

Mechanical work and muscular efficiency in walking children

B. Schepens, G. J. Bastien, N. C. Heglund and P. A. Willems*

Unité de Physiologie et Biomécanique de la Locomotion, Université Catholique de Louvain, 1 Place Pierre de Coubertin, B-1348 Louvain-la-Neuve, Belgium

*Author for correspondence (e-mail: patrick.willems@loco.ucl.ac.be)

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Summary

The effect of age and body size on the total mechanical work done during walking is studied in children of 3–12 years of age and in adults. The total mechanical work per stride (W_{tot}) is measured as the sum of the external work, W_{ext} (i.e. the work required to move the centre of mass of the body relative to the surroundings), and the internal work, W_{int} (i.e. the work required to move the limbs relative to the centre of mass of the body, $W_{\text{int,k}}$, and the work done by one leg against the other during the double contact period, $W_{\text{int,dc}}$). Above 0.5 m s^{-1} , both W_{ext} and $W_{\text{int,k}}$, normalised to body mass and per unit distance ($\text{J kg}^{-1} \text{ m}^{-1}$), are greater in children than in adults; these differences are greater the higher the speed and the younger the subject. Both in children and in adults, the normalised $W_{\text{int,dc}}$ shows an inverted U-shape curve as a

function of speed, attaining a maximum value independent of age but occurring at higher speeds in older subjects. A higher metabolic energy input ($\text{J kg}^{-1} \text{ m}^{-1}$) is also observed in children, although in children younger than 6 years of age, the normalised mechanical work increases relatively less than the normalised energy cost of locomotion. This suggests that young children have a lower efficiency of positive muscular work production than adults during walking. Differences in normalised mechanical work, energy cost and efficiency between children and adults disappear after the age of 10.

Key words: walking children, mechanical work, energy cost, muscular efficiency.

Introduction

Children consume more energy per unit body mass to walk at a given speed than do adults (DeJaeger et al., 2001). The difference in the net mass-specific metabolic energy cost per unit distance (i.e. the cost of transport, the energy required to operate the locomotory machinery) between adults and children is greater the higher the speed and the younger the subject. For example, at a speed of 1 m s^{-1} , a 3–4-year-old has a net oxygen consumption 33% greater than adults. This difference disappears by the age of 11–12 years.

In order to take into account the difference in size between children and adults, the speed of progression can be normalised using the dimensionless Froude number, $\bar{V}_f^2/(gl)$, where \bar{V}_f is mean walking speed, g is acceleration of gravity and l is leg length (Alexander, 1989). In this case, the difference in the cost of transport between children and adults for the most part disappears. This indicates that, after the age of 3–4 years, the difference in the cost of transport may be explained mostly on the basis of body size (DeJaeger et al., 2001).

As previously observed in running (Schepens et al., 2001), body size can also affect the positive muscle–tendon work (W_{tot}) performed during walking. W_{tot} naturally falls into two categories: the external work (W_{ext}), which is the work necessary to sustain the displacement of the centre of mass of the body (COM) relative to the surroundings, and the internal

work (W_{int}), which is the work that does not directly lead to a displacement of the COM . Only some of W_{int} can be measured: (1) the internal work done to accelerate the body segments relative to the COM ($W_{\text{int,k}}$) and (2) the internal work done during the double contact phase of walking by the back leg, which generates energy that will be absorbed by the front leg ($W_{\text{int,dc}}$). On the contrary, the internal mechanical work done for stretching the series elastic components of the muscles during isometric contractions, to overcome antagonistic co-contractions, to overcome viscosity and friction cannot be directly measured (although this unmeasured internal work will affect the efficiency of positive work production; Willems et al., 1995).

Walking is characterised by a pendulum-like exchange between the kinetic and potential energy of the COM . In children, the ‘optimal speed’ at which these pendulum-like transfers are maximal increases progressively with age from 0.8 m s^{-1} in 2-year-olds up to 1.4 m s^{-1} in 12-year-olds and adults (Cavagna et al., 1983). At all ages, the optimal speed is close to the speed at which the mass-specific work to move the COM a given distance, W_{ext} , is at a minimum. Above the optimal speed, the energy transfers decrease. This decrease is greater the younger the subject. The decreased transfers result in a greater power required to move the COM : at 1.25 m s^{-1} ,

the mass-specific external power (\dot{W}_{ext}) is twice as great in a 2-year-old child than in an adult. When normalising the speed with the Froude number, \dot{W}_{ext} is similar in children and in adults.

The work done by one leg against the other ($W_{\text{int,dc}}$) was not counted in the 'classic' measurements of the positive muscular work done during walking, which was calculated as $W_{\text{tot}}=W_{\text{ext}}+W_{\text{int,k}}$ (Cavagna and Kaneko, 1977; Willems et al., 1995); consequently, $W_{\text{int,k}}$ has previously been referred to simply as W_{int} . Using force platforms, Bastien et al. (2003) studied the effect of speed and age (size) on $W_{\text{int,dc}}$ in 3–12-year-old children and in adults. $W_{\text{int,dc}}$ as a function of speed shows an inverted U-shape curve, attaining a maximum value of approximately $0.15\text{--}0.20\text{ J kg}^{-1}\text{ m}^{-1}$, which is independent of size but occurs at higher speeds in larger subjects. The differences due to size disappear for the most part when $W_{\text{int,dc}}$ is normalised with the Froude number.

These observations indicate that, as for the energy expenditure, the speed-dependent changes in W_{ext} and $W_{\text{int,dc}}$ are primarily a result of body size changes. To our knowledge, the internal work due to the movement of the limbs relative to the COM ($W_{\text{int,k}}$) has never been measured in walking children. In the present study, we measure simultaneously W_{ext} , $W_{\text{int,k}}$ and $W_{\text{int,dc}}$ in children and in adults walking at different speeds and calculate W_{tot} and efficiency.

W_{tot} is calculated from W_{ext} , $W_{\text{int,k}}$ and $W_{\text{int,dc}}$ over a complete stride, taking into account any possible energy transfers that would reduce the muscular work done. Transfers between W_{ext} and $W_{\text{int,k}}$ were analysed by Willems et al. (1995). Energy transfers between the back and the front legs in the computation of $W_{\text{int,dc}}$ were discussed by Bastien et al. (2003). In the present study, we analyse the possible transfers between $W_{\text{int,k}}$ and $W_{\text{int,dc}}$; we show that, during the double contact phase, some positive work done by the back leg in pushing the body forwards can result in an increase of the kinetic energy of the front leg moving backwards relative to the COM.

The total mechanical work is compared with the energy expenditure to evaluate the efficiency of positive work production. It is shown that children younger than 6 years are less efficient than adults in producing positive work during walking.

Materials and methods

Measurements of the mechanical work during walking were performed on the same subjects and during the same sessions as the previously published measurements of the mechanical work during running (Schepens et al., 2001). The details of the methods used to compute W_{ext} are given in Cavagna (1975) and Willems et al. (1995), those used to compute $W_{\text{int,k}}$ are given in Cavagna and Kaneko (1977) and Willems et al. (1995), and those used to compute $W_{\text{int,dc}}$ are given in Bastien et al. (2003); these methods are only summarised here.

Subjects and experimental procedure

Twenty-four healthy children of 3–12 years of age and six

healthy adults participated in the experiments. They were divided into six age groups: the 3–4-year-old group included subjects 3 years to <5 years old; the 5–6-year-old group included subjects 5 years to <7 years old, etc. Each group comprised 4–6 children; the averaged physical characteristics of these groups are given in table 1 of Schepens et al. (2001). Written informed consent of the subjects and/or their parents was obtained. The experiments involved no discomfort, were performed according to the Declaration of Helsinki and were approved by the local ethics committee.

Subjects were asked to walk across a 6 m-long force platform at different speeds. The mean speed (\bar{V}_f) was measured by two photocells placed at the level of the neck and set 0.7–5.5 m apart depending upon the speed. In each age group, the data were gathered into speed classes of $0.13\text{--}0.14\text{ m s}^{-1}$ (0.5 km h^{-1}).

Measurement of positive mechanical work done per stride

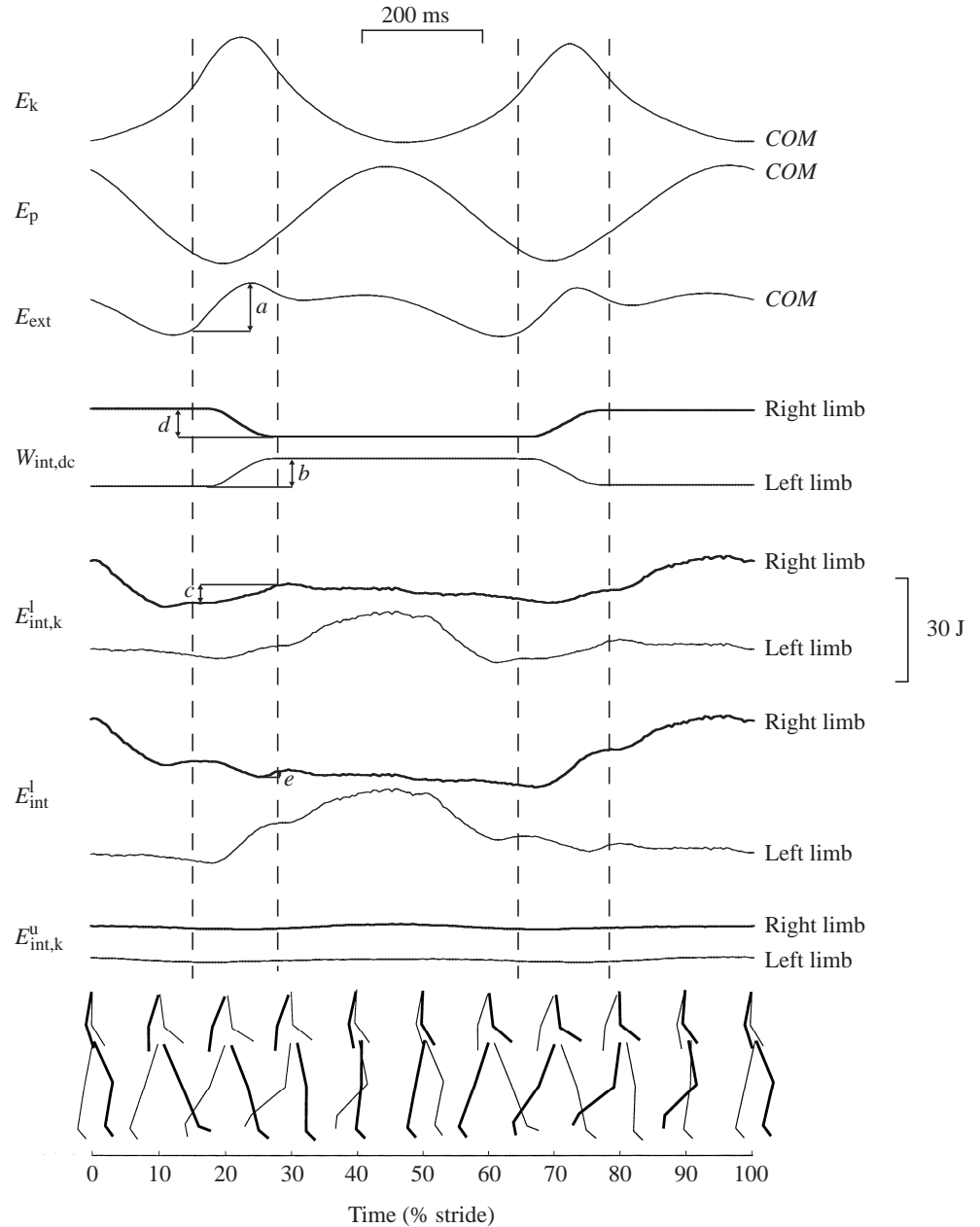
The kinetic internal work ($W_{\text{int,k}}$), the external work (W_{ext}) and the work done during the double contact phase ($W_{\text{int,dc}}$) were measured simultaneously on 531 complete strides according to the procedures described below. A stride was selected for analysis only when the subject was walking at a relatively constant average height and speed. Specifically, the sum of the increments in both vertical and forward velocity of the COM could not differ by more than 25% from the sum of the decrements (Cavagna, 1975). According to these criteria, the average vertical force was within 4% of the body weight, and the difference in the forward velocity of the COM, from the beginning to the end of the selected stride, was less than 5% of \bar{V}_f in 95% of the trials (at very low speeds, it was less than 10% of \bar{V}_f).

Measurement of positive internal work due to the segment movements per stride

$W_{\text{int,k}}$ was computed from the segment movements and anthropometric parameters. The body was divided into 11 rigid segments (Willems et al., 1995): one head/neck/trunk segment and two thigh, two shank, two foot, two upper arm and two lower-arm/hand segments. The head/neck/trunk segment and the right limb segments were delimited by infrared emitters placed at their extremities (see table 2 in Schepens et al., 2001). The coordinates of the infrared emitters in the forward and vertical directions were measured every 5 ms by means of a SELSPOT II[®] system (SELCOM[®], Göteborg, Sweden). The coordinates were smoothed with a cubic spline function (Dohrmann et al., 1988).

A 'stick man' of the position of each segment relative to the head/neck/trunk segment was constructed every frame (Fig. 1). The movements of the head/neck/trunk segment relative to the COM were ignored because their contribution to $W_{\text{int,k}}$ is negligible (Willems et al., 1995). The left side of the subject, opposite to the camera, was reconstructed from the right-side data on the assumption that the movements of the segments of one side were equal and 180° out of phase with the other side. The angular velocity of each segment and the translational

Fig. 1. Fluctuations of the external and internal mechanical energy during one stride of walking. The three upper curves present the mechanical energy changes of the centre of mass of the body (COM): E_k is the kinetic energy due to its velocity relative to the surroundings, E_p is the potential energy and E_{ext} is the external energy, which is the sum of the E_k and E_p curves. Due to a pendular-like energy transfer between E_k and E_p , the variations of the E_{ext} curve are smaller than those of the E_k and E_p curves. The increment a represents the work done on the COM during the first double contact phase of the stride. The internal work ($W_{int,dc}$) made by one leg against the other is presented as a function of time in the fourth and fifth curves: the positive work done by the back leg during the first double contact phase (increment b) is equal to the negative work (decrement d) absorbed in the front leg. The $E_{int,k}^l$ and $E_{int,k}^u$ curves are the kinetic energy changes of the lower and upper limbs, respectively, due to their velocity relative to the COM. The increment c represents the positive work to accelerate the front lower limb during the double contact phase. The internal energy–time curve of the lower limb ($E_{int,k}^l$) is the sum of the $E_{int,k}^l$ and $W_{int,dc}$ curves. This procedure assumes that the internal positive work done by the back leg during the double contact phase (increment b in $W_{int,dc}$) increases passively the backward velocity of the front leg relative to the COM (see Materials and methods). Consequently, the internal work done by the front leg is reduced (increment e in $E_{int,k}^l$).



The 'stick-man' at the bottom of the figure shows the position of the limb segments each 10% of the stride: thick lines refer to the segments on the right side of the body that were recorded by infrared cameras; thin lines refer to the segments of the left side of the body that were reconstructed on the assumption that the movements of the left segments during one half-stride were equal to the movements of the right segments during the other half-stride. The vertical broken lines delimit the two double contact phases of the stride and were determined from the force traces. The curves are from a 20-year-old woman (mass, 70.1 kg) walking at 1.5 m s⁻¹.

velocity of its centre of mass relative to the head/neck/trunk segment were calculated from the derivative of their position *versus* time relationship. The position of the centre of mass and the moment of inertia of the body segments were calculated using the anthropometric parameters of table 2 in Schepens et al. (2001).

The kinetic energy of each segment due to its displacement relative to the head/neck/trunk segment and due to its rotation was then calculated as the sum of its translational and

rotational energy. The kinetic energy *versus* time curves of the segments in each limb were summed. The internal work due to the movements of the upper limbs, $W_{int,k}^u$, was then calculated by adding the increments in their kinetic energy–time curves (Fig. 1). In order to minimise errors due to noise, the increments in kinetic energy were considered to represent positive work actually done only if the time between two successive maxima was greater than 20–110 ms, according to the speed of progression. The same procedure was used with

the kinetic energy–time curves of the lower limbs to compute the internal work due to their movements, $W_{\text{int},k}^1$ (Fig. 1). $W_{\text{int},k}$ was then computed as the sum of $W_{\text{int},k}^u$ and $W_{\text{int},k}^l$. This procedure allowed energy transfers between segments of the same limb but disallowed any energy transfers between different limbs (Willems et al., 1995).

Measurement of positive external work per stride

W_{ext} was calculated from the vertical and forward components of the force exerted on a 6 m×0.4 m force platform mounted 25 m from the beginning of a 40 m walkway. The platform was made of 10 different plates, similar to those described by Heglund (1981). The plates measured the fore–aft and vertical components of the forces exerted by the feet on the ground. The responses were linear within 1% of the measured value for forces up to 3000 N. The natural frequency of the plates was 180 Hz.

The signals from the platform were digitised synchronously with the camera system. The integration of the vertical and forward components of the ratio force/mass yielded the velocity changes of the *COM*, from which the kinetic energy (E_k) was calculated after evaluation of the integration constants (Cavagna, 1975; Willems et al., 1995). The kinetic energy of the *COM* is equal to $E_k = \frac{1}{2}m(\mathbf{V}_f^2 + \mathbf{V}_v^2)$, where m is body mass and \mathbf{V}_f and \mathbf{V}_v are the forward and vertical components, respectively, of the velocity of the *COM*. A second integration of the vertical velocity yielded the vertical displacement of the *COM*, from which the gravitational potential energy (E_p) was calculated. Potential energy of the *COM* is equal to $E_p = mg\mathbf{S}_v$, where g is the gravitational constant and \mathbf{S}_v is the vertical displacement of the *COM*.

The mechanical energy of the *COM* (E_{ext}) was the sum of the E_k and E_p curves over a complete stride. W_{ext} was the sum of the increments in the E_{ext} curve (Fig. 1). Similarly, W_k , the positive work done to sustain the velocity changes of the *COM*, was the sum of the increments of the E_k curve, and W_p , the positive work done against gravity, was calculated from the increments in the E_p curve (Fig. 1). The increments in mechanical energy were considered to represent positive work actually done only if the time between two successive maxima was greater than 20 ms.

Walking can be compared to a pendular mechanism where potential energy is transformed into kinetic energy and *vice versa* (Cavagna et al., 1976). The recovery (R) of energy due to this pendular mechanism was estimated by:

$$R = 100 \times \frac{W_k + W_p - W_{\text{ext}}}{W_k + W_p}. \quad (1)$$

This equation differs slightly from the ‘classical’ equation of recovery (e.g. Cavagna et al., 1976; Willems et al., 1995), which is given by:

$$R_c = 100 \times \frac{W_f + W_v - W_{\text{ext}}}{W_f + W_v}, \quad (2)$$

where W_f is the sum of the increments of the E_{kf} curve

($E_{kf} = \frac{1}{2}m\mathbf{V}_f^2$), and W_v is the sum of the increments of the $E_p + E_{kv}$ curve ($E_{kv} = \frac{1}{2}m\mathbf{V}_v^2$). Equation 2 evaluates the amount of energy recovered through the transfer between energy due to the forward motion of the *COM* (E_{kf}) into energy due to its vertical motion ($E_p + E_{kv}$). R differs slightly from R_c because E_{kv} is included in the W_k term of equation 1 and is included in the W_v term of equation 2.

Measurement of positive internal work made by one leg against the other during double contact

In walking, during the double contact phase, positive work is done by the back leg pushing forwards while negative work is done by the front leg pushing backwards. The forces exerted by each lower limb on the ground were measured separately. The powers generated against the external forces by the front and back legs were calculated from the dot product of the vertical and horizontal components of the ground reaction forces acting under each leg multiplied, respectively, by the vertical and horizontal velocity of the *COM* (Donelan et al., 2002; Bastien et al., 2003). The positive work done by the ground reaction forces was calculated independently for the back (W_{back}) and the front (W_{front}) limb from the time-integral of the power curves, taking into account any energy transfers (Bastien et al., 2003). Part of the positive work done by the limbs results in an acceleration and/or an elevation of the *COM*. In order not to count the same work twice, the positive muscular work realised by one leg against the other during double contact $W_{\text{int},dc}$ was evaluated by:

$$W_{\text{int},dc} = W_{\text{back}} + W_{\text{front}} - W_{\text{ext}}. \quad (3)$$

Since $W_{\text{int},dc}$ was computed from the individual limb ground reaction forces, it was necessary that the two feet were on different plates during the double contact phase. This requirement could not often be fulfilled over consecutive double contact phases. For this reason, $W_{\text{int},dc}$ was measured on a single double contact phase of the stride and the result was doubled to obtain the $W_{\text{int},dc}$ for the whole stride. In 10% of the trials, two successive measurements of $W_{\text{int},dc}$ were possible within a stride; the two measurements were not statistically different ($t = -0.995$, $P < 0.32$, $N = 53$).

Evaluation of total positive muscular work done each stride

In order to compute the total positive muscular work done (W_{tot}), it is necessary to account for the possible energy transfers between W_{ext} , $W_{\text{int},k}$ and $W_{\text{int},dc}$. Willems et al. (1995) showed that W_{tot} was best evaluated when no transfers of energy were allowed between W_{ext} and $W_{\text{int},k}$. Bastien et al. (2003) carefully analysed which part of the positive mechanical work done by the legs can be attributed to W_{ext} and to $W_{\text{int},dc}$. In the following paragraphs, we analyse the possible energy transfers between $W_{\text{int},k}$ and $W_{\text{int},dc}$.

During the double contact phase, the push of the back leg that increases the forward speed of the *COM* relative to the surroundings also increases the backward speed of the front limb relative to the *COM*. This is shown, for example, in the first period of double contact in Fig. 1. The back leg (in this

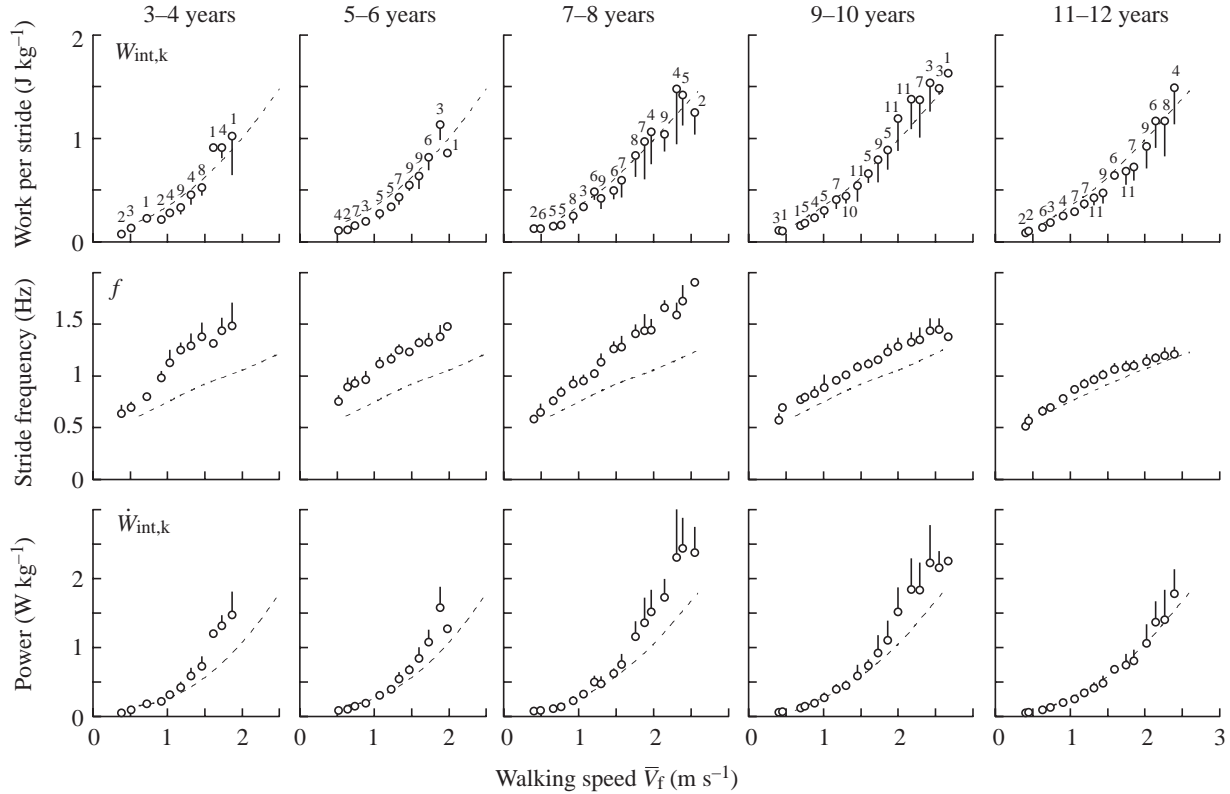


Fig. 2. The mass-specific internal work done per stride to accelerate the limbs relative to the centre of mass of the body ($W_{\text{int},k}$) and the stride frequency (f) are shown as a function of speed in each age group (top and middle row, respectively). The mass-specific internal power spent to move the limbs relative to the centre of mass of the body ($\dot{W}_{\text{int},k} = W_{\text{int},k} \times f$) is presented as a function of speed in the bottom row. Each symbol is the mean of the data grouped into $0.13\text{--}0.14\text{ m s}^{-1}$ (0.5 km h^{-1}) intervals along the abscissa. Bars indicating the s.d. of the mean are drawn when they exceed the size of the symbol. The figures near each symbol in the top row represent N . The broken lines indicate the adult trends: in the top and middle panels, lines represent the weighted mean of the adult data, whereas in the bottom panels, lines are a second-order polynomial fit (KaleidaGraph 3.6). Note that the mass-specific $\dot{W}_{\text{int},k}$ is larger in children due to a higher stride frequency with an approximately equal internal work per stride.

case, the left leg) does positive muscular work to lift and to accelerate the *COM* (increment a in E_{ext} ; Fig. 1). The back leg also does positive muscular work on the front leg (increment b in $W_{\text{int},\text{dc}}$; Fig. 1). The work done on the front leg can appear as an increase in the rotational and translational kinetic energy of the front leg relative to the *COM* (increment c in $E_{\text{int},k}^1$; Fig. 1) rather than just being absorbed and dissipated as negative work in the muscles of the front leg (decrement d in $W_{\text{int},\text{dc}}$; Fig. 1). In order to allow this transfer, the $E_{\text{int},k}^1$ and $W_{\text{int},\text{dc}}$ curves of each leg are added instant-by-instant. Due to this transfer during the double contact phase, the increment e in E_{int}^1 (Fig. 1) is smaller than increment c in $E_{\text{int},k}^1$. The sum of the increments of the resulting curve, E_{int}^1 , is the internal work done on a lower limb (W_{int}^1).

The total positive work done by the muscles during walking, after allowing reasonable energy-saving transfers, is:

$$W_{\text{tot}} = W_{\text{ext}} + W_{\text{int}} = W_{\text{ext}} + W_{\text{int}}^1 + W_{\text{int},k}^1. \quad (4)$$

The total positive mechanical work done, not allowing energy transfers between W_{ext} , $W_{\text{int},k}$ and $W_{\text{int},\text{dc}}$, would be:

$$W_{\text{tot}} = W_{\text{ext}} + W_{\text{int}} = W_{\text{ext}} + W_{\text{int},\text{dc}} + W_{\text{int},k}$$

$$W_{\text{ext}} + W_{\text{int},\text{dc}} + W_{\text{int},k}^1 + W_{\text{int},k}^1. \quad (5)$$

Normalisation of the mechanical work done during a stride

In order to compare subjects of different body size, the work done per stride was divided by the subject's body mass. This mass-specific work can then be either divided by the stride length to obtain the work done per unit distance or divided by the stride period to obtain the mean mechanical power expended during walking. In the sections that follow, the work symbols (W) usually refer to the mass-specific work done per unit distance ($\text{J kg}^{-1} \text{ m}^{-1}$), and the symbols with a dot (\dot{W}) refer to the mass-specific power (W kg^{-1}).

Efficiency of positive work production

Efficiency of positive work production is calculated as the ratio of the total positive muscular mechanical power to the net steady-state energy consumption rate (\dot{M}_{net}). The \dot{M}_{net} is the energetic equivalent of the total oxygen consumption rate

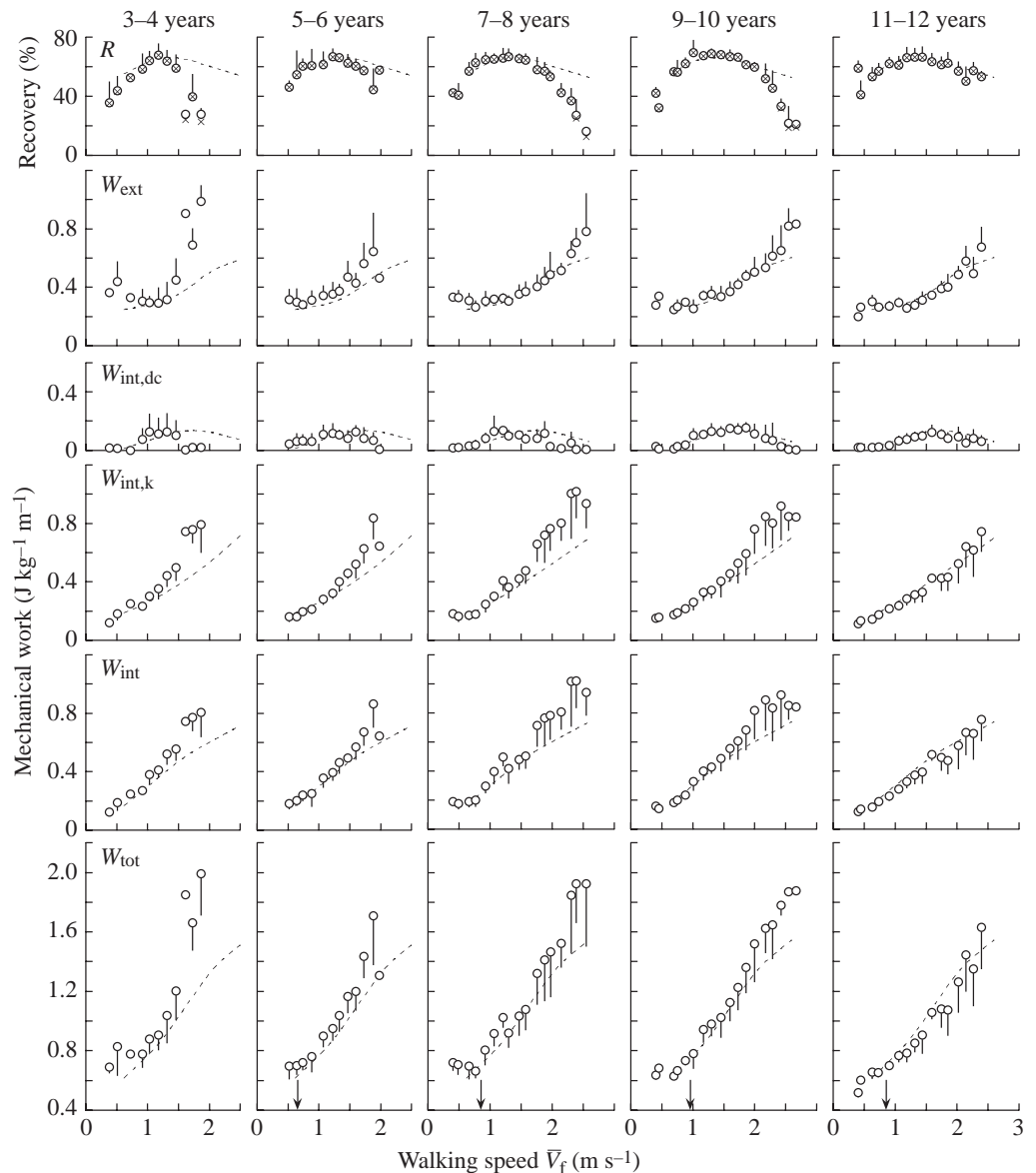


Fig. 3. Energy recovery and mass-specific mechanical work per unit distance as a function of walking speed in different age groups. The pendular recovery of mechanical energy defined by equation 1 (R ; circles) and by equation 2 (R_c ; crosses) and the external work (W_{ext}) are presented in the two upper rows. The internal work done by one leg against the other ($W_{int,dc}$) is presented in the third row. The kinetic internal work ($W_{int,k}$; fourth row) is measured, allowing energy transfer between the segments of the same limbs but not between limbs. The internal work (W_{int} ; fifth row) is measured, allowing energy transfer between $W_{int,dc}$ and $W_{int,k}$ (see Materials and methods). The bottom row shows the total work ($W_{tot}=W_{ext}+W_{int}$). The broken lines represent the weighted mean of the adult data (other indications are as in Fig. 2). Note that above $\sim 1 \text{ m s}^{-1}$, W_{ext} , W_{int} and W_{tot} are greater in children than in adults; these differences are greater the younger the subject and tend to disappear after the age of 10.

minus the standing oxygen consumption rate. The total oxygen consumption rate for children was taken from the data of DeJaeger et al. (2001).

Results

Internal power due to the movements of the limb segments relative to the COM

As walking speed goes up, the velocity of the head/neck/trunk segment relative to the surroundings increases. As a consequence, the backward velocity of the supporting limb relative to the *COM* increases. Furthermore, the stride length becomes longer and the time to reset the limbs becomes shorter. As a result, the forward velocity of the swing leg increases relative to the *COM*. For these reasons, the mass-specific $W_{int,k}$ done per stride increases with speed, both in children and in adults (top row, Fig. 2). Note that, at a given

speed, children and adults do the same amount of $W_{int,k}$ per unit body mass each stride.

Since the stride frequency (f) at a given speed is higher in children than in adults (middle row, Fig. 2), the mass-specific internal power ($\dot{W}_{int,k} = \text{work per stride multiplied by stride frequency}$) is greater in the children (bottom row, Fig. 2). The difference is greater at high speeds and in the young subjects and becomes negligible at speeds less than 1 m s^{-1} and in subjects older than 10 years.

External, internal and total mechanical work

At all ages, the recovery (R ; equation 1) of mechanical energy *via* the pendulum-like transfer between E_p and E_k attains a maximum of $\sim 65\%$ at intermediate walking speeds (circles in upper row of Fig. 3), although the speed of the maximum R increases with age during growth. In the same panels of Fig. 3, the crosses show the recovery R_c (equation 2).

Table 1. Statistical test of differences between children and adult W_{tot} ($J\ kg^{-1}\ m^{-1}$)

Speed class	Age group (years)				
	3–4	5–6	7–8	9–10	11–12
0.56–0.69 $m\ s^{-1}$	–	$F=3.957\ P=0.0473$	n.s.	n.s.	n.s.
0.69–0.83 $m\ s^{-1}$	n.s.	$F=10.763\ P=0.0011$	n.s.	n.s.	n.s.
0.83–0.97 $m\ s^{-1}$	n.s.	$F=6.961\ P=0.0086$	n.s.	n.s.	n.s.
0.97–1.11 $m\ s^{-1}$	n.s.	$F=9.307\ P=0.0024$	n.s.	n.s.	n.s.
1.11–1.25 $m\ s^{-1}$	n.s.	$F=13.675\ P=0.0002$	$F=4.561\ P=0.0333$	n.s.	n.s.
1.25–1.39 $m\ s^{-1}$	n.s.	$F=16.478\ P=0.0001$	n.s.	n.s.	n.s.
1.39–1.53 $m\ s^{-1}$	$F=10.182\ P=0.0015$	$F=25.245\ P=0.0001$	n.s.	n.s.	n.s.
1.53–1.67 $m\ s^{-1}$	$F=29.257\ P=0.0001$	$F=23.643\ P=0.0001$	n.s.	n.s.	n.s.
1.67–1.81 $m\ s^{-1}$	$F=33.887\ P=0.0001$	$F=20.411\ P=0.0001$	$F=3.993\ P=0.0463$	n.s.	n.s.
1.81–1.94 $m\ s^{-1}$	$F=46.886\ P=0.0001$	$F=4.253\ P=0.0398$	$F=4.985\ P=0.0261$	n.s.	$F=6.308\ P=0.0124$
1.94–2.08 $m\ s^{-1}$	–	$F=11.542\ P=0.0007$	n.s.	$F=12.188\ P=0.0005$	n.s.
2.08–2.22 $m\ s^{-1}$	–	–	n.s.	$F=9.428\ P=0.0023$	n.s.
2.22–2.36 $m\ s^{-1}$	–	–	$F=28.574\ P=0.0001$	$F=12.156\ P=0.0005$	n.s.
2.36–2.50 $m\ s^{-1}$	–	–	$F=22.325\ P=0.0001$	$F=5.273\ P=0.0221$	n.s.
2.50–2.64 $m\ s^{-1}$	–	–	$F=10.440\ P=0.0013$	$F=10.032\ P=0.0016$	–

n.s., not statistically different.

R and R_c are very similar because the variations of E_{kv} are small compared with the variations of E_p and E_{kf} . Since the vertical velocity of the COM is nil when it reaches its highest and lowest point, the maximum and minimum of the E_p curve are likely to be the same as those of the E_p+E_{kv} curve.

The mass-specific external work per unit distance (W_{ext} ; second row, Fig. 3) reaches a minimum at a speed slightly lower than where R is maximal. Above this ‘optimal’ speed, W_{ext} increases more in children than in adults since the decrease of R with speed is greater in children than in adults (the effect of speed and growth on the link between R and W_{ext} was discussed in detail by Cavagna et al., 1983).

Both in children and in adults, the mass-specific $W_{int,dc}$ per unit distance shows an inverted U-shape curve as a function of speed (third row of panels in Fig. 3). $W_{int,dc}$ attains a maximum value of $\sim 0.15\ J\ kg^{-1}\ m^{-1}$, independent of age, although the speed at which this maximum occurs increases from $\sim 1.1\ m\ s^{-1}$ at the age of 3 years to $\sim 1.6\ m\ s^{-1}$ above the age of 10 years. As a consequence, the maximum mass-specific power developed by one leg against the other (which is the product of mass-specific $W_{int,dc}$ per unit distance multiplied by speed) increases with age, from $0.15\ W\ kg^{-1}$ at the age of three to $0.25\ W\ kg^{-1}$ above the age of 10.

The mass-specific $W_{int,k}$ per unit distance (fourth row, Fig. 3) represents the work done to move the limbs relative to the centre of mass; it is the sum of $W_{int,k}^l+W_{int,k}^u$. The difference between $W_{int,k}$ in children and in adults is greater the younger the subject and the higher the speed and becomes negligible after the age of 10.

The mass-specific internal work per unit distance, W_{int} (fifth row, Fig. 3), is not equal to the sum of $W_{int,dc}$ and $W_{int,k}$. Indeed, due to the energy transfer between the $W_{int,dc}$ and $E_{int,k}^l$ curves (Fig. 1), W_{int} is very similar to $W_{int,k}$. Compared with adults, W_{int} is noticeably greater in subjects younger than 11 years and at speeds higher than $1.5\ m\ s^{-1}$.

The total mass-specific muscular work per unit distance, W_{tot} (bottom row, Fig. 3), is calculated as the sum of the mass-specific external work per unit distance, W_{ext} , plus the mass-specific internal work per unit distance, W_{int} . The arrows in the bottom panels indicate the speed at which the net energy cost is minimal (see fig. 3 of DeJaeger et al., 2001). Contrary to the net energy cost of walking, the curve of W_{tot} as a function of speed does not have a well-defined minimum, although this could occur at speeds lower than the ones explored. Above $0.5\ m\ s^{-1}$, W_{tot} increases with walking speed more steeply in children than in adults. A two-way repeated-measures analysis of variance with contrasts (SuperANOVA, 1.11) was made to determine the speed at which W_{tot} differs between children and adults. Specifically, the effect of speed was analysed within each age group, and the speed at which W_{tot} in children became significantly different from that in adults was determined (Table 1). In children younger than 11 years, W_{tot} is always greater at high walking speeds. The contrast analysis also shows a statistical difference in W_{tot} between the 5–6 years group and the adults, even at very low speeds. This difference is of the order of $0.04\ J\ kg^{-1}\ m^{-1}$, which represents $\sim 5\%$ of the adult values. Even if this difference is statistically significant it is unlikely to be biologically significant.

Discussion

In the present study, the internal work done to accelerate the limb segment relative to the COM ($W_{int,k}$) is measured for the first time in children walking at different speeds. $W_{int,k}$ is measured simultaneously with the external work (W_{ext}) and the work done by one leg against the other ($W_{int,dc}$) per stride. The $W_{int,k}$, W_{ext} and $W_{int,dc}$ are combined, taking into account possible energy transfers, to get the total mechanical work (W_{tot}) per stride. The results obtained for the mass-specific W_{ext} and $W_{int,dc}$ per unit distance are in agreement with those

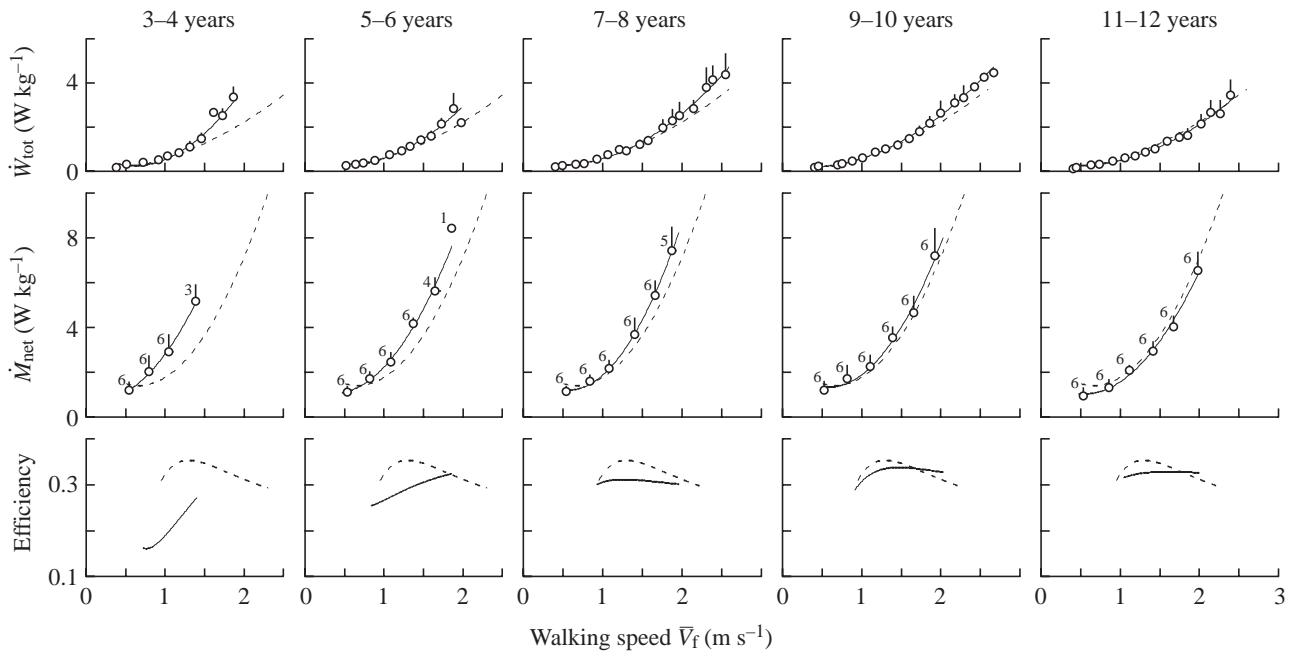


Fig. 4. Mechanical power, net metabolic power and efficiency of positive work production in walking children. The top row presents the mass-specific total positive mechanical power (\dot{W}_{tot}) as a function of speed in each age group. The second row shows the net energy consumption rate at steady state (\dot{M}_{net}); these data are taken from DeJaeger et al. (2001). The efficiency of positive work production during walking (bottom row) is calculated as \dot{W}_{tot} divided by \dot{M}_{net} (equation 6). The values of efficiency are only presented at speeds above $\sim 0.75 \text{ m s}^{-1}$ where results are considered to be robust (see text). The continuous and broken lines are fitted through all the data of children and adults, respectively, using a second-order polynomial function (KaleidaGraph 3.6). Efficiency is computed using these polynomial functions. Other indications are as in Fig. 2. Note that in children younger than six, the efficiency of positive work production during walking is lower than in adults.

of Cavagna et al. (1983) and Bastien et al. (2003), respectively.

Efficiency of positive work production during walking

The efficiency of positive work production by the muscles and tendons during walking is calculated as the ratio of the total mechanical power (\dot{W}_{tot} ; i.e. the work per stride multiplied by the stride frequency) to the net energy consumption rate (\dot{M}_{net} ; i.e. the gross energy consumption rate minus the standing energy expenditure rate):

$$\text{Efficiency} = \dot{W}_{tot} / \dot{M}_{net} . \tag{6}$$

The total mechanical power is shown as a function of walking speed in the top row of Fig. 4. \dot{M}_{net} , the cost of operating the locomotory machinery, is presented in the middle row of Fig. 4 (data from DeJaeger et al., 2001). At all ages, both \dot{W}_{tot} and \dot{M}_{net} increase with walking speed, although the increase is greater the younger the subject. The differences in \dot{W}_{tot} and in \dot{M}_{net} between adults and children disappear after the age of 10.

The efficiency of positive work production is presented in the bottom row of Fig. 4. Assuming the precision of the mechanical power measurement is as good as 0.1 W kg^{-1} , then at low speeds, where the total mechanical power is small, a change in \dot{W}_{tot} of 0.1 W kg^{-1} would result in a change in the efficiency of >0.05 . For this reason, the values of efficiency are considered to be robust only at speeds above $\sim 0.75 \text{ m s}^{-1}$.

In adults, the efficiency reaches a maximum of 0.30–0.35 at

$\sim 1.25 \text{ m s}^{-1}$; at lower and higher speeds the efficiency decreases. These values are in good agreement with those of Cavagna and Kaneko (1977) and Willems et al. (1995). At speeds greater than $\sim 1 \text{ m s}^{-1}$, the efficiency of positive work production is greater than the maximal efficiency of the conversion of chemical energy into positive work by muscles (≤ 0.25 ; Dickinson, 1929), suggesting that elastic energy is stored during the phase of negative work to be recovered during the following phase of positive work (Willems et al., 1995).

Before the age of seven, the increase in \dot{M}_{net} cannot be explained only by an increase in \dot{W}_{tot} . Part of the extra cost of walking in young children appears to be due to a reduction in the efficiency of positive work production. For example, in 3–4-year-old children, the efficiency is 0.15–0.25, while after the age of six the efficiency is similar in children and adults. The lower efficiency in young children could be explained, at least in part, by the immature muscular pattern observed during walking before the age of five (Sutherland et al., 1988), which may require more isometric and/or antagonistic contractions to stabilise the body segments. These contractions would result in an increased energy expenditure without any increase in the mechanical work (Griffin et al., 2003).

Contribution of external and internal power to the total mechanical power during walking

At speeds below 1 m s^{-1} , the internal power is smaller than the external power in all age groups (Fig. 5). This is due to the

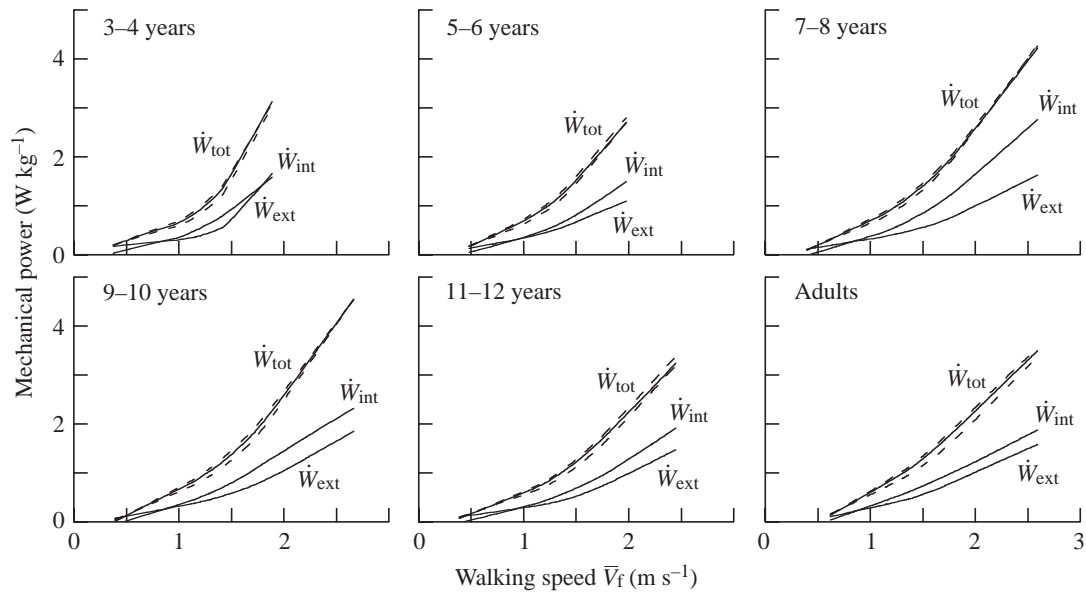


Fig. 5. Contribution of external and internal power to the total mechanical power spent during walking. In each age group, the mass-specific external power (\dot{W}_{ext}), internal power (\dot{W}_{int}) and total power (\dot{W}_{tot}) are presented as a function of the walking speed. For \dot{W}_{tot} , the solid line represents the total mechanical power based upon equation 4, which allows reasonable energy transfers (see Materials and methods). The lower broken line shows the total mechanical power computed as the sum of \dot{W}_{ext} and $\dot{W}_{\text{int},k}$ (as has been done in the past). The upper broken line shows the total mechanical power based upon equation 5, which does not allow any energy transfers between \dot{W}_{ext} , $\dot{W}_{\text{int},k}$ and $\dot{W}_{\text{int},dc}$. Lines represent the weighted mean of the data (KaleidaGraph 3.6). Note that at low speeds, \dot{W}_{ext} is greater than \dot{W}_{int} .

fact that the two components of the internal power tend towards zero as speed approaches zero. On the contrary, the external power, specifically the power necessary to sustain the vertical movements of the *COM*, does not tend towards zero as speed approaches zero (Cavagna et al., 1983). As speed is increased above 1 m s^{-1} , \dot{W}_{int} increases faster than \dot{W}_{ext} , and at high walking speed it is 20–40% greater than \dot{W}_{ext} (except in the 3–4-year olds).

In the present study, the two components of the internal power, and the energy transfers between them, are taken into account for the first time in the computation of the total muscular power of walking. \dot{W}_{tot} , based upon equation 4 (i.e. allowing all reasonable energy transfers, as explained in the Materials and methods), is shown by the solid line in Fig. 5. If, on the other hand, the total power is based upon equation 5 (i.e. assuming no energy transfers), then the resulting total power is shown by the upper broken line in Fig. 5. At the other limit, if the total power is calculated simply as the sum of $\dot{W}_{\text{ext}} + \dot{W}_{\text{int},k}$, ignoring $\dot{W}_{\text{int},dc}$ as has been done in the past, the result is the lower broken line in Fig. 5. It can be seen that at all ages, $\dot{W}_{\text{int},dc}$ represents a small fraction of the total muscular power spent during walking: $\dot{W}_{\text{int},dc}$ represents $\sim 10\%$ of the total power at intermediate speeds, decreasing to zero at low speeds and $< 5\%$ at high speeds.

Normalisation for body size

At a given speed, $\dot{W}_{\text{int},k}$ per unit body mass and per stride is the same in all age groups (top row, Fig. 2) in spite of large differences in stride frequency, movement amplitude and limb

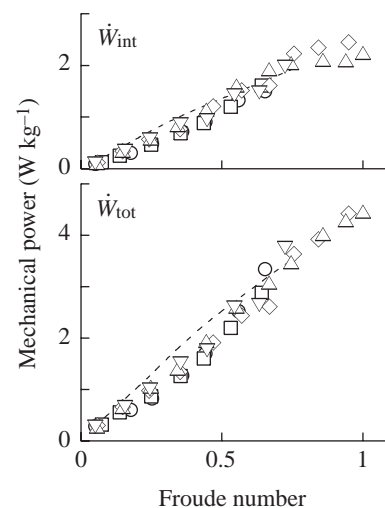


Fig. 6. The mass-specific internal power (\dot{W}_{int}) and total mechanical power (\dot{W}_{tot}) are shown as a function of walking speed. The speed is normalised using the dimensionless Froude number $[\bar{V}_f^2(g/l)]$, where \bar{V}_f is the forward mean walking speed, g is the acceleration of gravity and l is the leg length], which allows different size subjects to be compared. Each age group is represented by a different symbol (circles, 3–4 years; squares, 5–6 years; diamonds, 7–8 years; triangles, 9–10 years; inverted triangles, 11–12 years). Broken lines represent the weighted mean of the adult data (KaleidaGraph 3.6). Other indications are as in Fig. 2. Note that normalisation of the speed reduces the differences between adults and children.

dimensions. In other words, this normalisation of $\dot{W}_{\text{int},k}$ makes it independent of the amplitude/duration of the oscillation and

takes into account the different dimensions of the children and adults.

Different size subjects can be compared at equivalent, size-independent speeds if the mean velocity is normalised using the Froude number (Alexander, 1989). This assumes that children and adults move in a dynamically similar manner, i.e. all lengths, times and forces scale by the same factors. In a situation such as walking, where inertia and gravity are of primary importance, size-dependent speed differences should disappear if the assumption of dynamic similarity is justified.

The upper panel of Fig. 6 shows \dot{W}_{int} as a function of the Froude speed. For the most part, the differences between children and adults disappear, although at the same Froude speed the data of the smaller subjects tend to be lower than those of the larger subjects, indicating that not all differences can be explained simply on the basis of size. The same can be seen for \dot{W}_{tot} (Fig. 6, lower panel). Likewise, when \dot{W}_{ext} , \dot{M}_{net} and $\dot{W}_{\text{int,dc}}$ are expressed as a function of the Froude number, the differences between children and adults also tend to disappear (Cavagna et al., 1983; DeJaeger et al., 2001; Bastien et al., 2003). These observations indicate that, after the age of three, the differences observed in the mechanics and energetics of walking during growth may be explained, for the most part, on the basis of dynamic similarity. The fact that efficiency is lower in very young children compared with in adults suggests that factors other than size scaling, such as developmental changes in the neuromuscular system, may play a role before the age of six.

List of symbols

COM	centre of mass of the body
E_{ext}	mechanical energy of the COM
E_{int}^l	internal energy of the lower limb
$E_{\text{int,k}}^l$	kinetic energy change of the lower limbs due to their velocity relative to the COM
$E_{\text{int,k}}^u$	kinetic energy change of the upper limbs due to their velocity relative to the COM
E_k	kinetic energy of the COM
E_{kf}	kinetic energy due to the forward motion of the COM
E_{kv}	kinetic energy due to the vertical motion of the COM
E_p	gravitational potential energy of the COM
f	stride frequency
g	gravitational acceleration
l	leg length
m	body mass
\dot{M}_{net}	net steady-state energy consumption rate
R	recovery of mechanical energy through a pendular mechanism
S_v	vertical displacement of the COM
\bar{V}_f	mean walking speed
V_f	forward component of the velocity of the COM
V_v	vertical component of the velocity of the COM
W_{back}	positive muscular work done by the back leg during double contact

W_{ext}	external work
\dot{W}_{ext}	mass-specific external power
W_f	work done to sustain the forward motion of the COM
W_{front}	positive muscular work done by the front leg during double contact
W_{int}	internal work
\dot{W}_{int}	mass-specific internal power
$W_{\text{int,dc}}$	positive muscular work realised by one leg against the other during double contact
$\dot{W}_{\text{int,dc}}$	mass-specific power expended by one leg against the other during the double contact phase
$W_{\text{int,k}}$	work required to move the limbs relative to the COM
$\dot{W}_{\text{int,k}}$	mass-specific internal power expended to move the limbs relative to the COM
W_{int}^l	internal work done on a lower limb
$W_{\text{int,k}}^l$	internal work due to the movements of the lower limbs
$W_{\text{int,k}}^u$	internal work due to the movements of the upper limbs
W_k	work done to accelerate the COM
W_p	potential gravitational energy changes of the COM
W_{tot}	total mechanical work
\dot{W}_{tot}	total mass-specific mechanical power
W_v	work done to sustain the vertical motion of the COM

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