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ORIGINAL ARTICLE

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Mechanical power and efficiency in running children

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Abstract The effect of age and body size on the total mechanical power output ($\dot{W}_{tot}$) during running was studied in children of 3–12 years of age and in adults. $\dot{W}_{tot}$ was measured as the sum of the power required to move the body's centre-of-mass relative to the surroundings (the "external power", $\dot{W}_{ext}$) plus the power required to move the limbs relative to the body's centre-of-mass (the "internal power", $\dot{W}_{int}$). At low and intermediate speeds (less than about 13 km h^{-1}) the higher step frequency used by young children resulted in a decrease of up to 40–50% in the mass-specific external power and an equal increase in the mass-specific internal power relative to adults. Due to this crossed effect, the mass-specific $\dot{W}_{tot}$ is nearly independent of age. At high speeds the mass-specific $\dot{W}_{tot}$ is 20–30% larger in young children than in adults, due to a greater forward deceleration of the centre-of-mass at each step. The efficiency of positive work production, calculated as the positive mechanical power divided by the net energy consumption rate, appears to be similar in children and adults (i.e. 0.40–0.55).

Keywords Running children · Mechanical work · Energy Cost · Step frequency · Efficiency

Introduction

The running mechanism used by human adults and other vertebrates is characterised by an elastic rebound of the body at each step [9]. The step period and the vertical oscillation of the body's centre-of-mass can be divided into two parts: the period during which the vertical ground reaction force is greater than body weight (the lower part of the oscillation, taking place during the contact of the foot on the ground) and the period during which the vertical ground reaction force is less than body weight (the upper part of the oscillation, taking place both during the ground contact and the aerial phase). The duration of the lower part of the oscillation can be considered to be one-half of the period of the elastic bounce of the body. The half-cycle period is related to the vertical stiffness k of the body's elastic system by the relation $\pi\sqrt{m/k}$, where m is the body mass [7].

The basic bouncing mechanism of running is also utilised by children [37], although at a given speed, children use a higher step frequency because they have shorter legs. To increase the step frequency, children reduce the duration of the lower part of the oscillation by increasing the mass-specific vertical stiffness of the bouncing system. The centre-of-mass consequently undergoes a smaller vertical displacement at each step, resulting in a reduced mass-specific power spent against gravity [37]. This effect tends to reduce the external power required to maintain the movement of the body's centre-of-mass relative to the surroundings in children.

For adults running at different imposed step frequencies a trade-off exists between the external power $\dot{W}_{ext}$, which decreases with increasing step frequency, and the internal power $\dot{W}_{int}$, which increases with increasing step frequency [10]. It seems likely that in children the total mechanical power ($\dot{W}_{tot}=\dot{W}_{ext}+\dot{W}_{int}$) will also depend on the relative influence of the step frequency on $\dot{W}_{ext}$ and $\dot{W}_{int}$. Although $\dot{W}_{ext}$ has been measured in children [37], $\dot{W}_{int}$, W˙tot and the efficiency of positive work production in children are unknown. In this study, W˙ext and W˙int were measured simultaneously in children and in adults running at different speeds and W˙tot calculated. The total work so determined was combined with published values of energy expenditure to calculate the efficiency of positive work production as a function of age and speed.

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Materials and methods

Subjects and experimental procedure

Experiments were performed on 24 healthy children aged 3–12 years and 6 healthy adults. The subjects were divided into six age groups defined as follows: the 3- to 4-year-old group included subjects from 3 to less than 5 years of age; the 5- to 6-year-old group included subjects from 5 to less than 7 years, etc. The mean characteristics of each age group are given in Table 1.

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 subjects wore swimming suits and gym shoes. They were asked to run across a 6-m-long force platform at different speeds. Running at speeds at which one generally walks is rather artificial and sometimes difficult for children. For this reason, some of them had to train to run at very low speed before starting the experiments.

The average velocity ($\overline{V}_f$) was measured by two photocells placed at the level of the neck and set 0.7–5.5 m apart depending upon the speed. The first photocell was used to start the data acquisition systems synchronously (see below). In each age group, data were gathered into velocity classes of 1 km h^{-1}. In most cases, two trials per subject were recorded in each velocity class. A total of 590 runs were analysed.

Measurement of positive work

The positive muscle-tendon work performed during locomotion (W_{tot}) can be divided into two parts: the work necessary to accelerate the body segments relative to the centre-of-mass (W_{int}) and the work necessary to raise and accelerate the centre-of-mass relative to the surroundings (W_{ext}). W_{int} and W_{ext} were measured simultaneously according to the following procedures.

Internal work

W_{int} is the positive work done to accelerate the body segments relative to the body's centre-of-mass; it is computed from segment movements and anthropometric parameters. In this study the position of the centre-of-mass was assumed to be fixed in the head/trunk segment. In fact, displacements of the body's centre-of-mass within the trunk have little effect on the determination of W_{int} [45].

The body was divided into 11 rigid segments (Table 1) delimited by infrared emitters placed at their extremities [45]. The head/trunk segment was defined as extending from the chin-neck intercept to the hip, the other segments were defined as indicated in Table 2. The co-ordinates of the infrared emitters in the forward, lateral and vertical directions were measured using a Selspot II system (Selcom, Sweden) with an absolute accuracy of ±5 mm in the sagittal plane. The combined field of the three cameras encompassed approximately 4 m of the platform. The camera system measured the co-ordinates of the infrared emitters every 5 ms. Displacements in the lateral direction were ignored because their contribution to segment velocity is negligible in adults [46]. The co-ordinates of each emitter were smoothed with a cubic spline function [20].

A "stick figure" of the position of each segment relative to the head/trunk segment was constructed for every frame (Fig. 1). The translational velocity of the centre-of-mass of each segment relative to the head/trunk segment and its angular velocity were calculated from the derivative of the position/time relation. The position of the centre-of-mass of the segments was calculated using the anthropometric parameters of Table 2. This method is similar to that described by Willems et al. [45], except that the movements of the head and trunk relative to the body's centre-of-mass were neglected because the kinetic energy of the head/trunk segment calculated from its velocity relative to the common centre-of-mass is negligible [45].

The kinetic energy of each segment due to its displacement relative to the head/trunk segment and to its rotation was then calculated as the sum of the translational and rotational energy. The curves relating kinetic energy of the segments in each limb to time were summed. W_{int} was then calculated by adding the increments in the four resulting kinetic energy/time curves (Fig. 1). This pro-

Table 1 Mean (±SD) characteristics of the subjects (*f* female)

Age group (years)	No. subjects total (f)	Age (years)	Mass (kg)	Height (m)	Trunk (m)	Upper arm (m)	Lower arm (m)	Thigh (m)	Leg (m)	Foot (m)
3–4	5 (4)	4.53±0.23	18.38±2.09	1.08±0.02	0.35±0.03	0.18±0.01	0.14±0.01	0.24±0.00	0.25±0.01	0.08±0.00
5–6	5 (3)	6.23±0.82	20.80±2.01	1.19±0.06	0.40±0.02	0.20±0.01	0.15±0.01	0.26±0.02	0.26±0.01	0.09±0.01
7–8	5 (4)	8.23±0.41	26.26±2.66	1.29±0.05	0.40±0.02	0.22±0.01	0.17±0.00	0.29±0.02	0.30±0.02	0.10±0.01
9–10	5 (2)	10.32±0.35	30.48±2.70	1.40±0.02	0.45±0.01	0.24±0.01	0.19±0.01	0.33±0.01	0.32±0.00	0.11±0.01
11–12	4 (2)	11.87±0.68	41.56±4.60	1.54±0.01	0.47±0.01	0.27±0.02	0.21±0.02	0.37±0.02	0.38±0.02	0.11±0.01
Adult	6 (3)	21.62±1.54	71.68±9.17	1.80±0.04	0.62±0.03	0.32±0.02	0.25±0.01	0.42±0.02	0.43±0.02	0.13±0.01

Table 2 Anthropometric parameters during growth

Segment	Definition	Segment mass/total body mass[a]		Centre of mass to proximal joint dist./segment length	Radius of gyration/segment length
		<11 years	≥11 years		
Thigh	Great trochanter–femoral condyle	$0.0431+0.00890x-0.000274x^2$	0.115	0.451	0.296
Leg	Femoral condyle–medial malleolus	$0.0218+0.00485x-0.000190x^2$	0.046	0.416	0.283
Foot	Medial malleolus–head metatarsal V	$0.0134+0.00147x-0.000071x^2$	0.016	0.461	0.388
Upper arm	Glenohumeral axis–elbow axis	$0.0234+0.00070x$	0.031	0.454	0.307
Lower arm	Elbow axis–ulnar styloid	$0.0228+0.00026x$	0.025	0.671	0.389

[a] *x* represents the age in years

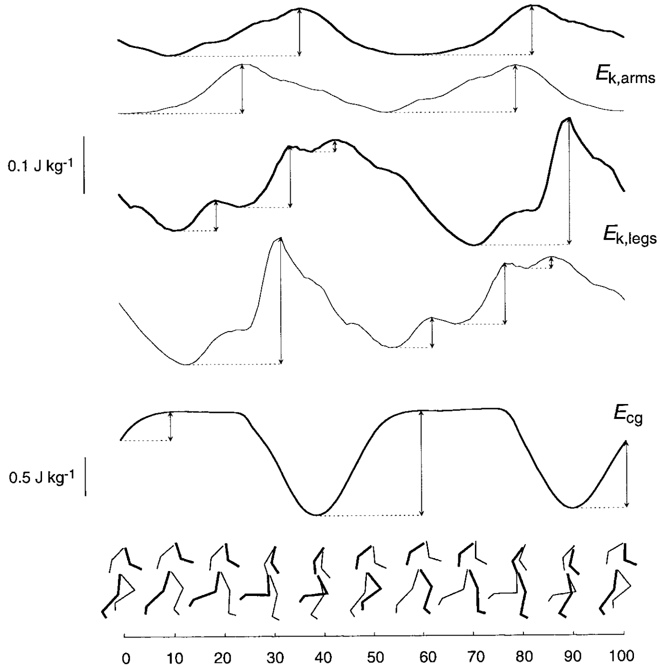

Fig. 1 Mechanical energy (E) changes of the limbs and of the centre-of-mass during one stride of running. The kinetic energy changes of arms ($E_{k,arms}$, *first two* traces) and legs ($E_{k,legs}$, *third* and *fourth* traces) were calculated by adding the kinetic energy curves of the segments in each limb. The sum of the increments of the curves represent the internal mass-specific positive work (W_{int}) done to increase the kinetic energy of the upper and lower limbs relative to the head/trunk segment (see text). The *thick* and *thin lines* correspond to the *thick* and *thin segments* of the *stick figure*. The mechanical energy of the centre-of-mass, E_{cg}, is shown in the *bottom* trace. The sum of the increments in this curve represent the external mass-specific positive work done to maintain the motion of the body's centre-of-mass in the sagittal plane relative to the surroundings (W_{ext}). The *stick figure* shows the segment positions each 10% of the stride period of 0.655 s (two steps): the stick figure consists of ten segments (two upper arms, two lower arms, two thighs, two legs and two feet). The *thick* lines indicate the position of the segments closest to the camera. The *thin* lines indicate the reconstructed positions of the non-filmed segments, on the assumption that the movements of these segments during one step were equal to the movements on the filmed side during the other step. The beginning and end of the stride correspond to the instant of maximum upward velocity of the body's centre-of-mass. This record is from an 8-year-old boy running at 9.3 km h^{-1} (weight 29.9 kg, height 1.28 m)

cedure allows energy transfers between segments of the same limb, but disallows energy transfers between different limbs [45].

The anthropometric parameters needed to calculate W_{int} for each segment are the mass, the position of the centre-of-mass and the radius of gyration about the centre-of-mass. Many different studies have been conducted to estimate the anthropometric parameters in adults, but results vary considerably [3, 4, 12, 13, 18, 25, 49]. Despite the fact that body morphology changes during growth, only one study has measured the anthropometric parameters in children [24]. Although the absolute values of the anthropometric parameters change until adulthood, that study showed that the greatest change in the relative mass of the body segments occurs up to age 10, after which the values lay within the scatter of adult values. Consequently the equations in [24] were used to calculate the relative segment mass up to the age of 10, and constant values equal to the average adult data were used after that age [38]. Contrary to the mass, the relative position of the centre-of-mass and the radius of gyration of the segments do not change with age; for this reason, average data from all the earlier studies were used (Table 2).

External work

The positive work done to raise and accelerate the centre-of-mass in the sagittal plane (W_{ext}) was calculated from the vertical and forward components of the force exerted on a 6×0.4-m force platform mounted in the middle of a 40-m runway. 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 yields the velocity changes of the centre-of-mass from which the kinetic energy can be calculated after evaluation of the integration constants [5, 45]. A second integration of the vertical velocity yields the vertical displacement of the centre-of-mass from which the gravitational-potential energy can be calculated. The mechanical energy of the centre-of-mass (E_{cg}) is the sum of the gravitational-potential energy and the kinetic energy. W_{ext} is the sum of the increments, within a step, in the E_{cg} curve (Fig. 1). Similarly, W_f, the positive work done to sustain the forward velocity changes of the body's centre-of-mass, is the sum of the increments, within a step, of its kinetic energy of forward motion. W_v, the positive work done against gravity, is calculated from the increments in the gravitational potential energy curve during the step. The details of the method used to compute W_{ext} have been described elsewhere [5, 37].

Total work

W_{tot} was calculated as the sum of W_{ext} and W_{int}. This procedure assumes that there are no transfers of energy between W_{ext} and W_{int}. This is a reasonable approximation of the muscle-tendon work done during locomotion [45].

Power

The average mechanical power was calculated as the product of work per step and the step frequency.

Efficiency of positive work production

Efficiency of positive work production was calculated as the ratio of the $\dot{W}_{tot}$ to the net energy consumption rate at steady state ($\dot{E}_{net}$). $\dot{E}_{net}$ is the energetic equivalent of the difference between total oxygen consumption rate and the standing oxygen consumption rate. The total oxygen consumption rate for children was taken as the average of the data from the literature [1, 14, 16, 17, 23, 26, 27, 28, 29, 30, 33, 35, 36, 39, 40, 41, 42, 43, 44, 48]. An energy equivalence of 20.9 kJ/l O_2 was assumed [32]. For adults the total oxygen consumption rate was calculated from [31].

Values for standing oxygen consumption rate during growth are not available in the literature, consequently the standing rate was calculated from the resting rate, assuming the standing rate to be 1.27 times greater than the resting rate (as estimated for adults in [6]). The resting energy expenditure rate as a function of age was derived from equations in [22] and from the weight/age relationship determined for 123 subjects in this (Table 1) and previous [37, 38] studies.

When the standing energy consumption rate is subtracted from the gross energy consumption rate during running, the intercept value at zero running speed is often not zero, although it varies about zero. Most studies assume that the net cost of transport, calculated as the quotient of the net energy consumption rate and running speed, is independent of speed; this assumes that the intercept is negligible [6, 19, 31, 47]. This may be the case for adult subjects running at high speeds, where the intercept represents a small fraction of the net energy consumption rate. However, for children

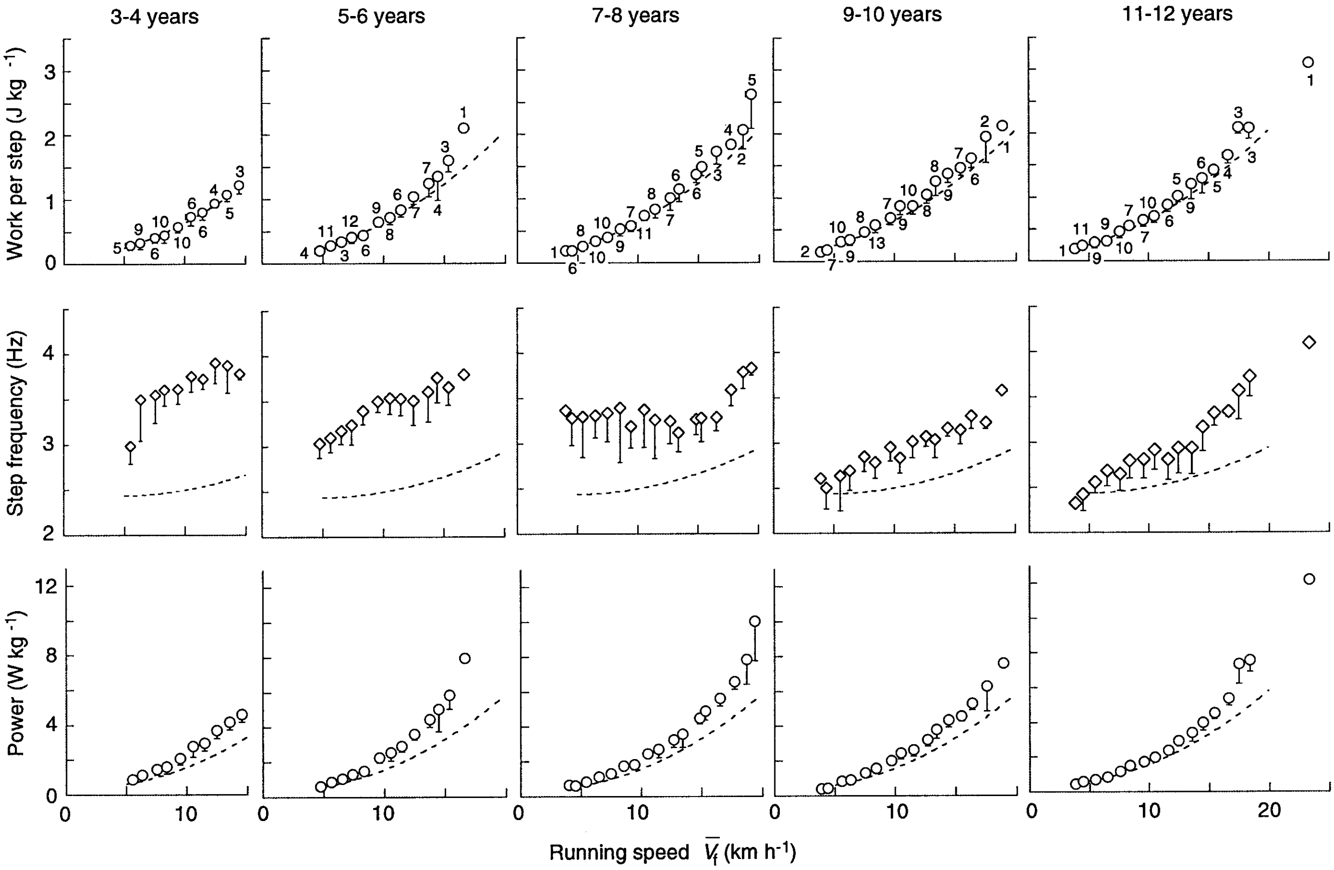

Fig. 2 Internal work (W_{int}) and power ($\dot{W}_{int}$) due to the mechanical energy changes of the segments relative to the body's centre-of-mass. In each age group, the mass-specific W_{int} per step (*upper panels*) and the mass-specific $\dot{W}_{int}$ (*lower panels*) spent moving the body segments relative to the body's centre-of-mass are given as a function of the mean running speed $\overline{V}_f$). The step frequency is shown in the *middle panels*. The *symbols* represent means (*n* is given by the *number* near each *symbol*) of data grouped into the following intervals along the abscissa: 1 to <2, 2 to <3 … 23 to <24 km h^{-1}. *Bars* indicating the SD of the mean are shown when they exceed the size of the *symbol*. The *interrupted lines* indicate a second-order polynomial fit of the adult trends. Note that $\dot{W}_{int}$ is larger in children due to a higher step frequency with an about equal W_{int} per step

running at relatively slow speeds the intercept can represent a significant fraction of the net energy consumption rate. For this reason, in this study, the net energy consumption rate was calculated taking into account the non-zero intercept value, both in children and adults.

Results

The mass-specific internal work W_{int} done at each step increased with running speed in children and in adults (Fig. 2, upper panels). This is because the velocity attained by the lower limb relative to the centre-of-mass during the contact phase must increase as the velocity of the centre-of-mass increases relative to the ground. At a given speed, children and adults do the same amount of internal work per unit body mass at each step to move the limbs relative to the body's centre-of-mass, in spite of the large differences in step frequency and dimensions of the limbs. This indicates that W_{int} per step is independent of the duration and the amplitude of the oscillation and that normalising W_{int} per unit of body mass takes into account the different dimensions of the limbs of children and adults.

Since the step frequency at a given speed is higher in children than in adults (Fig. 2 middle panels), the mass-specific $\dot{W}_{int}$ (i.e. W_{int} per step×step frequency) is greater in the children (Fig. 2 lower panels).

The total mass-specific mechanical power in running, $\dot{W}_{tot}$ (squares in Fig. 3), is calculated as the sum of $\dot{W}_{ext}$ (i.e. W_{ext} per step×step frequency, shown by the triangles in Fig. 3, which are in good agreement with Schepens et al. [37]) and $\dot{W}_{int}$ (circles in Fig. 3, from Fig. 2). $\dot{W}_{tot}$ increases with running speed more steeply in children than in adults. A two-way, repeated measures ANOVA with contrasts was made to determine the speed at which it became significantly different between children and adults. Specifically, the effect of speed was analysed within each age group and the speed at which $\dot{W}_{tot}$ in children became significantly different from $\dot{W}_{tot}$ in adults determined (Table 3); for children younger than 11 years old this was the case above 12–14 km h^{-1}.

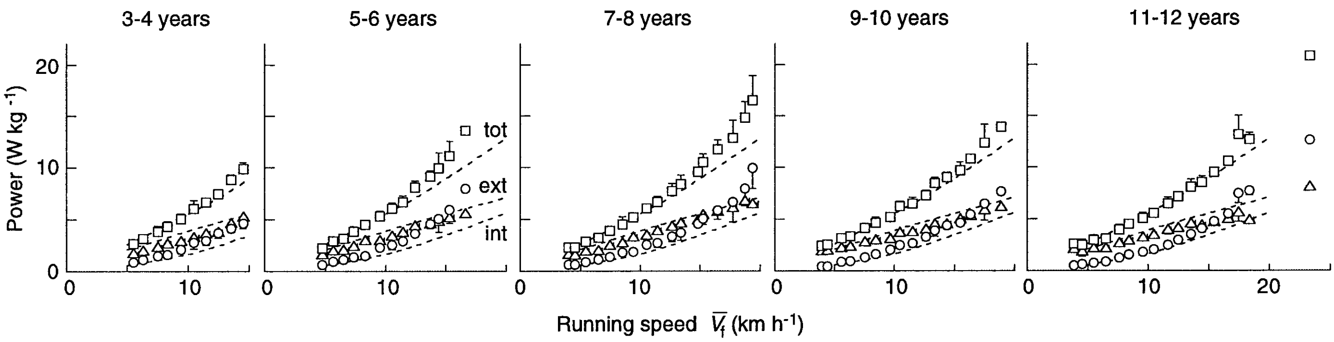

Fig. 3 Internal, external and total mechanical power. The mass-specific internal (*circles*), external (*triangles*) and total (*squares*) power is given for each age group as a function of the running speed. The *interrupted lines* show the adult weighted mean trends of internal (*int*), external (*ext*) and total (*tot*) power. The total power is greater in children than in adults at high speeds, otherwise it is similar to the total power in adults due to a lower external power and a higher internal power. Other details as in Fig. 2

Table 3 Speed at which the total power (W kg^{-1}) is statistically different in children and adults (*n.s.* not significant)

Speed class (km h^{-1})	Age group (years)				
	3–4	5–6	7–8	9–10	11–12
5	n.s.	n.s.	n.s.	n.s.	n.s.
6	n.s.	n.s.	n.s.	n.s.	n.s.
7	n.s.	n.s.	n.s.	n.s.	n.s.
8	n.s.	n.s.	n.s.	n.s.	n.s.
9	n.s.	n.s.	n.s.	n.s.	n.s.
10	n.s.	n.s.	n.s.	n.s.	n.s.
11	n.s.	n.s.	n.s.	n.s.	n.s.
12	n.s.	F=11.06, P=0.0009	n.s.	n.s.	n.s.
13	F=5.803, P=0.0164	F=10.56, P=0.0012	n.s.	n.s.	n.s.
14	F=19.53, P=0.0001	F=24.19, P=0.0001	F=15.97, P=0.0001	F=6.353, P=0.0120	n.s.
15		F=22.00, P=0.0001	F=12.73, P=0.0004	n.s.	n.s.
16		F=29.67, P=0.0001	F=10.73, P=0.0011	n.s.	n.s.
17			F=17.80, P=0.0001	F=6.702, P=0.0099	F=24.39, P=0.0001
18			F=21.25, P=0.0001	F=5.781, P=0.0166	n.s.
19			F=45.09, P=0.0001		

Discussion

The effect of step frequency on mechanical power

The total mechanical power can be expressed as the sum of $\dot{W}_{ext}$ and $\dot{W}_{int}$ [6, 45]. Since during the ground-contact phase of running (when external work is done) there is little exchange between potential and kinetic energy of the body's centre-of-mass [8], $\dot{W}_{ext}$ can be approximated as the sum of the power expended against gravity $\dot{W}_v$ and the power expended to reaccelerate the centre-of-mass forwards, $\dot{W}_f$. Hence:

$$\dot{W}_{tot} \approx \dot{W}_{ext} + \dot{W}_{int} \approx \dot{W}_v + \dot{W}_f + \dot{W}_{int}. \quad (1)$$

In adults running at a given speed with different step frequencies (dictated by a metronome) $\dot{W}_{ext}$ decreases, whereas $\dot{W}_{int}$ increases with increasing frequency [10]. The decrease in $\dot{W}_{ext}$ with step frequency at a given speed is mainly due to a reduction in $\dot{W}_v$ and, to a much lesser extent, to a reduction in $\dot{W}_f$ [11]. Assuming a linear spring-mass model to simulate the body's vertical bounce at each running step, $\dot{W}_v$ is inversely proportional to step frequency [11]:

$$\dot{W}_v = Af^{-1} \quad (2)$$

where A is an increasing function of speed and f the step frequency (Hz). Since A is independent of age [37], during running at the freely chosen step frequency $\dot{W}_v$ is lower in pre-teens than in adults, due to the higher step frequency used by children at a given speed. In the same study it was also shown that at a given speed, the mass-specific horizontal power to move the body's centre-of-mass ($\dot{W}_f$) was about equal or slightly greater in children than in adults:

$$\dot{W}_f \approx B \tag{3}$$

where *B* is an increasing function of running speed [37].

Finally, we show here that $\dot{W}_{int}$, the mass-specific internal power spent moving the body segments relative to the body's centre-of-mass, at a given speed, is proportional to the step frequency (Fig. 2):

$$\dot{W}_{int} = Cf \tag{4}$$

where *C* is an increasing function of speed, independent of age. These results relating to $\dot{W}_{int}$ are in general agreement with the prediction of the theoretical model proposed by Minetti [34] that shows that the internal work per kilogram and per step is proportional to the square of the speed and is unaffected by frequency, and that the internal power per kilogram is proportional to the product of frequency and the square of the speed.

The combination of Eqs. 2, 3 and 4 shows that, at a given speed, $\dot{W}_{tot}$ is a function of step frequency. However, as described below, over the range of step frequency used in human running up to 11 km h^{-1}, the effect of step frequency on $\dot{W}_{tot}$ is negligible because of the opposing effects of step frequency on $\dot{W}_v$ and $\dot{W}_{int}$.

In conclusion, the three components of $\dot{W}_{tot}$ in Eq. 1 may be affected differently by age, running speed and step frequency. To determine the effect of age on the mechanics of running it is therefore necessary to compare the different age groups at the same speed and step frequency. The present study allows a direct determination of the effect of age and body size per se on $\dot{W}_{tot}$, by maintaining the running speed and the step frequency constant in both children and adults. This can be done by plotting, at a given speed, the three terms of Eq. 1 as functions of step frequency during running in children and adults (Fig. 4). In the case of the children and adults in this study (symbols), the frequency is the average, freely-chosen step frequency in the different age groups, whereas in the case of the adults in the previous studies (lines) the step frequency was changed by imposing a frequency with a metronome [10, 11]. In other words, the step frequency on the abscissa of Fig. 4 changes in the children because their body dimensions change, whereas the changes in the step frequency in the adults are forced while the body dimensions remain the same; this allows the appreciation of the effect of the body dimensions per se. $\dot{W}_v$ decreases with frequency similarly in children and adults, independently of age and of body dimensions [37]. $\dot{W}_{int}$ increases with step frequency, also independently of age and body dimensions. $\dot{W}_f$, on the contrary, remains about constant or increases with frequency in children, whereas it decreases slightly with frequency in adults, and this difference becomes greater with increasing speed.

This different effect of body dimensions on $\dot{W}_f$ is probably due to the fact that, at a given speed and step frequency (i.e. at a given step length), the angle of contact with the ground (i.e. the angle of the link between the point of contact and the hip, relative to the vertical, see Fig. 8 in [37]) is larger in children than in adults due to the lower height of their centre-of-mass. A larger an-

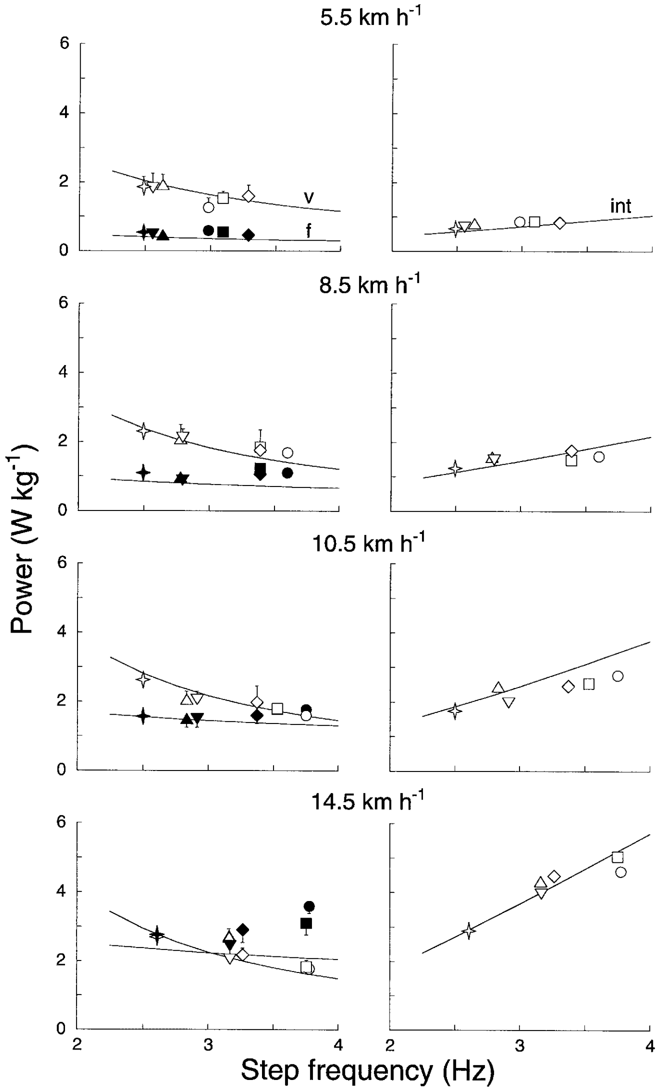

Fig. 4 Effect of step frequency and body size on the different components of mechanical power. The mass-specific external power spent against gravity ($\dot{W}_v$, *open symbols, left column*) and to sustain the forward speed changes ($\dot{W}_f$, *filled symbols, left column*), as well as the internal power required to maintain the movements of the body segments relative to the centre-of-mass ($\dot{W}_{int}$, *right column*) are shown as a function of the freely chosen step frequency at four selected average speeds for the six different age groups (*circles* 3- to 4-year-olds, *squares* 5–6, *diamonds* 7–8, *upright triangles* 9–10, *inverted triangles* 11–12, *stars* adults). *Bars* show the SD of the external power (SD of the internal power and frequency are shown in Fig. 2). Note that an increase in frequency leads to an increase in $\dot{W}_{int}$ and a decrease in $\dot{W}_v$. The *solid lines* indicate how power changes when adults maintain the indicated speeds with the frequencies, shown on the *abscissa*, imposed by a metronome [10, 11]. The different trends of the *symbols* and *lines* shows the effect of body dimensions per se. Body size has no effect on $\dot{W}_v$ and $\dot{W}_{int}$, but, particularly at high speeds, the smaller size of the body increases $\dot{W}_f$. Other details as in Fig. 2

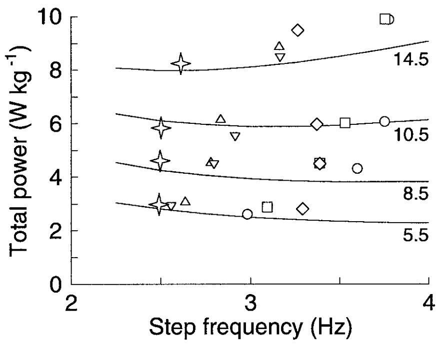

Fig. 5 Effect of step frequency and body size on the total mechanical power. The mass-specific total mechanical power (from Fig. 3) during running at four selected speeds (5.5, 8.5, 10.5 and 14.5 km h^{-1} as indicated) in the different age groups is plotted as a function of the freely-chosen step frequency (from Fig. 2). The *solid lines* show the total mass-specific power measured in adults running at the selected speeds using different imposed step frequencies; these lines are the sum of $\dot{W}_{ext}$ (calculated from the equations in Table 2 of [10]) and $\dot{W}_{int}$ (calculated from Eq. 1 of [11]). Other details as in Fig. 4. Note that at 14.5 km h^{-1} the total mechanical power in children running with the highest frequencies is greater than in adults running with the same imposed frequency (*line*) and with the freely chosen step frequency (*star*). As shown in Fig. 4 this is due to a greater power to sustain the forward speed changes

gle of contact is expected to cause a greater deceleration of the body each step [21] and hence a larger $\dot{W}_f$. The data in Fig. 4 also show that $\dot{W}_v$ and $\dot{W}_f$ can change with step frequency, independently of each other.

$\dot{W}_{tot}$ is given as a function of step frequency, in Fig. 5, at the same average speeds as in Fig. 4. When adults forcibly increase their step frequency above their freely-chosen step frequency (indicated by the stars in Fig. 5), $\dot{W}_{tot}$ decreases if the speed is lower than about 13 km h^{-1} whereas $\dot{W}_{tot}$ increases if the speed is greater than 13 km h^{-1} (lines in Fig. 5, from [10]). The symbols in Fig. 5 show average values measured in this study during free running in the different age groups. In children, $\dot{W}_{tot}$ is about equal to or slightly greater than $\dot{W}_{tot}$ in the adults of the present study (stars) and the previous study (lines) at low and intermediate speeds (5.5, 8.5 and 10.5 km h^{-1}). At high speeds (14.5 km h^{-1}) $\dot{W}_{tot}$ in children is greater than expected from the experiments on adults with imposed step frequency and also greater than $\dot{W}_{tot}$ measured in adults during free running (stars in Fig. 5, and squares v. interrupted lines in Fig. 3).

Thus, in children running with a freely-chosen step frequency, $\dot{W}_{int}$ is greater than in adults due to the higher step frequency; this is expected on the basis of the experiments on adults with imposed step frequencies. However, $\dot{W}_{ext}$ decreases with increasing frequency less than expected on the basis of the adult imposed-frequency experiments. As described above, this is most likely to be due to a greater angle of contact in children, which increases $\dot{W}_f$ without affecting $\dot{W}_v$ (Fig. 4). As a consequence, $\dot{W}_{tot}$ in children is similar to $\dot{W}_{tot}$ in adults at low speeds and is greater than $\dot{W}_{tot}$ in adults at high speeds.

Energy cost of running in children

Energy consumption can be measured from the steady-state oxygen consumption rate. The mass-specific gross oxygen consumption rate increases linearly with running speed [31] and decreases with increasing age [1, 14]. Much of the available data on the energy consumption of children is unusable for this study for one or more of the following reasons: i) the age groups are too broad (e.g. 6- to 12-year-old children grouped together), thereby masking the effect of age; ii) the experimental procedure involved running on an inclined treadmill; iii) the subject pool included athletes; iv) the study involved handicap/pathologic gait; v) the speed of progression was not reported. Nevertheless, a large pool of usable data (see Materials and methods) was selected and regrouped into the age groups used in our measurements of $\dot{W}_{tot}$. The results are plotted as a function of speed in Fig. 6. The gross oxygen consumption rate increases linearly with speed and is higher the younger the subject. There is remarkably little scatter in the data, despite the fact that for any particular age group the data were compiled from up to 13 different sources. The effect of age on gross oxygen consumption rate during running was tested (ANOVA) and was significant (P=0.0001).

To determine the energy expenditure attributable to the running exercise per se, rather than to other body functions requiring metabolic energy, the mass-specific net energy consumption rate during running $\dot{E}_{net}$ was calculated as the difference between the energy equivalent of the gross oxygen consumption rate during running and the oxygen consumption rate during standing. $\dot{E}_{net}$ in each age group is shown in the lower right panel of Fig. 6 as a function of running speed. The adult value (solid line) was taken from [31]. The effect of age class on $\dot{E}_{ent}$ during running was tested (ANOVA) and was not significant (P=0.393), indicating that the gross oxygen consumption rate during running is greater in children than in adults only due to their greater standing oxygen consumption rate. The inset in the lower right panel of Fig. 6 shows the average standing energy consumption rate, calculated as described in Materials and methods from the available resting oxygen consumption data [1, 22, 36]. The standing energy consumption rate decreases with age from 3.55 W kg^{-1} in the 2-year-old age group to 1.86 W kg^{-1} in young adults [22].

Efficiency of running in children

The efficiency of positive work production by the muscles and tendons during running was calculated as the ratio of $\dot{W}_{tot}$ to $\dot{E}_{net}$:

$$\text{Efficiency} = \dot{W}_{tot} / \dot{E}_{net}. \tag{5}$$

Up to the highest speeds for which oxygen consumption data are available for children, efficiency increases with speed, similarly to adults (Fig. 7), from about 0.37 to

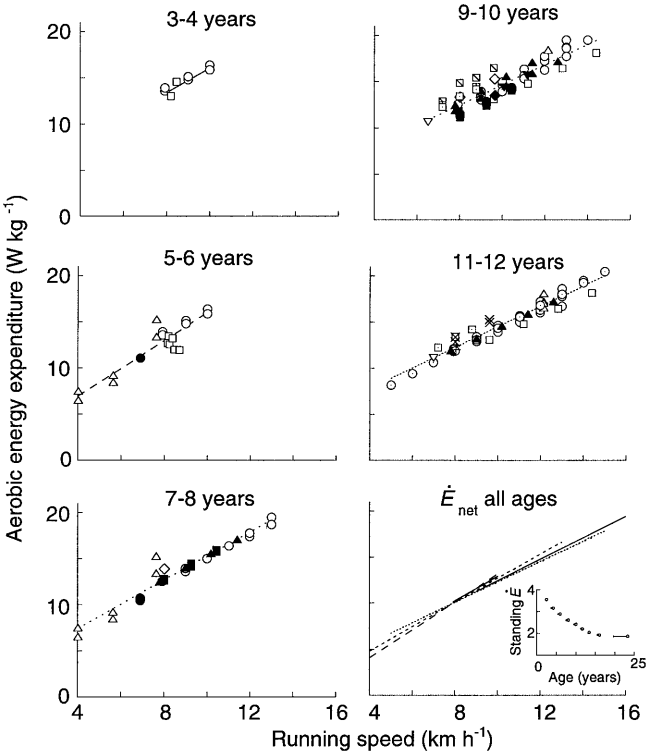

Fig. 6 Aerobic energy expenditure in running children. The energetic equivalent of the gross mass-specific oxygen consumption rate during running is given as a function of speed for five different age groups as indicated. The values were taken from the literature, each *symbol* representing one study as enumerated below. The net (gross minus standing) mass-specific aerobic power consumed during running ($\dot{E}_{net}$) is shown as a function of speed for each age group by the *straight lines* in the *lower right panel*; for comparison, the *solid line* between 9–16 km h^{-1} is for adults from [31]. All these lines practically superimpose, indicating that the net energy expenditure in running is independent of age. The *inset* shows the mass-specific standing aerobic power ($\dot{E}$, W kg^{-1}) as a function of age. The symbols for the left column are as follows: *open circles* [1]; *open triangles* [23]; *closed circles* [29]; *closed squares* [26]; *closed triangles* [33]; *open diamonds* [36]; *open squares* [48]. The *symbols* for the *right column* are as follows: *open circles* [1]; *open squares* [14]; *open upright triangles* [16]; *dotted circles* [17]; *closed circles* [28]; *closed squares* [27]; *closed upright triangles* [33]; *open diamonds* [30]; *closed diamonds* [35]; *crosses* [36]; *open inverted triangles* [39]; *closed inverted triangles* [40]; *barred squares* [41]; *quartered squares* [42]; *dotted squares* [43]; × [44]

0.53. At the speeds for which the oxygen consumption data are available for both children and adults, a two-factor ANOVA showed that running speed has a significant effect (P=0.0001) and age has a marginally significant effect (P=0.033) on efficiency. Given the scatter in the data, it is unlikely that the effect of age on efficiency has any physiological significance.

Although the energy consumption measurements were made on different subject pools than the work production measurements, the calculated efficiency values are relatively robust. The data for the energy consumption during running came from twenty different studies involving hundreds of subjects; likewise the measurements of resting energy consumption involved hundreds of subjects. The factor relating standing to resting energy consumption was measured in our laboratory on 36 subjects (B. Schepens, P.A. Willems, N.C. Heglund, unpublished data) and was about 8% greater than the value of 1.27 [6] used here. However, increasing or decreasing the factor of 1.27 by as much as 20% in the youngest subjects at the lowest running speed (a worst-case situation) would decrease or increase the calculated efficiency by less than 0.04.

In running adults, efficiency increases steadily with speed, from about 0.45 at 9 km h^{-1} to 0.65 at 20 km h^{-1}; assuming an energy cost of 4.18 J kg^{-1} m^{-1} (i.e. 1 kcal kg^{-1} km^{-1}), independent of speed [6]. Williams and Cavanagh measured a mean efficiency of 0.59±0.06 (mean±SD, n=55, range 0.48–0.73) in adults running at 13 km h^{-1} [47]; however in that study the energy cost, measured as the difference between total and standing oxygen consumption rates, was considerably lower than the value used in [6] (39.0±2.1 ml kg^{-1} min^{-1}, i.e. 3.76±0.20 J kg^{-1} m^{-1} vs. 4.18 J kg^{-1} m^{-1}) independent of speed, resulting in their higher efficiency. Di Prampero et al. have also found a speed-independent cost of transport of about 3.8 J kg^{-1} m^{-1} [19], although in well-trained adult athletes running at higher speeds than the children in this study. Changing the adult cost-of-transport line in Fig. 6 to 3.8 J kg^{-1} m^{-1} would increase the adult efficiency by up to 9%, depending upon the effect of the zero-speed intercept, as discussed above.

The ability to convert chemical energy into positive work was found to be equal in children and adults. The

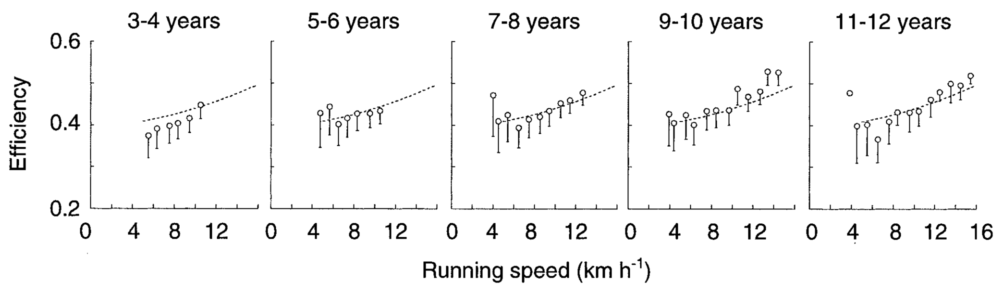

Fig. 7 Efficiency of positive work production in running children. In each age group, the efficiency of running, calculated as the ratio of the total positive mechanical power ($\dot{W}_{tot}$) to the net energy consumption rate at steady state ($\dot{E}_{net}$), is presented as a function of the speed. The *interrupted line* shows the adult trend over the range of speeds for which mechanical work and oxygen consumption measurements were made. The efficiency increases in children with running speed similarly to adults. Other details as in Fig. 2

mean value of the efficiency, calculated from the rate of change of oxygen consumption and rate of change of work production, using a ramp protocol with cycle ergometers, is about 0.29, independent of age and body size [15]. In another study using cycle ergometers, children over 6 years of age and adolescents had the same efficiency as adults (mean 0.25, range 0.18–0.30) [2].

During steady-state running, some of the potential and the kinetic energy absorbed during negative work (decrements of curves in Fig. 1) is stored and recovered during positive work (increments of curves in Fig. 1). This explains the increase in the efficiency, as measured here, above the value of the efficiency of the transformation of chemical energy into positive work when muscle shortens without previous stretching (metabolic efficiency, up to 0.25). On the other hand, the sum of the cost of negative work and the cost of additional activities not directly related to positive work production (isometric contractions, antagonistic muscle contractions, respiration etc.), tends to decrease this efficiency below the value of the metabolic efficiency.

At all ages, the efficiency of positive work production during running is greater than the metabolic efficiency, indicating that in the stretch-shorten cycle taking place during the step, the gain in $\dot{W}_{tot}$ due to the elastic storage and recovery of mechanical energy more than compensates for the increases in $\dot{E}_{ent}$ due to metabolic costs not directly related to the production of positive mechanical work. However, the same efficiency of positive work production could be attained with different partitions of energy storage, recovery, additional costs and metabolic efficiency.

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