The Journal of Experimental Biology 206, 2967-2978

doi:10.1242/jeb.00494

The double contact phase in walking children

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Accepted 14 May 2003

Summary

During walking, when both feet are on the ground (the double contact phase), the legs push against each other, and both positive and negative work are done simultaneously. The work done by one leg on the other ($W_{int,dc}$) is not counted in the classic measurements of the positive muscular work done during walking. Using force platforms, we studied the effect of speed and age (size) on $W_{int,dc}$. In adults and in 3–12-year-old children, $W_{int,dc}$ (J kg^{-1} m^{-1}) as a function of speed shows an inverted U-shaped curve, attaining a maximum value that is independent of size but that occurs at higher speeds in larger subjects. Normalising the speed with the Froude number shows that $W_{int,dc}$ is maximal at about 0.3 in both children and adults. Differences due to size disappear for the most part when normalised with the Froude number, indicating that these speed-dependent changes are primarily a result of body size changes. At its maximum, $W_{int,dc}$ represents more than 40% of W_{ext} (the positive work done to move the centre of mass of the body relative to the surroundings) in both children and adults.

Key words: child, double contact, locomotion, mechanics, walking, work.

Introduction

During walking, muscles must perform positive work to replace the energy lost from the body at each step, even if the average speed is constant and the terrain level. The measurement of the total muscular work during walking is difficult and often imprecise. The most common method of determining the total muscular work of locomotion is to measure the kinetic and potential energy of the body and to assume that increases in the total energy are due to positive muscular work and decreases are due to energy lost from the system.

The total muscular work is often divided into two parts: the external work and the internal work. The external work (W_{ext}) is performed to raise and accelerate the centre of mass of the body (*COM*) relative to the surroundings. The walking gait in humans and other terrestrial animals involves a pendulum-like transfer between potential and kinetic energy of the *COM*, which substantially reduces the amount of work required of the muscles to move the *COM* at a constant average speed on level terrain (Cavagna et al., 1977).

The internal work is performed to accelerate the body segments relative to the *COM*, to overcome internal friction or viscosity, to overcome antagonistic co-contractions and to stretch the series elastic components (Cavagna et al., 1964). Although any work that is not done on the environment nor changes the energy level of the *COM* is internal work, typically only the work done to accelerate the body segments relative to the *COM* has been measured as classical internal work ($W_{int,k}$), using cinematographic analysis (Cavagna and Kaneko, 1977).

During the double contact phase of walking (DC), when both feet are on the ground, the muscles perform more than just W_{ext} and $W_{int,k}$; they also have to perform work due to the fact that one leg is pushing against the other.

Recently, Donelan et al. (2002a) measured the work done by one leg pushing against the other during DC in walking adults. This mechanism had been discussed by Alexander and Jayes as early as 1978 (Alexander and Jayes, 1978), but the mechanical work had never before been measured. During DC, both legs are on the ground simultaneously and exert horizontal forces in opposite directions; the back leg is pushing forwards while the front leg is pushing backwards. The work performed during DC by the muscles of the back leg can be considered in two parts: the first is to accelerate and raise the *COM*, and the second is to compensate for the work simultaneously absorbed by the muscles of the front leg to redirect the trajectory of the *COM*. The first part is measured as W_{ext} but the second part, the work done by one leg against the other, $W_{int,dc}$, is not measured as W_{ext} nor as $W_{int,k}$.

During growth, body dimensions change significantly, almost 4-fold for the body mass and almost 2-fold for the leg length, between the age of 3 and adulthood (Schepens et al., 1998). The work done by one leg against the other should depend on the forces exerted by each leg and the displacement of the *COM* during DC, both of which may change with age.

The horizontal component of the force should increase as the angle between the legs increases, and the forward displacement of the *COM* during DC may be related to the length of the foot (after the moment of front foot heel-strike, the back foot is 'peeled off' the floor as the *COM* continues to move forwards; Cavagna et al., 1976). The effect of age and body dimensions on $W_{\mathrm{int,dc}}$ is unknown, yet $W_{\mathrm{int,dc}}$ may be an important factor in explaining the higher energy cost at a given speed of walking in children (DeJaeger et al., 2001). In this study, we measure $W_{\mathrm{int,dc}}$ in children and adults during walking at different speeds and compare it with W_{ext}, since, to date, no data exist for the total power output of walking children.

Materials and methods

Subjects

Experiments were performed on 24 healthy children of 3–12 years of age and six healthy young adults of 20–24 years of age. The subjects were divided into six age groups defined as follows: 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. The subjects are the same as those used in a simultaneous study on running; the mean characteristics of each age group are given in table 1 of Schepens et al. (2001).

Informed written 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. All of the subjects wore swimming suits and gym shoes. They were asked to walk across a force platform at different speeds.

The mean speed ($\overline{V}_{\mathrm{f}}$) was measured by two photocells placed at the level of the neck and set 1.5–5.0 m apart depending upon the speed. In each age group, the data were gathered into speed classes of 0.14 m s^{-1} (0.5 km h^{-1}). In most cases, two trials per subject were recorded in each speed class. A total of 895 steps were analysed.

Force platform measurements

The mechanical energy changes of the *COM* due to its motion in the sagittal plane during a walking step were determined from the vertical and horizontal components of the ground reaction forces (Cavagna, 1975). The work necessary to sustain the lateral movements of the *COM* in adults is small (Tesio et al., 1998) and was neglected.

The ground reaction force was measured by means of a force platform (6 m long and 0.4 m wide) mounted at floor level 25 m from the beginning of a path 40 m long. The force platform was made of 10 separate plates, similar to those described by Heglund (1981). The plates were sensitive to forces in the fore-aft and vertical directions and had a natural frequency of 180 Hz and a linear response to within 1% of the measured value for forces up to 3000 N. The difference in the electrical signal to a given force applied at different points on the surface of the 10 plates was less than 1%. The crosstalk between the vertical and forward axis was less than 1% of the applied force. The individual signals of the 10 plates were digitised by a 12-bit analogue-to-digital converter every 5 ms and processed by means of a desktop computer.

A complete step was selected for analysis only when the feet were on different force plates and when the subject was walking at a relatively constant average height and speed. Specifically, the sum of the increments in both forward and vertical velocity could not differ by more than 25% from the sum of the decrements (Cavagna et al., 1977). According to these criteria, the difference in the forward speed of the *COM* from the beginning to the end of the selected step was less than 6% of $\overline{V}_{\mathrm{f}}$ (except in four instances at very low speeds below 0.56 m s^{-1}, where it was up to 9%), and the mean vertical force was within 5% of the body weight.

The step length (L_{step}) was calculated as $\overline{V}_{\mathrm{f}}$ times the step period measured from the force tracings. The distance the *COM* moves forward during the period of double contact (L_{dc}) was calculated as the mean speed during DC multiplied by the DC period measured from the force tracings. The leg length, L_{leg}, was measured as the distance from the ground to the greater trochanter as the subjects stood vertically. The limb angle (measured in radians) was calculated as:

$$\text{Limb angle} = 2 \cdot \arcsin\left(\frac{L_{\mathrm{step}}}{2 \cdot L_{\mathrm{leg}}}\right). \tag{1}$$

Calculation of the positive muscular work done by one leg against the other during double contact, $W_{int,dc}$

The positive muscular work done by one leg against the other during DC is calculated in a three-step process: (1) measure all the work done by each leg on the *COM* (including passive work and external work); (2) subtract any work that may have been done passively, i.e. work that did not have to be done by muscular force; and (3) subtract the external work, W_{ext}. The remaining work is equal to the positive muscular work done by one leg against the other during double contact, $W_{\mathrm{int,dc}}$.

Step 1. Measure all the work done by each leg on the COM

This requires measuring the individual limb ground reaction forces, having each foot on a separate force plate. The work curves shown in Fig. 1B are calculated independently for the back and the front limb as:

$$\begin{aligned} W_{\mathrm{f,back}} &= \int_{t1}^{t2} (\mathbf{F}_{\mathrm{f,back}} \cdot \mathbf{V}_{\mathrm{f}}) \cdot \mathrm{d}t \qquad W_{\mathrm{v,back}} = \int_{t1}^{t2} (\mathbf{F}_{\mathrm{v,back}} \cdot \mathbf{V}_{\mathrm{v}}) \cdot \mathrm{d}t \\ W_{\mathrm{f,front}} &= \int_{t1}^{t2} (\mathbf{F}_{\mathrm{f,front}} \cdot \mathbf{V}_{\mathrm{f}}) \cdot \mathrm{d}t \qquad W_{\mathrm{v,front}} = \int_{t1}^{t2} (\mathbf{F}_{\mathrm{v,front}} \cdot \mathbf{V}_{\mathrm{v}}) \cdot \mathrm{d}t \end{aligned} \tag{2}$$

where *t1* and *t2* are, respectively, the beginning and end of a complete step, $\mathbf{F}_{\mathrm{f,back}}$, $\mathbf{F}_{\mathrm{f,front}}$, $\mathbf{F}_{\mathrm{v,back}}$ and $\mathbf{F}_{\mathrm{v,front}}$ are the forward and vertical components of the ground reaction force acting upon the back and front leg, and $\mathbf{V}_{\mathrm{f}}$ and $\mathbf{V}_{\mathrm{v}}$ are the forward and vertical instantaneous velocities of the *COM*. $W_{\mathrm{f,back}}$, $W_{\mathrm{v,back}}$, $W_{\mathrm{f,front}}$ and $W_{\mathrm{v,front}}$ are the work done on the *COM* as a function of time resulting from the forward and vertical components of the forces acting upon the back and front leg, respectively.

Step 2. Subtract any work that may have been done passively

Since the purpose of these measurements is to determine the muscular work done, any part of the work that is done passively, without the need of muscular intervention, should be excluded. For example, the external work (discussed in the next section) during walking involves a well-known pendular energy transfer between the kinetic ($E_{k,f}$) and potential energy ($E_p + E_{k,v}$) of the *COM*. It is generally accepted that the positive muscular work done will be overestimated if the pendular energy transfer is not allowed. Part of this pendular transfer takes place during DC. Logically, if one allows the transfer of energy in the external work calculations (the pendulum mechanism), one must allow similar energy transfer in the $W_{int,dc}$ calculations; the phenomenon is the same, only the method of measurement has changed.

In order to allow pendular energy transfers in the $W_{int,dc}$ calculations while disallowing any non-pendular transfers (i.e. the work done by one leg against the other), the work done on the *COM* in the vertical direction (W_v) must be allowed to exchange with the work done on the *COM* in the horizontal direction by each of the legs ($W_{f,back}$ and $W_{f,front}$). To obtain W_v, $W_{v,back}$ and $W_{v,front}$ can be summed with no loss or transfer of work because both legs are simultaneously doing positive or negative work, depending upon the vertical displacement of the *COM* and the fact that $\mathbf{F}_{v,back}$ and $\mathbf{F}_{v,front}$ are always positive. In contrast to $W_{v,back}$ and $W_{v,front}$, $W_{f,back}$ and $W_{f,front}$ cannot be summed without allowing non-pendular transfers, i.e. $W_{f,back}$ and $W_{f,front}$ have to be treated separately.

Work transfers between W_v and $W_{f,back}$ and between W_v and $W_{f,front}$ occur during DC. A close examination of Fig. 1 shows two opportunities where positive work may be done passively and incorrectly counted as positive muscular work unless it is subtracted.

The first opportunity is during the beginning of DC when the *COM* is 'falling down' off the back leg due to gravity (this is seen as the decrease in the W_v curve at the beginning of DC shown in Fig. 1B), passively pivoting around the point of contact of the back leg as the compliant front leg starts to take up the load. The curvilinear trajectory of the falling *COM* involves both tangential and normal accelerations, which can be decomposed into vertical and horizontal components. The horizontal component of the acceleration of the *COM* must

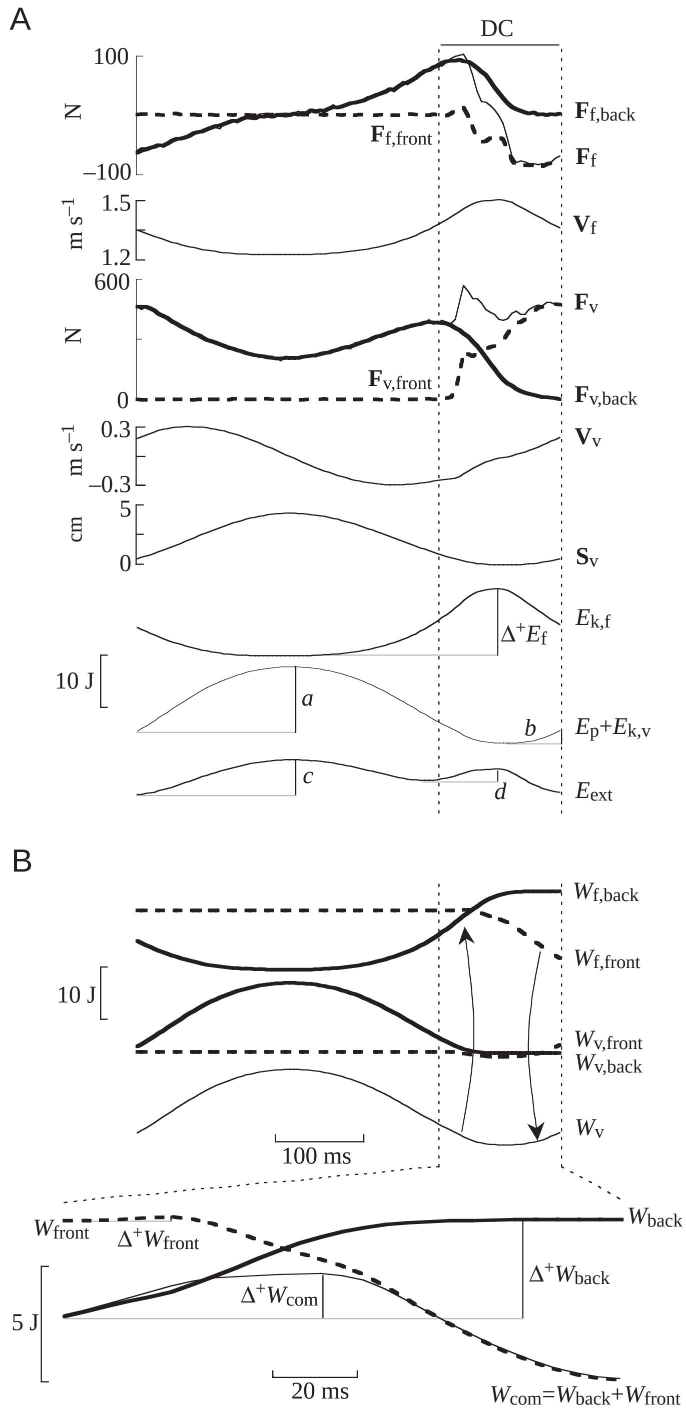

Fig. 1. Methods. (A) Ground reaction forces (**F**; measured in N), velocity (**V**; m s^{-1}), displacement (**S**; cm), energy of forward movement ($E_{k,f}$; J), energy of vertical motion (E_p+E_{kv}; J) and total mechanical energy (E_{ext}=E_{kf}+E_p+E_{kv}; J) of the centre of mass (*COM*) during a walking step. Vertical and forward components are indicated by the subscripts v and f, respectively. Bold continuous lines represent the back leg; broken lines represent the front leg, and thin continuous lines represent the sum of both legs. Back and front legs are indicated by the subscripts back and front, respectively. Increments of each energy curve are, respectively, Δ^+E_f, Δ^+E_v (a+b) and W_{ext} (c+d), representing the positive work done by the muscles to increase the level of each energy curve. The work done to maintain the motion of the *COM* is W_{ext}. (B) Work curves for each leg independently ($W_{f,front}$, $W_{f,back}$, $W_{v,front}$ and $W_{v,back}$) and curve W_v (sum of $W_{v,front}$ and $W_{v,back}$) during a step. Work curves are also presented during the double contact (DC) phase, W_{back}=$W_{f,back}$ + 'transfer from W_v' (see equation 3); W_{front}=$W_{f,front}$ + 'transfer from W_v' (see equation 4); W_{com}=W_{back}+W_{front}. The work done by one leg against the other during DC ($\Delta^+W_{int,dc}$) is equal to (Δ^+W_{back}+Δ^+W_{front})–Δ^+W_{com} (see Materials and methods; equation 6). Data are from a 10.5-year-old boy walking at 1.32 m s^{-1}. The step duration is 0.485 s and DC lasts for 0.14 s. DC is delimited by the vertical dotted lines.

result from a horizontal component of the force acting at the pivot. Part of this horizontal component of the force is derived passively from the acceleration of gravity and results in a forward acceleration of the *COM*. In other words, the passive displacement of the *COM* accelerating downwards and accelerating forwards under the influence of gravity would result in a passive horizontal component of the ground reaction force applied on the back leg. This force multiplied by the forward displacement of the *COM* results in a passive increase in $W_{\mathrm{f,back}}$ (this is part of the increase in the $W_{\mathrm{f,back}}$ curve at the beginning of the DC shown in Fig. 1B).

Thus, the positive work done by the horizontal component of the ground reaction force acting on the back leg during the first part of DC (the increase in the $W_{\mathrm{f,back}}$ curve during DC shown in Fig. 1B) should be reduced by the amount of simultaneous negative work resulting from the vertical forces (the decrease in the W_{v} curve during DC shown in Fig. 1B), as indicated by the upward arrow in the figure. The resulting curve, W_{back}, is the net muscular work done by the back leg during DC:

$$W_{\mathrm{back}} = W_{\mathrm{f,back}} - |W_{\mathrm{v}}|_{\mathrm{DEC}}\,, \tag{3}$$

where DEC indicates that the second term is subtracted only when W_{v} is decreasing.

The second opportunity for pendular transfer occurs during the latter part of DC when the *COM* starts to 'ride up' onto the front leg, passively pivoting around the point of contact of the front leg (this is seen as the increase in the W_{v} curve at the end of DC shown in Fig. 1B) as the kinetic energy of forward motion is converted into potential energy. As before, the curvilinear trajectory of the *COM* can be decomposed into a forward deceleration and vertical acceleration of the *COM*. Part of the vertical component of the ground reaction force is derived passively from the forward deceleration of the *COM*. This vertical force multiplied by the vertical displacement of the *COM* results in a passive increase in W_{v} (the increase in the W_{v} curve at the end of the DC shown in Fig. 1B).

The positive work done to raise the *COM* during the second part of double contact (the increase in the W_{v} curve during DC shown in Fig. 1B) should be reduced by the amount of simultaneous negative work done by the horizontal component of the ground reaction forces acting on the front leg (the decrease in the $W_{\mathrm{f,front}}$ curve during DC shown in Fig. 1B), as indicated by the downward arrow in the figure. The resulting curve, W_{front}, is the net muscular work done by the front leg during DC:

$$W_{\mathrm{front}} = W_{\mathrm{f,front}} + |W_{\mathrm{v}}|_{\mathrm{INC}}\,, \tag{4}$$

where INC indicates that the second term is only added when W_{v} is increasing.

The net positive muscular work done by each leg is equal to the sum of the increments in the W_{back} and W_{front} curves, respectively, $\Delta^{+}W_{\mathrm{back}}$ and $\Delta^{+}W_{\mathrm{front}}$.

Step 3. Subtract the external work

The external work is subtracted from the net positive muscular work done by each leg in order to count only the work that is not already measured by the W_{ext}.

The external work method uses the resultant of the ground reaction forces acting on both limbs (i.e. the vertical forces and, separately, the horizontal forces from all of the force plates were summed), resulting in the mechanical cancellation of simultaneous positive and negative work performed by the limbs during double support periods.

The principle of the method to measure W_{ext} and the procedures followed to compute the velocity in the forward and vertical directions, the vertical displacement, the changes in gravitational potential energy and the changes in kinetic energy of the *COM* from the platform signals have been described in detail by Cavagna (1975) and by Willems et al. (1995) and are only briefly described here. Provided that air resistance is negligible, the acceleration of the *COM* in the forward ($\mathbf{a}_{\mathrm{f}}$) and vertical ($\mathbf{a}_{\mathrm{v}}$) directions can be calculated by:

$$\mathbf{a}_{\mathrm{f}} = \frac{\mathbf{F}_{\mathrm{f}}}{m} \quad \text{and} \quad \mathbf{a}_{\mathrm{v}} = \frac{\mathbf{F}_{\mathrm{v}} - \mathbf{P}}{m}\,, \tag{5}$$

where $\mathbf{F}_{\mathrm{f}}$ and $\mathbf{F}_{\mathrm{v}}$ are the forward and vertical components of the ground reaction force measured by the force platform, $\mathbf{P}$ is body weight and m is body mass. The accelerations $\mathbf{a}_{\mathrm{f}}$ and $\mathbf{a}_{\mathrm{v}}$ were integrated numerically by the trapezoidal method to determine the forward ($\mathbf{V}_{\mathrm{f}}$) and vertical ($\mathbf{V}_{\mathrm{v}}$) components of the velocity of the *COM* plus an integration constant. In the forward direction, the integration constant was calculated on the assumption that during the measurement period the mean speed of the *COM* was equal to the mean speed of the neck, as measured by the photocells. In the vertical direction, since the subject was walking on the level, the integration constant was set to zero over an integral number of steps on the assumption that the mean vertical speed was nil. The vertical displacement ($\mathbf{S}_{\mathrm{v}}$) of the *COM* was computed by numerical integration of $\mathbf{V}_{\mathrm{v}}$ (see Fig. 1A).

The kinetic energy of the *COM* due to its motion in the forward direction was calculated as $E_{\mathrm{k,f}}=(m\cdot\mathbf{V}_{\mathrm{f}}^{2})/2$. The energy of the *COM* due to its vertical movement was calculated as $E_{\mathrm{p}}+E_{\mathrm{k,v}}=(m\cdot\boldsymbol{g}\cdot\mathbf{S}_{\mathrm{v}})+[(m\cdot\mathbf{V}_{\mathrm{v}}^{2})/2]$, and the total mechanical energy of the *COM* was calculated as $E_{\mathrm{ext}}=(E_{\mathrm{p}}+E_{\mathrm{k,v}})+E_{\mathrm{k,f}}$. The sum of the increments in $E_{\mathrm{k,f}}$, $E_{\mathrm{p}}+E_{\mathrm{k,v}}$ and E_{ext} represents the positive work done to accelerate the *COM* forward ($\Delta^{+}E_{\mathrm{f}}$), the positive work done against gravity and to accelerate the *COM* upward ($\Delta^{+}E_{\mathrm{v}}$; *a*+*b* in Fig. 1A) and the positive work done to maintain the motion of the *COM* in the sagittal plane (W_{ext}; *c*+*d* in Fig. 1A), respectively.

As noted above, the W_{ext} method sums all the vertical forces and, separately, all the horizontal forces before performing the work calculations on the resultant forces (Fig. 1A), while the $W_{\mathrm{int,dc}}$ method measures the vertical and horizontal force of each foot separately and performs the work calculations on the individual foot forces (Fig. 1B). The two methods are closely related. In fact, the $E_{\mathrm{k,f}}$ curve of Fig. 1A is exactly equal to the sum of the $W_{\mathrm{f,front}}$ plus $W_{\mathrm{f,back}}$ curves of Fig. 1B. Similarly, the $E_{\mathrm{p}}+E_{\mathrm{k,v}}$ curve of Fig. 1A is exactly equal to the W_{v} curve, which is the sum of the $W_{v,front}$ plus $W_{v,back}$ curves of Fig. 1B. And the E_{ext} curve of Fig. 1A is exactly equal to the sum of the $W_{f,front}+W_{f,back}+W_{v,front}+W_{v,back}$ curves of Fig. 1B. The sum of the W_{back} and W_{front} curves results in the W_{com} curve, which is exactly equal to the classic external energy (E_{ext} curve in Fig. 1A) during the period of double contact.

The positive muscular work realised by one leg against the other during double contact ($\Delta^{+}W_{int,dc}$) is therefore equal to:

$$\Delta^{+}W_{int,dc} = (\Delta^{+}W_{back} + \Delta^{+}W_{front}) - \Delta^{+}W_{com}\,, \qquad (6)$$

where $\Delta^{+}W_{back}$ and $\Delta^{+}W_{front}$ are the positive increments of the W_{back} and W_{front} curves, and $\Delta^{+}W_{com}$ is the positive increment of the W_{com} curve (Fig. 1B). The mass-specific work per unit distance done by one leg against the other is $W_{int,dc}$ and is expressed in J kg^{-1} m^{-1}.

Results

The double contact phase as a function of speed and age

At low walking speeds in both children and adults, the DC duration is about 40% of the step period, and the horizontal component of the ground reaction force applied on each leg is small. For instance, the force of the back leg pushing forward ($\mathbf{F}_{f,back}$) is a maximum of only 19 N for an 18 kg 3–4-year-old child and 77 N for a 65 kg adult (Fig. 2). As speed increases, the DC becomes a smaller fraction of the step period (see also Cavagna et al., 1983), and the ground reaction forces increase. At high walking speeds, the DC reduces to about 12% of the step period with a peak $\mathbf{F}_{f,back}$ of 55 N in the 3–4-year-old children, as compared with 19% of the step period with a peak $\mathbf{F}_{f,back}$ of 230 N in the adults (Figs 2, 3); i.e. the DC duration decreases 2–3-fold while the peak $\mathbf{F}_{f,back}$ increases ~3-fold.

The timing of the peak $\mathbf{F}_{f,back}$ force (indicated by the arrows in Fig. 2) also changes with speed and age. At slow and intermediate speeds, the peak $\mathbf{F}_{f,back}$ occurs during the first part of DC in both children and adults. At high walking speeds in adults, the peak $\mathbf{F}_{f,back}$ occurs before the DC period starts, while it remains within the DC period for the youngest children.

At all ages, L_{step} increases with

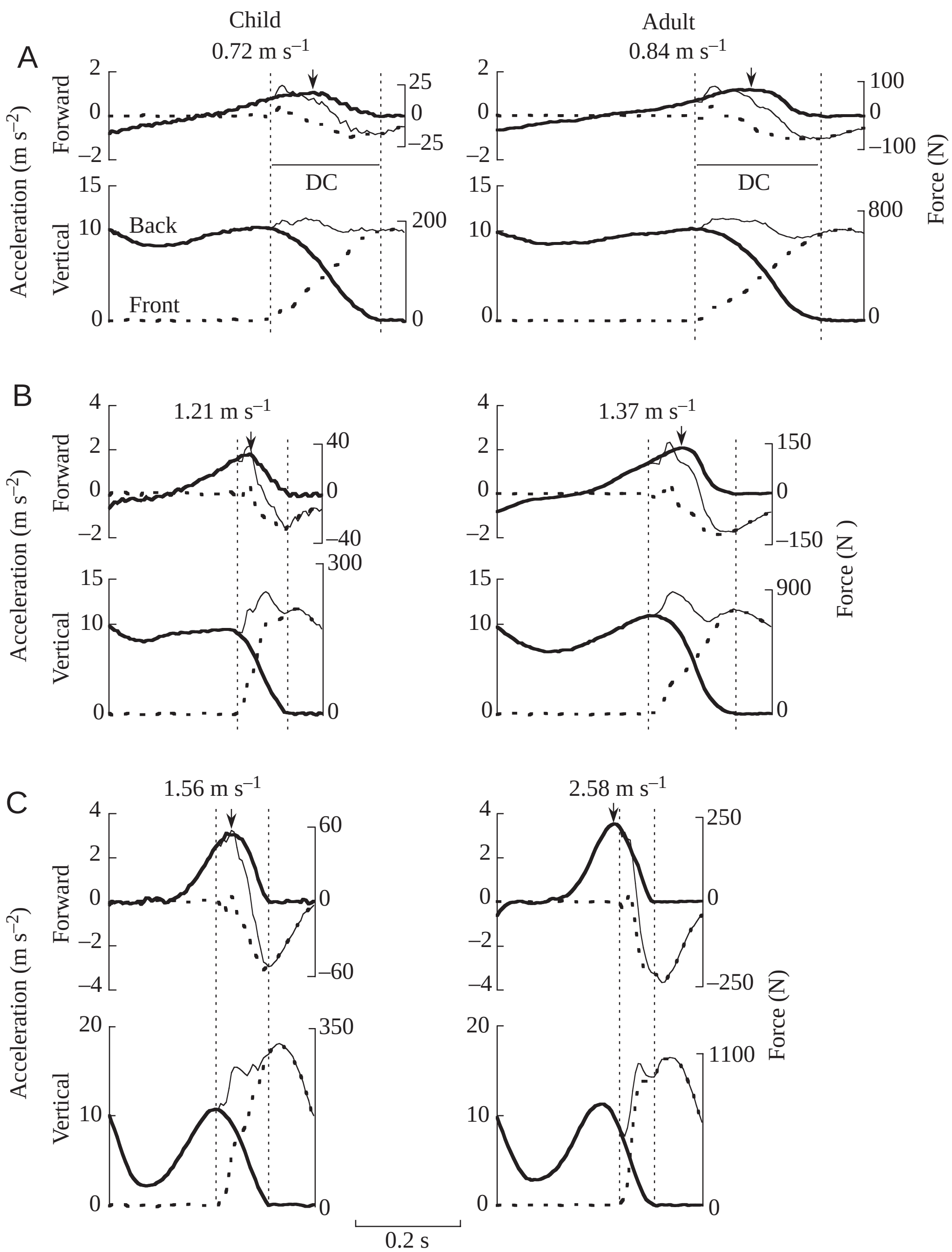

Fig. 2. Typical accelerations (m s^{-2}) and ground reaction forces (N) in the forward ($\mathbf{F}_{f}$) and vertical ($\mathbf{F}_{v}$) direction during a step at a low (A), intermediate (B) and fast (C) speed in a young child (left column) and an adult (right column). The double contact (DC) phase is delimited by the vertical dotted lines. Arrows indicate the peak of the forward ground reaction force on the back leg (peak $\mathbf{F}_{f,back}$). Left column: a 4.9-year-old female, mass of 17.75 kg, leg length of 0.535 m, walking at 0.72 m s^{-1}, 1.21 m s^{-1} and 1.56 m s^{-1} (A to C). Right column: a 20.2-year-old male, mass of 64.90 kg, leg length of 0.919 m, walking at 0.84 m s^{-1}, 1.37 m s^{-1} and 2.58 m s^{-1} (A to C). Other indications are as in Fig. 1.

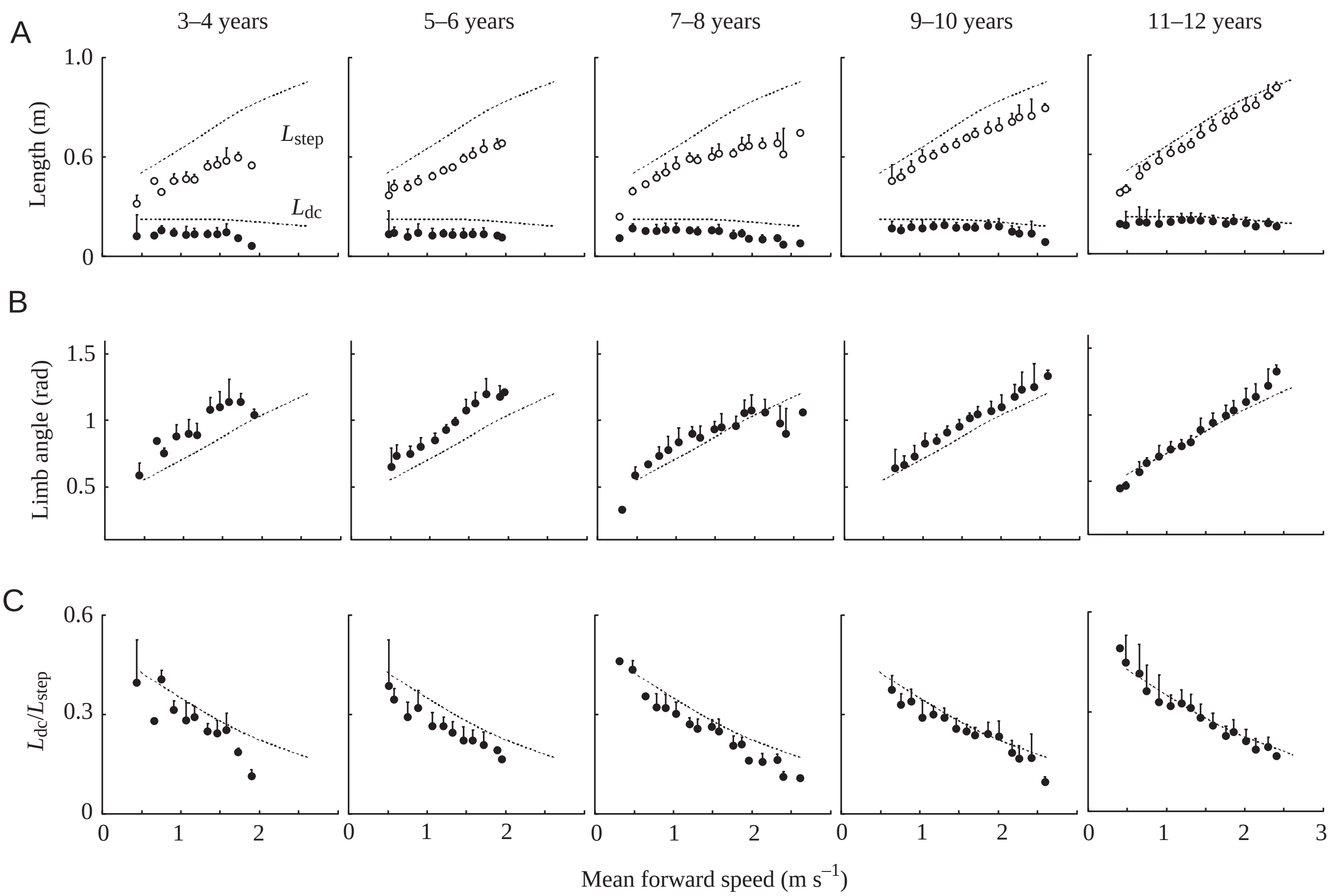

Fig. 3. Description of the double contact (DC) phase as a function of speed and age. (A) In each age group, the step length (L_{step}; measured in metres) and the forward displacement of the centre of mass taking place at each step when both feet contact the ground (L_{dc}; m) are given as a function of the walking speed. L_{dc} was calculated as the mean forward speed during DC multiplied by the fraction of the step during which both feet contact the ground. (B) The angle of contact with the ground during a step was computed from L_{step} and the leg length as shown in the Materials and methods. (C) The relative importance of DC (L_{dc}/L_{step}) is shown as a function of the walking speed. The symbols represent mean values of data grouped into the following intervals along the abscissa: 0.28 m s^{-1} to <0.42 m s^{-1}, 0.42 m s^{-1} to <0.56 m s^{-1}…2.5 m s^{-1} to <2.64 m s^{-1}. *N* is from low to high speed classes for 3–4 years: 2, 1, 7, 8, 6, 13, 7, 9, 7, 2, 3; for 5–6 years: 4, 3, 11, 7, 13, 10, 9, 18, 18, 12, 2, 1; for 7–8 years: 1, 4, 1, 9, 14, 8, 16, 20, 10, 13, 10, 13, 2, 10, 5, 3, 1; for 9–10 years: 3, 9, 16, 22, 19, 23, 19, 12, 12, 11, 17, 10, 8, 3, 3 and for 11–12 years: 1, 4, 5, 6, 8, 13, 18, 18, 12, 13, 19, 14, 16, 8, 6, 3. Bars indicating the S.D. of the mean are drawn when they exceed the size of the symbol. The broken lines indicate the adult trend.

increasing walking speed. At a given speed, children younger than 11 have a smaller L_{step} than adults, in spite of a larger limb angle (Fig. 3A,B). The limb angle increases with speed in children and adults, from 0.35 rad at slow speed to 1.22 rad at high speed.

At slow and intermediate speeds, the forward displacement of the *COM* during double contact (L_{dc}) is independent of speed for all subjects. At the maximal speed, L_{dc} shows a tendency to decrease in all age groups. The relative importance of DC (L_{dc}/L_{step}) decreases with speed for each age group (from 0.4 to 0.1), although young children show a slight tendency to have an overall smaller value compared with adults (see Fig. 3C). Note that the duty factor β, the fraction of stride duration for which a particular foot is on the ground (Alexander and Jayes, 1978), is related to the L_{dc}/L_{step} ratio by: $\beta=[(L_{step}+L_{dc})/2L_{step}]=0.5[1+(L_{dc}/L_{step})]$.

The work done by one leg against the other during DC

$W_{int,dc}$ represents the work done by one leg against the other during DC. The $W_{int,dc}$ normalised to body mass and distance travelled (J kg^{-1} m^{-1}) shows an inverted ∪ shape as a function of walking speed, with a maximum at intermediate speeds for all ages (Fig. 4A). For comparison, the W_{ext} curve tends to a minimum at intermediate speeds (Fig. 4A; see also fig. 4 in Cavagna et al., 1983). The $W_{int,dc}/W_{ext}$ ratio shows an inverted ∪ shape with speed (Fig. 4B), attaining a maximum value of around 0.4 for all ages (except the 3–4-year-old children, who seem to have a higher maximum value).

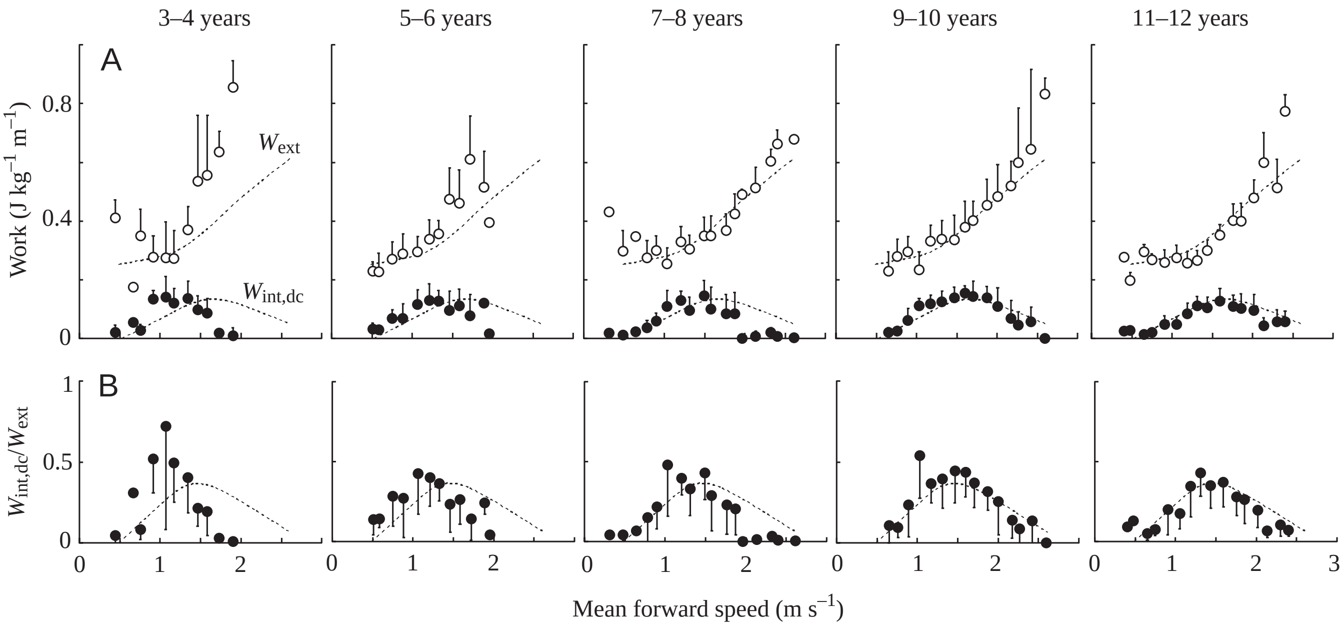

Fig. 4. (A) The mass-specific work per distance ($W_{int,dc}$; J kg^{-1} m^{-1}; filled circles) done by one leg against the other during the double contact (DC) phase and the mass-specific external work per distance (W_{ext}; J kg^{-1} m^{-1}; open circles) done to maintain the centre of mass (*COM*) motion in the sagittal plan are given for each age group as a function of the walking speed. (B) The ratio $W_{int,dc}/W_{ext}$ is given for each age group as a function of speed in the lower panels. Other indications are as in Fig. 3.

Discussion

During the DC phase of walking, the back leg performs almost exclusively positive work while at the same time the front leg performs almost exclusively negative work; each leg is working against the other. This work is ignored by the classic W_{ext} and $W_{int,k}$ measurements (Cavagna et al., 1963, 1983; Cavagna, 1975; Cavagna and Kaneko, 1977; Willems et al., 1995), yet it can amount to a significant fraction of the external work done during walking, for example see Fig. 4.

Relation to previous studies

In 1980, Alexander showed that the classic method (‘energy’ method) of calculating the net work performed during walking, the sum of the increases in mechanical energy of the body, did not measure the work done by one leg against the other during DC (Alexander, 1980) and therefore makes an error in deficit. On the other hand, the ‘hybrid energy/work’ method used by Alexander and Jayes (1978) measured work as the product of a force multiplied by a displacement when the angle between them was 90° and therefore makes an error in excess. In order to avoid these errors, Alexander subsequently developed a many-legged model where the work done by the muscles was calculated separately for each leg (Alexander, 1980).

The method used here to calculate the work done by one leg against the other ($W_{int,dc}$) is in complete agreement with the latter analysis presented by Alexander (1980). However, we do not agree that the ‘energy’ method is at fault because it does not measure every case of simultaneous positive and negative work; in particular, because it does not measure the $W_{int,dc}$ (although it does correctly measure the pendulum-like transfer between potential and kinetic energy of the *COM*, as pointed out by Alexander). The classical method of measuring W_{ext}, originally conceived by Fenn (1930) and developed into an easy to use tool by Cavagna (1975), precisely measures only the work done to accelerate and/or lift the *COM* and some of the work done on the environment (e.g. sand; Lejeune et al., 1998). In addition, the classical method of measuring $W_{int,k}$ (Cavagna and Kaneko, 1977; Willems et al., 1995) measures only the work done to accelerate the body segments relative to the *COM*, although all muscular work other than W_{ext} or work done on the environment should be classified as $W_{int,k}$ (including $W_{int,dc}$). Neither of the classic W_{ext} nor the $W_{int,k}$ methods can be expected to measure $W_{int,dc}$. Similarly, neither the energy nor the work methods, nor a combination of the two, are able to measure all of the muscular work done during locomotion; for example, the positive and negative work done by different muscles in the same leg cannot be measured by these methods (Alexander, 1980).

The work done by one leg against the other has been estimated in adults using a method that explicitly does not allow any transfer of work from one leg to the other, although it implicitly does allow transfers within each leg: the ‘individual limb method’ of Donelan et al. (2002a). These authors state that work by one leg cannot be transferred to the other leg because there are no muscles that cross from one leg to the other. This, however, would not seem to be the case. In general, if two actuators are attached to the same mass, not only can both actuators do work on the mass but they can also do work on each other provided they are not maintained in an exactly 90° orientation to each other. In this case, the actuators

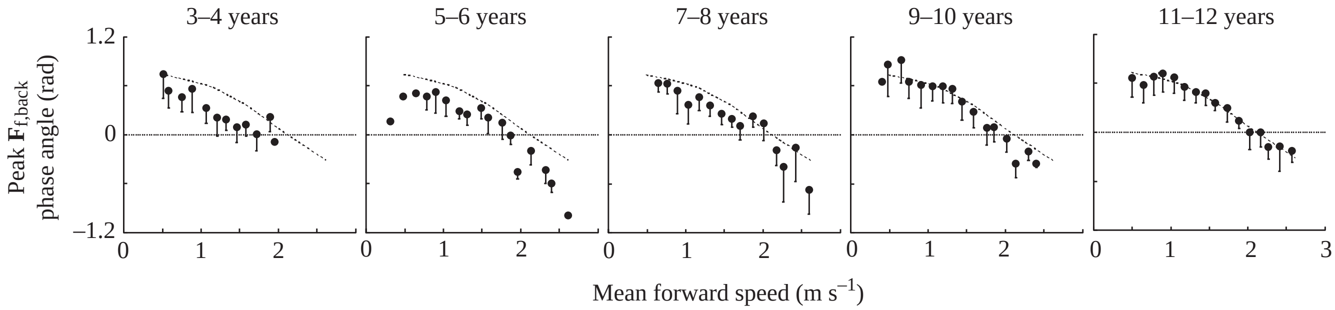

Fig. 5. The phase angle between the peak in the forward push (peak in the $\mathbf{F}_{f,back}$ curve) and the beginning of the double contact (DC) phase is shown as a function of walking speed for the different age groups. The phase angle (rad) is calculated as $2\pi(\Delta t/T)$, where Δt is the difference between the time at which $\mathbf{F}_{f,back}$ is maximal and the beginning of DC, and T is the duration of the step. A positive value means that peak $\mathbf{F}_{f,back}$ occurs during DC; a negative value means that peak $\mathbf{F}_{f,back}$ occurs during the single contact phase preceding the DC phase. Other indications as in Fig. 3.

are the legs and the mass is the *COM*; two specific examples of energy transfers that would be incorrectly disallowed by the individual limb method are given in the Materials and methods.

The basis for all these work measurements is the $W_{f,back}$, $W_{f,front}$, $W_{v,back}$ and $W_{v,front}$ curves, which are derived from the vertical and fore-aft components of the ground reaction forces exerted by each leg on the *COM*, as shown in Fig. 1. If the four curves are summed instant-by-instant and then the increments in the resulting curve are added up, we obtain the classical external work W_{ext}. The instant-by-instant summation of the curves allows decrements in one curve to cancel simultaneous increments in another curve. In other words, W_{ext} allows all energy transfers, in particular the well-known pendular transfers that characterise the walking gait.

Alternatively, if the $W_{f,back}$ and the $W_{v,back}$ curves, and similarly the $W_{f,front}$ and the $W_{v,front}$ curves, are summed instant-by-instant and then the increments in the two resulting curves are added up, we obtain the individual limb method work. This method only allows energy transfers within a limb and excludes any energy transfers between the limbs. Furthermore, this work contains both external work (the work to lift and accelerate the *COM*) and internal work done by one leg against the other during DC (unfortunately, this work is incorrectly, and very confusingly, called 'external work' by Donelan et al.), although it calculates neither one exactly. Part of the passive pendular energy transfer taking place during DC is excluded by disallowing transfers from one leg to the other, resulting in an external work component that is too large. Likewise, part of the energy that is transferred from one leg to the other *via* the energy of the *COM* during DC, as is detailed in the Materials and methods (see equations 3, 4), is excluded as well, resulting in a work done by one leg on the other that is too large. When the individual limb method is applied to our adult data, we obtain the same results over the limited speed range (0.75–2.0 m s^{-1}) studied by Donelan et al. (2002a). However, since fewer energy-saving work transfers are allowed, over the entire speed range studied in adults (0.49–2.61 m s^{-1}) the individual limb method results in a mean of 0.031±0.018 J kg^{-1} m^{-1} (mean ± S.D., N=231) greater work done during DC than the sum of $W_{int,dc}$ plus the W_{ext} done during DC (~10% greater at intermediate speeds, increasing to ~20% at low or high speeds). Subsequent studies that have used the individual limb method have incurred the same errors (Donelan et al., 2002b; Griffin et al., 2003).

In contrast to the individual limb method, $W_{int,dc}$ is calculated by first summing the $W_{v,back}$ and $W_{v,front}$ curves instant-by-instant to obtain the W_v curve (Fig. 1). Next, the W_v curve is summed instant-by-instant with either the $W_{f,back}$ or the $W_{f,front}$ curves to obtain the W_{back} and W_{front} curves, as detailed in the Materials and methods. This summation allows all pendular energy transfers between the vertical work of the *COM* and the fraction of the forward work on the *COM* that can be attributed to each of the legs while avoiding any cancellation of the work done on one leg due to the horizontal push of the other. Finally, the increments in the W_{back} and W_{front} curves are added up and the external work Δ^+W_{com} is subtracted to obtain $W_{int,dc}$.

$W_{int,dc}$ includes only work that is not measured as W_{ext} nor as the 'classical' $W_{int,k}$. Consequently, $W_{int,dc}$ can be directly compared with the last ~70 years of measurements of W_{ext} and $W_{int,k}$ in humans and, with caution, may be simply summed with W_{ext} and $W_{int,k}$ to obtain a measure of total work (acknowledging, of course, the caveats mentioned in the Introduction). The lateral forces were not measured in this study, and the work done by one leg against the other during DC in the lateral direction was ignored. This lateral $W_{int,dc}$ work is a fraction of the lateral component of the work as measured by the individual limb method, and the whole of the lateral component is described as 'small' in adults by Donelan et al. (2002a). The effect of age on the lateral $W_{int,dc}$ has never been measured and is unknown but can be presumed to be small since, by the age of 4 years, children have a lateral displacement of the *COM* not significantly different from that of adults (Lefebvre et al., 2002).

$W_{int,dc}$ *as a function of speed and age*

The $\Delta^+W_{int,dc}$ can only occur when one leg is doing positive work and the other is simultaneously doing negative work, as shown by simultaneous increases and decreases in the W_{back} and W_{front} curves (Fig. 1B). However, the shape of these curves

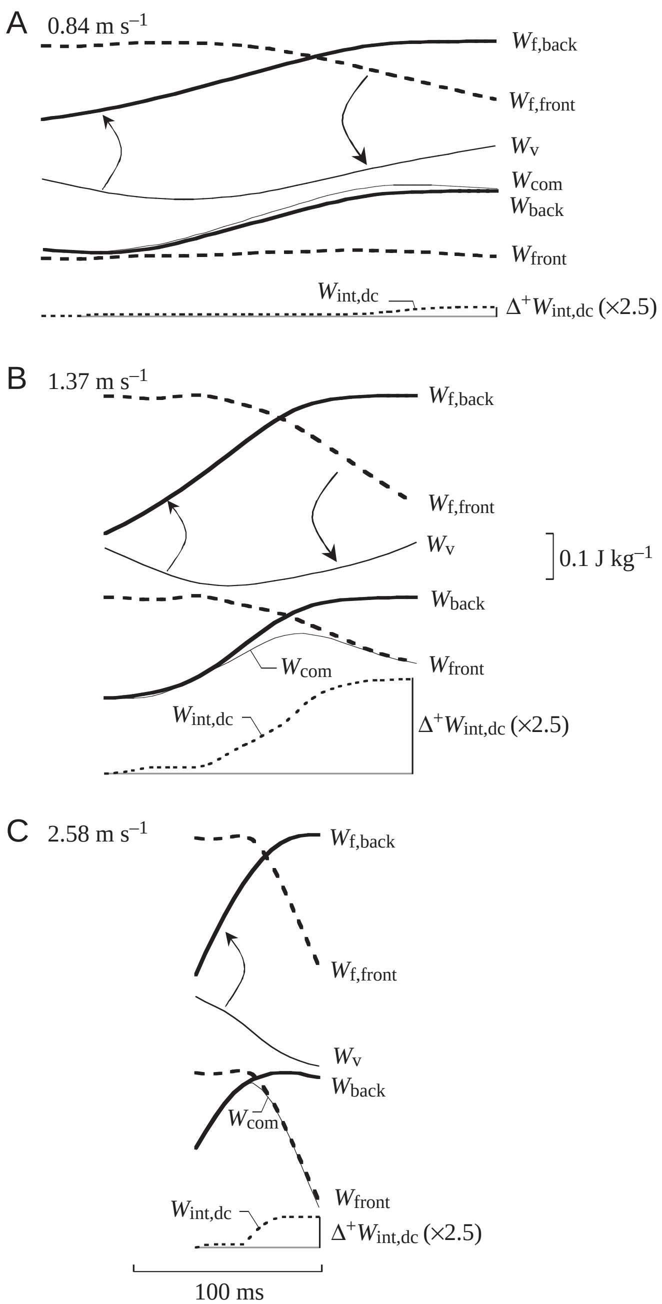

Fig. 6. The components of $W_{int,dc}$ ($W_{f,front}$, $W_{f,back}$, W_v, W_{back}, W_{front} and W_{com}; in J kg^{-1}) are presented as a function of time during double contact (DC) for a slow speed step at 0.84 m s^{-1} (A), a medium speed step at 1.37 m s^{-1} (B) and a high speed step at 2.58 m s^{-1} (C). The $W_{int,dc}$ curve is obtained by subtracting instant-by-instant the positive increments in W_{com} from the positive increments in W_{back} and W_{front} (see Materials and methods). $\Delta^+W_{int,dc}$ is the total increment in the $W_{int,dc}$ curve (fine broken line) and is the work done by one leg against the other during DC. Note that the scale of the $W_{int,dc}$ curve is 2.5 times that of the other curves. Other indications are as in Fig. 1. Data are from a 20.2-year-old 64.9 kg male subject.

is highly dependent upon work transfers to/from the W_v and upon the relative timing of the horizontal forces. All positive work done by either leg during DC, after taking into account any passive work done, results in either Δ^+W_{com} or $\Delta^+W_{int,dc}$ (equation 6).

The effect of horizontal force timing

In adults and children at slow and intermediate walking speeds, the peak in the $\mathbf{F}_{f,back}$ curve occurs at about 20–40% of the way through DC (Fig. 2). With increasing speed, this peak shifts towards the beginning of the DC period, until at the highest walking speeds the peak often occurs during the single contact phase preceding DC (negative phase angle values in Fig. 5). The push performed by the back foot before the DC period is an additional means of increasing the step length independent of an increase in the limb angle as speed increases. This progressive shift in phase angle is observed in all age groups except the youngest children, who always have the $\mathbf{F}_{f,back}$ peak within the DC period (see 3–4-year-old children in Fig. 5). At high walking speeds, by the time of mid-DC, when the horizontal velocity is maximal, the $\mathbf{F}_{f,back}$ has already fallen to about half its peak value, thereby reducing the work that one leg could perform against the other and thus reducing $W_{int,dc}$. The negative phase angle of the $\mathbf{F}_{f,back}$ peak occurs simultaneously with, and is related to, the lifting of the heel of the back foot before the front leg contacts the ground at high walking speeds; the resulting reduction in the L_{dc} further reduces $W_{int,dc}$ at these speeds. This phase angle does not become negative in the youngest children, but nevertheless their $W_{int,dc}$ still goes down to zero, suggesting that this shift in phase angle alone cannot explain the $W_{int,dc}$ decrease at the highest speeds.

The change in the timing of the $\mathbf{F}_{f,back}$ peak during the step, especially whether it occurs during or before DC, affects the amount of work done by one leg against the other. The work done during the forward push of the back foot to accelerate the *COM* forward during the single contact phase is counted entirely as W_{ext} and is needed to maintain the forward speed of the body. On the other hand, the same work done to accelerate the *COM* forward during DC is counted as either W_{ext} or $W_{int,dc}$, the latter representing energy lost from the system.

The effect of passive work transfers

At low walking speeds, the mass-specific work done by one leg against the other, $\Delta^+W_{int,dc}$ (J kg^{-1}), is minimised in both children and adults because there is almost no simultaneous increase and decrease in W_{back} and W_{front} (Fig. 6). This is a consequence of the flattening of the W_{back} and W_{front} curves due to passive work transfers between $W_{f,back}$ or $W_{f,front}$ and W_v (see arrows on the low speed traces of Fig. 6A). In particular, the W_{front} curve becomes almost completely flat during the latter part of DC as the body rides up onto the front leg, minimising any possibility of $\Delta^+W_{int,dc}$. Nearly all the positive work done during DC results in Δ^+W_{com} (external work done during DC) rather than in $\Delta^+W_{int,dc}$.

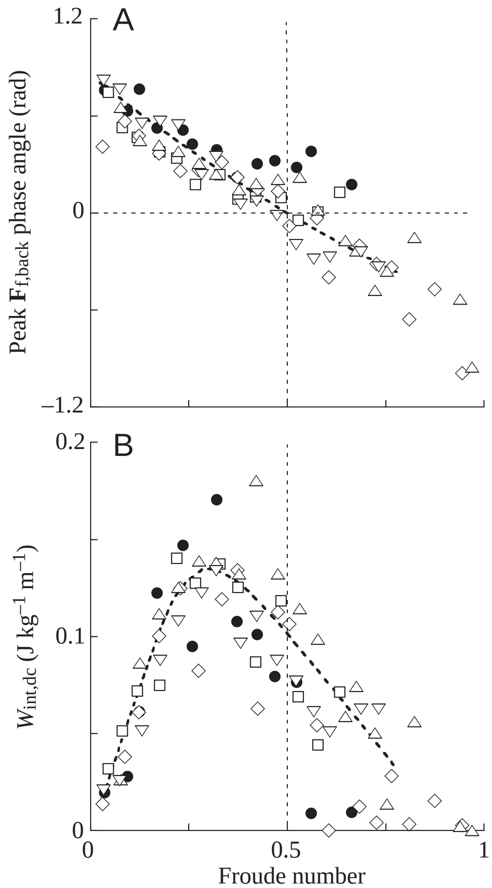

Fig. 7. (A) The phase angle (rad) between the peak in the forward push of the back leg (peak $\mathbf{F}_{f,back}$) and the beginning of the double contact phase is presented as a function of the walking speed expressed as a Froude number. Each age group is presented with a different symbol (filled circles, 3–4 years; squares, 5–6 years; diamonds, 7–8 years; triangles, 9–10 years; inverted triangles, 11–12 years). (B) The mass-specific work per distance done by one leg against the other ($W_{int,dc}$; J kg^{-1} m^{-1}) is presented as a function of the Froude number for all age groups. The broken lines show the adult trends.

At intermediate walking speeds, $\Delta^+W_{int,dc}$ is at a maximum in both children and adults. The amplitude of the $W_{f,back}$ and $W_{f,front}$ curves is much greater than at low speeds, while the amplitude of the W_v curve remains relatively unchanged. Consequently, although the passive work transfers between $W_{f,back}$ or $W_{f,front}$ and W_v are similar (see arrows on the mid-speed curves of Fig. 6B), the resulting changes in the W_{back} and W_{front} curves are large and of opposite sign at the intermediate walking speeds. Consequently the $\Delta^+W_{int,dc}$ is large, approximately equal to Δ^+W_{com}.

At high walking speeds, $\Delta^+W_{int,dc}$ again becomes reduced in both children and adults. In this case, the W_v decreases throughout the DC period (as the body is falling down) while the $W_{f,back}$ increases. Consequently, the amplitude of W_{back} is greatly reduced due to the work transfer from W_v to $W_{f,back}$ (see arrow on the high speed curves of Fig. 6C), decreasing the work available to perform $\Delta^+W_{int,dc}$. In addition, the work transfer has the effect of limiting the increase in the W_{back} curve to earlier in the DC period, reducing the time during which W_{back} increases and W_{front} simultaneously decreases and reducing the opportunity to perform $\Delta^+W_{int,dc}$. The net result is that $\Delta^+W_{int,dc}$ approaches zero at the highest walking speeds in all age groups (Fig. 4).

Normalisation using the Froude number

$W_{int,dc}$ normalised for body mass and distance travelled shows an inverted U shape with speed and maximum value independent of age; however, the speed range and the speed at which the maximum value is attained clearly change with age (Fig. 4A). When comparing subjects of different size, it is often useful to normalise the speed based on the assumption that the subjects move in a dynamically similar manner, i.e. assuming all lengths, times and forces scale by the same factors (Alexander, 1989). In a situation where inertia and gravity are of primary importance, such as in walking, expressing the speed by the dimensionless Froude number is appropriate:

$$\text{Froude number} = \overline{V}_f^2/(\boldsymbol{g} \cdot h)\,, \tag{7}$$

where $\overline{V}_f$ is the mean walking speed in m s^{-1}, $\boldsymbol{g}$ is the acceleration of gravity in m s^{-2}, and h is a characteristic length, typically the leg length in metres. If the assumption of dynamic similarity is justified, then the differences due to a change in size should disappear.

The peak $\mathbf{F}_{f,back}$ phase angle and the mass-specific $W_{int,dc}$ per unit distance are shown as a function of Froude number in Fig. 7; it can be seen that the differences observed between children and adults for the most part disappear, with the exception of the youngest age group. Therefore, despite the changes in body dimensions with age, the Froude number indicates that people above 5 years of age walk in a dynamically similar way. Dynamic similarity has been demonstrated in several previous studies involving various other walking parameters as a function of size (Cavagna et al., 1983; DeJaeger et al., 2001; Minetti, 2001).

The phase angle of the $\mathbf{F}_{f,back}$ peak decreases as a function of Froude number for all subjects (Fig. 7A), attaining negative values at speeds greater than Froude 0.5, except in the youngest subjects. A Froude speed of 0.5 is approximately the speed at which people and animals spontaneously change from a walk to a run or trot, as shown for differently sized subjects, i.e. children (Cavagna et al., 1983), for males and females (Herljac, 1995), for pygmies (Minetti et al., 1994), for short stature growth-hormone-deficiency patients (Minetti et al., 2000) and for different species (Alexander, 1989). Although it is possible to walk at Froude speeds up to 1.0 (Fig. 7), higher speeds require a different gait. Theoretically, this is because at a Froude speed of 1.0 the centrifugal force as the subject rotates on a rigid leg over the ankle ($m\cdot\overline{V}_f^2/h$) becomes equal to the gravitational force ($m\cdot\boldsymbol{g}$) holding the subject in contact with the ground, and the subject starts to have an aerial phase.

The mass-specific $W_{int,dc}$ done per unit distance also appears to be independent of size when expressed as a function of Froude speed (Fig. 7B). The 'optimal' walking speed, in terms of maximum % recovery (a measure of the relative quantity of energy saved by the pendulum mechanism of walking), minimum W_{ext} and minimum energy consumption, occurs at a Froude speed of about 0.2–0.3 in children and adults (Cavagna et al., 1983; DeJaeger et al., 2001; Willems et al., 1995). Notably, at this speed, the energy consumption is minimal despite the fact that the $W_{int,dc}$ is maximal (Fig. 7B). This is likely because $W_{int,dc}$ is, at most, only 40% of W_{ext}, despite the fact that W_{ext} is at its minimum at this speed (Froude 0.2–0.3). $W_{int,dc}$ represents a futile work, energy lost from the system for no gain; presumably, if there were no $W_{int,dc}$ the energy consumption would be even less. The mere fact that $W_{int,dc}$ is a maximum at about the same speed that the energy consumption is a minimum shows that $W_{int,dc}$ is not a major determinant of the energy cost of walking in humans. Nevertheless, the previously reported peak efficiency, measured in adults but not taking into account $W_{int,dc}$ (Willems et al., 1995), was underestimated by about 10%. The effect of $W_{int,dc}$ on the total work and efficiency of children remains to be seen.

List of symbols

- $\mathbf{a}_f$ — acceleration of the centre of mass in the forward direction
- $\mathbf{a}_v$ — acceleration of the centre of mass in the vertical direction
- β — fraction of stride duration for which a particular foot is on the ground
- *COM* — centre of mass of the body
- E_{ext} — total mechanical energy of the centre of mass
- $E_{k,f}$ — kinetic energy of the centre of mass due to its forward movement
- $E_{k,v}$ — kinetic energy of the centre of mass due to its vertical movement
- E_p — potential energy of the centre of mass
- $\mathbf{F}_{f,back}$ — forward component of the ground reaction force acting upon the back leg
- $\mathbf{F}_{f,front}$ — forward component of the ground reaction force acting upon the front leg
- $\mathbf{F}_{v,back}$ — vertical component of the ground reaction force acting upon the back leg
- $\mathbf{F}_{v,front}$ — vertical component of the ground reaction force acting upon the front leg
- $\boldsymbol{g}$ — gravitational acceleration
- L_{dc} — distance the centre of mass moves forward during the period of double contact
- L_{leg} — leg length
- L_{step} — step length
- $\mathbf{S}_v$ — vertical displacement of the centre of mass
- $\mathbf{V}_f$ — forward instantaneous velocity of the centre of mass
- $\overline{V}_f$ — mean walking speed
- $\mathbf{V}_v$ — vertical instantaneous velocity of the centre of mass
- W_{back} — net muscular work done by the back leg during double contact
- W_{ext} — external work performed to raise and accelerate the centre of mass of the body relative to the surroundings
- $W_{f,back}$ — work done on the *COM* as a function of time resulting from the forward component of the forces acting upon the back leg
- $W_{f,front}$ — work done on the *COM* as a function of time resulting from the forward component of the forces acting upon the front leg
- W_{front} — net muscular work done by the front leg during double contact
- $W_{int,dc}$ — work done by one leg against the other during double contact
- $W_{int,k}$ — internal work performed to accelerate the body segments relative to the centre of mass
- W_v — sum of $W_{v,back}$ and $W_{v,front}$
- $W_{v,back}$ — work done on the *COM* as a function of time resulting from the vertical component of the forces acting upon the back leg
- $W_{v,front}$ — work done on the *COM* as a function of time resulting from the vertical component of the forces acting upon the front leg

This study was supported by the Fonds National de la Recherche Scientifique of Belgium and the Fonds Spécial de Recherche of U.C.L.

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