Strength Training for Prepubescent Boys and Girls.

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Abstract

The purpose of this study was to determine the effect of strength training in prepubescent boys and girls on muscle strength and cross-sectional area of upper arm muscle. Subjects were ninety-nine healthy elementary school children who belonged to 1st, 3rd and 5th grades and they were assigned to two groups of training (N=52) and control (N=47). Training group participated in strength training program for 12 weeks which consisted of maximum sustained isometric contraction of elbow flexion for ten sec, whereas control group did not participate in special training program in this period. In order to determine the changes due to training, cross-sectional areas of the tissues in upper arm, such as the whole tissue, muscle, fat and bone, were measured by the ultrasonic methods. Maximum isometric and isokinetic muscle strengths of elbow flexion and extension were measured by means of isokinetic cybex dynamometer. In order to assess the development of physological maturity. TW2 method was used to estimate the skeletal age in each subject by taking the hand-wrist X-ray photograph. After 12-week training period, the cross-sectional area of the whole tissue significantly increased in both training (2.52 cm^2, 8.9%) and control groups (2.11 cm^2, 7.3%). This increase was due to significant increases in muscle and bone areas in the training group and, on the other hand, due to the significant increase only in fat area in the control group. In the training group increase in muscle area was about 50% of that derived from the study on adults (Fukunaga, 1978). The increment in cross-sectional area of muscle with training was significantly correlated with the skeletal age ($r=0.36$, $p<0.01$). Isometric strength of elbow extension showed significant increase (1.17 kg, 17.5%) and for 5th grade males this increase was about 40% of that obtained from adults, whereas isokinetic strength unchanged with training. Muscle strength per cross-sectional area did not show a significant increase except the training group of 5th grade boys. In conclusion, the effects of strength training on cross-sectional muscle area and muscle strength for prepubescents were similar in its direction to but different in its magnitude from those found in adults.

Key words: isometric strength training, prepubescent boys and girls, skeletal age, muscle strength, muscle area

Introduction

Strength training causes the increase in maximum muscle strength and the hypertrophy of muscle fiber, if training protocol such as intensity, frequency, and period are enough to stimulate the muscle. Those morphological and functional changes in muscle due to strength training were almost derived from postpubescent children[5], adults [5] and animal preparations[10]. However, it is not well known whether prepubescent children would have a similar training effects on muscle as obtained in postpubescents and adults.

In endurance training on the other hand, many investigators[2),3] recognized the gain in aerobic capacity through training on pubescent children. In strength training, Vrijens, J[12] showed little effect on muscle strengths in the prepubescent children. On the contrary, Pfeiffer et al.[9] demonstrated significant increases in isokinetic muscle strength through weight training for prepubescent, pubescent and post-pubescent males. Fournier, M[4] indicated the unchanged muscle fiber area and increased activity of PFK, but lower than that of adults, after 3 months sprint training program on 16–17 year old boys. Recently National strength and Conditioning Association (NSCA) and sports medicine groups in America are coming to support and recommend the supervised strength training for prepubescent children[1].

From those background, it is necessary to determine the possibilities of strength training gains on prepubescent children. The purpose of the present study was to measure the effects of strength training on muscle strength and cross-sectional area of muscles related to skeletal age in prepubescent elementary school children.

Methods

Ninety-nine healthy elementary school children of first, third and fifth grades, aged 6–11 years old, were randomly assigned to two groups; training group (N=52) and control group (N=47). Informed consent was obtained from each subject and was countersigned by a parent. Physical characteristics of subjects before, middle and after the training period are shown in Table 1.

Training group participated in strength training program which consisted of maximum voluntary isometric elbow flexion for ten seconds using a newly designed training device as shown in Fig. 1. Three repetitions of this sustained contraction incorporated with 3 to 5 minutes rest between contractions were performed twice a day at three days per week for 12 weeks. Each subject recorded by

Fig. 1. Newly designed device for training of elbow flexion.

Table 1. Chronological and skeletal age of subjects and changes in body height and weight through 12 weeks training program. M: male and F: female. m and SD, respectively, show mean and standard deviation.

Training group

grade	sex	n		chronological age (yrs)	skeletal age (yrs)				body height (cm)			body wieght (kg)		
						(max.)	(min.)	(range)	BT	MT	AT	BT	MT	AT
1st	M	8	m	6.9	* 6.2	(6.8)	(5.6)	(1.2)	116.4	117.0	117.6**	21.9	22.3	22.5**
			SD	0.3	0.5				3.1	3.3	3.5	3.9	3.9	3.8
	F	7	m	7.0	6.5	(8.7)	(4.6)	(4.1)	120.0	120.2	121.0**	24.3	24.7	24.9
			SD	0.3	1.6				6.2	6.4	6.0	5.6	5.7	5.6
3rd	M	10	m	9.0	* 8.1	(9.9)	(6.5)	(3.4)	129.6	129.8	130.6***	29.2	30.6	31.2
			SD	0.3	1.1				5.7	6.2	6.1	8.7	8.4	8.4
	F	7	m	9.0	8.6	(10.0)	(7.6)	(2.4)	126.8	127.1	127.8**	26.2	26.8	27.0
			SD	0.4	0.8				4.4	4.5	4.6	1.9	1.7	1.6
5th	M	10	m	11.0	10.7	(14.1)	(7.7)	(6.4)	140.1	140.4	141.1*	35.2	35.2	35.3
			SD	0.3	2.0				8.8	9.0	9.1	9.0	8.9	9.2
	F	10	m	10.9	10.7	(11.8)	(9.1)	(2.7)	139.7	140.3	141.2***	39.7	40.6	40.6*
			SD	0.3	0.9				7.5	7.2	7.4	12.5	12.5	12.5

Control group

grade	sex	n		chronological age (yrs)	skeletal age (yrs)				body height (cm)			body weight (kg)		
						(max.)	(min.)	(range)	BT	MT	AT	BT	MT	AT
1st	M	8	m	7.0	6.4	(7.8)	(5.1)	(2.7)	120.4	120.7	121.4**	24.8	25.2	25.6***
			SD	0.3	0.9				4.7	4.6	4.5	6.4	6.5	6.3
	F	6	m	7.0	6.0	(7.8)	(4.8)	(3.0)	117.1	117.4	118.4**	23.3	23.0	23.3
			SD	0.3	1.1				4.0	4.0	3.8	2.2	2.3	2.0
3rd	M	8	m	9.0	8.8	(9.5)	(7.4)	(2.1)	131.8	132.5	132.9**	33.4	33.2	33.8*
			SD	0.2	0.6				4.5	4.6	4.8	8.4	8.2	8.4
	F	9	m	9.0	* 8.3	(9.3)	(6.4)	(2.9)	127.5	127.1	128.7***	27.8	28.0	28.2
			SD	0.3	0.9				5.7	5.8	6.0	3.2	3.0	2.8
5th	M	8	m	11.1	10.8	(12.1)	(9.2)	(2.9)	140.9	141.5	142.1***	35.0	35.5	34.0
			SD	0.2	1.0				6.4	6.4	6.4	4.7	4.9	4.2
	F	8	m	11.2	10.9	(11.5)	(9.5)	(2.0)	141.2	141.9	142.6***	36.9	37.5	37.3
			SD	0.2	0.7				4.3	4.2	4.3	3.2	3.4	3.9

***: P<0.001 **: P<0.01 *: P<0.05 BT: before training MT: 6th week of training AT: after training himself the maximum values of strength developed during three repetitions on a training card in order to motivate to this training program. The control group did not engage in any special physical activity program during this three-month training period.

The following determinations were made before, middle, and after the three months training program.

The cross-sectional area of tissues such as muscles, fat, and bone in upper arm were measured by means of ultrasonic method (SSD-120, ECHO VISION, ALOKA, JAPAN) described by Ikai (1968)[6]. The frequency of the ultrasonic wave was chosen to be 5 MHz. The subjects immersed his upper arm along the central axis of a water tank. The measured site was 60% distal of humerus shaft in right upper arm. The scanner circurates around the tank and produces an image of arm cross-section of the upper arm. Photograph of the cross-section on the oscilloscope was taken by 35 mm camera. The cross-sectional areas were measured by planimeter for the whole tissue, muscles (m. biceps brachii, m. brachialis and m. triceps brachii), fat, and bone, respectively.

The maximum isometric and isokinetic strength of flexion and extension of elbow joint were measured using a cybex dynamometer (Lumex Co. New York). Subject seated on the specially designed chair and the isometric strength of elbow flexion and extension were measured in the elbow joint at 110 degrees and 130 degrees, respectively (full extension: 180 degrees). Isokinetic strength of elbow extension and flexion were measured at three constant speed of 60, 180, and 300 degrees per sec.

Hand-wrist X-ray (Softex Co. Japan) were taken before training for each subject and the skeletal age was determined by radiologist according to the TW2 methods[11].

Training and control groups were respectively divided into subgroups based on grade and sex. The differences in variables between before- and after- training were examined by means of dependent t-test and they were defined as statistically significant if t value was less than 5%.

Results

Table 2 shows the cross-sectional areas of the whole, lean, fat, and bone. After 12 weeks of training, the increases in the whole area were observed in both training (2.52 cm^2, 8.9 %) and control groups (2.11 cm^2, 7.3 %). In control group the fat area increased significantly, except for 3rd grade male (3M) and 5th grade female (5F). However, in all training subgroups, no significant change in fat area was observed. The bone area increased significantly in the training groups of 3M ($p<0.01$), 5M ($p<0.001$), and 5F ($p<0.05$), while no significant increase was observed in all control groups.

The significant increases in muscle area (1.29 cm^2, 10.3%) were obserbed in training group except for only one subgroup of 1M, whereas in control group no muscle area indicated significant difference except for 5F (Table 3). The muscle areas in training group remarkablly increased for fifth graders; for male (1.88 cm^2, 12.5%, $p < 0.001$) and for female (1.80 cm^2 12.7%, $p<0.01$). In fifth grade students, the increases in muscle area of the flexor were 0.9 cm^2 (12.2%, $p<0.001$) and 0.8 cm^2 (11.8%, $p<0.05$) for male and female, respectively. Extensor muscle area also increased with the training by 1.1 cm^2 (13.2%, $P<0.01$) for male and 0.7 cm^2 (9.1%, $P<0.05$) for female. In control group, insignificant increase (0.83 cm^2, 5%) in muscle area was observed except for the subgroup of 5F.

Significant correlation was observed between the skeletal age and the increment of muscle area in

Table 2. Change in cross-sectional area of tissues in upper arm such as the whole, lean, fat and bone.

Training group

grade	sex		whole			Δ	lean			fat			bone		
			BT	MT	AT	AT-BT	BT	MT	AT	BT	MT	AT	BT	MT	AT
1st	M	m	24.8	25.7	26.2	1.4	12.5	13.2	13.5	12.3	12.5	12.7	1.0	1.4	1.3
		SD	9.6	7.9	7.6		2.6	1.4	1.3	7.5	6.8	6.9	0.3	0.2	0.2
	F	m	24.4	27.2	27.6	3.2	11.0	13.2	12.9	13.4	14.1	14.8	1.0	1.6	1.3
		SD	7.0	9.0	7.9		1.9	3.7	2.8	5.0	5.8	5.9	0.2	0.7	0.3
3rd	M	m	29.6	31.3	31.9**	2.3	14.8	15.7	15.9**	14.9	15.7	16.0	1.3	1.6	1.7**
		SD	12.6	12.6	13.1		3.0	3.1	3.1	9.8	10.0	10.1	0.3	0.4	0.3
	F	m	25.5	27.5	27.8	2.3	12.2	14.0	13.7*	13.3	13.5	14.2	1.1	1.3	1.4
		SD	3.1	3.4	2.6		1.9	1.6	1.6	1.8	3.9	2.4	0.4	0.2	0.3
5th	M	m	30.3	32.5	33.3***	3.0	16.6	18.7	19.1***	13.7	13.8	14.2	1.6	2.1	2.2***
		SD	8.4	8.5	9.0		2.6	3.1	3.1	7.3	6.7	7.1	0.3	0.4	0.4
	F	m	36.7	38.0	39.6**	2.9	15.6	16.6	17.6**	21.1	21.4	21.9	1.3	1.7	1.7**
		SD	13.6	13.0	13.7		3.0	2.5	3.6	11.0	11.0	10.4	0.2	0.4	0.5

Control group

grade	sex		whole			Δ	lean			fat			bone		
			BT	MT	AT	AT-BT	BT	MT	AT	BT	MT	AT	BT	MT	AT
1st	M	m	25.9	27.6	28.4*	2.5	14.4	14.5	14.8	11.4	13.2	13.6**	1.5	1.6	1.6
		SD	9.9	9.5	10.9		3.9	3.4	4.2	6.2	6.6	7.0	0.4	0.3	0.3
	F	m	25.5	29.5	28.2*	2.7	12.3	13.7	12.5	13.2	15.8	15.7**	1.2	1.5	1.2
		SD	2.8	3.9	3.2		0.9	1.5	0.7	2.7	4.1	3.1	0.3	0.2	0.4
3rd	M	m	34.9	35.6	36.0	1.1	16.3	16.8	16.7	18.7	18.8	19.3	1.7	1.7	1.7
		SD	11.0	11.3	12.2		2.9	3.1	2.7	8.6	8.5	10.2	0.2	0.3	0.3
	F	m	27.4	28.1	28.8*	1.4	14.2	13.8	14.4	13.3	14.3	14.3**	1.7	1.4	1.5
		SD	4.6	4.1	4.3		1.6	1.4	1.8	4.2	3.7	3.8	0.2	0.2	0.2
5th	M	m	30.8	32.5	32.8**	2.0	17.6	18.5	18.7*	13.2	13.9	14.1*	2.0	2.0	2.2
		SD	5.9	6.0	6.7		2.3	2.3	2.8	4.9	4.8	4.7	0.2	0.3	0.3
	F	m	33.1	34.3	36.1***	3.0	16.4	17.1	18.0**	16.8	17.2	18.0	1.9	1.9	1.9
		SD	4.1	4.3	4.5		1.5	1.9	1.9	3.9	3.0	3.2	0.3	0.3	0.3

***: P<0.001 **: P<0.01 *: P<0.05 BT: before training MT: 6th week of training AT: after training

Table 3. Changes in cross-sectional area of muscle.

Training group

grade	sex		muscle			Δ	flexor			Δ	m. biceps brachii			m. brachialis			extensor			Δ
			BT	MT	AT	AT−BT	BT	MT	AT	AT-BT	BT	MT	AT	BT	MT	AT	BT	MT	AT	AT-BT
1st	M	m	11.5	11.8	12.2	0.7	5.3	5.0	5.3	0.0	3.0	2.7	2.0	2.3	2.3	2.2	6.2	6.9	6.9	0.7
		SD	2.3	1.3	1.2		1.0	0.7	0.6		0.6	0.4	0.3	0.5	0.5	0.3	1.5	0.9	0.7	
	F	m	10.1	11.6	11.5*	1.4	4.8	5.0	4.9	0.1	2.6	2.7	2.5	2.2	2.3	2.4	5.3	6.6	6.6**	1.3
		SD	1.8	3.1	2.6		0.7	1.0	1.1		0.6	0.5	0.5	0.3	0.5	0.7	1.1	2.2	1.6	
3rd	M	m	13.4	14.0	14.2*	0.8	6.2	5.9	6.3	0.1	3.6	23.3	3.4	2.7	2.6	2.8	7.2	8.1	7.9**	0.7
		SD	2.8	2.8	2.9		1.5	1.3	1.5		0.9	0.7	0.9	0.7	0.8	0.7	1.8	1.8	1.5	
	F	m	11.1	12.8	12.2*	1.2	5.3	5.2	5.3	0.1	3.1	2.8	2.0	2.2	2.3	2.3	5.8	7.6	6.9**	1.1
		SD	1.6	1.6	1.5		0.8	0.7	0.7		0.5	0.7	0.7	0.6	0.3	0.2	1.0	1.6	1.0	
5th	M	m	15.0	16.7	16.9***	1.9	6.7	7.4	7.5**	0.9	3.8	4.2	4.5**	3.0	3.2	3.1	8.3	9.3	9.4**	1.1
		SD	2.3	2.8	2.8		1.3	1.4	1.3		0.8	0.9	0.8	0.7	0.6	0.5	1.3	1.6	1.6	
	F	m	14.2	14.9	15.9**	1.8	6.5	6.8	7.5*	0.8	3.6	3.9	3.2**	2.9	2.9	3.2	7.7	8.1	8.5*	0.7
		SD	2.8	2.2	3.2		1.5	1.3	1.8		0.8	0.9	0.1	0.7	0.6	1.0	1.5	1.3	1.7	

Control group

grade	sex		muscle			Δ	flexor			Δ	m.biceps brachii			m. brachialis			extensor			Δ
			BT	MT	AT	AT-BT	BT	MT	AT	AT-BT	BT	MT	AT	BT	MT	AT	BR	MT	AT	AT-BT
1st	M	m	12.9	12.9	13.2	0.3	6.1	5.6	5.3*	−0.8	3.4	3.3	3.0*	2.8	2.3	2.3	6.8	7.3	7.9**	1.1
		SD	3.7	3.3	4.0		1.6	1.3	1.6		0.9	0.8	0.9	0.8	0.6	0.8	2.2	2.1	2.4	
	F	m	11.1	12.2	11.3	0.2	5.0	5.5	4.9	−0.1	2.8	3.3	2.7	2.3	2.2	2.2	6.1	6.7	6.4	0.4
		SD	0.9	1.5	0.4		0.4	1.0	0.4		0.1	0.7	0.3	0.3	0.4	0.3	0.7	0.7	0.5	
3rd	M	m	14.5	15.1	15.1	0.5	6.6	6.6	6.5	−0.2	3.4	3.7	3.4	3.2	2.9	3.0	7.9	8.5	8.5	0.6
		SD	2.7	2.9	2.5		1.1	1.2	1.0		0.5	0.9	0.7	0.6	0.5	0.6	1.8	1.9	1.7	
	F	m	12.5	12.4	13.0	0.5	5.7	5.2	6.0	0.3	3.1	3.0	3.3	2.6	2.2	2.6	6.9	7.1	7.1	0.2
		SD	1.5	1.3	1.6		0.7	0.4	0.6		0.2	0.4	0.4	0.5	0.2	0.5	1.0	1.1	1.3	
5th	M	m	15.5	16.6	16.5	1.0	7.0	7.5	7.3	0.2	3.7	4.2	4.0	3.3	3.3	3.2	8.5	9.0	9.3	0.7
		SD	2.2	2.2	2.7		1.1	1.2	1.2		0.7	0.6	0.6	0.7	0.6	0.6	1.4	1.2	1.6	
	F	m	14.4	15.2	16.1**	1.7	5.9	6.3	6.8	0.9	3.4	3.4	3.8	2.5	2.8	3.0*	8.6	9.0	9.3	0.7
		SD	1.3	1.7	1.8		1.0	0.8	0.5		0.7	0.6	0.5	0.5	0.5	0.4	0.4	1.3	1.5	

***: $P<0.001$ **: $P<0.01$ *: $P<0.05$ BT: before training MT: 6th week of training AT: after training

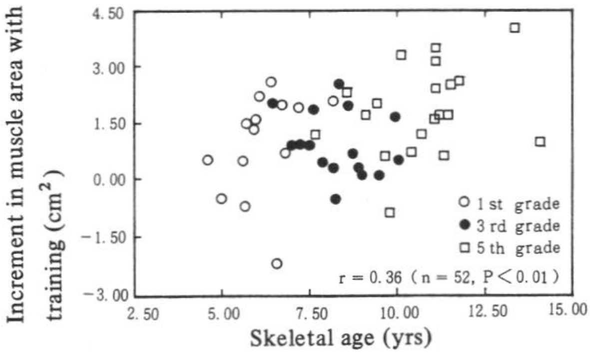

Fig. 2. Relationship between skeletal age and increment in cross-sectional area of muscle with strength training.

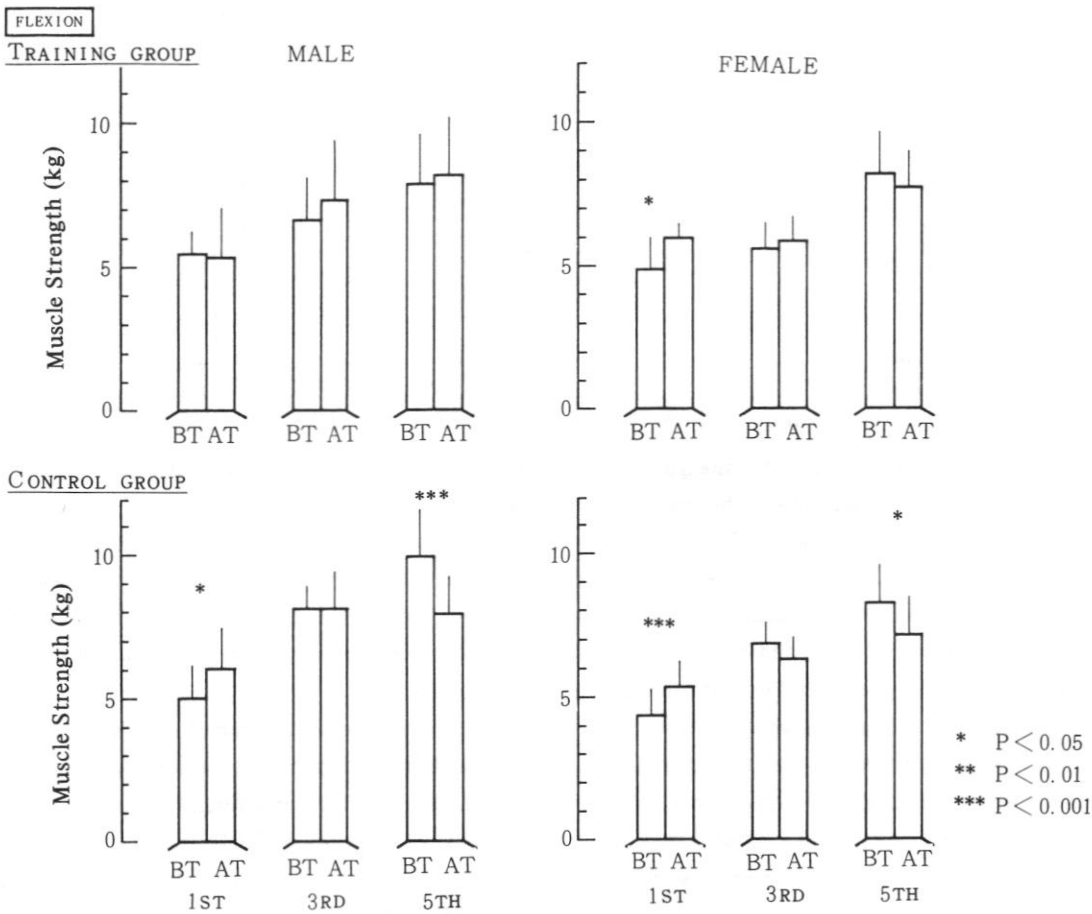

Fig. 3. Maximum isometric strength of elbow flexion before (BT) and after (AT) strength training.

training group ($r=0.36$, $p<0.01$, Fig. 2).

Fig. 3 and Fig. 4 show the changes in isometric muscle strength of elbow flexion and extension

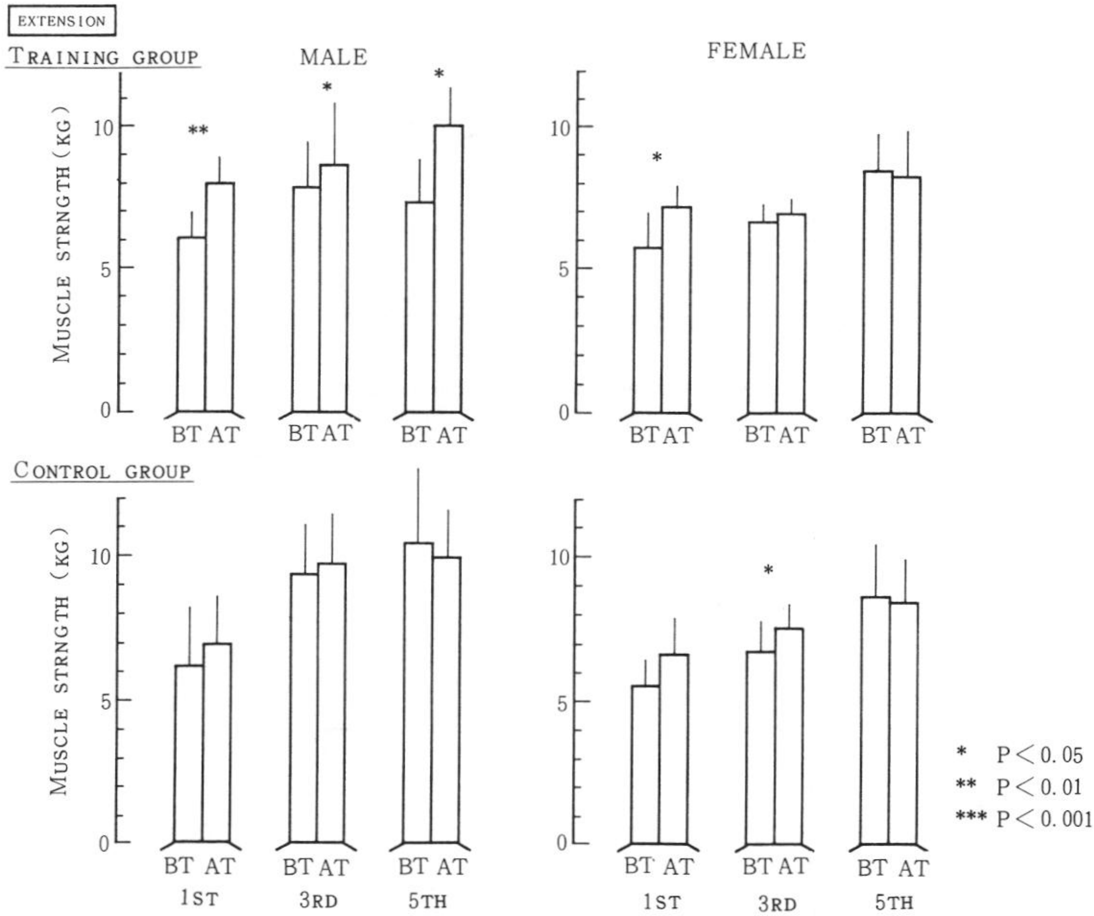

Fig. 4. Maximum isometric strength of elbow extension before (BT) and after (AT) strength training.

with the training, respectively. The mean increases in muscle strength of flexion and extension were respectively 0.3kg (5.7%) and 1.17kg (17.5%) for training group and -0.25kg (-1.0%) and 0.3kg (5.7%) for control group. The strength of extension increased more than that of flexion. The increase in strength of extension were statistically significant in subgroups of 1M (30.6%, $p<0.01$), 1F (23.0%, $p<0.05$), 3M (10.5%, $p<0.05$) and 5M (37.1%, $p<0.05$). These three subgroups also exhibited the significant increase in muscle area of extensor except a subgroup of 1M.

Significant correlations were observed between cross-sectional areas and strengths of extensor and flexor muscles both before and after trainings (Fig. 5). Muscle strength per cross-sectional area did not change through training. However, only 5M indicated a significant increase in strength of extension per unit muscle area from 4.4±0.8 kg/cm^2 to 5.3±0.5 kg/cm^2 (22.5% increase, $p<0.01$).

Isokinetic strength did not increase with the training except for the strengths of extension at 60 degrees per sec ($p<0.001$) and at 180 degrees per sec ($p<0.05$) in 1F.

Discussion

Fig. 5 is the summary of the results of this study in comparison with the Fukunaga's data[5)]

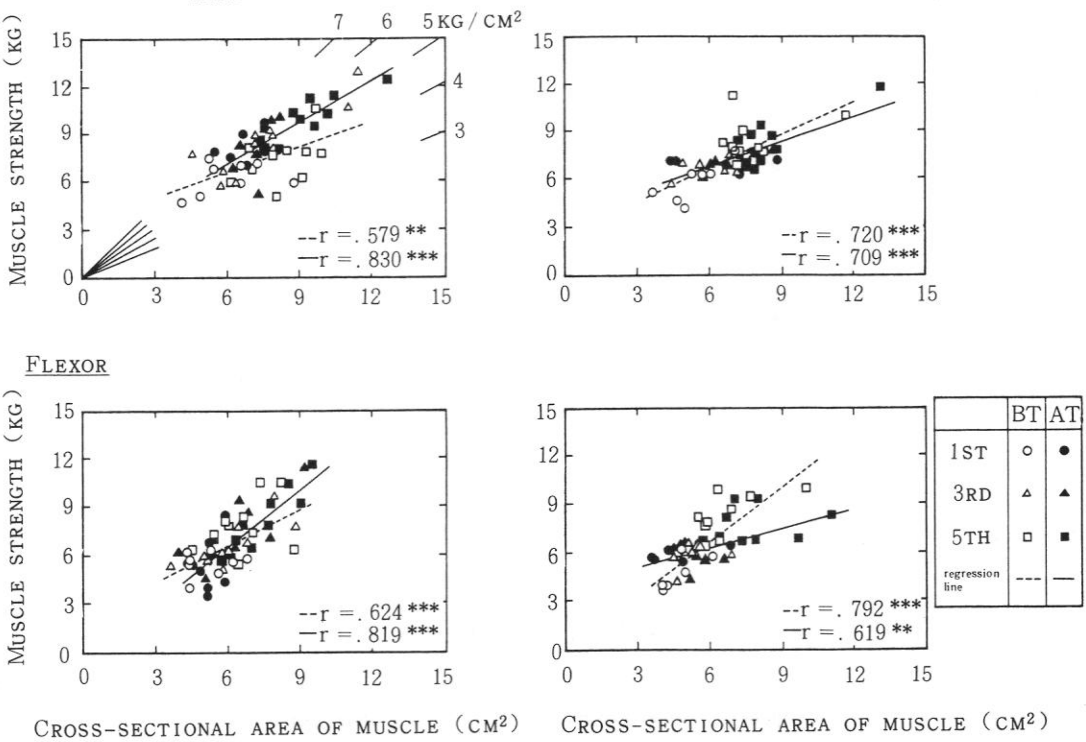

Fig. 5. Relationships between cross-sectional area of muscle and muscle strength for extensor and flexor. BT: before training and AT: after training. (**:p<0.01, ***:p<0.001)

obtained in 13-years old students and adults under the same training program as used in this study.

In this study maximum increased ratio in isometric strength through training was 37.1% for the subgroup of fifth-grade boys (11.0 ± 0.3 years old) and this value almost equaled to 60% and 40% of the value obtained in 13-year old boys and adults, respectively. Vrijens, J.[12] reported no consistent strength gains in prepubescents due to weight training. On the other hand, Pfeiffer, R.D. et al.[9] reported 17.7% increases in isokinetic strength of elbow flexion at the speed of 120 degrees per sec through various weight training on prepubescent males aged of 10.26±1.17 years old. This study could not demonstrate the improvement in isokinetic strength through training. The difference between Pfeiffer's results and ours may be due to the difference in the type of strength training. Pfeiffer used the dynamic muscle contraction such as weight training, while subjects in this study were trained through sustained isometric contraction.

The mean increase in muscle area with training in this training was about 160% of the value obtained from 13-year old males and about 50% of that from adults (Fig. 5). Increase in muscle area in this study suggests that even in prepubescent boys and girls, muscle hypertrophy may be caused by strength training as indicated in adults[5].

Skeletal age is used to assess the development of physiological maturity[11]. Significant correlation between skeletal age and the increase in muscle area suggests that physiological age must be one of the limiting factor to derive the muscle hypertrophy through strength training in prepubescent boys and

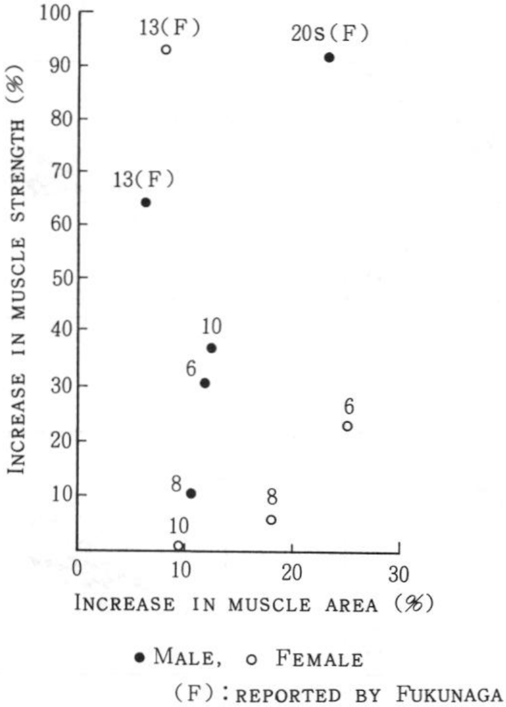

Fig. 6. Relative values of increase in muscle area and muscle strength with strength training. Numbers above symbol indicate the chronological age of the subjects. (F) indicates the value reported by Fukunaga, T. in 1978[5].

girls.

In this study, area of extensor muscle group also increased in spite of intending to produce hypertrophy in elbow flexor muscles. This implies that, during isometric elbow flexion, extensor muscle group was activated to a great extent. The reason for this would be explained from following two points; one is the co-contraction of agonist and antagonist muscles due to the undevelopment in reciprocal innervation in the prepubescent age, and the other is an anatomical problem, i.e., muscle of Caput longum of triceps brachii is a two-joint muscle and, therefore, this muscle has a function to adduct the upper arm in such a case of this training method as shown in Photo. 1.

Muscle strength per cross-sectional area did not increase with training except a subgroup of 5M. This finding does not agree with the result in adult males (Fukunaga[5]). Fournier, M. et al.[4] reported that in 16-year old adolescent boys, low phosphofructokinase activity and the failure of the FTb fibers to hypertrophy with sprint training differed from the findings in adults. It is considered that the unchanged muscle strength per cross-sectional area in prepubescent children would be attributed to the different effects of training on glycolytic enzyme activities, FT fiber area, and motor unit activity[7),8)] from those of adults.

It is concluded that the effects of strength training on cross-sectional muscle area and muscle strength for prepubescents were similar in its direction to but different in its magnitude from those found in adults.

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References

(1) Duda, M. Prepubescent strength training gains support. The Physician and Sports Medicine. 14(2), 157 161, 1986.

(2) Ekbolm, B. Effect of physical training in adolescent boys. J. Appl. Physiol. 27(3), 350–355, 1969.

(3) Eriksson, B.O., P.D. Gollnick, and B. Saltin. Muscle metabolism and enzyme activities after training in boys 11–13 years old. Acta Physiol. Scand. 87, 485–497, 1973.

(4) Fournier, M., J. Ricci, A.W. Taylor, R.J. Ferguson, R.R. Montpetit, and B.R. Chaitman. Skeletal muscle adaptation in adolescent boys: sprint and endurance training and detraining. Med. Sci. Sports Exercise, 14(6), 453–456, 1982.

(5) 福永哲夫. ヒトの絶対筋力 — 超音波による体肢組成・筋力の分析—. 杏林書院, 1978.

(6) Ikai, M. and T. Fukunaga. Calculation of muscle strength per cross-sectional area of human muscle by means of ultrasonic measurement. Int. Z. Angew. Physiol. 26, 26–32, 1968.

(7) Komi, P.V. Training of muscle strength and power: Interaction of neuromotoric, hypertrophic, and mechanical factors. Int. J. Sports Med. Supplement, 7, 10–15, 1986.

(8) Milner-Brown, H.S., R.B. Stein, and R.G. Lee. Syncronyzation of human motor units: possible roles of exercise and supraspinal reflexes. Electroencephalogr. Cli. Neurophysiol. 38, 245–254, 1975.

(9) Pfeiffer, R.D., and R.S. Francis. Effects of strength training on muscle development in prepubescent, pubescent, and postpubescent males. The Physician and Sports Medicine. 14(9), 134–143, 1986.

(10) Rowe, R.W. The effect of hypertrophy on the properties of skeletal muscle. Comp. Biochem. Physiol. 28, 1449–1453, 1969.

(11) Tanner, J.M., R.H. Whitehouse, W.A. Marshall, M.J.R. Healy, and H. Goldstein. Assessment of skeletal maturity and prediction of adult height (Tw2 Method), Academic Press, 1975.

(12) Vrijens, J. Muscle strength development in the pre- and postpubescent age. Med. Sport. 11, 152–158, 1978.