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A Study on Training Effect on Strength Per Unit Cross-Sectional Area of Muscle by Means of Ultrasonic Measurement

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Summary. The training effect on the human arm flexor was studied by subjecting 5 healthy males. The training was made by isometric maximum contraction, 3 times (10 seconds/bout) a day, every day except Sunday for 100 days. Ultrasonic photography was employed to estimate the cross-sectional area of the muscle.

1. The muscle training of 100 days increased the maximum strength by 91.7% and the cross-sectional area of muscle by 23.0%.

2. The average values of strength per unit cross-sectional area of muscle increased from 6.3 to 10.0 kg/cm² after 100th day of training at extended position of arm, from 4.7 to 7.5 kg/cm² at flexed position of arm.

3. The increase of maximum strength was associated with the increase in cross-sectional area and the increase in strength per unit cross-sectional area.

Key-Words: Training — Muscle Strength — Cross Section.

As was mentioned by several authors, the strength must be closely related to the cross-sectional area of the muscle. On the other hand, the values of strength per unit area calculated by these authors are distributed in a wide range: 11.1 kg/cm² (Franke, 1920), 9.15 kg/cm² (Morris, 1948) and 4 kg/cm² (Hettinger, 1961) in the elbow flexors; 6.24 kg/cm² (Hermann, 1898) and 3.9 kg/cm² (Haxton, 1944) in the ankle plantar flexors. Most authors had applied the results obtained in the muscle of cadavers to the muscles of living subject for these calculation.

In the previous study by the present authors, a new method was introduced by using ultrasonic measurement. The result confirmed by the preceding study was as follows: 1. The arm strength was fairly proportional to the cross-sectional area of muscle, regardless of age and sex. 2. The strength per unit cross-sectional area of the arm flexor was 6.3 kg/cm² in the average with the standard deviation of 0.81 kg/cm², when calculated at extended position of the arm. The strength per unit area was 4.7 kg/cm² when calculated at the flexed position of the arm. 3. As to the individual variation, the strength per unit area was distributed in a range from 4 kg/cm^2 to 9 kg/cm^2, when calculated at extended position of the arm.

The problem is why individual variation of the strength per unit cross-sectional area is distributed in such a wide range as from 4 to 9 kg/cm^2 in human subjects. The authors conducted this study to find out the changes in the strength per unit cross-sectional area of the muscle by muscle training.

Method and Procedure

The ultrasonic photography was used for measurement of cross-sectional area of the arm flexor muscle at the extended position of the elbow before and after the regular training. The method was the same as that described in the previous paper (1968).

The cross-sectional area of the arm was photographed by using an ultrasonic apparatus (Fig. 1), with which 2 different frequencies (5 and 10 MC) were applied to ascertain the boundaries among the tissues such as muscle, bone and subcutaneous fat. As shown in Fig. 2, the 2 traced pictures for the pre- and post-training were overlapped to measure the difference in their cross-sectional areas of the flexor (A) and the extensor (B).

An arm dynamometer was used for measurement and training of the flexor muscle strength. In sitting position, the isometric strength was measured with maximal effort at right angle of the elbow joint. A belt, 45 mm wide was fixed

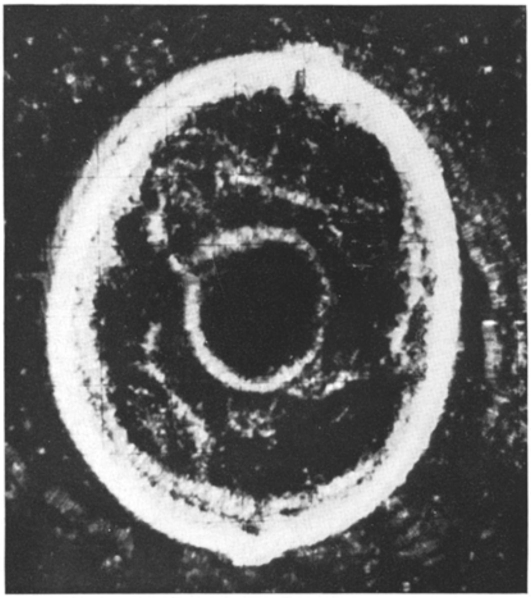

Fig. 1. Ultrasonic photograph of the right upper arm before the training

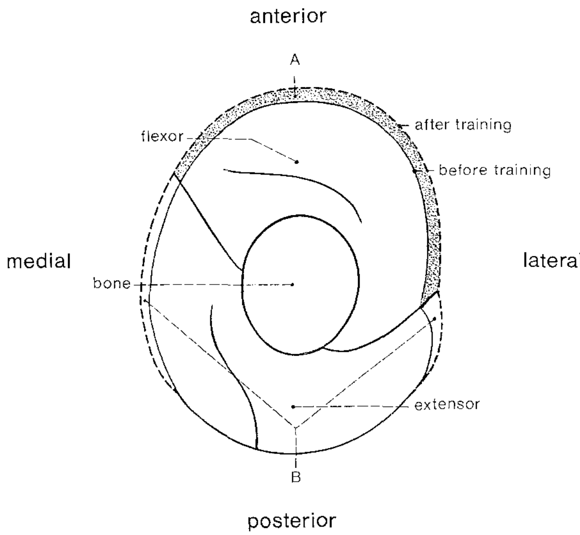

Fig. 2. Overlapped picture of the two traced pictures before and after training. ——— before training, - - - after training. *A:* difference in the cross-sectional area of flexor between before and after training (dotted space). *B:* difference in the cross-sectional area of extensor between before and after training

on the wrist at the supinated position. The bottom end of the belt and a straingauge tensiometer were combined with a chain. The highest value in three trials was adopted as the maximum strength of each individual.

To calculate the maximum strength in the flexor, including m. biceps brachii and brachialis, the following formula was used: $A = 4.90 X M$ where "A" is maximum strength in the flexor, "M" is the measured strength and 4.90 is a constant due to the lever ratio of "resistance arm" against "force arm". X-ray photographs were taken in 5 boys and 10 adult men to estimate the lever ratio. The distance between the arm and the X-ray tube was 2 meters. Based on these measurements, the strength per unit cross-sectional area of muscle was calculated.

Training Schedule

Six healthy male grasuate students, ranged from age 23 to 28, served as the subjects for this training, including one subject who dropped from the training after 60th day training. The muscle training for this experimental project was from July to December in 1968. The subject was asked to contract his right arm flexor maximally for 10 seconds and repeated 3 times with 1 minute intermissions, once a day except Sunday. The maximum strength and the cross-sectional area of the arm were measured after the 20th, 40th, 60th and 100th day of training.

Results

The results were presented in the Table. It was found that the strength was increased progressively on the trained arm flexor in all subjects. As shown in the Table and Fig. 3, the average increase of strength was about

Table. *Training effect on strength, size of muscle and strength per unit cross-sectional area*

Measures	Right Left	Before training	Training period (day)			Increase in per cent of before training		
			20th	40th	100th	20th	40th	100th
Cross-sectional area	R	19.4 ± 0.4	20.8 ± 1.2	21.9 ± 0.5	23.9 ± 0.6	108.2	112.3*	123.0***
of flexor (cm^2)	L	19.5 ± 0.7	18.6 ± 1.1	18.8 ± 0.9	20.4 ± 0.5	95.5	96.1	105.0
Maximum strength	R	126.0 ± 9.7	149.4 ± 14.6	184.6 ± 15.2	241.4 ± 21.2	118.4*	147.5**	191.7***
(kp)	L	126.1 ± 7.0	135.2 ± 11.7	140.6 ± 7.0	164.2 ± 9.0	107.1	112.5*	132.1*
Strength per unit	R	6.3 ± 0.4	7.1 ± 0.5	8.4 ± 0.8	10.0 ± 0.6	110.0	134.6*	159.3***
area (kp/cm^2)	L	6.4 ± 0.4	7.3 ± 0.6	7.5 ± 0.2	8.0 ± 0.4	113.9	118.9*	126.7*

Mean ± S.E. — N = 5. — * Significant level of $P < 0.05$. — ** Significant level of $P < 0.01$. — *** Significant level of $P < 0.001$.

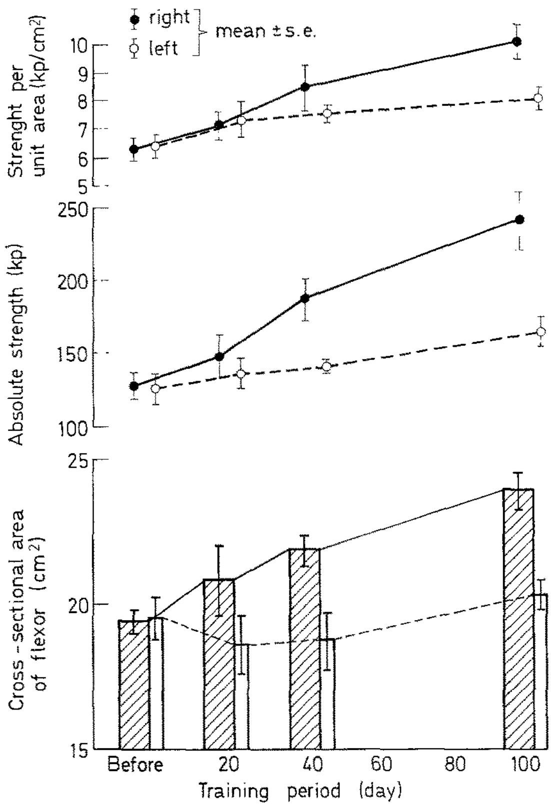

Fig. 3. Cross-sectional area (below), maximum strength (middle), and strength per unit cross-sectional area (above) of the trained right (———) and the untrained left arm flexor (– – –) during 100 days training period

90 per cent after the 100th day of training, which was statistically significant ($P < 0.001$). On the untrained left arm flexor, the average increase was about 30 per cent ($P < 0.05$). On the cross-sectional area of the trained right arm flexor, any significant increase was not found at the 20th day of training. At the 40th day of training, however, an increase of 12.3 per cent was found ($P < 0.05$), and at the 100th day of training, a significant increase of 23.0 per cent was found ($P < 0.001$). On the untrained left arm, no increase was found throughout this training period. As the result, the strength per unit cross-sectional area increased on the trained arm in every subject as shown in Fig. 4. The average values increased from 6.3 to 10.0 kg/cm^2 after 100th day of training ($P < 0.001$). The cross-sectional area for the arm flexed was calculated from the measured girth of upper arm. For this calculation it was assumed that the cross-sectional area of all the other tissues except

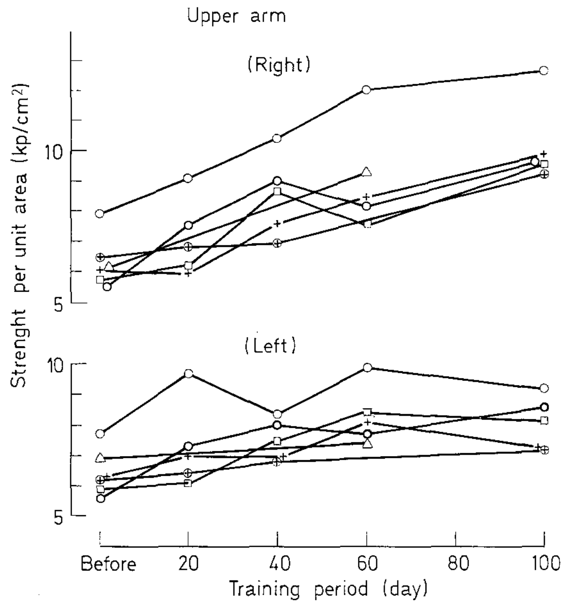

Fig. 4. Strength per unit cross-sectional area of the trained right (above) and untrained left arm flexor (below) in each individual during 100 days training period

flexor muscle might be constant in the arm flexed of extended and thus, the change in the area by flexing arm is only due to shifting in the flexor muscle mass. The percentage for the tissues except the flexor muscle was estimated on the ultrasonic photograph taken in the arm extended. The strength per unit area of the arm flexed was calculated as 4.7 kg/cm^2 before training, and 7.5 kg/cm^2 after the 100th day of training.

Discussion

The cross-sectional area of muscle can be estimated in two different conditions for the muscle with and without contraction. As above mentioned, several authors computed the cross-sectional area of the arm from the girth without muscle contraction. Morris (1948) calculated the cross-sectional area of upper arm by excluding subcutaneous fat from the data of upper arm girth at the largest part, depth, width and four fat measurements (dorsal, ventral, medial, lateral) in the arm extended. The approximate area of flexor muscle used in the strength test was used to be estimated from the cross-sectional area of upper arm except subcutaneous fat based on the percentage of the flexor muscle in the upper arm of cadavers. Franke (1920) calculated the cross-sectional area of flexor muscle of upper arm at extended position by the following formula:

$$\text{Cross-sectional area of the flexor} = (\text{Girth of upper arm in living subject})^2 \times \frac{\text{Cross-sectional area of flexor in cadaver}}{(\text{Girth of upper arm in cadaver})^2}$$

It is necessary to know the lever ratio of elbow flexor in order to get the strength in the muscle. Wilkie (1950) measured the origines and insertions for the 5 flexors of the upper arm, i.e., pronator teres, extensor carpi radialis longus, brachialis, biceps brachii and brachioradialis in living human subjects by X-ray photograph. He estimated the lever ratio on the elbow joint axis to be 5.5 in biceps brachii. The lever ratio (4.9) in the present study was derived from the measurements of the distance between the elbow joint axis and the insertions of biceps brachii and brachialis. Franke (1920) used the lever ratio of biceps brachii and brachialis as the main muscles of elbow flexion to calculate the strength per unit cross-sectional area of elbow flexor. In the present study, the lever ratio of elbow flexor was measured on biceps brachii and brachialis, and the other muscles, such as pronator teres, extensor carpi radialis longus, and brachioradialis were neglected in the calculation of the lever ratio, because of difficulty to differentiate in the picture.

Considering these factors, it becomes clear that a regular isometric training resulted in a significant increase in the strength per unit cross-sectional area of the trained arm flexor. It was concluded that the scheduled training, extending for 100 days, was effective to increase in the maximum strength as well as in the size of muscle bundle.

Therefore it may be concluded that two factors primarily contribute to the development of muscle strength by voluntary effort; one is the increase in cross-sectional area of the muscle bundle, another is the increase in nerve discharge to the acting muscles. Of these two contributing factors, it must be more easy to increase the nervous discharge than the increase in the cross-sectional area of muscle. This idea is based on an experimental works by Ikai and Steinhaus (1961) and Ikai *et al.* (1967).

They found that the maximum strength increased as much as about 30 per cent over the ordinary maximum level under the conditions of "Shout" by himself or a suggestion in a hypnotic state. In addition to this result, an experimental work (Ikai *et al.*, 1967) by electrical stimulation over the ulnar nerve through the skin near the elbow joint revealed that the maximum strength of the thumb adductor was increased by 30 per cent over the ordinary voluntary maximum level of strength. This experiment by electrical stimulation supports the results obtained by the preceding work using "Shout" or hypnosis. Putting these studies into consideration, it could be likely that the strength per unit area shifted toward a considerably higher level, even if without any increase of cross-sectional area of muscle.

As to the strength increase (about 30%) in the untrained left flexor, it may be attributed to the irradiation of nervous impulse to the contralateral limbs (Hellebrandt, 1947).

This evidence would give some informations on evaluation of training effect of muscular strength with respect to the contributing factors of the muscle tissue and the central nervous system.

References

Fick, R.: Handbuch der Anatomie und Mechanik der Gelenke unter Berücksichtigung der bewegenden Muskeln. Jena: Fischer 1910.

Franke, F.: Die Kraftkurve Muskeln bei willkürlicher Innervation und die Frage der absoluten Muskelkraft. Pflügers Arch. ges. Physiol. **184**, 300—322 (1920).

Hellebrandt, F. A., Parrish, A. M., Houtz, S. J.: Cross education. The influence of unilateral exercise on the contralateral limb. Arch. phys. Med. **28**, 76—85 (1947).

Hermann, L.: Zur Messung der Muskelkraft am Menschen. Pflügers Arch. ges. Physiol. **73**, 429—437 (1898).

Hettinger, Th.: Isometrisches Muskeltraining. Stuttgart: Thieme 1968.

— Physiology of Strength. Springfield (Ill.): Thomas 1961.

Ikai, M., Fukunaga, T.: Calculation of muscle strength per unit cross-sectional area of human muscle by means of ultrasonic measurement. Int. Z. angew. Physiol. **26**, 26—32 (1968).

— Steinhaus, A. H.: Some factors modifying the expression of human strength. J. appl. Physiol. **10**, 157—163 (1961).

— Yabe, K., Ischii, K.: Muskelkraft und muskuläre Ermüdung bei willkürlicher Anpassung und elektrischer Reizung des Muskels. Sportarzt und Sportmedizin. Heft **5**, 197—211 (1967).

Morris, C. B.: The measurement of the strength of muscle relative to the cross-section. Res. Quart. Amer. Ass. Hlth phys. Educ. **19**, 295—303 (1948).

Wilkie, D. R.: The relation between force and velocity in human muscle. J. Physiol. (Lond.) **110**, 249—280 (1950).

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