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THE EFFECT OF REPEATED MUSCULAR EXERTION ON MUSCLE STRENGTH

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In a series of experiments designed to determine the effect of different joint positions on the maximum isometric forces that can be exerted in pronation and supination of the hand, it was noted that, although twelve exertions were made at ½-min intervals twice a day for 15 days, there was no consistent increase in the force that could be developed (Darcus, 1951; Salter & Darcus, 1952). However, when these experiments were repeated with maximum isotonic contractions against a heavy load instead of isometric contractions, there was a progressive increase in the distance that the load could be raised, indicating an improvement in the performance of the muscles. Because of this apparent difference between the effects of repeated isometric and isotonic contractions, it was decided to test specifically the response of muscles to these two forms of activity.

Isometric activity has been considered more fatiguing than isotonic, the deterioration so produced masking any improvement in muscle strength that may have occurred. To eliminate this variable as far as possible, preliminary work was undertaken to determine the maximum rate at which maximum isometric contractions could be repeated without causing deterioration in applied muscle strength. It was also necessary to find the number of contractions that it was possible to make each day at this rate without producing adverse after-effects, such as muscle stiffness or pain, which would be likely to inhibit a maximum effort subsequently. From the results of this preliminary study, a daily training session of thirty maximum exertions at 1-min intervals was adopted, although longer sessions and shorter intervals could be tolerated by some subjects. The procedure was the same for maximum isotonic contractions. The training session was repeated on 5 or 6 consecutive days in each week. The pronator and the supinator groups of muscles were used.

Initially training was limited to 1 week, but as at the end of this time 'static' training gave no consistent results, whereas 'dynamic' training produced immediate and progressive improvement, it was decided to continue both methods for a longer period.

METHODS

The strain-gauge dynamometer (Darcus, 1951, 1953) was used for static training. The subject was required to make repeated maximum efforts to rotate the spindle of the dynamometer, the rotation being resisted by a spring steel bar traversing the spindle and fixed at either end. The dimensions of the bar were such that the maximum amount of movement allowed was about 1°, so that the muscular contraction was virtually isometric. For dynamic training the subject was required repeatedly to rotate the spindle (*S*) of the dynamometer as far as possible against a resistance provided by a known weight suspended from a pulley (*P*) attached to the spindle (Fig. 1). In this ins tance, the spring steel bar was free to rotate in the required direction, but

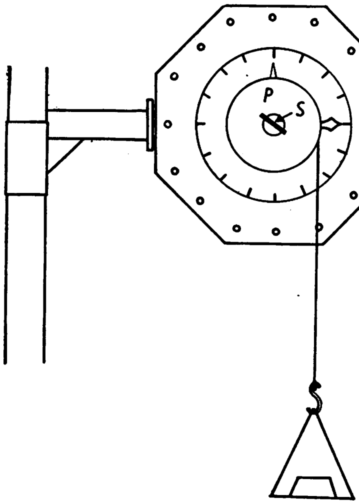

Fig. 1.

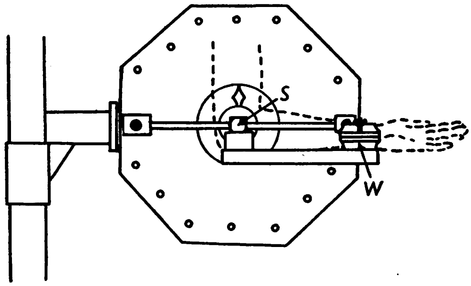

Fig. 2.

Fig. 1. Back view of the dynamometer, adapted for the measurement of isotonic work, showing the spindle (*S*) and pulley (*P*).

Fig. 2. Front view of the strain-gauge dynamometer, adapted for the measurement of the strength of isometric elbow flexion, showing the spindle (*S*) and wrist clamp (*W*).

movement in the reverse direction, due to the pull of the applied load, was prevented by allowing the bar to rest at either end on metal pegs. The load chosen was one which would allow a maximum initial rotation of the spindle of between 20 and 30°, so that even if the maximum effort did fall off a certain amount of movement could always be achieved. In this method of dynamic training there was a large but constant static component provided by the load before the applied muscle force reached a level sufficient to cause rotation of the spindle. The isometric force in static training was measured in kilogram-metres (kg.m) and the isotonic work in dynamic training in metre-kilograms (m.kg) (calculated from the load and the distance through which this was moved).

The muscle force in pronation and supination was applied through a handle fixed to the end of the spindle of the apparatus (Darcus, 1951). For flexion of the elbow, the handle was replaced by a bar attached at right angles to the spindle (*S*) (Fig. 2) (Darcus, 1953). The forearm rests on this bar, so that the axis of the elbow joint corresponds with that of the spindle, and is fixed to the bar by a clamp (*W*) over the proximal end of the radius and ulna.

The joint position chosen for static training and for the initial position for dynamic training was as near to that in which the greatest applied force could be developed as adjustment of the apparatus would allow. For pronation this was 60° towards full supination (+60°) and for supination 60° towards full pronation (−60°), the zero position being with the plane of the hand vertical and the palm facing medially (Darcus, 1951). The shoulder was adducted and the elbow flexed to a right angle. For flexion, the elbow was at a right angle with the shoulder adducted.

All experiments were conducted with the subject seated. The chair was adjusted so that the subject sat in a comfortable erect position with the thighs horizontal and the legs vertical, and the apparatus was adjusted so that the upper limb was in the required position. The heights of the chair and apparatus were recorded to assist in reproducing the relative position of the subject and the apparatus on successive occasions. During the training, one observer recorded the readings and a second observer watched the subject for gross changes of posture and for trick movements. The first observer gave the subject a 'stand by' warning 5 sec before instructing him to exert his maximum effort. It was found that approximately 4 sec was sufficient time for attaining the highest readings in a static exertion, and the same time was allowed for the build up of a maximum isotonic contraction.

As it is difficult to standardize and maintain a constant level of motivation, it was decided to reduce it to a minimum. Thus, although the subjects were told of the purpose of the experiment, they were not shown their results. However, in dynamic training, some assessment of progress may have been obtained from seeing the degree of rotation achieved; in static training no indication was available.

The effects of training were determined by making tests before and after each experiment, each consisting of ten maximum contractions at 1 min intervals, of isometric force and of isotonic work. It was shown in a control series that such tests at weekly intervals were not sufficient to produce a training effect. The significance of any difference between the tests was determined by the '*t*' test. In addition, correlation coefficients and equations for the regression lines were calculated for each training period. The percentage changes in strength resulting from training were obtained from the tests and where applicable from the regression lines.

Experimental procedures

Static and dynamic pronation training was carried out by two groups of six subjects for 5 or 6 days. All were trained on the right side, and one from each group on both sides. Six subjects, two from the 'static' group and four from the 'dynamic' group, continued training for 5 days a week until twenty to twenty-eight sessions had been completed. In addition to the tests described above, further tests were made on two subjects in each group who trained for the longer period. Before and after the experiment, three measurements were made at 1 min intervals of the maximum isometric pronation and supination force exerted in six different hand positions (−60°, −30°, 0, +30°, +60° and +90°) on the trained side. In the two subjects who were trained on one side only, isometric and isotonic strength tests were made of pronation and supination on the opposite side. In one subject, who completed thirty-three 'dynamic' training sessions, tests were made subsequently at fortnightly intervals for 1 year.

Supination of the hand was trained statically on the right side in two subjects and flexion of the elbow in two subjects. Three subjects carried out twenty-five training sessions during 5 weeks. After the sixth session, the other subject, who was training in supination, experienced pain in the region of the biceps tendon when making a maximum contraction. Nine more training sessions were made, but as the pain persisted and the readings were falling off, it was decided to give him a rest of 1 week. After this, the pain had disappeared and training was continued for a further five sessions.

Tests were made before and after training of the strength of isometric supination and flexion on both right and left sides in all four subjects.

RESULTS

The effect of static training on the maximum isometric force (Tables 1 and 2; Fig. 3). The shorter periods of training usually resulted in an increase in the maximum isometric force that could be exerted, but there was no consistent trend in the mean values over the 5 or 6 days. However, the longer periods always caused a significant improvement. The curves compiled for each subject indicated a progressive increase in the training effect, with the highest rate occurring in the second week. In no case was a plateau level reached.

TABLE 1. Results of short periods of static training

				From regression line		From test contractions		Dynamic test contractions	
Name	Movement trained	Side	No. of training sessions	Significance of r	% increase	Significance of t	% increase	Significance of t	% increase
P.D.	Pronation	R	5	*	—	0·02–0·01	+9·6	—	—
P.D.	Pronation	L	5	0·001	+15·8	0·05–0·02	−4·9	—	—
K.P.	Pronation	R	5	*	—	*	—	—	—
J.G.	Pronation	R	6	0·01–0·001	−12·5	0·01–0·001	+15·4	0·02–0·01	−24·0
M.W.	Pronation	R	6	0·001	+55·9	0·001	+14·0	*	—
M.B.	Pronation	R	5	0·01–0·001	+17·1	*	—	0·001	+63·6
D.K.	Pronation	R	6	0·001	+65·8	0·001	+39·6	—	—
J.B.	Supination	R	5	0·001	+20·5	0·001	+73·2	—	—
C.W.	Supination	R	5	0·001	+17·4	0·001	+32·5	—	—
A.L.	Flexion	R	5	*	—	0·001	+18·8	—	—
R.W.	Flexion	R	5	0·01–0·001	+6·6	0·001	+22·4	—	—

* not significant.

TABLE 2. Results of longer periods of static training

				From regression line		From test contractions		Dynamic test contractions	
Name	Movement trained	Side	No. of training sessions	Significance of r	% increase	Significance of t	% increase	Significance of t	% increase
P.D.	Pronation	R	28	0·001	+33·4	0·001	+45·6	0·001	−18·6
P.D.	Pronation	L	28	0·001	+21·9	0·001	+21·7	0·01–0·001	+10·9
K.P.	Pronation	R	28	0·001	+81·9	0·001	+35·0	0·001	+41·2
C.W.	Supination	R	25	0·02–0·01	+ 7·2	0·001	+18·4	—	—
J.B.	Supination	R	20	—	—	0·001	+30·4	—	—
A.L.	Flexion	R	25	0·001	+31·4	0·001	+36·1	—	—
R.W.	Flexion	R	25	0·001	+33·3	0·001	+42·2	—	—

The effect of dynamic training on the maximum isotonic work (Tables 3 and 4; Fig. 3). This method of training produced an immediate and progressive improvement in the maximum isotonic work that could be achieved, with the most rapid improvement during the first week. In the one subject who completed thirty-three training sessions, a plateau level was reached after the twenty-sixth. Following the total amount of training, the tests made at fortnightly intervals showed a decrease in muscle strength. The decrease was greatest in the first 6 weeks, but even after 1 year the readings were still more than double those taken before training.

The effect of static training on the maximum isotonic work and vice versa (Tables 1–4). The shorter periods of static training had a variable effect on the

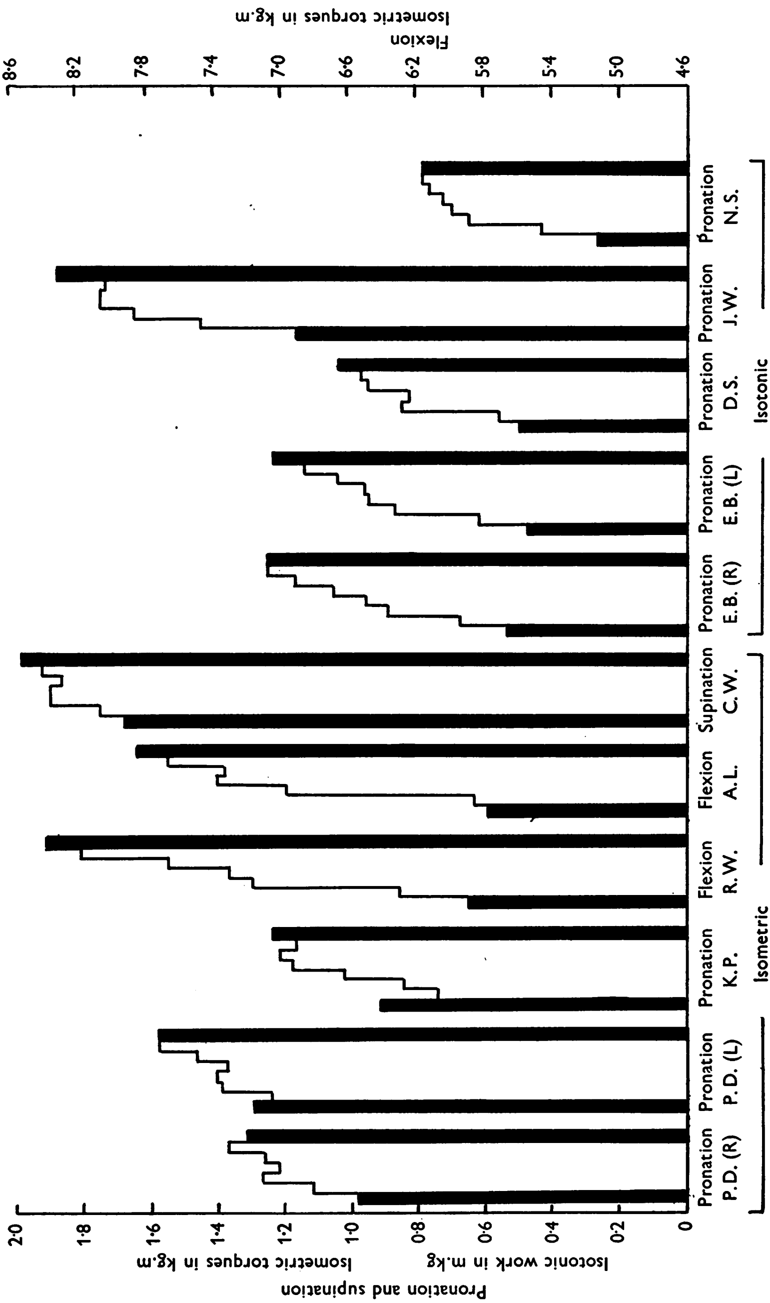

Fig. 3. Histograms to show muscle strength before, during and after twenty to twenty-eight training sessions. ■, test (mean of ten readings on one occasion). □, training (mean of all readings in each week, usually 5 × 30).

muscle strength measured isotonically. In the three subjects tested, one showed an increase, one no change and the other a decrease. In the latter case, there was also a decrease in the maximum isometric force. Two subjects were tested after the longer period of static training. In one there was an increase in the maximum isotonic work and in the other, trained on both sides, there was an increase on the left side and a decrease on the right side. It is considered that the latter result may be spurious, as the percentage improvement measured isometrically was of the same order on both sides.

Both the short and longer periods of dynamic training produced an improvement in the maximum isometric force. In every case the percentage increase was less than for the maximum isotonic work.

TABLE 3. Results of short periods of dynamic training

Name	Movement trained	Side	No. of training sessions	From regression line: Significance of r	From regression line: % increase	From test contractions: Significance of t	From test contractions: % increase	Static test contractions: Significance of t	Static test contractions: % increase
E.B.	Pronation	R	5	0·001	+36·4	0·001	+41·3	—	—
E.B.	Pronation	L	5	0·001	+51·3	0·05–0·02	+21·5	—	—
D.S.	Pronation	R	5	0·001	+144·7	0·001	+149·2	—	—
R.L.	Pronation	R	5	0·001	+97·5	0·001	+108·1	—	—
J.W.	Pronation	R	6	0·001	+44·2	0·001	+44·3	0·05–0·02	+4·5
L.P.	Pronation	R	6	0·001	+136·0	0·001	+150·0	0·001	+40·3
N.S.	Pronation	R	6	0·001	+150·9	0·001	+168·2	0·001	+34·3

TABLE 4. Results of longer periods of dynamic training

Name	Movement trained	Side	No. of training sessions	From regression line: Significance of r	From regression line: % increase	From test contractions: Significance of t	From test contractions: % increase	Static test contractions: Significance of t	Static test contractions: % increase
E.B.	Pronation	R	28	0·001	+99·4	0·001	+135·4	0·001	+59·8
E.B.	Pronation	L	28	0·001	+81·7	0·001	+158·7	0·001	+43·5
D.S.	Pronation	R	20	0·001	+78·7	0·001	+109·3	0·001	+26·9
J.W.	Pronation	R	24	0·001	+25·9	0·001	+61·6	—	—
N.S.	Pronation	R	25	0·001	+80·5	0·001	+200·4	—	—

The effect of the longer period of static and dynamic pronation training on the maximum isometric pronation and supination force exerted in different positions of the hand (Fig. 4). Although static training was carried out in only one position of the hand while dynamic training involved movement from this position through a variable proportion of the total range, an increase was found in all positions under both conditions. Similar results were obtained for the maximum isometric supination forces.

The effect of the longer period of training in pronation on the strength of the antagonist muscles (Fig. 5). In all the subjects the strength of isometric and isotonic supination was increased. The greatest differences were found in the isotonic measurements, but there was no significant difference between the effect of static and dynamic training.

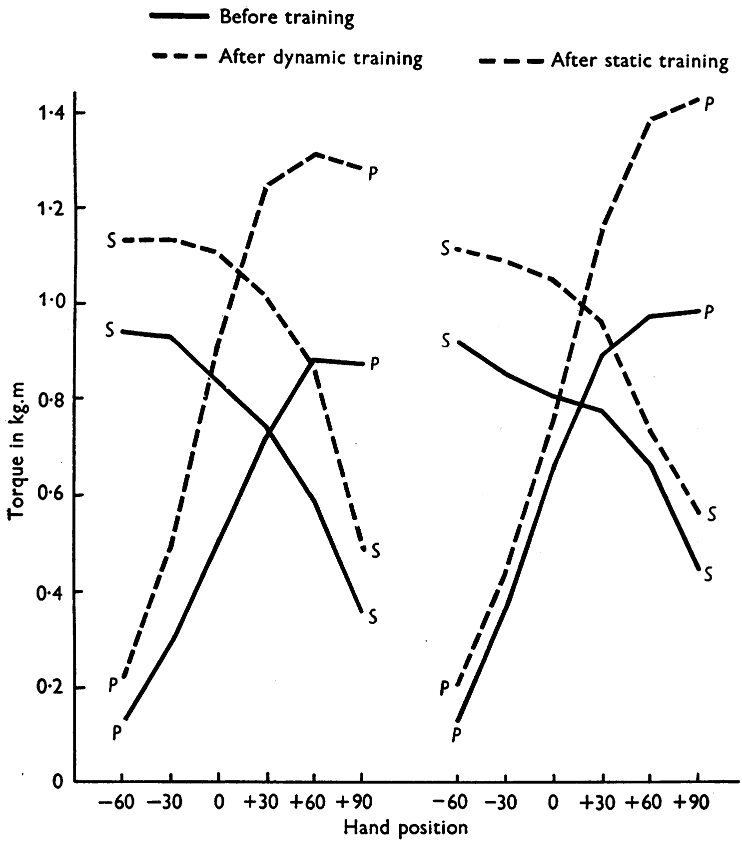

Fig. 4. Graphs showing the increase in strength of pronation (P–P) and supination (S–S) measured isometrically in six hand positions after static and dynamic training in pronation.

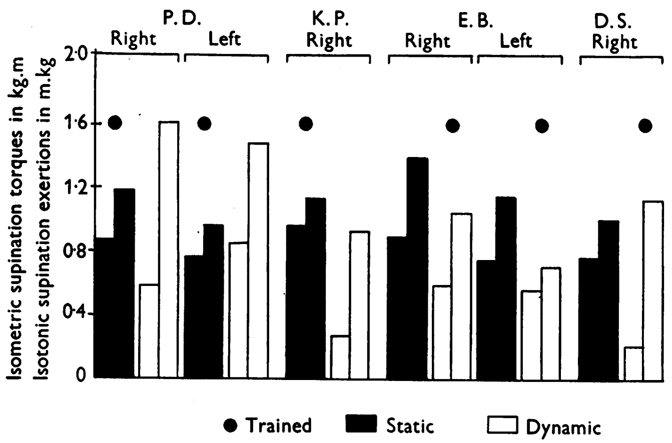

Fig. 5. Histograms showing the strength of supination measured isotonically and isometrically before and after twenty-eight training sessions in pronation.

The effect of the longer period of static flexion training on the maximum isometric supination force and vice versa (Fig. 6). Whether the subjects were trained in supination or flexion, an increase was found both in supination and in flexion.

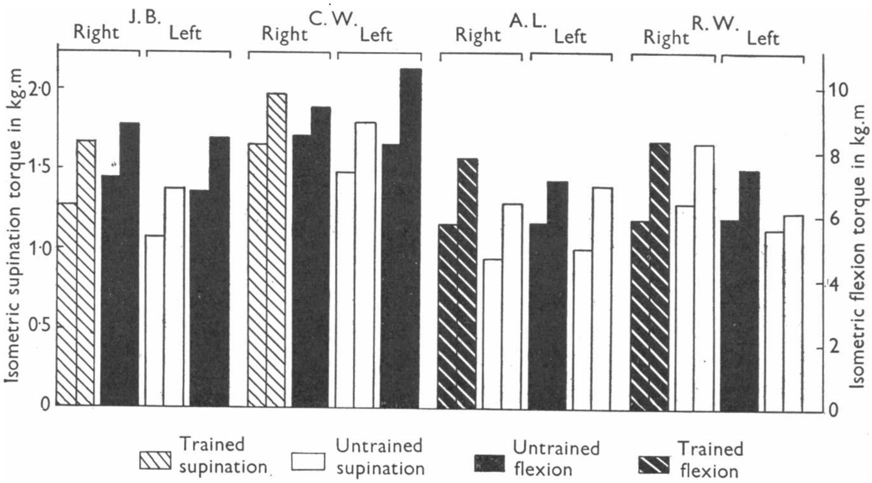

Fig. 6. Histograms showing the strength of supination and flexion measured isometrically before and after twenty-five training sessions.

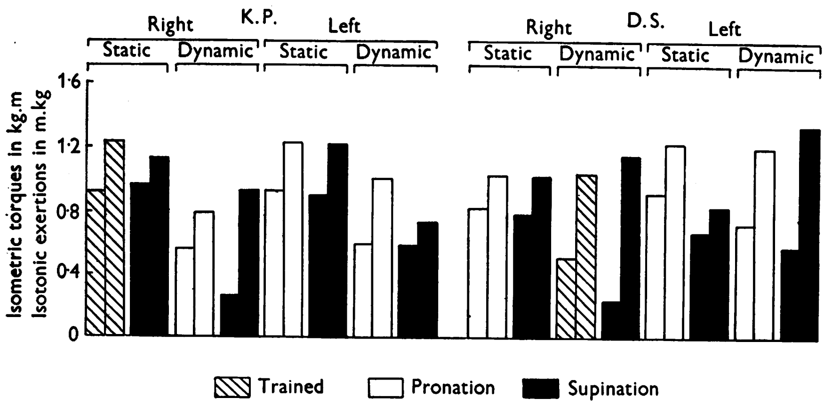

Fig. 7. Histograms showing the strength of pronation and supination measured isotonically and isometrically on the right and left sides before and after training in pronation on the right side.

The effect of the longer period of training on the strength of corresponding muscle groups of the opposite side (Figs. 6, 7). Following either static or dynamic training of pronation on one side, there was an increase in the isotonic and isometric strength of pronation and supination on the other side. There was no significant difference between the effects of either method of training.

In static flexion or supination training, there was also an improvement in the maximum isometric force exerted in supination and flexion on the opposite side.

DISCUSSION

Although it is well established that the strength of muscles can be increased by systematic voluntary exercise, there is no agreement regarding the most effective way in which this can be achieved. No doubt because of this, there is still no generally accepted method of muscle training, although many have been described. The majority of these methods are based on the ergographic technique originally devised by Mosso (1890). In this, the subject is required to lift a weight at a rapid repetition rate either until he can no longer maintain the prescribed rhythm or range of movement or until he fails to move the weight. The most carefully presented clinical training procedure of this nature is that described by Delorme (1945).

The method that we have adopted appears to be original in that the subject makes maximum exertions at intervals that are designed to allow full recovery, so that no 'fatigue curve' is produced. It should also be pointed out that our static training involves isometric contractions only held momentarily, whereas the 'static' training procedure used by other workers has involved holding submaximal weights for a period of time (Asmussen, 1949).

Comparison of our results with those of others is limited by the fact that other investigators have used different techniques and different criteria of improvement. Furthermore, in contrast with certain experiments of this kind, our subjects were offered no incentive in the form of knowledge of results or prizes, so that their level of motivation was low. The results of many previous training experiments have been reviewed by Steinhaus (1933).

Comparison of dynamic and static training

Among the problems not yet solved is the question whether repeated dynamic or static activity produces a different effect on muscle strength. The results of our experiments, unfortunately, do not throw any further light on this, as we consider the differences found to be too small to allow any final conclusion to be drawn. Both forms of training lead to an increase in muscle strength, whether the criterion is the maximum isometric force that can be exerted or the maximum distance through which a heavy load can be lifted.

In general, dynamic training causes a greater percentage improvement than static training. One possible explanation for this difference is that, although the subjects were not told of their results during the course of the experiment, those performing dynamic work may have derived some encouragement by assessing for themselves the increase in range of movement on successive occasions, whereas those doing static training had no index of their achievement. Because of the boredom that may result from this, Ionesco (1949) has suggested that static training should not be used therapeutically. However, had our subjects been allowed to watch the movement of the galvanometer light spot produced by their efforts, it might have provided an incentive comparable to that pertaining in dynamic training. Another possible reason for the slightly greater improvement produced by dynamic training is that in our experiments more work was imposed on the muscles in this routine than in static training. The subject had to raise the load and then also to control its return to the resting position, whereas in static activity, once the maximum contraction had been developed, the muscles could immediately relax.

A difference was found in the pattern of the training curves in the two types of muscular exercise. Dynamic activity usually resulted in an immediate and rapid improvement, whereas static activity produced no consistent upward trend until the second week. This has been noted also by Asmussen (1949), and it is possible that this finding has been at least partly responsible for the apparent disfavour of isometric exercise for muscle re-education. It is not clear why there should be this delay before improvement occurs in static training, but the impression gained was that it was partly due to the difficulty in acquiring the knack of exerting a maximum isometric contraction.

The only study comparing static and dynamic activity that has been found is that by Asmussen (1949). He studied the effects on muscle strength of lifting and of holding heavy weights, and he found that each produced approximately the same degree of improvement. In spite of this, however, he does suggest that dynamic training may not be as efficient as static because it does not usually allow sufficient time for the muscles to reach their maximum tension.

Retention of training effect

It has been reported by Abramson (1929) and McMorris & Elkins (1954) that the improvement in muscle strength resulting from training is retained for a considerable period after training has ceased. This is confirmed in one of our subjects on whom it was possible to take measurements after the training period. In this case, even after 12 months the muscle strength was double the original value, although it was less than that achieved at the end of training. It would appear that training has some permanent or semi-permanent effect on the neuromuscular system. Whether or not the retention is related to the length of training or the level of muscle strength reached is not known.

The effect of training on 'unexercised' muscle groups

As well as an improvement in the strength of muscles directly exercised, an increase was also found in the strength of the antagonist group following both static and dynamic training. However, Hellebrandt, Parrish & Houtz (1947), studying only dynamic training, found no statistically significant improvement in antagonist muscles. The explanation for our finding is obscure; the antagonists may have been exercised to a certain extent, but electromyographic investigations have shown that, in general, there is no activity in the antagonists when the contraction is against an opposed external resistance, whether it is isotonic (Hoefer, 1941) or isometric (Seyffarth, 1941).

The finding of an increase in the strength of muscle groups in the limb opposite to the one specifically exercised was first noted at the end of the last century by Scripture, Smith & Brown (1894). They observed that training of hand grip on one side was associated with an increase in grip strength on the other side. Davis (1898) found that training increased the endurance of muscular contraction both of the muscle group exercised and of other groups, particularly those in close anatomical relationship and corresponding groups of the opposite side. Wissler & Richardson (1900) reported similar findings for the strength of muscular contraction. No further reference to this aspect of muscle training has been found before the work of Hellebrandt *et al.* (1947). On the basis of their experiments, they suggested that cross-education depends on the involuntary spread of activity to the opposite side of the body during severe unilateral exercise. In their ergographic technique, the load applied was so heavy that it could not be lifted without great effort, and it produced a precipitous 'fatigue curve'. The results of our experiments, in which fatigue was minimal, suggest that it is unnecessary to exercise muscles to this degree in order to get the 'transference' effect.

Variability in muscle strength

Although the training routine was designed to eliminate chance variations as far as possible, there were considerable fluctuations in maximum strength measured in any one subject on different occasions. Similar findings have been reported in previous studies involving the measurement of maximum muscular activity, and various explanations have been put forward to account for them (Lombard, 1892; Fischer, 1947; Weinland, 1947). The impression gained during our experiments was that at least part of the variation was due to the difficulty the subject had in knowing when he had reached his maximum performance, since he could not see the effect of his efforts. This seems to be borne out by the fact that the variations tended to decrease as training progressed.

There is no doubt that there were fluctuations in the willingness of the subjects to exert themselves fully. These may have been due to the tedious nature of the experiment and to the fact that the subjects had no particular interest in improving their muscle strength. Furthermore, owing to lack of interest, the subjects may have been prone to distractions which would lead to variability in recordings.

A further factor in the variability appeared to be that, since the subject knew he had to make thirty exertions, he 'saved' his strength in the early part and built up a final spurt.

SUMMARY

1. Studies are described on the effects of repeated maximum isotonic and isometric contractions on the strength of pronation and supination of the hand and flexion of the elbow. Each daily training session consisted of thirty contractions at intervals of 1 min. This was carried out by one group of subjects for 5 or 6 days. Another group continued until twenty to twenty-eight training sessions had been completed.

2. Both types of training resulted in an increase in the strength measured both isotonically or isometrically, although the effects of 'static' training were not immediately apparent.

3. 'Static' training, although carried out in only one position of the joint, resulted in an increase in all other positions tested.

4. An improvement in muscle strength was also found in the antagonists of the same side and the corresponding groups of the opposite side.

5. 'Static' training in flexion caused an increase in the strength of supination and vice versa.

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