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A 2-year follow-up study on muscle size and dynamic strength in teenage tennis players

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Growth trends in the cross-sectional area of the quadriceps femoris (CSA_{QF}) and its dynamic strength in 12 teenage tennis players (six boys and six girls), aged from 10.7 to 13.2 years at the onset of the study, were investigated through a 2-year follow-up survey. CSA_{QF} values at the three levels (proximal, mid, and distal to the knee joint) and dynamic torques during knee extensions at three pre-set velocities (1.05, 3.14, and 5.24 rad/s) were determined year by year, i.e., three times (T1, T2, and T3), using magnetic resonance imaging and an isokinetic dynamometer, respectively. In both genders, the CSA_{QF} values at the three levels tended to increase across the measurement times, with greater gains in the boys than in the girls at the levels mid and distal to the knee joint. Among these changes, only the CSA_{QF} at the level proximal to the knee joint significantly increased regardless of changes in both skeletal age and body height. The ratios of torque to the sum of CSA_{QF} at the three levels (T/CSA) at 3.14 and 5.24 rad/s for the boys and at 5.24 rad/s for the girls were significantly higher in T2 and T3 than T1. Further, the relative increases in torque and T/CSA values at 3.14 and 5.24 rad/s were greater in the boys than the girls. The findings presented here indicate that young tennis players who are in the earlier stage of adolescence increase the CSA of the QF muscle beyond normally expected growth change at the level proximal to the knee joint and show a predominant development in torque generation capability during high-velocity knee extensions, with a greater gain in boys compared with girls.

The morphological and functional profiles of young athletes have been extensively studied (e.g., Birrer & Levine, 1987; Malina, 1994). For the children and young teenage athletes, however, less information on the growth trends of muscle size and strength relative to muscle size is available. In addition, it is unknown as to how the two variables differ between the genders in young athletes. It has been indicated that the quantitative change of a muscle may not be the only factor explaining the development of muscle strength capability during growth stage (Asmussen & Heebøll-Nielsen, 1954). In addition, some researchers (Blimkie, 1993; Guy & Micheli, 2001) have suggested that, as the effects of resistance training, pre-adolescents probably do not develop significant muscle hypertrophy, and that training-induced strength gains during this period are largely independent of changes in gross muscle size. Considering these points, it seems that the observable strength increase in children and/or young teenage athletes may largely depend on an improvement of muscle strength relative to muscle size.

A prior study (Gur et al., 1999) on elite male soccer players aged from 18 to 28 years indicated that the reciprocal peak torque ratios during knee muscle contractions were more likely to be the result of the training background of the players than their chronological ages. From the finding of a longitudinal study (Hansen et al., 1999) on male soccer players aged 11 years, however, the development of muscle strength for both elite and non-elite players together is related to changes in serum testosterone concentrations. This finding suggests that the profiles of muscle strength in young athletes who are in the earlier stage of growth may be maturation rather than training condition. On the other hand, a recent study using magnetic resonance imaging (MRI) indicated that relatively short-term physical training program was found to increase thigh muscle volume significantly in non-obese girls with a mean age of 9 years (Eliakim et al., 2001). Moreover, a prior study (Kanehisa et al., 2003b) indicated that junior Olympic weight lifters aged from 15 to 17 years have already achieved a 28% greater muscle cross-sectional area (CSA) at mid-thigh as compared with male non-athletes of almost the same chronological age. Taking these findings into account, it may be assumed that, even in the early stages of adolescence, participation in organized sports training produces an increase in muscle size regardless of gender, which substantially contributes to increased muscle strength beyond normally expected growth changes.

In the present study, the CSA of the quadriceps femoris (QF) and dynamic strength in teenage tennis players of both genders, aged from 10.7 to 13.2 at the onset of the study, were determined three times at yearly intervals over a 2-year period. In addition, skeletal age was determined as an index of biological maturation. This study aimed at investigating the growth changes of muscle CSA and dynamic strength in teenagers who regularly participate in sports training, with specific emphasis on the effect of gender. This study was performed as a part of the Research Project on the Growth and Development of Young Athletes, supported by the Japan Amateur Sports Association.

Materials and methods

Subjects

Twelve teenage tennis players (six boys and six girls) participated in this study. All tennis players were recruited as elite junior athletes to the research project of the Japan Amateur Sports Association. All subjects had participated in national junior competitive meets within the research period, and had ranked within the top 8. The determinations of muscle CSA and dynamic strength were performed year by year, i.e., three times (T1, T2, and T3) during the study period. None of the subjects dropped out during the test period. The mean chronological ages at the times of laboratory testing were not significantly different between the boys and girls: 12.1 ($\pm$ 0.5) (T1), 13.0 ($\pm$ 0.5) (T2), and 14.0 ($\pm$ 0.5) years (T3) for the boys, and 12.0 ($\pm$ 0.9) (T1), 12.9 ($\pm$ 0.9) (T2), and 13.9 ($\pm$ 0.9) years (T3) for the girls. In addition, a total of 59 non-athletes of both genders aged from 11.5 to 14.4 years participated in the muscle strength measurement only for making a comparison with the tennis players in terms of strength development. This control group was divided into three age groups in accordance with the average value of the tennis players in each of T1, T2, and T3: a 12-year-group (age range = 11.5–12.4 years, 9 boys and 9 girls), a 13-year-group (12.5–13.4 years, 10 boys and 11 girls), and a 14-year-group (13.5–14.4 years, 10 boys and 10 girls). The means and standard deviations (SDs) of age, height, and body mass in each age group are shown in Table 1. The average values of chronological age, height, and body mass for each age group did not differ significantly from the corresponding values for the tennis players in each of T1, T2, and T3 (Table 2), with the exception that the average height and body mass values for the boys in the 13-year group were significantly greater than those for the tennis players in T2. This study was approved by the Office of the Department of Sports Sciences, University of Tokyo and was consistent with their requirements for human experimentation. Each subject and their parents were informed of the procedures to be used as well as the purpose of the study, and they gave their written informed consent.

Table 1. Descriptive data on age, height, and body mass in the control group

Variables	Age groups			
	Gender	12-year group	13-year group	14-year group
Age (years)	Boys	11.9 $\pm$ 0.5	12.9 $\pm$ 0.2	13.9 $\pm$ 0.3
	Girls	12.0 $\pm$ 0.2	13.1 $\pm$ 0.2	13.9 $\pm$ 0.3
Height (cm)	Boys	144.7 $\pm$ 8.1	156.9 $\pm$ 2.0	159.9 $\pm$ 1.2
	Girls	150.2 $\pm$ 2.8	151.7 $\pm$ 2.0	155.6 $\pm$ 1.3
Body mass (kg)	Boys	37.4 $\pm$ 6.7	45.1 $\pm$ 1.9	48.0 $\pm$ 3.2
	Girls	41.2 $\pm$ 5.2	44.5 $\pm$ 2.3	48.2 $\pm$ 2.0

Values are means $\pm$ standard deviations (SDs).

Measurement of skeletal age

An X-ray of the left hand and wrist was used to determine skeletal age in accordance with Tanner–Whitehouse II method (Tanner et al., 1983). Skeletal age was assessed based on an radius, ulna, and short finger bones (RUS) score and taken to the nearest month.

Measurements of muscle CSA

Magnetic resonance images of the right thigh were obtained using a 1.5 T superconducting magnet (Sigma MR system, General Electric Medical System, Waukesha, WI, USA) with a body coil. T1-weighted, spin-echo, and axial plane imaging were performed with the following variables: TR, 450 ms; TE, 20 ms; matrix, 256 $\times$ 172; field of view, 300 mm; and slice thickness, 10 mm. The subjects were imaged supine with the knee joint kept fully extended. First, the coronal scan of the thigh was carried out to determine the measurement position. The length of the femur, taken as the distance between the greater trochanter and the edge of the lateral epicondyle, was measured on a coronal plane. Subsequently, axial images were obtained from three levels of femur length (Fl). The levels selected were 30 (proximal to the knee, 30% Fl), 50 (mid, 50% Fl), and 70% (distal to the knee, 70% Fl) of Fl. From the axial images, the outline of the QF was traced, and the traced images were transferred to a computer (Power Macintosh 8600/200, Apple Computer) for the calculation of CSA. The calculated CSA of the QF was referred to as CSA_{QF}. The analyses of the MRI images obtained in each of T1, T2, and T3 were performed by a well-trained person who was independent of the information on the subjects and measurement times.

Measurement of dynamic strength

The concentric torque output during maximum voluntary knee extension was recorded using a Cybex II isokinetic dynamometer at the pre-set constant velocities of 1.05, 3.14, and 5.24 rad/s. The procedure for torque measurements was in accordance with that described in a prior study (Kanehisa et al., 1994). To standardize the measurements and localize the action to a muscle group, the subjects sat in an adjustable chair with support for the back, shoulders, and hips. During torque measurements, the hips and back of the subject were held tightly with adjustable belts. The rotation axis of the knee joints was aligned with that of the lever arm of the dynamometer. The length of the lever arm was adjusted to the length of each subject's lower leg. Calibration of the dynamometer was performed using weights placed on the lever arm prior to testing.

Table 2. Descriptive data on height, weight, thigh girth, and CSA measurements in the tennis players

Variables	Gender	Measurement time			
		T1	T2	T3	$\%T_{1-3}$
Height (cm)	Boys	146.6 ± 5.7 (137.2–151.2)	151.5 ± 7.2* (142.0–160.7)	160.0 ± 6.9*† (151.9–167.9)	10.7 ± 1.8‡ (8.7–13.5)
	Girls	149.7 ± 6.2 (141.6–158.2)	153.0 ± 5.0* (146.7–159.4)	155.6 ± 4.7*† (148.9–160.5)	4.1 ± 3.5 (1.0–9.2)
Body mass (kg)	Boys	34.1 ± 3.3 (29.4–38.7)	39.7 ± 4.0* (34.7–46.5)	45.5 ± 4.8*† (39.8–54.2)	33.3 ± 3.7‡ (23.9–40.1)
	Girls	39.1 ± 7.7 (29.5–49.0)	42.3 ± 6.3* (33.3–49.8)	45.6 ± 6.9*† (35.8–55.5)	9.2 ± 6.0 (8.8–29.6)
Thigh girth (cm)	Boys	40.8 ± 1.6 (38.7–42.6)	43.0 ± 1.3* (40.8–44.6)	45.4 ± 1.7*† (43.9–48.6)	11.3 ± 3.1‡ (5.4–14.1)
	Girls	44.4 ± 4.2 (38.7–49.2)	45.8 ± 4.8* (39.8–50.3)	47.0 ± 4.6*† (40.7–52.3)	5.9 ± 0.7 (5.2–6.9)
CSA_{QF30} (cm^2)	Boys	27.3 ± 8.5 (17.0–36.1)	29.7 ± 6.4 (19.4–36.8)	32.5 ± 7.6* (24.6–45.9)	23.9 ± 24.7 (– 0.8–60.1)
	Girls	32.1 ± 7.0 (19.0–39.3)	35.0 ± 7.0 (28.6–43.1)	37.2 ± 3.7* (33.4–42.6)	20.6 ± 27.7 (5.0–76.8)
CSA_{QF50} (cm^2)	Boys	42.0 ± 6.3 (32.4–48.8)	44.9 ± 8.4 (31.8–58.0)	53.2 ± 9.5*† (38.7–68.1)	26.5 ± 8.7‡ (18.4–39.5)
	Girls	45.6 ± 9.1 (33.3–57.0)	48.8 ± 9.4* (38.2–60.3)	49.4 ± 5.6* (43.5–56.0)	10.1 ± 11.3 (– 1.8–30.6)
CSA_{QF70} (cm^2)	Boys	40.6 ± 6.6 (30.3–47.1)	43.9 ± 5.8* (35.0–52.3)	51.3 ± 7.7*† (39.4–62.4)	26.9 ± 8.0‡ (12.9–33.4)
	Girls	41.3 ± 6.4 (33.5–49.2)	42.8 ± 6.7 (37.2–54.2)	44.8 ± 3.4 (41.6–50.4)	9.7 ± 10.4 (– 4.9–24.2)

Values are means ± SDs. $\%T_{1-3}$, relative change from T1 to T3.

*denotes significantly different from T1.

†denotes significantly different from T2.

‡denotes significantly different from the average value for the girls.

Figures within the parentheses show the range.

SDs, standard deviations; CSA, cross-sectional area; CSA_{QF}, CSA of the quadriceps femoris.

During the torque measurements, the subjects sat in a chair with the right ankle attached to the lever arm of the dynamometer. The subject's right thigh was fixed with a strap to avoid any upward movement while the muscle force was developed. The knee extension task was performed with a range of knee joint angles from 1.92 rad of the flexed position to the fully extended position (= 0 rad). Before maximal testing, each subject was given a practice bout to allow the muscle to warm up, and enable the subjects to familiarize themselves with the apparatus. The warm-up consisted of five to eight repetitions at each test speed with submaximal effort. Subjects were allowed to rest for approximately 3 min between the practice period and actual testing. The order of the pre-set test velocity was random for each subject. The subjects performed more than three maximal trials at each test velocity. A period of 10 s separated successive attempts, and a 1 min rest was allowed between each test velocity. At each test velocity, the peak torque was recorded in every trial and the highest value among the trials was used for analyses as a score of torque for individuals. For the data obtained from the tennis players, the ratio of torque to the sum of the CSA_{QF} values at the three levels (T/CSA) was calculated as an index representing strength relative to muscle size.

Statistics

For all measurement variables, the descriptive data were presented as means and SDs. The percentage of the difference between T1 and T3 (T3 minus T1) to T1 was calculated and referred to as $\%T_{1-3}$. A simple linear regression analysis was used to calculate the correlation coefficients between $\%T_{1-3}$ values for either the RUS score or height and those for the other measured variables. A Friedman test was used to locate significant differences across age for CSA_{QF} and torque at each test velocity. The significance of differences across site and test velocity for the $\%T_{1-3}$ values of CSA_{QF} and torque, respectively, was tested by a Wilcoxon's test. A Mann–Whitney test was used to identify the effect of gender on CSA_{QF} and torque at each test velocity and their $\%T_{1-3}$ values. In addition, a Mann–Whitney test was also used to test the significance of difference between the tennis players and control groups in torque at each test velocity. Statistical significance was set at $P \leq 0.05$.

Results

Longitudinal changes in the tennis players

The mean skeletal ages at the three time points of laboratory testing were 12.7 (± 2.1) (T1), 13.3 (± 1.7) (T2), and 14.5 (± 0.7) years (T3) for the boys, and 13.0 (± 1.1) (T1), 13.8 (± 1.2) (T2), and 14.4 (± 1.0) years (T3) for the girls. Only the girls at T1 showed a significantly higher skeletal than chronological age. No significant difference between the boys and girls was found in skeletal age at any measurement time.

Table 2 summarizes the descriptive data on anthropometric and CSA_{QF} measurements. In both genders, the height, weight, and thigh girth significantly increased year-by-year. CSA_{QF} values at the three levels except for the value at 70% Fl for the girls were significantly greater in T3 than in either T1 or T2. There was a tendency for the average anthropometric and CSA_{QF} values to be lower in the boys than in the girls at T1 and vice versa at T3, although these differences were insignificant at all measurement times. This resulted in significant differences between the boys and girls in the $\%T_{1-3}$ values of the three anthropometric variables and CSA_{QF} values at 50% Fl and 70% Fl.

Torque values at 1.05 rad/s for the boys were significantly greater in T3 than in T1 and T2, but those for the girls did not show a significant effect of age (Table 3). On the other hand, the corresponding values at 3.14 and 5.24 rad/s increased year-by-year in both genders, with an exception that the change between T2 and T3 in torque at 3.14 rad/s for the girls was not significant. The T/CSA at 1.05 rad/s for both genders did not show significant age-related differences. However, T/CSA values at 3.14 and 5.24 rad/s for the boys significantly increased year by year. Again, T/CSA at 5.24 rad/s for the girls was significantly higher in T2 and T3 than in T1. The $\%T_{1-3}$ values of torque and T/CSA at 3.14 and 5.24 rad/s for the boys and at 5.24 rad/s for the girls were significantly higher than those at 1.05 rad/s. There were no significant gender-related differences in torque values at the three velocities in every measurement time. However, the boys showed significantly greater T/CSA values at 3.14 and 5.24 rad/s than the girls in T3. Furthermore, the $\%T_{1-3}$ values of torque and T/CSA at 3.14 and 5.24 rad/s were significantly higher in the boys than in the girls.

In both genders, there were no significant correlations between $\%T_{1-3}$ values of the skeletal ages and measured variables. On the other hand, $\%T_{1-3}$ in height was positively correlated to that in CSA_{QF} at 70% Fl for the boys ($r = 0.847$, $P < 0.05$) and at each of 50% Fl ($r = 0.887$, $P < 0.05$) and 70% Fl ($r = 0.905$, $P < 0.05$) for the girls (Fig. 1). In these relationships, the values for the boys were plotted around an extension of the regression lines between

Table 3. Descriptive data on torque and its relative value to the sum of CSA_{QF} at the three levels (T/CSA) in the tennis players

Variables	Gender	Measurement time			
		T1	T2	T3	$\%T_{1-3}$
Torque (Nm)					
1.05 rad/s	Boys	98.7 ± 21.9	95.8 ± 21.4	121.3 ± 34.6*†	23.3 ± 20.0
		(63.0–122.0)	(71.0–130.0)	(85.0–183.0)	(1.6–56.4)
	Girls	99.7 ± 15.7	99.7 ± 15.7	105.2 ± 25.9	6.5 ± 28.6
		(84.0–122.0)	(59.0–131.0)	(57.0–134.0)	(– 33.7–41.1)
3.14 rad/s	Boys	55.0 ± 14.1	75.8 ± 18.8*	97.0 ± 23.1*†	81.1 ± 33.0‡§
		(28.0–67.0)	(49.0–99.0)	(63.0–130.0)	(40.7–125.0)
	Girls	63.7 ± 12.6	73.7 ± 16.0*	78.8 ± 13.7*	25.7 ± 20.8§
		(47.0–78.0)	(54.0–93.0)	(61.0–96.0)	(2.7–60.0)
5.24 rad/s	Boys	38.8 ± 9.6	59.5 ± 14.5*	78.8 ± 20.2*†	108.4 ± 45.0‡§
		(21.0–47.0)	(37.0–77.0)	(63.0–130.0)	(36.2–159.5)
	Girls	47.2 ± 11.9	58.2 ± 11.3*	63.0 ± 11.7*†	36.4 ± 18.0§
		(32.0–64.0)	(45.0–74.0)	(61.0–96.0)	(17.0–57.1)
T/CSA (Nm/cm^2)					
1.05 rad/s	Boys	0.895 ± 0.084	0.808 ± 0.094	0.874 ± 0.094	– 1.6 ± 13.6
		(0.790–1.005)	(0.650–0.887)	(0.771–1.037)	(– 23.3–17.0)
	Girls	0.853 ± 0.157	0.783 ± 0.139	0.797 ± 0.176	– 4.7 ± 28.9
		(0.666–1.092)	(0.554–0.928)	(0.479–0.969)	(– 40.6–37.0)
3.14 rad/s	Boys	0.496 ± 0.079	0.635 ± 0.079*	0.703 ± 0.074*†‡	44.4 ± 23.4‡§
		(0.351–0.568)	(0.507–0.707)	(0.613–0.801)	(16.1–64.2)
	Girls	0.538 ± 0.074	0.579 ± 0.060	0.597 ± 0.059	12.9 ± 21.9
		(0.421–0.611)	(0.507–0.651)	(0.513–0.660)	(– 6.7–55.4)
5.24 rad/s	Boys	0.353 ± 0.070	0.499 ± 0.069*	0.570 ± 0.062*†‡	60.7 ± 32.0‡§
		(0.263–0.434)	(0.414–0.591)	(0.487–0.618)	(12.3–94.2)
	Girls	0.394 ± 0.053	0.460 ± 0.052*	0.476 ± 0.048*	22.1 ± 17.1§
		(0.328–0.453)	(0.421–0.542)	(0.413–0.525)	(6.3–52.6)

Values are means ± SDs.
*denotes significantly different from T1.
†denotes significantly different from T2.
‡denotes significantly different from the average value for the girls.
§denotes significantly different from the values at 1.05 rad/s.
Figures within the parentheses show the range.
SDs, standard deviations; CSA, cross-sectional area; CSA_{QF}, CSA of the quadriceps femoris; T/CSA, ratios of torque to the sum of CSA_{QF}.

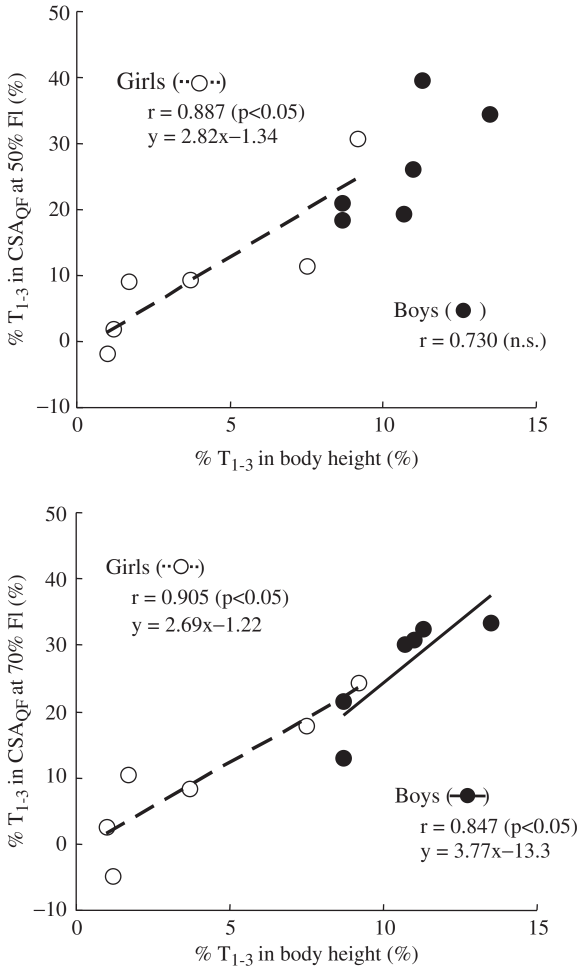

Fig. 1. Relations between the $\%T_{1-3}$ values of body height and cross-sectional area of the quadriceps femoris (CSA_{QF}) at 50% femur length (Fl) (upper panel) and 70% Fl (lower panel).

the $\%T_{1-3}$ values of height and CSA_{QF} for the girls. And so, the correlation coefficients between the $\%T_{1-3}$ values of height and CSA_{QF} were 0.901 ($P<0.05$) at 50% Fl and 0.938 ($P<0.05$) at 70% Fl, when data for both the boys and girls were included. However, the corresponding correlation for 30% Fl was insignificant ($r=0.469$, $P>0.05$).

Comparison of torque output between the tennis players and controls

Table 4 indicates the mean and SD of torque relative to body mass for the tennis players at each measurement and those for the corresponding age groups of the controls. For the boys, the tennis players showed significantly higher values than the control groups at 1.05 rad/s in T1 and 5.24 rad/s in T2 and T3. In the girls, too, the mean values of torque relative to body mass at 5.24 rad/s in T1 and T2, and at 3.14 and 5.24 rad/s in T3 were significantly higher in the tennis players than in the control groups.

Discussion

The tennis players of both genders showed hypertrophic changes in the QF muscle, with greater gains in the boys than in the girls at 50% and 70% Fl. Because no CSA measurements were performed for the non-athletic population, we cannot conclude whether the hypertrophic changes observed here can be attributed to the training for tennis. Beunen et al. (1981) have shown that a fairly high percentage of the variation in body dimensions between 13 and 16 years of age is explained by skeletal age. Moreover, Malina and Johnston (1967) reported that, as a result of cross-sectional observation between 6 and 16 years, a significant correlation between skeletal age and muscle width of the upper arm was found on and after 11 years –of age in boys. Hence, if the observed increase in CSA_{QF} is influenced predominantly by natural growth rather than training for tennis, it seems that the hypertrophic change may be correlated to that in skeletal age. In the present study, however, $\%T_{1-3}$ in CSA_{QF} did not significantly correlate with that in skeletal age, suggesting that the observed gains in CSA may be considered an effect of physical training rather than biological maturation.

Before accepting the explanation mentioned above, however, it should be mentioned that $\%T_{1-3}$ values in CSA_{QF} at 50% and 70% Fl were highly correlated to those in height as a result of regression analysis including the data for boys and girls (Fig. 1). From the findings of Malina (1994), regular physical activity, participation in sport, and training for sports have no effect on attained height and the rate of growth in height. Tanner et al. (1981) have shown, on the basis of longitudinal observations on muscle widths of the upper arm and calf from the age of 3 to 18 years, that the age of the peak velocity of the muscle width increase nearly coincides with that of sitting height. Therefore, if height rather than skeletal age is more sensitive for detecting the relationship with muscle growth, the present result implies that hypertrophic changes at 50% and 70% Fl can be attributed to natural growth rather than the account of physical training performed during the research period. Further, the greater gains in the CSA_{QF} of these levels for the boys compared with the girls may be explained by the significant gender difference in $\%T_{1-3}$ in height (Table 2).

Among the three thigh levels taken for the CSA measurements, only 30% Fl did not show a significant correlation between the $\%T_{1-3}$ values of CSA_{QF} and either skeletal age or height. In a prior study in

Table 4. Comparison between the tennis players and control group of torque relative to body mass (Nm/kg)

Groups	Gender	Test velocity (rad/s)		
		1.05	3.14	5.24
Tennis players				
T1	Boys	2.87 ± 0.51* (2.14–3.61)	1.59 ± 0.33 (0.95–1.88)	1.13 ± 0.24 (0.71–1.39)
	Girls	2.60 ± 0.48 (2.14–3.36)	1.64 ± 0.19 (1.36–1.88)	1.20 ± 0.11* (1.03–1.32)
T2	Boys	2.40 ± 0.37 (2.05–2.81)	1.90 ± 0.38 (1.41–2.24)	1.49 ± 0.30* (1.07–1.79)
	Girls	2.32 ± 0.34 (1.77–2.82)	1.73 ± 0.13 (1.53–1.87)	1.37 ± 0.09* (1.23–1.42)
T3	Boys	2.64 ± 0.50 (2.14–3.38)	2.12 ± 0.37 (1.58–2.55)	1.72 ± 0.32* (1.28–2.01)
	Girls	2.30 ± 0.50 (1.59–2.85)	1.73 ± 0.17* (1.56–2.00)	1.38 ± 0.12* (1.22–1.60)
Control				
12-year-group	Boys	2.29 ± 0.16 (2.02–2.49)	1.62 ± 0.16 (1.41–2.14)	1.08 ± 0.11 (0.78–1.34)
	Girls	2.32 ± 0.41 (1.84–3.18)	1.56 ± 0.21 (1.28–1.93)	0.95 ± 0.16 (0.78–1.20)
13-year-group	Boys	2.45 ± 0.36 (1.86–2.80)	1.75 ± 0.22 (1.34–1.86)	1.10 ± 0.16 (0.91–1.21)
	Girls	2.37 ± 0.36 (1.91–3.12)	1.54 ± 0.20 (1.17–1.87)	0.95 ± 0.11 (0.75–1.09)
14-year-group	Boys	2.92 ± 0.41 (2.25–3.62)	2.12 ± 0.27 (1.78–2.64)	1.31 ± 0.17 (1.00–1.58)
	Girls	2.15 ± 0.40 (1.64–2.68)	1.41 ± 0.20 (1.19–1.79)	0.88 ± 0.17 (0.58–1.20)

Values are means ± SDs.

*denotes significantly different from the control group at $P<0.05$ in the comparison within the same generation (i.e., T1 vs 12-year-group, T2 vs 13-year-group, and T3 vs 14-year-group).

Figures within the parentheses show the range.

SDs, standard deviations.

which the CSA of the QF in junior Olympic weight lifters was determined longitudinally, a preferential hypertrophic change was found at the thigh level proximal to the knee joint (Kanehisa et al., 2003b). Previous studies examining untrained adult populations have shown that resistance training causes a non-uniform increase in muscle CSA along the muscle length within the QF or between the constituents of the QF (Narici et al., 1989, 1996; Housh et al., 1992). As an explanation for the phenomenon, a difference in tension generated or training stimulus along the muscle belly, which can be attributed to the exercise mode during training, has been suggested (Housh et al., 1992; Narici et al., 1996). For the tennis players tested in this study, however, resistance exercises aimed mainly at improving muscle strength had not been included in their training programs. On the other hand, Eliakim et al. (2001), who observed a significant increase in the thigh muscle volume of non-obese girls aged 9 years as a result of a 5-week physical training program, reported that hypertrophic changes occurred mainly in part proximal to the knee. In the prior study, the exercise programs used consisted of running, jumping, aerobic dance, and age-appropriate competitive sports (e.g., basketball, soccer, etc). Taking the findings into account together with the results here, it seems that regular participation in training for sports during the teenage years increases the CSA of the quadriceps muscle at the level proximal to the knee joint beyond that achieved by normal growth.

In this study, the ratio of torque to the sum of the CSA_{QF} values at the three levels (T/CSA) was calculated as an index representing strength relative to muscle size. Before interpreting the present result on T/CSA, we should comment that the muscle image obtained here was the anatomical cross-section of muscle at right angles to the long axis of the limb, not the physiological cross-section at right angles to all muscle fibers. In addition, we have no data on muscle architecture, i.e., the fascicle arrangements of the muscles examined. The physiological CSA has been shown to be greater than the anatomical one in a muscle having a pennate structure (Fukunaga et al., 1992). Moreover, hypertrophic adaptations in a muscle with a pennate structure increase fascicle pennation angles (Kawakami et al., 1995; Aagaard et al., 2001). Aagaard et al. (2001) indicated that, as a result of a 14-week heavy resistance strength training of the lower limb muscles, an increase in pennation angle allowed physiological CSA, and thereby maximal force generation capacity, to increase significantly more than anatomical CSA and volume. Therefore, if the magnitude of gain in the physiological CSA of the QF muscle is greater than that in the CSA determined here, we cannot rule out a possibility that the use of T/CSA might overestimate the changes in the strength capability normalized to muscle size in the tennis players.

Although there is a limitation mentioned above, an interesting result obtained here is that the tennis players showed a predominant increase in torque and T/CSA at high-velocity contractions, with a greater gain in the boys than in the girls. This implies that, for the younger teenage athletes, the improvement in strength capability at high-velocity contractions involves factors other than hypertrophic change. Regardless of athletic and non-athletic populations, very few studies have been published in which the development of the torque–velocity relationship was followed longitudinally during an earlier stage in teenagers (Seger & Thorstensson, 2000). From the limited findings available, the general shape of the torque-velocity relation for knee extensors exhibits an adult-like pattern both before and after puberty, and does not differ between genders (Seger & Thorstensson, 2000). In the prior study cited above, however, the pre-set velocity for strength measurements was 0.79–3.14 rad/s. On the other hand, as a result of cross-sectional observations in normal children (aged 6–9 years) and young adults, it was found that age- and gender-related differences in knee extension torque became larger with increasing contraction velocities in the range from 1.05 to 5.24 rad/s (Kanehisa et al., 1994). Ramsey et al. (1990) reported that, in pre-adolescent boys, 78% of available motor units were activated during voluntary maximum knee extension. Again, in comparison with young adults, children have a lower maximum rate of force production (Going et al., 1987), being largely dependent on the amount and rate of neural activation (Komi, 1986). Given these findings, the predominant increases in torque and T/CSA at high-velocity contractions for the tennis players may be considered to reflect a more natural development of neuromuscular functions contributing to force production during rapid movements.

In the present study, however, most of the significant differences between the tennis players and the control group in torque relative to body mass were found at the highest velocities. Because the collection of torque data differed between the athletic and non-athletic populations, i.e., longitudinal vs cross-sectional measurement, we cannot consider the observed difference in torque relative to body mass as a conclusive evidence, indicating that the tennis players have achieved a greater development in torque at high-velocity contractions as compared with non-athletic individuals. However, a 2-year follow-up survey (Kanehisa et al., 2003a) on non-athletic boys aged 12.7–13.5 years at the start of the study failed to find significant increases in knee extension torques developed at 3.14 and 5.24 rad/s, expressed as the values relative to muscle volume estimated from the muscle thickness measurements. Thorland et al. (1987) indicated that, although knee extension torque relative to body mass at 1.05 rad/s for non-athletic girls was similar or superior to that of female sprinters and distance runners, the corresponding value at 3.14 rad/s was greater in the athletic than non-athletic population. These findings support the assumption that the participation in training for tennis outside the school curriculum contributes predominantly to the increase in torque at high-velocity contractions. If so, however, the reason for the greater gains in torque and T/CSA at high-velocity contractions for the boys than girls remains a question.

It is known that the relative distribution of fast twitch fibers in the vastus lateralis muscle influences the force–velocity relation during knee extensions (Thorstensson et al., 1976; Coyle et al., 1979). Ryushi and Fukunaga (1986) have shown that the percentage of fast-oxidative-glycolytic fibers in vastus lateralis muscle is significantly correlated to dynamic strength relative to the CSA of the QF. This tempts us to assume that there is a different growth change in muscle fiber composition between boys and girls and so it may have resulted in the gender-related difference in relative gains in torque at high-velocity contractions in T3. However, a prior cross-sectional study has shown that the relative distribution of the subtypes of fast twitch fibers is approximately the same in 6-year-old children and adults (Bell et al., 1980). Moreover, Saltin et al. (1977) have reported that the relative distribution of slow twitch fibers in the vastus lateralis muscle was similar in both genders with an age of 16 years. On the other hand, Behm and Sale (1993) have suggested that the key training stimuli for improving torque output at high-velocity contractions appear to be either one or both of (1) the motor command and motor unit activation pattern associated with attempted high-velocity movements and (2) a high rate of force development of the ensuing muscle contraction, regardless of its type. A cross-sectional study (Gavarry et al., 2003) provided evidence indicating that, in an age span from primary school to high school, boys engaged significantly more time than girls in vigorous physical activity during school and free days. In the present study, no analysis on the level and/or content of physical activity was performed during the research period. With advancing growth, however, if the boys have begun to perform more ballistic, high-velocity movements in daily physical activities involving the training for tennis compared with the girls, it might be a reason for the gender-related differences in the relative gains in torque and T/CSA at high-velocity contractions.

Perspectives

The findings presented here indicate that young tennis players who are in the earlier stage of adolescence increase the CSA of the QF muscle beyond normally expected growth change at the level proximal to the knee joint and show a predominant development in torque generation capability during high-velocity knee extensions, with a greater gain in boys compared with girls. However, the present study examined only a small sample for a limited sport event. No longitudinal measurements were performed for the non-athletic and other athletic populations. Therefore, we cannot conclude whether the observed changes in the CSA of the QF along its length and torque relative to CSA are specific to the sport event selected. Further investigation on this point is needed.

Key words: isokinetic strength, strength relative to muscle CSA, gender difference, young athletes.

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