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PROGRESSIVE RESISTANCE EXERCISE TRAINING OF THE HYPOTROPHIC QUADRICEPS MUSCLE IN MAN

The Effects on Morphology, Size and Function as well as the Influence of Duration of Effort

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ABSTRACT. The effects of progressive resistance exercise (PRE) training for 4 weeks on the hypotrophic quadriceps muscle were investigated in 23 young healthy male soccer players, who had been immobilized in a plaster cast 4–6 weeks after knee ligament injuries. The subjects were allocated to two training regimes where the injured leg was trained for periods of varying duration, whereas the intensity and frequency of exercise were alike in the two groups. However no significant differences were detected between the two training groups. In the whole material the lean thigh volume of the injured leg increased from 4.09 to 4.47 litres ($p<0.001$), whereas the fat component of the thigh was unchanged. The dynamic strength (1 RM) of the injured leg increased from 14.0 kg to 27.0 kg and amounted to 87% of the control leg after 4 weeks of training. At this time the maximum isometric strength amounted to 114 Nm, which was 63% of strength in the control leg. Succinate dehydrogenase (SDH) in homogenates of muscle biopsy sample increased (i.e. 20%, $p<0.05$) to the same level as found in the control leg. No changes in phosphofructokinase (PFK) were observed. The type I fibre distribution was lower in the immobilized leg than in the control leg. These results indicate that, following muscular hypotrophy resulting from 4–6 weeks of immobilization, dynamic exercise can restore the oxidative potential, whereas the size and strength are only partly recovered.

Key words: Exercise therapy, muscle fibre recruitment, soccer player

Muscular hypotrophy, decrease in oxidative muscle potential, degeneration of muscle fibres and decrease in muscular strength all occur when limbs are immobilized (4). Quadriceps muscle hypotrophy after knee injuries is also a well-known clinical finding and it has been demonstrated that 4–6 weeks immobilization in a high plaster cast of the leg caused a selective hypotrophy of the quadriceps muscle (18). It is primarily the oxidative type I muscle fibre, which is affected during immobilization (12). In rehabilitation various forms of training regimes have been tried but only a few reports are available in which the effects of such programs have been evaluated.

In the present study the effects of a dynamic training program using progressive resistance exercise (PRE) training on the hypotrophied quadriceps muscle was evaluated. The present investigation focused on the muscle function, fibre characteristics, enzyme potentials and muscle volume.

MATERIAL AND METHODS

23 healthy well-trained soccer players (mean age 25 years (range 17–31)) participated in the study. Height and body weight (mean and (range)) were 1.76 m (1.65–1.90) and 70.7 kg (58–89), respectively. Each had an acute lesion of a ligament of one knee, 20 were treated surgically by primer suture, all were immobilized in a high plaster cast, without heel. Walking without a crutch was allowed. The cast was removed after median 30 days (range 22–45). The experimental procedure was explained to and informed consent given by all subjects before the study.

Anthropometric measurements. Total thigh volume including the lean and fat component was estimated as previously described (16). Whole-body measurements included body weight (BW) as well as lean body mass (LBM) and fat fraction (FF) estimated from two skinfolds (right subscapular and anterior thigh (uninjured)) by use of the Sloan & Weir nomogram (24).

Physical performance. Maximum dynamic strength of knee extension was measured as one repetition maximum (1 RM), which is the load (kg) that can be lifted to full knee extension once (8). The subject was seated with legs hanging over the end of the examining table and the hips flexed to 90°. A weighted boot (Fig. 1) was applied to the foot and the knee was extended from 90° to 0°, the full extension was held for 1 sec. The test procedure is demonstrated in Fig. 2. Maximum isometric strength (MIS) was measured at a knee angle of 90° in a modified Darcus dynamometer (2), during maximum voluntary extensions, and a mean of three contractions was applied.

Muscle biopsies. Muscle tissue was taken from the vastus lateralis muscle, with a needle biopsy technique (1). The side and depth of needle insertion were standard-

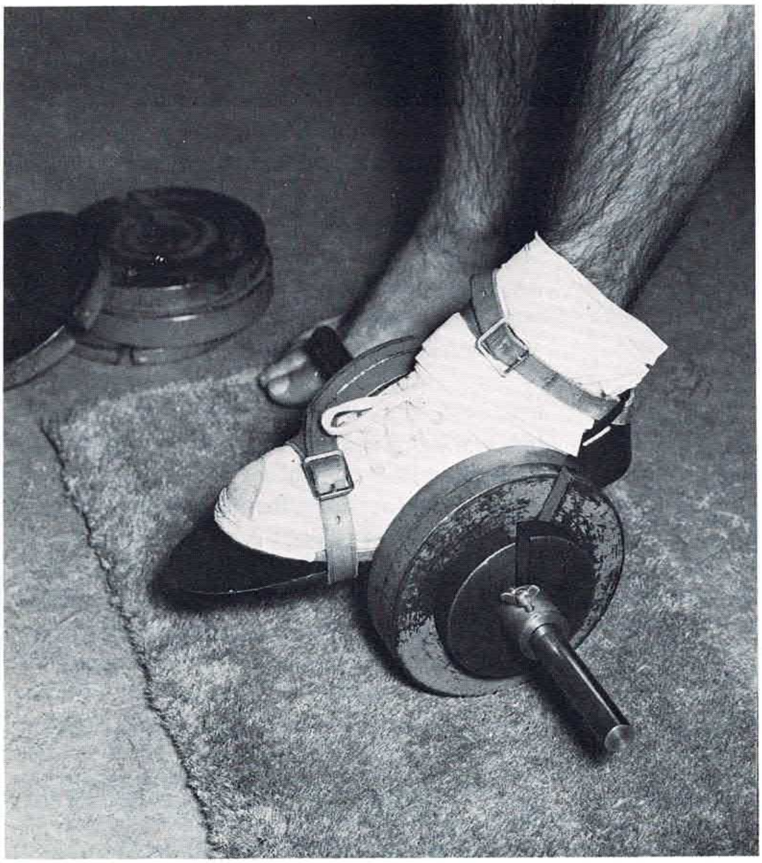

Fig. 1. The De Lorme boot.

ized for all subjects. One biopsy sample was used for classification of muscle fibres into type I and type II by staining for myofibrillar ATPase, pH 9.4, after pre-incubation, pH 10.3 (22). Photomicrographs of the ATPase-stained section were made for area measurement using planimetry; 20 fibres of each type were measured (14).

Muscle enzymes. Some part of the muscle sample was assayed for total content of succinate dehydrogenase (SDH) (6) and phosphofructokinase (PFK) (23), 20 mg muscle tissue were used. The incubation was done at 25°C. The coefficient of variation for SDH and PFK determined on paired muscle samples were 16.4% and 10.6%, respectively ($n=35$).

Muscle training. The subjects were initially treated with mobilizing exercises for the injured knee, and the training program began when the knee joint could be moved to 90° of flexion (which occurred median 7.0 days after removal of the cast, range 0–32). The subjects trained three times a week by PRE, the load was initially 50% of 1 RM and, after 10 contractions, was increased to 75% of 1 RM and this load was maintained to exhaustion (=unable to extend the knee joint) (Fig. 2). The frequency was about 10 per min and exhaustion occurred after a total of about 30 contractions. The maximum dynamic strength (1 RM) was measured every week, and the absolute training load thereafter adjusted.

Muscle fibre recruitment. Two additional young subjects performed the training procedure twice when the immobilized knee could be moved to 90° of flexion; one subject had both (weak and control) muscles examined and the other the control muscle only. Muscle biopsies were obtained before as well as after in order to evaluate the fibre recruitment pattern using glycogen depletion pattern. The histochemically-determined glycogen concentration in each fibre type was calculated from the mean absorbance (A) divided by the thickness of the PAS-

Table I. *Muscle enzyme activities*

$n=23$	Before training	After training	p
SDH activity (μmol$\times$g ww$^{-1}\times$min^{-1})			
Trained leg	1.85* (1.21/2.11)	2.21 (1.98/2.80)	<0.05
Control leg	2.11 (1.64/3.07)	2.11 (1.77/3.24)	NS

Medians (lower/upper quartiles).
* Significant different ($p<0.05$) from the control leg.

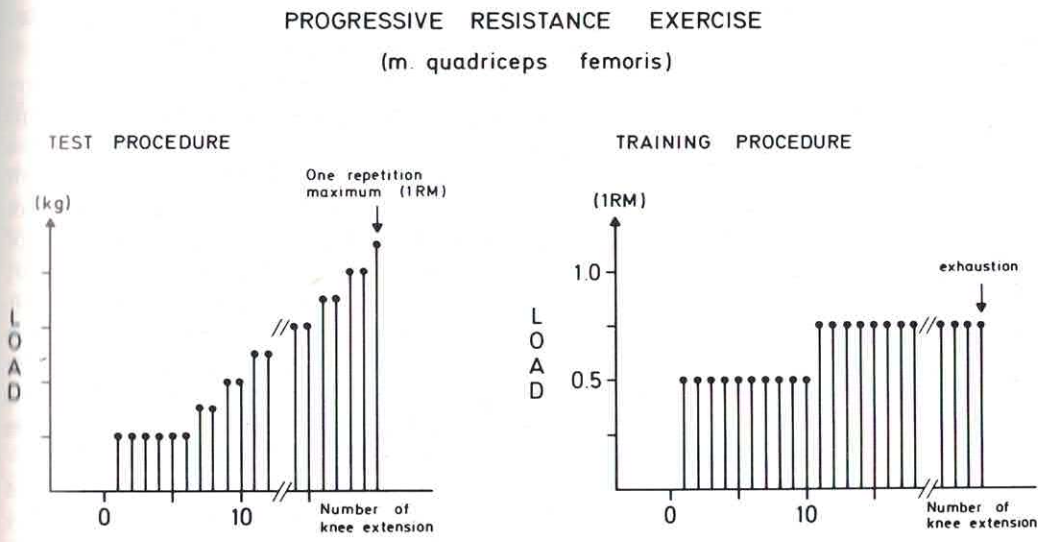

Fig. 2. The principle for the testing procedure (*left*) and training procedure (*right*) of progressive resistance exercise in the present study.

stained section and expressed in arbitrary units ($A \cdot \mu m^{-1}$) (13). 20 fibres of each type were measured in each biopsy.

Procedure. The first examination was carried out when the knee could be moved to 90° and included measurements of the injured (immobilized) as well as the uninjured leg. The training programs were then performed, and the subjects were allocated to two training groups; one performed the training program once and the other group twice with a 15-min rest interval. The second examination was carried out after 4 weeks of physical training and the measurements of the two legs were repeated. The training was continued until no difference could be detected in 1 RM between the two legs.

The observed data are presented as the median to indicate the level, and the lower and upper quartiles to characterize the variation. The results were evaluated statistically with rank-sum tests: Mann-Whitney's to examine the presence of difference between the two groups; Wilcoxon's to examine the presence of differences on paired data and Spearman correlation coefficient to describe the association between two variables (5).

RESULTS

Training procedures. The two physical training regimes resulted in the same improvement. In the following results the two groups are therefore combined.

Muscle performance. The maximum dynamic strength (1 RM) of the weak quadriceps muscle increased during the training period from a median value 14.0 kg to 27.0 kg (Fig. 3). In the trained leg the increase was highly significant ($p<0.001$) from week to week. However, even in the non-trained leg there were significant ($p<0.001$) increases from week to week from a median value of 26.0 kg to 31.0 kg. The dynamic training was continued until no significant difference in 1 RM could be detected between the two legs; this occurred after a median of 44 days (range 21–120) from the removal of the plaster cast. The retraining time (i.e. the time from plaster removal to equality between the two legs) was positively related to the immobilization time

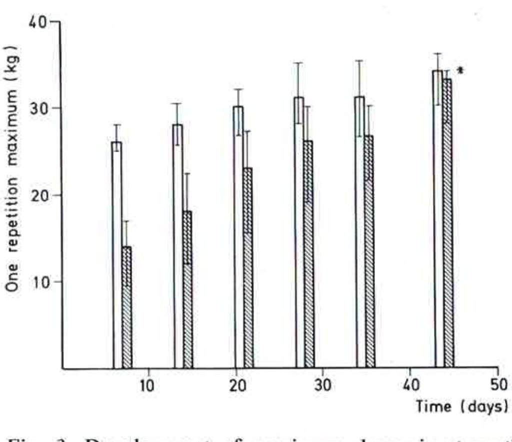

Fig. 3. Development of maximum dynamic strength (1 RM) of knee extensor muscles during the training period. ▨, The immobilized muscle; □, the control muscle. The bars represent median (upper/lower quartiles) values. Asterisk indicates no significant difference.

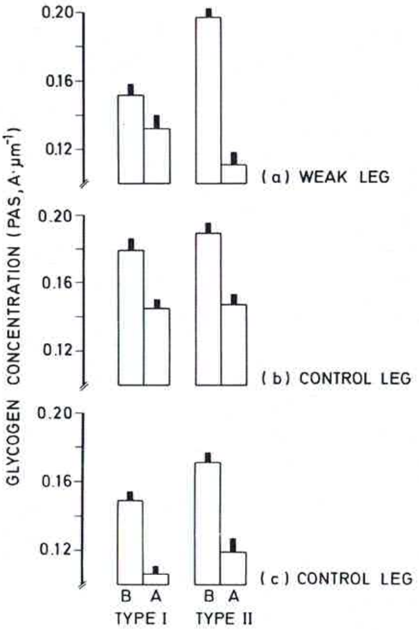

Fig. 4. Mean value (SEM) for glycogen concentration (PAS, $A \cdot \mu m^{-1}$) in type I and type II muscle fibres in vastus lateralis of one weak (*a*) and two control (*b, c*) muscles. *B*=before, *A*=after dynamic contractions with 75% of maximum dynamic strength. 20 fibres of each type were measured.

(r=0.46, p<0.05). MIS of the knee extension was measured after 4 weeks' training, the median values for the trained and the non-trained control leg were 114 Nm and 180 Nm, respectively (p<0.001). No significant difference was demonstrated in MIS before and after the training period in the control leg. After the training period the dynamic strength in the trained leg averaged 87% of the control leg, whereas the corresponding difference for MIS was 63%.

Muscle fibre recruitment. The glycogen-depletion patterns for the three muscles (one weak (*a*) and two control (*b* & *c*) muscles) are shown in Fig. 4. The muscle performed initially 10 dynamic contractions with a load of 50% of 1 RM followed by 16 contractions with 75% of 1 RM and this session was repeated after 15 min rest. 1 RM equalled 12, 20 and 24 kg for *a, b* and *c,* respectively. It is seen that both fibre types are recruited; the decreases in glycogen content were in all three cases significant at the 0.001 level of confidence. In the two control muscles the depletion was of equal amount, whereas type II depletion dominated in the weak muscle. The type I distribution was 59, 48 and 42%, for the *a, b* and *c* muscle, respectively.

Anthropometry. The 4 weeks of progressive resistance exercise training of the weak quadriceps muscle resulted in considerable increases in the lean thigh volume (4.09 (3.53/4.48) to 4.47 (3.87/4.99) litres, p<0.001); however, even in the non-trained leg the increase was significant (4.73 (4.25/5.01) to 5.09 (4.38/5.45) litres, p<0.05). However, after the training period a highly significant difference (p<0.001) still exist between the two lean thigh volumes. No changes were observed in the fat component in either leg. Body Weight (and LBM) increased about 1 kg and paralleled the changes in leg volumes.

Muscle fibre composition. In the immobilized vastus lateralis the relative number of type I fibres tended to be smaller than in the control muscle. No changes were observed during the training period, but the difference between the two legs reached a significant level (34.9 (28.6/48.7) vs. 40.4 (34.8/52.8)%, p<0.05). The absolute area of type I and II fibres did not change during the training period, and no differences between the two legs at the two examinations were revealed.

Muscle enzyme activities. There was a significant increase in SDH after training in the exercised quadriceps muscle, whereas SDH was unchanged in the control muscle (Table I). The individual increase in SDH in the trained leg was inversely related to their initial concentration (r=−0.681, p<0.001). PFK activity were unchanged in both legs (25.2 (19.5/31.3) μmol/g ww/min).

DISCUSSION

The present study demonstrated that dynamic muscle training primarily increases the dynamic muscle function of hypotrophic knee extensor muscles, as the largest increase was observed in dynamic strength, compared with static strength. This is in agreement with previous studies in normal subjects, demonstrating that the improvement in muscle performance is primarily obtained in the trained muscle function (3). The present study further demonstrated that the duration of effort is of minor importance as no differences were detected between the two training regimes. This is in accordance with quantitated training studies, where it has been demonstrated that the most important factor is the intensity of effort (7), but frequency and duration may also be of importance (21).

Muscle fibre recruitment

In the present study the glycogen depletion pattern demonstrated that both fibre types are involved in progressive resistance exercise. In the control muscles the same degree of glycogen depletion were observed in both fibre types, whereas in the weak muscle, depletion of type II fibres dominated. This is in agreement with the results of Hultén and coworkers (15), who in intermittent isometric and dynamic isokinetic knee extension exercises found an increased dependency on type II fibres with increased work load, and that subjects with a relatively large reduction in strength or a small number of type I fibre demonstrated more depletion of these fibres than other subjects. Thus the fibre recruitment pattern may also be regulated by the absolute load, besides the relative load of muscle contraction. It may also be suggested that the greater dependency on the type II fibres in the weak muscle is a consequence of falling out of type I fibres. The present result of a significant lower type I distribution in the weak muscle concurs with this view. The principle of progressive resistance exercises may be looked upon as an effective way to recruit both major types of muscle fibre. As immobilization of the human muscle affects primarily the aerobic function (i.e. type I fiber function), the De Lorme training principle seems to be a potential stimulus for the muscle rehabilitation after inactivity.

The present results disclosed also an increase in dynamic strength of the untrained knee extensor and points out the so-called 'cross-transfer' of training. Similar results have been obtained in other unilateral training studies. For example, Komi and coworker (20), investigating isometric strength training of the right leg in normal subjects, found in addition to the increase in the trained leg an increased strength in the untrained leg. In the present study it was only the dynamic strength that was affected, whereas the isometric strength was unchanged in the control leg; thus it seems possible that there may exist a specificity in the phenomenon of 'cross-transfer' of training.

Quadriceps muscle hypotrophy after knee injuries is a well-known clinical finding, and this was also indicated in the present study as the difference in lean thigh volume averaged 0.64 litres corresponding to 16% between the two legs. It has previously been shown by computerized tomography that plaster immobilization solely affects the quadriceps muscle (18). Assuming 50% of the lean thigh volume to be the quadriceps muscle, a difference of 0.64 litres equals about 30% between the two quadriceps muscles. After 4 weeks of training a regain in lean thigh volume of the immobilized leg of 0.38 litres (an increase in quadriceps of about 19%) was demonstrated, although a significant difference with the control leg still existed. From animal experiments (4) it is known that the regain in muscle weight after prolonged muscular atrophy produced by limb immobilization is a relatively lengthy process, and that the return of wet weight and total protein content of slow-twitch muscle to control values is must faster than the rate of recovery of maximum isometric tension. In the present study a differential rate of recovery of 1 RM and of MIS was observed; although this could be an effect of the specific training program, it could also be a consequence of differences in protein synthesis rate between the fibre types. Thus the observed changes in the recovery period may be a result of changes in the muscle tissue itself, however adaptation in the nerve system cannot be ruled out.

Muscle SDH activity was significantly decreased in the immobilized muscle before the training period compared with the control leg and after the training period a significant increase was demonstrated. No change was observed in the muscle PFK, an enzyme which has been focused upon as a rate-limiting enzyme in glycolysis. These results demonstrate that immobilization in plaster of Paris primarily affects the oxidative function of the skeletal muscle, a function which is primarily located to the type I fibre. This concurs with the result of the fibre distribution, where the immobilized leg showed a decreased type I fibre distribution. However no changes in the fibre distribution were observed in the training period. An increased oxidative potential in skeletal muscle has also been demonstrated in normal subjects after isometric training (10), which is in accordance with the present result demonstrating increased muscle SDH after a strength training program. The actual level of SDH seems rather low compared with other investigations; however, the present analysis was run at a temperature of 25°C, and these values are within the same levels as reported by others (9).

The decrease in type I fibre distribution after the immobilization period has previously been reported (12), and concurs with the results of Young and co-workers (25) in unilateral knee injury patients with quadriceps muscle wasting. The physiological interpretation of this decrease in type I fibre distribution as an effect of immobilization may be found in a restricted stimulus for these fibres, as the plaster cast makes it impossible for the muscle to contract dynamically, and this type of contraction may be the main stimulus for the type I fibres. As no changes were revealed in fibre area in the present study, the decreased type I distribution could be a result of disappearance of type I fibres. In animal studies a decline in the percentage of slow-twitch muscle fibres has also been observed in the immobilized soleus muscle. The etiology of this change in fibre distribution is still controversial (4).

Clinical implications

The present injured athletes were rehabilitated using a progressive resistance exercise training program, and the dynamic strength was regained in a curvilinear fashion, as is usually seen in physical training studies (Fig. 3). The retraining time in the present study was positively related to the duration of the inactivation period. Moderate or severe pain in the knee of the athletes was never noticed either during or after the training sessions. Thus the present study supports the guidelines for muscular strength improvements primarily advanced by De Lorme in 1945, that rapid hypertrophy in weakened atrophied muscle is obtained by strenous exercise, at regular intervals, to the point of maximum exertion (8). It should be mentioned, however, that there has been some concern in the literature about using resistive knee extension exercises for post-knee surgery rehabilitation (19). The straight leg raising procedure has been advocated to strengthen atrophied quadriceps, even in the absence of chondromalacia of the patella and with normal joint range of motion. On the other hand has it recently been demonstrated that the tension development in the quadriceps muscle is greater during knee extension than during straight leg raising, the difference being greater with increasing levels of activity (19). Therefore, if high tension development of the quadriceps muscle is the objective, then the knee extension exercise seems to be more effective than the straight leg raising procedure. However, it may be that a greater training effect is obtained with isokinetic exercise (17) as maximum resistance can be performed through the whole range of motion, whereas in weight training the torque is only maximal for the last part of joint motion. Some results may speak in favour of this view (11). The PRE training principle is recommended for well-motivated subjects—it is simple and requires a minimum of equipment.

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