Body Size and the Growth of Maximal Aerobic Power in Children: A Longitudinal Analysis

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Adjustment of VO₂max for changes in body size is important in evaluating aerobic fitness in children. It is important, therefore, to understand the normal relationship between changes VO₂max and body size during growth. Over the course of 5 years, 20 children (11 boys, 9 girls) underwent annual maximal treadmill testing to determine VO₂max. The mean longitudinal allometric scaling exponent for VO₂max relative to body mass (M) was 1.10 ± 0.30 in the boys and 0.78 ± 0.28 in the girls (p < .05). Respective cross-sectional values were 0.53 ± 0.08 and 0.65 ± 0.03. VO₂max expressed relative to M¹⁰, M⁰.⁷⁵, and M⁰.⁶⁷ rose during the 5 years in the boys, but not the girls. Significant gender differences remained when VO₂max was related to lean body mass. These findings suggest (a) factors other than body size affect the development of VO₂max in children, and (b) gender differences exist in VO₂max during childhood which are independent of body composition.

When measured in absolute terms (L · min⁻¹), maximal oxygen uptake (VO₂max) progressively increases during the course of childhood. Analysis of cross-sectional and longitudinal reports indicates an average rise of approximately 200 ml · min⁻¹ per year in both boys and girls prior to the age of puberty (3, 10, 13). These increases have been attributed to dimensional changes in the components of the oxygen delivery chain (heart, lung, muscle, blood volume) that occur with growth (17). The contribution of size-independent functional changes, such as improvement in myocardial contractility or increased activity of cellular aerobic enzymes, remains uncertain.

Adjusting VO₂max values in children for body size is critical when (a) comparing aerobic fitness between two groups, (b) establishing fitness level of an individual compared to norms, and (c) assessing changes in fitness in individual subjects over time. The optimal means of making such adjustment for size would also reflect differences in body composition, an important issue for gender comparisons, even...
in prepubertal subjects. The most appropriate means of “normalizing” $\text{VO}_2\text{max}$ for body size and composition, however, remains elusive.

Allometric analysis allows $\text{VO}_2\text{max}$ to be expressed in terms of change in body mass ($M$) by the equation $\text{VO}_2\text{max} = kM^b$, where $b$ is the scaling exponent. $M^b$ can then be potentially utilized as a factor to account for differences in size in intra- and interindividual comparisons of aerobic fitness (27). The expected value of $b$ in the growing pediatric population has not, however, been clarified.

Relating $\text{VO}_2\text{max}$ to body mass ($\text{ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$), where $b = 1.0$, is the traditional means of adjusting maximal oxygen uptake to body size. Body mass is an easily measured factor and is an indicator of the load transported in weight-bearing activities. The accuracy of body mass in adjusting $\text{VO}_2\text{max}$ for body size is weakened, however, by the confounding effect of body fat. Moreover, $\text{VO}_2\text{per kilogram}$ is inversely related to body mass within populations of normal subjects. Therefore, larger individuals are penalized, with lower mass-relative $\text{VO}_2\text{max per kilogram}$ than smaller subjects (23).

Dimensionality theory holds that energy expenditure (both resting and maximal $\text{VO}_2$) should relate to body mass by a scaling exponent of 0.67. Mathematical principles dictate that in geometrically similar objects, surface area relates to the square, and volume to the cube, of linear dimensions. Heart, muscle, and lung mass, which determine $\text{VO}_2\text{max}$, should therefore be expected to vary by height$^{3.0}$. Time is considered to relate to height$^{1.0}$, and $\text{VO}_2$ per time should then be proportionate to height$^{1.0}$/height$^{1.0}$, or height$^{2.0}$. Since mass relates to height$^{3.0}$, resting $\text{VO}_2$ and $\text{VO}_2\text{max}$ can be expected by dimensionality theory to vary by mass$^{0.67}$ (3).

Studies of adult animals do not, however, bear this out. Treadmill studies of $\text{VO}_2\text{max}$ in adult animal species ranging in size from pigmy mice to cattle indicate an average scaling exponent to body mass of 0.81 (95% confidence limits 0.75 to 0.87) (24). Empirical observations of mature animals with similar range in size indicates that resting $\text{VO}_2$ relates to mass by the exponent 0.75 (21). The explanation for these departures from theoretical expectations is obscure.

It has been suggested from cross-sectional studies that whether aerobic fitness can be considered to increase, decrease, or remains stable during the childhood years depends on which of the above denominators one uses to adjust $\text{VO}_2\text{max}$ for size (4). For instance, combined studies indicate that $\text{VO}_2\text{max}$ per kilogram remains stable in boys between ages 6 and 16 years, while values slowly decline in girls. On the other hand, if $\text{VO}_2\text{max}$ is expressed relative to $M^{0.75}$, values rise during childhood in both genders (11).

Empirical identification of mass-relative scaling factors for $\text{VO}_2\text{max}$ in cross-sectional studies of children of similar ages have produced disparate values, ranging from 0.37 to 1.02 (1, 6, 15, 16, 26). Longitudinal information is limited. Bailey et al. (2) described a height exponent of 2.46 relative to serial measurements of $\text{VO}_2\text{max}$ in boys between 8 and 15 years of age (which would equate to $M^{0.82}$). Beunen et al. (5) recently reported scaling exponents between 0.23 and 0.97 in a longitudinal studies of 78 children between ages 11 and 14 years. Considerable variability was observed between gender and maturational status.

It is important to recognize that any “normalizing” exponent of body mass for $\text{VO}_2\text{max}$ in growing children may potentially reflect not only increases in body size but also changes in functional capacity and other influences that might develop at rates which are not parallel to those of size. If so, mass exponents for $\text{VO}_2\text{max}$ derived from cross-sectional data (reflecting principally differences in
body size) might be different from those indicated by longitudinal studies (affected by both size and biological development).

While the rate of increase in VO$_2$max during childhood is similar in boys and girls, gender differences in aerobic fitness are identifiable even in the prepubertal years (3, 10, 13). Mean values of absolute VO$_2$max are consistently greater in boys, and this difference becomes exaggerated when maximal oxygen uptake is expressed relative to body mass. These observations have been attributed to differences in body composition (girls have a greater percent body fat) that are evident even prior to puberty as well as higher levels of habitual physical activity in boys (12).

This longitudinal investigation of 20 children studied annually over 5 years was designed to evaluate changes in VO$_2$max and its relationship to body mass over time. Specifically, this study was designed to (a) define the normal rise in VO$_2$max with growth, identifying the mass-relative allometric scaling exponent describing this increase in both boys and girls, and (b) examine the influence of body composition in explaining gender differences in the development of maximal oxygen uptake and its relationship to body mass. In addition, this study sought to provide insight on the contribution of size-independent factors to the normal development of VO$_2$max by comparing (a) changes in VO$_2$max in growing children to those predicated by theoretical factors for size, and (b) longitudinal allometric scaling exponents with those obtained from cross-sectional analyses.

**Methods**

Twenty-one children (10 girls, 11 boys) were recruited for determination of VO$_2$max by annual treadmill testing over 5 consecutive years. One girl elected to drop out after the 1st year, and data are reported for the remaining 20 subjects. Results are otherwise complete with the exception of 1 girl who moved away during the final year. Testing results in these subjects for ventilatory changes and gender-related differences in submaximal walking economy are included in other reports (19, 20).

Informed permission and assent for participation were obtained from the parents and children, respectively. This study was approved by the Institutional Review Board of the Baystate Medical Center.

The subjects were healthy, nonobese, and taking no medications that would affect endurance performance. All were Caucasian, with the exception of one African American, and resided in an upper-middle-class community. Mean age at the beginning of the study was 9.2 (SD = 0.5) years (range = 7.9 to 10.3 years). At the end of the study, 3 of the 8 females had experienced menarche. At the same time, 7 of the 11 boys demonstrated (by parental report) development of pubertal hair, voice change, or facial hair, indicative of pubertal onset.

The study group as a whole was physically active and inclined toward sports participation. Habitual physical activity level of the subjects was assessed at the beginning and end of the study by asking the parent to describe the child using the following categories:

- **Inactive:** Watches television, reads, or does homework after school; no extracurricular sports
- **Occasionally active:** Prefers sedentary activities, but sometimes plays outside
• *Moderately active:* Takes opportunities to become involved in physical activity and enjoys it

• *Active:* Takes initiative to participate in physical exercise and prefers this to sedentary activities; at least three times a week involved in vigorous exercise

• *Very active:* Participates regularly in extracurricular sports; dislikes sedentary activities.

At the beginning of the study, 3 were identified as occasionally active, 10 as moderately active, 5 as active, and 2 as very active. At the end of the 5 years, 2 were classified as occasionally active, 6 as moderately active, 5 as active, and 6 as very active.

At the onset of the study, 17 of the 20 children were participants on community sports teams, mostly soccer, but only 1 was in a program of regular endurance training (swimming). At Year 5, 13 of the 19 subjects were on recreational teams, and none was engaged in aerobic training.

Treadmill exercise testing was performed annually in an identical manner for 5 years in the same month (September). Testing was conducted in an air-conditioned laboratory (20–22 °C). Height and weight were recorded before each test. Triceps and scapular skinfolds were measured by the same individual in triplicate and averaged using standard techniques. Values were converted to estimated percent body fat content by the equations of Slaughter et al. (22). Lean body mass was estimated as the difference of body mass and body fat mass.

Subjects completed a 2-min warm-up at 3.25 mph, 6% grade prior to each test. The test protocol consisted of an initial steady state walk at 3.25 mph, 8% grade for 4 min. Treadmill speed was then individualized between 3.25 and 3.75 mph, depending on subject size and fitness, with elevation increased 2% every minute to subject exhaustion. Subjects were encouraged uniformly by the testing staff to produce a maximal effort. No holding of handrails was permitted.

Heart rate was determined electrocardiographically. Gas exchange variables were measured using a computerized metabolic cart (Q-Plex Cardio-Pulmonary Exercise System, Quinton Instrument Co., Seattle) with standard open circuit techniques. Subjects breathed through a 94-ml dead-space Rudolph valve, and minute ventilation was recorded using a pneumotachometer. Expired gas samples from a mixing chamber were analyzed for oxygen and carbon dioxide by Zirconia oxide and infrared analyzers, respectively. Data were averaged every 15 s and were used to calculate oxygen uptake, expired ventilation, carbon dioxide output, and respiratory exchange ratio (RER). The system was calibrated before each test with standard gases of known oxygen and carbon dioxide concentrations.

Peak VO$_2$ and RER were defined as the average of the two highest values during the final minute of exercise. Peak VO$_2$ was considered equivalent to VO$_2$max if the subject displayed objective signs of exhaustion (unsteady gait, hyperpnea, facial flushing) and either (a) peak heart rate >190 bpm or (b) RERmax >1.00.

Changes in anthropometric variables, VO$_2$max, RERmax, and HRmax relative to gender and time were assessed by two-way ANOVA. Paired post hoc differences were examined by the Scheffé test. Stability of VO$_2$max ranking within the group over the 5 years was examined by Spearman correlation coefficient. Allometric analysis of the data based on the equation $y = ax^b$ (where $y = VO_2$max, $x$ = body mass, and $b$ is the scaling exponent) entailed log transformation of each individual subject's VO$_2$max and body mass such that linear regression could be used.
to solve for $b$ (27). This analysis was performed in two ways. First, to assess the cross-sectional relationship between VO$_2$ max and body mass, allometric analysis was applied to the data from each of the 5 years for each gender. This resulted in one exponent (plus standard deviation from the regression analysis) for each year by gender. Second, allometric analysis was performed for each subject across 5 repeated years to examine longitudinal changes in VO$_2$ max with respect to body mass. Therefore, one body mass exponent was calculated for each subject based on his or her five VO$_2$/body mass pairs of data. Means and standard deviations of these longitudinal values for $b$ for the groups (boys vs. girls) were then compared. Longitudinal changes in VO$_2$ max expressed relative to $M^{1.0}$, $M^{0.75}$, $M^{0.67}$, lean body mass (LBM), and LBM$^{0.75}$ were analyzed by time and gender by two-way ANOVA. Statistical significance was defined as $p < .05$.

**Results**

All subjects satisfied criteria for maximal effort during the five testing sessions. Changes in anthropometric and maximal physiological variables are indicated in Table 1. There were no significant differences in maximal heart rate or RER over the 5 years, indicating that exercise efforts were similar for each testing session.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Longitudinal Anthropometric and Maximal Physiological Variables</th>
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<tbody>
<tr>
<td>Year</td>
<td>1</td>
</tr>
<tr>
<td>Mass (kg) Males</td>
<td>37.1 ± 6.1</td>
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<tr>
<td>Females</td>
<td>35.4 ± 11.1</td>
</tr>
<tr>
<td>Height (cm) Males</td>
<td>142 ± 4</td>
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<tr>
<td>Females</td>
<td>140 ± 8</td>
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<tr>
<td>Body fat (%) Males</td>
<td>20.5 ± 7.3</td>
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<tr>
<td>Females</td>
<td>17.8 ± 8.2</td>
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<td>VO$_2$ max (L · min$^{-1}$) Males</td>
<td>1.78 ± .19</td>
</tr>
<tr>
<td>Females</td>
<td>1.63 ± .37</td>
</tr>
<tr>
<td>Heart rate max (b · min$^{-1}$) Males</td>
<td>198 ± 4</td>
</tr>
<tr>
<td>Females</td>
<td>202 ± 4</td>
</tr>
<tr>
<td>RER max     Males</td>
<td>1.10 ± .05</td>
</tr>
<tr>
<td>Females</td>
<td>1.06 ± .03</td>
</tr>
</tbody>
</table>

*Note.* Values are $M ± SD$. 

The absolute values and rates of increase in body mass were not significantly different in boys and girls. Changes in percent body fat over the 5 years are depicted in Figure 1. No significant gender differences were observed until the final year, when girls showed 23% body fat compared to 17% in the boys ($p < .05$). Similarly, lean body mass was comparable between genders until the last year, when values for boys exceeded those of girls ($p < .05$).

Improvements in absolute $V_O^2_{max}$ are indicated in Figure 2. A linear relationship with chronological age was observed in both males and females, with significant gender differences in both yearly values and rate of $V_O^2_{max}$ rise. $V_O^2_{max}$ was significantly greater in the boys after the first year. Maximal oxygen uptake improved with an average annual increase of 333 ml·min$^{-1}$ in the boys and 195 ml·min$^{-1}$ in the girls ($p < .05$). The increase in $V_O^2_{max}$ ($y$) to year of study ($x$) was expressed by $y = 1.523 + 0.309x$ in boys and $y = 1.447 + 0.185x$ in the girls.

Spearman rank correlation coefficient for the total group between Year 1 and Year 3 was 0.90 and between Year 1 and Year 5 was 0.81. This suggests a close tracking of $V_O^2_{max}$ by individual children over the 5 years. The mean individual scaling exponent for longitudinal changes in $V_O^2_{max}$ relative to body mass was 1.10 ($SD = 0.30$) for the boys and 0.78 ($SD = 0.28$) for the girls ($p < .05$). Individual scaling exponents were marked by significant variability, with values as high as 1.74 and as low as 0.75 in the boys. The range of exponents among the girls was 0.18 to 1.11. The average cross sectional scaling exponents for each of the five years were 0.40 ($SD = 0.20$), 0.53 ($SD = 0.24$), 0.52 ($SD = 0.22$), 0.61 ($SD = 0.16$), and 0.56 ($SD = 0.19$) in the boys. Respective values for the girls were 0.64 ($SD = 0.12$), 0.63 ($SD = 0.13$), 0.70 ($SD = 0.14$), 0.66 ($SD = 0.13$), and 0.62 ($SD = 0.21$). The mean cross-sectional exponents for the entire study were 0.53 ($SD = 0.08$) and 0.65 ($SD = 0.03$) for the boys and girls, respectively.

![Figure 1 — Longitudinal changes in percent body fat by skinfold measurements during the 5-year study in boys and girls.](image-url)
Figure 2 — Absolute values for maximal oxygen uptake in boys and girls during the 5-year longitudinal study.

Figure 3 — Changes in $V_O_{2,max}$ per kilogram in boys and girls over the 5 years.

$V_O_{2,max}$ values expressed as $\text{ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1} (M^{1.0})$ demonstrated a small but significant rise over the 5 years in the boys ($p < .02$), while those in the girls were stable (Figure 3). No gender differences in $V_O_{2,max}$ per kg were observed at the initial testing, but values were significantly greater for the boys for the remaining 4 years.
Figure 4 — Gender-related changes in VO$_2$\textsubscript{max} expressed relative to mass$^{0.67}$ over the 5 years.

Figure 5 — Gender-related changes in VO$_2$\textsubscript{max} expressed relative to mass$^{0.75}$ over the 5 years.

When expressed relative to M$^{0.75}$ and M$^{0.67}$, the rise in VO$_2$\textsubscript{max} in boys was more dramatic, while values were again stable in girls (Figures 4 and 5). In both cases, values for boys and girls were similar at the beginning of study, but those for boys were significantly greater by the end of the 5 years.
When VO₂ max was expressed relative to lean body mass, a pattern similar to the above was again observed (Figure 6). Values for boys and girls were not different at the initial assessment. However, in the remaining 4 years, values were significantly greater in the boys. The mean scaling exponent for VO₂ max relative to LBM was 1.04 (SD = 0.19) for the boys and 0.81 (SD = 0.14) for the girls (p < .05). The same pattern of gender-related changes were observed when VO₂ max was related to LBM⁰.⁷⁵.

Discussion

The aerobic fitness levels of the subjects enrolled in this study are comparable to those previously described for older prepubertal children. The mean VO₂ max per kilogram over the 5 years was 52.0 ml · kg⁻¹ · min⁻¹ in the boys and 46.2 ml · kg⁻¹ · min⁻¹ in the girls. These values are almost identical to the average recorded in 1,730 girls and 2,180 boys in multiple studies described by Bar-Or (3).

Body fatness was somewhat higher in the boys than that previously described by densitometry (12). However, the pattern of change in percent body fat was as expected, with stable values until the final year of the study. At that point, values that increased in the girls and decreased in the boys presumably reflected onset of pubertal effects.

Gender differences in absolute VO₂ max were consistent with prior observations. Values of boys in the present study were consistently greater than girls, with a 9% difference at the beginning of the study increasing to a 29% advantage for the boys at the end of the 5 years. The longitudinal report by Mirwald and Bailey (13) indicated that at age 9 years and 13 years the VO₂ max in boys was greater in boys than in girls by approximately 14 and 10%, respectively.

The longitudinal scaling exponent for VO₂ max relative to body mass of 1.10 in the boys is consistent with the value of 1.02 observed by Cooper et al. in a cross-
sectional study of children ages 6–17 years (6). Others have described somewhat lower cross-sectional exponents in boys of 0.95 (1), 0.92 (26), and 0.37 (16). Similarly, the mean cross-sectional scaling exponent of 0.53 for the boys in the present study was considerably lower than that derived from longitudinal analysis.

The mean longitudinal scaling exponent was significantly lower in the girls (0.79) compared to that of the boys. This trend is also observed in the cross-sectional research literature, with past reports of 0.91 (6), 0.79 (6), 0.84 (26), and 0.68 (16) in girls. Similarly, the longitudinal study of Beunen et al. (5) describes scaling exponents of 0.52 to 0.97 in three groups of boys and 0.23 to 0.42 in girls.

The number of subjects in this study is not large, and this may have contributed to the variability of identified scaling exponents. Similarly, the small numbers weaken the generalizability of the findings to other subject populations. Still, several descriptive findings of the present study may provide insight into the normal development of aerobic fitness in children:

1. An extremely wide variability was evident in individual longitudinal mass scaling exponents for VO$_2$ max. The study included subjects with an exponent as low as 0.18 and as high as 1.74, with a large standard deviation around mean values. This suggests that factors other than body mass contribute significantly to the rise of VO$_2$ max during childhood or alter the VO$_2$ max–mass relationship. A list of potential determinants might include individual variations in geometric similarity, changes in the ratio of leg muscle mass to body mass (14, 25), differences in habitual physical activity and athleticism, and varying rates of development of size-independent factors such as muscle aerobic enzyme capacity or myocardial contractility. The variability of exponents in this study, as well as in the research literature, suggests that it is unlikely that a single exponent will be identified that accurately normalizes VO$_2$ max in the childhood population.

2. Differences in longitudinal mass scaling exponents are evident between boys and girls, even when body size and composition are similar. Higher values for VO$_2$ max and VO$_2$ max per kilogram in boys has been traditionally explained by greater average values for lean body mass in boys and greater body fat in girls, which are evident even in the prepubertal years. In this study, body mass values were similar in boys and girls, and lean body mass and percent body fat were not significantly different until the final year of the study. Despite these body composition similarities, absolute VO$_2$ max values were greater in the boys, and the relationship of VO$_2$ max to body mass over time, as demonstrated by varying scaling exponents, was gender dependent. Moreover, the mean scaling factor for VO$_2$ max relative to lean body mass, which eliminates the influence of body composition, was significantly greater in the boys than in the girls (1.04 vs. 0.81, $p < .05$).

These findings suggest that factors other than body composition influence gender-related differences in the development of VO$_2$ max during childhood. Such variations cannot be explained by gender differences in hemoglobin concentration, which are similar in boys and girls before the age of puberty (8). Whether differences in habitual activity previously described in boys and girls (18) or participation in athletics, are sufficient to explain prepubertal gender differences in
VO$_2$max is problematic. The question cannot be addressed in the present study, a great majority of both boys and girls reported participation in sports team and physically active lifestyle. It is possible, however, that intensity of sports play could have been different in the boys and girls, and potentially influential on gender values for VO$_2$max. This is suggested by the 50% greater rate of rise in VO$_2$max with age in the boys compared to the girls, a difference at variance with previous reports.

Alternatively, there may currently be unrecognized biological differences between males and females in factors affecting aerobic fitness. The existence of such inherent differences has been proposed by others (7, 9), who found that 5–9% differences in VO$_2$max persisted between adult males and females, even when body composition and training status were considered.

### 3. Differences are evident when cross-sectional mass exponents for VO$_2$max are compared in the same subjects to longitudinal exponents. In this study, such a result was most obvious in the boys, whose mean longitudinal exponent (1.10) was more than twice that of the average cross-sectional exponent (0.53). This suggests that the mass exponent for VO$_2$max derived from a cross-sectional allometric analysis of a group of 10-year-old children provides different information than that produced when the same children are followed over time. It is possible, for instance, that potential influences on the VO$_2$max–mass relationship listed under Observation 1 above are different in cross-sectional versus longitudinal analyses.

### 4. Among the boys, changes in VO$_2$max relative to body mass over time did not conform to theoretical expectations based on size alone. If improvements in maximal oxygen uptake are exclusively related to increase in body size (and, by inference, size of the heart, lungs, blood volume, and muscle mass), the mass-relative exponent over time is expected to be 0.67 by dimensionality theory or 0.81 by empiric observations in adult animals. The finding of a higher mass exponent in this and other studies supports the concept that factors other than body size contribute to the growth of VO$_2$max during childhood. It is of interest that girls, on the other hand, generally demonstrate mass-relative exponents for VO$_2$max that do correspond more closely to those expected from size changes alone (0.79 in this study). This suggests that size-independent factors influencing the development of aerobic fitness in children may be gender dependent.

In summary, the information derived from this combined longitudinal and cross-sectional study of a small group of children suggests that (a) factors other than body size are influential in the development of maximal oxygen uptake during childhood, (b) gender differences that are independent of body composition exist in the relationship of VO$_2$max with body size during growth, and (c) it is unlikely that a single scaling factor for VO$_2$max relative to body mass can be identified to accurately adjust values of VO$_2$max for body size in the pediatric population. Consequently, the most appropriate means of “normalizing” VO$_2$max for body size and biological maturity in children and adolescents remains problematic.

### References

1. Åstrand, P.O. *Experimental Studies of Physical Working Capacity in Relationship to Sex and Age*. Copenhagen: Munksgaard, 1952.


