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EMG, muscle fibre and force production characteristics during a 1 year training period in elite weight-lifters

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Summary. The effects of a 1 year training period on 13 elite weight-lifters were investigated by periodical tests of electromyographic, muscle fibre and force production characteristics. A statistically non-significant increase of 3.5% in maximal isometric strength of the leg extensors, from 4841 ± 1104 to 5010 ± 1012 N, occured over the year. Individual changes in the high force portions of the force-velocity curve correlated ($p < 0.05–0.01$) with changes in weight-lifting performance. Training months 5–8 were characterized by the lowest average training intensity (77.1 + 2.0%), and this resulted in a significant ($p < 0.05$) decrease in maximal neural activation (IEMG) of the muscles, while the last four month period, with only a slightly higher average training intensity (79.1 ± 3.0%), led to a significant ($p < 0.01$) increase in maximum IEMG. Individual increases in training intensity between these two training periods correlated with individual increases both in muscular strength ($p < 0.05$) and in the weight lifted in the clean & jerk ($p < 0.05$). A non-significant increase of 3.9% in total mean muscle fibre area occurred over the year. The present findings demonstrate the limited potential for strength development in elite strength athletes, and suggest that the magnitudes and time courses of neural and hypertrophic adaptations in the neuromuscular system during their training may differ from those reported for previously untrained subjects. The findings additionally indicate the importance of training intensity for modifying training responses in elite strength athletes.

Key words: Neural activation – Hypertrophy – Training intensity – Strength training

Introduction

Muscle strength, power and speed are attributes which have attracted considerable interest among researchers and performers. The mechanisms of adaptation of these performance features are challenges, and for example, several attempts have been made to characterize the events leading to increase in muscle strength. This information has come primarily from studies conducted among initially untrained subjects, and although this "mechanism" itself is far from the final answer, these studies have resulted in considerable advancement in understanding the neuromuscular responses to strength training (e.g., Komi and Buskirk 1972; MacDougall et al. 1977; Moritani and DeVries 1979; Komi et al. 1978; 1982; Häkkinen et al. 1981; Häkkinen and Komi 1983; Houston et al. 1983).

Athletes who have already undergone considerable training may pose a special problem in the study of strength training adaptation. In order to get more understanding of this question, the present study was undertaken to follow an elite group of weight-lifters for a period of one year, in which time the athletes maintained their normal training programme. It was hoped that, by analyzing the training and by performing several repeated laboratory tests on neuromuscular performance, some further insight could be obtained regarding the interrelationships between variations in training intensity (and volume) and the adaptive responses in the neuromuscular system.

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Methods

Subjects. Thirteen elite male weight-lifters volunteered as subjects. They had undergone regular strength training and participated in weight-lifting competitions for 7.1 ± 2.0 years. They were all Finnish champions and/or Finnish national record holders in their various weight categories, from 52.0 to 110.0 kg. Table 1 presents their physical characteristics.

Testing. The subjects were tested in four identical sessions at four-month intervals before, during and after the 12-month experiment period. The tests were performed in a fixed order in each session.

Maximal bilateral isometric force and various force-time (f-t) parameters (see Viitasalo and Komi 1978) of the leg extensor muscles were measured by an electromechanical dynamometer (Komi 1973). The test contractions were performed at knee and hip angles of 107° and 110° respectively. The subjects performed three to four maximal contractions at the maximum rate of force development. The force in each contraction was recorded on magnetic tape (Racal Store 7) for computer (HP 1000 F) analysis. In addition to maximum force, the entire force-time (f-t) curve was analyzed so that the times needed to increase the force from 10% to 30%, 60% and 90% MVC could be calculated on a relative scale (Häkkinen et al. 1980): On the asolute scale, starting from a force level of 100 N, the times to reach 500, 1500, 2500 and 3500 N were obtained. Analysis of the f-t curve also included calculations of the average force produced during different absolute time periods (100 ms in duration) from the start of force production up to 500 ms (Häkkinen et al. 1985a).

Force-velocity curves for the leg extensor muscles were measured by performing various maximal voluntary vertical jumps on a force-platform (Komi et al. 1974). The tests included a squat jump (SJ) from a static semisquatting position (a knee angle of 90 degrees measured by an electrical goniometer) with no preliminary counter movement, and a counter movement jump (CMJ) from a standing position with a preliminary counter movement (Komi and Bosco 1978). In these jumping conditions without extra load, the subjects kept their hands on their hips throughout the entire jump. The subjects also performed the respective squat and counter movement jumps with an extra load (Bosco and Komi 1979). In these jumps on the force-platform, a barbell was held on the shoulders and loads of 40, 80, 100 and 140 kg were used. Two attempts in each jumping condition were recorded from each subject. The flight time measured from the force signal was used in calculating the height of rise of the body centre of gravity (h(C.G.)) (Asmussen and Bonde-Petersen 1974) with a computer (HP 1000 F). The final analysis was performed on the load-vertical jumping height relationships, which have also been shown to characterize the force-angular velocity relationship in SJ and CMJ jumps (Viitasalo 1985).

Table 1. Physical characteristics of the elite weight-lifters before and after 12 months of heavy resistance weight-lifting training

Variable	Before		After	
	Mean	SD	Mean	SD
Age (years)	23.0	2.8	–	
Height (cm)	171.1	9.6	–	
Mass (kg)	78.9	14.7	78.8	14.3
Fat (%)	12.1	3.3	12.0	2.2
Thigh girth (cm)	53.6	4.6	53.9	4.2

The subjects were also tested on the force-platform by various drop jumps. In these, the subjects dropped from heights of 20, 40, 60, 80 and 100 cm onto the force-platform and immediately jumped upwards (Komi and Bosco 1978). Two trials of each drop jump were recorded from each subject for calculation of the heights of rise of the centre of gravity.

Electromyographic activity (EMG) was recorded from the right vastus lateralis (VL) and vastus medialis (VM) during both the isometric tests and those on the force-platform. Bipolar (20 mm interelectrode distance) surface EMGs were obtained from Beckman miniature skin electrodes placed longitudinally over the motor-point area as determined by a Neuroton 626 stimulator. The electrode positions were marked on the skin by small ink dot tattoos (see Häkkinen and Komi 1983). These dots ensured the same electrode positioning in each test over the 12-month experimental period. EMG signals were recorded telemetrically (Medinik AB Model IC-600-G) on magnetic tape and integrated (IEMG for 1 s) and averaged for the two muscles for maximal isometric contraction and for the eccentric and concentric phases of floor contact in the jumping performances. In the isometric contractions the EMG was also integrated (IEMG for 1 s) for periods of 100 ms to obtain an IEMG-time analysis from the start of contraction similar to that for isometric average force (see Häkkinen et al. 1985a).

In tests of the Olympic lifts of snatch and clean and jerk, subjects warmed up with a weight of 50—60% of their maximum, and the tests proper started with a weight of 70% of maximum and continued with increases of 10% up to the maximum. After two misses with the same weight the test was terminated.

Muscle biopsies were obtained from the left vastus lateralis by needle biopsy (Bergström 1962). Histochemical staining for myofibrillar ATPase (Padykula and Herman 1955) was used to classify the fibres as fast twitch (FT) or slow twitch (ST) (Gollnick et al. 1972). For calculation of fibre cross-section areas and FT/ST area ratios, ten representative fast and ten representative slow cells were selected. This selection always took place from the same area, in which the cross-section appeared perpendicular to the fibre orientation. The sample was projected from a microscope onto a digital board connected to the computer for calculation of the average cross-sectional areas of the FT and ST cell groups (Viitasalo and Mäkinen 1980; Viitasalo et al. 1980).

The percentage of body fat and the fat-free weight were estimated from measurements of skinfold thickness (Durnin and Rahaman 1967). Thigh girth was measured with a tape applied around the relaxed muscles with the subject in a sitting position. The proximal, middle and distal parts of the thigh were measured and then averaged.

Ordinary statistical methods were used for calculations for means, standard deviations, standard errors, and coefficients of correlation. Differences between the values before and after training were tested for significance by the Student *t* test.

Training. The subjects trained for weight-lifting according to the individual training programmes designed by their personal coaches. They kept training diaries for the whole experimental period so that their training could be analyzed in detail, the training volume and intensity (load) in each training session being determined. During the year the subject group trained on average 5 times a week. The training included the normal strengthening exercises used by elite weight-lifters, such as the

Olympic lifts (snatch and clean & jerk), various power lifts, various pulling exercises, various squat-lifts to strengthen the legs, various pressing exercises to strengthen the arms, and some other strengthening exercises for selected muscle groups. Training of the leg extensor muscles by squat-lifts took place 3 times a week on average. The average weekly volumes of these squat-exercises were 7997 ± 2499, 7165 ± 2130 and 8703 ± 1245 kg for the first, second and third four-month training periods respectively, and the average intensities of training over these periods were 77.9 ± 1.9, 77.1 ± 2.0 and 79.1 ± 3.0% of one maximum repetition (see also Fig. 1).

Results

Physical characteristics and muscle fibres

Body mass, thigh girth and percentage of body fat of the subject group remained statistically unaltered during the 12-month experimental period (Table 1). The same was true for the mean areas of FT and ST muscle fibres, although the average values demonstrated increases of 4.5 and 2.9%, respectively. Similarly, total mean fibre area increased (ns.) by 3.9% (Fig. 1) and the FT percentage of vastus lateralis also remained statistically unaltered (from 53.7 ± 10.5 to 52.1 ± 8.6%).

Maximal isometric force, maximum IEMG, force-time and IEMG-time curves

The maximal isometric leg extension force changed insignificantly by 3.5% from 4841 ± 1104 to 5010 ± 1012 N during the 12-month experimental period. Figure 1 demonstrates the alteration of this force during the course of training. No statistically significant change was seen when the averaged maximum IEMG before and after training were compared. During the second training period, in which the lowest average training intensity was used, a significant ($p < 0.05$) decrease was observed in the maximum IEMG from 0.38 ± 0.08 to 0.32 ± 0.11 mV · s (Fig. 1). During the last training period, when the highest training intensity was used, the maximum IEMG increased significantly ($p < 0.05$) back to 0.37 ± 0.11 mV · s. The individual changes in maximum IEMG and maximal isometric force in this last training period correlated significantly ($r = 0.56$, $p < 0.05$).

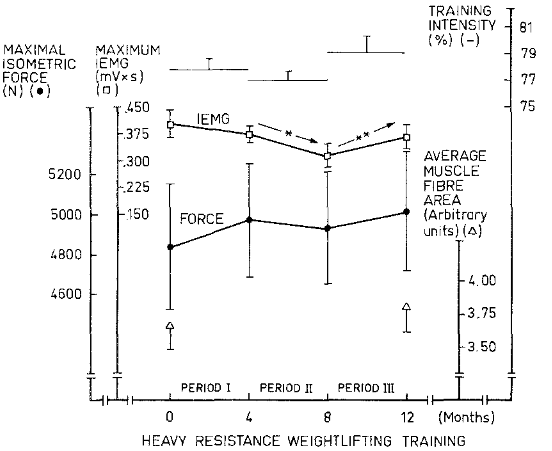

Fig. 1. Mean (± SE) maximal IEMG (averaged for vastus lateralis and medialis), mean (± SE) maximal force of isometric bilateral leg extension and average (arbitrary units ± SE) total FT and ST muscle fibre areas of vastus lateralis during a 12-month study of heavy resistance strength training in elite weight-lifters. The average (± SE) intensity ranges used for the leg extensor muscles during each of the three training periods are also shown (* = $P < 0.05$. ** = $P < 0.01$)

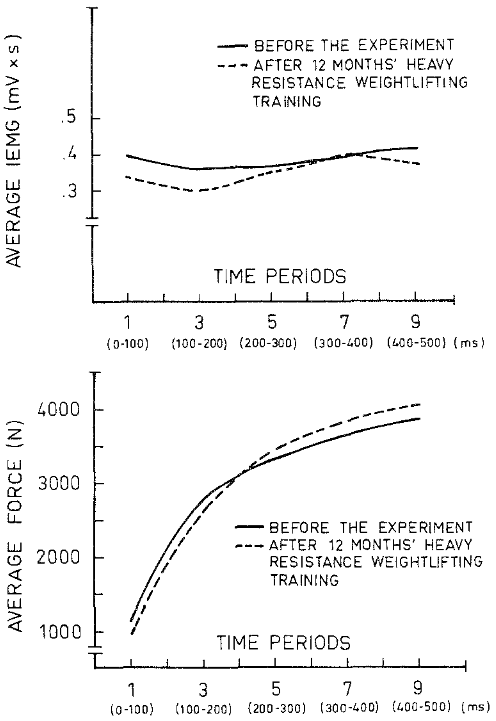

Fig. 2. Average IEMG-time and force-time curves (IEMG averaged for vastus lateralis and medialis) of rapid isometric bilateral leg extension before and after the 12-month period of heavy resistance strength training in elite weight-lifters

Figure 2 presents the average IEMG-time and force-time curves before and after the year of training. Although the positions of the curves were slightly different after training, no statistically significant differences could be observed.

Force-velocity curve and IEMGs during the concentric contractions

The 12-month heavy resistance weight-lifting training resulted in slight increases in the SJ

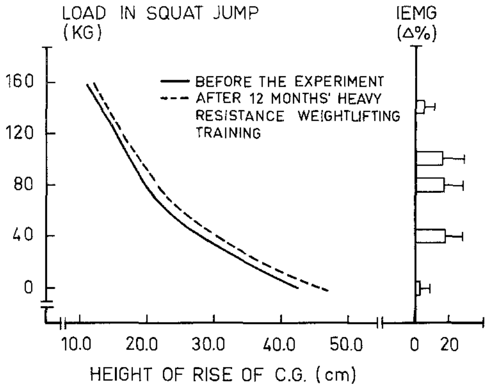

Fig. 3. Average force-velocity (load-vertical jumping height) curves of the leg extensor muscles during concentric contractions before and after the 12-month period of heavy resistance strength training in elite weight-lifters. Relative changes (±SE) in IEMG of vastus lateralis and medialis during the concentric phases of the vertical squat jumps are also shown

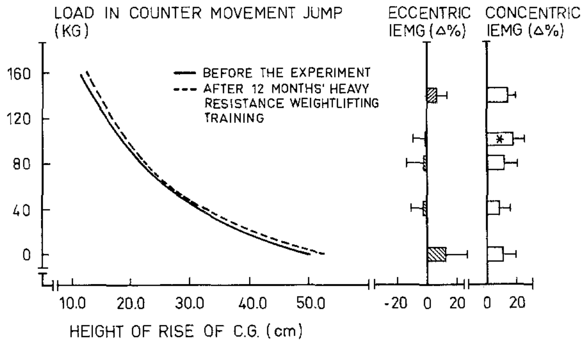

Fig. 5. Average force-velocity (load-vertical jumping height) curves of the leg extensor muscles during the counter movement jumps before and after the 12-month study of heavy resistance strength training in elite weight-lifters. The relative changes (±SE) in IEMG for vastus lateralis and medialis during the eccentric and concentric phases of the counter movement jumps are also shown (* = $P < 0.05$)

jumping heights at all loads from 0 to 140 kg (Fig. 3). Statistically significant ($p < 0.05$) increases occurred during training in SJO (from 42.6±3.8 to 46.5±6.5 cm) and SJ80 (from 19.4±3.6 to 21.1±3.1 cm). Slight but statistically non-significant increases occured during the training in the maximal IEMGs of the two muscles recorded during the contacts of the squat jumps (Fig. 3). Figure 4 demonstrates the alteration in maximum IEMG and SJ140 jumping height during the course of the training. During the second training period, when the lowest training intensity was used, maximum IEMG decreased ($p < 0.05$) but increased significantly ($p < 0.05$) during the last training period with the highest training intensity.

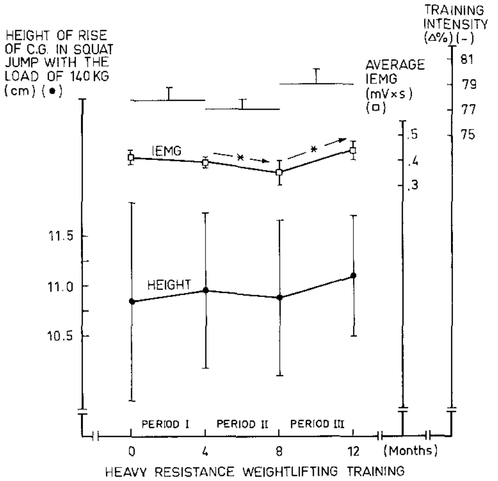

Fig. 4. Mean (±SE) heights of rise of the centre of gravity (C.G.) in the vertical squat jump with the highest load of 140 kg, and average (±SE) IEMG for vastus lateralis and medialis during the concentric phase of the jump during the 12-month study of heavy resistance strength training in elite weightlifters. The average (±SE) intensity ranges used for the leg extensor muscles during each of the three training periods are also shown (* = $P < 0.05$) (see also Fig. 1)

Force-velocity curve and IEMGs during the counter-movement exercises

No statistically significant change took place during the 12-month training in CMJ heights at any

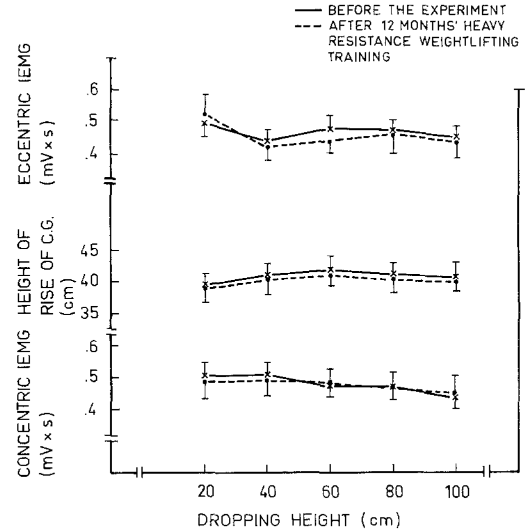

Fig. 6. Mean (±SE) heights of rise of the centre of gravity (C.G.) in vertical drop jumps performed from heights of 20, 40, 60, 80 and 100 cm, and the average (±SE) IEMG for vastus lateralis and medialis during the eccentric and concentric phases of the drop jumps before and after the 12-month study of heavy resistance strength training in elite weight-lifters

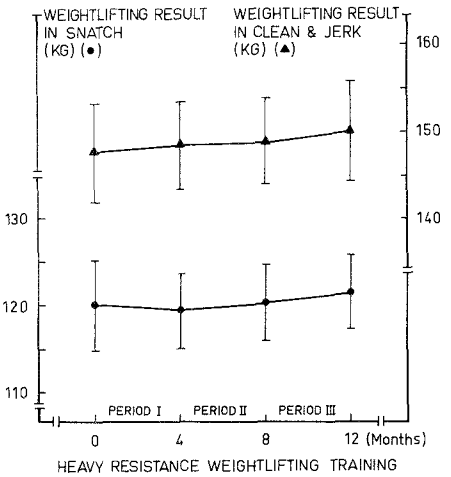

Fig. 7. Mean (±SE) weight-lifting results in the Olympic snatch and clean & jerk during the 12-month study of heavy resistance strength training in elite weight-lifters

load examined from 0 to 140 kg (Fig. 5). The maximal IEMGs of the two muscles during the eccentric phases of CMJ also remained unaltered (Fig. 5). Slight increases occured during the training in the maximal IEMGs in the concentric phases of CMJ. This increase was significant ($p < 0.05$) in the IEMG of CMJ100.

Jumping heights and IEMGs during the drop jump performances

The drop jump performances from different dropping heights (from 20 to 100 cm) remained unaltered during the 12 month period of heavy resistance weight-lifting training (Fig. 6). The same was true for the maximal IEMGs during both contact phases of all drop jumps (Fig. 6).

Weight-lifting results

Slight but statistically insignificant increases occured during the 12-month training period both in the snatch (from 120.0±18.1 to 121.4±14.6 kg) and in the clean & jerk (from 147.5±20.1 to 150.0±20.3 kg) (Fig. 7).

Comparison between force production and weight-lifting

The correlations between the relative changes during training in the heights of rise of C.G. in the SJ's and in those in the weight-lifting results increased, on average, with the increase in load.

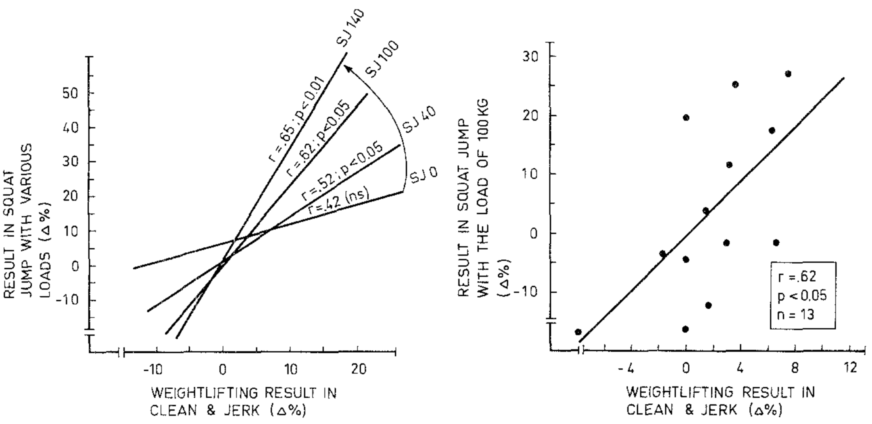

Fig. 8. Relationships between the relative changes in vertical height of rise of the centre of gravity (C.G.) in squat jumps performed with loads of 0, 40, 100 and 140 kg and the changes in weight-lifting results in the clean & jerk (A), and the between the relative changes in jumping height in the squat jump performed with a load of 100 kg and the changes in clean & jerk (B), after the 12-month period of heavy resistance strength training in elite weight-lifters

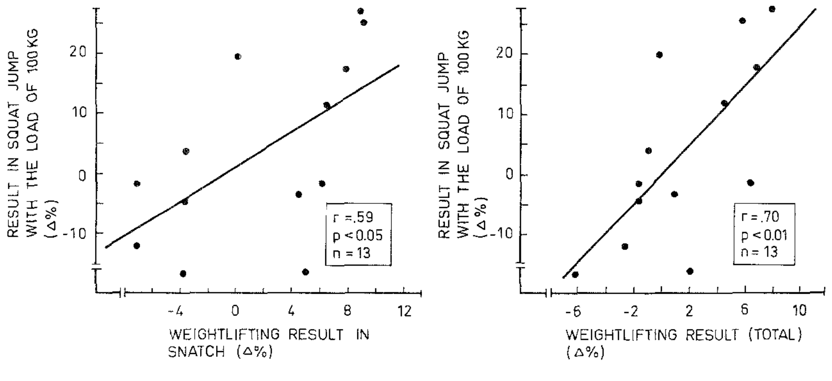

Fig. 9. Relationships between the relative changes in the vertical height of rise of the centre of gravity (C.G.) in the squat jump performed with a load of 100 kg, and the changes in weight-lifting results in the snatch (A) and between the changes in the same jump and those in the weight-lifting total result (snatch + clean & jerk) (B) after the 12-month period of heavy resistance strength training in elite weight-lifters

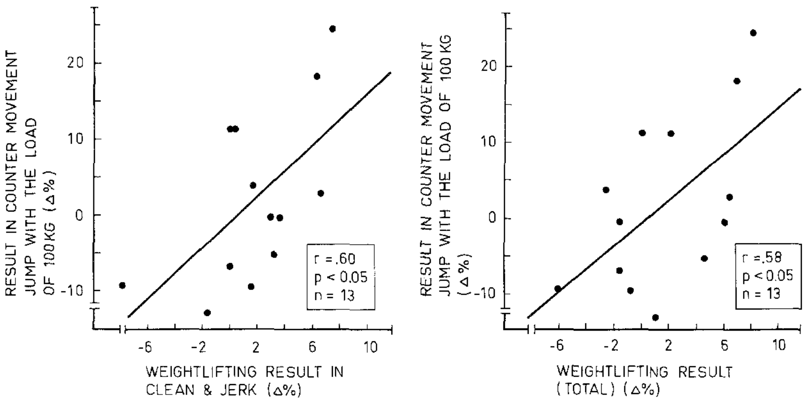

Fig. 10. Relationships between the relative changes in the vertical height of rise of the centre of gravity (C.G.) in the counter movement jump performed with a load of 100 kg and the changes in weight-lifting results in the clean & jerk (A) and between the changes in the same jump and those in the weight-lifting total result *(snatch + clean & jerk)* (B) after the 12-month period of heavy resistance strength training in elite weight-lifters

Figure 8A presents these correlations for the clean & jerk (from SJ0: $r = 0.42$. ns. up to SJ140: $r = 0.65$. $p < 0.01$) (see also Fig. 8B). The correlations between relative changes in jumping height and the snatch were, on average, somewhat smaller, the highest correlation being that of SJ100 ($r = 0.59$. $p < 0.05$. Figure 9A). The highest correlation ($r = 0.70$, $p < 0.01$) was observed between the relative changes in SJ100 and the changes in the weight-lifting total results (Fig. 9B).

The correlations between the relative changes during training in CMJ performances and in the weight-lifting results also increased on average with the increase in load. Figure 10A and B shows the correlations between the changes in CMJ100 and the clean & jerk ($r = 0.60$, $p < 0.05$) and the weight-lifting total result ($r = 0.58$, $p < 0.05$).

The correlations between the relative changes in isometric force production and the weight-lifting results were positive, but were not statistically significant.

Discussion

Over the year, the present findings demonstrated only small increases in muscular strength and weight-lifting performance in the elite weight-lifters. There were no marked improvements in the group averages, but significant correlations were observed between the changes in the upper portions of the force-velocity curves and the changes in weight-lifting results. The four-month period of low intensity training resulted in a significant decrease in the maximum IEMG of the trained muscles, while another training period of the same duration, but with a slightly higher average intensity, led to a significant increase in maximal neural activation of the same muscles. Muscle hypertrophy was also unexpectedly small, as judged from the non-significant changes in muscle fibre areas over the experimental period. Muscle activation and force production, both in the early portion of the isometric force-time curve and in the high velocity drop jump tests, remained unaltered throughout.

These changes in performance criteria are much smaller than those one would expect in untrained "normal" individuals, among which almost any method can cause increases in muscle strength, provided that the frequency of training sessions and the training intensities are progressively increased (Komi 1986). The actual mechanism and the magnitudes of increases may therefore take place differently, depending on the initial training status of the subjects. In untrained individuals it is a commonly accepted view that the influence of strength training can be seen as an increase in neural activation to the muscles. This is then followed by increases in muscle fibre size, and this hypertrophic effect may be more pronounced in fast twitch fibres (for details see e.g., MacDougall et al. 1977; Moritani and DeVries 1979; Häkkinen et al. 1981; Komi et al. 1982; Häkkinen and Komi 1983; Houston et al. 1983). However, in strength athletes with a considerable training background, the response to training may differ considerably. This is characterized by less pronounced hypertrophic and neural changes (see e.g., Häkkinen 1985; Häkkinen et al. 1985a), and the results presented in Fig. 1 are in line with these previous observations.

The primary question concerning adaptive responses in well trained athletes is how the training can be changed periodically to obtain the designed results. Variations both in magnitude and intensity may be relevant in this regard (see e.g., Häkkinen 1985). The present study over one year of training revealed periods during which both the volume and intensity were different from "normal" training conditions. Period II, lasting for four months, had a slightly reduced intensity of training, and this resulted in significant performance decrements, particularly in maximum IEMG (see Figs. 1 and 4). When the training intensity was again increased (training period III) these decrements were reversed, and IEMG increased significantly. The average curve of muscle strength followed the responses of IEMG, but the changes were not significant (see Figs. 1 and 4). These findings support observations reported earlier (Häkkinen et al. 1985a) which indicate that in strength training an intensity ≥80% of the maximum concentric load is required before any EMG increases can be seen in well trained strength athletes. It may additionally be justified to conclude that the overall training in the present one year period was of too low an intensity to cause observable changes in EMG or force parameters over that time. Figure 11A, B may also be taken as indications that, when training intensity is increased, then the changes can be seen not only in the parameters tested in the laboratory but also in the weight-lifting performance as well. Although not presented in any of the figures, the changes in the volume of training, as opposed to its intensity, did not induce responses in the parameters tested. The fact that the laboratory tests were sensitive enough to reflect changes in the weight-lifting results is encouraging for further examination of training problems among elite weight-lifters. In this connection, the interrelationship between the changes in the higher force portions of the force-velocity curve (Figs. 8—10) and the weight-lifting results are useful, and stress the importance of the maximal strength of the leg extensors, as reported in practical weight-lifting papers (e.g. Oleshko 1979).

The mechanisms giving rise to strength and performance increase among elite weight-lifters may not be different from those suggested for less trained individuals (for details see Komi and Buskirk 1972; Moritani and DeVries 1979; Komi et al. 1978; 1982; Häkkinen et al. 1981; Häkkinen and Komi 1983; Houston et al. 1983). But the initial training status of the athletes makes the process more complicated to follow and more difficult to substantiate. In untrained and/or less trained subjects the kind of training used may not be so critical as long as the volume and intensity are of "sufficient" levels (see e.g., Häkkinen and Komi 1981). In strength athletes, however, the time courses of adaptations are likely to be different, and therefore the training variation, particularly in intensity, must be well programmed. The difficulty here again lies in the problem that, although information is available regarding the methods used to increase muscle size in people such as bodybuilders (e.g., MacDougall et al. 1982; Tesch and Larsson 1982; Häkkinen et al. 1984; 1986), this information may not be directly applicable to the planning of training programmes for weight-lifters. Similar problems may arise with other "performance" criteria as well.

In previously untrained and/or less trained subjects the specificity of heavy resistance strength training can be "easily" demonstrated as great increases in maximal strength, while the concomitant changes in force production in the very early portions of the isometric force-time and/or concentric force-velocity curves tend to be only slight (or sometimes periodically decreasing) (e.g., Ikai 1970; Sukop and Nelson 1974; Häkkinen et al. 1980; 1981). Specificity of training has been observed also among well trained subjects when the training methods have been changed drastically, for example, using heavy resistance instead of explosive type strength training (Häkkinen et al. 1985a, b). Therefore one might expect that this strong specificity would not be observed

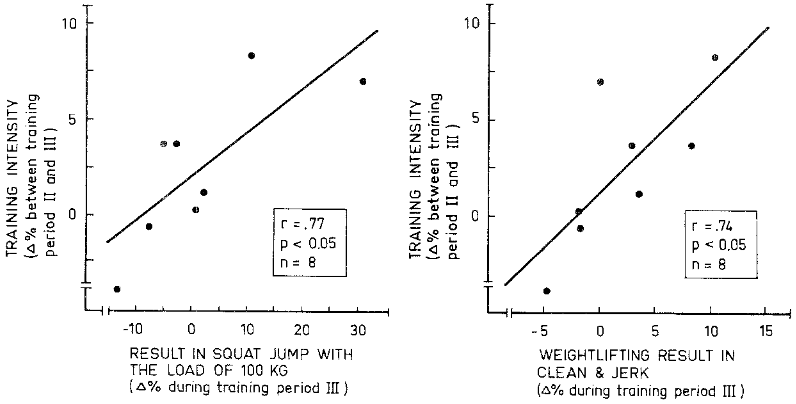

Fig. 11. Relationships between the relative changes in training intensity of the leg extensor muscles between training periods II and III and the changes in vertical height of rise of the center of gravity (C.G.) in the squat jump with a load of 100 kg (A), and between the changes in training intensity and the changes in the clean & jerk results (B) after the third period of 4 months training of elite weight-lifters (see also Figs. 1, 4 and 7)

during the years training of our elite weight-lifters, when the improvement in maximal strength itself was rather limited. The results presented in Figs. 2 and 6, however, indicate that the phenomenon of specificity of strength training might be similar both in previously untrained subjects and in highly trained strength athletes.

In summary, the present findings, which demonstrated only limited strength development, suggest that the magnitudes and time courses of both the neural and the hypertrophic adaptations in the neuromuscular system during strength training in elite strength athletes may differ from those adaptations reported for previously untrained subjects. The actual mechanisms of strength increase among the two "subject" groups may, however, be basically the same. The findings suggest additionally that training intensity has an important role in modifying changes in maximal muscle activation with concomitant alterations in muscular strength.

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