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Mechanical efficiency in children with different body weight: a longitudinal assessment of the quality cohort

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ABSTRACT: Net mechanical efficiency (MEnet), which reflects the body's ability to transfer energy above resting levels in external work, is similar in young children regardless of their body weights. However, it is unclear whether MEnet remains stable during growth and maturation. We sought to determine whether net mechanical efficiency (MEnet) changes over a period of 3 years in children and to identify the factors associated with possible changes. A total of 169 children participating in the QUALITY (Quebec Adipose and Lifestyle InvesTigation in Youth) cohort completed an incremental cycling test, resulting in the same maximal power output during both visits. For MEnet, resting energy consumption was subtracted from total energy consumption at each exercise stage. Physical activity was measured using an accelerometer worn for 7 days. Participants were measured at year one and again two years later. MEnet did not differ across the visits at the 25, 50 and 75 watt stages. However, the participants exhibited lower MEnet values at follow-up for the 100 and 125 W stages (23(3) vs. 20(1)%; 25(4) vs. 20(2)%; $p<0.01$). Declines in MEnet correlated positively with declines in moderate-to-vigorous physical activity levels ($r=0.78$, $p<0.05$). The declines in moderate-to-vigorous physical activity levels across the visits were identified as significant predictors of MEnet changes at 100 and 125 W over 3 years, accounting for 22% of the relationship. In children, MEnet, determined at high exercise intensity, decreases within a period of three years, and the decrement appeared to be related to moderate-to-vigorous physical activity.

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INTRODUCTION

The role of physical activity in the treatment and prevention of obesity is well known [1, 2]. In fact, physical activity improves several health-related outcomes (e.g. increased lipid oxidation, reduced insulin resistance) and facilitates long-term weight control [3]. Unfortunately, excess body fat negatively affects both aerobic and anaerobic fitness in children and adults [1, 2] by reducing oxygen uptake by working muscles, motor unit activation and muscle strength [4, 5].

In addition to these important parameters, mechanical efficiency (ME) is also a variable of interest. Mechanical efficiency reflects the total amount of energy expended to facilitate external work via the ratio of external work produced to energy expended. Despite significant imbalances in energy equilibrium, ME is rarely studied in the context of obesity. However, ME is reported to be lower among obese adults compared with normal weight adults (17% vs. 25%) [6, 7]. Lower ME indicates that more energy is consumed at a given work output. Therefore, individuals with lower ME values should be less efficient with respect to performance and may therefore be limited in terms of physical activity.

In children, mechanical efficiency is similar among normal weight individuals with obese and normal weight parents [8]. Although ME does not differ between children at risk for obesity due to parental history and children not at risk for obesity [8], a recent study performed by our group demonstrated that this parameter is significantly lower among obese children compared with normal weight children [9]. However, that difference was due to increased resting energy expenditure secondary to excess body weight. Therefore, in contrast to what occurs among obese adults, MEnet, ME not accounting for resting energy expenditure, was not deteriorated among obese and overweight children. However, it is currently unclear whether the differences in MEnet among individuals with and without excess body weight manifest in the future.

Indeed, a longitudinal study by DeLany et al. [10] reported variations in energy expenditure among obese children both at rest and during exercise over a two-year follow-up period [10]. Thus, it is possible that MEnet may be modified following prolonged obesity. Horton [11] observed that the factor primarily responsible for decreases in energy expenditure during childhood was changes in physical activity level, which resulted in increased prevalence of obesity in this population [12]. However, Jabbour et al. [13] recently observed that both energy expenditure and ME levels were preserved in obese children at a level comparable with those of both normal weight and overweight children when these children engaged in at least 30 minutes of moderate-to-vigorous physical activity per day. Conversely, inactive obese children exhibited significantly lower ME values compared with both normal weight and overweight children. Based on these cross-sectional studies, children with higher levels of moderate-to-vigorous physical activity, irrespective of their body weights, will exhibit increased ME values. Hence, the current study aimed 1) to report changes in ME over a 3-year period in children nearing puberty and 2) to determine whether changes in factors such as physical activity levels, maturation, and anthropometric measurements are associated with these changes.

MATERIALS AND METHODS

The Quebec Adipose and Lifestyle InvesTigation in Youth (QUALITY) Cohort study includes 630 Caucasian children of Western European ancestry aged 8-10 years [14]. Exclusions criteria were: a diagnosis of type 1 or 2 diabetes; serious illness, or either mental illness or cognitive deficits hindering participation in some or all of the study's activities; and the use of either anti-hypertensive medications or steroids (unless administered topically or via an inhaler), or dietary restrictions (<600 kcal/day). The ethics committees of both Sainte-Justine Hospital and Laval Hospital approved the project. All participants and their parents provided informed consent.

In the present study (Figure 1), only prepubertal children at Tanner stage 1 who were evaluated by a trained nurse during their initial visit (Visit 1) were included. The participants took part in a full day of evaluations, including a standardized breakfast (1.75 g of glucose per kg of body weight, with a maximum of 75 g) and an ad libitum standardized lunch (pasta, fruit juice and yogurt).

The incremental cycling test took place during the afternoon, approximately 3 hours after lunch. The children were instructed to refrain from participating in vigorous physical activity both the day prior to and on the morning of the evaluation. The one-day testing protocol was the same for the initial visit (Visit 1) and for the follow-up visit after three years (Visit 2). The cycling test was designed to reach individual maximal capacity (see the Maximal cycling test section); a total of 169 children participating in the QUALITY cohort exhibited a maximal power of 125 watts at both visits and were subsequently selected for the current study (Figure 1). This maximal power was used to determine whether any changes in energy expenditure occurred at the same relative exercise intensity, a principal component of ME, over a 3-year follow-up period. In this study, the 125 W stage was chosen, given that more participants ended their test at that intensity during visits 1 and 2 compared with any other level, as 30(9)% of the sample ended at 125 W, whereas 6(0.3)% ended at 145 W, and 3(2.1)% ended at 100 W.

Anthropometric measurements

During each visit, body weight was determined using body mass index (BMI) percentiles derived from the Center for Disease Control and the Prevention Clinical Growth Charts for children 2 years of age and older [15] and interpreted according to Canadian guidelines [16]. Dual-energy X-ray absorption was used to assess body mass, total body fat percentage (% BF), and fat-free mass (FFM) (Prodigy Bone Densitometer System, DF+14664, GE Lunar Corporate, Madison, WI, USA). Body mass was measured to the nearest 0.1 kg, with the participant in light clothing and without shoes, and height was determined to the nearest 0.1 cm as described previously [14].

Maximal cycling test

Children performed an incremental maximal test on a cycle ergometer to determine peak oxygen consumption ($\dot{V}O_{2peak}$ in ml·kg^{-1}·min^{-1}). Before beginning the test, the children remained seated for 5 min

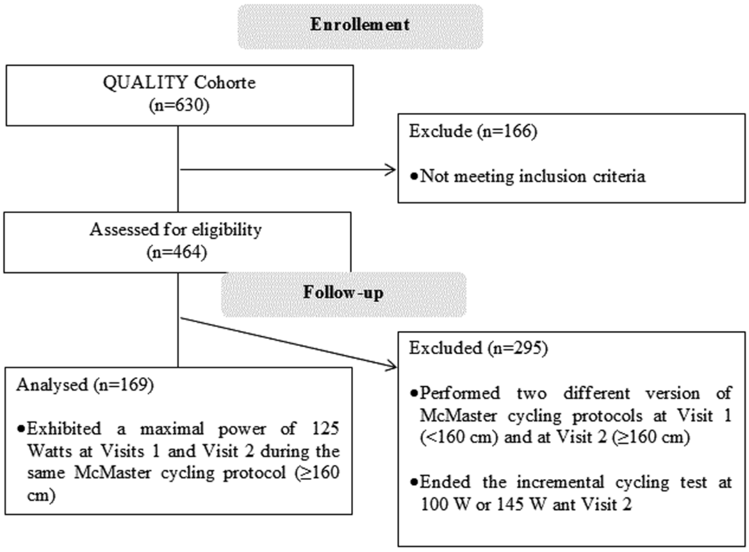

FIG. 1. Flow chart of study design and participants' enrolment

on the bicycle ergometer in the same position as that used for exercise. Resting oxygen consumption was based on the mean oxygen consumption of the last 30 seconds of minutes 3, 4, and 5. The protocol of the test starts at an initial power of 25 watts and increases by 25 watts every 2 min until exhaustion [17]. During the test, the children were instructed to pedal at a rate of 50-70 revolutions per minute. The test was terminated when the participant requested to stop the exercise or could no longer maintain the required pedalling rate (revolutions per minute < 40). A recovery phase of 5 minutes at 25 watts followed the test.

A breath-by-breath automated metabolic system was used to determine $\dot{V}O_{2peak}$ (Oxycon pro; Jaeger, Bunnick, the Netherlands in Montreal; Cosmed, Quark B2, Italy, Rome in Quebec City). Calibration was performed prior to each test using standard gases of known oxygen and carbon dioxide concentrations, as well as a calibration syringe. The data were averaged over 30-second intervals, and both oxygen uptake and respiratory exchange ratios were measured. Achievement of $\dot{V}O_{2peak}$ was attained with either the achievement of a maximal heart rate of >195 beats per minute as measured via an electrocardiogram or a respiratory exchange ratio greater than 1.0 at $\dot{V}O_{2peak}$ [17]. All participants satisfied this requirement.

Physical activity level

Physical activity was measured using an accelerometer (Actigraph LS 7164 activity monitor, Actigraph LLC, Pensacola, FL, USA) worn for 7 days. For this study, only children who achieved a minimum of 10 hours of accelerometer recordings over ≥ 4 days were included [18]. Daily physical activity level was defined as the mean accelerometer counts per valid minute of monitoring (cpm). The threshold for a moderate-to-vigorous physical activity level (MVPA) was set as ≥ 2,296 cpm [19].

Energy consumption and mechanical efficiency

$\dot{V}O_{2net}$ was obtained by subtracting resting oxygen consumption from total oxygen consumption at each exercise stage. The net energy consumption (Enet) in watts was calculated as follows: (4.94 · respiratory exchange ratio + 16.04) · ($\dot{V}O_{2net}$, in ml·min^{-1}) · 60^{-1} [20]. Mechanical efficiency was calculated in net terms (MEnet) for each of the five workloads (25, 50, 75, 100, and 125 W) as follows: work produced in watts · (Enet, in watts^{-1}) · 100^{-1} [7].

Statistical analysis

The data are presented as means (standard deviations). Normality was tested using the Kolmogorov–Smirnov test. Paired t-tests were used to determine whether significant changes occurred at each workload in MEnet between visits 1 and 2. The relationship between changes in MEnet and changes in physical activity (MVPA and CPM), anthropometric measurements (height, weight, BMI percentiles and fat mass) and maturation (Tanner stage) between visits were assessed via Pearson correlations. Multiple linear regression with an extended-model approach was subsequently used to document the effects of the variables on ME changes. Therefore, a series of multiple linear regression models was built for each anthropometric measurement, maturation level and physical activity level to determine the relationship between each variable and changes in ME. A value of $p<0.05$ was statistically significant. The analyses were performed using IBM SPSS Statistics 19 software (IBM SPSS Statistics for Windows, Version 19.0. Armonk, NY: IBM Corp.).

RESULTS

Participant characteristics are presented in Table 1. During their initial visit (Visit 1), all were prepubertal (Tanner stage 1) and after three years, most participants had reached Tanner stage 3 (0.78).

TABLE 1. Age, anthropometric and aerobic fitness parameters and physical activity profile of children groups at Visit 1 and Visit 2.

	Visit 1	Visit 2	Δ (Visit 2 - Visit 1	Paired t-test	
				FT	P
Age (*year*)	9.9 ± 0.6	12.6 ± 0.9	2.7± 0.3	39.8	<0.001
Tanner stage	1.1 ± 0.1	3.1 ± 0.8	2.1 ± 0.7	19.2	<0.001
Height (*cm*)	1.4 ± 0.61	1.5 ± 0.91	0.1 ± 0.3	1.4	0.15
Body mass (*kg*)	38.5 ± 14.1	49.1 ± 14.1	10.5 ± 1.1	29.6	<0.001
BMI (*Percentile*)	79.2 ± 29.1	84.1 ± 16.1	4.9 ± 11	30.2	<0.001
FM (%)	29 ± 11	35 ± 17	6 ± 6	33.8	<0.001
FFM (*kg*)	24.2 ± 6.1	26.2 ± 11.1	2 ± 5	1.3	0.16
HR peak ($beats.min^{-1}$)	196 ± 12	197 ± 9	1 ± 3	1.4	0.13
RERpeak	1.1 ± 0.1	1.1 ± 0.1	-	1.1	0.19
$\dot{V}O_{2peak}$ ($ml.min^{-1}.kg^{-1}$)	45.2 ± 1.4	46.2 ± 3.4	1 ± 2	2.4	0.13
CPM ($daily\ counts.min^{-1}$)	627 ± 121	660 ± 141	33 ± 20	2.1	0.16
MVPA ($min.day^{-1}$)	29 ± 6	7 ± 8	-22 ± 2	27.4	<0.001

Note: Values are expressed as the mean ± standard deviation. BMI: Body Mass Index, FM: Fat Mass, FFM: Fat Free Mass, RER: respiratory exchange ratio, MDPA: Mean daily physical activity, MVPA: Moderate to vigorous physical activity, Δ: The differences between Visit 1 and Visit 2.

TABLE 2. Mean values of net energy consumption and net mechanical efficiency of groups at Visit 1 and Visit 2.

	Visit 1	Visit 2	Δ ± Visit 2 - Visit 1	Paired t-test	
	Net energy consumption in Watts ± W			FT	P
Rest	94 ± 14	96 ± 18	2 ± 1	4.4	0.7
25 W	144 ± 33	148 ± 32	4 ± 1	4.8	0.33
50 W	244 ± 28	246 ± 29	2 ± 1	7.4	0.55
75 W	368 ± 28	379 ± 29	11 ± 1	6.6	0.7
100 W	444 ± 28	530 ± 33	86 ± 5	11.2	<0.01
125 W	464 ± 33	620 ± 35	156 ± 2	14.9	<0.01
	Net mechanical efficiency in percentage (%)			*FT*	*P*
25 W	18 ± 2	17 ± 2	-1 ± 1	2.8	0.13
50 W	20 ± 1	19 ± 3	-1 ± 2	1.4	0.15
75 W	21 ± 2	20 ± 1	-1 ± 1	1.6	0.11
100 W	23 ± 3	20 ± 1 a	-3 ± 2	32.3	<0.001
125 W	25 ± 4	20 ± 2 a	-5 ± 2	27.7	<0.001

Values are expressed as the mean ± standard deviation. Δ: The differences between Visit 1 and Visit 2.

At 8-10 years of age, 46% of the children were normal weight [mean BMI percentile = 49.5 (8.1)]; 24% of the children were overweight [mean BMI percentile = 89.8 (1.6)], and 30% of the children were obese [mean BMI percentile = 97.2 (3.1)]. At follow-up, 40% of the children were normal weight [mean BMI percentile = 51.5 (3.1)]; 28% of the children were overweight [BMI percentile = 87.2 (4.1)], and 32% of the children were obese [BMI percentile = 98.4 (2.1)].

Peak oxygen consumption expressed per unit of body mass did not significantly differ between Visit 1 and Visit 2 (Table 1).Consequently, for each stage, all participants pedalled at the same relative intensity to $\dot{V}O_{2peak}$. As a result, stages 25, 50, 75, 100, and 125 W correspond to 33, 55, 72, 87, and 98% of $\dot{V}O_{2peak}$, respectively, which was similar over a period of 3 years in children (data not shown).

Net energy consumption (Enet, in watts), an indicator that accounts for both oxygen consumption and the respiratory exchange ratio, was significantly higher at Visit 2 at 100 and 125 W compared with Visit 1 and was accompanied by decreased MEnet values at 100 and 125 W over time (23(3) vs. 20(1)%; 25(4) vs. 20(2)%; $p<0.01$) (Table 2). However, Enet and MEnet did not differ between the two visits at 25, 50 and 75 W (Table 2).

No relationships were observed between MEnet changes at 100 and 125 W and changes in anthropometric measurements (height; $r=0.04$, $p=0.41$, weight; $r=0.09$, $p=0.6$ and BMI; $r=0.08$, $p=0.7$), daily activity in cpm ($r=0.02$, $p=0.62$) or Tanner stage ($r=0.06$, $p=0.51$). However, the declines in MEnet observed at both 100 and 125 W correlated positively with declines in MVPA levels ($r=0.78$, $p<0.05$). The multiple linear regression analysis demonstrated that the MVPA changes contributed significantly to variations in ME over 3 years at both 100 and 125 W ($r=0.46$). This model accounted for 22% ($r^2 = 0.22$) of the variation ($\beta = 0.355$; 95% CI 0.036–0.491; $p=0.024$).

DISCUSSION

To the best of our knowledge, this study was the first to examine MEnet changes during cycling over a 3-year period in children with different body weights. It revealed that at low or intermediate intensities, MEnet values did not differ between Visit 1 and Visit 2. However, both near and at maximal intensities (100 and 125 W), MEnet decreased significantly over a relatively short period of time of 3 years. MVPA levels were significantly lower during the second visit, a change that correlated significantly with MEnet reductions at both 100 and 125 W. Being active represents an important goal with respect to the prevention of a variety of health problems among children; engaging in a sustainable MVPA appears to be an effective means of preserving an important component of physical fitness such as MEnet.

A rise in MEnet with increased workload may be explained by a rise in the amount of energy required to perform [21]. As expected, we observed that Enet and the MEnet increased from one stage to the next during both visits. After three years, the MEnet values did not differ statistically from those recorded at baseline at intensities near or below 60% of maximal power output, which indicated that submaximal MEnet was preserved. This longitudinal assessment suggested that there were no alterations in energy use at intensities equivalent to 20%, 40% and 60% of maximal power output for children entering puberty or roughly between Tanner stages 1 and 3. To date, there are no data concerning ME changes over several years during the latter stages of pubertal maturation. Some studies have focused on longitudinal changes in resting energy expenditure in children and demonstrated that resting metabolic rates were significantly increased among African American and Caucasian boys and girls (2 years of follow-up) [10] as well as girls from late childhood through mid-adolescence (4 years of follow-up) [10]; these changes were associated with decreased physical activity. Unfortunately, there are no results available on exercise testing that would yield information on ME and MEnet.

Although the transfer of internal energy consumption to external work output was preserved at lower intensities during Visit 2, the energy consumption increased significantly at 100 and 125 W after three years of follow-up. Alterations in energy expenditure may be explained by differences in body size and composition [22]. However, a recent study by Jabbour et al. [13] demonstrated using a cross-sectional approach that a minimal engagement in MVPA of 30 minutes may preserve Enet during exercise, irrespective of body weight. In this study, the Enet at 100 and 125 W increased significantly compared with baseline. Indeed, at these intensities, the children expended more energy compared with Visit 1. This increased energy consumption was responsible for significant decreases in mechanical efficiency during Visit 2, decreases of -3 and 5% at 100 and 125 W, respectively.

Neither changes in BMI percentiles nor changes in either overall physical activity level (cpm) or Tanner stage progression were associated with MEnet changes at either 100 or 125 W. In fact, MVPA changes over 3 years correlated positively with decreases in MEnet, accounting for 22% of the variations in this variable. These results contrasted with those of several cross-sectional studies, highlighting the importance of adiposity: lower MEnet values were observed among obese adults and children compared with normal weight individuals [7, 23]. However, these studies were hindered by several limitations, including the calculation of ME in both crude values and resting values, as well as a lack of information regarding changes in ME with respect to the performance of specific tasks and the absence of age-matched control participants. However, a recent well-controlled sample of children between 8 and 11 years of age demonstrated that increased body weight does not affect the energy required to perform a given activity on a cycle ergometer when resting values are excluded [9].

Gutin et al. [24] reported that a higher index of cardiovascular fitness (oxygen consumption, heart rate) was associated with higher amounts of MVPA. Given that the ability of muscle to produce mechanical work requires greater energy consumption with optimal motor unit involvement at higher intensity levels such as 100 and 125 W, engaging in MVPA may preserve the efficacy of muscle, as higher intensity training has been linked to higher muscle performance [25]. As reported by Delaffey et al. [26], by 12 years, children are able to perform complex inter-muscular coordination of the lower limb, revealing efficient neural control early during childhood. Therefore, it is reasonable to encourage children to engage in MVPA and other forms of exercise (e.g. jumping or sprinting) during their development, which may facilitate sustainable muscle performance, particularly at workloads of higher intensity.

However, reduced MVPA will most likely result in a decreased ability to undertake high intensity activities efficiently. Future studies must address what occurs during the final stages of pubertal maturation; however, the results of recent studies indicate that the detrimental changes in ME observed among obese adults may start to occur during earlier stages of pubertal maturation, at least for activities performed at higher intensity. Results may also vary between children who maintained their maximal power output over a 3-year period compared with children who either increased or decreased their physical performance, since only children who maintained a maximal performance over time were selected in the current study.

CONCLUSIONS

This study investigated the relationships between changes in anthropometric measurements, maturation and physical activity profiles on Enet and MEnet among prepubertal children over a three-year period. Our results indicated that increases in energy expenditure and reductions in ME are observed at high exercise intensities and may be partially explained by a reduction in MVPA. This longitudinal follow-up study was the first step in elucidating the important role of physical activity over a period of several years and was also the first study to encourage children to engage in MVPA to preserve their ability to efficiently perform physically demanding activities. More studies are necessary to assess this phenomenon throughout puberty and to determine whether improvements in mechanical efficiency occur following MVPA interventions.

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