimal' speed; there exists a striking similarity between this value (open circles) and the lower boundary which correspond to a minimum of muscular activity; the similarity holds for the whole range of statures. This finding, as the exact opposition of phase between gravitational potential energy and kinetic energy, the maximum exchange between them and the minimum work done per unit distance support the conclusion that at the freely chosen speed the mechanics of walking is dominated by gravity with a passive pendulum-like mechanism.

The 'optimal' walking speed at the different ages is therefore determined by a predictable step duration, which changes little, and by a step length, which changes more depending on the linear dimensions of the body. Plotting the variables of Fig. 4 as a function of the step duration, instead of the speed, results in a much smaller difference between the different ages (Fig. 8). This means that for a given step duration the mechanics of walking is similar independently of age; this is also shown by the similar trend of the tracings in each column of Fig 2. It is worth stressing that whereas the weight specific power output to lift the centre of mass and to accelerate it forward at each step is merely a function of speed relative to the ground independent of size (Fig. 3), the interaction between them, which determines the mechanics of the movement and then the external work done in unit time to maintain the motion of the centre of mass, requires a well-defined period and is independent of speed.

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