Gait & Posture 98 (2022) 146–152

Contents lists available at ScienceDirect

Gait & Posture

journal homepage: www.elsevier.com/locate/gaitpost

Energy cost of gait in children and the effect of speed, age, and body size

Yngvild Gagnat [a,b,*], Laura M. Oudenhoven [c], Siri Merete Brændvik [b,d], Ellen Marie Bardal [b], Karin Roeleveld [a,b]

[a] Orthopaedic Research Center, Clinic for Orthopaedics, Rheumatology and Skin Diseases, St. Olavs University Hospital, Trondheim, Norway
[b] Department on Neuromedicine and Movement Science, Faculty of Medicine and Health Sciences, Norwegian University of Technology and Science, NTNU, Trondheim, Norway
[c] Amsterdam UMC, Vrije University of Amsterdam, Department of Rehabilitation Medicine, Amsterdam, Movement Sciences, de Boelelaan 1117, Amsterdam, Netherlands
[d] Clinical Services, St. Olavs University Hospital, Trondheim, Norway

ARTICLE INFO

Keywords:
Energy cost of walking
Energy expenditure
Normalisation
Children
Speed
Body size

ABSTRACT

Background: Energy cost (EC) of comfortable walking is often used in clinical evaluation of children with altered gait function. EC is presented as energy expenditure per kg bodyweight per meter, either in total (grossEC) or in addition to resting energy expenditure (netEC). GrossEC is considered more reliable and netEC less affected by between-subject variations in speed, age, and body size. However, the effect of the individual child's speed on EC is rarely considered, while altered gait function may affect both speed and EC.
Research question: To what extent are grossEC and netEC affected by within-subject variation in speed and between-subject variations in speed, age, and body size?
Methods: Forty-two typically developing children (7–15 y) were included in this cross-sectional study. Age, height, and bodyweight were obtained. Breath-to-breath gas-exchange measures of VO_2 and VCO_2 were conducted during rest and five over-ground gait conditions: walking at slow, comfortable, and fast speed, jogging and running. All conditions lasted 3–5 min. Body surface area, non-dimensional speed, grossEC, and netEC were calculated. Regression analyses and mixed model analyses were conducted to explain the effect of speed, age, and body size on variations in EC.
Results: GrossEC showed a non-significant, concave up relation to within-subject variation in speed, with a minimum around comfortable/fast walking speed. NetEC had a strong positive linear relation to within-subject variation in speed. For each gait condition, grossEC was more affected by between-subject variations in speed, age, and body size compared to netEC. However, the effect of age and body size was not eliminated for netEC but was quadratic.
Significance: Although normalised to speed and bodyweight, grossEC and netEC are still affected by those factors. However, they are affected differently for within- and between-subject variations. This must be considered when interpreting EC in children in relation to gait function.

1. Introduction

Energy expenditure during gait provides an indication of gait function and is often increased in children with movement disability [1–3]. Energy expenditure is regularly investigated for treatment evaluation as reducing energy expenditure during gait is a frequently used treatment goal [3–6]. Indirect calorimetry through gas-exchange measurements of oxygen (VO_2) and carbon dioxide (VCO_2) is considered the gold standard for investigating energy expenditure during gait [7]. To allow for comparison between individuals, energy expenditure is commonly normalised to body weight and presented in J/kg/min [8]. Energy expenditure measurements from indirect calorimetry requires at least one-minute steady state. To reach such a period with steady state during gait from rest, usually takes five minutes. Due to time limits and possibility of fatigue with longer periods of gait, clinical evaluation is usually performed at only one gait condition, commonly at self-selected,

Abbreviations: BSA, Body surface area; EC, Energy cost; EE, Energy expenditure; RER, Respiratory exchange ratio; VO_2, Oxygen uptake; VCO_2, Carbon dioxide production.

* Correspondence to: Department of Neuromedicine and Movement Science, Faculty of Medicine and Health Sciences, NTNU, NO-7491 Trondheim, Norway.
E-mail address: yngvild.gagnat@ntnu.no (Y. Gagnat).

https://doi.org/10.1016/j.gaitpost.2022.09.005
Received 24 February 2022; Received in revised form 7 June 2022; Accepted 7 September 2022
Available online 9 September 2022

comfortable speed. However, energy expenditure increases with speed and self-selected speed decreases with movement disability [2,3,9–11]. Therefore, to quantify gait efficiency in children with disabilities, energy expenditure is often normalised to speed and referred to as energy cost (EC, J/kg/m).

Although EC is an objective, quantitative measure, there are several methodological issues, especially when evaluating children in growth [12]. While EC of gait is commonly normalised to weight and speed, this normalised EC is still reported to be affected by speed and growth-related subject characteristics, such as age, height, bodyweight, and body surface area (BSA) [12–14]. This is partly thought to be caused by the resting energy expenditure (restEE) which changes with maturation [3,14]. RestEE consists of the basal metabolic rate and the resting muscular consumption during sitting or standing. While grossEC represents the total cost required for movement, including restEE, netEC represents the EC of gait after subtraction of restEE. Due to difficulties measuring restEE in children, grossEC has shown greater reproducibility compared to netEC [15,16]. However, subtracting restEE has shown to reduce the effect of growth-related subject characteristics [1]. In an attempt to remove the effect of anatomical and physiological variables, a non-dimensional normalisation of netEC has been proposed [17]. However, a dimensionless outcome is more difficult to interpret and, according to the normalisation scheme, the only difference between the netEC and the non-dimensional netEC is determined by a constant factor, the gravitational force. Thus, its relation to speed and growth-related subject characteristics is therefore the same as netEC [1].

Superiority of grossEC with respect to reproducibility and netEC with respect to its relative independency of growth-related subject characteristics seems to be largely accepted knowledge. However, the influence of individual variations in gait speed on EC is less systematically investigated. Gait function may affect both speed and EC independently, but the effect of the individual child's speed on EC is rarely considered. To establish a more complete basis for clinical interpretation of EC in children, this study aims to evaluate to what extent grossEC and netEC are affected by within-subject variations in speed, and by between-subject variations in speed and growth-related subject characteristics, in typically developing children.

2. Methods

2.1. Participants

The present study is part of a larger project evaluating activity and energy expenditure in children. The children in this project were recruited from a local elementary and junior high school. The tests were performed at the school premises and within school hours. Data from 42 typically developing children, aged between seven and 15 years old, without physical disability or medical conditions affecting their gait were analysed in this study.

2.2. Procedure and equipment

Characteristics of the children were recorded prior to testing, including age, height, and bodyweight. Body surface area (BSA, m^2) was calculated as follows [18]:

$$BSA(m^2) = \sqrt{\frac{bodyweight(kg) \times height(cm)}{3600}}$$

Energy expenditure was measured at rest and during gait tests. During rest, the children were sitting and standing for three minutes each. The gait tests lasted for five minutes each, and time of rest in between the tests was determined by the children themselves. The children wore shoes and were instructed to *walk as you normally do, walk slower than you normally do, walk faster than you normally do, jog, and run,* in that specific order. All speeds were self-selected, and the tests were conducted around a handball field of 40 times 20 m or on a 400-meter track. A portable indirect calorimeter, Metamax, version II (Cortex Biophysik GmbH, Leipzig, Germany) was carried as a backpack by the children and used to measure oxygen uptake (VO_2) and carbon dioxide production (VCO_2). Reliability and validity of this system as well as comparable systems have been reported before [19,20]. Prior to testing, the calorimeter was calibrated according to the manufacturer's instructions. The children wore a facemask placed over nose and mouth which was carefully inspected for leakage.

2.3. Data analyses

Speed (m/s) was calculated from the total distance over time during each gait test. Non-dimensional speed was calculated using the following equation [21]:

$$Non-dimensional\ speed = speed(m/s) \Big/ \sqrt{(9.81 m/s^2 \times leg\ length(m))}$$

From the resting and gait tests, VO_2 (l/min) and VCO_2 (l/min) were averaged over a two-minute visually inspected steady state period, where fluctuations in VO_2 and VCO_2 changed the least [1]. Respiratory exchange ratio (RER) was calculated by dividing VO_2 by VCO_2. The mean VO_2 relative to bodyweight (ml/kg/min) and RER were used to calculate resting and gross energy expenditure (restEE and grossEE, both in J/kg/min) using the following equation [22]:

$$EE(J/kg/min) = (4.940 \times RER + 16.040) \times VO_2(ml/kg/min)$$

Of the two resting tests, the test with the lowest restEE was subtracted grossEE to obtain net energy expenditure (netEE, J/kg/min). Gross and net energy cost (grossEC and netEC, J/kg/m) were calculated by dividing grossEE and netEE by speed (m/min).

2.4. Statistical analyses

Normal distributions of the included variables were evaluated and confirmed based on visual inspection of Q-Q-plots. To evaluate the differences in non-dimensional speed between gait conditions, a mixed model analysis was conducted with non-dimensional speed as dependent variable, gait condition was set as factor and subject as random factor to account for repeated measures. To evaluate the difference in grossEC and netEC between gait conditions, and the effect of within-subject variations of speed on grossEC and netEC, mixed model analyses were conducted. GrossEC and netEC were separately set as dependent variables and non-dimensional speed as independent variable. Gait condition was set as factor and subject as random factor to account for repeated measures. Univariate regression analyses were conducted to evaluate the relation between non-dimensional speed, growth-related subject characteristics, grossEC and netEC for each gait condition. Depending on the model, grossEC and netEC were set as dependent variables and non-dimensional speed, age, height, bodyweight and BSA as independent variables. Where visual inspections revealed curvilinear relations, quadratic terms were included in the specific models. The most appropriate model for each dependent variable is presented. Separate linear regression analyses were in addition conducted for the ascending and descending parts of the quadratic curves for growth-related subject characteristics, for comparisons to the linear relations.

Statistical analyses were carried out using SPSS version 27 (IBM Statistics). Statistical significance was set to $p < 0.05$.

3. Results

Characteristics of the children are reported in Table 1. Of the 42 participating children, 41 completed the gait conditions slow and comfortable walking, 42 fast walking, 39 jogging and 32 running. One child did not perform restEE measurements. Mean values, standard

Table 1
Characteristics of the participating children, presented as mean ± SD, 95% confidence interval (CI) and/or frequencies (N).

	Mean ± SD	95% CI	N
Gender (boys/girls)			23/19
Age (years)	10.6 y ± 2.6 y	10.2 y – 10.9 y	42
Height (cm)	149.7 ± 15.9	147.5 – 151.9	42
Bodyweight (kg)	43.4 ± 12.5	41.7 – 45.1	42
Body surface area (m^2)	1.34 ± 0.26	1.30 – 1.37	42

deviations, and the 95% confidence interval of restEE (J/kg/min), gait speed (m/min), grossEC (J/kg/m) and netEC (J/kg/m) are presented in Table 2.

Mixed model analyses showed that the non-dimensional speed significantly increased between the gait conditions, from an average of 0.33 during slow walking to an average of 0.94 during running ($p < 0.001$).

GrossEC showed a non-significant, concave up relation to within-subject variation in speed, with a turning point around comfortable/fast walking speed ($p = 0.2$, Fig. 1; Left column, Table 3). Testing between the gait conditions, did neither show a significant difference in grossEC between comfortable and fast walking ($p = 0.4$), nor between slow, walking, jogging, and running ($p < 0.4$). However, grossEC was significantly higher during the three latter conditions compared to comfortable and fast walking ($p < 0.01$).

NetEC showed a significant, linear relation to within-subject variation in speed, where non-dimensional speed explained 41% of the variance in netEC and increased from slow walking to running ($p < 0.001$, Fig. 1; Left column, Table 3). Testing between the gait conditions also showed a significantly higher netEC during fast walking, jogging, and running compared to slow and comfortable walking ($p < 0.006$), and during jogging and running compared to fast walking ($p < 0.001$). However, netEC was not significantly different between slow and comfortable walking ($p = 0.7$) nor between jogging and running ($p = 0.5$).

For each gait condition, grossEC was to a greater extent affected by the between-subject variation in speed compared to netEC (Fig. 1; Right column, Table 3). Linear regression analyses showed that non-dimensional speed explained between 3% and 29% of the variance in grossEC. With a one unit increase in non-dimensional speed, grossEC decreased with 6.75 J/kg/m during slow walking ($p = 0.006$), 3.23 J/kg/m during jogging ($p = 0.007$) and 3.97 J/kg/m during running ($p = 0.002$, Table 3). There were no significant relations between non-dimensional speed and netEC during slow, comfortable, or fast walking, nor jogging ($p > 0.2$). During running non-dimensional speed explained 18% of the variance in netEC, where an increase in speed was significantly related to decrease in netEC ($p = 0.02$).

GrossEC was highly affected by growth-related subject characteristics, while netEC to a lesser extent, and with dissimilarity between the gait conditions (Fig. 2). Linear regression analyses showed that grossEC decreased with increase in age, height, bodyweight and BSA for all gait conditions (Fig. 2; Left column, Table 4).

For every year increase in age, there was a decrease in grossEC with the lowest value during jogging (0.15 J/kg/m) and the greatest value during slow walking (0.28 J/kg/m, $p < 0.006$). For every cm increase in height, there was a decrease in grossEC with the lowest value during jogging (0.02 J/kg/m) and the greatest value during slow walking (0.05 J/kg/m, $p < 0.009$). For every kg increase in bodyweight there was a decrease in grossEC with the lowest value during jogging (0.03 J/kg/m) and the greatest value during fast walking (0.05 J/kg/m, $p < 0.009$). Also, for every m^2 increase in BSA, there was a decrease in grossEC with the lowest value during jogging (1.4 J/kg/m) and the greatest value during slow walking (2.6 J/kg/m, $p < 0.007$). During slow walking, the growth-related subject characteristics explained between 25% and 35% of the variance in grossEC, during comfortable walking between 35% and 42%, during fast walking between 39% and 45%, during jogging between 17% and 23% and during running between 20% and 23%.

Quadratic regression analyses showed that significant relations between netEC and growth-related subject characteristics were mainly present during comfortable and fast walking (Fig. 2; Right column, Table 4). During comfortable walking, age and age^2, and BSA and BSA^2, explained 19% and 18% of the variance in netEC respectively ($p < 0.03$). Height and height^2, and bodyweight and bodyweight^2, explained 14% and 15% of the variance (borderline significant, $p < 0.06$). During fast walking, all growth-related subject characteristics in combination with their squared explained between 18% and 23% of the variance in netEC ($p < 0.03$). While during jogging, age and age^2 explained 15% of the variance (borderline significant, $p = 0.055$). The significant relations followed a concave down shape, where netEC increased until the turning point at approximately the age of ten years, height of 140 cm, bodyweight of 40 kg and BSA of 1.2 m^2. Linear regression analyses of the ascending and descending parts of the quadratic curves showed that netEC was barely affected of growth-related subject characteristics up to the turning points, while approximately half of the relations of the descending parts of the curves showed significant decreases in netEC with increases in age, height, bodyweight and BSA (Table 4).

Table 2
Speed and energy expenditure measures during rest and during the five gait conditions, presented as mean ± SD and 95% confidence interval (CI) with frequencies (N).

Condition	Mean ± SD	95% CI	N
	RestEE (J/kg/min)		
Rest	155.2 ± 47.1	140.3 – 170.1	41
	Speed (m/min)		
Slow walking	57.8 ± 14.9	53.1 – 62.5	41
Comfortable walking	79.7 ± 11.6	76.0 – 83.4	41
Fast walking	92.5 ± 13.4	88.3 – 96.7	42
Jogging	139.8 ± 23.6	132.1 – 147.4	39
Running	167.6 ± 30.5	156.6 – 178.6	32
	GrossEC (J/kg/m)		
Slow walking	5.46 ± 1.24	5.07 – 5.85	41
Comfortable walking	4.64 ± 1.01	4.32 – 4.96	41
Fast walking	4.81 ± 0.95	4.51 – 5.11	42
Jogging	5.64 ± 0.84	5.37 – 5.92	39
Running	5.60 ± 1.02	5.23 – 5.97	32
	NetEC (J/kg/m)		
Slow walking	2.61 ± 0.75	2.37 – 2.85	40
Comfortable walking	2.66 ± 0.66	2.45 – 2.88	40
Fast walking	3.08 ± 0.68	2.87 – 3.30	41
Jogging	4.48 ± 0.69	4.25 – 4.70	38
Running	4.61 ± 0.82	4.31 – 4.91	31

4. Discussion

The aim of this study was to evaluate the effect of speed and growth-related subject characteristics on gross and net energy cost in typically developing children. Our findings show that grossEC was barely affected by within-subject variation in speed, but netEC was highly affected. Conversely grossEC was more affected by between-subject variations in speed compared to netEC. GrossEC decreased as age and body size increased, while this relation was less strong and non-linear for netEC.

The children participating in this study were instructed to walk slow, comfortable, and fast, and to jog and run. Our findings show that the speed significantly increased between the gait conditions, indicating that the speed instructions were consistent with the implementations. To walk at self-selected comfortable walking speed is thought to be close to an optimal, where the combination of step length, frequency and width diminishes the energy expenditure per meter [23]. Increasing deviations of these parameters are expected to increase the energy expenditure per meter and our findings of grossEC confirms this. Accordingly, grossEC was significantly higher during slow walking, jogging, and running

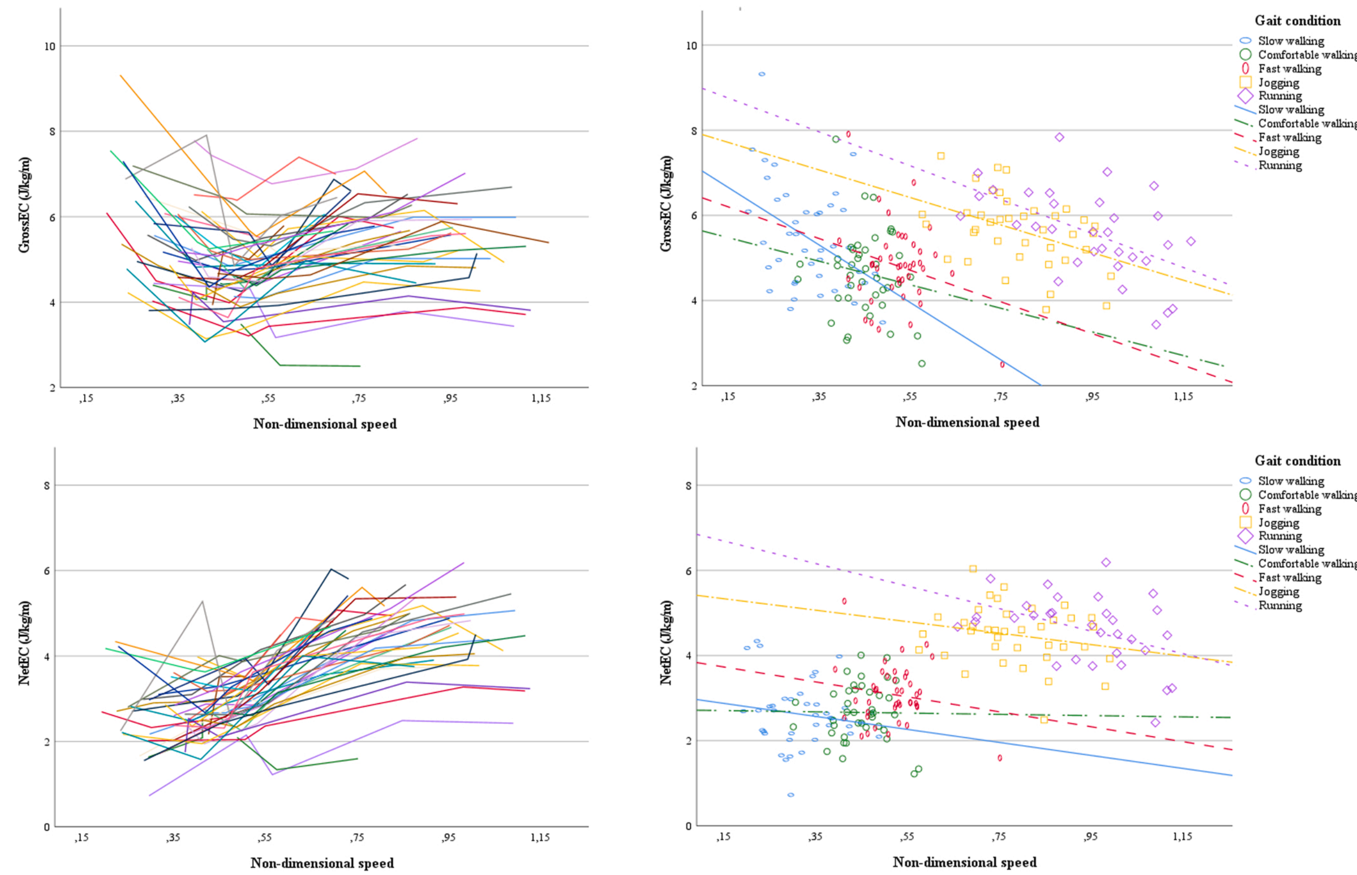

Fig. 1. GrossEC (top) and netEC (bottom, both in J/kg/m) as a function of non-dimensional speed, at individual level where each line represents one child (left column) and for the five gait conditions with fit lines of each condition (right column).

Table 3
Explained variance (R^2), statistical significance level (p-value) and slopes with standard errors (B (SE)) of regression models between gait speed and energy cost (EC). For the quadratic regression model of within-subject variation for grossEC, the B(SE) of the independent variable's squared is also presented. In addition, number of participants is presented (N). Significant relations are presented in bold (p-value <0.05).

	GrossEC (J/kg/m)				NetEC (J/kg/m)			
	R^2	p-value	B (SE)	N	R^2	p-value	B (SE)	N
Within-subject variation								
Non-dimensional speed	0.012	0.21	-2.02 (1.84)	42	**0.41**	**< 0.001**	**3.03 (0.27)**	**41**
Non-dimensional speed^2			1.74 (1.38)					
Between-subject variations								
Slow walking	**0.18**	**0.006**	**-6.75 (2.30)**	**41**	0.03	0.3	-1.53 (1.56)	40
Comfortable walking	0.03	0.3	-2.77 (2.66)	41	0.00	0.9	-0.15 (1.84)	40
Fast walking	0.06	0.1	-3.72 (2.25)	42	0.03	0.3	-1.76 (1.70)	41
Jogging	**0.18**	**0.007**	**-3.23 (1.14)**	**39**	0.05	0.2	-1.35 (1.03)	38
Running	**0.29**	**0.002**	**-3.97 (1.14)**	**32**	**0.18**	**0.02**	**-2.64 (1.03)**	**31**

compared to comfortable walking. NetEC on the contrary, increased from slow walking to running, implying comfortable walking speed is not the most beneficial energetically. These differences may be explained by the relative more prominent contribution of restEE to the total cost required for movement during slow walking, and the increasing relative contribution of cost required for movement with increasing speed [14].

Conducting energy expenditure measurements during various gait conditions makes it possible to evaluate how different gait speeds may affect the different measures of EC. NetEC has been recommended over grossEC due to its less effect of speed during comfortable walking [9]. However, gait speed is related to functional ability and may be a useful measure of disability [24]. Indeed, improvement in gait speed after treatment has been reported for children with cerebral palsy [25,26]. Our findings indicate that a potential decrease in EC as a result of increased gait speed, due to improved gait function, may be concealed using netEC when evaluating individual treatment effects. GrossEC may prove to be more robust against individual variations of speed and may therefore be expected to be more reliable. This agrees with previous studies, recommending grossEC as a more sensitive measure when evaluating clinically relevant changes at individual levels in children with cerebral palsy [15]. In addition, the observation that children with higher self-selected speed during specific gait condition have reduced grossEC, agrees with the expectation that children with better gait function have reduced EC of gait and increased speed [2,26,27].

Normalising energy expenditure to bodyweight should in theory allow for comparisons between different ages and body sizes, however our results indicate that this is not applicable for children in growth. Our

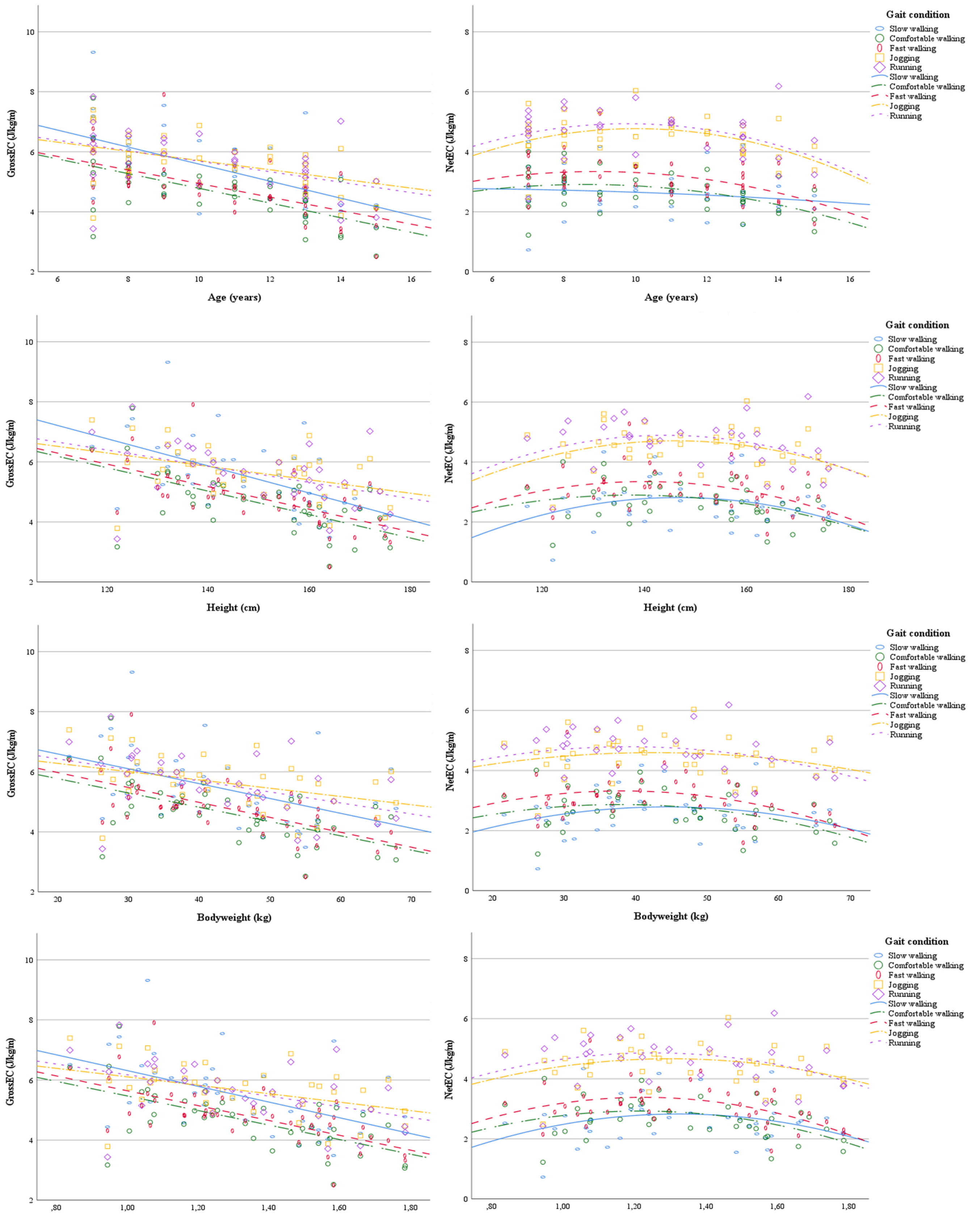

Fig. 2. GrossEC (left column) and netEC (right column, both in J/kg/m) as a function of age (top), height (second), bodyweight (third) and body surface area (BSA, bottom), for the five gait conditions with fit lines of each condition.

Table 4
Explained variance (R^2) and statistical significance level (p-value) of regression models between age, height, bodyweight, body surface area (BSA), and energy cost (EC). Slopes with standard errors of linear regression models are presented for grossEC (B (SE)). For illustration in comparison, slopes with standard errors of linear regression models for ascending (B_1 (SE_1)) and descending (B_2 (SE_2)) parts of the quadratic relations of netEC are presented. In addition, number of participants is presented (N). Significant relations are presented in bold (p-value <0.05) and borderline significant relations are presented in italic ($p < 0.08$).

	GrossEC (J/kg/m)				NetEC (J/kg/m)					
	R^2	p-value	B (SE)	N	R^2	p-value	B_1 (SE_1)	N	B_2 (SE_2)	N
Age (years)							<= 10 y		>=11 y	
Slow walking	**0.35**	**< 0.001**	**-0.28 (0.06)**	**41**	0.02	0.6	-0.05 (0.18)	*20*	-0.05 (0.12)	20
Comfortable walking	**0.42**	**< 0.001**	**-0.25 (0.05)**	**41**	**0.19**	**0.02**	0.02 (0.15)	20	**-0.20 (0.09)**	**20**
Fast walking	**0.39**	**< 0.001**	**-0.23 (0.05)**	**42**	**0.20**	**0.02**	0.08 (0.14)	20	-0.16 (0.09)	21
Jogging	**0.23**	**0.002**	**-0.15 (0.05)**	**39**	*0.15*	*0.055*	0.10 (0.17)	20	**-0.28 (0.09)**	**18**
Running	**0.23**	**0.006**	**-0.18 (0.06)**	**32**	0.13	0.1	0.14 (0.20)	16	-0.24 (0.15)	15
Height (cm)							<= 140 cm		>= 141 cm	
Slow walking	**0.33**	**< 0.001**	**-0.05 (0.01)**	**41**	0.07	0.2	0.03 (0.04)	13	**-0.03 (0.01)**	**27**
Comfortable walking	**0.39**	**< 0.001**	**-0.04 (0.01)**	**41**	*0.14*	*0.059*	-0.001 (0.04)	13	**-0.03 (0.01)**	**27**
Fast walking	**0.40**	**< 0.001**	**-0.04 (0.01)**	**42**	**0.18**	**0.03**	0.04 (0.03)	13	**-0.03 (0.01)**	**28**
Jogging	**0.19**	**0.005**	**-0.02 (0.01)**	**39**	0.11	0.1	0.04 (0.03)	13	-0.01 (0.01)	25
Running	**0.20**	**0.009**	**-0.03 (0.01)**	**32**	0.11	0.2	0.06 (0.04)	11	-0.02 (0.02)	20
Bodyweight (kg)							<= 40 kg		>= 41 kg	
Slow walking	**0.25**	**< 0.001**	**-0.05 (0.01)**	**41**	0.06	0.3	**0.07 (0.04)**	**20**	-0.02 (0.02)	20
Comfortable walking	**0.35**	**< 0.001**	**-0.05 (0.01)**	**41**	*0.15*	*0.052*	0.05 (0.03)	19	*-0.03 (0.02)*	*21*
Fast walking	**0.43**	**< 0.001**	**-0.05 (0.01)**	**42**	**0.19**	**0.02**	0.02 (0.03)	20	**-0.05 (0.02)**	**21**
Jogging	**0.17**	**0.009**	**-0.03 (0.01)**	**39**	0.04	0.5	0.04 (0.03)	19	-0.02 (0.02)	19
Running	**0.21**	**0.008**	**-0.04 (0.01)**	**32**	0.08	0.3	0.04 (0.05)	15	-0.03 (0.03)	16
BSA (m^2)							<=1.20 m^2		>= 1.21 m^2	
Slow walking	**0.29**	**< 0.001**	**-2.62 (0.65)**	**41**	0.08	0.2	1.91 (2.47)	14	**-1.53 (0.73)**	**26**
Comfortable walking	**0.39**	**< 0.001**	**-2.42 (0.49)**	**41**	**0.18**	**0.03**	0.80 (2.20)	13	**-2.09 (0.58)**	**27**
Fast walking	**0.45**	**< 0.001**	**-2.47 (0.43)**	**42**	**0.23**	**0.008**	1.73 (2.23)	14	**-1.85 (0.58)**	**27**
Jogging	**0.19**	**0.005**	**-1.41 (0.48)**	**39**	0.07	0.3	2.73 (2.22)	13	-0.94 (0.71)	25
Running	**0.22**	**0.007**	**-1.78 (0.61)**	**32**	0.11	0.2	3.35 (2.52)	12	-1.11 (1.01)	19

findings agree with previous research reporting a decrease in grossEC with increase in age and body size for children and adolescents [1,14, 28]. Additionally, our study shows that this applies to different speeds of walking and running. Our findings confirm that grossEC is more affected by growth-related subject characteristics, compared to netEC [1,12,17]. Although less strong, linear inverse relations have been reported during self-selected comfortable walking speed for netEC, age and height [1]. However, even though the average speed, age and body size did not differ significantly from our study sample, we revealed quadratic relations, indicating that until a certain age and body size, gait gets less energy efficient.

Doing separate linear regression analyses on ascending and descending parts of the quadratic curves indicated that the older, taller, and heavier children changed their netEC with growth roughly in between 50% and 75% of the amount of grossEC (Table 4; comparing B_2 with B). Although this not always reached statistical significance, the amount would still be physiologically and clinically relevant. For the younger and smaller children, netEC was less affected by growth, but there was a greater spread in the data, like observed in other studies [1]. This may reflect the challenges of measuring restEE in the youngest children.

There are some considerations to highlight. There was no randomization of order of the conditions in the gait test, and the children themselves decided duration of rest in between the conditions. This could potentially have affected the energy expenditure measurements if they were more and more fatigued throughout the testing. However, the children were visually observed to ensure proper rest in between the conditions. Measuring resting energy expenditure in children may be challenging, and high within-subject variability has been reported both for typically developing children and children with cerebral palsy [15, 16]. As an attempt to provide valid measurements, the resting protocol of the present study included both sitting and standing for three minutes each, where the lowest resting energy expenditure measure was used for subsequent calculations. Moreover, the procedures were carefully performed by ensuring the face mask was properly attached, giving explicit instructions, and monitoring of the measurements. However, this will be an element of uncertainty when it comes to using netEC measurements in children.

4.1. Conclusion

Evaluating grossEC and netEC during five different gait conditions showed that grossEC was less affected by within-subject variation in speed compared to netEC, indicating grossEC is favourable evaluating individual changes in EC. On the contrary, netEC was less affected by between-subject variations in speed. Where grossEC had a strong negative linear relation to growth-related subject characteristics during all gait conditions, netEC was less affected, but the relations were quadratic. NetEC showed the highest effect of growth-related subject characteristics during comfortable and fast walking. Our findings underpin the importance of being cautious when grossEC and netEC are used to evaluate children of different ages and body sizes, even during self-selected, comfortable walking speed.

Ethics approval and consent to participate

This study was approved by the Norwegian Centre for Research Data (NSD, Project nr: 469863). A written informed consent was signed by parents or guardians prior to participation and the study was performed in accordance with the Declaration of Helsinki.

Conflict of interest statement

The authors report no conflicts of interest.

Acknowledgement

This study was funded by the Regional Health Authorities in Norway, the Liaison Committee between the Central Norway Regional Health Authority (RHA), the Joint Research Committee between St.Olavs Hospital and the Faculty of Medicine and Health Sciences, the Norwegian University of Science and Technology (NTNU). The data collection was performed with equipment from the NeXtMove core facility, NTNU. The authors would like to acknowledge Annet Dallmeijer for the project idea and Line Fjørstad, Sondre Smeby, Tone Sommerset and Åsmund Holmås for their contribution in data collection. The authors are grateful to the children participating in the study.

References

[1] E.A.M. Bolster, A.C.J. Balemans, M.A. Brehm, A.I. Buizer, A.J. Dallmeijer, Energy cost during walking in association with age and body height in children and young adults with cerebral palsy, Gait Posture 54 (2017) 119–126.
[2] F.A. Kamp, N. Lennon, L. Holmes, A.J. Dallmeijer, J. Henley, F. Miller, Energy cost of walking in children with spastic cerebral palsy: relationship with age, body composition and mobility capacity, Gait Posture 40 (1) (2014) 209–214.
[3] R.L. Waters, S. Mulroy, The energy expenditure of normal and pathologic gait, Gait Posture 9 (3) (1999) 207–231.
[4] M.A. Brehm, J. Harlaar, M. Schwartz, Effect of ankle-foot orthoses on walking efficiency and gait in children with cerebral palsy, J. Rehabil. Med 40 (7) (2008) 529–534.
[5] B. Balaban, E. Yasar, U. Dal, K. Yazicioglu, H. Mohur, T.A. Kalyon, The effect of hinged ankle-foot orthosis on gait and energy expenditure in spastic hemiplegic cerebral palsy, Disabil. Rehabil. 29 (2) (2007) 139–144.
[6] T. Goihl, E.A.F. Ihlen, E.M. Bardal, K. Roeleveld, A. Ustad, S.M. Brændvik, Effects of ankle-foot orthoses on acceleration and energy cost of walking in children and adolescents with cerebral palsy, Prosthet. Orthot. Int 45 (6) (2021) 500–505.
[7] D.H. Sutherland, The evolution of clinical gait analysis part III – kinetics and energy assessment, Gait Posture 21 (4) (2005) 447–461.
[8] R. Waters, Energy expenditure, in: J. Perry, J.M. Burnfield (Eds.), Gait Analyses Normal and Pathological Function, SLACK Incorporated, Thorofare, NJ 08086 USA, 2010, pp. 483–518.
[9] R. Baker, A. Hausch, B. McDowell, Reducing the variability of oxygen consumption measurements, Gait Posture 13 (3) (2001) 202–209.
[10] R.N. Boyd, H.K. Graham, Objective measurement of clinical findings in the use of botulinum toxin type A for the management of children with cerebral palsy, Eur. J. Neurol. 6 (S4) (1999) s23–s35.
[11] J. Rose, J.G. Gamble, J. Medeiros, A. Burgos, W.L. Haskell, Energy cost of walking in normal children and in those with cerebral palsy: comparison of heart rate and oxygen uptake, J. Pediatr. Orthop. 9 (3) (1989) 276–279.
[12] S.S. Thomas, C.E. Buckon, M.H. Schwartz, M.D. Sussman, M.D. Aiona, Walking energy expenditure in able-bodied individuals: a comparison of common measures of energy efficiency, Gait Posture 29 (4) (2009) 592–596.
[13] T.R. Bowen, N. Lennon, P. Castagno, F. Miller, J. Richards, Variability of energy-consumption measures in children with cerebral palsy, J. Pediatr. Orthop. 18 (6) (1998) 738–742.
[14] D. DeJaeger, P.A. Willems, N.C. Heglund, The energy cost of walking in children, Pflug. Arch. 441 (4) (2001) 538–543.
[15] M.A. Brehm, J. Becher, J. Harlaar, Reproducibility evaluation of gross and net walking efficiency in children with cerebral palsy, Dev. Med. Child Neurol. 49 (1) (2007) 45–48.
[16] M.A. Brehm, D.L. Knol, J. Harlaar, Methodological considerations for improving the reproducibility of walking efficiency outcomes in clinical gait studies, Gait Posture 27 (2) (2008) 196–201.
[17] M.H. Schwartz, S.E. Koop, J.L. Bourke, R. Baker, A nondimensional normalization scheme for oxygen utilization data, Gait Posture 24 (1) (2006) 14–22.
[18] R.D. Mosteller, Simplified calculation of body-surface area, N. Engl. J. Med 317 (17) (1987) 1098.
[19] T. Meyer, R.C. Davison, W. Kindermann, Ambulatory gas exchange measurements–current status and future options, Int. J. Sports Med. 26 (Suppl 1) (2005) S19–S27.
[20] P.U. Larsson, K.M. Wadell, E.J. Jakobsson, L.U. Burlin, K.B. Henriksson-Larsén, Validation of the MetaMax II portable metabolic measurement system, Int. J. Sports Med. 25 (2) (2004) 115–123.
[21] A. Hof, Scaling gait data to body size, Gait & Posture, GAIT POSTURE 4 (1996) 222–223.
[22] L. Garby, A. Astrup, The relationship between the respiratory quotient and the energy equivalent of oxygen during simultaneous glucose and lipid oxidation and lipogenesis, Acta Physiol. Scand. 129 (3) (1987) 443–444.
[23] A.D. Kuo, J.M. Donelan, Dynamic principles of gait and their clinical implications, Phys. Ther. 90 (2) (2010) 157–174.
[24] N.G. Moreau, A.W. Bodkin, K. Bjornson, A. Hobbs, M. Soileau, K. Lahasky, Effectiveness of rehabilitation interventions to improve gait speed in children with cerebral palsy: systematic review and meta-analysis, Phys. Ther. 96 (12) (2016) 1938–1954.
[25] R.M. Hoffman, B.B. Corr, W.A. Stuberg, D.J. Arpin, M.J. Kurz, Changes in lower extremity strength may be related to the walking speed improvements in children with cerebral palsy after gait training, Res. Dev. Disabil. 73 (2018) 14–20.
[26] S.S. Thomas, C.E. Buckon, J.H. Piatt, M.D. Aiona, M.D. Sussman, A 2-year follow-up of outcomes following orthopedic surgery or selective dorsal rhizotomy in children with spastic diplegia, J. Pediatr. Orthop. B 13 (6) (2004) 358–366.
[27] T.E. Johnston, S.E. Moore, L.T. Quinn, B.T. Smith, Energy cost of walking in children with cerebral palsy: relation to the gross motor function classification system, Dev. Med. Child Neurol. 46 (1) (2004) 34–38.
[28] R.L. Waters, H.J. Hislop, L. Thomas, J. Campbell, Energy cost of walking in normal children and teenagers, Dev. Med. Child Neurol. 25 (2) (1983) 184–188.