Influence of puberty on muscle development at the forearm

C. M. Neu, F. Rauch, J. Rittweger, F. Manz, and E. Schoenau

Children’s Hospital, University of Cologne, 50924 Cologne; Research Institute of Child Nutrition, 44225 Dortmund; and Institute of Physiology, Free University of Berlin, 14195 Berlin, Germany

Received 3 October 2001; accepted in final form 23 October 2001

Influence of puberty on muscle development at the forearm. Am J Physiol Endocrinol Metab 283: E103–E107, 2002. First published November 20, 2001; 10.1152/ajpendo.00445.2001.—Despite its fundamental importance for physical development, the growth of the musculoskeletal system has received relatively little consideration. In this study, we analyzed the relationship between cross-sectional area (CSA) of forearm muscles and maximal isometric grip force with age and pubertal stage. The study population comprised 366 children, adolescents, and young adults from 6 to 23 yr of age (185 female) and 107 adults (88 female) aged 29 to 40 yr. By use of peripheral quantitative computed tomography, muscle CSA was determined at the site of the forearm, whose distance to the ulnar styloid process corresponded to 65% of forearm length. Both muscle CSA and grip force were higher in prepubertal boys than in girls. The gender differences decreased until pubertal stage 3 and increased thereafter. In girls at pubertal stage 5, muscle CSA no longer increased with age (P > 0.4), whereas there was still some age-related increase in grip force (P = 0.02). In boys at pubertal stage 5, both muscle CSA and grip force increased significantly with age (P < 0.005 each). Specific grip force (grip force per muscle CSA) adjusted for forearm length increased by almost one-half between 6 and 20 yr of age, with no difference between the genders. In conclusion, forearm muscle growth takes a gender-specific course during puberty, indicating that it is influenced by hormonal changes. However, the increase in specific grip force is similar in both genders and thus appears to be independent of sex hormones.

Musculoskeletal development is one of the key features of childhood and adolescence. The musculoskeletal system determines the ability for locomotion, which during evolution has been of crucial importance for an individual’s survival. Moreover, the action of the musculoskeletal system imposes functional requirements on other vital organ systems such as lungs and heart. Although skeletal growth and maturation have been the focus of considerable research activities in recent years, the development of the second component of the musculoskeletal unit, the muscle system, has received relatively little consideration.

This may be partly due to methodological difficulties in quantifying muscle growth in the setting of clinical studies. A crude measure of muscle size can be gained by measuring the circumference of a limb. However, limb circumference not only reflects muscle size but is also influenced by the amount of fat tissue. Several decades ago, a number of large longitudinal trials used standard limb X-rays to quantify muscle size (7, 15). However, the amount of radiation exposure involved in such studies would not be considered acceptable at present.

Muscle size can also be assessed by quantitative computed tomography (QCT). Several small studies have used this technique to study limb muscle development in children (1), but the radiation exposure was quite high with early computed tomographic devices, which prevented large-scale studies in children. In recent years, peripheral QCT (pQCT) has gained popularity for the analysis of bone geometry and density, mostly of the forearm (2). This technology can also be used to quantify the cross-sectional area (CSA) of forearm muscles. The radiation exposure of a measurement run with a modern system is far below that of a standard hand X-ray, which makes this technique suitable for use in children.

In this study, we used pQCT to determine muscle CSA at the proximal forearm in a large and well-characterized group of healthy children and young adults. We compared these data with a traditional measure of forearm muscle function, maximal isometric grip force. The aims of this investigation were to examine the changes with age and puberty in forearm muscle size and force.

SUBJECTS AND METHODS

Subjects. The original study population comprised 371 healthy children and adolescents as well as those of their parents who were below 40 yr of age (n = 107; ages 29 to 40 yr; 19 men, 88 women). Five children had to be excluded from the present analysis because of motion artifacts during the measurement run. Thus 366 children and adolescents (181 male, 185 female) were included in the following evaluation.

The children were participants in the DONALD (Dortmund Nutritional and Anthropometric Longitudinally Designed) Study, an ongoing observational study investigating the interrelations of nutrition, growth, and metabolism in...
healthy children. This study is performed at the Research Institute for Child Nutrition in Dortmund, Germany. The cohort was initially recruited for an anthropometric study in a representative sample of school children of Dortmund and, later, through personal recommendations of parents whose children were already participating. Overall, the study population comprised middle-class families, and all participants were of Caucasian origin. On an annual basis, all children were already participating. Overall, the study population comprised middle-class families, and all participants were of Caucasian origin. On an annual basis, all children were already participating. Overall, the study population comprised middle-class families, and all participants were of Caucasian origin. On an annual basis, all children were already participating.

Anthropometric characteristics:

**Table 1. Anthropometric characteristics: variation with age**

<table>
<thead>
<tr>
<th>Age, yr</th>
<th>Females</th>
<th>Males</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Height</td>
<td>Forearm length</td>
</tr>
<tr>
<td>6–7</td>
<td>28</td>
<td>122 ± 5</td>
</tr>
<tr>
<td>8–9</td>
<td>26</td>
<td>134 ± 5</td>
</tr>
<tr>
<td>10–11</td>
<td>30</td>
<td>149 ± 8</td>
</tr>
<tr>
<td>12–13</td>
<td>31</td>
<td>158 ± 8</td>
</tr>
<tr>
<td>14–15</td>
<td>25</td>
<td>167 ± 7†</td>
</tr>
<tr>
<td>16–17</td>
<td>23</td>
<td>171 ± 8‡</td>
</tr>
<tr>
<td>18–23</td>
<td>22</td>
<td>170 ± 7‡</td>
</tr>
<tr>
<td>Adults</td>
<td>88</td>
<td>168 ± 6‡</td>
</tr>
</tbody>
</table>

Values are means ± SD in cm. The significance for the difference between females and males of the same age group is indicated: †P < 0.05; ‡P < 0.01; §P < 0.001.

**Grip force.** Maximal isometric grip force of the nondominant hand was determined with a standard adjustable-handle Jamar dynamometer (Preston, Jackson, MI). The handle was adjusted so that the line of the subject’s proximal interphalangeal joints rested exactly on top of it. Consequently, setting 1 of the Jamar dynamometer was used for the younger children and setting 2 for most of the older children and adolescents; setting 3 was used in some of the adolescents and adults, whereas settings 4 and 5 were never used.

The subject was seated with the shoulder adducted and neutrally rotated. The dynamometer was held freely, without support. The elbow was flexed at 90°, and care was taken that it did not touch the trunk. The forearm was in a neutral position, and the wrist was held at between 0 and 30° dorsiflexion and between 0 and 15° ulnar deviation. The subjects were told to put maximal force on the dynamometer. The maximal value of two trials was noted. We use the term “grip force” instead of the more widely used “grip strength,” because “force” is a term that is clearly defined by physics, whereas “strength” is used inconsistently in the medical literature, denoting a variety of different parameters, including force, torque, and power.

**Determination of muscle CSA by pQCT.** pQCT analysis was performed at the nondominant forearm by use of an XCT-2000 device (Stratec, Pforzheim, Germany). The scanner was equipped with a low-energy (38 keV) X-ray tube. The effective radiation was ~0.1 μSv from a radiation source of 45 kV at 150 μA. Calibration of the machine was performed once every 3 days (single slice) or once a month (multiple slice – cone phantom), respectively, with phantoms provided by the manufacturer.

The scanner was positioned at the site of the forearm, whose distance to the ulnar styloid process corresponded to 65% of forearm length. This site of measurement was chosen to analyze the forearm at its maximum circumference. Preliminary measurements in 317 subjects from 6 to 40 yr of age had shown that the circumference at the 65% site averaged 99.5% of the maximum circumference of the forearm. A 2-mm-thick single tomographic slice was sampled at a voxel size of 0.4 mm. The speed of the translational scan movement was set at 15 mm/s. The resulting time for a measurement run was ~2–3 min in the smaller children and 4–5 min in adults, depending on the cross-sectional size of the forearm.

Image processing and the calculation of numerical values were performed using the manufacturer’s software package (version 5.40). For the purpose of the present analysis, the outer bone contours of radius and ulna were detected at a threshold of 710 mg/cm³. Voxels peripheral to the bones’ outer edges with an absorptiometric density between 20 and 60 mg/cm³ were interpreted as representing muscle. The corresponding muscle CSA was calculated by the software.

The reproducibility of this method was determined in a group of nine healthy adult volunteers (all women; age 34–56 yr) by performing the measurement twice, with repositioning of the forearm. Reproducibility was not tested in children, because it was judged unethical to perform repeated analyses involving ionizing radiation in children solely for methodological purposes. The precision error was calculated as root mean square standard deviations of the duplicate measurements, as proposed by Gliuer et al. (3). Reproducibility was 1.93% for muscle CSA.

**Statistical analysis.** Throughout, a P value <0.05 was considered significant. For comparisons between two groups, t-tests were used. The significance of differences among more than two groups was calculated by one-way or two-way analysis of variance (ANOVA), as appropriate.

In an attempt to assess the velocity of the changes in children and adolescents, regression curves were fitted to the

**Table 2. Anthropometric characteristics: variation with pubertal stage**

<table>
<thead>
<tr>
<th>Pubertal Stage</th>
<th>Females</th>
<th>Males</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n</td>
<td>Height</td>
</tr>
<tr>
<td>1</td>
<td>64</td>
<td>133 ± 11</td>
</tr>
<tr>
<td>2</td>
<td>13</td>
<td>150 ± 10</td>
</tr>
<tr>
<td>3</td>
<td>14</td>
<td>155 ± 4*</td>
</tr>
<tr>
<td>4</td>
<td>9</td>
<td>161 ± 5*</td>
</tr>
<tr>
<td>5</td>
<td>58</td>
<td>168 ± 83</td>
</tr>
</tbody>
</table>

Values are means ± SD in cm. The significance for the difference between females and males of the same age group is indicated: *P < 0.05; †P < 0.01; §P < 0.001.
age-dependent pQCT results for girls and boys. Linear, exponential, logarithmic, and hyperbolic simple regression models, as well as polynomials of second, third, and fourth order, were tested. The relationship with age was assumed to be linear unless one of the other models yielded a coefficient of determination ($r^2$) that was higher by $\geq 0.03$. In this case, the model with the maximum $r^2$ was chosen. The maximum velocity of the increase and the corresponding age were calculated for parameters that were best fitted by a polynomial regression.

For the analysis of the significance of pubertal effects, the "adult" group was not included. Associations between two parameters were tested using Pearson’s correlation coefficient. Stepwise multiple regression analyses were performed in the forward mode. For these calculations, the SPSS 6.0 software package (SPSS; Chicago, IL) was used.

### RESULTS

The anthropometric characteristics of the study population are given in Tables 1 and 2. Individual results of forearm muscle analyses are shown in Fig. 1. Boys were taller than girls after the age of 13 yr and after pubertal stage 2. Forearm length was significantly higher in boys than in girls in all pubertal stage groups and in age groups after the age of 13 yr. When related to body height, forearms were significantly longer in boys after the age of 11 yr (Fig. 2).

Both muscle CSA and grip force were higher in boys than in girls in the youngest age group of this study (Table 3). However, muscle CSA and grip force appeared to increase more rapidly in girls during the...
following years, and gender differences were not significant between 10 and 13 yr of age. In girls, a maximum increase of grip force occurred at ~10.5 yr of age (Fig. 1). The growth of muscle CSA did not exhibit a clear maximum in girls but was faster before the age of 10 yr than after that age. Boys experienced maximal increases in both muscle CSA and grip force after the age of 14 yr (Fig. 1).

Prepubertal boys had a larger muscle CSA and higher grip force than prepubertal girls (Table 4). The gender differences decreased until pubertal stage 3 and reincreased thereafter. In girls at pubertal stage 5, muscle CSA no longer increased with age ($P > 0.4$), whereas there was still some age-related increase in grip force ($P = 0.02$). In boys at pubertal stage 5, both muscle CSA and grip force continued to increase significantly with age ($P < 0.005$ each).

The developmental changes in muscle shape were analyzed by comparing cross-sectional muscle size and forearm length, which can be regarded as a surrogate measure of muscle length. Because length is a one-dimensional measure whereas CSA is two dimensional, the ratio between these two parameters will increase during development even if muscle grows to scale in all three dimensions. Therefore, we converted muscle CSA into a one-dimensional measure by calculating the square root of CSA. To give this one-dimensional measure an “anatomical” meaning, it was further divided by the square root of $\pi$. The result corresponds to the radius of the muscle cross section ("muscle radius") if a circular shape is assumed. The ratio between muscle radius and forearm length varied with age and pubertal stage in boys ($P < 0.001$) but not in girls ($P > 0.20$ each). The muscle radius-to-forearm length ratio was significantly higher in boys than in girls after 15 yr of age and after pubertal stage 3 (Fig. 2).

Finally, we examined the developmental changes in the relationship between grip force and muscle CSA. In a parallel-fibered muscle, the maximum force increases linearly with the physiological muscle CSA, i.e., the force per area is constant. In pennated muscles such as the forearm, however, the force per anatomical cross-sectional area depends on muscle length (9, 16). The magnitude of this effect was examined by linear regression analysis of the grip force/muscle CSA ratio (= specific grip force ($GF_{spec}$)) over forearm length. To exclude the influence of developmental changes, this analysis was limited to the adult population from 29 to 40 yr of age. Because there was no gender difference, the regression was performed for both sexes grouped together. A significant correlation between forearm length and $GF_{spec}$ ($P < 0.001$) was found, with $GF_{spec}$ (N/cm²) $= 2.45 \pm 0.288 \times$ forearm length (cm).

The slope of this regression was used to normalize $GF_{spec}$ to a forearm length of 25 cm in all subjects. This yielded the new variable $GF_{spec25}$ [$GF_{spec25} = GF_{spec} + 0.288 \times (25 \text{ cm} - \text{forearm length})$]. As can be seen in Fig. 3, $GF_{spec25}$ was similar between the sexes ($P > 0.2$ by two-way ANOVA for sex and age group) and increased during childhood and adolescence. These data were best fitted with a second-order regression, which indicated an increase of 44% between 6 and 20 yr of age.

**DISCUSSION**

In this study, we evaluated the forearm muscle system in children, adolescents, and young adults. Children $<6$ yr of age were not included in this study, because a high degree of collaboration is necessary for the grip force test. In addition, younger children usually are not able to keep their arms in a fixed position for the time required to complete the pQCT measurement run. We chose the “65% site” for these analyses, because preliminary measurements had shown that...
forearm circumference was close to the maximum at that location. In a single pQCT run at the 65% site, data can be collected not only on muscle CSA but also on the architecture and density of radius and ulna, so that the relationship between muscle and bone development can be examined (12).

QCT has been used to analyze forearm muscle CSA in adults (8), but to our knowledge no detailed pediatric studies on forearm muscle CSA have been published. Maresh (7) examined the forearm muscle width of children on standard X-rays but presented results as the sum of muscle widths from various anatomical locations. Tanner et al. (15) also used standard X-rays to longitudinally follow upper-arm muscle width in a large cohort of children and adolescents. Similar to the present data, these authors found that muscle width was slightly higher in boys than in girls already before puberty. They also reported a decreasing gender difference in muscle width until 13 yr of age and an increasing gender dichotomy thereafter. However, Tanner et al. detected a peak in muscle growth in both sexes, whereas in the present study no such peak was discernible for girls. Presumably, this is because the age of accelerated muscle growth is spread over a wide range, and therefore this peak is hard to detect in a cross-sectional study.

If the forearm muscles maintained their basic shape during growth, the ratio between muscle radius and forearm length should remain constant. This actually appeared to be the case in girls, where this ratio did not vary with age or pubertal stage. However, in boys after the age of 15 yr, this ratio increased, showing that the muscle increased more in width than in length. Our data demonstrate that there are at least three effects of gender-specific pubertal development, which all contribute to higher forearm muscle mass and force in boys compared with girls. First, boys on average become taller than girls. This by itself should lead to generally greater force, since greater body height means greater bone length, which is an important determinant of muscle mass and force (10, 15). Second, the gender difference in forearm length is even more pronounced than would be expected from the difference in height. This is because, during puberty, the forearm length-to-body height ratio increases in boys but not in girls. Third, even when the differences in forearm length are accounted for, forearm muscles grow wider in boys than in girls.

This study does not allow analysis of the basis for this gender-related dichotomy in muscle development during puberty. Higher testosterone levels in boys are obviously an attractive explanation, given the known muscle-anabolic effect of this hormone (13). In fact, Round et al. (10) found that testosterone levels could explain most of the gender difference in maximal isometric biceps force during puberty. Although the growth in muscle CSA clearly was greater in boys, GFspec25 increased similarly in the two genders. On the one hand, this finding shows that the gender difference in grip force is entirely due to the higher muscle CSA in boys. On the other hand, the similarity of the increase in GFspec25 in both genders suggests that this effect is independent of the hormonal changes occurring during puberty. A number of previous studies have found increasing muscle performance per unit muscle CSA during childhood and adolescence (4, 5, 11), but the physiological basis for this phenomenon is still unclear. Possible explanations include changes in muscle enzyme activity, an increasing proportion of type II fibers (6), changes in the recruitment of muscle fibers, or decreased negative feedback from Golgi tendon organs.

In conclusion, this study suggests that the increase in maximal isometric grip force during childhood and adolescence has two components. The first is muscle growth, which takes a gender-specific course during puberty, indicating that it is influenced by hormonal changes. The second is an increase in grip force per muscle CSA, which is similar in both genders and thus appears to be independent of sex hormones.

We are indebted to the entire staff of the Research Institute for Child Nutrition for continuing support. The technical support of Stratec (Pforzheim, Germany) is gratefully acknowledged.

REFERENCES