Cardiovascular responses to treadmill and cycle ergometer exercise in children and adults

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Turley, Kenneth R., and Jack H. Wilmore. Cardiovascular responses to treadmill and cycle ergometer exercise in children and adults. J. Appl. Physiol. 83(3): 948–957, 1997.—This study was conducted to determine whether submaximal cardiovascular responses at a given rate of work are different in children and adults, and, if different, what mechanisms are involved and whether the differences are exercise-modality dependent. A total of 24 children, 7 to 9 yr old, and 24 adults, 18 to 26 yr old (12 males and 12 females in each group), participated in both submaximal and maximal exercise tests on both the treadmill and cycle ergometer. With the use of regression analysis, it was determined that cardiac output (Q) was significantly lower (P < 0.05) at a given O2 consumption level (V\text{O2} \text{, l/min}) in boys vs. men and in girls vs. women on both the treadmill and cycle ergometer. The lower Q in the children was compensated for by a significantly higher (P < 0.05) arterial-mixed venous O2 difference to achieve the same or similar VO2. Furthermore, heart rate and total peripheral resistance were higher and stroke volume was lower in the children vs. in the adult groups on both exercise modalities. Stroke volume at a given rate of work was closely related to left ventricular mass, with correlation coefficients ranging from \( r = 0.89–0.92 \) and \( r = 0.88–0.93 \) in the males and females, respectively. It was concluded that submaximal cardiovascular responses are different in children and adults and that these differences are related to smaller hearts and a smaller absolute amount of muscle doing a given rate of work in the children. The differences were not exercise-modality dependent.

submaximal exercise; cardiac output; blood pressure; left ventricular mass

It has been reported that both boys (2, 16, 30, 32, 42, 52) and girls (30, 32, 42, 52) have a lower cardiac output (Q) than adults at a given absolute submaximal rate of work or O2 uptake (VO2). This lower Q at a given submaximal rate of work is attributed to a lower stroke volume (SV), which is only partially compensated for by a higher heart rate (HR). A higher arterial-mixed venous O2 difference (a-vO2) in children then compensates for their lower Q to achieve the same or similar VO2 (2, 15, 32, 42). Although the majority of studies have reported a lower Q in children vs. adults at a given submaximal rate of work, others have reported similar Q values for adults and children (17–19).

A close examination reveals a number of weaknesses in these studies that have reported comparisons of cardiovascular responses to submaximal exercise in children vs. adults. First, many of the studies did not collect data on adults but instead have compared data on children with adult values reported elsewhere (2, 16–18, 30). In addition, all of the studies that have compared submaximal cardiovascular responses with exercise in children and adults, only one used children with a mean age younger than 10 yr, and that study used only three boys with a mean age of 9.7 yr (19). Furthermore, all of these studies have used the cycle ergometer as the exercise modality. Whether cardiovascular response differences between children and adults are attenuated, exacerbated, or the same on the treadmill is unknown. Finally, none of these studies has attempted to determine the mechanism behind the differences that are generally reported between children and adults. Only one study measured submaximal blood pressure (BP) (16), and none attempted to estimate heart size to see whether differences may be related to either peripheral resistance or differing heart sizes of the subjects.

The present study investigated cardiovascular responses to submaximal exercise using both the cycle ergometer and treadmill with 7- to 9-yr-old children and young adults to determine the differences, if any, in responses between boys vs. men and girls vs. women and to determine whether these relationships are affected by the exercise modality. Left ventricular mass (LVM) and submaximal BP were measured to define the mechanism for any differences that may exist.

METHODS

Subjects. Twenty-four healthy 7- to 9-yr-old children (12 boys and 12 girls) and 24 healthy 19- to 26-yr-old adults (12 men and 12 women) agreed to participate in this study. The children were recruited from a local private school. To be included, the children filled out an activity questionnaire to ensure that they were active but not participating in formal training or organized sports. In addition, although pubertal status was not assessed, parents of the children were asked whether their child exhibited any overt signs of pubertal onset (e.g., pubertal hair, breast development). If so, these children were excluded from participation (2 girls were excluded based on this criterion). Adult subjects volunteered in response to flyers that were posted on the college campus. Written informed consent was obtained from each of the children and their parents and from each of the adult subjects. After the children had completed all but their final testing day, they were asked to sign a separate consent form specifically for a blood draw. A separate consent form for the blood draw in children was used so that they were not discouraged from participating in the study solely based on their fear of having their blood drawn. The study design and consent forms had been previously approved by The University of Texas at Austin Institutional Review Board. All subjects, both adults and children, were active but not participating in formal training or organized sports.

Study design. All testing was conducted in the Human Performance Laboratory at The University of Texas at Austin. Each subject visited the laboratory six times. During the first visit maximal O2 consumption (VO2max) was determined
(random draw of either treadmill or cycle ergometry), anthropometric measurements were obtained, and a 10-min accommodation period on the treadmill (5 min at both 3.0 and 5.0 miles/h [mph]) was provided. On the second visit for children, a submaximal steady-state 4.0-mph walk on the treadmill and a second maximal test on the ergometer (whichever was not used in the first test) were conducted, with the tests being separated by 20–30 min. On the second visit for adults, only the second maximal test was conducted. On each of the next four visits, one of four randomized submaximal steady-state exercise tests was conducted (2 cycle and 2 treadmill tests). Both children and adults exercised at three different submaximal rates of work on each ergometer so that accurate regression lines could be developed through as wide a range of $\dot{V}O_2$ values as possible.

On the final visit, M-mode echocardiography was used to determine the subject’s left ventricular dimensions at rest, just before exercise, and a blood sample was drawn immediately after exercise (optional for the children) to determine hemoglobin concentration ([Hb]) for use in the calculation of Q. Testing for each subject was conducted within a 2- to 4-wk period, with a minimum of 24 h between tests.

Maximal-exercise tests. Before the commencement of the maximal tests on the motor-driven treadmill (Quinton Q65), both children and adults practiced walking and running for 3–5 min, after which the protocol began. For children, the protocol began with walking at 3.0 mph at 0% grade for 1 min, with a 2.5% increase in grade at the beginning of both minute 2 and minute 3. At the start of minute 4, the speed was increased to 5.0 mph, with an additional increase to 5.5 mph at the beginning of minute 5. Grade was then increased 2.5% at the start of both minutes 6 and 7, after which the speed was increased 0.5 mph each minute until exhaustion. For safety purposes, a spotter was positioned behind the children during maximal treadmill testing. The adult protocol began with walking at 3.0 mph for 1 min, with a subsequent 0.5 mph increase in speed at the beginning of every minute up to 6.5–7.5 mph, dependent on the fitness level of the subject. Once maximal speed was reached, grade was subsequently increased 2.5% at the start of every minute until exhaustion. Maximal tests on the electronically braked cycle ergometer (Ergoline 800S, SensorMedics) used different continuous incremental protocols for children and adults. The children performed unloaded cycling at 65–75 revolutions/min (rpm) for the first minute, after which the work rate was increased to 20 W for the second minute, and then increased by 15 W increments at the start of every minute until exhaustion. The adults pedaled at 65–75 rpm at 50 W for the first minute, after which the work rate was increased by 25 W at the beginning of every minute until exhaustion. The cycle ergometer was calibrated daily.

During maximal tests, the subjects exercised to volitional fatigue. Tests were considered maximal in children when at least two of the following criteria were achieved: 1) failure to maintain the work rate, 2) respiratory exchange ratio (RER) ≥ 1.00, and 3) maximal HR ≥ 95% of age-predicted maximum. Because it has recently been reported that a plateau in $\dot{V}O_2$ is seldom achieved in children (45, 46) or adolescents (41), attainment of a plateau was not used as a criterion for $\dot{V}O_2_{\text{max}}$ in children. For adults, a test was considered a valid maximal test when at least two of the following criteria were achieved: 1) failure to maintain the work rate, 2) RER ≥ 1.10, 3) maximal HR ≥ age-predicted maximum, and 4) an increase in work rate with no further increase in $\dot{V}O_2$. If two or more of these criteria were not achieved, a second maximal test was performed.

Submaximal exercise tests. Submaximal exercise tests on the treadmill were at 3.0, 4.0, and 5.0 mph for children and at 3.0 and 5.0 mph and ~ 60% of $\dot{V}O_2_{\text{max}}$ for the adults. A relative work rate was used in adults so that a similar physiological stress was experienced by both the children and adults, thus also allowing comparison of cardiovascular responses at similar relative rates of work and increasing the range of $\dot{V}O_2$ values from which regression lines were developed. From the results of pilot work, we found that children were just able to complete steady-state cardiovascular measurements on the treadmill when they exercised at both 3.0 and 5.0 mph on the same day. Hence, the children completed the 4.0-mph portion of their submaximal treadmill test on their second visit, as described above. Children completed the 4.0-mph work rate only once. One boy did not do the 4.0-mph work rate.

On the cycle, children exercised at 20, 40, and 60 W, whereas adults exercised at 40 and 60 W and at ~60% of $\dot{V}O_2_{\text{max}}$, both groups cycling at 65 ± 5 rpm. One girl was not able to complete the 60-W work rate. As with the treadmill, a relative work rate was used in adults to increase the range of $\dot{V}O_2$ values from which regression lines were developed.

Before the commencement of both the treadmill and cycle ergometer submaximal tests, the children and adults were allowed a 3–5 min warm-up period. The treadmill was calibrated at each speed during each submaximal test to ensure that the appropriate speed was maintained, and the cycle ergometer was calibrated daily. Although the electronically braked cycle ergometer used in this study maintained the work rate independent of rpm, rpm during submaximal testing was the same for both children and adults (65 ± 5) to eliminate the possible effects that different pedaling speeds might have on their metabolic and cardiovascular responses (49). During all submaximal tests, subjects were allowed to drink water ad libitum, and a fan was used for cooling at an airflow rate of ~2.0–3.0 m/s.

Submaximal cardiovascular and metabolic data were collected for all subjects during the steady-state exercise. Steady state for all subjects was defined as a HR response within ± 5 beats/min, and three consecutive 20-s values for both $\dot{V}O_2$ and CO$_2$ production (VCO$_2$) within ± 10%. On average, both children and adults exercised for ~ 3–6 min before steady state was achieved, and each steady-state work rate lasted ~ 14–18 min. Once steady state had been achieved, Q, HR, $\dot{V}O_2$, and BP measurements were obtained in duplicate. For children, a 3- to 5-min rest period was allowed between each work rate and between duplicate measurements at the highest work rate when necessary. For adults, a 3- to 5-min rest period was given between the two highest work rates.

Before the start of the submaximal treadmill and cycle tests, subjects were connected to a Colin model STBP-780 semi-automated BP-measurement device (Colin Medical Instruments, San Antonio, TX). The BP cuff was selected so that the cuff bladder width was ~ 40% of the subject’s upper arm circumference measured at midbiceps (20, 26).

Once steady state was achieved, a BP measurement was taken, followed by measurements of HR, VCO$_2$, and $\dot{V}O_2$. The HR and $\dot{V}O_2$ (collected as the rolling average of 3 consecutive 20-s intervals) were used as steady-state values were a 1-min average taken just before the CO$_2$-rebreathing maneuver. Once these steady-state values had been attained, end-tidal CO$_2$ pressure (PETCO$_2$) values were collected and a CO$_2$-rebreathing Q measurement was performed.

Measurements. Height, weight, and skinfold thicknesses were measured during the subject’s first visit to the laboratory. Relative body fat in children was estimated from triceps and subscapular skinfold thicknesses by using the equations...
of Slaughter et al. (see Ref. 25). For adult men, abdominal, chest, and thigh skinfolds were used to estimate body density via the Jackson and Pollock equation (23), and the Brozek et al. equation (6) was used to estimate relative body fat from body density. Body density of the women was estimated from the Jackson, Pollock, and Ward equation (24) by using the triceps, abdominal, supraillium, and thigh skinfolds. The Lohman equation (37) was then used to determine relative fat in women. Fat mass (FM) was determined by relative body fat (%) times body weight (kg) divided by 100. Fat-free mass (FFM) was determined by body weight (kg) minus FM. Relative body fat was estimated on two separate occasions in six subjects of each group (boys, girls, men, and women) to determine reliability of the measurement. Body surface area (BSA, m²) was calculated by using the Haycock et al. formula (21). Body mass index (BMI) was calculated by dividing body weight (kg) by stature squared (m²).

Expired gases during both the maximal and submaximal tests were collected and analyzed by using a SensorMedics 2900 metabolic cart (Yorba Linda, CA), which utilizes a zirconium oxide cell for fractional percentage of expired O₂ determination, an infrared absorption analyzer for fractional percent of expired CO₂ (FeCO₂) determination, and a mass flowmeter for measuring minute ventilation. Both before and after each test, the gas analyzers were calibrated with gases of known concentration and the flowmeter was calibrated with a known volume of air. VO₂max and maximal RER were the average of the two highest consecutive 20-s values.

HR was monitored and recorded with a Polar HR monitor at 5-s intervals throughout the treadmill and cycle maximal tests and at 15-s intervals during the submaximal tests. Q was measured indirectly by using the CO₂-rebreathing equilibration method (7). The CO₂-rebreathing apparatus was modified for the children. A 2600 series Hans Rudolph two-way valve (48-ml dead space) was connected to an 8200 series Hans Rudolph rebreathing switching system for the children, whereas a 2700 series Hans Rudolph two-way valve (108-ml dead space) was attached to the rebreathing switch for the adults. In addition, a 3-liter bag was used for CO₂-rebreathing in children and small adults, and a 5-liter bag was used in larger adults. Gas concentrations used during rebreathing for children ranged from 8.0 to 10.0% whereas values for adults ranged from 9.0 to 13.5%.

Of the variables used to calculate Q, VO₂ was obtained by averaging three consecutive 20-s VO₂ values during steady-state exercise. The partial pressure of CO₂ in arterial blood (PaCO₂) was estimated from a 20-s average of PetCO₂. The partial pressure of CO₂ in mixed venous blood (PvCO₂) was estimated from the equilibration method as described by J ones (28, 29). The downstream correction was applied to the partial pressure of equilibrium CO₂ to adjust PaCO₂ for the alveolar-to-blood PCO₂ difference (27, 40). PvCO₂ and PaCO₂ were converted to content of CO₂ in the venous (CVO₂) and arterial blood (CAO₂), respectively, through an equation derived from the CO₂ dissociation curve as described by J ones and Campbell (27) and as adapted from Mc Ardley (39). This content was then corrected for the effect of [Hb] on CO₂-carrying capacity of the blood (27, 39). The [Hb] used for the children who did not consent to having their blood drawn was the average value obtained in this study for their gender.

SV (ml) was calculated as Q (ml)/HR (beats/min). MBP (mmHg) was determined as systolic BP + (2·diastolic BP)/3. Total peripheral resistance (TPR, units) was calculated as MBP/Q. VO₂ was divided by Q to calculate (a-VO₂) (ml/100 ml).

Left ventricular dimensions were measured from standard M-mode echocardiography obtained with an Aloka & J ohnson Ultrasound Imaging System with the use of a 3.0-MHz transducer. The subjects were measured in the left lateral decubitus position. M-mode tracings were obtained at the level just above the papillary muscle and recorded onto a standard videocassette recorder tape for off-line measurements.

Left ventricular dimensions were measured offline with a digital imaging-acquisition system (Freeland and Prism) according to the American Society of Echocardiography (47) and using leading edge-to-leading edge methodology. The intraventricular septal wall thickness, left ventricular internal diameter (LVIDd and LVIDs), and left ventricular posterior wall thickness were measured in both diastole (d) and systole (s), respectively. Each dimension was measured from three different cardiac cycles, and the average value was used. All M-mode tracings and dimensions were measured by the same technologist. M-mode tracings of 17 subjects were read twice, once on each of two separate days to assess intraobserver reliability (R = 0.97). Interobserver reliability (R = 0.98) was assessed on six subjects by comparing the measurements of the primary technologist with those of a registered cardiac sonographer.

Fractional shortening fraction (SF, %) was calculated as [(LVIDd – LVIDs)/LVIDd]×100. LVM was calculated using the formula proposed by the American Society of Echocardiography (47), as described by Devereux et al. (13), which has been validated in adult necropsy studies (12, 13), a child autopsy study (11), and in a study of animals with heart sizes that were similar to those of the children involved in this study (9).

Immediately after the last submaximal exercise test in adults and children, blood was collected for [Hb] assessment. A venipuncture in the antecubital vein was performed while subjects were in the sitting position. [Hb] was measured in quadruplicate by the cyanmethemoglobin method. An average of the four measurements was used as the [Hb]. To most accurately adjust Q for the change in [Hb] during exercise, blood was drawn immediately after exercise.

Analysis. The differences in submaximal cardiovascular responses to exercise between the boys and girls have been reported elsewhere (51). Because the primary focus of this paper is child vs. adult differences in submaximal cardiovascular responses to exercise, the differences between the men and women are presented but not discussed, and only the differences between the boys vs. men and girls vs. women are presented in detail. Differences in descriptive variables between groups were analyzed with an analysis of variance (ANOVA). Test-retest reliability of submaximal metabolic and cardiovascular variables for each modality was determined by intraclass correlation R calculated from a one-way ANOVA model and is reported as the reliability of the mean of the test scores (MS) for each subject [(MSb – MSw)/MSb], while reliability for relative fat and LVM is reported as the reliability of scores collected on 1 day (MSb – MSw)/(MSb + MSw) (3), where MSb is mean square between and MSw is mean square within.

For the adult vs. child comparisons of the cardiovascular variables measured during submaximal exercise, the mean of the values collected on the first day and second day for both the treadmill and cycle ergometer was used. Differences between adults and children in metabolic and cardiovascular variables at a given rate of work were determined with a one-way ANOVA. Child vs. adult cardiovascular response differences at a given VO₂ were determined by regression analysis. Analysis of covariance of heterogeneous regression lines (SPSS) was used to determine whether significant differences existed between the slopes and intercepts of the
cardiovascular variables on \( V\dot{O}_2 \) (l/min) for children vs. adults. All significant differences are at the \( P \leq 0.05 \) level unless stated otherwise.

**RESULTS**

The physical characteristics of the subjects are presented in Table 1. All values for the subjects' physical characteristics were significantly lower in the children (boys and girls) than in both the men and women except for relative fat and SF. Relative fat was significantly higher in the women than in both the children (boys and girls) and men. Furthermore, relative fat was significantly higher in the girls than men, but it was not significantly different between the boys and men. The reliability coefficients for relative fat estimates in this study for 12 children and 12 adults were \( R = 0.96 \) and \( R = 0.98 \), respectively. SF was not different between any of the groups.

Table 2 presents the \( V\dot{O}_2\max \) data from both the treadmill and cycle ergometer for all groups. \( V\dot{O}_2\max \) relative to body mass (ml·kg\(^{-1}\)·min\(^{-1}\)) was not different between the children (boys and girls) and men, but it was significantly lower in the women than in the boys, girls, and men on both the treadmill and cycle ergometer. Maximal HR in the women was significantly lower than in the boys and girls on both modalities. Maximal RER was significantly higher in the girls than men, but it was not significantly different between the boys and men. The reliability coefficients for relative fat estimates in this study for 12 children and 12 adults were \( R = 0.96 \) and \( R = 0.98 \), respectively. SF was not different between any of the groups.

Day-to-day reliability for each of the steady-state submaximal cardiovascular variables was moderately high for both modalities in all groups (Table 3). \( V\dot{O}_2 \) (l/min) day-to-day reliability was also high on both the cycle ergometer and treadmill in all groups (Table 3).

The cycle ergometer and treadmill submaximal metabolic and cardiovascular data for the boys vs. men and girls vs. women are summarized in Tables 4 and 5, respectively. There were significant differences in \( V\dot{O}_2 \) (l/min) at equivalent rates of work between both groups on the treadmill, and between the boys and men on the cycle ergometer. Thus, to determine whether there were significant differences in cardiovascular responses between the groups at equivalent \( V\dot{O}_2 \) (l/min) levels, the regression lines of each of the cardiovascular variables on \( V\dot{O}_2 \) (l/min) were statistically compared.

Figures 1–5 present the mean cardiovascular data on \( V\dot{O}_2 \) (l/min) for each work rate for all groups on both the cycle ergometer (A) and treadmill (B). The insets in each of these figures present the regression equation for the specific cardiovascular variable and \( V\dot{O}_2 \) (l/min), and the legends give the statistical significance of differences, if any, in slopes and intercepts of the regression lines between the groups.

Table 1. Physical characteristics of subjects

<table>
<thead>
<tr>
<th>Variable</th>
<th>Boys</th>
<th>Girls</th>
<th>Men</th>
<th>Women</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, yr</td>
<td>9.1 ± 0.7</td>
<td>8.8 ± 0.7</td>
<td>22.8 ± 2.0</td>
<td>23.6 ± 2.1</td>
</tr>
<tr>
<td>Height, cm</td>
<td>134.4 ± 6.3</td>
<td>132.6 ± 6.3</td>
<td>180.6 ± 4.2</td>
<td>166.0 ± 3.1</td>
</tr>
<tr>
<td>Weight, kg</td>
<td>29.5 ± 4.3</td>
<td>28.5 ± 4.8</td>
<td>80.0 ± 5.0</td>
<td>63.3 ± 6.2</td>
</tr>
<tr>
<td>BMI, kg/m(^2)</td>
<td>16.2 ± 1.5</td>
<td>16.2 ± 2.0</td>
<td>24.6 ± 1.4</td>
<td>22.9 ± 2.5</td>
</tr>
<tr>
<td>BSA(^{ef})</td>
<td>1.04 ± 0.10</td>
<td>1.02 ± 0.11</td>
<td>2.01 ± 0.08</td>
<td>1.71 ± 0.13</td>
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<tr>
<td>Fat, %</td>
<td>15.8 ± 4.3</td>
<td>16.8 ± 4.4</td>
<td>13.6 ± 2.9</td>
<td>23.1 ± 5.2</td>
</tr>
<tr>
<td>Fat mass, kg(^{ef})</td>
<td>4.8 ± 1.8</td>
<td>4.9 ± 2.0</td>
<td>10.8 ± 2.7</td>
<td>14.8 ± 4.6</td>
</tr>
<tr>
<td>FFM, kg(^{ef})</td>
<td>24.7 ± 3.1</td>
<td>23.6 ± 3.1</td>
<td>69.3 ± 4.6</td>
<td>48.5 ± 5.3</td>
</tr>
<tr>
<td>[Hb], g/dl(^{abc})</td>
<td>13.2 ± 0.8</td>
<td>13.5 ± 0.7</td>
<td>15.9 ± 1.2</td>
<td>14.3 ± 1.0</td>
</tr>
<tr>
<td>LVM, g(^{ef})</td>
<td>78.8 ± 12.2</td>
<td>66.0 ± 11.6</td>
<td>202.5 ± 26.9</td>
<td>140.6 ± 31.0</td>
</tr>
<tr>
<td>SF, %</td>
<td>34.1 ± 3.8</td>
<td>32.3 ± 4.4</td>
<td>32.9 ± 5.1</td>
<td>32.1 ± 3.2</td>
</tr>
</tbody>
</table>

Values are means ± SD. BMI, body mass index; BSA, body surface area; FFM, fat free mass; [Hb], hemoglobin concentration; LVM, left ventricular mass; SF, shortening fraction. *: \( n = 9 \); \( \dagger \): \( n = 8 \). Significant difference (\( P < 0.05 \)): \( \ddagger \): between men and women; \( \ddagger \): between men and boys; \( \ddagger \): between men and girls; \( \ddagger \): between boys and girls; \( \ddagger \): between both men and women compared with both boys and girls.

Table 2. Treadmill and cycle ergometer maximal data

<table>
<thead>
<tr>
<th>Variable</th>
<th>Boys</th>
<th>Girls</th>
<th>Men</th>
<th>Women</th>
</tr>
</thead>
<tbody>
<tr>
<td>( V\dot{O}_2\max ), l/min(^{f})</td>
<td>1.60 ± 0.21</td>
<td>1.51 ± 0.23</td>
<td>4.23 ± 0.52</td>
<td>2.95 ± 0.44</td>
</tr>
<tr>
<td>( V\dot{O}_2\max ), ml·kg(^{-1})·min(^{-1})</td>
<td>54.4 ± 5.5</td>
<td>53.1 ± 4.4</td>
<td>53.2 ± 5.3</td>
<td>46.9 ± 4.3</td>
</tr>
<tr>
<td>HR, beats/min(^{de})</td>
<td>200 ± 11</td>
<td>202 ± 9</td>
<td>198 ± 10</td>
<td>192 ± 6</td>
</tr>
<tr>
<td>RER(^{f})</td>
<td>1.08 ± 0.06</td>
<td>1.10 ± 0.05</td>
<td>1.20 ± 0.06</td>
<td>1.20 ± 0.06</td>
</tr>
<tr>
<td>Cycle ergometer</td>
<td>1.49 ± 0.20</td>
<td>1.33 ± 0.26</td>
<td>3.93 ± 0.64</td>
<td>2.66 ± 0.52</td>
</tr>
<tr>
<td>( V\dot{O}_2\max ), ml·kg(^{-1})·min(^{-1})</td>
<td>50.7 ± 4.6</td>
<td>47.0 ± 5.5</td>
<td>48.9 ± 6.7</td>
<td>41.9 ± 5.4</td>
</tr>
<tr>
<td>HR, beats/min(^{de})</td>
<td>195 ± 10</td>
<td>199 ± 8</td>
<td>192 ± 10</td>
<td>185 ± 8</td>
</tr>
<tr>
<td>RER(^{f})</td>
<td>1.09 ± 0.05</td>
<td>1.12 ± 0.07</td>
<td>1.21 ± 0.05</td>
<td>1.24 ± 0.06</td>
</tr>
</tbody>
</table>

Values are means ± SD. \( V\dot{O}_2\max \), maximal \( O_2 \) consumption; HR, heart rate; RER, respiratory exchange ratio. Significant difference (\( P \leq 0.05 \)): \( \ddagger \): between men and women; \( \ddagger \): between men and boys; \( \ddagger \): between men and girls; \( \ddagger \): between women and boys; \( \ddagger \): between women and girls; \( \ddagger \): between both men and women compared with both boys and girls.

The comparison of SV-\( V\dot{O}_2 \) between the groups is presented in Fig. 3, A and B, for both the cycle ergometer and treadmill, respectively. The intercept of SV on \( V\dot{O}_2 \) for the boys vs. men and girls vs. women was significantly lower on both modalities. The slopes of these relationships were not different between the groups.
Table 3. Cycle ergometer and treadmill reliability ranges

<table>
<thead>
<tr>
<th>Variable</th>
<th>Boys</th>
<th></th>
<th>Girls</th>
<th></th>
<th>Men</th>
<th></th>
<th>Women</th>
</tr>
</thead>
<tbody>
<tr>
<td>V̇O₂, l/min</td>
<td>Cycle</td>
<td>Treadmill</td>
<td>Cycle</td>
<td>Treadmill</td>
<td>Cycle</td>
<td>Treadmill</td>
<td>Cycle</td>
</tr>
<tr>
<td>0.96–0.97</td>
<td>0.96–0.97</td>
<td>0.90–0.92</td>
<td>0.95–0.99</td>
<td>0.88–0.98</td>
<td>0.70–0.98</td>
<td>0.75–0.83</td>
<td>0.88–0.97</td>
</tr>
<tr>
<td>SV, ml</td>
<td>0.94–0.98</td>
<td>0.88–0.90</td>
<td>0.78–0.94</td>
<td>0.79–0.88</td>
<td>0.86–0.95</td>
<td>0.91–0.98</td>
<td>0.56–0.69</td>
</tr>
<tr>
<td>HR, beats/min</td>
<td>0.96–0.99</td>
<td>0.97–0.99</td>
<td>0.93–0.98</td>
<td>0.99</td>
<td>0.83–0.91</td>
<td>0.90–0.95</td>
<td>0.84–0.90</td>
</tr>
<tr>
<td>(a-VO₂) ml/100 ml</td>
<td>0.93–0.97</td>
<td>0.92–0.94</td>
<td>0.88–0.96</td>
<td>0.94–0.95</td>
<td>0.81–0.91</td>
<td>0.61–0.93</td>
<td>0.57–0.79</td>
</tr>
<tr>
<td>TPR, units</td>
<td>0.83–0.89</td>
<td>0.80–0.85</td>
<td>0.71–0.87</td>
<td>0.83–0.87</td>
<td>0.72–0.93</td>
<td>0.68–0.96</td>
<td>0.64–0.81</td>
</tr>
<tr>
<td>V̇O₂, l/min</td>
<td>0.97–0.99</td>
<td>0.99</td>
<td>0.97–0.99</td>
<td>0.99</td>
<td>0.85–0.95</td>
<td>0.93–0.98</td>
<td>0.80–0.99</td>
</tr>
</tbody>
</table>

Values are range of reliability for all rates of work. Cycle, cycle ergometer reliability; Treadmill, treadmill reliability. Q̇, cardiac output; SV, stroke volume; (a-VO₂), arterial-mixed venous O₂ difference; TPR, total peripheral resistance; V̇O₂, O₂ consumption.

Table 4. Cycle ergometer and treadmill submaximal metabolic and cardiovascular data by work rate for boys and men

<table>
<thead>
<tr>
<th>Ergometer/Work Rate</th>
<th>Boys</th>
<th></th>
<th>Girls</th>
<th></th>
<th>Men</th>
<th></th>
<th>Women</th>
</tr>
</thead>
<tbody>
<tr>
<td>V̇O₂, l/min</td>
<td>Cycle</td>
<td>Treadmill</td>
<td>Cycle</td>
<td>Treadmill</td>
<td>Cycle</td>
<td>Treadmill</td>
<td></td>
</tr>
<tr>
<td>0.95–0.97</td>
<td>0.95</td>
<td>0.90–0.92</td>
<td>0.95–0.99</td>
<td>0.88–0.98</td>
<td>0.70–0.98</td>
<td>0.75–0.83</td>
<td>0.88–0.97</td>
</tr>
<tr>
<td>SV, ml</td>
<td>0.94–0.98</td>
<td>0.88–0.90</td>
<td>0.78–0.94</td>
<td>0.79–0.88</td>
<td>0.86–0.95</td>
<td>0.91–0.98</td>
<td>0.56–0.69</td>
</tr>
<tr>
<td>HR, beats/min</td>
<td>0.96–0.99</td>
<td>0.97–0.99</td>
<td>0.93–0.98</td>
<td>0.99</td>
<td>0.83–0.91</td>
<td>0.90–0.95</td>
<td>0.84–0.90</td>
</tr>
<tr>
<td>(a-VO₂) ml/100 ml</td>
<td>0.93–0.97</td>
<td>0.92–0.94</td>
<td>0.88–0.96</td>
<td>0.94–0.95</td>
<td>0.81–0.91</td>
<td>0.61–0.93</td>
<td>0.57–0.79</td>
</tr>
<tr>
<td>TPR, units</td>
<td>0.83–0.89</td>
<td>0.80–0.85</td>
<td>0.71–0.87</td>
<td>0.83–0.87</td>
<td>0.72–0.93</td>
<td>0.68–0.96</td>
<td>0.64–0.81</td>
</tr>
<tr>
<td>V̇O₂, l/min</td>
<td>0.97–0.99</td>
<td>0.99</td>
<td>0.97–0.99</td>
<td>0.99</td>
<td>0.85–0.95</td>
<td>0.93–0.98</td>
<td>0.80–0.99</td>
</tr>
</tbody>
</table>

Values are means ± SD. Cycle, cycle ergometer; W, watts; Tm, treadmill; mph, miles/h; 60%, 60% maximal V̇O₂ consumption (V̇O₂max). SBP, systolic blood pressure; DBP, diastolic blood pressure. *Significantly different (P < 0.05) from men at same work rate on same exercise modality.
V̇O₂. The lower SV is related to the smaller heart size in the children. The lower Q̇ in children at a given V̇O₂ is compensated for by a higher (a-φ)V̇O₂.

Several methodological factors must be considered when these data are interpreted. Both shorter (10) and longer (52) recirculation times have been reported in this age group.

### Table 5. Cycle ergometer and treadmill submaximal metabolic and cardiovascular data by work rate for girls and women

<table>
<thead>
<tr>
<th>Ergometer/Work Rate</th>
<th>V̇O₂, l/min</th>
<th>V̇O₂r, ml·kg⁻¹·min⁻¹</th>
<th>V̇O₂m, % V̇O₂max</th>
<th>RER</th>
<th>Q̇, l/min</th>
<th>SV, ml</th>
<th>HR, beats/min</th>
<th>(a-σ)V̇O₂, ml/100 ml</th>
<th>TPR, units</th>
<th>SBP, mmHg</th>
<th>DBP, mmHg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Girls</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cycle 20 W</td>
<td>0.51 ± 0.05</td>
<td>18.3 ± 3.0</td>
<td>39.8 ± 8.8</td>
<td>6.6</td>
<td>56.3</td>
<td>118.9</td>
<td>7.8</td>
<td>11.2</td>
<td>105.2</td>
<td>57.1</td>
<td></td>
</tr>
<tr>
<td>Cycle 40 W</td>
<td>0.75 ± 0.05</td>
<td>26.7 ± 2.7</td>
<td>57.9 ± 9.1</td>
<td>8.1</td>
<td>57.8</td>
<td>140.8</td>
<td>9.5</td>
<td>11.0</td>
<td>115.1</td>
<td>57.6</td>
<td></td>
</tr>
<tr>
<td>Cycle 60 W</td>
<td>0.98 ± 0.06</td>
<td>33.9 ± 5.0*</td>
<td>72.0 ± 13.9</td>
<td>9.1</td>
<td>57.6</td>
<td>159.7</td>
<td>10.8</td>
<td>9.2</td>
<td>127.0</td>
<td>61.2</td>
<td></td>
</tr>
<tr>
<td>Tm 3 mph</td>
<td>0.55 ± 0.06</td>
<td>19.4 ± 5.3*</td>
<td>36.7 ± 8.0</td>
<td>6.5</td>
<td>55.6</td>
<td>118.2</td>
<td>8.5</td>
<td>12.3</td>
<td>113.5</td>
<td>60.4</td>
<td></td>
</tr>
<tr>
<td>Tm 4 mph</td>
<td>0.87 ± 0.07</td>
<td>30.8 ± 2.0*</td>
<td>58.4 ± 3.7*</td>
<td>8.5</td>
<td>54.9</td>
<td>155.5</td>
<td>10.2</td>
<td>9.9</td>
<td>128.1</td>
<td>59.9</td>
<td></td>
</tr>
<tr>
<td>Tm 5 mph</td>
<td>1.13 ± 0.15</td>
<td>39.5 ± 4.3</td>
<td>74.7 ± 9.3</td>
<td>9.7</td>
<td>57.1</td>
<td>171.5</td>
<td>11.6</td>
<td>8.9</td>
<td>136.5</td>
<td>59.3</td>
<td></td>
</tr>
</tbody>
</table>

Values are means ± SD. Definitions as in Tables 1–4. *Significantly different (P ≤ 0.05) from women at same work rate on same exercise modality.

Fig. 1. Cardiac output (Q̇) on O₂ consumption (v̇O₂) for cycle ergometer (A) and treadmill (B). Insets: regression equations used in statistical analysis. *Intercept significantly different from corresponding adult value; P ≤ 0.05. †Intercept significantly different from women; P ≤ 0.05.

Fig. 2. Heart rate (HR) on V̇O₂ for cycle ergometer (A) and treadmill (B). Insets: regression equations used in statistical analysis. †Slope significantly different from corresponding adult value; P ≤ 0.05. ΔSlope significantly different from women; P ≤ 0.05.
children compared with adults. Differing recirculation times could affect Q estimations when the CO\textsubscript{2}-rebreathing method is used. However, we did not see an effect, as the rebreathing curves for both the children and adults showed good equilibration and no signs of recirculation. Furthermore, the accuracy of using a single postexertional hemoglobin (Hb) measurement for Q calculation is not ideal. However, to best account for the changes that occur in Hb levels during exercise, while still limiting the invasiveness of the procedures (which is necessary when working with young children), a single postexertional measurement is most appropriate.

In our study, Q at a $\dot{V}O_2$ of 1.0 l/min was 2.5 and 1.5 l/min lower on the cycle ergometer and was 2.9 and 1.3 l/min lower on the treadmill in boys vs. men and in girls vs. women, respectively. A lower Q of a similar magnitude on the cycle ergometer in children vs. adults at a given rate of work is supported by research literature (2, 16, 30, 32, 42, 52) but is in conflict with others who have reported Q on the cycle ergometer to be the same (17–19). The studies that have reported lower Q in...
children vs. adults have reported similar absolute values and age-related differences.

Of the studies that have reported no difference between children and adults, Gadzho and Jones (17) determined Q in two groups of 20 boys (mean ages of 11.1 and 13.5 yr) during cycling exercise at 200 and 400 kilopond m/min. They did not find a difference in Q compared with values for adults reported by Higgs et al. (22). Godfrey et al. (18) tested 117 boys and girls, ages 6–16 yr, on the cycle ergometer at one-third and two-thirds of their VO₂max. When they compared their results to those of Bevegard et al. (5), they concluded that there was no difference in Q at a given VO₂. Also, Godfrey et al. (19) measured Q during cycle ergometer exercise at 40 and 80 W in three children (mean age, 9.7 yr) and three adults (mean age, 23.3 yr). Although they did not compare their child vs. adult Q differences statistically, by comparing the Q-VO₂ relationship in their six subjects, combined with the data on children from Godfrey et al. (18) and the adult data from Rowell (43), they concluded that the child and adult Q values were not different. The reason for the discrepancies between our findings and the findings of these earlier studies (17–19) is uncertain.

Combining our results with the data from the remaining research literature, it can be concluded that, during exercise, Q at a given VO₂ (l/min) is ~1.0 to 2.9 l/min lower in young children than adults on both the cycle ergometer and treadmill. Additionally, our results indicate (Figs. 2 and 3), and other studies agree (2, 19, 32, 42), that HR is higher and SV is lower at a given VO₂ in children vs. adults. The lower SV in children is generally attributed to their smaller body size. We found that the significantly lower SV in children vs. adults was eliminated or greatly reduced when SV was scaled to BSA. We also found that resting estimated LV mass was closely correlated with both SV (see results) and HR in the males (r = −0.85, −0.90, −0.73, −0.64) and females (r = −0.80, −0.82, −0.60, −0.60) at 40 W, 60 W, 3 mph, and 5 mph, respectively. Because the adults did not do the 20-W work rate and the children did not do the 60% work rate, these rates of work were not included in this analysis.

It has been suggested that the lower Q-VO₂ relationship in children is an indicator of depressed myocardial functional reserve or inability to generate SV (1). This may not necessarily be the case. The increase in Q with increasing VO₂ is met by changes in both SV and HR. SV is related to body size (thus, it is higher in adults) and increases very little beyond light work rates. Thus, to complete the Fick equation, HR and (a-VO₂) increase more in children, so that they have a VO₂ similar to adults. Thus the cardiovascular response of children seems to be normal for their size. Our similar Q-VO₂ slopes in children and adults (Fig. 1) further support this normal cardiovascular response of children to exercise that is relative to their body size. Also, there were no significant differences in LVM/FFM between boys vs. men (3.21 ± 0.49 vs. 2.92 ± 0.29) or girls vs. women (2.81 ± 0.36 vs. 2.89 ± 0.50), suggesting that the heart mass available to generate SV during exercise is not different.

Other factors may contribute to the lower SV in children. It has been suggested that SV contributions to Q are higher with larger muscle mass activity (14). In the following section, we suggest that children use a smaller muscle mass to do a given amount of work. The smaller muscle mass in children could result in an attenuated venous return (preload) and thus contribute to their lower SV. Additionally, the higher whole body TPR (Fig. 5) may represent a higher afterload, one of three primary factors that affect SV (14), and thus contribute to a lower SV in children.

As previously mentioned, we suggest that for children to do the same rate of work (VO₂) as adults, the children most likely use a smaller absolute amount of muscle mass. A smaller absolute muscle mass is thus stressed to a relatively greater extent, resulting in a greater buildup of metabolites, thus providing more feedback to the medulla to increase HR (8). The assumption of a smaller absolute muscle mass in children vs. adults, during exercise using the same muscle group, is based on the fact that adults have a significantly larger body mass relative to muscle mass. Not only are children smaller, but the percentage of their body weight that is muscle is less. The total muscle mass of a 7- to 9-yr-old boy represents ~44% of his body weight, whereas that of a 20- to 29-yr-old man is ~52% (38). This trend is not found in girls and women, likely due to their greater increase in FM with growth. The higher HR and lower SV response associated with a smaller muscle mass has been demonstrated in studies in adults comparing large and small muscle masses during exercise (4, 36, 50).

The possibility that children use a smaller absolute amount of muscle mass than adults use to exercise at the same rate of work has been proposed by others (30, 32) as a possible mechanism for the higher (a-VO₂) in children, as found in the present study and others (2, 15, 32, 42). As stated above, the smaller muscle mass would be stressed to a relatively greater extent and thus would likely generate a larger amount of metabolic by-products (36) and heat per unit of muscle, which would then 1) increase O₂ liberated from Hb by decreasing its affinity for O₂ at the muscle; 2) increase vasodilatation of the arteries entering the muscle (36), thus increasing muscle blood flow (33, 34); and 3) increase feedback to the medulla via a-sympathetic nerves, thus providing a greater buildup of metabolites, thus providing more feedback to the medulla to increase HR (8), as discussed earlier.

Furthermore, the higher (a-VO₂) in children may be due to more of their blood flow going to active muscle. This is supported by the work of Koch (33, 34), who reported higher muscle blood flow in 12- to 14-yr-old boys compared with 25-yr-old adults after ischemic work and during maximal cycle ergometer exercise. The possibility of higher muscle blood flow in children is indirectly supported by work of Saltin et al. (48) in adults. They reported that leg blood flow was inversely related to [Hb]. However, Kudjak et al. (35) report that in maximally working canine muscle in situ, lower [Hb] did not significantly change blood flow distribution.
The [Hb] of the children in the present study was significantly lower (P ≤ 0.05) than that of the adults (see Table 1). When we scaled our Q (l/min) and TPR (units) to FFM (kg) we found that Q·FFM−1·min−1 was higher and TPR/FFM was lower in the children vs. adults at a given Vo2 on both the cycle ergometer and treadmill. Because muscle receives up to 80–85% of the Q, or blood flow, during exercise (44), these results suggest that for a given muscle mass (FFM) children have a larger Q or blood flow and a lower TPR (higher conductance to accept the higher Q at the muscle) than adults have at a given rate of work, indirectly indicating higher muscle blood flow in children. Higher muscle blood flow combined with a lower Q at a given Vo2 seems incongruent but may be explained by a smaller muscle mass performing a given rate of work in children vs. adults, as discussed above.

Finally, it has been reported that maximal (a-VO2) in boys is not different from that in men (16). Furthermore, the (a-VO2) of children is higher at a given submaximal V02 (l/min). Thus, the (a-VO2) of children at a given absolute submaximal V02 (l/min) is nearer their maximal value. This may partially explain the higher (a-VO2) values at a given submaximal V02 (l/min) in children compared with adults.

In conclusion, in this group of 7- to 9-yr-old children was significantly lower in boys vs. men and girls vs. women at a given VO2 than that of the adults for the giving of their own time so their children could participate.

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