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Strength and cross-sectional area of knee extensor muscles in children

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Abstract. Iksokinetic strength and cross-sectional area (CSA) of knee extensor muscles were examined in 60 boys and girls, aged 6–9 years, and in 71 young adult men and women to investigate the influences of age and gender on the strength capabilities in relation to muscle size. A single anatomical CSA of quadriceps femoris at the right mid-thigh was measured by using a B-mode ultrasonic apparatus. Isokinetic strength produced at three kinds of constant velocity, 1.05, 3.14, and 5.24 $rad \cdot s^{-1}$, was significantly correlated to the product of CSA and thigh length (TL) in separate samples by age and gender. In both genders, however, young adults had significantly higher ratios of strength to CSA·TL ($ST \cdot CSA^{-1} \cdot TL^{-1}$) than children at all measurement velocities. Relative differences in $ST \cdot CSA^{-1} \cdot TL^{-1}$ between children and young adults became larger with increasing test velocity. Within the same generation, men had significantly higher $ST \cdot CSA^{-1} \cdot TL^{-1}$ than women at all measurement velocities except for the ratio in children at 1.05 $rad \cdot s^{-1}$. These results indicate that the ability to produce strength proportional to muscle size is lower in children than in young adults, regardless of gender, and lower in women than in men within the same generation.

Key words: Isokinetic strength – Developmental age – Age and gender differences – Ultrasound

Introduction

The growth trends in muscle strength have been well documented. However, only a few studies (Ikai and Fukunaga 1968; Davies et al. 1983) have investigated this subject in relation to muscle size. Ikai and Fukunaga (1968) have shown that the ratio of isometric strength to the cross-sectional area (CSA) for elbow flexors was almost the same over an age span encompassing adolescence and early adulthood. In contrast, some studies (Asmussen and Heebøll-Nielsen 1954, 1955; Davies 1990; Saavedra et al. 1991) involving pre-adolescent children have reported that growth in body mass, or lean body mass, is not necessarily responsible for age-related increments in muscle strength and anaerobic performances. However, interpretation of these findings is complicated by methodological problems and difficulties of accurate measurement of muscle size by anthropometric techniques. Whether the strength capability of pre-adolescent children is different from that of adults when expressed per unit muscle size thus remains unresolved.

In the present study, isokinetic strength and CSA of knee extensor muscles were measured in children aged 6–9 years and in young adults. The purpose of this study was to investigate the ability of pre-adolescent children to produce dynamic strength allowing for variation in muscle CSA.

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Methods

Subjects. Sixty boys and girls, 6–9 years of age, and 71 young adult men and women, 18–25 years of age, served as subjects. The numbers in each subject group and their physical characteristics are shown in Table 1. No assessment of the stage of puberty was made in the present study. However, taking into account the age of children, it is likely that they were prepubertal or in the early stage of puberty.

The subjects and the parents of the children were fully informed of the procedures to be used as well as the purpose of the study, and their written informed consent was obtained. The children were not involved in any specific physical training program beyond their normal school curriculum activities. The young adults were either sedentary or mildly active, but none was currently involved in any type of exercise program exceeding 30 min/day and 2 days/week.

Strength. Maximum voluntary isokinetic torques of the right knee extensor muscles were measured with a Cybex II isokinetic dynamometer. Prior to testing, the Cybex II system was calibrated using weights on the lever arm. To standardize the measurement and localize the action to the proper muscle group, the subjects were seated in an adjustable chair with support for the back and

Table 1. Physical characteristics of subjects

Groups	n	Age years	Height (m)	mass (kg)
Boys	30	7.7 (0.2)	1.229 (0.011)	24.0 (0.5)
Girls	30	7.8 (0.2)	1.220 (0.009)	23.8 (0.5)
Men	36	20.2 (0.2)	1.701 (0.012)	62.1 (1.2)
Women	35	19.8 (0.3)	1.585 (0.008)	56.0 (1.4)

Values are mean (SE)

hips. The axis of the knee joint was aligned with the axis of the dynamometer lever arm and the ankle fixed to the end of the adjustable lever arm of the Cybex machine. After a period of standardized warm-up and familiarization with the measurement apparatus the subjects were encouraged to perform maximal voluntary muscle actions isokinetically at three constant velocities of 1.05, 3.14 and 5.24 $rad \cdot s^{-1}$ throughout a range of knee-joint angles from 1.57 rad to full extension. Test order of the experimental conditions was random for each subject. The greatest torque from three to five attempts was recorded for each velocity. A period of 10 s was permitted between successive attempts and a 1-min rest allowed between each contraction. The force was calculated by dividing the torque by the length of the lever arm.

Muscle CSA. A single cross-section of the right thigh was measured using the ultrasonic apparatus (SSD-120 Echo-Vision, Alka, Japan) described by Ryushi and Fukunaga (1986). The frequency of the ultrasonic wave was 5 MHz. The subjects sat with the right lower extremity perpendicular to the central axis of a water tank. The scanner, oscillating in a range of 1.05 rad, circulated around the tank for 30 s without contacting the thigh and created an image of cross-section of the thigh on the specially-designed oscilloscope, which was photographed with a 35-mm camera. The site at which the cross-section was measured was the midpoint of the distance between the greater trochanter of the femur and the articular cleft between the chondyles of the femur and the tibia. From the photograph of the ultra image the boundary of the quadriceps femoris muscles as knee extensors between other tissues was traced. Planimetric values were obtained, which were then converted into the actual CSA by the calibration formula.

The accuracy of measuring muscle CSA in this manner was determined by imaging a cadaver limb which was cut cross-sectionally into ten equal parts. After imaging, the muscle CSA of the cadaver limb was calculated from the photograph of the actual cross-section. The muscle CSA determined by ultrasound technique was 3.1% smaller than that calculated from the photograph of the actual cross-section. This difference was not statistically significant. The repeatability for measuring muscle CSA was assessed on 2 separate days in a pilot study with 33 boys and girls aged 6–9 years and 30 young adult men. The test-retest correlation coefficient (r) for muscle CSA was 0.979 for children and 0.995 for young adults. The coefficient of repeatability (twice the square root of the mean of the squared differences of the pairs, Bland and Altman 1986), was 2.6 cm^2 for children and 3.0 cm^2 for young adults.

Calculation of the ratio of strength to muscle size. The CSA obtained in the present study was a single, anatomical valve at right angles to the muscle's long axis and not the physiological CSA. Methods to measure the physiological CSA directly and accurately in intact human muscle are not presently available. However, it can be estimated as the product of muscle volume and the cosine of the angle of pinnation divided by the length of the muscle fibres (Wickiewicz et al. 1983) and is linearly correlated to muscle volume (Fukunaga et al. 1992). In pennate muscles such as the quadriceps femoris, the difference between the anatomical and physiological CSA will become larger as muscle length (i.e., muscle volume) increases. It is possible that the ratio of strength to anatomical CSA for young adults will be overestimated due to the larger muscle volume (i.e., larger physiological CSA) compared with children. The CSA measured in the present study was therefore multiplied by the length of the thigh (TL), the distance between the greater trochanter of the femur and the articular cleft between the chondyles of the femur and the tibia to approximate the muscle volume of the quadriceps femoris. The ratio of strength to the product of CSA and the TL ($ST \cdot CSA^{-1} \cdot TL^{-1}$) was calculated to allow for the influence of muscle size on the strength capability.

Statistics. Descriptive statistics included means (SE). A two-way analysis of variance was used to assess the effect of age or gender on the measurements. When a significant effect of age or gender was found, Student's t-test was used to identify locations of significant differences between several means. The linear correlation coefficient (r) was calculated using the method of least squares. The probability level accepted for statistical significance was set at $P<0.05$.

Results

Table 2 shows the results of CSA in each subject group. In all measurements, young adults had significantly larger values for CSA and CSA·TL than children within the same gender groups. While young men showed significantly higher values for CSA and CSA·TL than young women, the differences in these variables between boys and girls were insignificant.

Correlation coefficients for the relationship between CSA·TL and strength produced at each test velocity are summarized in Table 3. Strength at each measurement condition was significantly correlated to CSA·TL in different subject groups.

Strength and its ratio to CSA·TL are shown in Table 4. In both genders, strength of children was only 18–33% of that of young adults. Boys were significantly stronger than girls at 3.14 and 5.24 $rad \cdot s^{-1}$ and young men stronger than young women at all velocities. Although these differences diminished when expressed per unit CSA·TL, they were still statistically significant. This result was the same even when strength was expressed in terms of per unit CSA.

Table 2. Comparison of limb length and cross-sectional area (CSA) measurements between children and young adults

Groups	TL (m)	CSA (cm^2)	CSA·TL ($cm^2 \cdot m$)
Boys	0.282 (0.005)	33.0 (0.7)	9.36 (0.29)
Girls	0.282 (0.002)	30.8 (0.9)	8.71 (0.29)
Men	0.397 (0.003)	72.8 (1.7)	28.95 (0.78)
Women	0.377 (0.003)	58.3 (1.8)	21.92 (0.75)
Inter-group ratio (%)			
Boys/men	71.0*	45.3*	32.3*
Girls/women	74.8*	52.8*	39.7*
Boys/girls	100.0	93.3	93.1
Women/men	95.0*	80.1*	75.7*

Values are means (SE). TL, Thigh length; CSA, cross-sectional area of quadriceps femoris; CSA·TL, product of CSA and TL
*$P<0.05$ for differences between groups

Table 3. Correlation coefficients between CSA·TL and strength measurements in children young adults

Groups	Velocity ($rad \cdot s^{-1}$)		
	1.05	3.14	5.24
Boys	0.705	0.755	0.738
Girls	0.715	0.810	0.831
Men	0.710	0.764	0.731
Women	0.528	0.666	0.696

All correlations significant at $P<0.05$

Discussion

The present study confirmed the existence of significant correlations between CSA·TL and isokinetic strength in both children and young adults. Because the correlation analysis was performed for the separate populations by age and gender, the correlation coefficients obtained in the present study were somewhat lower than those reported by other studies using heterogeneous populations (Maughan et al. 1983; Schantz et al. 1983; Sale et al. 1987; Alway et al. 1990; Miller et al. 1993). In the study of Maughan et al. (1983), however, the correlation coefficients between CSA of knee extensor muscles and isometric strength in separate adult populations by gender were 0.59 for men and 0.51 for women, values which are comparable with those obtained in the present study for the young women (Table 3).

In the present results, there were significant differences in $ST \cdot CSA^{-1} \cdot TL^{-1}$ between children and young adults. Ikai and Fukunaga (1968) have reported no significant difference by age and gender in $ST \cdot CSA^{-1}$ for elbow flexors in an age span of 12–20 years. Davies et al. (1983) have also shown, by using CSA estimated from the anthropometric data, that $ST \cdot CSA^{-1}$ of triceps surae remained unchanged from adolescence through early adulthood. In these studies, however, the age of children studied and sites for CSA measurement are different from those in the present study.

The relative differences in the $ST \cdot CSA^{-1} \cdot TL^{-1}$ between children and young adults become greater with increasing test velocity (Table 4). Ryushi and Fukunaga (1986) have shown that the percentage proportion of FTa (fast-oxidative-glycolytic) fibres in muscles is significantly correlated to $ST \cdot CSA^{-1}$. Considering the effect of muscle fibre composition on the force/velocity relation (Thorstensson et al. 1976; Coyle et al. 1979), the increase of relative age differences in $ST \cdot CSA^{-1} \cdot TL^{-1}$ with increasing test velocity led to the assumption that a change in muscle fibre composition might occur during growth stages. A previous finding, however, has shown that the relative distribution of the subtypes of fast twitch fibres is approximately the same in 6-year-old children and adults (Bell et al. 1980).

In the growth stages involving pre-adolescence, muscle strength and motor performance increase more than would be expected from an assumption of geometrical similarity (Asmussen and Heebøll-Nielsen 1954, 1955). These extra gains in muscle strength and motor performance have been attributed to an increased ability to mobilize the muscle voluntarily rather than increases in muscle mass (Asmussen and Heebøll-Nielsen 1954). If children are undeveloped in their ability to recruit the available motor units during maximum voluntary muscle actions, at least in the large muscle groups such as the quadriceps femoris, children

Table 4. Comparison of strength measurements between children and young adults

Variables	Groups	Velocity ($rad \cdot s^{-1}$)		
		1.05	3.14	5.24
Strength (N)	Boys	141.1 (4.6)	95.4 (4.9)	58.7 (3.8)
	Girls	130.0 (5.1)	79.4 (4.1)	43.6 (2.5)
	Men	472.1 (13.9)	336.3 (10.8)	220.5 (7.6)
	Women	309.2 (11.5	224.3 (8.2)	139.2 (5.6)
Inter-group ratio (%)	Boys/men	29.9*	28.4*	26.6*
	Girls/women	42.0*	35.4*	31.3*
	Girls/boys	92.1	83.2*	74.3*
	Women/men	65.4*	66.7*	63.1*
$ST \cdot CSA^{-1} \cdot TL^{-1} (N \cdot cm^{-2} \cdot m^{-1})$	Boys	15.17 (0.36)	10.10 (0.36)	6.17 (0.30)
	Girls	15.02 (0.42)	9.04 (0.32)	4.94 (0.18)
	Men	16.38 (0.32)	11.64 (0.24)	7.62 (0.18)
	Women	14.27 (0.53)	10.26 (0.30)	6.35 (0.19)
Inter-group ratio (%)	Boys/men	92.6*	86.8*	81.0*
	Girls/women	105.7	88.1*	77.8*
	Girls/boys	99.0	89.5*	80.1*
	Women/men	87.1*	88.1*	83.3*

Values are means (SE)
* $P<0.05$ for differences between groups

will be inferior to young adults in producing strength corresponding to the muscle mass. This assumption is supported by evidence showing that the degree of motor unit activation in pre-adolescent boys was 78% of the total available motor units during voluntary maximum knee extension (Ramsey et al. 1990). Moreover, the maximum rate of force production, being largely dependent on the amount and rate of the neural activation (Komi 1986), is lower in children aged 8–11 years compared with that reported for college-aged men and women (Going et al. 1987).

Possible explanations for the differences between young adult women and men in $ST \cdot CSA^{-1} \cdot TL^{-1}$ include gender differences in the ability to recruit motor units during concentric actions (Ryushi et al. 1988; Colliander and Tesch 1989) or in the muscle-skeletal system transferring the force produced by knee extensors to the lower leg (Holloway and Beachle 1990). It is unknown whether this assumption can be applied to children. However, considering that gender differences in $ST \cdot CSA^{-1} \cdot TL^{-1}$ for children became greater with increasing test velocity (Table 4), it is likely that there is a difference between boys and girls in neural control during dynamic muscle actions with high contraction velocity.

In conclusion, at least in knee extensor muscles, the ability to produce dynamic strength proportional to muscle mass is lower in children than in adults regardless of gender, and lower in women than in men within the same age generation. The reasons for these age and gender differences might be attributed mainly to neural control during voluntary muscle actions.

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