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Effect of Isometric Strength Training on Mechanical, Electrical, and Metabolic Aspects of Muscle Function*

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Summary. Monozygous twin pairs (two female and four male) were used in a strength training study so that one member of each pair served as training subject (TS) and the other members as nonexercising controls (CS). TS trained four times a week for 12 weeks with maximal isometric knee extensions of the right leg. The parameters studied included muscle strength, endurance time, electromyographic activity, and activities of several key enzymes in nonoxidative and oxidative muscle metabolism. The results disclosed that in addition to a 20% increase in isometric knee extension strength in the trained leg of TS, an average increase of 11% was observed in strength of TS untrained leg. CS did not demonstrate any change in muscle strength. Training also included an improvement in the maintenance of a static load of 60% of the pretraining maximum. Increase in the maximum integrated electromyographic activity (IEMG) of the rectus femoris muscle occurred concomitantly with the knee extension strength. Training also caused reduction in the IEMG/tension ratio at submaximal loads indicating a more economical usage of the rectus femoris muscle. Muscle biopsies taken from the vastus lateralis muscle showed that the enzyme activities of MDH, SDH, and HK were higher, and LDH and CPK lower in the trained leg as compared to the nontrained control leg of TS or to the values of the untrained member of the twin pair. It is concluded that isometric strength training as used in the present study can cause increased recruitment of the available motor unit pool, improved efficiency at submaximal loads, and surprisingly also enchancement of the oxidative metabolism in the muscle.

Key words: Strength training – Electromyography – Twins – Enzyme activities – Fatigue.

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Despite the relative ease of demonstrating an increase of muscle tension through different kinds of strength training methods, the exact nature of the mechanisms leading to such strength increases is as yet unknown. Recent studies with electromyographic (e.g., Komi and Buskirk, 1972) and muscle biopsy techniques (e.g., Thorstensson, 1976) have attempted to obtain additional information about the possible sites to which the gain in muscle strength can be attributed.

Monozygous twins which possess similar genetic traits have been utilized both in strength (Meller et al., 1970) and endurance (Klissouras and Weber, 1972) training such that one member of the twin pair was used as an experimental subject and the other member served as control or was subjected to another kind of experimental treatment.

This study was therefore designed to investigate, with this kind of twin-study method the effects of a 12-week isometric strength training program on several measurable parameters, such as muscle tension, anthropometry, electromyographic activity, and activities of skeletal muscle enzymes. It was thought that utilization of identical twins as subjects would strengthen the control over the experimental design. Additional support for this was obtained from information that monozygous twins have identical muscle fiber composition (Komi et al., 1977).

Methods

Subjects

The subjects for the study were two female and four male monozygous twin pairs ranging in age from 13–15 years. Their physical characteristics are described in Table 1. The determination of zygosity was made through serological analysis (Komi et al., 1973). Subjects for the experimental group were selected randomly from each twin pair. In none of the functional parameters tested did the experimental and control groups differ significantly from each other.

Training and Testing

The subjects were first familiarized with the testing procedure on two occasions before the beginning of training. After two pretests the experimental group trained four times a week during a training period of 12 weeks. In testing and training situations the subject was seated on a dynamometer with knee and hip angles of 240 and 130 degrees respectively. The isometric knee extension was monitored with strain gauges installed on a steel wire connected to a cuff, which was fastened around the subject's ankle. The dynamometer has been described in detail previously (Viitasalo and Komi, 1975; Komi and Viitasalo, 1976).

Each test began with measurements of the right thigh girth. This was done with a tape applied around the relaxed muscles with the subject in a sitting position.

In the two pre- and posttests and on the fourth day of every training week the subjects were first instructed to exert three maximum isometric contractions of the quadriceps muscle group. The rest periods between contractions were 3 min. After 5 min of recovery the subject exerted the following submaximal contractions: 20%, 40%, 60%, and 80%. The recovery period between submaximal contractions was 2 min and each contraction was maintained at a steady level for 5–10 s. After a 10-min rest from the last submaximal contraction the subject was instructed to maintain a 60% isometric load as long as possible (fatigue test). The subject saw the required force level from a voltmeter placed in front of the dynamometer table.

Table 1. Physical characteristics of subjects before and after 12-week muscle conditioning program

Twin pairs	Age (years)	Height (cm)					
		Experimental			Control		
		before	after	Δ	before	after	Δ
1 ♂	15	164.7	166.9	2.2	163.8	166.0	2.2
2 ♂	14	149.1	152.4	3.3	150.1	152.0	1.9
3 ♀	13	148.8	150.7	1.9	151.0	153.0	2.0
4 ♀	13	156.8	157.7	0.9	158.4	160.2	1.8
5 ♂	15	182.2	184.3	2.1	181.1	183.5	2.4
6 ♂	14	174.0	177.0	3.0	172.5	176.0	3.5
Mean	14	162.6	164.8	2.2[a]	162.8	165.1	2.3[b]
± S.D.	0.9	13.6	13.7	0.9	11.2	12.7	0.6

Twin pairs	Age (years)	Weight (kg)					
		Experimental			Control		
		before	after	Δ	before	after	Δ
1 ♂	15	46.7	49.5	2.8	47.7	49.5	1.8
2 ♂	14	37.4	39.3	1.9	35.8	36.5	0.7
3 ♀	13	44.5	46.6	2.1	45.0	46.0	1.0
4 ♀	13	44.1	43.0	− 1.1	45.7	46.0	0.3
5 ♂	15	62.7	63.0	0.3	61.8	62.0	0.2
6 ♂	14	65.2	65.5	0.3	65.5	67.3	1.8
Mean	14	50.1	51.2	1.1	50.3	51.2	1.0
± S.D.	0.9	11.2	10.7	1.5	11.2	11.4	0.7

Twin pairs	Age (years)	Thigh girth (cm)					
		Experimental			Control		
		before	after	Δ	before	after	Δ
1 ♂	15	41.7	41.8	0.1	41.8	41.3	− 0.5
2 ♂	14	43.0	43.5	0.5	41.5	42.5	1.0
3 ♀	13	47.8	47.8	0.0	47.5	48.0	0.5
4 ♀	13	40.3	41.1	0.8	41.0	41.2	0.2
5 ♂	15	43.0	45.5	2.5	43.5	45.9	2.4
6 ♂	14	51.4	51.9	0.5	51.5	50.4	− 1.1
Mean	14	44.5	45.3	0.7	44.5	44.9	0.4
± S.D.	0.9	4.2	4.1	0.9	4.2	3.8	1.2

[a] $p < 0.01$
[b] $p < 0.001$

Training was performed in the same position and with the same apparatus as all the isometric tests. During the first week it consisted of five maximal isometric contractions, each of lasting 3–5 s. The rest period between the contractions was 30 s. After the first 2 weeks of training the number of contractions was increased by one every second week.

The control group and the control legs (left) of the experimental group were tested before and after the training period with the same program as described above.

EMG Recording and its Processing

EMG activity was picked up bipolarly (interelectrode distance 10 mm) using Beckmann miniature skin electrodes (4 mm). The electrode pair was placed over the motor point area of M. rectus femoris, this position being determined with a Neuroton 626 stimulator. The reference electrode was placed on the lateral side of the thigh. To ensure the same location of electrodes in each test day, the electrode site was marked on the skin by a drop of 20% $AgNO_3$ solution (see Komi and Buskirk, 1970).

EMG signals were amplified with a Tektronix RM 122 low-level preamplifier (60 dB; spectrum range 0.8 Hz to 10 kHz) and subsequently stored together with the force signal in analog form on magnetic tape (Philips Analog-7). The digitization of the analog signals – EMG and force – was performed with a final sampling frequency of 1600 Hz. After this conversion the subsequent analysis was performed from three records of 625 ms duration.

The EMG parameters after the processing phase were as follows: 1. Integral, IEMG (mV), 2. Power spectral density function, PSDF, and 3. Average motor unit potential, AMUP. IEMG was time-averaged for a 1 s period. The methods given by Bendat and Piersol (1971) were used to compute PSDF. The frequency of the mean power (MPF) was calculated according to the formula given by Kwatny et al. (1970). PSDF were further treated so that the relative (per cent) portion of selected bandwidths (24–56 Hz, 64–96 Hz, 104–136 Hz, and 144–800 Hz) were obtained from the total power density area. Computation of AMUP was based on the method of Lang et al. (1972). AMUP was further analyzed for its peak-to-peak amplitude and rise time (Viitasalo and Komi, 1975; Komi and Viitasalo, 1976).

Muscle Samples and Enzyme Assays

At the end of the training period muscle samples were taken from two pairs of twins by needle biopsy technique (Bergström, 1962). From both members of the twin pair No. 5 (boys) and the trained member of pair No. 3 (girls) the samples were obtained from the vastus lateralis muscle (MVL) of both thighs, and from the control member of pair No. 3 only from the left MVL. After weighing, a piece of the sample (approx. 8–10 mg) was immediately homogenized manually in an all-glass Potter-Elvehjem homogenizer in ice-cold buffer (1 M Tris-HCl, pH 7.5). An aliquot of the homogenate was centrifuged for 10 min at 1000 × *g* and the supernatant was used for the determination of malic dehydrogenase (MDH), hexokinase (HK), lactate dehydrogenase (LDH), and creatine kinase (CPK) activities. Succinate dehydrogenase (SDH) activity was assayed from the original homogenate. MDH was assayed according to Ochoa (1955), HK according to Silberberg (1970), LDH according to Kornberg (1955), SDH according to Pennington (1961) and CPK using TC 15926 Test kit of Biochimica Boehringer (Mannheim, Germany). Enzymatic activities at 21–22° C or 37° C (SDH) were referred per supernatant (MDH, HK, LDH and CPK) or homogenate (SDH) protein, which was determined according to Lowry et al. (1951).

Statistical Analysis

Ordinary statistical methods including means and their standard deviations (or standard errors) were calculated for each parameter. The training influence on selected parameters was tested using analysis of variance.

Results

Anthropometric Measurements

During the 12-week experimental period the twin pairs gained in height, on average, by 2.2 cm (exercise group, $p < 0.01$) and by 2.3 cm (control group, $p < 0.001$). Both groups also gained in weight by 1.1 and 1.0 kg, respectively. In the exercise group one subject decreased her weight by 1.1 kg (Table 1). Slight gains (n.s.) were also observed in the thigh girth measurements in the two groups.

Isometric Knee Extension Forces

The maximum isometric knee extension force increased in the exercise leg of the training group from 427 ± 106 N to 512 ± 130 N (Table 2). This corresponds to an average increase of 20% ($p < 0.01$). Figure 1 shows the development of this force increase during the course of the 12-week isometric training. The nonexercising control leg of the training group also demonstrated an increase ($p < 0.01$) of the maximum isometric knee extension strength from 396 ± 124 N to 437 ± 139 N (11%). The control group, however, showed no change in the force measurement between the pre- and posttests.

Table 2. Maximal isometric strength and IEMG before and after the training period

Variable		Experimental group			Control group			Control group		
		before	after	Δ_1	before	after	Δ_2	before	after	Δ_3
Max strength	M	427	512	85[b]	396	437	42[b]	448	441	− 7
(N)	S.D.	106	130	51	124	139	20	137	79	66
IEMG	M	501.7	691.4	189.7[a]	532.7	529.5	3.1	460.6	476.0	15.4
(μV)	S.D.	200.0	311.0	173.2	271.8	232.0	136.9	154.5	203.0	114.0

[a] $p < 0.05$
[b] $p < 0.01$

Table 3. Maximal isometric endurance time of the trained subjects at $0.6 \times P_0$ force level. P_0 is the maximal isometric force before the training

Subject	Fatigue time (s)		
	before	after	Δ
1	65	103	38
2	115	89	− 26
3	85	113	28
4	79	108	29
5	100	181	81
6	80	83	3
M	87.3	112.8	25.5
S.D.	17.6	35.3	35.8

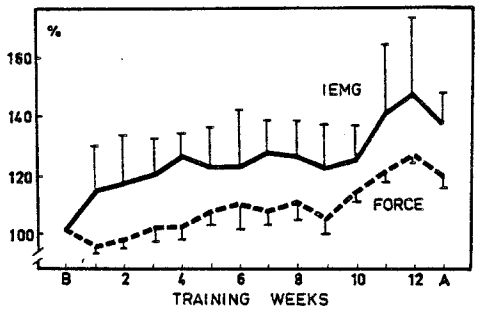

Fig. 1. Development of integrated EMG activity of M. rectus femoris and maximal isometric knee extension force during the course of 12 weeks' isometric strength training. The curves represent mean (± S.E.) values

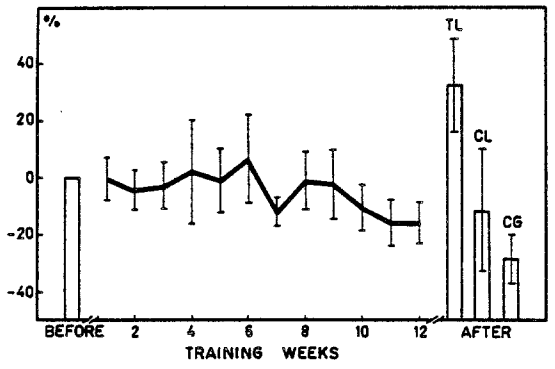

Fig. 2. Percentage (± S.E.) changes of endurance times from the pretraining value during the 12 weeks' training period. The endurance time of the continuous line was measured at 60% force level of each training week. The bars on the right denote relative changes of endurance times, measured at 60% of the pretraining maximum, for the trained leg (TL), control leg (CL) and control group (CG)

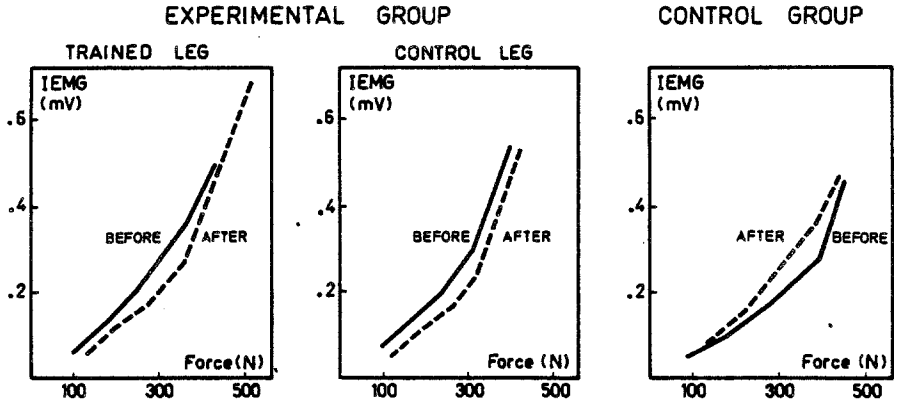

Fig. 3. Relationship between IEMG and muscle tension before and after the 12 weeks' training period for trained and control leg of the experimental group and for the control group

Endurance Time

When the maintenance of 60% isometric tension was measured at the end of each training week, the measured endurance time showed no change during the course of training. However, when the endurance time measured at 60% of the pretraining maximum force was compared between before and after training tests, it showed a

clear increase in all but one exercising subject (Table 3, Fig. 2). The average change was from 87–113 s, indicating an increase of 29%.

Electromyographic Measurements

The 12-week isometric strength training caused an increase in maximum IEMG of the rectus femoris muscle from 502 ± 200 to 691 ± 311 μV (increase of 38%, p

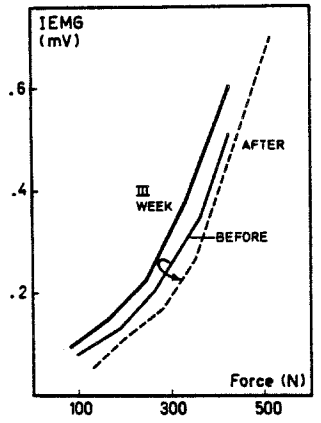

Fig. 4. Relationship between IEMG and isometric knee extension force for the trained leg before, during the third week and after the 12 weeks' training period. The curves represent average values for the training subjects

Table 4. Power spectral density function and average motor unit potential variables at maximal force level before and after the training

Variable		Experimental group			Control group		
		before	after	Δ_1	before	after	Δ_2
PSDF							
MPF (Hz)	M	86.4	81.9	− 4.5	82.3	96.9	14.6
	S.D.	16.8	8.1	13.5	5.0	20.7	24.1
24–56 Hz	M	34.9	25.8	− 9.1	35.3	22.8	− 12.5
(%)	S.D.	11.0	10.9	8.6	7.9	14.1	16.0
64–96 Hz	M	44.3	55.7	11.4	42.4	45.5	3.1
(%)	S.D.	4.7	7.0	9.8	17.3	9.2	8.2
104–136 Hz	M	12.4	12.4	0.0	12.9	16.3	3.4
(%)	S.D.	3.7	2.7	3.8	3.5	6.2	9.2
144–800 Hz	M	9.6	6.3	− 3.3	9.2	15.6	6.4
(%)	S.D.	6.7	3.1	5.9	2.5	11.1	12.1
AMUP							
Amplitude	M	440	400	− 40	400	360	− 40
(μv)	S.D.	130	130	140	130	140	120
No of spikes	M	39.4	35.4	− 4.0	40.1	40.1	0.0
	S.D.	2.0	5.1	4.3	0.7	1.5	1.2
Rise time	M	3.94	4.72	0.78[a]	4.00	3.52	− 0.48
(ms)	S.D.	0.67	0.24	0.62	0.50	1.15	1.47

[a] $P < 0.05$

< 0.05; see Table 2 and Fig. 1). Both in the control leg of the exercising subjects and in the control subjects the pre- and posttest values of IEMG were similar indicating no change during the experimental period.

The relationship between IEMG and muscle tension at the various tension levels of low submaximal to maximal are shown in Figure 3. When these data were analyzed, no significant training influence could be observed. In the training group, however, in five out of six subjects the IEMG/tension curve shifted to the right in the pre-posttest comparison. If this average curve is also drawn for the third week of training (Fig. 4), the mean IEMG values per unit of tension were slightly elevated. In this comparison one training subject behaved differently from the others, and the shift in the curve could not be proved statistically.

When the registered EMG signals were subjected to a more detailed analysis, it was observed that the power spectral density function (PSDF, see Table 4) showed

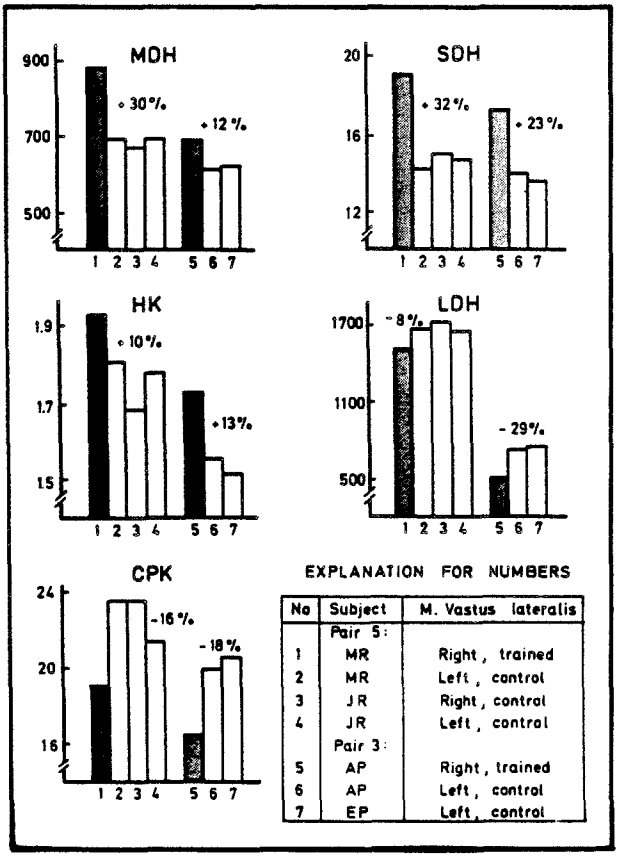

Fig. 5. Enzyme activities from M. vastus lateralis for the trained (dark bars) and control leg of the trained and untrained subjects of two twin pairs at the end of the training period. Activities are expressed for hexokinase (HK), lactate dehydrogenase (LDH), and malic dehydrogenase (MDH) as mmol substrate/min/mg protein at 21–22° C. Differing from this the unit for creatine kinase (CPK) is μmol/min/mg protein, and temperature for succinate dehydrogenase 37° C

no consistent change during the experiment in any of the frequency band-widths analyzed and for any of the groups studied. However, the average area of the frequency spectrum curve increased in the trained leg. The changes in the AMUP analysis were also minor: rise time of AMUP was the only variable to change significantly ($p < 0.05$) in the course of training.

Enzyme Activities

The results of enzyme activity assays performed from the post-experimental biopsy samples are given in Figure 5. In both pairs of subjects the activities of MDH, SDH and HK were higher in the trained leg as compared to the nontrained control leg or the values from the untrained member of the twin pair. In contrast to this the activities of LDH and CPK were lower in the trained leg.

Discussion

The present study was able to confirm that it is relatively easy to demonstrate the effect of strength training on increases in the strength performance of the trained muscle groups.

To clarify the additional information for the mechanism of increase of muscle strength there are certain results which are worth discussing in more detail. The increase in IEMG of the training group is contrary to earlier observations, e.g., Friedeboldt et al. (1957) and Thorstensson et al. (1976), who observed a trend toward reduction rather than increase in IEMG, when its value was compared before and after strength training. However, in the study of Friedeboldt et al. (1957) the early part of strength training period was associated with an apparent increase in EMG activity. In this connection the observed discrepancy with earlier studies may have several possible explanations: First, the subjects in the present study were youngsters under considerable influence of growth. This is demonstrated by the increases in anthropometric measurements such as weight and height. However, the control leg or the control subjects did not demonstrate any changes in IEMG during the experimental period. Secondly, and most likely, the increased maximal EMG activity must be attributed to the training effect per se. In this regard the training may have induced a reduction of inhibitory inputs to the active alpha-motor neurons, so that a greater inflow of activation would have reached the muscle site. The possible sites, if any, for reduced inhibition remain a matter of speculation.

The relationship between IEMG and tension changed in five experimental subjects during training. This is in agreement with earlier findings (Komi and Buskirk, 1972; Thorstensson et al., 1976) and it demonstrates a more economic usage of the rectus femoris muscle. In another feature, the results are also similar to those of Komi and Buskirk (1972) who observed that this relationship first changed in an opposite direction and then by the end of the training period demonstrated a clear reduction of EMG activity needed for a certain force production.

The improved muscle strength of the unexercised leg of the training subjects points out an interesting "cross-exercise" effect. Similar results have been obtained

in other investigations (e.g., Hellebrandt et al., 1947; Slater-Hammel, 1950) but some have reported no effect in cross-exercise training (e.g., Müller, 1957; Kruse and Matthews, 1958). Slight EMG activity has been reported in the contralateral muscles when either elbow flexor or quadriceps femoris muscles were contracting at several submaximal loads (Panin et al., 1961). Thus it is possible that under maximal contractions, such as used in the present study, the activation of the contralateral muscle group is strong enough to induce a slight increase of its isometric strength. This would then also explain a shift in the IEMG/tension curves of the contralateral leg in Figure 3.

Finally, the isometric strength training of 12 weeks duration caused an increase in the activities of enzymes MDH and SDH in the two biopsied subjects. This indicates enhancement of aerobic metabolism in their exercising muscle. Similar results have been obtained in animals, which were subjected to strength training exercises for several weeks (Roy et al., 1977). Thus it is likely that the training regimen of the present study which included maximal contractions with short intervals and full testing once a week with submaximal loads and fatigue loading, contained enough such exercises, which had a training effect on aerobic muscle metabolism.

In summary it can be stated that a 12-week isometric strength training program caused significant improvement not only in muscle strength but also in maximal integrated EMG activity. In addition, it caused the muscle to perform work more economically, which was demonstrated by a reduced need of EMG for production of a certain muscle tension. Furthermore, a slight cross-exercise effect was observed in the contralateral muscle. The exercising muscles also showed enhancement of aerobic metabolism due to strength training.

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