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WITH SPECIAL REFERENCE TO PROLONGED HEAVY RESISTANCE AND EXPLOSIVE TYPE STRENGTH TRAINING

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To investigate prolonged training-induced changes in electromyographic, muscle fibre and force production characteristics of leg extensor muscles and in serum hormones, eleven trained male subjects went through heavy resistance (loads between 70 and 120 %) and ten comparable male subjects through explosive type (jumping exercises with low loads) strength training for 24 weeks. Great increase in maximal strength (26.8-30.2 %, $p<.001$) during heavy resistance strength training was accompanied by significant ($p<.05-.01$) increases in the neural activation (IEMG) of the trained muscles during the periods with higher training loads. Explosive force development was slight during the entire training. Large muscular hypertrophy of especially FT fibre type ($p<.001$) occurred primarily during the first half of the training. Individual alterations in serum testosterone/cortisol ratio correlated ($p<.01$) with changes in muscular strength during the last training month. Great (24.1-32.5 %, $p<.001$) improvement in rapid force production during explosive type strength training correlated ($p<.05-.001$) with significant ($p<.05-.01$) increases noted in the neural activation of the trained muscles observable both during rapid isometric and concentric contractions and during high velocity stretch-shortening cycle exercises. Maximal strength development and hypertrophic changes were relatively slight. Selected decreases ($p<.05-.001$) occurred in IEMG, muscle fibre areas and in muscular strength during the following detraining periods for 12 weeks. The present findings indicate that training-induced enhancements in various aspects of force production are explainable by specific adaptations in the neuromuscular system and in endogenous hormone balance taking place in part with regard to type, loading and duration of strength training and perhaps to subject material.

strength training, neuromuscular performance, neural and hypertrophic adaptations, hormonal responses, specificity of training, detraining

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CONTENTS

PREFACE

This thesis is based on the following papers, which will be referred to by their Roman numerals:

I HÄKKINEN, K., PAKARINEN, A., ALÉN, M., KOMI, P.V. Serum hormones during prolonged training of neuromuscular performance. Eur J Appl Physiol 53: 287-293, 1985.

II HÄKKINEN, K., ALÉN, M., KOMI, P.V. Changes in isometric force- and relaxation-time, electromyographic and muscle fibre characteristics of human skeletal muscle during strength training and detraining. Acta Physiol Scand 125: 573-585, 1985.

III HÄKKINEN, K., KOMI, P.V., ALÉN, M. Effect of explosive type strength training on isometric force- and relaxation-time, electromyographic and muscle fibre characteristics of leg extensor muscles. Acta Physiol Scand 125: 587-600, 1985.

IV HÄKKINEN, K., KOMI, P.V. Changes in electrical and mechanical behavior of leg extensor muscles during heavy resistance strength training. Scand J Sports Sci 7: 55-64, 1985.

V HÄKKINEN, K., KOMI, P.V. Effect of explosive type strength training on electromyographic and force production characteristics of leg extensor muscles during concentric and various stretch-shortening cycle exercises. Scand J Sports Sci 7: 65-76, 1985.

VI HÄKKINEN, K., KOMI, P.V. Training-induced changes in neuromuscular performance under voluntary and reflex conditions. Eur J Appl Physiol, in press 1986.

The studies were carried out at the Department of Biology of Physical Activity, University of Jyväskylä, Finland, during the years 1982-1985. There are several persons who have contributed to my work and to whom I wish to express my gratitude:

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Jyväskylä, January 1986

Keijo Häkkinen

1. INTRODUCTION

The basic principles of strength training were expressed almost a century ago by Roux (1895). He concluded that strengthening of muscle is achieved mainly by an increase in work effort over that which characterizes the normal daily activities and not by repetitive efforts within the level of the normal daily activities for a longer period. At about the same time Morpurgo (1897) reported observations from his animal experiments that when muscles get stronger they also get larger. He found that muscle fibres in trained animals had a larger cross-section than those of untrained animals. This observation that increase in muscle cross-section might be primarily due to changes in fibre sizes, not in fibre number, was one of the first scientific observations of the process of muscular hypertrophy.

The research literature in strength training and in the mechanism of strength increase during training thereafter became more prolific from the late 1940's onwards. DeLorme (1945) and DeLorme and Watkins (1948) expressed principles of strength training that are in part still followed. They replaced the at that time often accepted principles of "low resistance and high repetition" training by the more effective "heavy resistance and low repetition" and/or "progressive resistance" training. In their terminology, one repetition maximum referred to the maximal load that a muscle can lift at one time, which therefore gave a basis for a more accurate determination of training loads for progressive strength training.

Hellebrandt and Houtz (1956) (see also Hellebrandt 1958) were able to confirm Roux's original statement and later expressed one of the very basic principles of strength training "the overload-principle". They examined the effects of using lighter "underload" and heavier "overload" training methods to finally establish the beneficial effects of the overload training. This overload-principle is in its basic function still valid today and utilized in part in modern strength training.

In the beginning of the 1960's Clarke (1960) proposed a theory for the mechanisms of strength increase according to which strength development might be explainable by reduced blood flow and by increased accumulation of lactic acid and other by-products in the muscle. However, it was demonstrated (e.g. see Hettinger 1961) under experimental conditions in which a tight bandage was applied around the upper arm that the increase in muscle strength was no greater than that obtained when the same stimulus was given without a bandage. The fatigue "substances" could therefore not be a reason for an increase in muscle strength during training. Muscle stretch as a plausible trophic stimulus to increase muscular hypertrophy and the force of muscle contraction was also suggested at about that time (e.g. Müller and Rohmert 1963).

The first results on the effects of isometric training were reported in the early 1950's by Hettinger and Müller (1953). These results, together with others on isometric strength training and on possible mechanisms of strength increase were later summarized by Hettinger (1961). He also concluded, in agreement with the overload-principle, that only an increase in intensity of work beyond that previously demanded of a muscle can be the main stimulus for an increase in strength during training. According to him the maximum training effect could be achieved by using only 40-50 % of the maximum strength in voluntary isometric contraction. This suggestion has received criticism, however, because some studies have demonstrated that increases in strength are related mainly to the intensity of the training stimulus (e.g. see Walters et al. 1960, Müller 1970, Coleman 1972). Hettinger's (1961) demonstrations that increases in strength during training might be largely individual holds still true.

Since the introduction of the isometric training method (Hettinger and Müller 1953) scientific interest was also concentrated on efforts to determine the most beneficial training method. A majority of the studies conducted in the 1950's and 1960's have used either isometric and/or concentric training contractions. The greatest overloading of muscle is achieved, however, in eccentric contraction (e.g. Asmussen et al. 1965). If the overload - principle is strictly followed, it would imply that the type of contractions which produces the highest tensions might cause the greatest increase in strength during training. Training utilizing repetitive eccentric contractions has been investigated in comparison to other types of muscle contractions since the end of the 1960's (see Rasch 1974). Although some indications of positive effects from high tension eccentric training are available (e.g. Komi and Buskirk 1972), some caution must be exercised in order to avoid over-simple generalizations. Reports of the effects of different methods of strength training on the development of maximal force may sometimes be conflicting (e.g. see Atha 1981). This conflict may have occurred partly because of the relative ease in demonstrating improvements in muscular strength with various training methods especially in previously untrained subjects. Some difficulty also exists in accurately comparing results due to a lack of uniformity in experimental design, e.g. the duration of the training period, the pretraining status of the subjects, the number of muscle contractions and the training loads used in each training regimen (e.g. see Atha 1981, Häkkinen and Komi 1981). Some of the conflicting results may in part be put down to specificity of strength training; because it has been demonstrated (e.g. Brunner 1967) that the type of muscle work used in training and in testing are interrelated.

These factors may also partly explain why some of the recent reports (e.g. Häkkinen and Komi 1981, Häkkinen et al. 1981; see also Pletnev 1975, 1976) indicate that during the earlier weeks of training, improvements in maximal strength may not be related strictly to the type of muscle contractions used; but during the later phases of training (from 2 to 3 months onwards) the beneficial effects of a combination of high loading concentric and eccentric (and/or isometric) training seem obvious. It is naturally very difficult to determine accurately the type, loading and amount of training that is optimal for each individual at a given time. It is additionally worth noting that the selection of training methods - isometric, concentric and/or eccentric - should also be related to the specific goals of the training, for example, in athletic training, in rehabilitation etc. (e.g. see Stoboy 1973).

Emphasis must therefore also be given to the notion that in addition to improvements in maximal strength, the influence of different strength training stimuli can be characterized by specific alterations in isometric force-time (e.g. Sukop and Nelson 1974, Häkkinen et al. 1980, 1981, Viitasalo et al. 1981) and/or in force-velocity curve (e.g. Ikai 1970, Coyle et al. 1981, Caiozzo et al. 1981, Kanehisa and Miyashita 1983a). To summarize the primary findings from these experiments: it can be suggested that due to the specificity of training, increases in maximal strength during high loading strength training are accompanied by relatively slight enhancements in time (or in the maximum rate) of isometric force production and/or in concentric explosive force production. Moreover, in training for longer durations (e.g. Häkkinen et al. 1980, 1981, Komi et al. 1982), the specific effects of strength training utilizing high tension contractions of a long duration (1-3 s) are more obvious and may be also demonstrated by a worsening in isometric force-time characteristics and/or in concentric explosive force production. To demonstrate improvements in explosive force production, which is an important performance characteristic in several sports activities, specific training with high contraction velocities using low loads seems to be required (e.g. Ikai 1970, Viitasalo et al. 1981, Komi et al. 1982, Kanehisa and Miyashita 1983b, Kaneko et al. 1983). A similar conclusion tends to apply to high loads when produced explosively and with short duration during strength training (e.g.

Schmidtbleicher 1985).

A major question in strength training is, however, still the same now as it was many decades ago: What are the detailed mechanisms causing the changes in the neuromuscular system during strength training (see also Komi 1985)? This is so despite the fact that it is often relatively easy to demonstrate increases in muscular (strength) performance by almost any method provided that the frequency of exercises and loading intensities are progressively increased. However, attempts to provide answers for some of these possible mechanisms with respect to the motor unit activation were being made as early as in the 1950's (e.g. Friedebolt et al. 1957, Stoboy et al. 1959). These studies showed that muscle conditioning might, for example, improve the economy of the neuromuscular system; indicating that fewer motor units might be activated after training for a given force of contraction. It is also very likely that the adaptations in maximum integrated electromyographic activity (IEMG) during strength training tend to be highly individual (e.g. Stoboy and Friedebolt 1968); resulting in changes, for example, in the economy of the muscle contraction at different times. Another common scientific approach has been based on attempts to investigate the underlying biochemical processes taking place in the muscle during strength training. The introduction of the needle biopsy technique (Bergström 1962) therefore led to studies designed to examine various training-induced adaptations also in different muscle types of human skeletal muscle. Although evidence, for example, for muscular hypertrophy seems to exist, the magnitudes and the time courses of both neural and hypertrophic changes during strength training have not been conclusively determined (for a review see McDonagh and Davies 1984).

It can, however, be summarized from the present evidence available that in previously untrained subjects it seems reasonable to assume their great initial increases in muscular strength take place mainly due to increases in the neural activation of the muscles with a gradually increasing contribution of hypertrophic factors (e.g. Moritani and Devries 1979; see also Häkkinen and Komi 1983a). These early increases observable in maximum IEMG may result from increased synchronization of motor units (e.g. Friedebolt et al. 1957, Düntsch and Stoboy 1966) and/or from an increased number of active motor units and/or from an increase in their firing frequency due to the training effect per se. The decreases noted in maximum IEMG during detraining following heavy resistance strength training tend to be in line with these suggestions (e.g. Häkkinen and Komi 1983a). In addition to these possible adaptations taking place within the nervous system in voluntary contractions, training effects may also take place in reflex responsiveness (e.g. Milner-Brown et al. 1975, Sale et al. 1979, 1982). Hypertrophic changes have been reported to take place during prolonged heavy resistance strength training in both muscle fibre types, although it may be larger in fast twitch muscle fibres (e.g. MacDougall et al. 1977, Häkkinen et al. 1981, Komi et al. 1982, Houston et al. 1983). Strength training has not, however, been shown up till now to cause any changes in muscle fibre distribution. The reason for this may be the fact that the strength training stimuli indeed may not be sufficient to cause any transformation of the slow twitch type into the fast twitch type fibres and/or that the stimuli received during the recovery periods to the muscles (possibly through Ia afferent drive) overrule the neurogenic stimuli during training (e.g. see Howald 1982). These notions support the belief that genetic factors are important in determining the variance observed among individuals in muscle fibre composition (Komi et al. 1977; see also Saltin 1973). The variations observable in the presently available information about various training-induced adaptations may, however, lead one to suggest that the magnitudes and the time courses of the adaptations in various components of the neuromuscular system during strength training might be related, for example, to the type, intensity and/or duration of the training. Less is also known about these adaptations during the prolonged intensive training of well trained subjects. The pretraining status of the subjects may therefore be of great importance in this respect (e.g. Düntsch and Stoboy 1966, Müller 1970), while it is known that improvements in strength are more limited in highly trained subjects and/or elite strength athletes (e.g. Alén et al. 1984, Häkkinen 1985) than in previously untrained subjects.

Since training for explosive force production with high contraction velocities and with low loads will result in different enhancements in neuromuscular performance in comparison to training for maximal strength, the adaptations in the neuromuscular system responsible for this change may also vary to some degree. It has been demonstrated (e.g. Coyle et al. 1981, Komi et al. 1982) that training with high contraction velocities with low loads will result in smaller muscle hypertrophy than that which results from heavy resistance strength training. Only some suggestion is available to indicate that neurological factors might to a great degree contribute to the improvement in voluntary explosive force production during training with high contraction velocities with low loads (e.g. see Schmidtbleicher 1985). Because of the nature of normal movement and of most sports activities (Komi 1984), investigation of training-induced changes and possible adaptations of the neuromuscular system during various stretch-shortening cycle exercises would therefore correspond to both scientific and practical interests.

The endocrine system is known to respond to an acute exercise bout (e.g. Kuoppasalmi et al. 1981) and also to long-term physical activity and/or training (e.g. Aakvaag et al. 1978, Remes et al. 1979). However, less is known about hormonal adaptations during strength training. Lack of appropriate control of intensity and duration of the training stimuli may have contributed to the relatively great variation in the obtained results (for a review see Terjung 1979, Galbo 1983). Only minor changes have been reported to occur in examined endogenous hormone levels during short term strength training (Young et al. 1976, Hetrick and Wilmore

1979). Neither is much information available on these aspects during prolonged strength training of different types and on hormonal adaptations of well trained subjects. It has, however, been suggested (e.g. Remes et al. 1979, Kuoppasalmi et al. 1981) that long-term physical training could, for example, increase endogenous androgen production during vigorous training.

These variations observable in the present state of knowledge, especially that concerning the magnitudes and the time courses of various adaptations taking place in the neuromuscular system during strength training, led to the present series of experiments. More specifically, the present studies were designed:

1) to investigate the effects of prolonged heavy resistance strength training of different intensities on electromyographic, muscle fibre and various force production characteristics of leg extensor muscles and on some serum hormone levels. The testing of the present subjects, who were already accustomed to strength training, was carried out periodically to enable examination of the neuromuscular function during the whole course of the 24-week training period.

2) to utilize similar methods in another training project of the same duration carried out in order to investigate possible specific effects of explosive type strength training, including exercises with high contraction velocities with low loads, on various variables of force production and on possible adaptations in the neuromuscular system taking place during the training

3) to examine the possible effects of detraining by performing the measurements in both training projects during the course of 12 weeks following the training periods.

2. RESEARCH METHODS

2.1. Subjects

A total of 29 healthy male subjects accustomed to strength training in a non-competitive manner for their own conditioning purposes volunteered for the present studies (I-VI). From this subject material 11 subjects (called group A) participated in the supervised heavy resistance strength training. The data collected from this training project are presented selectively in papers I, II, IV and VI. The data from 10 subjects (group B) who took part in the supervised explosive type strength training are reported in papers III and V and also selectively in papers I and VI. 8 subjects (group C) who maintained their normal unsupervised training throughout the entire experimental period were used as a control group (reported concomitantly in papers I, II, IV and VI). Table 1 presents the physical characteristics of these three subject groups at the beginning of the projects.

2.2. Testing procedures and experimental design

The experimental period of 36 weeks consisted of 24 weeks of training and 12 weeks of detraining. The subjects in the heavy resistance as well as in the explosive type strength training projects were tested primarily on ten identical occasions at four-week intervals before, during and after the entire experimental period. The measurements in the unilateral isometric conditions and the muscle biopsies were performed on separate testing occasions one week after the bilateral measurements four times at twelve weeks intervals.

Blood samples for the determination of serum hormones were taken at four and/or eight-week intervals during the course of the experiments.

TABLE 1. Mean (±SD) of the physical characteristics of the subject groups during the pretests

Subject groups	n	Age (years)	Height (cm)	Weight (kg)	Percentage of body fat (%)
Papers I, II, IV and VI					
Heavy resistance strength training (group A)	11	25.6±4.3	178.5±6.7	77.4±6.9	15.8±5.0
Papers I, III, V and VI					
Explosive type strength training (group B)	10	27.1±3.2	176.3±5.4	74.7±9.6	14.7±2.8
Papers I, II, IV and VI					
Control group (group C)	8	27.0±5.1	179.7±3.7	75.6±8.2	14.2±3.0

Figure 1 summarizes the experimental design and the timetable of the various tests performed four to ten times during the course of the experimental periods. The control group participated in the identical pre- and post-measurements which consisted of all the examined testing variables.

EXPERIMENTAL DESIGN

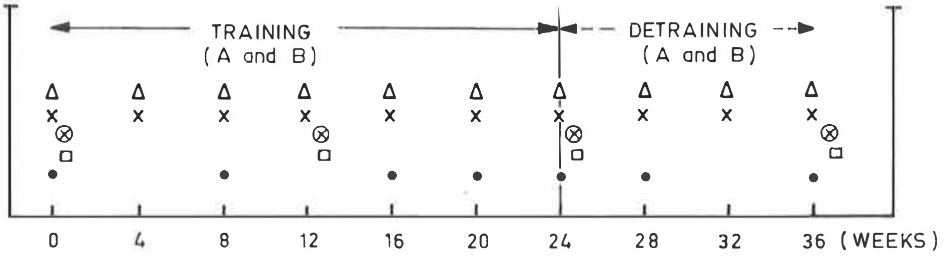
STRENGTH TRAINING PROJECTS:

A. Heavy resistance strength training: (n=11)

- supervised training with variable high loads for 24 weeks
- detraining for 12 weeks

B. Explosive type strength training: (n=10)

- supervised training with variable explosive type jumping exercises with low loads for 24 weeks
- detraining for 12 weeks



MEASUREMENTS:

(4-10 times in projects A and B)

Neuromuscular performance:

Δ Antropometric variables:
- bodyweight
- body fat
- thigh girth

⊗ Muscle biopsy
- fibre distribution
- average fibre areas

• Blood samples:
- serum hormones

x Bilateral isometric leg extension:
- maximal force
- force-time variables
- relaxation

x Jumping performances on force platform:
- concentric force-velocity curve
- counter-movement jumps
- drop jumps

□ Unilateral isometric knee extension
- maximal force
- force-time variables
- relaxation

□ Reflex measurements
- reflex time variables
- reflex amplitude

x □ Electromyographic measurements:
- maximal IEMG
- IEMG-force curve
- IEMG-time curve
- reflex EMG

Control group (n=8):
- unsupervised habitual strength training
- all measurements at the pre- and post-testing occasions

FIGURE 1. Experimental design of the present studies

2.2.1. Maximal voluntary bilateral isometric force, force-time and relaxation (I-III)

Maximal isometric force and various force-time and relaxation-time variables in the bilateral leg extension were measured by an electromechanical dynamometer (Komi 1973). In these measurements the knee and hip angles of the subjects sitting on the dynamometer were 107 and 110 degrees, respectively. The force was sensed by a strain-gauge system, amplified and stored on magnetic tape (Racal Store 7) and analyzed with a HP 1000 F computer system.

During the testing sessions the subjects were advised carefully to produce their maximal force against the footplate in response to an auditory signal as quickly as possible; and to maintain the maximal force as long as the signal continued (2.5 s). They were also instructed to relax the force as quickly as possible when the signal ceased. These instructions were repeated carefully every ten testing sessions during the course of the training and detraining periods. Each testing occasion consisted of a few familiarization and warm-up trials followed by three to six actual testing contractions.

Each contraction was first analyzed for its maximal force level during the recorded time period. The entire force-time curve was then analyzed. In the relative scale the times taken to increase the force from the level of 10 per cent separately to 30, 60 and 90 % of maximal force were calculated (see Viitasalo and Komi 1978, Häkkinen et al. 1980). In the absolute scale the corresponding calculations were performed from the level of 100 N to 500, 1000, 2000 and 3000 N force level. The maximal rate of force production ($N \times s^{-1}$) was also calculated (for details see Viitasalo et al. 1980). The analysis of the f-t curve also consisted of the calculations of average force produced during different absolute time periods from the start of the force production after the selected threshold. Each time period was 100 ms in duration; so that the force was analyzed for 9 consecutive (and half over each other) periods up to 500 ms (0-100, 50-150, 100-200, 150-250, 200-300, 250-350, 300-400, 350-450, 400-500 ms). The relaxation-time curve was analyzed in the relaxation phase of the contraction with a starting force level of 85 %. The times needed to relax the force to 60, 30 and 10 % as well as the maximal rate of relaxation ($N \times s^{-1}$) were calculated (for details see Viitasalo et al. 1980).

The reproducibility of the measurement of maximal isometric force is reportedly high (r = .98, e.g. Viitasalo et al. 1980). In the f-t analyses the force threshold of 50 N was used for the starting point of the calculations; and the selection of the present variables were also based on our previous investigations (Viitasalo and Komi 1978, Viitasalo et al. 1980) demonstrating relatively high reproducibilities for these f-t variables both in the test-retest (r = .80-.92) and in the day to day (r = .66-.76) comparisons.

2.2.2. Jumping performances (IV and V)

Each subject performed maximal voluntary jumps on the force-platform (Komi et al. 1974) sensitive to the vertical ground reaction force. The first jump, called a squat jump (SJ) was performed from a semisquatting position (a knee angle of 90 degrees measured by an electrical goniometer) with no allowance for preparatory counter movement (Komi and Bosco 1978). In a second jump, called a counter-movement jump (CMJ) (Komi and Bosco 1978) the subject started from a standing position with a preliminary counter movement (down to the phase corresponding to the starting position in SJ) followed by an immediate jump upwards. The squat and counter-movement jumps on the force platform were also performed with various extra loads (Bosco and Komi 1979a). In these jumps the loaded barbell was kept on the shoulders and loads of 20, 40, 60, 80 and 100 kg were used. Two to three testing attempts in each jump were recorded from each subject.

These jumping performances were recorded on magnetic tape

(Racal Store 7). A vertical force-time curve produced by each jump and the flight time gave a basis for computerized (HP 1000 F) calculation of average eccentric and concentric contact times, vertical velocity at take-off, average force, average mechanical power and the height of rise of center of gravity (for details see Asmussen and Bonde-Petersen 1974, Bosco and Komi 1979b, Bosco 1982). Further analysis was carried out of the load-vertical jumping height relationships, which has been shown also to characterize the force-(angular) velocity relationship in SJ and CMJ jumps (Viitasalo 1985).

The subjects were also tested on the force platform with various drop jumps (DJ). In these tests the subjects dropped themselves from heights of 20, 40, 60, 80 and 100 cm on to the force platform with subsequent jumps upwards (for details see Komi and Bosco 1978). These performances were also recorded on magnetic tape. Vertical force-time curves of the jumps were computed for average eccentric and concentric contact times, average force, average mechanical power and height of rise of center of gravity (e.g. Bosco and Komi 1979a, Bosco 1982). Two testing jumps from each dropping height were recorded from each subject.

To ensure that the SJ, CMJ and DJ jumps were performed primarily by the leg extensor muscles, the subjects were instructed to keep their hands on the hips throughout the entire jump and to minimize lateral and horizontal displacement during the performance. In the SJ and CMJ performance with the various loads on the shoulders, the subjects gripped their hands on the barbell at the width of the shoulders. In all jumping performances the subjects were also instructed to land on the force platform in a position similar to that of the take-off. The test-retest reproducibility of the present jumping performances has been demonstrated in previous experiments (Komi and Bosco 1978, Bosco 1982, Bosco and Viitasalo 1982) to be very high (r = .90-.97). The day-to-day reproducibility of these jumping performances has also been reported to be relatively good (r = .75-.99, Viitasalo 1985).

2.2.3. Average maximal knee angular velocity (IV and V)

Average maximal knee angular velocity during the concentric knee extension movement was obtained using an electrogoniometer attached to the lateral side of the subject's knee joint. In this test the subject lay in a supine position with the knees flexed to a starting position of 90 degrees and the hips and the heels were kept on the ground. From this position the subject was instructed to extend his knees at the maximum speed for calculation of average knee angular velocity according to the duration of the phase and to the angular displacement (for details see Bosco and Komi 1979a and Bosco 1982). Two to three trials were recorded in each test from every subject.

2.2.4. Maximal squat lift (IV and V)

Maximal concentric force of the leg extensor muscles was measured by the squat lift exercise (Häkkinen and Komi 1981). In this test the subject bent his knees with a loaded barbell on the shoulders to a full squat (down to 70 degrees) and thereafter extended himself up. The trunk was kept as straight as possible and no bouncing was allowed at the bottom position of the squat. After a few warm-up lifts with weights from 60 to 85 % the subject started at the weight of 90 % of his supposed maximum and continued with increments of 2.5-7.5 kg. After two misses with the same weight the test was terminated. All the subjects had been familiarized with this lift in their previous normal training sessions before the premeasurements of the present studies.

2.2.5. Maximal voluntary unilateral isometric force, force-time and relaxation (VI)

Maximal isometric force and various force- and relaxation-time variables in the unilateral right knee extension were measured by a special dynamometer (Komi et al. 1979). The knee and hip angles of the subjects sitting on the dynamometer were kept at 90 and 110 degrees, respectively. The force was sensed by a strain-gauge system, amplified and stored on magnetic tape (Racal Store 7) and later analyzed using a HP 1000 F computer system. The methods used for this measurement and the instructions given to the subjects at each of the four testing occasions were similar to those of the measurement of the bilateral leg extension force parameters (see 2.2.1.).

Each contraction was first analyzed for its maximal force level. In the force-time analysis (see also 2.2.1.) in the relative scale the times needed to increase the force from the level of 10 per cent separately to 30, 60 and 90 % were calculated. In the absolute scale the corresponding calculations were performed from the level of 20 N to 100, 200, 300, 400, 500 and 600 N force level (see also Häkkinen and Komi 1983b). The analysis of f-t curves also consisted of the calculations of average force produced during 9 consecutive (and half over each other) absolute time periods (100 ms in duration) from the start of the force production after the threshold of 5 N (see also 2.2.1.). The relaxation-time curve was analyzed in the relaxation phase of the contraction with a starting force level of 85 % and the times needed to relax the force to 60, 30 and 10 % were calculated (see also 2.2.1.).

2.2.6. Electromyographic measurements during voluntary isometric and jumping performances (II-VI)

Electromyographic activity (EMG) was recorded from the rectus femoris (RF), vastus lateralis (VL), and vastus medialis (VM) muscles of the right leg both during several voluntary isometric and various jumping performances and also during reflex contractions (for reflex EMG analyses see 2.2.7.).

Bipolar (20-mm interelectrode distance) surface EMG recording (Beckman miniature-sized skin electrodes) was employed. The electrodes were placed longitudinally on the motor point areas of the examined muscles as determined by a Neuroton 626 stimulator. The skin was prepared by sponging it with alcohol and rubbing it with sand paper. The positions of the electrodes were marked on the skin by small ink dots with the help of a needle following the established practice (Häkkinen and Komi 1983a). These stained dots ensured the same electrode positioning in each test throughout the entire 36-week experimental periods. EMG signals were amplified with Brookdeal 9432 preamplifiers (60 dB, 1-1000 Hz) and stored on magnetic tape simultaneously with all the other recorded signals. Electromyographic activity of each testing performance was integrated (IEMG for 1 s) for each muscle separately using a HP 1000 F computer system. In some instances IEMG was averaged for the three examined muscles to have a parameter to express the total type of activity of the leg extension movements. The sampling frequency employed in the analog-to-digital conversion was 1000 Hz for both EMG and forces. In the maximal bilateral and unilateral isometric contractions the sampling time for EMG was similar (2.0 s) to that of the respective average maximal force (from 500 ms after the force thresholds to 2500 ms). In the various jumping performances (SJ, CMJ and DJ, see 2.2.2.) this sampling time for EMG consisted of the periods of the eccentric and concentric phases of each jump. The reproducibilities of IEMG and/or IEMG/average force have shown satisfactorily high values in our previous studies both during isometric (r = .98, Viitasalo et al. 1980) and jumping performances (r = .94-.97, Bosco 1982). The day-to-day reproducibility for IEMG has also been reported to be relatively good (r = .73-.86, Viitasalo and Komi 1975, see also Komi and Buskirk 1970).

The EMG of the maximal isometric bilateral and unilateral contractions was also analyzed for the IEMG-time curves. In this IEMG-time analysis, EMG was integrated (expressed also for 1 s) for 9 consecutive time periods of 100 ms in duration (0-100, 50-150, 100-200, 150-250, 200-300, 250-350, 300-400, 350-450, 400-500 ms) from the start of the isometric contraction after the thresholds used for the calculations of the respective average forces (see also 2.2.1. and 2.2.5.).

The maximal isometric bilateral and unilateral contractions (see 2.2.1. and 2.2.5.) were followed by the measurements of five submaximal contractions. In these submaximal contractions the subject raised the force to the required level, which was maintained for 2.5 s, during which time the recording was made. The submaximal force levels were registered in a random order at 20 % intervals between 20 and 80 % of the maximum contraction. EMGs of each muscle during these contractions were also integrated (from 500 ms to 2500 ms) and expressed for 1 s similarly to that of the maximal isometric contractions.

The EMGs during the maximal concentric knee extension movement (see 2.2.3.) were recorded for the period of the performance. These EMGs were integrated (IEMG for 1 s) and averaged for the three muscles examined.

2.2.7. Reflex measurements (VI)

The patellar reflexes of the right knee were measured on the dynamometer (Komi et al. 1979) also used for the unilateral voluntary isometric contractions. Here too the knee and hip angles of the subject were 90 and 110 degrees, respectively. During these measurements the subjects kept their eyes closed and were instructed to relax while sitting on the dynamometer. Six to nine reflexes were measured in each testing session; these were preceded by a few warm-up voluntary contractions.

The reflex hammer (see Viitasalo et al. 1980, Häkkinen and Komi 1983b,d) was dropped from an angle of 90 degrees with respect to the patellar tendon. The tap to the tendon was sensed by a microswitch embedded in the hammer. The force produced during these reflex contractions in isometric condition was recorded and stored on magnetic tape simultaneously with a signal of the microswitch, with EMGs (of the RF, VL and VM muscles) and a timing signal of 1000 Hz. The signals were later led via a tape recorder to a multichannel graphic recorder with a speed reduction of 16 times.

In the analysis of these reflex contractions the total reflex time was divided into reflex latency (LAT) and reflex electromechanical delay (EMD), using the threshold of .010 mV and 1 N for EMG and force, respectively. For both the time and the amplitude variables of EMG the average for the values of the three (RF, VM and VL) muscles were calculated. The reading accuracy from the graph paper for time was 1 ms. The reproducibilities for LAT and EMD have in our earlier studies (e.g. Viitasalo et al. 1980, Häkkinen and Komi 1983b,d) been found to be satisfactory (r = .90-.91). EMG and the force of the reflex contractions were also analyzed for their peak-to-peak amplitudes (for details see Häkkinen and Komi 1983d). The reading accuracy for EMG amplitude was 0.5 mm (1 mm = .010 mV) and for reflex force amplitude 1 N. The reflex responses were analyzed if the peak-to-peak amplitude of the force had reached the level of 10 N. This selection was based on our previous studies (Häkkinen and Komi 1983b,d) to increase the reproducibility of the examined variables. For each reflex parameter the average of two best reflexes was used for further analyses.

2.2.8. Muscle biopsy variables (II and III)

Muscle biopsies were obtained in the training projects A and B four times at twelve week intervals (see Figure 1) from the vastus lateralis muscle of the left leg of the subject with the needle biopsy technique (Bergström 1962). Special care was taken to take all the biopsies at each session at comparable positions from the origin of the muscle and at the same depth in the muscle of each subject. The importance of the control of these aspects has recently been demonstrated (e.g. Lexell et al. 1983, Henriksson-Larsén et al. 1985).

Histochemical stainings for myofibrillar ATPase (Padykula and Herman 1955) were used to classify the fibres as fast twitch (FT) or slow twitch (ST) fibres (Gollnick et al. 1972). The number of the fibres counted from the photographs in training project A was 424 (± 258), 463 (± 105), 572 (± 270) and 515 (± 257) and in training project B 452 (± 173), 559 (± 221), 656 (± 227) and 485 (± 140) for the four measurements, respectively. The corresponding values for the two measurements of the control group (C) were 589 (± 215) and 501 (± 103), respectively.

For calculation of average fibre cross-section areas and FT/ST area ratio, ten representative fast and ten slow cells were selected. This selection always took place from the same are, in which the cross-section appeared perpendicular to the fibre orientation. Care was also taken to choose fibres with distinct cell borders, never close to the edge of the sample and with no tendency to longitudinal cuts. These criteria have been demonstrated to have an important role in this selection (e.g. Blomstrand et al. 1984). The sample was reflected by a microscope (Prado Universal Ernst Leitz 6 MBH Wetzlar) onto a digital board (Summagraphics 10, Data Tablet/ Digitizer) which was connected to a computer (HP 1000 F). The circumferences of the cells were stored in the system, which calculated the average cross-section areas for the FT and ST cell groups separately (for details see Viitasalo and Mäkinen 1980). The representativeness of this type of subsample in the calculation of the fibre cell areas for the entire biopsy sample has been demonstrated to be relatively high (r = .90-.92, Viitasalo and Mäkinen 1980) with this summagraphics system. The fibre areas represent arbitrary but in relative terms correct values used for repetitive intraindividual comparisons and for comparisons of the relative changes during the experimental period between the groups. This computerized method has been utilized previously for these types of comparisons of muscle fibre areas calculated in arbitrary units (e.g. Häkkinen et al. 1981, 1984, Alén et al. 1984). Using the FT% and FT/ST area ratio values the relative area occupied by the FT cells in the total fibre area was also calculated (the corrected FT%, in detail see Viitasalo et al. 1980).

2.2.9. Anthropometric measurements (I-VI)

In addition to the measurement of the weight and height of the subject, the amount of fat in the body (fat percentage) and fat free weight (FFW) were calculated from measurements of skinfold thickness (Durnin and Rahaman 1967). The measurement of the thigh girth was made with a tape applied around the relaxed muscles with the subject in a sitting position. The proximal, medial and distal portions of the thigh were measured and averaged for further analyses.

2.2.10. Blood samples (I)

After 12 h of fasting and 1 day of reduced training, blood samples were drawn at 8.00 a.m. from the antecubital vein of each subject in the training projects A and B at four/eight-week intervals during the course of these two experiments (see Figure 1). Serum samples for the hormone determinations were kept frozen at -20°C until assayed. All the analyses were performed at the Department of Clinical Chemistry in the University of Oulu.

The assays of serum cortisol, testosterone, follitropin (FSH), lutropin (LH), and estradiol were performed by radioimmunoassays using reagent kits from Farmos Diagnostica (Turku and Oulunsalo, Finland); of prolactin using radioimmunoassay kits from Diagnostic Products Corporation (Los Angeles, Ca., USA); and of somatotropin using kits supplied by Pharmaxia Diagnostics (Uppsala, Sweden). The concentrations of serum sex hormone binding globulin (SHBG) were determined by an immunoradiometric method using reagent kits from Farmos Diagnostica. All the assays were carried out according to the instructions of the manufacturers.

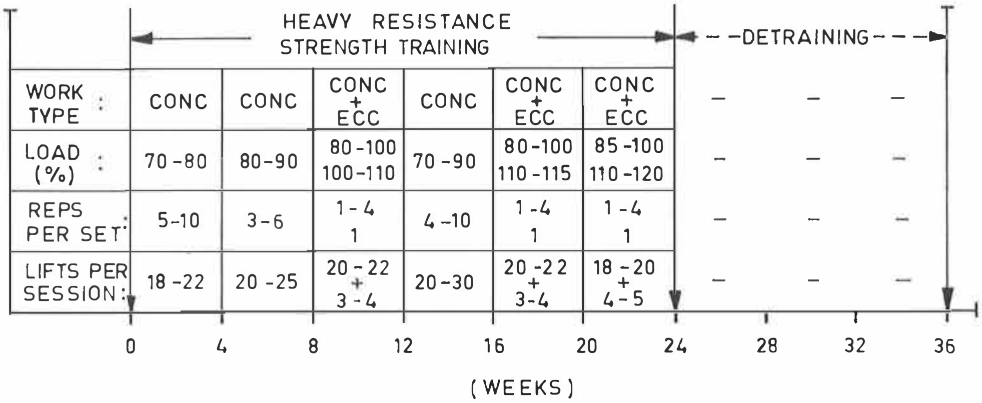
2.2.11. Statistical methods

Conventional statistical methods were employed to calculate the mean ($\bar{x}$), standard deviation (SD), standard error of the mean (SE), and linear coefficient of correlation. In the training project A, differences between values before and after the heavy resistance strength training and separately after this training and the detraining were tested for significance by Student's two tailed t-test (paired). This testing was also used in the training project B. The differences between the pre- and post-values of the control group (C) were also tested by Student's two tailed t-test (paired). The training influences on the examined parameters between the groups were additionally tested for significance using analysis of variance and Student's two tailed t-test (unpaired). The level of significance was set at 0.05.

2.3. Training programs

2.3.1. Heavy resistance strength training

The training program in the heavy resistance strength training project (group A, n=11) consisted of three training sessions a week over a 24-week period. A full squat-lift, in which the subject squatted with a loaded barbell on the shoulders, was the main strengthening exercise for the leg extensor muscles. The load on the barbell ranged variably between 70 and 120 % (of one maximum repetition) during each training month (see Figure 2). The total number of lifts per



WORK TYPE :	CONC	CONC	CONC + ECC	CONC	CONC + ECC	CONC + ECC	–	–	–
LOAD (%) :	70-80	80-90	80-100 100-110	70-90	80-100 110-115	85-100 110-120	–	–	–
REPS PER SET :	5-10	3-6	1-4 1	4-10	1-4 1	1-4 1	–	–	–
LIFTS PER SESSION :	18-22	20-25	20-22 + 3-4	20-30	20-22 + 3-4	18-20 + 4-5	–	–	–

FIGURE 2. Training program of the subjects in the heavy resistance strength training project (group A)

training session varied between 18 and 30. In the concentric squats with the loads between 70 and 100 % 1-10 reps per one set were performed. During the third, fifth and sixth training months the subjects also performed 3-5 eccentric squat lifts (1 rep per set) with the load of 100-120 % of one maximum (concentric) repetition (Figure 2). In these eccentric contractions the subject lowered (3-4 s in duration) the barbell from an erect position to a full squat, and thereafter was helped to stand up by two assistants helping at the ends of the barbell. The training program also included light (60-80 % of one maximum repetition) concentric exercises for trunk, arms and legs to minimize the risk of injury, and to make training more interesting. Each training session during the course of the entire heavy resistance strength training period of 24 weeks was carefully supervised.

The heavy resistance strength training was followed by a 12-week detraining period (see Figure 2). During this period the strength training was terminated but the subjects maintained their normal daily activities throughout the entire detraining.

2.3.2. Explosive type strength training

The training program in the explosive type strength training project (group B, n=10) consisted of three training sessions a week for a period of 24 weeks. In order to develop primarily explosive force production of the leg extensor muscles, several jumping exercises without extra load and with light loads were performed. The subjects were carefully instructed to perform all the jumping exercises with maximal effort. The following jumping exercises were used:

1) a counter-movement jump with a loaded barbell on the shoulders
   - with loads ranging variably between 10-60 % of one maximum repetition
   - 10-25 jumps (4-6 reps per one set) per training session

2) a standing 5-jump
   - 30-60 jumps per training session

3) a hurdle jump with 5 hurdles
   - 30-60 jumps per training session

4) a drop jump
   - from the dropping heights of 30 to 60 cm followed by immediate rebounds
   - 30-60 jumps per training session

5) a drop jump with a reduced body weight
   - from the dropping heights of 30-60 cm followed by immediate rebounds

- the body weight was reduced by a rubber band fixed between the waist of the jumper and the ceiling of the gymnasium
- 30-60 jumps per training session

Jumping exercises 1, 3 and 4 were used all the time during the entire training period; and exercise 2 from the third training month on; and exercise 5 only during the fifth and sixth training months. The total number of jumps per training session ranged variably between 100 and 200 (100-120, 140-160, 130-150, 160-200, 140-160 and 120-140 during each consecutive training month). The subjects also performed some light strengthening exercises (with loads of 60 to 80 % of one maximum repetition) for the leg extensor muscles, trunk and arms to prevent injuries and to make training more interesting. Each training session during the course of the entire 24-week period was carefully supervised.

This training period was followed by a 12-week detraining period. During the detraining the explosive type strength training was terminated, but the subjects maintained their normal daily activities.

2.3.3. Training of the control group

The subjects of the control group (group C, n=8) were comparable to those participating in the heavy resistance and in the explosive type strength training projects in terms of their normal daily physical activities. These subjects did not participate in the supervised intensive and specific training but maintained their normal habitual strength training 1-3 times a week throughout the entire experimental period of 36 weeks between the pre- and post-testing occasions.

This habitual training with moderate intensity consisted of some overall strength training for the legs, arms and trunk and participating in other physical activities such as football, volleyball and jogging. The subjects were exercised only for their own conditioning purposes, that is, to keep fit. It was not expected that any great improvements in the neuromuscular performance capacities of these subjects would take place as a result of this light training, since these subjects had a training background of several years.

3. RESULTS

The results presented below represent only the most important findings obtained from the present series of experiments. For more details the original papers (I-VI) should be consulted. The results section is organized so that the results from the heavy resistance strength training and the following detraining are always presented first, followed by the findings from the explosive type strength training. The results of the control group are always presented last.

3.1. Maximal voluntary bilateral leg extension isometric force, force-time and relaxation

Heavy resistance strength training

The maximal isometric bilateral leg extension force increased during the 24-week heavy resistance strength training (group A) from 3987 ± 1025 to 5056 ± 1286 N corresponding to an average increase of 26.8 % ($p<0.001$). The increase in force was greater during the first 12 weeks than during the latter half of the period, and a plateau phase was noted during the last training month (Figure 3A). During the subsequent detraining the force decreased by 11.4 % down to 4482 ± 1064 N ($p<0.01$).

The average force-time curves in the absolute scale changed during training so that the times taken to reach lower force levels remained unaltered but a significant ($p<0.01$) decrease occurred in the time needed to reach the high (3000 N) force level. Only slight (ns.) changes took place during training in average forces of the first 4 time periods in the force- (absolute) time curve; but significant ($p<0.01$-0.001) increases were noted in the forces from the fifth

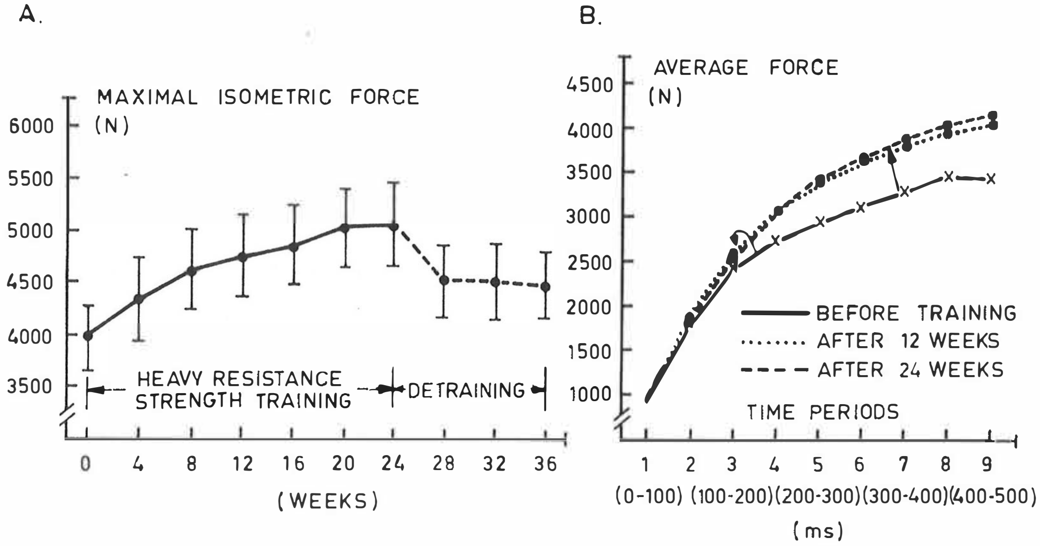


FIGURE 3. Mean (±SE) maximal bilateral leg extension isometric force during the course of the 24-week heavy resistance strength training and the following 12-week detraining (A); and average force-(absolute) time curves before and after the corresponding 12- and 24-week training (B).

(200-300 ms) period onwards (Figure 3B). In the relative scale the times needed to reach the examined force levels (30, 60, 90 %) were increased ($p<0.05$) during this type of training. During the detraining the changes in the examined force-time variables were relatively slight. Nonsignificant changes were noted in the relaxation-times both during training and detraining.

Explosive type strength training

The 24-week explosive type strength training (group B) resulted in an increase of 10.8 % ($p<0.05$) in maximal bilateral isometric force from 4001 ± 1112 to 4434 ± 1212 N (Figure 4A). This increase was smaller ($p<0.01$) than that of group A.

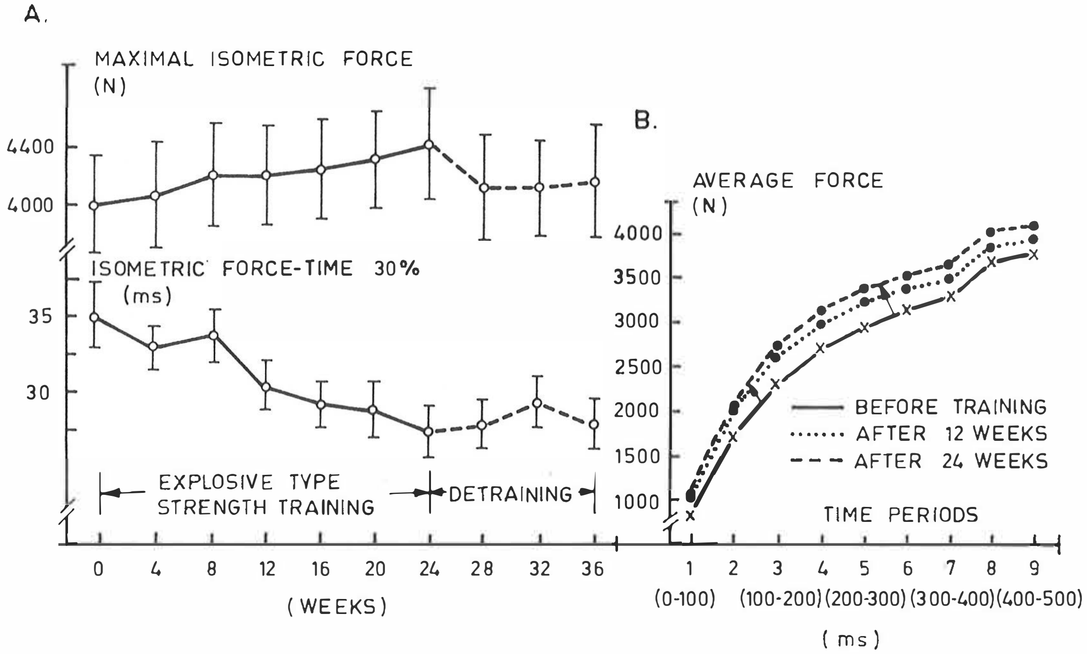


FIGURE 4. Mean (±SE) maximal bilateral leg extension isometric force and mean (±SE) time needed to produce a relative force level of 30 % during the course of the 24-week explosive type strength training and the following 12-week detraining (A); and average force- (absolute) time curves before and after the corresponding 12- and 24-week training (B)

During the following 12-week detraining a decrease of 5.9 % ($p<0.05$) took place in maximal force down to 4171 ± 1256 N.

Significant ($p<0.05$) decreases in the times of force production were observed both in the absolute and relative scales. This shortening in time to produce a low relative force level of 30 % from 35.3 ± 12.5 to 27.5 ± 7.7 ms ($p<0.05$) corresponded to a percentage change of 22.0 % (Figure 4A). This shortening differed highly significantly ($p<0.001$)

from the corresponding lengthening noted in group A. Significant ($p<0.05-0.01$) increases in average forces of the first 6 time periods in the force- (absolute) time curve took place during the training (Figure 4B). These increases for the first 3 periods were greater ($p<0.05$) than those of group A. The increase in the maximal rate of force production during training from 34171 ± 6772 to 42428 $N \times s^{-1}$ was 24.1 % ($p<0.001$) which was different ($p<0.05$) from the value noted for group A. During the detraining a slight (ns.) worsening in the examined force-time variables was observed. The relaxation-time parameters remained unaltered both during training and detraining.

Control group

A statistically nonsignificant increase in maximal isometric force from 3844 ± 1480 to 3919 ± 1657 N was observed in the control group between pre- and post-testing. The values for the examined force- and relaxation-time parameters remained unaltered in this group between the two measurements.

3.2. Maximal voluntary unilateral knee extension isometric force, force-time and relaxation

Heavy resistance strength training

The maximal voluntary unilateral knee extension isometric force increased during the 24-week heavy resistance strength training (group A) from 733 ± 201 to 835 ± 215 N ($p<0.01$) corresponding to an average increase of 13.9 %. This increase occurred primarily during the first half of the training period. During the following 12-week detraining the force decreased by 6.5 % ($p<0.05$) down to 781 ± 200 N.

Slight (ns.) shortening in the times taken to reach absolute higher force levels and concomitantly slight (ns.) increases in average forces of the examined time periods in the force- (absolute) time curve were noted during this training. In the relative scale, slight but nonsignificant increases in the times of isometric force production took place during the training. During the detraining the changes in the examined force-time parameters were slight. Statistically nonsignificant changes occurred in the relaxation-times both during training and detraining.

Explosive type strength training

A slight (ns.) increase in maximal unilateral knee extension isometric force from 633 ± 216 to 640 ± 184 N was noted during the 24-week explosive type strength training (group B). This increase was smaller ($p<0.05$) than that found for group A. During the following 12-week detraining the force decreased slightly (ns.) down to 603 ± 180 N.

The times of isometric force production decreased during this training both in the absolute and relative scales, reaching statistical significance ($p<0.05$) as regards the shortening of the force-time 30 % from 33.3 ± 4.3 to 29.9 ± 4.0 ms. This shortening differed ($p<0.05$) from the corresponding slight lengthening noted for group A. Slight but nonsignificant increases were noted in average forces of the examined time periods in the force- (absolute) time curve. During the 12-week detraining slight (ns.) worsening in the examined force-time variables were observed. Statistically nonsignificant changes took place in the relaxation-times both during training and detraining.

Control group

The control group showed a statistically nonsignificant change (from 644 ± 157 to 648 ± 112 N) in maximal unilateral isometric force between the pre- and post-tests. Slight worsening was noted in the examined force-time variables but the only significant ($p<0.05$) decrease was that of average force of the first time period in the force- (absolute) time curve. The relaxation-times remained unaltered in the control group between the first and last measurements.

3.3. Force-velocity curve during concentric contractions

Heavy resistance strength training

The 24-week heavy resistance strength training (group A) resulted in great increases primarily in the high force portions of the force-velocity curve (Figure 5A). This was observable during the course of the entire training period (Figure 5B). An average increase of 30.2 % ($p<0.001$) from 118.1 ± 19.2 to 153.9 ± 19.4 kg took place in the maximal concentric force of the leg extensors (the squat lift). A great incrase of 26.9 % ($p<0.001$) in the vertical jumping height and take-off velocity of SJ 100 was also noted during the training. The improvements became gradually smaller near the high velocity parts of the curve, where an increase of 7.3 % ($p<0.05$) in the jumping height of SJ 0 (from 34.3 ± 4.3 to 36.8 ± 4.2 cm) and a nonsignificant increase in the maximal knee extension velocity were observed. The shortening in the concentric contact times of SJ's during the training was slightly smaller at lower loads (SJ 0 - SJ 20; $p<0.05$) in comparison to that observed at higher loads (SJ 40 - SJ 100; $p<0.05$-0.01). The increase during this type of training in average forces and mechanical power produced during the contact phases of SJ's were more significant ($p<0.01$-0.001) at higher loads (SJ 40 - SJ 100). During the following 12-week detraining the maximal concentric force decreased by 11.2 % ($p<0.001$) down to 136.6 ± 17.8 kg and significant ($p<0.05$-0.01) decreases were observed in the heights and take-off velocities in SJ 20 - SJ 100. Slight but nonsignificant decreases in the height of SJ 0 and in the maximal knee extension velocity were noted during this period.

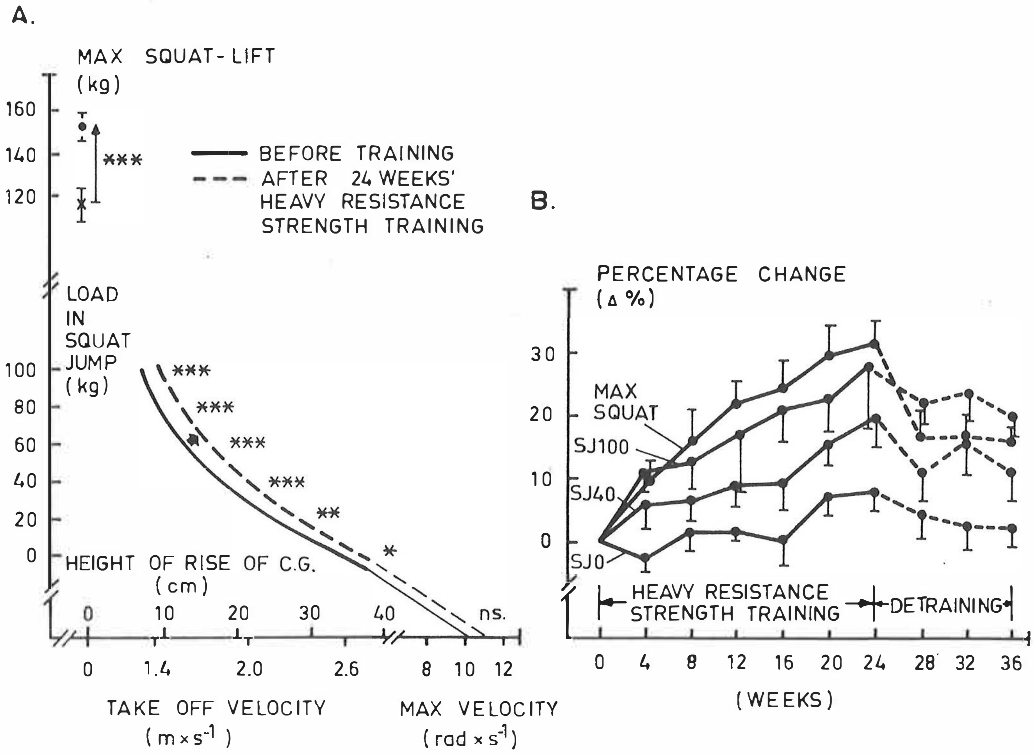


FIGURE 5. Average force-velocity curves of the leg extensor muscles during various concentric contractions before and after the 24-week heavy resistance strength training (A) and relative changes (±SE) in the heights of rise of C.G. in the squat jumps with loads of 0, 40 and 100 kg and in maximal squat lift during the course of the corresponding 24-week training and the following 12-week detraining (B)

Explosive type strength training

An increase of 6.9 % ($p<0.05$) from 119.3 ± 25.3 to 127.5 ± 24.8 kg in the maximal concentric force of the leg extensors occurred during the 24-week explosive type strength training (group B) (Figure 6). This change was smaller ($p<0.001$) than that noted in group A. The increases in other parts of the force-velocity curve were greater, and an improvement of 21.2 % ($p<0.001$) from 35.8 ± 4.0 to 43.4 ± 5.6 cm in the height of SJ 0 was noted during the training; which was distinct ($p<0.01$) from the values obtained for group A. This kind of training resulted in a great ($p<0.001$) improvement in the maximal knee extension velocity; differing ($p<0.05$) from the corresponding change noted in group A. The training

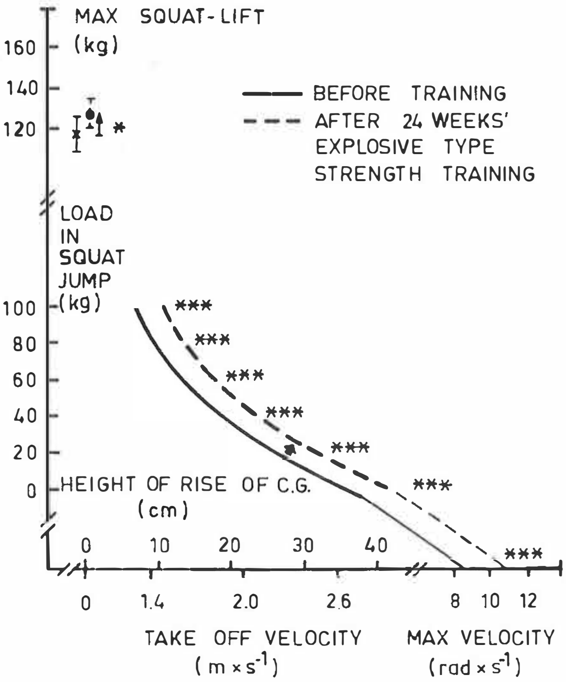


FIGURE 6. Average force-velocity curves of the leg extensor muscles during various concentric contractions before and after the 24-week explosive type strength training

resulted in a shortening in the concentric contact times which reached statistical significance ($p<0.05-0.001$) at lower loads. Significant ($p<0.05-0.01$) increases in average forces produced during the contacts of SJ's were observed during the training. The corresponding increases in average mechanical power were relatively large ($p<0.001$) at lower loads (SJ 0 - SJ 20) in comparison to the respective changes ($p<0.05-0.01$) at higher loads. During the detraining a decrease of 3.9 % ($p<0.05$) down to 122.5 ± 24.0 kg in the maximal concentric force was observed. The decrease in other parts of the force-velocity curve were generally relatively slight when, for example, the height of SJ 0 decreased (ns.) down to 41.3 ± 6.2 cm.

Control group

The control group demonstrated statistically nonsignificant changes in the force-velocity curve between the pre- and post-tests. A slight but nonsignificant increase was observed in the maximal concentric force of the leg extensors from 118.8 ± 23.8 to 122.9 ± 22.9 kg between the two measurements.

3.4. Counter-movement jumping performances at various loads

Heavy resistance strength training

Significant ($p<0.01-0.001$) improvements in the jumping heights of CMJ performances were noted during the 24-week heavy resistance strength training (group A). At higher loads this improvement in jumping height and take-off velocity was slightly greater. In CMJ 100 the magnitude of this increase from 8.5 ± 1.5 to 10.1 ± 2.0 cm was 18.8 % ($p<0.001$), while a corresponding increase in CMJ 0 from 35.7 ± 4.2 to 39.5 ± 4.7 cm was 10.8 % ($p<0.01$). Only slight changes occurred in the unweighing and in the eccentric times of CMJ's, while significant ($p<0.05-0.01$) shortening of the concentric contact times in all CMJ was noted. Average forces and average mechanical power calculated from various CMJ's showed significant ($p<0.01$) changes during the concentric phases of the contacts. During the 12-week detraining the heights of CMJ decreased ($p<0.05$).

Explosive type strength training

The jumping height of CMJ 0 increased during the 24-week explosive type strength training (group B) from 39.3 ± 3.9 to 46.2 ± 6.0 cm, corresponding to an average increase of 17.8 % ($p<0.001$). This change was larger ($p<0.05$) than that observed for group A. Significant ($p<0.001$) increases also took place in CMJ 20 - CMJ 100. Times of the unweighing and decelerating phases of CMJ 0 - CMJ 100 shortened ($p<0.05-0.01$) and great ($p<0.001$) decreases were noted in the concentric contact times of CMJ 0 - CMJ 80, and slightly smaller ($p<0.05$) in CMJ 100. Significant ($p<0.05-0.001$) increases were noted during the training in average forces and in average mechanical power produced during the unweighing, decelerating and positive work phases of all CMJ performances. During the 12-week detraining the heights of CMJ decreased ($p<0.05$).

Control group

The heights and the calculated parameters from the force records in CMJ 0 - CMJ 100 remained statistically unaltered in the control group between the two measurements.

3.5. Drop jumps performed from different dropping heights

Heavy resistance strength training

The drop jump performances from different dropping heights (from 20 to 100 cm) remained unaltered during the 24-week

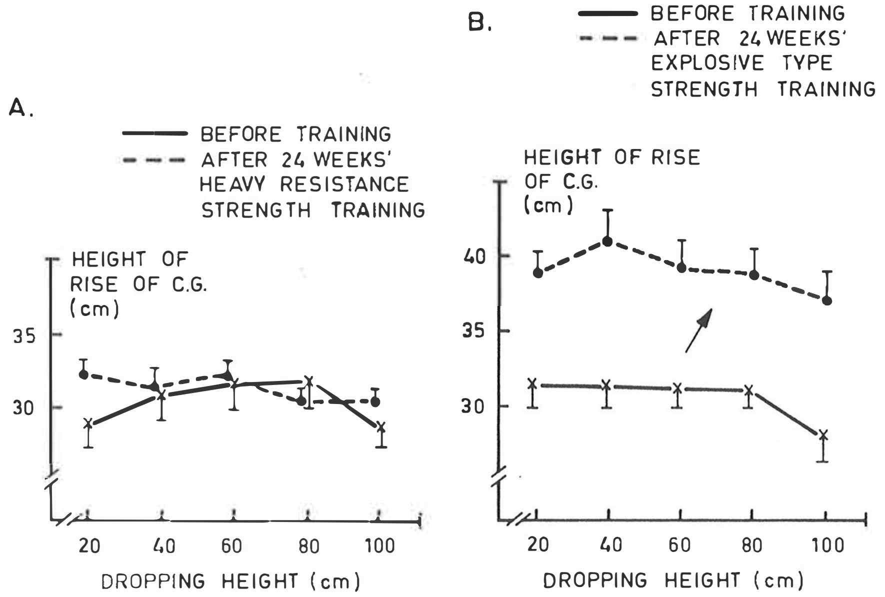


FIGURE 7. Mean (±SE) heights of rise of C.G. in the drop jumps performed from different dropping heights before and after the 24-week heavy resistance strength training (A) and before and after the 24-week explosive type strength training (B)

heavy resistance strength training (group A) (Figure 7A) with only one exception: the height of DJ 20 increased ($p<0.05$). Eccentric and concentric contact times lengthened ($p<0.05$) during the training in DJ 20 and DJ 40. Statistically non-significant increases were noted in average forces and average power during both contact phases of DJ performances. During the 12-week detraining only slight (ns.) changes occurred in the examined DJ performances.

Explosive type strength training

The 24-week explosive type strength training (group B) resulted in highly significant ($p<0.01$-0.001) increases in the jumping heights of all DJ performances (Figure 7B). These increases were greater ($p<0.05-0.01$) than those found with group A. Only slight changes occurred in the contact times of DJ performances. No statistically significant changes took place in average forces and in average mechanical power in the eccentric phases of DJ 0 - DJ 100; while the increases in the respective values of the concentric phases were significant ($p<0.05-0.001$). During the 12-week detraining the jumping heights of all DJ's decreased ($p<0.05$).

Control group

No statistically significant changes took place in the heights and the calculated parameters from the force records in DJ performances in the control group between the pre- and post-tests.

3.6. Electromyographic variables and their relationships to other performance criteria

3.6.1. Electromyographic variables in bilateral voluntary isometric leg extension

Heavy resistance strength training

Figure 8A shows the alterations of the maximum IEMGs of the VL, VM and RF muscles in the maximal bilateral isometric contraction during the course of the entire 24-week heavy resistance strength training (group A). During the first training month with low loads (70-80 %) the maximum IEMGs decreased ($p<0.05$). When the load intensities were increased and/or the training also included eccentric contractions, the values for the IEMG increased (except for the last training month). Significant increases occurred between the 4th and 12th week in the maximum IEMG of the VM ($p<0.05$), the RF ($p<0.01$) and the VL ($p<0.05$) muscles. This increase in the

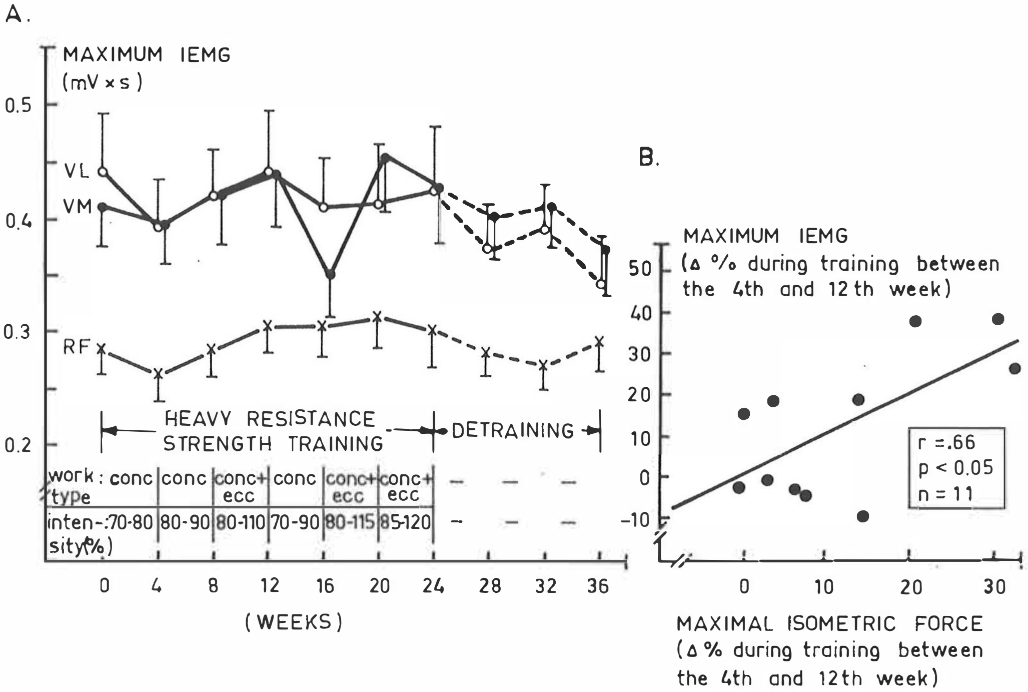


FIGURE 8. Mean (±SE) maximal integrated electrical activities (IEMG) of the vastus lateralis (VL), vastus medialis (VM) and rectus femoris (RF) muscles in the bilateral maximal isometric leg extension during the course of the 24-week heavy resistance strength training and the 12-week detraining (A) and the relationship between the relative changes in maximum averaged IEMG of the three leg extensor muscles and the relative changes in maximal force between the 4th and 12th week during the corresponding training (B)

overall average maximum IEMG of the three muscles correlated (r = .66, $p<0.05$) with the increase in maximal isometric force (Figure 8B). During the training with low loads from the 12th to the 16th week the maximum IEMG of the VM muscle decreased highly significantly ($p<0.001$). During the training between the 16th and 20th week significant increases were noted in the IEMGs of the VM ($p<0.01$) and in the average of the three muscles ($p<0.05$). During the 12-week detraining significant ($p<0.05$) decreases were noted in the average maximum IEMG of the examined muscles. This decrease in the maximum IEMG during detraining correlated ($r = .68$, $p<0.01$) with the decrease in maximal isometric force.

The average IEMG/force curve shifted to the right at all force levels ($p<0.01$-0.001) during the heavy resistance strength training when the force was expressed in the absolute scale. However, no significant changes were noted in the IEMG/force ratio in the relative scale.

The average IEMG-time curve of the muscles examined in the rapid isometric contraction shifted upwards during the first 12 weeks of heavy resistance strength training ($p<0.05$, for the time periods 2-6). The individual changes in this curve in overall average IEMG of the muscles for the time period 1 (0-100 ms) correlated ($r = .56$, $p<0.05$) to the changes in the corresponding average force of the same time period in the force- (absolute) time curve during this first 12 weeks of training. The entire IEMG-time curve shifted slightly downwards during the last half of the 24-week training period. During the 12-week detraining the IEMG-time curve remained statistically unaltered.

Explosive type strength training

Significant ($p<0.05$) increases in the maximum IEMGs of the examined muscles (VL, VM and RF) in the maximal bilateral isometric contraction took place during the 24-week explosive type strength training (group B). During the first half of the training the increases were slight; but larger during the latter half of the training when this increase in IEMG correlated ($r = .55$, $p<0.05$) with the respective change in maximal isometric force. During the 12-week detraining the maximum IEMGs decreased reaching a statistically significant

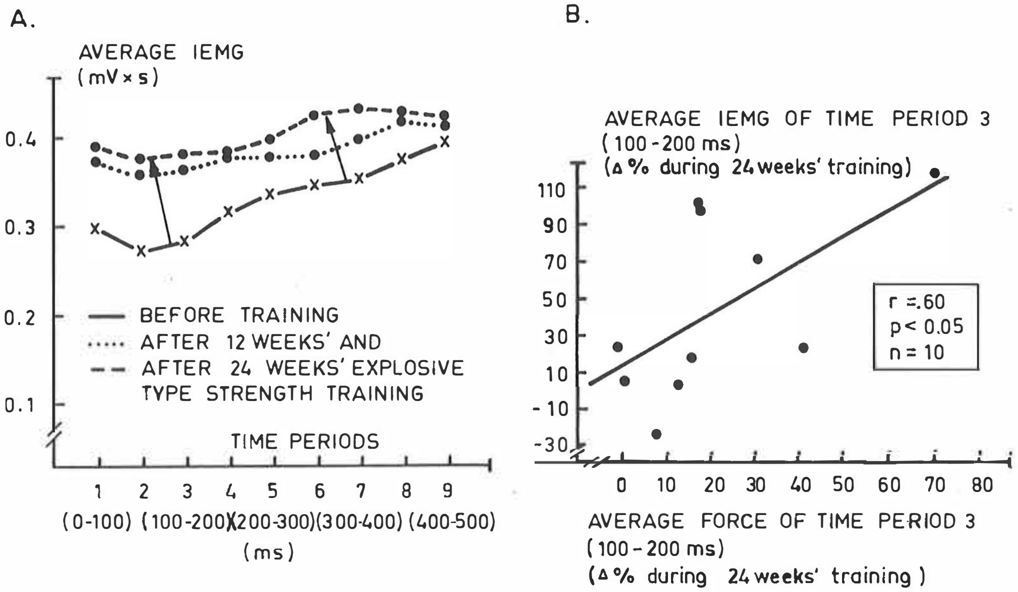


FIGURE 9. Average IEMG-time curves calculated from (maximal) average integrated electrical activities (IEMG averaged for the vastus lateralis, vastus medialis and rectus femoris muscles) produced during 9 consecutive (and half over each other) time periods of 100 ms in duration in rapid isometric bilateral leg extension before and after the 12- and 24-week explosive type strength training (A) and the relationship between the relative changes in averaged IEMG of the examined muscles in the beginning (the 3rd time period from 100 to 200 ms) of the IEMG-time curve and the relative changes in the corresponding force in the beginning of the force-(absolute) time curve after the corresponding 24-week training (B)

level ($p<0.05$) for the VL muscle.

No statistically significant changes were noted during the 24-week explosive type strength training in the examined average IEMG/force curves.

The average IEMG-time curve of the examined muscles in the rapid isometric contraction shifted upwards ($p<0.05-0.01$) during the course of the entire 24-week explosive type strength training (Figure 9A). The increases in overall average IEMG for the earlier portions (time periods 1-7) of the curve were larger ($p<0.05$) in comparison to those noted in group A. These increases in the IEMGs of the three muscles during the training correlated ($p<0.05-0.01$) with the increases in the average forces of the corresponding time periods in the force- (absolute) time curve as shown, for example, for the time period 3 ($r = .60$, $p<0.05$) in Figure 9B. During the 12-week detraining a slight (ns.) decrease was noted in the IEMG-time curve. These individual changes in the IEMGs correlated with the changes in the respective average force (for example, for the time period 3, $r = .71$, $p<0.05$).

Control group

The control group demonstrated only slight (ns.) changes in the averaged maximum IEMG of the examined muscles in the maximal bilateral isometric contraction between the pre- and post-measurements. The examined average IEMG/force and IEMG-time curves remained statistically unaltered between the first and last tests.

3.6.2. Electromyographic variables in unilateral voluntary isometric knee extension

Heavy resistance strength training

A significant ($p<0.05$) increase in the averaged maximum IEMG of the examined muscles in the maximal unilateral isometric knee extension took place during the first 12 weeks of heavy resistance strength training (group A). No change was noted in this variable during the last half of the training. The individual changes during training in the maximum averaged IEMG and in maximal isometric force correlated significantly with each other ($r = .74$, $p<0.01$). During the 12-week detraining a slight (ns.) decrease in maximum IEMG was observed.

A slight (ns.) shifting in the average IEMG/force curve to the right was noted during this training.

The average IEMG-time curve shifted slightly (ns.) upwards during the first 12 weeks of heavy resistance strength training; while an opposite change (ns.) downwards took place during the latter half of the training. The detraining caused only minor (ns.) changes in the IEMG-time curve.

Explosive type strength training

The averaged maximal IEMG of the three muscles increased slightly (ns.) during the 24-week explosive type strength training (group B); and decreased slightly (ns.) during the following 12-week detraining.

No statistically significant changes took place during this training in the average IEMG/force curve.

The average IEMG-time curve shifted slightly (ns.) upwards during the course of the entire 24-week training, and slightly (ns.) downwards during the 12-week detraining.

Control group

The control group demonstrated only minor (ns.) changes in the averaged maximum IEMG, in the average IEMG/force and in the average IEMG-time curves between the pre- and post-measurements.

3.6.3. Electromyographic variables in force-velocity curve during concentric contractions

Heavy resistance strength training

The 24-week heavy resistance strength training (group A) caused selective changes in the maximum IEMGs of the VM, VL and RF muscles recorded during the contacts of the squat jumps. While no change occurred in RF, the IEMG values of the VM and VL muscles increased during the training at all loads and the changes were significant ($p<0.05-0.01$) for the IEMG of VM in SJ 0 - SJ 100 and for the IEMG of VL in SJ 0. The individual changes in the maximum averaged IEMG of the three muscles in SJ 80 correlated ($r = .60$, $p<0.05$) with the changes in the jumping height of the respective SJ 80 during the earlier four weeks of training. The maximum averaged IEMG of the examined muscles in the test for maximal knee extension velocity increased only slightly during the training. Only slight (ns.) changes occurred in the IEMGs of the three muscles in SJ's during the detraining.

Explosive type strength training

Significant ($p<0.05-0.01$) increases in the maximum IEMGs of the VM and VL muscles recorded during the contacts of SJ performances at all loads took place during the 24-week explosive type strength training (group B). Only slight (ns.) changes were noted in the IEMG of the RF muscle. Significant ($p<0.05-0.01$) correlations between the individual changes in the averaged IEMG of the three muscles and in the jumping heights of the respective SJ performances (SJ 0 - SJ 100) were observed during the training. Figure 10A presents, as an example, the correlation for the changes in SJ 40 during the training ($r = .80$, $p<0.01$). A significant ($p<0.05$) increase in the maximum average IEMG of the examined muscles in the test for maximal knee extension velocity also took place during the training. Significant ($p<0.05$) decreases occurred in the IEMGs during the 12-week detraining in the VL muscle at all loads, while only minor changes were noted in the IEMGs of the VM and RF muscles. These decreases in the averaged IEMG of the muscles in SJ performances correlated with the changes in the respective jumping heights (for example, in SJ 40; $r = .66$, $p<0.05$, Figure 10B).

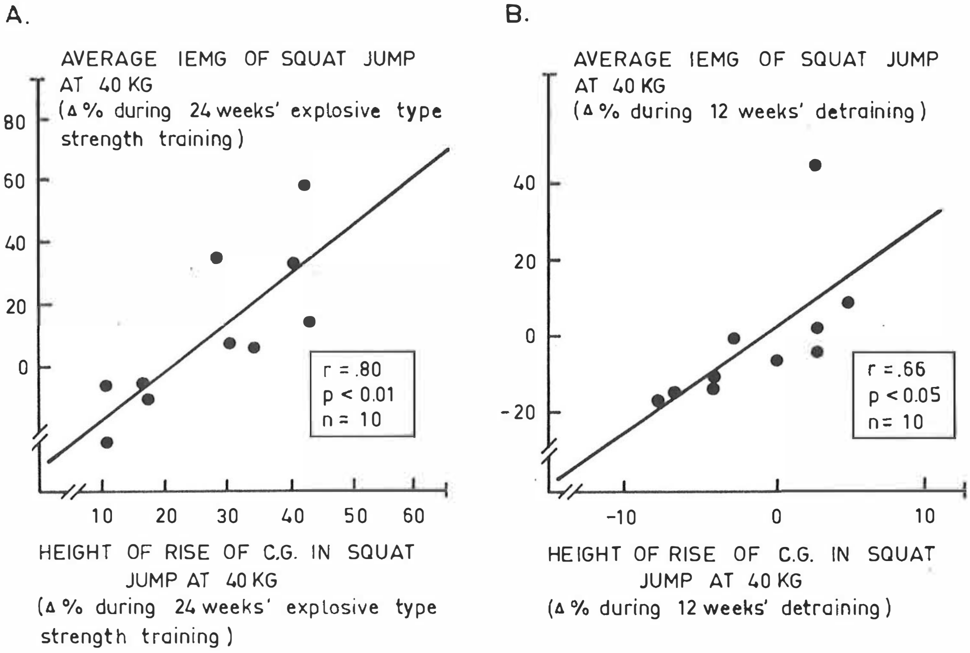


FIGURE 10. The relationships between the relative changes in maximal averaged integrated electrical activities (IEMG) of the three leg extensor muscles during the concentric contact phase of the vertical squat jump with a load of 40 kg (SJ 40) and the relative changes in the height of rise of C.G. in the corresponding squat jump after the 24-week explosive type strength training (A) and after the following 12-week detraining (B)

Control group

The control group showed only minor changes in the examined IEMGs of SJ performances during the experimental period. The only significant ($p<0.05$) change was the decrease in the IEMG of the VL muscle in SJ 60. The maximal averaged IEMG of the test for maximal knee extension velocity remained unaltered between the two test occasions.

3.6.4. Electromyographic variables in counter-movement jumps at various loads

Heavy resistance strength training

The IEMGs of the eccentric phases of the CMJ performances remained statistically unchanged at all loads (CMJ 0 - CMJ 100) during the 24-week heavy resistance strength training (group A). Significant ($p<0.05-0.01$) increases occurred during training in the IEMG of the VM muscle in the concentric phases of CMJ performances at all loads, while only slight (ns.) increases took place in the IEMGs of the VL and RF muscles. The IEMGs of CMJ performances remained statistically unchanged during the detraining.

Explosive type strength training

The 24-week explosive type strength training caused great increases ($p<0.05-0.01$) in the maximum IEMG of the VM muscle at all loads (CMJ 0 - CMJ 100) both during the eccentric and concentric phases. The corresponding increases in the VL muscle were significant ($p<0.05$) in CMJ 0 and CMJ 80, while only slight (ns.) changes occurred in the IEMG of the RF muscle. The individual changes during training in the maximum averaged IEMG of the three muscles during the contact phases of all CMJ's correlated with the changes in the jumping heights of the respective CMJ performances as shown, for the best correlation calculated, for CMJ 40 ($r = .95$, $p<0.001$) in Figure 11. During the 12-week detraining significant ($p<0.05$) decreases occurred in the IEMG of the VL muscle in the eccentric phase of CMJ 0 and 40, and in the concentric phase of CMJ 80 and 100.

Control group

The control group demonstrated only slight (ns.) changes in the maximal IEMGs of the examined muscles during the contact phases of the CMJ performances between the pre- and post-tests.

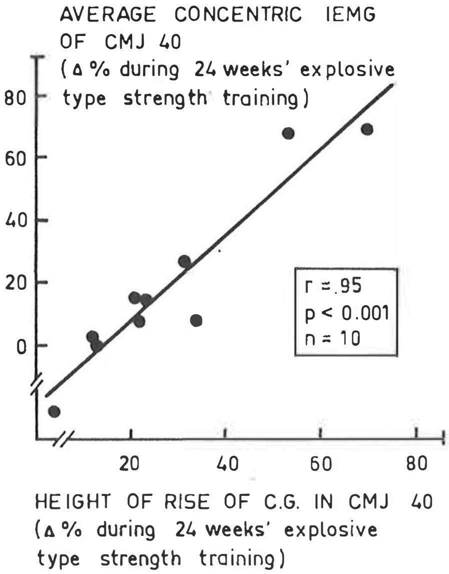


FIGURE 11. The relationship between the relative changes in maximal averaged electrical activity (IEMG) of the three leg extensor muscles during the concentric phase of the vertical counter-movement jump with a load of 40 kg (CMJ 40) and the relative changes in the height of rise of C.G. of the corresponding CMJ performance after the 24-week explosive type strength training

3.6.5. Electromyographic variables in drop jumps

Heavy resistance strength training

The maximal IEMGs of the examined muscles during the contact phases of the drop jumps performed from various (20-100 cm) dropping heights remained statistically unaltered both during the 24-week heavy resistance strength training (group A) and the following 12-week detraining.

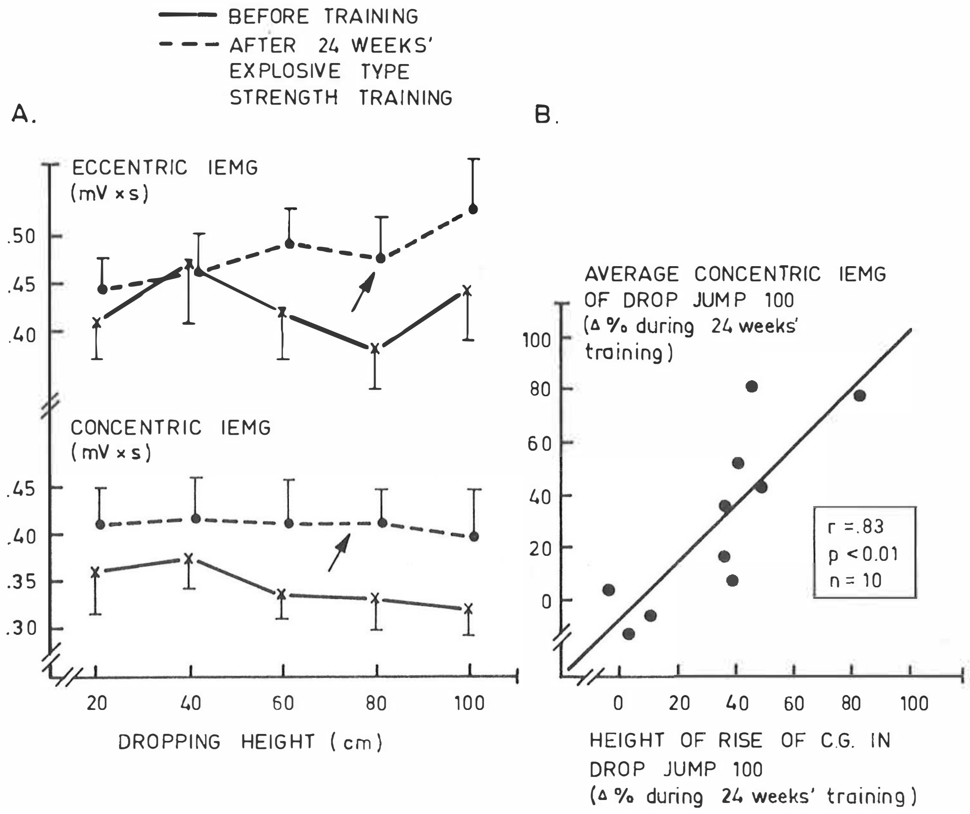


FIGURE 12. Mean (±SE) maximal averaged electrical activity (IEMG) of the three leg extensor muscles during the eccentric and concentric phases of the drop jumps performed from the various (20-100 cm) dropping height before and after the 24-week explosive type strength training (A) and the relationship between the relative changes in the concentric IEMG of DJ 100 and the relative changes in the heights of rise of C.G. of the corresponding DJ performance after the corresponding 24-week training (B)

Explosive type strength training

The 24-week explosive type strength training (group B) resulted in considerable increases in the averaged maximum IEMG of the examined muscles during the eccentric and concentric phases of the drop jumps (Figure 12A). The increases were significant ($p<0.05$) as regards the IEMGs of the VM and VL muscles in DJ 60 - DJ 100, while only a slight (ns.) increase was noted in the IEMG of the RF muscle. The changes in the averaged maximum IEMG of both phases of DJ 80 and 100 differed ($p<0.05$) from those of group A. The individual changes during the training in the averaged maximum IEMG of the three muscles during the concentric contact phases correlated with the changes in the jumping heights of the respective drop jumps as shown, for example, for DJ 100 ($r = .83$, $p<0.01$) in Figure 12B. During the detraining only slight (ns.) decreases were noted in the IEMGs of the various drop jumps.

Control group

The control group demonstrated only slight (ns.) changes in the maximum IEMGs of the contact phases of the examined drop jumps between the pre- and post-tests.

3.7. Reflex variables

Heavy resistance strength training

Statistically nonsignificant changes occurred in reflex latency from 24.1 ± 3.8 to 24.4 ± 3.3 ms and in reflex electromechanical delay from 25.4 ± 7.2 to 28.1 ± 9.5 ms during the 24-week heavy resistance strength training (group A); and further detraining had no effect on these variables.

The peak-to-peak amplitude of the reflex EMG decreased (from 0.55 ± 0.42 to 0.43 ± 0.40 mV) ($p<0.05$) during this training, while only a slight (ns.) decrease (from 32.0 ± 31.8 to 27.6 ± 35.3 N) occurred in the corresponding reflex force. A slight (ns.) decrease was therefore noted in the EMG/force ratio of the reflex contraction. The individual changes in the EMG/force ratio of the reflex contraction correlated (r = .59, $p<0.05$) with the changes in the maximal IEMG/force ratio of the voluntary isometric contraction. During the 12-week detraining there was a slight (ns.) increase in reflex EMG (up to 0.44 ± 0.50 mV). This was accompanied by a slight (ns.) decrease in reflex force (down to 24.2 ± 32.0 N).

Explosive type strength training

The changes in the pre- and posttraining values for reflex latency from 22.9 ± 1.7 to 24.5 ± 2.0 ms, and for electromechanical delay from 27.0 ± 8.9 to 30.5 ± 9.3 ms were statistically nonsignificant during the 24-week explosive type strength training (group B), and only slight (ns.) alterations occurred during the following detraining.

Significant ($p<0.05$) decreases in reflex EMG (from 0.52 ± 0.24 to 0.30 ± 0.22 mV) and in reflex force (from 23.2 ± 6.4 to 15.7 ± 5.8 N) took place during the training. A slight (ns.) decrease was noted in the EMG/force ratio of the reflex contraction during the training. The individual changes in this ratio correlated (r = .67, $p<0.05$) with the changes in the maximal IEMG/force ratio of the voluntary isometric contraction. During the detraining a slight increase in reflex EMG (up to 0.35 ± 0.17 mV) and a slight decrease in reflex force (down to 15.2 ± 3.9 N) were observed.

Control group

The control group showed no statistically significant changes in the examined reflex variables between pre- and post-tests.

3.8. Muscle fibre characteristics and their relationships to voluntary neuromuscular performance variables

Heavy resistance strength training

The FT percentage of the VL muscle (49.5 ± 13.6 %) remained statistically unchanged during the 24-week heavy resistance strength training (group A), and during the following 12-week detraining. A large ($p<0.001$) increase in the mean area of the FT fibres was noted during the first 12 weeks of training, while the corresponding increase in the ST area was slight (Figure 13A). The FT/ST area ratio increased ($p<0.05$) during the training from 0.9 to 1.1 and an increase ($p<0.05$) in the corrected FT% of the muscle from 43.9 to 53.2 was also observed. A positive but nonsignificant correlation was noted between the individual changes in the mean fibre areas of the VL muscle and in maximal bilateral isometric force during the training ($r = .49$, ns.). The FT percentage of the muscle did not correlate with the increase of maximal force during the training.

In addition to the noted changes in the muscle fibre areas, large gains in FFW (from 65.0 ± 5.5 to 67.2 ± 5.6 kg, $p<0.001$) and in thigh girth (from 50.5 ± 2.1 to 52.1 ± 1.9 cm, $p<0.001$) were observed during the first 12 weeks of training. Only slight changes occurred in these variables during the last 12 weeks of training.

During the detraining significant ($p<0.05$) decreases took place in the mean areas of both fibre types and in the thigh girth.

Explosive type strength training

Nonsignificant changes occurred in the FT percentage of the muscle both during the 24-week explosive type strength training (group B) and during the following 12-week detraining from its prevalue of 50.2 ± 12.9 %. The mean area of the FT fibres increased ($p<0.001$) during training. This increase was, however, smaller ($p<0.01$) than that noted in group A.

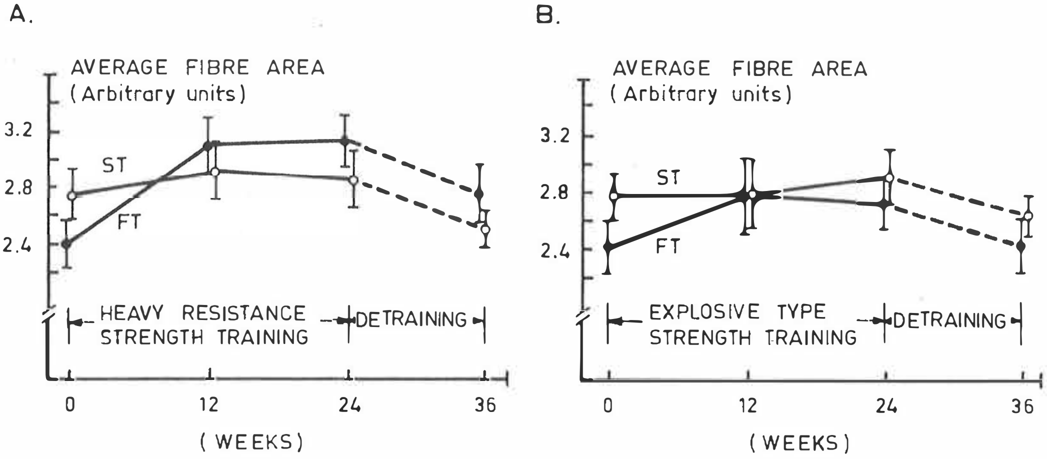


FIGURE 13. Average (arbitrary units ±SE) fibre areas of the FT and ST fibre types (of the vastus lateralis muscle) during the 24-week heavy resistance strength training and after the following 12-week detraining (A); and during the 24-week explosive type strength training and after the following 12-week detraining (B)

The increase in the ST area in group B was also slight (ns.) (Figure 13B). The FT/ST area increased ($p<0.05$) from 0.9 to 1.0 but the corrected FT percentage remained statistically unaltered during the training. The individual changes in the mean fibre areas of the VL muscle did not correlate with the changes in maximal isometric force which took place during the training. The individual changes during training in the FT/ST area ratio of the VL muscle correlated ($r = -.55$, $p< 0.05$) with the changes in time of isometric force production to a 30 % force level (Figure 14A). Positive correlations were found between the FT percentage of the VL muscle and the increases in maximal average forces of the time period 1 ($r = .71$, $p<0.05$) and 3 ($r = .67$, $p<0.05$, Figure 14B) in the

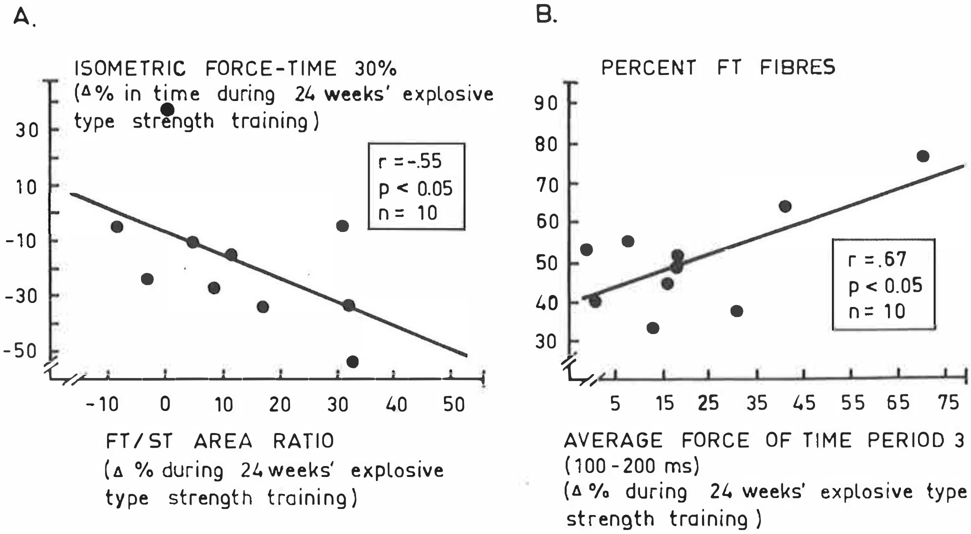


FIGURE 14. The relationship between the relative changes in time to produce a relative bilateral isometric leg extension force level of 30 % and the relative changes in the FT/ST fibre area ratio (of the vastus lateralis muscle) after the 24-week explosive type strength training (A) and the relationship between the percentage of the FT fibres and the relative changes in average force in the beginning (the 3rd time period from 100 to 200 ms) of the force- (absolute) time curve in rapid bilateral isometric leg extension after the corresponding 24-week training (B)

force- (absolute) time curve during the 24-week training.

A slight (ns.) increase in the thigh girth (from 49.8 ± 3.2 to 50.2 ± 3.1) and an increase in FFW (from 63.5 ± 7.0 to 64.3 ± 7.1, $p<0.05$) took place during the training. These increases were, however, smaller ($p<0.05-0.01$) in comparison to those noted in group A.

During the detraining significant ($p<0.05$) decreases occurred in the mean areas of both fibre types.

Control group

Statistically nonsignificant changes were noted in the control group in the measured muscle fibre characteristics, in FFW, and in the thigh girth between the two measurements.

3.9. Serum hormones and their relationships to voluntary neuromuscular performance variables

Heavy resistance strength training

A decrease in mean serum cortisol from 0.74 ± 0.15 to 0.60 ± 0.09 $\mu mol \times l^{-1}$ ($p<0.01$) was observed during the 24-week heavy resistance strength training (group A). The mean serum testosterone concentration was 25.9 ± 6.3 $nmol \times l^{-1}$ before the training period and 25.7 ± 7.2 $nmol \times l^{-1}$ after it. Serum testosterone/cortisol ratio increased ($p<0.05$) during the training. The concentration of serum SHBG did not change during the training from its prevalue of 30.9 ± 12.5 $nmol \times l^{-1}$. A significant correlation was observed between the individual changes in testosterone/cortisol ratio and in maximal bilateral isometric force during the last four weeks of training ($r = .86$, $p<0.01$, Figure 15A). The correlation between the individual changes in testosterone/SHBG ratio and in maximal isometric force was also positive but nonsignificant ($r = .36$, ns.). No statistically significant changes were observed in the concentrations of serum estradiol, FSH, LH, prolactin and somatotropin during the training period. During the detraining the serum testosterone/cortisol ratio decreased slightly, and this change correlated with the decrease in maximal bilateral isometric force ($r = .70$, $p<0.05$). A similar correlative change during the detraining was noted between the testosterone/SHBG ratio and maximal force ($r = .64$, $p<0.05$).

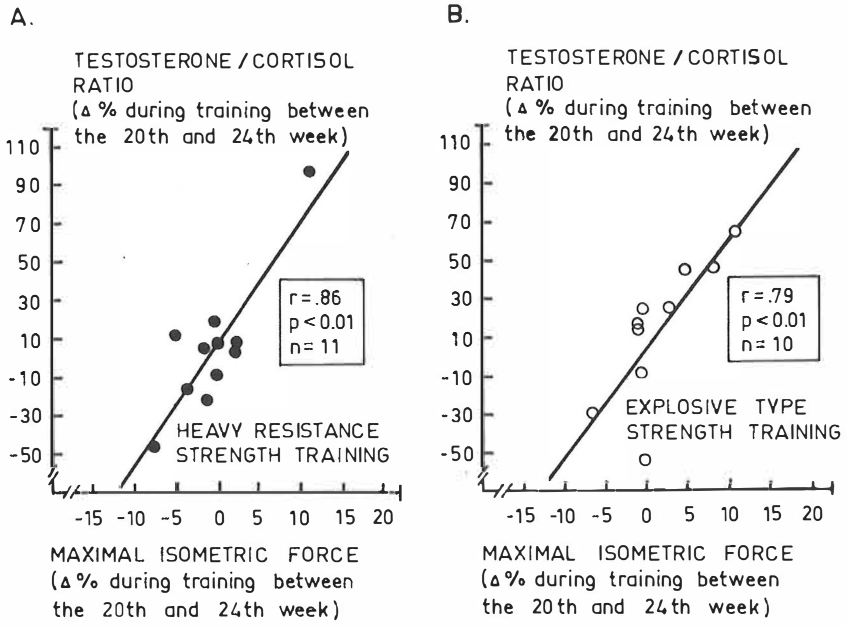


FIGURE 15. The relationship between the relative changes in serum testosterone/cortisol ratio and the relative changes in maximal bilateral isometric leg extension force during the last four weeks of training between the 20th and 24th week of the 24-week heavy resistance (A) and of the 24-week explosive type strength training periods (B)

Explosive type strength training

A slight (ns.) decrease in mean serum cortisol from 0.70 ± 0.13 to 0.64 μmol x l^{-1} took place during the 24-week explosive strength training (group B). There was a significant ($p<0.05$) increase in serum testosterone during the first 16 weeks of training from 28.9 ± 9.4 to 34.5 ± 1.4 nmol x l^{-1}, while at the end of the training period the respective value had decreased down to 29.5 ± 8.0 nmol x l^{-1}. The serum testosterone/cortisol ratio increased ($p<0.05$) during the first 8 and 16 weeks of training, after which a slight decrease took place during the last 8 weeks of training. Serum SHBG concentration did not change during training from its prevalue of 37.5 ± 16.9 nmol x l^{-1}; and no significant changes occurred in other serum hormones examined during training. During the last four weeks of training a significant correlation ($r = .79$, $p<0.01$) was observed between the individual changes in serum testosterone/cortisol ratio and in maximal isometric bilateral force (Figure 15B); and between the individual changes in serum testosterone/SHBG ratio and in isometric force ($r = .64$, $p<0.05$). During detraining only slight changes were observed in the serum hormones examined.

Contrl group

No statistically significant changes were observed in the serum hormones examined in the control group between the pre- and post-tests.

4. DISCUSSION

4.1. Primary findings

The present prolonged heavy resistance and explosive type strength training regimens resulted in specific enhancements in voluntary neuromuscular performance. These primary findings are summarized as follows:

1) Great increase in maximal isometric strength and highly significant shifting of the high force portions of the force-velocity curve took place during heavy resistance strength training, while smaller improvements occurred in rapid isometric force production, in the high velocity portions of the force-velocity curve and in performance during the examined high velocity stretch-shortening cycle exercises.
2) The increase in maximal strength was accompanied by significant increases in the neural activation of the trained muscles during the periods of very intensive heavy resistance strength training with high loads, and by muscular hypertrophy taking place primarily during the earlier half of the training period.
3) The individual hormonal alterations noted in serum testosterone/cortisol ratios correlated with the changes in muscular strength during the latest vigorous training phase.
4) The explosive type strength training resulted in great improvements in rapid isometric force production, in the high velocity portions of the force-velocity curve and in performance during the high velocity stretch-shortening cycle exercises, while smaller increses occurred in maximal strength.

5) The highly significant increases in explosive force production during this specific training were accompanied by and correlated with considerable increases in the neural activation of the trained muscles observable under all examined testing conditions of rapid force production.
6) Hypertrophic changes were relatively slight during the explosive type strength training, but the FT percentage of the trained muscle and the increase noted in the FT/ST fibre area ratio correlated with the improvement of rapid isometric force production.
7) During the following detraining periods, decreases in maximal force were accompanied by significant decreases in the neural activation of the muscles, and by muscular hypotrophy (atrophy).

The following discussion is organized so that the effects of the heavy resistance strength training are interpreted first; followed by a discussion of the results of the explosive type strength training, and finally of the effects of both detraining periods.

4.2. Heavy resistance strength training

The utilization of a combination of high loading concentric and eccentric contractions has been reported, during shorter term strength training, to be beneficial for the development of maximal strength (Pletnev 1975, 1976, Häkkinen and Komi 1981, Häkkinen et al. 1981). The great magnitude of the development of maximal bilateral isometric and concentric leg extension strength during the present heavy resistance strength training is therefore well in line with these previous observations. This finding must be given additional attention, because the present subjects were not untrained at the beginning of the training period, but accustomed to strength training undertaken for their own personal conditioning purposes. The pretraining strength status is known to influence strength development (e.g. Düntsch and Stoboy 1966, Müller 1970), and some recent reports (e.g. Häkkinen and Komi 1982, Alén et al. 1984, Häkkinen 1985) have additionally demonstrated that improvements in maximal strength in highly trained subjects and/or in elite strength athletes might be rather limited. It was therefore not unexpected that the improvement in maximal strength of the present subjects during the later conditioning phases was relatively slight (see Figure 3A). This might also be one result of overtraining as indicated, for example, by the selective changes in hormone balance discussed later (also see Figure 15A). Both of these observations might also be plausible explanations for the finding that only slight improvement was observable in maximal unilateral isometric knee extension force between the mid- and post-training tests (see also Häkkinen and Komi 1983a,b); although this notion may also be explained by the specificity of the utilized training exercises.

The improvement in maximal isometric strength was accompanied by significant increases in the maximum IEMGs of the trained muscles during the course of strength training with higher loads and/or when eccentric high loading contractions were utilized (see Figure 8A). This increase in the maximum IEMG during the training was also observable in the maximal unilateral knee extension test. The increased maximal neural activation of the trained muscles during high loading strength training is also in agreement with some other recent observations (e.g. Komi et al. 1978, Moritani and DeVries 1979, Häkkinen and Komi 1983a). The significant correlations noted both in bilateral (Figure 8B) and in unilateral testing conditions between the increases in IEMG and force tend to emphasize the importance of the adaptation of neural activation of the muscles for maximal strength development. The decreases observed in the maximum IEMG during the training periods with submaximal loads (especially the first training month) need further attention, because it has been rather well demonstrated (e.g. Moritani and DeVries 1979) in previously untrained subjects that early improvements in strength may be accounted for largely by the neural factors. While this may still hold true with regard to untrained subjects, the present findings suggest that in trained subjects and/or in strength athletes (see also Alén and Häkkinen 1985) the role of training loading may be of great importance to maintain training-induced increase in maximal neural activation. The results presented in Figure 8A additionally imply that the changes in the IEMGs of the leg extensor muscles were also muscle specific as indicated by the great alteration noted in the IEMG of the VM muscle during the course of the training. The present observation that no increase occurred in the maximum IEMG during the very last high loading training month may be one of the indications of overstrain taking place in trained subjects after prolonged intensive training (see also Häkkinen and Komi 1983a).

It has been suggested that the increases in maximum IEMG, especially during earlier strength training result from increased syncronization of motor units (e.g. Friedebolt et al. 1957, Düntsch and Stoboy 1966). While this suggestion may in part be also valid for more trained subjects, the present increases noted in IEMG during the most intensive training periods may have concomitantly resulted from an increased number of active motor units and/or from an increase in their firing frequencies due to high loading training stimuli. The increases taking place in maximum IEMG, however, suggest that part of the training effect resides in the facilatory and inhibitory neural pathways acting at the various levels in the nervous system and contributing to a greater inflow of activation occurring in the muscle. Although no exact conclusion is possible with regard to the sources of the present increase in IEMG, it has been suggested (Milner-Brown et al. 1975) that the role of higher motor centers in increasing their descending activity might, however, be more important (see also Shapovalov 1966).

The enlargements in muscle fibre areas (Figure 13A) accompanied by the increases in FFW and in the thigh girth tend to demonstrate, in addition to the observed neural adaptations, the important contribution of hypertrophic factors for maximal strength development; although some experiments (e.g. Thorstensson et al. 1976b, Dons et al. 1979) have not been able to demonstrate muscular hypertrophy during shorter term training. The present observations, that a greater degree of hypertrophy took place in the FT fibres than in ST fibres, support some previous findings (e.g. MacDougall et al. 1977, 1980, Häkkinen et al. 1981, Komi et al. 1982, Houston et al. 1983). Training-induced hypertrophy in skeletal muscle is associated with increases in both the size and number of the myofibrils within the fibre (e.g. MacDougall et al. 1976). The exact mechanisms, however, by which heavy resistance strength training might stimulate a net increase in protein synthesis in the muscle are still unknown (e.g. see MacDonagh and Davies 1984).

The time course of training-induced hypertrophy or its limits are also factors which have not been determined conclusively. In previously untrained subjects (e.g. Moritani and DeVries 1979) and/or in subjects having only some experience in strength training (e.g. Häkkinen et al. 1981) the contribution of hypertrophic adaptations tends to accompany improved muscle strength primarily during later conditioning. Muscle hypertrophy of the present more experienced subjects, however, took place mainly during the earlier half of the training period; when, on average, a greater number of repetitions was performed in each set (Figure 13A). Only minor hypertrophy occurred during the latter 12 weeks of the training. These smaller enlargements in muscle fibre areas were accompanied by only slight changes in FFW and in the thigh girth during the corresponding later training period. This slight hypertrophy, together with the noted small increase in the maximal neural activation of the muscles may therefore also in part explain the observed limited strength development during this period. A suggestion has actually been made (e.g. MacDougall et al. 1982, Tesch and Larsson 1982) that there might be an optimal or ceiling size for enlargements of individual fibres undergoing hypertrophy; leading to muscle hyperplasia in highly trained subjects. The present notion that no significant changes occurred in the percentage of the different fibre types in the muscle during the training does not, however, exclude this possibility. However, the methods used and the results obtained concerning this limited hypertrophy in the present study do not allow any accurate conclusion as to mechanism to be made with regard to the phenomenon of hyperplasia, which has also been under critical evaluation by some authors (e.g. Gollnick et al. 1981, MacDougall et al. 1984).

The important role of the pretraining status of the subjects is, however, observable through the comparative data from our recent experiment (Alén et al. 1984); in which an even smaller degree of muscle hypertrophy was noted in elite strength athletes in comparison to the present subjects during a strength training period of the same duration. These obvious differences in the time courses of the adaptations in the neuromuscular system during strength training in subjects with different pretraining status may also in part explain why, for example, no significant correlations between the changes in maximum IEMG, force and/or muscle hypertrophy may sometimes be obtained, especially if only the pre- and posttraining values are compared (see also Häkkinen et al. 1981, Häkkinen and Komi 1983a). The type of strength training may also be of some importance, because elite weightlifters have been shown to possess somewhat larger isometric and dynamic maximal strength than bodybuilders despite of their smaller muscular mass (Häkkinen et al. 1985).

The present endocrinological findings from the examined serum hormones, observable primarily as an increase in serum testosterone/cortisol ratio, demonstrate a training-induced increase in anabolic-androgenic activity. This phenomenon has not been demonstrated during some short term strength training experiments (see Young et al. 1976, Hetrick and

Wilmore 1979). It was also interesting, although rather expectable, to observe the occurrence of a plateau phase in the maximal strength during the last vigorous training month (Figure 3A). However, large individual variations in strength development were noted during this phase. Some subjects were able to increase their strength, while even decreases in strength were observed in others. These changes occurred concomitantly with the changes in serum testosterone/cortisol ratios, which was seen as the high correlation between the individual force alteration and the individual changes in this hormone ratio (Figure 15A). This observation suggests the importance of the balance between androgenic-anabolic activity and the catabolizing effects of glucocorticoids during the later courses of the prolonged vigorous strength training. The positive correlation also observed during this training phase, between the changes in strength and in testosterone/SHBG ratio tends to support the view that, during prolonged training, the levels of biologically active unbound testosterone may be of importance for trainability (e.g. Remes et al. 1981). These present findings may therefore also have some implications for the more accurate determination of the trainability status of an individual so that training loading for maximal strength development at a given time would be more optimal. The role of this phenomenon might therefore be important in attempts to avoid overtraining, especcially in athletes undergoing prolonged training.

The present findings as to the training-induced changes in voluntary neuromuscular performance capacity as regards both the isometric force-time (Figure 3B) and concentric force-velocity curves (Figure 5A) give strong support to the concept of the specificity of training. Great increases in maximal strength may be expected during heavy resistance strength training which utilizes high training loads with slow contraction velocities, while improvements tend to be smaller in time of isometric force production (e.g. Sukop and Nelson 1974, Häkkinen et al. 1980, 1981), or in the high velocity portions of the concentric force-velocity curve (e.g. Ikai 1970, Caiozzo et al. 1981, Coyle et al. 1981, Kanehisa and Miyashita 1983a, Alén et al. 1984). The present changes in various areas in the concentric force-velocity curve (Figure 5B) are an additional demonstration of the consistency of this specificity, which was observable during the course of the entire heavy resistance strength training period. Additional support for this strong specificity can be drawn from the very small changes in the very early parts of the force-time and IEMG-time curves, and in the very high velocity end of the force-velocity curve; as well as in maximal IEMG in the high velocity test. It is therefore possible that only some adaptations in the activation pattern of the motor units may have taken place to contribute to those slight improvements of rapid force production noted mainly during the first part of conditioning (see Figure 3B) when lower training loads were utilized. The additional finding that even some worsening was noticeable in the force-times (in the relative scale) during the later training periods also indicates this specificity of prolonged heavy resistance strength training. Because of the slow contraction speed (but high activation) used in the present heavy resistance strength training, especially in the eccentric training contractions (3-4 s in duration) during the last two months, changes of this kind might be expected (see also Häkkinen et al. 1980). The shifting of the IEMG-time curve slightly backwards observed during this last half of the training period tends to support this conclusion. The finding that no changes occurred in the relaxation-time variables during the present strength training might be one additional indication of the specificity of heavy resistance strength training.

The present changes in positive work phases, and consequently in the heights of the CMJ performances were almost similar to those of the respective SJ performances, and similarly demonstrated a slightly larger shifting of the high load portions of the load-vertical jumping height curve. No significant changes were noted during the present heavy resistance strength training in the differences between CMJ and SJ performances at the examined loads. The present observations may therefore suggest that no changes in the utilization of stored elastic energy of the muscles may have taken place during this type of training (see also Häkkinen and Komi 1983c). The utilization of stored elastic energy during stretch-shortening cycles has been shown to be associated with efficient prestretching, including, for example, great stretching velocity and short eccentric-concentric coupling time (e.g. Bosco 1982). The unaltered neuromuscular performance capacity of the present subjects in the examined drop jumps (Figure 7A) during the heavy resistance strength training might therefore be in line with this concept (see also Häkkinen and Komi 1983c). The present notion that the performances in these drop jumps were even smaller than in SJ 0 (see Figure 5A) both in the pre- and posttests is in agreement with the reported specific performance characteristics of elite strength athletes such as powerlifters, who have a heavy resistance strength training background of several years (Häkkinen et al. 1984). The present findings that no systematic changes were noted in the IEMGs of the examined drop jumps additionally suggest that heavy resistance strength training might not influence the neural activation in the voluntary and/or reflex control during the stretch-shortening cycle exercises, in which high contraction velocities are utilized (see also Bosco and Viitasalo 1982).

In reflexly-induced contractions, in which reflex responsiveness was measured in the relaxed muscles, no statistically significant changes were observed in reflex time components during the present heavy resistance strength training. As regards reflex latency, this may therefore indicate that no changes had occurred in sensory and/or motor nerve conduction characteristics. This observation is in line with our previous results from shorter term strength training (Häkkinen and Komi 1983b). The observation that the reflex EMD also remained unaltered may indicate that the peripheral motor time component may not be sensitive to strength training, although some contradictory findings are available (Francis and Tipton 1969). Some caution must, however, be exercised with regard to these findings due to the differences in the methods employed between the studies.

The present strength training resulted, however, in a significant decrease in the peak-to-peak amplitude of reflex EMG, while only a slight decrease in the respective reflex force was noted (see also Häkkinen and Komi 1983b). The former notion may imply that a decrease in sensitivity of a muscle spindle may have taken place. This may have resulted from possible training-induced diminution in the gamma discharge to the intrafusal fibres (see also Maynard and Tipton 1971). This would in turn lead to the elevation in the threshold level of the responsibility of the facilatory primary (Ia) afferents activated by the present stimulus. Because this mechanical stimulus was always constant, a decrease in a response of a muscle spindle might therefore be recorded during the course of the training. It is naturally difficult to determine the exact mechanisms involved due to the limitations of the present methodology. In spite of this possible decrease in sensitivity of a muscle spindle in the present testing condition, the mechanical response of the muscle remained, however, concomitantly unaltered during the strength training. This may result from the improvement in strength of individual motor units during the heavy resistance strength training. The correlative changes noted in the reflex EMG/force ratio and in the corresponding changes in the IEMG/force ratio of the voluntary unilateral contraction tend to support this notion.

4.3. Explosive type strength training

The present explosive type strength training regimen resulted in specific changes in neuromuscular performance different from those taking place during heavy resistance strength training. Great improvements were observed in rapid isometric force production (Figure 4), in the high velocity portions of the concentric force-velocity curve (Figure 6), and in performance in the drop jumps at all examined high stretching velocities (Figure 7); while a slighter increase occurred in maximal strength (Figures 4 and 6). The present findings are in line with previous observations of training-induced specificity caused by training, in which high contraction velocities with loads are used. The effects are observable both in isometric (Viitasalo et al. 1981, Komi et al. 1982) and in pure concentric conditions (e.g. Ikai 1970, Caiozzo et al. 1981, Coyle et al. 1981, Kanehisa and Miyashita 1983a,b).

The increase noted, however, in maximal bilateral isometric leg extension strength was accompanied by significant increases in the maximum IEMGs of the trained muscles; taking place primarily during the later conditioning when a significant correlation between these changes was observed. These increases in EMG activity can be therefore attributed to the intense and prolonged training, utilizing exercises in which the activation of the trained muscles was always kept as maximal as possible. This finding indicates that adaptations at various levels in the nervous system may have taken place, contributing to a greater inflow of activation occurring in the muscle as already suggested with respect to heavy resistance strength training. The notion that only a slight increase occurred in the maximum IEMG in the unilateral knee extension may be explainable by the specificity of the training consisting of several jumping exercises performed always with both legs. Relatively slight hypertrophy as judged from the present changes in muscle fibre areas, in FFW and in the thigh girth were noted during the present explosive type strength training, in comparison to those occurring during the heavy resistance strength training of the same duration. Although the activation of the muscles of the subjects during the various maximal jumping exercises was probably very high (e.g. see Bosco 1982), the time of this activation due to the lower training loads used may have therefore been too short to induce great muscular growth. Since muscle hypertrophy is known to contribute to the increase in maximal strength (e.g. MacDougall et al. 1977, Häkkinen et al. 1981, Komi et al. 1982) it is therefore understandable that the increase in maximal strength observable during the present explosive type strength training regimen was much smaller than that induced by heavy resistance strength training (see Figures 3A and 4A, see also Komi et al. 1982). This smaller increase in maximal strength was also observable in the test for maximal concentric strength (Figure 6); and even more clearly in the maximal unilateral isometric knee extension.

The highly significant improvements noted in explosive force production during the present explosive type strength training were accompanied by significant increases in the neural activation of the trained muscles. This was observable both during the rapid isometric and high velocity concentric contractions and during the examined high velocity stretch-shortening cycle exercises. The results presented in Figure 9 give additional support for this strong and long-term specificity. Training-induced adaptations in respect of the firing frequencies (Kawakami 1955, Cracroft and Petajan 1977) and/or perhaps in the recruitment pattern of the motor units may have caused this increase in the amount of neural input to the muscle during a short period of time and contributed to this improvement in explosive force production. The significant correlations found between the increases in the IEMG and explosive force production during the early part of the rapid isometric contraction (Figure 9B), during the high velocity concentric (Figure 10A) and during the examined high velocity stretch-shortening cycle exercises (Figures 11 and 12B) indicate the importance of the neural component for this specific training-induced enhancement in the neuromuscular performance. The notion that only slight training-induced increases occurred in the IEMG of the RF muscle during the concentric and stretch-shortening cycle exercises may have resulted from large intermuscular and interindividual variations observed in the activation patern of the leg extensor muscles in various jumping performances (e.g. Bosco and Viitasalo 1982). It is possible that the strong role of the RF as a hip flexor may also affect the results. The present training-induced increases noted in the IEMG and in explosive force production should be given special attention because of their relevance for practical purposes; because the effective time taken by muscles to contract in normal movements and especially in athletic activities is known to be very short.

While neural adaptations may contribute to a great degree to explosive force development during specific training, an attractive additional explanation for the present changes might also be an enhancement of the force-time characteristics, primarily in the FT muscle fibres. Although in slow isometric tension development, motor units are thought to be recruited according to a size principle (Henneman et al. 1965), during rapid isometric force production (Gydikov and Kosarov 1974) and during dynamic contraction where high acceleration or a high rate of force development is needed (Grimby and Hannerz 1968, 1977, Gydikov and Kosarov 1974), FT motor units have been reported to be very active. The importance of the percentage of FT fibres of the muscle for time of isometric force production (e.g. Viitasalo and Komi 1978, Viitasalo et al. 1981b) and for the force and/or torque produced at high contraction velocities (Thorstensson et al. 1976a, Coyle et al. 1979, Bosco and Komi 1979b, Häkkinen et al. 1984) has in fact been rather well demonstrated. It might therefore also be expected that repeated utilization of explosive type exercises would have a long-term training influence on the FT fibres of the muscle. The present training-induced increase noted in the FT/ST fibre area ratio tends to support this view. The importance of this type of adaptation is demonstrated by the results presented in Figure 14A; which imply that the shortening in the time needed to produce the relative force level of 30 % was greater, the larger the increase in the FT/ST muscle fibre area ratio was. The present findings shown in Figure 14B tend additionally to emphasize the importance of the FT percentage of the muscle for the trainability of the capability for explosive force production. It can therefore be suggested that in addition to specific type training, these genetic factors may be important in determining the ultimate potential of the trainability of the neuromuscular performance capacity, in which explosive force production is essential.

Muscle elasticity is a phenomenon which is characteristic of the stretch-shortening cycle exercises (e.g. Bosco 1982, Komi 1984). It has been suggested that differences between the CMJ and SJ performances are one indication of the utilization of stored elastic energy (e.g. Komi and Bosco 1978, Bosco and Komi 1979a). This increase in performance in CMJ may be attributed to a combined role of pure mechanical and myoelectrical potentiation of the muscle activation (Schmidtbleicher et al. 1978, Bosco et al. 1982, Komi 1984). The present results, however, demonstrated that only slight increases were observable during the present explosive type strength training in the difference between CMJ and SJ performances at all examined stretching loads. This notion may therefore indicate that training-induced changes in elasticity observable as a greater increase in the difference between CMJ and SJ performances might be expected only after several years of specific training (see also Bosco and Komi 1982, Viitasalo and Aura 1984). Although the methodology used allows no conclusions as to whether changes in the contributing roles of pure mechanical and myoelectrical potentiation of the muscle activation may have taken place, the present electromyographic results (e.g. Figure 11) tend to emphasize the important adaptive role of the neural component for the training-induced improvement of performance during the examined stretch-shortening cycle exercises.

This importance of the training-induced adaptation of the neural component in the neuromuscular performance was also clearly observable with respect to the examined drop jumps, in which high contraction velocities are used during the stretch-shortening cycle (e.g. Bosco and Komi 1979a). Significant training-induced increases in the maximal averaged IEMG took place both during the eccentric and concentric phases of the DJ performances at higher stretching velocities (and/or loads) (Figure 12A). Within the limitations of the present methodology, these observations may indicate that in addition to possible adaptations in voluntary neural control (e.g. Komi et al. 1978, Häkkinen and Komi 1983a,b) training-induced changes in inhibitory and/or facilatory reflexes may have taken place due to the present training contributing to the improvements in tolerance of higher stretching loads. The high correlation observed between increases in the maximal IEMG and in the height of DJ 100 (Figure 12B) tends to support this suggestion.

The effects of the explosive type strength training on the examined variables of the present reflexly-induced contractions were, however, relatively slight and of same nature as those occurring during the heavy resistance strength training as already discussed. While no changes took place in reflex time components, a significant decrease was noted in the peak-to-peak amplitude of reflex EMG. As already discussed this decrease might imply that a change in the sensituvuty of a muscle spindle response may have taken place and/or that some other mechanisms may have been involved. A concomitant decrease in the respective reflex force was also noted during this type of training, while this force remained unaltered during the heavy resistance strength training. This decrease in reflex force may result from the notion that only a slight increase might have occurred in the strength of individual motor units during the explosive type strength training. The correlative changes in the reflex EMG/force ratio and in the IEMG/force ratio of the voluntary contraction noted during the training might support this notion.

It must, however, be noted that the training-induced changes in reflex responsiveness measured in the relaxed muscles may be different from those which take place when the active muscle is subjected to a forceful stretch. It has been suggested (Komi 1985) that improvement in the stiffness regulation of muscle is one of the primary objectives of neuromuscular training. In this regulation the length feedback component of the hypothetical stretch reflex (Houk 1974) functioning through the muscle spindles would contribute increased stiffness by increased spindle discharge for the same stretch load. The force-feedback component via the inhibitory connection from the Golgi tendon organ might correspondingly decrease during proper training. The present observations as to the training-induced changes in the examined high velocity stretch-shortening cycle exercises (e.g. Figure 12A and B) do not exclude this possibility.

The present long-term explosive type strength resulted in changes in endogenous hormone production observable primarily as an increase in the serum testosterone/cortisol ratio. This demonstrates a training-induced increase in anabolic-androgenic activity as already suggested with respect to the heavy resistance strength training. The high correlation observed between the individual changes in serum testosterone/cortisol ratio and in muscular strength during the last training month (Figure 15B) additionally supports the suggestion which has been made concerning the importance of the balance between androgenic-anabolic activity and the catabolizing effects of glucocorticoids during the later courses of vigorous strength training. The importance of this phenomenon with respect to explosive force development was additionally confirmed by corresponding correlations observed during the later training phase between the change in this hormone ratio and in the heights of SJ and CMJ performances at lower loads ($r = .56-.79$, $p<0.05-0.01$). These findings may therefore indicate that, while training-induced specificity was clearly observable in the neuromuscular system during the explosive type strength training in comparison to heavy resistance strength training, the response of the endocrine system might be rather similar. These observations may therefore provide additional indication of the possibility of a more accurate and more specific determination of the trainability status of the neuromuscular performance of an individual at a given time.

4.4. Detraining

During the present detraining following the heavy resistance strength training, a large decrease took place in maximal bilateral isometric leg extension force (Figure 3A) and in the squat lift (Figure 5B) (see also Thorstensson 1977, Häkkinen et al. 1981). This change was accompanied by significant decreases in the maximum IEMGs (Figure 8A) and in mean areas of both fibre types of the VL muscle (Figure 13A) (see also MacDougall et al. 1977, Häkkinen et al. 1981, Häkkinen and Komi 1983a). The decreases in the maximum IEMGs can be attributed to the detraining effect; which may be regarded as the opposite effects of training. The significant correlation found between the decrease in the maximum IEMG and in maximal force supports a view of the importance of neural activation of the muscles for strength output. Significant decreases during the detraining in muscle fibre areas accompanied by concomitant changes in the thigh girth and in FFW are obvious signs of hypotrophy (atrophy) due to the termination of heavy resistance strength training. These adaptations in the neuromuscular system in well trained subjects during detraining strongly support the observations made regarding the opposite specific effects observed to have taken place during the present heavy resistance strength training. The notion of the high correlation during detraining between the changes in the serum testosterone/cortisol ratio and in maximal isometric strength supports the suggested importance of anabolic-androgenic influence during heavy resistance strength training.

Significant decreases both in maximal bilateral isometric force (Figure 4A) and in the squat-lift, although to a lesser degree in comparison to those observed in group A, were also observed during the detraining following the explosive type strength training. This smaller decrease during detraining in maximal force in group B in comparison to that noted in group A is also in line with the suggested specific effects of prolonged training. The decrease in isometric force in group B was also accompanied by decreases in the maximum IEMG of the VL muscle and in the areas of both muscle fibre types (Figure 13B). This finding may therefore indicate that a decrease during this detraining phase had occurred in the normal daily activities of these subjects after the present experimental training period. Because the values of the maximum IEMGs of the bilateral isometric leg extension remained, however, greater than those noted at the beginning of the present training project, the level of maximal force after the detraining was slightly higher than that of the pretest.

The changes in the early part of the isometric force-time curve during detraining following the heavy resistance strength training were relatively slight (see also Häkkinen et al. 1981). This observation may therefore indicate that no changes might have taken place with respect to the activation pattern of the motor units. The notion that only slight changes were observable during the detraining in the corresponding portions of the IEMG-time curve tends to support this suggestion. The present findings additionally demonstrated that the decreases in the high velocity portions of the force-velocity curve were smaller than those noted in the high force end (Figure 5B). This supports the concept of the specificity of the heavy resistance strength training resulting primarily in great increases in the high-force portions of the force-velocity curve.

While significant decreases during the detraining following the explosive type strength training in some of the examined variables of explosive force production were observed, large individual variation was also noticeable. The latter observation may in part result from the fact that the later weeks of the training period may have been too stressful for some individuals, leading probably to overstrain contribution to those decreases in their performances already observable during the later phases of the training period. The effects of this detraining gave, however, support for those specific changes noted in explosive force production during the preceeding training period. The significant correlation found during the detraining between the individual changes in the average IEMG-time and changes in the corresponding force-time curve agrees well with the noted training-induced specific adaptations in the neuromuscular system. The significant correlation observed between the individual changes during the detraining in the neural activation of the muscles and changes in performance in the velocity portions of the force-velocity curve (Figure 10B) tends additionally to support the concept of the specificity of prolonged training.

4.5. Conclusions

The conclusions which can be drawn from the main results of the present experiments may be summarized as follows:

1) Prolonged heavy resistance strength training tends to lead to improvements primarily in maximal force production characteristics of human skeletal muscle.

This conclusion is based on the observation that great increases occurred during the present heavy resistance strength training in maximal isometric strength and in the high force portions of the force-velocity curve. The corresponding changes in rapid isometric force production, in the high velocity end of the force-velocity curve and in performance during the examined high velocity stretch-shortening cycle exercises were only slight. These findings thus give support to the concept of the specificity of training.

2) The increase in maximal strength during heavy resistance strength training seems to be accompanied both by adaptations in the neural activation of the trained muscles and by muscular hypertrophy contributing to concomitant maximal strength development.

This suggestion is based on the periodical increases noted in the maximum IEMG of the trained muscles and in the selective increase observable in the average muscle fibre areas of the examined muscles.

3) The magnitudes and the time courses in these neural and hypertrophic changes contributing to strength development may, however, vary due to differences in the type, in the loading intensity and/or in the duration of strength training; and perhaps in the pretraining status of the subjects.

In previously untrained subjects, early increases in strength may be accounted for largely by neural factors, with a gradually increasing contribution of the hypertrophic factors. However, the present findings indicate that in well trained subjects (who have already had previous experience in strength training) the role of a high training loading may be of great importance in maintaining training-induced increases in maximal neural activation;

because submaximal training loads tend to lead to periodical decreases in the maximum IEMG of the muscles. The notion that muscular hypertrophy occurred primarily during the earlier half of the present training period indicates that training-induced hypertrophy may be limited in highly trained subjects; and perhaps even more limited in strength athletes.

4) The adaptive responses in the endocrine system are linked with the trainability of muscular strength, especially during the later courses of vigorous prolonged strength training.

This conclusion receives support from the present correlative changes noted between serum testosterone/cortisol ratio and muscular strength during the last four weeks of training. This finding indicates the importance of the balance between androgenic-anabolic activity and the catabolizing effects of glucocorticoids during the later periods of prolonged intense strength training. These observations may therefore be utilized as additional indications in order to determine the trainability status of each individual more accurately so that training loading for maximal strength development at a given time can be optimal. This consideration should receive special attention in attempts to avoid overtraining in athletes during prolonged training periods.

5) Prolonged explosive type strength training tends to lead to specific changes in muscular performance which differ very much from those changes taking place during heavy resistance strength training of the same duration.

This phenomenon was demonstrated by the observation that the present explosive type strength training utilizing high training contraction velocities with low loads resulted in highly significant increases in time of isometric force production, in the high velocity portions of the force-velocity curve and in the performance during the examined high velocity stretch-shortening cycle exercises. Slight increases occurred during this type of training in maximal strength. These observations thus give strong additional support for the concept of the specificity of training, and they also have relevance for practical purposes especially in athletic activities.

6) Neural adaptations are primarily responsible for the improvements in rapid force production observed during explosive type strength training.

The high correlations found between the great increases in the IEMG and force production during the early part of the rapid isometric contraction, during the high velocity concentric and during the examined high velocity stretch-shortening cycle exercises tend to support the importance of specific training-induced adaptations of the neural component. The hypertrophic adaptations observed during the present explosive type strength training observable as a selective increase in the average muscle fibre area of the FT type were much smaller than those which took place during heavy resistance strength training of the same duration. Both of these observations as to neural and hypertrophic adaptations give additional support to the concept of the specificity of training, and they may also have relevance for practical purposes.

7) In addition to the important role of training-induced neural adaptations, the genetic factors must be taken into consideration. They may determine the ultimate potential of the trainability of neuromuscular performance, in which rapid force production is essential.

The percentage of FT fibres in the muscle is known to be of importance for rapid tension development. The present correlation noted between the FT percentage of the trained muscle and the decrease in time of isometric force production during the explosive type strength training gives support to the suggested importance of genetic factors in determining to a great degree the ultimate potential of this specific aspect of the neuromuscular performance capacity.

8) Detraining tends to lead to specific adaptive changes in the neuromuscular system, and these take place in the opposite direction to those resulting from heavy resistance and/or explosive type strength training.

This conclusion comes from the observed selective decreases in the neural activation of the muscles and also from the observation of muscular hypotrophy (atrophy) during detraining periods. These findings therefore give further support to the concept of the specificity of training. The specific training-induced adaptations in the neuromuscular system may be responsible for these changes in performance as well.

TIIVISTELMÄ

Tämän tutkimuksen tarkoituksena oli selvittää pitkäaikaisen maksimi- ja nopeusvoimaharjoittelun vaikutuksia alaraajojen ojentajalihaksiston sähköisiin aktiivisuuksiin, lihassolukkoon ja voimantuotto-ominaisuuksiin sekä seerumin hormonipitoisuuksiin. Ensimmäisessä harjoitteluprojektissa 11 aiempaa voimaharjoittelukokemusta omaavaa koehenkilöä toteutti valvotusti maksimivoimaharjoituksia (vaihtelevasti 70-120 %:n kuormituksilla maksimivoimasta) 3 kertaa viikossa 24 viikon ajan. Toisessa harjoitteluprojektissa 10 niin ikään aiempaa voimaharjoittelukokemusta omaavaa koehenkilöä suoritti valvotusti maksiminopeudella erilaisia nopeusvoimatyyppisiä hyppelyharjoitteita (ilman kuormaa ja keveillä kuormituksilla) 3 kertaa viikossa 24 viikon ajan. Molempia harjoittelujaksoja seurasi 12 viikon harjoitustauko, jona aikana edellä kuvattu spesifinen voimaharjoittelu lopetettiin kokonaan mutta koehenkilöt toteuttivat edelleen jo projektien aikana suorittamaansa omaehtoista kevyttä kuntoilua. Tutkimusten kontrolliryhmänä oli 8 myös aiempaa voimaharjoittelukokemusta omaavaa henkilöä, jotka eivät osallistuneet em. ohjattuun voimaharjoitteluun vaan toteuttivat omaehtoista kevyttä voimailua sisältävää kuntoilua 1-3 kertaa viikossa pitääkseen yllä saavuttamaansa kuntotasoa.

Tutkimusten koehenkilöt testattiin neljän viikon välein yhteensä 10 kertaa koko 36 viikon seurantajakson aikana. Kontrollihenkilöt testattiin seurantajakson alussa ja lopussa. Laboratoriotestaukset sisälsivät alaraajojen ojentajalihasten isometrisen voima- ja relaksaatio-aika ominaisuuksien mittaamisen, konsentrisen voima-nopeuskäyrän mittaamisen voimalevyanturilla sekä erilaisten venymis-lyhenemissyklus-testien (vertikaalihypyt esikevennyksellä ilman kuormaa ja kuormalla sekä pudotushypyt) suorittamisen. Tämän lisäksi suorituskykyä mitattiin yhden raajan tahdonalaisessa ja lepotilan reflektorisessa isometrisessa ojennuksessa. Tutkittavien

lihasten sähköiset aktiivisuudet (EMG) rekisteröitiin em. suorituskykytestien yhteydessä pintaelektrodeilla. Lihasnäytteet otettiin solujakauman ja solujen keskimääräisen pinta-alan määrittämiseksi uloimmasta reisilihaksesta kolmen kuukauden välein. Verinäytteet otettin 4-8 viikon välein seerumin hormonipitoisuuksien määrittämiseksi. Lisäksi mitattiin kehon koostumus erilaisilla antropometrisilla mittauksilla.

Tutkimuksen päätulokset osoittivat, että maksimivoimaharjoittelu paransi maksimaalista lihasvoimaa erittäin paljon (26.8 -30.2 %; $p<0.001$). Lihasten sähköiset aktiivisuudet kasvoivat merkitsevästi ($p<0.05$-0.01) vain niillä harjoitusjaksoilla, joilla käytetty kuormitus oli suuri (80-120 %), mutta laskivat ($p<0.05$) harjoiteltaessa selvästi submaksimaalisella (70-80 %) intensiteettialueella. Lihaksiston hypertrofiset muutokset ilmenivät reiden ympärysmitan ($p<0.001$) ja pääasiassa nopeiden lihassolujen keskimääräisen pinta-alan merkitsevänä ($p<0.001$) kasvuna kolmen ensimmäisen harjoituskuukauden aikana mutta kolmen viimeisen harjoituskuukauden aikana reiden ympärysmitan ja solujen keskimääräisten pinta-alojen muutokset olivat hyvin pieniä. Seerumin hormonipitoisuudet muuttuivat pääasiassa siten, että testosteroni/kortisoli -suhde lisääntyi jonkin verran harjoitusjakson aikana. Viimeisen kovimman harjoituskuukauden aikana muutokset em. hormonisuhteessa ja lihasvoimassa olivat hyvin yksilöllisiä, jolloin joillakin koehenkilöillä lihasvoima vielä kasvoi mutta joillakin sen sijaan väheni. Testosteroni/kortisoli -suhteen yksilölliset muutokset korreloivat tällöin merkitsevästi ($p<0.01$) vastaavan ajan yksilöllisiin lihasvoiman muutoksiin. Isometrisessä voimantuottonopeudessa ja dynaamisissa nopeusvoima-ominaisuuksissa sekä lepotilassa mitatussa reflektorisessa supistuksessa maksimivoimaharjoittelu aiheutti vain vähän muutoksia. Maksimivoimaharjoittelujakson jälkeisen kolmen kuukauden tauon aikana sekä lihasvoima että lihasten sähköinen aktiivisuus vähenivät merkitsevästi ($p<0.001$ ja 0.05) ja nopeiden sekä hitaiden solujen keskimääräiset pinta-alat pienenivät ($p<0.05$).

Nopeusvoimatyyppinen harjoittelu lisäsi erittäin merkitsevästi (24.1-32.5 %; $p<0.001$) sekä isometrista voimantuottonopeutta että dynaamista nopeusvoima-ominaisuutta. Nämä muutokset olivat myös merkitsevästi ($p<0.05-0.001$) suurempia kuin vastaavat muutokset maksimivoimaharjoittelun aikana. Lihasten sähköiset aktiivisuudet lisääntyivät nopeusvoimaharjoittelun aikana merkitsevästi ($p<0.05-0.001$) ja korreloivat ($p<0.05-0.001$) vastaavan ajan nopeusvoima-ominaisuuden muutokseen sekä räjähtävässä isometrisessa ja konsentrisessa lihastyössä että myös nopeissa venymis-lyhenemissyklus-testeissä. Lihaksen hypertrofiset muutokset ja maksimivoiman lisääntyminen olivat merkitsevästi ($p<0.01$) pienempiä nopeusvoima- kuin maksimivoimaharjoittelussa. Lihaksen nopeiden solujen prosenttiosuudella sekä nopeiden ja hitaiden solujen keskimääräisen pinta-alasuhteen kasvulla ($p<0.05$) oli positiivinen korrelaatio ($p<0.05$) räjähtävän isometrisen voiman kasvuun. Seerumin hormonipitoisuuksissa todettiin harjoittelun aikana testosteroni/kortisoli -suhteen lisääntyminen. Lisäksi viimeisen harjoituskuukauden aikana em. hormonisuhteen muutos korreloi merkitsevästi ($p<0.05-0.01$) sekä maksimivoiman että eräiden nopeusvoimamuuttujien muutoksiin. Reflektoristen lepovasteiden muutokset olivat harjoittelun aikana vähäiset. Nopeusvoimaharjoittelun jälkeinen kolmen kuukauden pituinen harjoitustauko aiheutti lihasvoiman, eräiden nopeusvoimamuuttujien ja lihasten sähköisten aktiivisuuksien vähenemisen ($p<0.05$) sekä nopeiden ja hitaiden solujen keskimääräisten pinta-alojen pienenemisen ($p<0.05$).

Tämän tutkimuksen kontrollihenkilöiden maksimaalisessa lihasvoimassa, isometrisessa voimantuottonopeudessa ja dynaamisessa nopeusvoimassa, lihasten sähköisessä aktiivisuudessa, lihassolujen pinta-aloissa sekä seerumin hormonipitoisuuksissa ei ilmennyt systemaattisia muutoksia alku- ja loppumittausten välillä.

Tutkimuksen päätulokset viittaavat siihen, että pitkäaikainen maksimivoima- ja nopeusvoimaharjoittelu aiheuttavat spesifisiä muutoksia voimantuotto-ominaisuuksissa, jotka ovat yhteydessä hermo-lihasjärjestelmässä ilmeneviin spesifisiin adaptaatioprosesseihin. Tämän tutkimuksen perusteella hermostollinen adaptaatio näyttää olevan tärkeä sekä maksimaalisen lihasvoiman että nopeusvoiman kehittymiselle. Lisäksi tulokset osoittavat harjoittelumenetelmän spesifisyyden ja ennen kaikkea tehokkuuden keskeisen merkityksen hermostollisessa adaptaatiossa. Tällöin lihaksiston spesifinen voimantuottokyky saattaa ajoittain parantua oikein valitun tehokkaan harjoittelumenetelmän ansiosta vaikkei suurta lihasmassan kasvua ilmenisikään, mikä on eduksi useissa urheilulajeissa. Hermo-lihasjärjestelmässä tapahtuvien adaptaatioprosessien ja voimantuottokyvyn muutosten suuruudet ja ilmenemisen ajankohdat näyttäisivät siten olevan yhteydessä voimaharjoittelutapaan, intensiteettiin ja harjoittelujakson pituuteen sekä mahdollisesti myös kulloistenkin koehenkilöiden ja/tai urheilijoiden kuntotasoon. Elimistön hormonitasapainon merkitys näyttää korostuneesti tulevan esiin pitkäaikaisen intensiivisen harjoittelujakson loppuvaiheessa, jolloin elimistön anabolia/katabolia -tasapainotilan muutokset näyttävät olevan yhteydessä voimantuotto-ominaisuuksien muutoksiin. Nämä hermostolliset ja hormonaaliset ilmiöt viittavat yksilöllisen harjoitusohjelman keskeiseen merkitykseen lihaksiston voimantuottokyvyn kehittämisessä. Sen sijaan harjoittelutauko näyttää hyvin harjoitelleilla henkilöillä ja/tai urheilijoilla aiheuttavan lihasvoima-ominaisuuksien merkitsevän heikkenemisen jo ainakin neljän viikon kuluessa. Näinkin lyhyessä ajassa havaittava lihasten hermostollisen aktiivisuuden lasku saattaa siten olla jo tässä vaiheessa yhteydessä suorituskyvyn heikkenemiseen. Nämä havainnot viittaavat osaltaan ympärivuotisen, säännöllisen ja oikein jaksotetun harjoittelun tärkeään merkitykseen. Tutkimuksen tulosten perusteella voidaan lopuksi todeta, että hermo-lihasjärjestelmän adaptaatioprosesseja, hormonitasapainoa ja spesifistä voimantuottokykyä systemaattisesti mittaamalla pystyttäneen seuraamaan elimistön harjoitettavuustilaa suhteellisen tarkasti ja kehittämään jatkossa entistä tehokkaampia ja yksilöllisempiä harjoitusmenetelmiä ja täten esim. välttämään liian kovasta harjoittelusta mahdollisesti aiheutuvaa ylikuntotilaa.

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