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ORIGINAL ARTICLE

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The energy cost of walking in children

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Abstract Size, morphology and motor skills change dramatically during growth and this probably has an effect on the cost of locomotion. In this study, the effects of age and speed on the energy expended while walking were determined during growth. The rate of oxygen consumption and carbon dioxide production were measured in 3- to 12-year-old children and in adults while standing and walking at different speeds from 0.5 $m \cdot s^{-1}$ to near their maximum aerobic walking speed. Standing energy expenditure rate decreases with age from 3.42±0.48 $W \cdot kg^{-1}$ (mean±SD, n=6) in the 3- to 4-year-olds to 1.95±0.22 $W \cdot kg^{-1}$ (n=6) in young adults. At all ages the gross cost of transport has a minimum which decreases from 5.9 $J \cdot kg^{-1} \cdot m^{-1}$ in 3- to 4-year-olds to 3.6 $J \cdot kg^{-1} \cdot m^{-1}$ after 10 years of age. The speed at which this minimum occurs increases from 1.2 $m \cdot s^{-1}$ to 1.5 $m \cdot s^{-1}$ over the same age range. At low and intermediate walking speeds the net cost of transport is similar in children and adults (about 2 $J \cdot kg^{-1} \cdot m^{-1}$). In young children walking at their highest speeds the net cost of transport is 70% (3- to 4-year-olds) to 40% (5- to 6-year-olds) greater than in adults.

Keywords Children · Energy cost · Oxygen consumption · Walking

Introduction

Children usually start to walk at about 1 year of age. During their growth from that age to adulthood, their body mass will increase about 6- to 9-fold and their height will increase about 2- to 2.6-fold [7]. Comparative allometric studies show that a comparable body mass range in adult animals would result in a 50% decrease in the metabolic cost required to move a unit of body mass a unit distance [29]; a similar size effect could occur during growth. However, during growth, there are also widespread changes in the neuromuscular system that could affect the metabolic cost of walking. For example, compared to a 1-year-old, leg length decreases by 25% relative to trunk length up to the age of 12 [17, 20]; muscle fibre cross-sectional area increases 25-fold up to the age of about 16 [1, 4]; and the ability to control both fine and gross movements improves dramatically up to the age of about 11 [8, 9, 11, 13, 26].

Although the effect of the change in body shape and mass on the mechanics of walking in children has been studied [5], little data exist on the effect of growth on the energy cost of walking. Previous studies on the energy cost of walking in children have : (1) averaged data from subjects of a wide age range together, thus masking any effect of age [22, 23, 27, 33]; (2) included only one walking speed [18, 24]; (3) included children with a handicap or pathological gait, thus data from only one-speed control subjects are available [30]; (4) involved walking on an inclination [19, 28]; or (5) not recorded the speed of progression, thus ignoring the effect of speed [32]. Furthermore, to the best of our knowledge, no previous study has measured the energy consumption of standing, making calculations of the net cost of locomotion much less secure. In this study we determine for the first time the energy cost of standing and of walking as a function of speed in children from 3 to 12 years of age, and in young adults.

Materials and methods

Measurement of energy cost

The energy cost of walking was estimated from oxygen consumption and carbon dioxide production measured with a K4 telemetric system (Cosmed, Italy) [12]. The K4 system consists of a portable unit worn by the subject, and a base station for recording the data. The portable unit weighs 0.8 kg and consists of a silicon mask containing a flow-rate turbine which is fixed on the subject's face, a processing unit containing the O_2 and CO_2 analysers which is placed on the subject's chest, and a transmitter/battery pack which

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is placed on the subject's back. Each day the turbine was calibrated with a 3-l syringe, and a two-point calibration of the O_2 and CO_2 analysers was carried out using ambient air and a standard calibration gas mixture (5% CO_2, 16% O_2, 79% N_2).

The mass-specific gross energy consumption rate (P_{gross} in $W \cdot kg^{-1}$) was obtained from the oxygen consumption rate using an energetic equivalent of oxygen, taking into account the measured respiratory quotient (*RQ*) [16]. Only trials with $RQ \leq 1$ were recorded and analysed. The mass-specific gross cost of transport (C_{gross} in $J \cdot kg^{-1} \cdot m^{-1}$) was calculated by dividing P_{gross} by the walking speed in $m \cdot s^{-1}$.

The mass-specific net energy consumption rate (P_{net} in $W \cdot kg^{-1}$) was calculated from the energy consumption that can be attributed to the walking per se: the energy consumption rate while walking minus energy consumption rate while standing. The mass-specific net cost of transport (C_{net} in $J \cdot kg^{-1} \cdot m^{-1}$) was calculated as P_{net} divided by the speed.

Experimental procedure

All subjects wore sports shoes. They were asked to walk along a nearly circular indoor track (35 m long, 1 m wide) at different speeds ranging from 0.5 $m \cdot s^{-1}$ to 2.3 $m \cdot s^{-1}$. The walking speed was measured by ten pairs of photocells placed at neck level along the track. Subjects were given verbal commands in order to maintain their actual speed equal to the desired speed. Sometimes an adult walked alongside the youngest children, but off the track, compelling the speed. The average variation in the walking speed, measured every 3.5 m, within any test was 0.07 $m \cdot s^{-1}$.

Each experiment began with measurement of the standing oxygen consumption rate. This phase was maintained as long as necessary to obtain a steady oxygen consumption rate for at least 3 min. Then, a maximum of seven different speeds of walking were successively imposed in an increasing or decreasing sequence of speeds. The order of the speeds was systematically rotated to eliminate any possible sequence effects. As in the standing measurements, data recording during walking were maintained as long as necessary to obtain a steady-state period of at least 3 min. When a subject was unable to maintain the imposed speed, or the *RQ* exceeded 1.0, the trial was stopped, the data were not recorded and the experiment was resumed at a lower speed.

Subjects

Experiments were carried out on 30 healthy children aged 3–12 years and six healthy young adults; we were not able to obtain steady-state measurements from children less than 3 years old. The characteristics of the subjects were averaged into six age groups defined as follows: "3–4 years" containing subjects aged 3 to <5 years; "5–6 years" containing subjects aged 5 to <7 years, and so on (Table 1). Written informed consent from the subjects or their parents was obtained. Experiments were performed according to the Declaration of Helsinki.

Results

The mass-specific gross power, P_{gross}, is presented for each age group as a function of walking speed in Fig. 1. P_{gross} increases with walking speed. As observed in other studies of adults and adolescents, this relationship is non-linear, whatever the age group. In order to determine the speed and age at which P_{gross} was no longer different in children and adults, a two-way repeated measures ANOVA (SuperANOVA version 1.1) with contrasts was applied to the data. For children younger than 9 years old, P_{gross} is significantly greater than in adults at all speeds ($P \leq 0.01$).

The mass-specific power measured during standing is shown in the same figure at a speed of zero; it decreases with age from 3.42±0.48 $W \cdot kg^{-1}$ (mean ±SD, $n=6$) in the 3- to 4-year-olds to 1.95±0.22 $W \cdot kg^{-1}$ ($n=6$) in young adults.

The mass-specific gross cost of transport, C_{gross}, is shown as a function of speed for the different age groups in Fig. 2. The minimum C_{gross} decreases with age; for children younger than 9 years old, C_{gross} is significantly greater than in adults at all speeds ($P \leq 0.005$). The speed at which the minimum C_{gross} occurs increases with age from about 1.2 $m \cdot s^{-1}$ in 3- to 4-year-olds to 1.5 $m \cdot s^{-1}$ in young adults.

The mass-specific net cost of transport, C_{net}, is shown as a function of speed for the different age groups in Fig. 3. For adults and children above 4 years of age C_{net} takes the form of the well-known U-shaped curve as a function of speed [15]; the curve shows a non-linear increase as a function of walking speed in the youngest children. C_{net} is significantly less in adults than in 3- to 4-year-old children walking at speeds above 0.8 $m \cdot s^{-1}$ ($P \leq 0.001$), and in 5- to 6-year-old children above 1.1 $m \cdot s^{-1}$ ($P \leq 0.05$).

Discussion

Although speed seems to be the principal cause of variation in oxygen consumption during walking in adults [31], little data are available about the effect of age. During adolescence (12–18 years old) the effect of age does not appear to be significant [31]. No significant age effect was found in the averaged P_{gross} for girls 8–13 years old versus female adults walking on a treadmill at 1.33 $m \cdot s^{-1}$ [24], although it seems clear that no

Table 1 Mean (±SD) characteristics of the subjects

Age group (years of age)	Number of subjects total (females)	Age (years)	Body mass (kg)	Height (m)
3–4	6 (4)	4.07±0.58	18.03±1.83	1.03±0.06
5–6	6 (6)	6.22±0.45	21.27±1.83	1.17±0.06
7–8	6 (4)	7.64±0.39	25.18±1.50	1.27±0.04
9–10	6 (3)	9.85±0.58	34.03±4.57	1.40±0.05
11–12	6 (3)	11.56±0.47	39.62±4.00	1.52±0.06
Adults	6 (3)	24.28±3.44	64.87±8.25	1.77±0.09

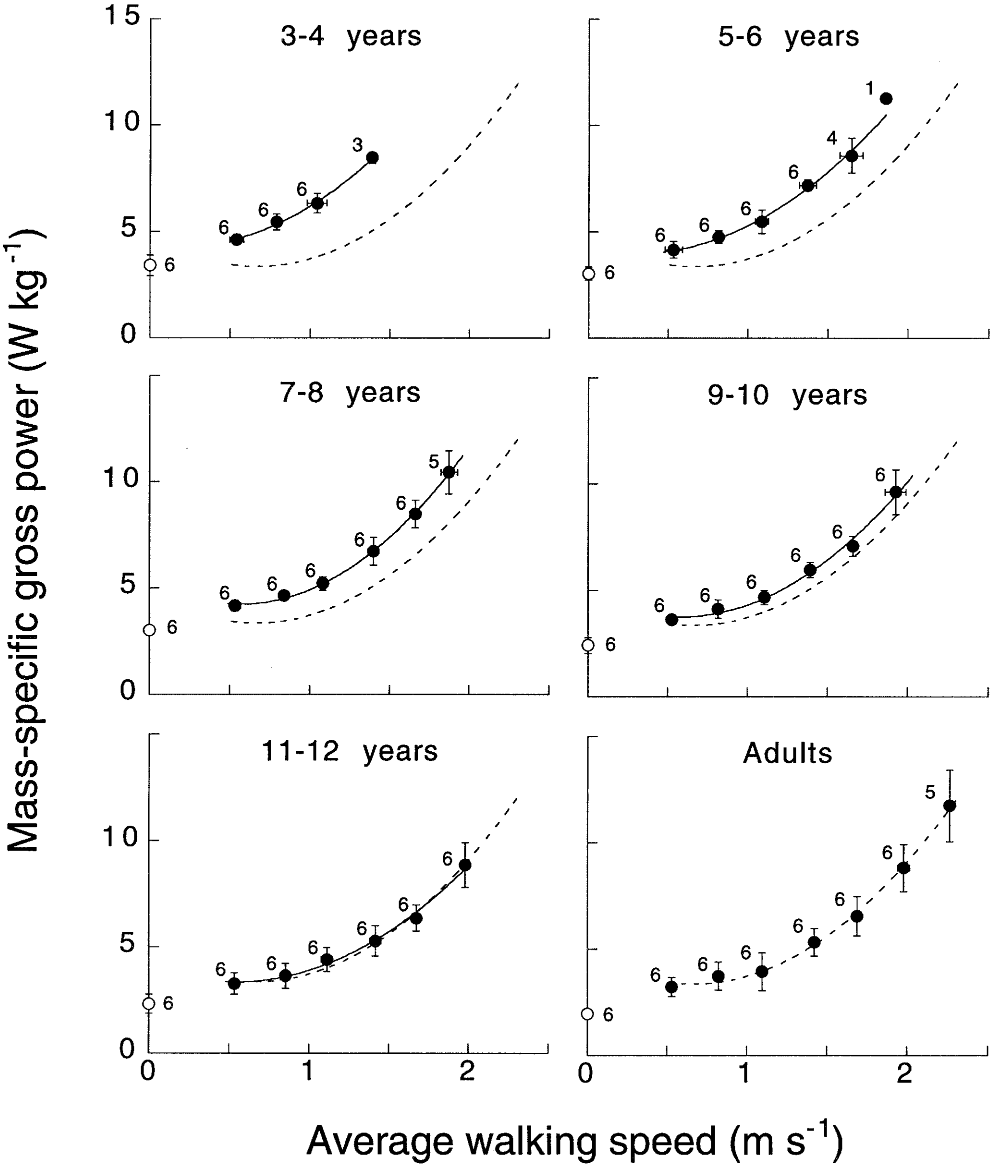


Fig. 1 The mass-specific total metabolic power (W·kg^{-1}) as a function of walking speed in children and adults. The *filled circles* show the average for the subjects in the indicated age group at each speed (*n* is indicated next to each *symbol*); the standard deviation bars for the speed and power are drawn when they exceed the size of the *symbol*. The *lines* are second-order polynomial fits (Kaleidagraph) of all the data points, the *dotted line* in each *panel* is the adult line for reference. The *open circles* at zero speed are the average standing values for all the subjects in the indicated age group; the standard deviation bars are drawn when they exceed the size of the *symbol*

age difference was demonstrable because data from a wide age range were averaged (11.3±1.1 years, mean ±SD, n=18). No significant difference was found in the oxygen consumption of children between 6 and 11 years old walking on a treadmill at different speeds, although this was probably because the number of subjects was only four; no comparison with adults was made [27].

In contrast, our Fig. 1 clearly shows a trend in gross oxygen consumption as a function of age. For example, at a speed of 1 m·s^{-1}, the average gross oxygen consumption of 3- to 4-year-olds was about 70% higher than that of adults, at the same speed the 5- to 6-year-olds are 45% higher, the 7- to 8-year-olds are 30% higher, the 9- to 10-year-olds are 15% higher, and the difference seems to have disappeared by the age of 11–12 years. At all speeds P_{gross} is significantly greater in children younger than 9 years than in adults. A large part of this trend is undoubtedly due to the age dependence of the standing oxygen consumption rate.

The standing energy cost is higher the younger the subject (open circles at zero speed in Fig. 1); this is the same trend as seen in the literature for resting energy cost [3, 10, 21]. In fact, the ratio of the measured standing oxygen consumption rate to the resting rate calculated from the equation of the Food Agriculture Organization of the United Nations [10] is 1.37±0.17 (mean ±SD, n=36), which is about 8% greater than the value of 1.27 quoted in the literature [6]. The higher resting energy cost in younger children has been attributed to differences in body composition (proportionally greater fat-free mass in children) and to their greater surface area/mass ratio [24, 31].

The mass-specific gross cost of transport curves show that there is one speed at which the gross cost of transport is minimal. The minimum cost decreases with age,

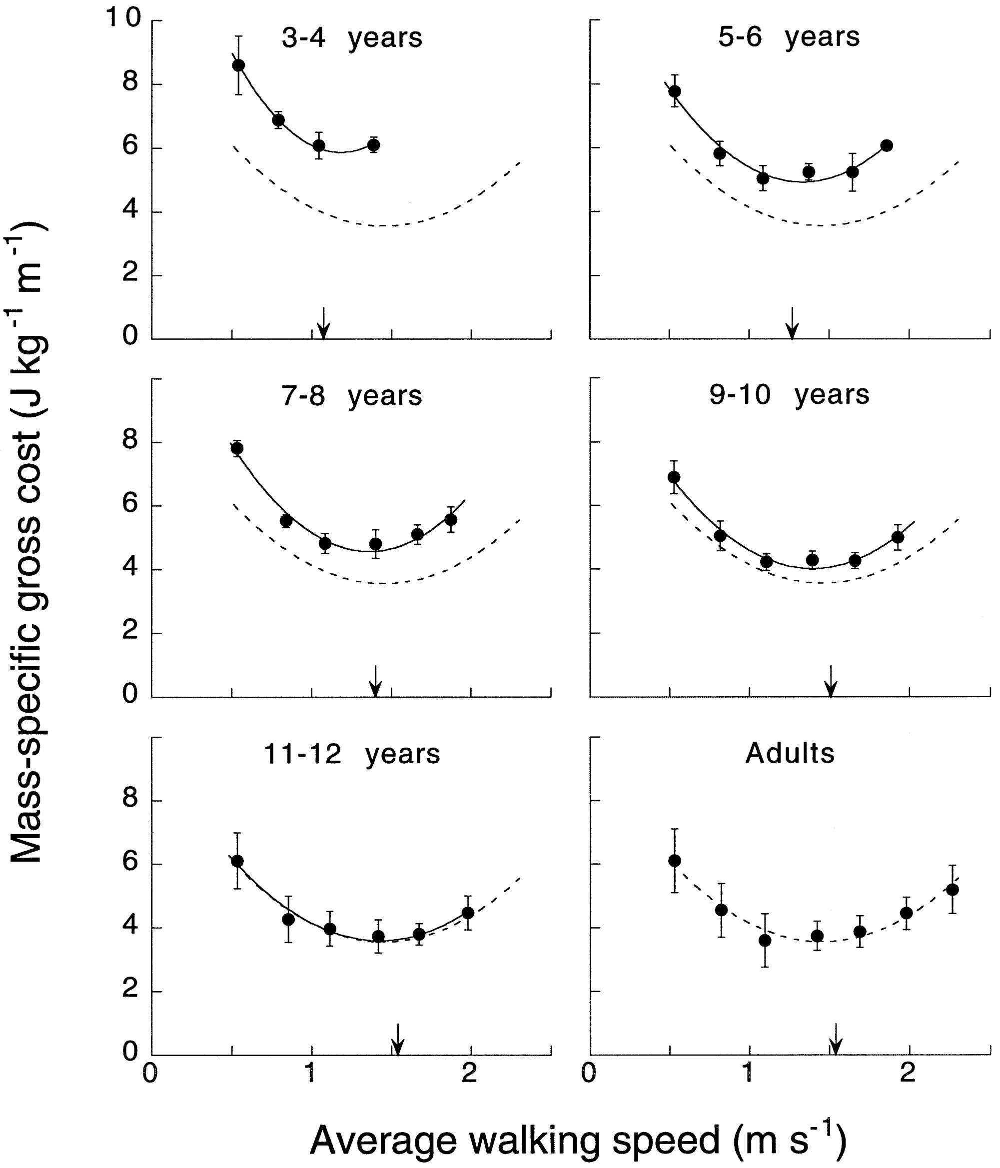


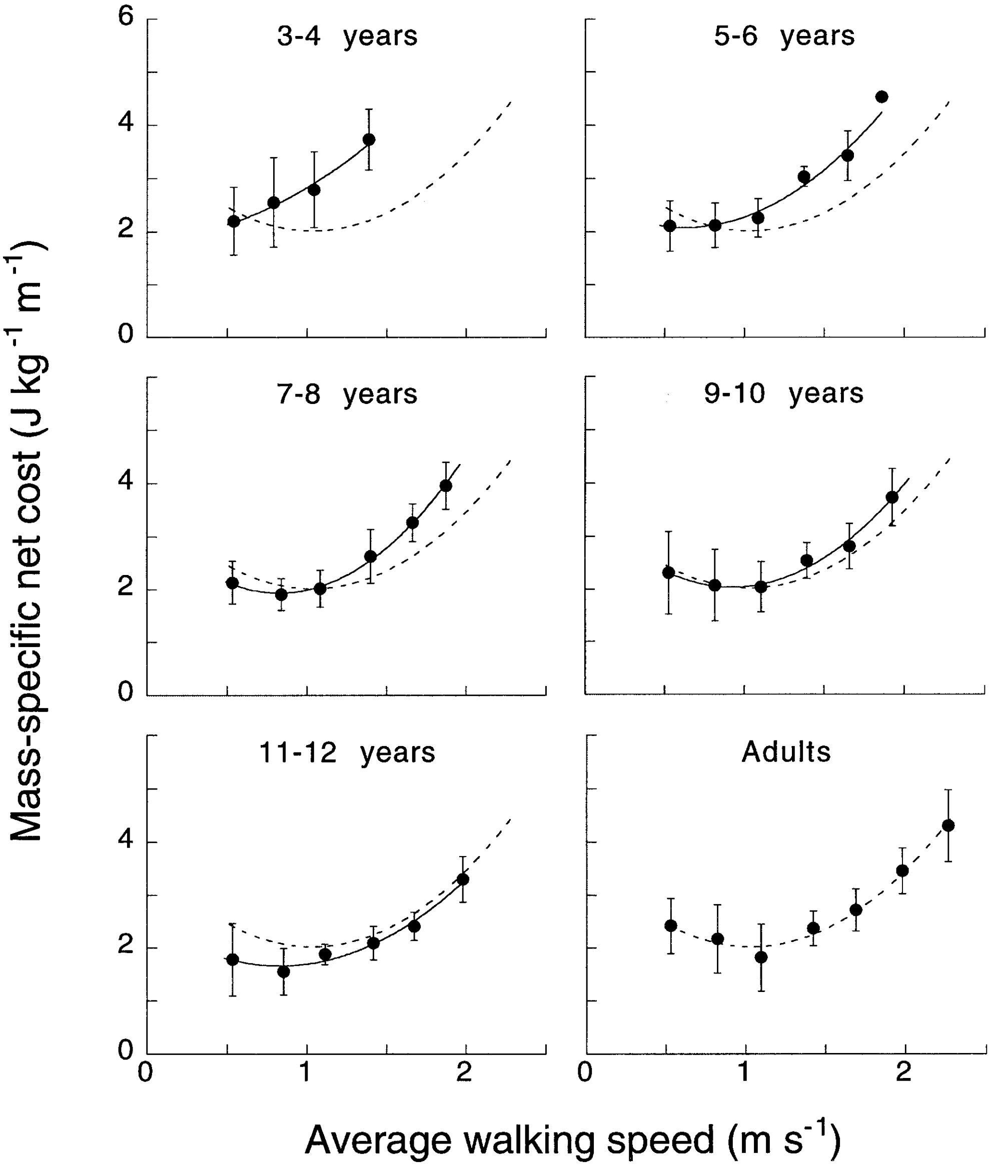
Fig. 2 The mass-specific gross cost of locomotion ($J \cdot kg^{-1} \cdot m^{-1}$) as a function of walking speed in children and adults. The total energy expenditure rate of each subject at each speed was divided by the walking speed, then grouped according to age and speed, and averaged. The number of subjects averaged, and the standard deviation of the walking speed are as indicated in Fig. 1. The *arrows* on the *abscissa* indicate the speed at which the pendular transfer of mechanical energy is maximal [5]

and the speed at which the minimum cost occurs increases with age (Fig. 2). The gross cost of transport is the cost which will be of interest to ecologists, for example, since it is the total energy cost required to move 1 kg of body mass a distance of 1 m. At low walking speeds this cost increases rapidly because the standing energy cost becomes the largest part of the total cost of transport. At high walking speeds the gross cost of transport also increases, because of the curvilinear increase in gross power with increasing walking speed (Fig. 1). Interestingly, the minimum in gross cost of transport occurs at a walking speed that is similar to the speed at which the pendular transfer of energy between the kinetic and potential energy of the centre of mass is maximal [5], as indicated by the arrow at the bottom of each panel of Fig. 2.

The effect of age on C_{net} also depends on speed (Fig. 3). A plot of C_{net} versus walking speed is a characteristic U shape for adults [15], horses [14], and children older than 6 years (Fig. 3). Our data do not show a minimum in the C_{net} curve for children younger than 7 years; it could be that there is a minimum, but at walking speeds lower than we were able to obtain with the youngest children. At the lowest walking speeds studied, there is little difference in C_{net} at any age. However, at the higher walking speeds, C_{net} is significantly greater in the young children than in adults; this difference diminishes with age, disappearing after the age of 7 years.

The decrease in the net cost of transport to be expected just on the basis of increasing body size can be calculated from comparative allometric data taken from different adult animals [29]. Over the same range of body mass studied here (18–65 kg, Table 1), the comparative data would predict a 33% decrease in the net cost of transport. The upper left panel of Fig. 3 shows that the actual decrease ranges from 0% to 40%, depending upon the walking speed.

Fig. 3 The mass-specific net cost of locomotion ($J \cdot kg^{-1} \cdot m^{-1}$) as a function of walking speed in children and adults. The standing energy expenditure rate was subtracted from the total rate to obtain the net rate; the net energy expenditure rate was divided by the walking speed, then grouped and averaged as in Fig. 2



The different speed ranges used by subjects of different age, walking speeds up to 1.4 $m \cdot s^{-1}$ in 3- to 4-year-olds versus 2.3 $m \cdot s^{-1}$ in adults in this study for example, make it difficult to compare directly the results from subjects of different size. Often it is useful to normalize the speed based on the assumption that the subjects move in a dynamically similar manner (i.e. all lengths, times and forces scale by the same factors) [2]. In a situation where inertia and gravity are of primary importance, such as in walking, expressing the speed by the dimensionless Froude number, $V^2 \cdot g^{-1} \cdot l^{-1}$, is appropriate ($V$ is the average walking speed in $m \cdot s^{-1}$, g is the acceleration of gravity in $m \cdot s^{-2}$, and l is a characteristic length, typically the leg length in m). If the assumption of dynamic similarity is justified, then the differences due to a change in size should disappear. The mass-specific net power is shown as a function of Froude number in Fig. 4; it can be seen that the considerable differences observed between children and adults for the most part disappear, indicating that people of all ages walk in a dynamically similar way. This finding, plus the allometric argument given above, indicate that after the age of 3–4 years the differences in cost of transport may be explained mostly on the basis of body size alone, and that developmental changes in the neuromuscular system play a relatively minor role.

The C_{net} curve is of particular interest to muscle physiologists, for example, since it represents the cost of operating the locomotory machinery per se, and thus can be compared to the measurements of the mechanical work done. We would expect the minimum net cost of transport to occur at the speed where the total mechanical work per unit distance is minimal. In adults this speed has been shown to be higher than the speed of optimal energy transfer due to the pendular mechanism of walking. To date, no data exist for the total power output of walking children.

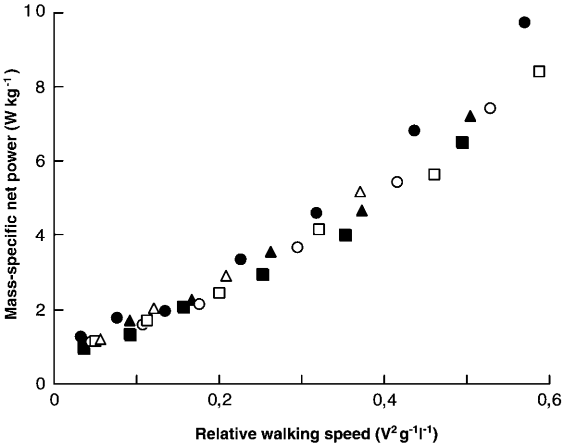


Fig. 4 The mass-specific net power (W·kg^{-1}) as a function of the average walking speed expressed as the Froude number. The dimensionless Froude number is calculated as $V^2 \cdot g^{-1} \cdot l^{-1}$, where V is the average walking speed in m·s^{-1}, g is the acceleration of gravity in m·s^{-2}, and l is the leg length in m. The values for leg length were taken from Table 1 of Schepens et al. [25]. The *symbols* show the average for the subjects in the indicated age group at each speed (*n* for each *symbol* is indicated Fig. 1). *Open triangles* are the 3- to 4-year-olds; *open squares* are the 5- to 6-year-olds; *open circles* are the 7- to 8-year-olds; *filled triangles* are the 9- to 10-year-olds; *filled squares* are the 11- to 12-year-olds; and *filled circles* are the adults

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References

1. Aherne W, Ayyar DR, Clarke PA, Walton JN (1971) Muscle fibre size in normal infants, children and adolescents: an autopsy study. J Neurol Sci 14:171–182
2. Alexander RM (1989) Optimization and gaits in the locomotion of vertebrates. Physiol Rev 69:1199–1227
3. Astrand PO (1952) Experimental studies of physical working capacity in relation to sex and age. Ejnar, Munkgaard, Copenhagen, pp 124–135
4. Bowden DH, Goyer RA (1960) The size of muscle fibres in infants and children. Arch Pathol 68:188–189
5. Cavagna GA, Franzetti P, Fuchimoto T (1983) The mechanics of walking in children. J Physiol (Lond) 343:323–339
6. Cavagna GA, Kaneko M (1977) Mechanical work and efficiency in level walking and running. J Physiol (Lond) 268: 467–481
7. Diem K, Lentner C (1972) Documenta Geigy tables scientifiques. Ciba-Geigy, Basle, Switzerland, pp 704–711
8. Fayt C, Minet M, Schepens N (1992) Children's and adults' learning of a visuomanual coordination: role of ongoing visual feedback and of spatial errors as a function of age. Percept Mot Skills 77:659–669
9. Fayt C, Schepens N, Minet M (1992) Children's development of reaching: temporal and spatial aspects of aimed whole-arm movements. Percept Mot Skills 75:375–384
10. Finan K, Larson E, Goran MI (1997) Cross-validation of prediction equations for resting energy expenditure in young, healthy children. J Am Diet Assoc 97:140–145
11. Gachoud JP, Mjounoud P, Hauert A, Viviani P (1983) Motor strategies in lifting movements: a comparison of adult and child performance. J Mot Behav 15:202–216
12. Hausswirth C, Bigard AX, Lechevelier JM (1997) The Cosmed K4 telemetry system as an accurate device for oxygen uptake measurement during exercise. Int J Sports Med 18: 449–453
13. Hay L (1990) Developmental changes in eye-hand coordination behaviours: preprogramming versus feedback control. In: Bard C, Fleury M, Hay L (eds) Development of eye-hand coordination across the life span. University of South Carolina Press, Columbia, pp 217–244
14. Hoyt DF, Taylor CR (1981) Gait and the energetics of locomotion in horses. Nature 292:239–240
15. Margaria R (1938) Sulla fisiologica e especialmente sul consumo energetico della marcia e della corsa a varia velocita ed inclinazione del terreno. Atti dei Lincei 7:299–368
16. McArdle WD, Katch FY, Katch VL (1996) Exercise physiology, energy nutrition and human performance. Williams and Wilkins, Baltimore, Md., p 147
17. McCammon RB (1970) Human growth and development. Charles C. Thomas, Springfield, Ill.
18. Montoye HJ, Ayen T, Nagle F, Howley ET (1985) The oxygen requirement for horizontal and grade walking on a motor-driven treadmill. Med Sci Sports Exerc 17:640–645
19. Morse M, Schlutz W, Cassels DE (1949) Relation of age to physiological responses of the older boy (10–17 years) to exercise. J Appl Physiol 1:683–709
20. Roche AF, Malina RM (1983) Manual of physical status and performance in childhood, vol. 1 Physical status. Plenum, New York
21. Rogers DM, Olson BL, Wilmore JH (1995) Scaling for the VO_2 to body size relationship among children and adults. J Appl Physiol 79:958–967
22. Rose J, Gamble JG, Medeiros J, Burgos A, Haskell WL (1989) Energy cost of walking in normal children and in those with cerebral palsy: comparison of heart rate and oxygen uptake. J Pediatr Orthop 9:276–279
23. Rose J, Haskell WL, Gamble JG (1993) A comparison of oxygen pulse and respiratory exchange ratio in cerebral palsied and nondisabled children. Arch Phys Med Rehabil 74:702–705
24. Rowland TW, Green GM (1988) Physiological responses to treadmill exercise in females: adult–child differences. Med Sci Sports Exerc 20:474–478
25. Schepens B, Willems PA, Cavagna GA (1998) The mechanics of running in children. J Physiol (Lond) 509:927–940
26. Shumway-Cook A, Woollacott MH (1985) The growth of stability: postural control from a developmental perspective. J Mot Behav 17:131–147
27. Silverman M, Anderson SD (1972) Metabolic cost of treadmill exercise in children. J Appl Physiol 33:696–698
28. Skinner JS, Bar-Or O, Bergsteinova V, Bell CW, Royer D, Buskirk ER (1971) Comparison of continuous and intermittent tests for determining maximal oxygen intake in children. Acta Paediatr Scand Suppl 217:24–28
29. Tayor CR, Heglund NC, Maloiy GMO (1982) Energetics and mechanics of terrestrial locomotion I. Metabolic energy consumption as a function of speed and body size in birds and mammals. J Exp Biol 97:1–21
30. Unnithan VB, Dowling JJ, Frost G, Bar-Or O (1996) Role of cocontraction in the O_2 cost of walking in children with cerebral palsy. Med Sci Sports Exerc 28:1498–1504
31. Walker JL, Murray TD, Jackson AS, Morrow JR, Michaud TJ (1999) The energy cost of horizontal walking and running in adolescents. Med Sci Sports Exerc 31:311–322
32. Waters RL, Hislop HJ, Thomas L, Campbell J (1983) Energy cost of walking in normal children and teenagers. Dev Med Child Neurol 25:184–188
33. Waters RL, Lunsford BR, Perry J, Byrd R (1988) Energy-speed relationship of walking: standard tables. J Orthop Res 6:215–222