Neuromuscular and hormonal adaptations in athletes to strength training in two years

K. HÄKKINEN, A. PAKARINEN, M. ALÉN, H. KAUHANEN, AND P. V. KOMI
Departments of Biology of Physical Activity and Health Sciences, University of Jyväskylä, SF-40100 Jyväskylä, and Department of Clinical Chemistry, University of Oulu, SF-90220 Oulu, Finland

HÄKKINEN, K., A. PAKARINEN, M. ALÉN, H. KAUHANEN, AND P. V. KOMI. Neuromuscular and hormonal adaptations in athletes to strength training in two years. J. Appl. Physiol. 65(6): 2406–2412, 1988.—Neuromuscular and hormonal adaptations to prolonged strength training were investigated in nine elite weight lifters. The average increases occurred over the 2-yr follow-up period in the maximal neural activation (integrated electromyogram, IEMG; 4.2%, P = NS), maximal isometric leg-extension force (4.9%, P = NS), averaged concentric power index (4.1%, P = NS), total weight-lifting result (2.8%, P < 0.05), and total mean fiber area (5.9%, P = NS) of the vastus lateralis muscle, respectively. The training period resulted in increases in the concentrations of serum testosterone from 19.8 ± 3.3 to 25.1 ± 5.2 nmol/l (P < 0.05), luteinizing hormone (LH) from 8.6 ± 0.8 to 9.1 ± 0.8 U/l (P < 0.05), follicle-stimulating hormone (FSH) from 4.2 ± 2.0 to 5.3 ± 2.3 U/l (P < 0.01), and testosterone-to-serum sex hormone-binding globulin (SHBG) ratio (P < 0.05). The annual mean value of the second follow-up year for the serum testosterone-to-SHBG ratio correlated significantly (r = 0.84, P < 0.01) with the individual changes during the 2nd yr in the averaged concentric power. The present results suggest that prolonged intensive strength training in elite athletes may influence the pituitary and possibly hypothalamic levels, leading to increased serum levels of testosterone. This may create more optimal conditions to utilize more intensive training leading to increased strength development.

METHODS

Subjects. Nine elite male weight lifters volunteered as subjects. They had undergone regular strength training and participated in weight lifting competitions for 7.0 ± 2.1 yr. They were all Finnish champions and/or Finnish national record holders. Some of the weight lifters had earlier been subjects in a follow-up experiment of 1 yr (11, 13). Table 1 presents the physical characteristics of the subject group. The subjects were not taking exogeneous anabolic-androgenic steroids or other drugs expected to affect physical performance or hormone balance for several months before or during this study.

Training. The subjects trained for weight lifting according to the individual training programs designed by their personal coaches. Because the weight lifters were quite a homogenous group of elite athletes, their training schedules were rather well synchronized with each other. Every subject was therefore in practice in a quite similar phase of training during each yearly cycle. The subjects also kept training diaries for the whole experimental period to substantiate intense training. During the follow-up the athletes trained, on average, 5 times/wk. The training included the normal strengthening exercises used by elite weight lifters, such as the Olympic lifts (snatch and clean and jerk), various power lifts, various pulling exercises, various squat lifts to strengthen the legs, and some other strengthening exercises for selected muscle groups. Training of the leg extensor muscles by squat lifts took place 3 times/wk on average.

Testing: neuromuscular performance. The subjects were tested in seven identical sessions at 4-mo intervals before, during, and after the 24-mo experimental period. The tests were performed in a fixed order in each session.

MUSCLE STRENGTH can be easily increased during intensive strength training by initially untrained subjects as well as previously less highly trained nonathletes (e.g., 7, 17, 25). Neural and muscular adaptations play important roles in strength development during strength-training periods lasting for several weeks or a few months (9, 10, 12, 19, 21–23). Recent experiments have demonstrated that the endocrine system also responds to strength training (6, 13, 14). Individual changes during the course of strength training in the level of some serum hormones, especially androgens, may be related to the concomitant changes in physical performance, especially in strength of the trained muscles (13, 14). These observations suggest that endocrine system responses during strength training may be related to the trainability status of an individual. Elite-strength athletes with several years of an intensive training background may represent an interesting subject population in which to examine physiological adaptations to training. Because it is expected that training responses in elite athletes will be limited in magnitude, a considerably longer follow-up period may be required to substantiate these changes.

The present study was undertaken to follow an elite group of weight lifters for 2 yr to determine the training-induced adaptations in the neuromuscular and endocrine systems in elite-strength athletes. The performance of repeated laboratory measurements on neuromuscular performance and analysis of serum hormone concentrations provided insight into the relationship of hormone responses and strength.
TABLE 1. Physical characteristics of elite weight lifters before experiment and after 12 and 24 mo of weight-lifting training

<table>
<thead>
<tr>
<th>Variable</th>
<th>Before Experiment</th>
<th>After 12 mo</th>
<th>After 24 mo</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, yr</td>
<td>22.3±2.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weight, kg</td>
<td>78.3±15.7</td>
<td>78.5±15.9</td>
<td>79.1±16.8</td>
</tr>
<tr>
<td>Height, cm</td>
<td>171.4±11.0</td>
<td>171.6±11.4</td>
<td>171.3±11.8</td>
</tr>
<tr>
<td>Fat-free weight, kg</td>
<td>68.4±12.3</td>
<td>68.1±12.9</td>
<td>70.0±12.9*</td>
</tr>
<tr>
<td>Fat, %</td>
<td>19.0±3.5</td>
<td>11.8±3.1</td>
<td>11.0±3.9</td>
</tr>
</tbody>
</table>

Values are means ± SD. * P < 0.05.

Maximal bilateral isometric force and various force-time (F-T) parameters (9, 26) of the leg extensor muscles were measured by an electromechanical dynamometer (16). The test contractions were performed at knee and hip angles of 107° and 110°, respectively. In addition to maximal force, the entire F-T curve was analyzed by a computerized system so that the times needed to increase the force from 10 to 30%, 60 and 90% of the maximum, could be calculated on a relative scale (9). On the absolute scale, starting from a force level of 100 N, the times to reach 500, 1,500, 2,500, and 3,500 N were obtained. Analysis of the F-T curve also included calculations of the average force produced during different absolute time periods from the start of force production up to 500 ms (9). Force-velocity curves for the leg extensor muscles were measured by performing various maximal voluntary vertical jumps on a force platform (20) from a static semisquatting position with no preliminary countermovement (18). The subjects also performed the respective squat jump with an extra load (3). In these jumps on the force platform, a barbell was held on the shoulders with a computer. The final analyses were performed on the load-vertical jumping height relationship, which has also been shown to characterize the force-velocity relationship in squat jumps (SJ) (25). In addition, an average concentric power index was calculated from the jumping performances (0, 40, 80, 100, 140) according to the following formula:

\[
\text{(body wt + load) \times \text{jumping ht}} / \text{body wt}
\]

This index has been demonstrated to characterize the overall neuromuscular performance of the weight lifter (15).

Electromyographic (EMG) activity was recorded from the right vastus lateralis (VL) and vastus medialis (VM) during both the isometric and concentric tests. 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 Neurometer 626 stimulator. The electrode positions were marked on the skin by small ink-dot tattoos (10). These dots ensured the same electrode positioning in each test over the 24-mo 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 the maximal phase of the isometric contraction and for the concentric phases of floor contact in the jumping performances. In the isometric contractions the EMG was also integrated (IEMG for 1 s) from the start of the contraction to obtain an IEMG time analysis (9).

The subjects participated also in the official weight-lifting competitions at the same intervals as the laboratory measurements to record their maximal results in the Olympic snatch and clean and jerk. In these competitions the weight lifters competed in their normal weight categories.

Muscle biopsies were obtained from the left VL by needle biopsy (2). Histochemical staining for myofibrillar adenosinetriphosphatase (24) was used to classify the fibers as fast twitch (FT) or slow twitch (ST) (5). For calculation of the fiber cross-sectional areas and the FT- to ST area ratios, 10 representative fast and 10 representative slow cells were selected. This selection always took place from the same area, in which the cross section appeared perpendicular to the fiber orientation. The sample was projected from a microscope onto a digital board connected to the computer for calculation of the average cross-sectional areas (in arbitrary units) of the FT and ST cell groups (J. Viitasalo, unpublished observations).

The percent of body fat and the fat-free weight were estimated for measurements of skinfold thickness (4). 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.

Analytic methods. After 12 of h of fasting and 1 day of reduced training, blood samples were drawn at 8 A.M. from the antecubital vein. Serum samples for the hormone determinations were kept at -20°C until assayed. The assays of serum cortisol, testosterone, follicle-stimulating hormone (FSH), and luteinizing hormone (LH) were performed by radioimmunoassays by use of reagent kits from Farmos Diagnostica (Turku and Oulunsalo, Finland). The concentrations of serum sex hormone-binding globulin (SHBG) were determined by an immunoradiometric method by use of reagent kits from Farmos Diagnostica. The sensitivity of the cortisol assay was 0.005 μmol/l, the coefficient of intra-assay variation was 4.0%, and that of interassay variation was 6.2%. The respective values were 0.26 nmol/l, 7.0%, and 9.7% for the testosterone assay, 0.8 U/l, 4.5%, and 7.6% for the FSH assay, 1.0 U/l, 3.2%, and 6.3% for the LH assay, and 0.5 nmol/l, 3.2%, and 5.0% for the SHBG assay.

Ordinary statistical methods were used for the calculations of means, standard deviations, standard errors, and correlation coefficient (parametric). Differences between the values before (the first measurement) and after the training (the last measurement) were tested for significance by two-tailed Student's t test.

RESULTS

Physical characteristics and muscle fibers. Significant increases occurred during the 24-mo experimental period in the subject group in fat-free weight from 68.6 ± 12.3
NEUROMUSCULAR AND HORMONAL ADAPTATIONS TO TRAINING

FIG. 1. Average fiber areas of fast-twitch (FT) and slow-twitch (ST) fiber types of vastus lateralis muscle and average thigh girth in elite weight lifters during a 24-mo follow-up study of weight-lifting training (means ± SE). *P < 0.05.

to 70.0 ± 12.9 (SD) kg (P < 0.05, Table 1) and in thigh girth from 53.6 ± 5.0 to 54.3 ± 4.6 cm (P < 0.05, Fig. 1). Slight, but statistically nonsignificant, increases occurred during this period in the mean areas of the FT and ST fibers of the VL muscle (Fig. 1). Similarly, a slight (P = NS) increase of 5.9% occurred in total mean fiber area during the entire experimental follow-up. The FT percent of the VL muscle was unchanged (from 57.1 ± 8.6 to 55.4 ± 9.2%, P = NS).

Maximal isometric force, maximum IEMG, and F-T and IEMG-time curves. There was periodical alteration in the maximal isometric leg extension force during the course of the 24-mo follow-up (Fig. 2), but a nonsignificant increase of 4.9% (4,984 ± 1,239 to 5,228 ± 1,394 N) was observed between the first and last measurements. A similar alteration was also noted in the averaged maximum IEMG of the examined muscles (Fig. 2), but a nonsignificant increase of 4.2% was seen between the averaged values before and after the 24-mo training period. The average isometric F-T and IEMG-time curves were unchanged during the experimental period.

Force-velocity curve and IEMG. Slight increases were observed in the SJ jumping heights at all loads from 0 to 140 kg during the 24-mo follow-up period (Fig. 3). The same was true for the averaged maximal concentric power index (an increase of 4.1 ± 10.1%, P = NS) and for the IEMGs of the muscles recorded during the contacts of the squat jumps.

Weight-lifting results. There was periodical alteration in the maximal weight-lifting results during the course of the follow-up and a significant (P < 0.05) increase in the weight-lifting total result from 272.2 ± 40.4 to 279.7 ± 37.9 kg was observed between the first and last competitions (Fig. 4).

Serum hormones and SHBG. A significant (P < 0.01) increase occurred in mean serum testosterone concentration from its starting value of 19.8 ± 5.3 to 25.1 ± 5.2 (SD) nmol/l during the 24-mo follow-up (Fig. 5). The annual mean value of 20.2 ± 3.4 nmol/l for all the serum testosterone measurements during the first year increased (P < 0.01) to 23.5 ± 4.0 nmol/l recorded correspondingly during the 2nd yr (Fig. 5). No change occurred in mean serum SHBG from its starting level of 22.8 ± 5.9 nmol/l during the experiment. The serum testosterone-to-SHBG ratio increased (P < 0.05) periodically during the follow-up. There was a significant (P < 0.05) increase from 0.96 ± 0.18 to 1.15 ± 0.29 in the serum testosterone-to-SHBG ratio between the annual mean values of the 1st and 2nd follow-up yr (Fig. 5). There was no change in mean serum cortisol from its starting
value of 0.58 ± 0.14 μmol/l. Serum testosterone-to-cortisol ratio did not change during the period of study. There was no significant change in serum testosterone-to-cortisol ratio between the annual mean values of the 1st and 2nd yr (Fig. 5). The concentrations of serum LH and FSH increased (P < 0.01 and P < 0.001) during the 24 mo follow up. There were also significant increases from 8.6 ± 0.8 to 9.1 ± 0.8 U/l in the annual mean values of LH (P < 0.05) and from 4.2 ± 2.0 to 5.3 ± 2.3 U/l in the annual mean values of FSH (P < 0.001) between the 1st and 2nd yr (Fig. 6). A significant (r = 0.77, P < 0.05) correlation was observed between the 1st and 2nd follow-up yr between the individual changes in the mean level of the testosterone-to-cortisol ratio and the changes in the mean level of maximal force (Fig. 7). During the 2nd follow-up yr the annual mean level of serum testosterone-to-SHBG ratio correlated significantly (r = 0.84, P < 0.01) with the individual changes in the averaged concentric power index (Fig. 8).

**DISCUSSION**

Large initial increases, such as 10–20%, in maximal strength of human muscle can be attained relatively easily in previously untrained subjects after only some weeks of intensive training (7, 17). These improvements are accompanied during the earlier periods of training by considerable neural adaptations, resulting in increased motor unit activation, and by gradual increase in the synthesis of contractile proteins leading to muscular hypertrophy (10, 12, 19, 21–23). In more trained subjects and especially in strength athletes the magnitude of these adaptive neuromuscular responses during strength training are much smaller and the changes may differ considerably with respect to their time courses (9, 11). The basic neuromuscular mechanisms increasing strength during training among elite-strength athletes might not differ from those for less-trained individuals, but the initial trained status of the athletes makes the process more complicated to follow and more difficult to substantiate (11).

The present elite-strength athletes demonstrated comparable periodic alterations in the group average of the maximum IEMG of the trained muscles and in their isometric strength development (Fig. 2). This indicates that the training-induced adaptations in the nervous system, although of small magnitude, may have an important role in modifying the periodic alterations in the strength of these elite athletes (11). The minor increases in the group averages of the maximum IEMG, strength, and power, as well as in the actual weight-lifting performances, during the 2-yr period of study are in good accordance with the impression of the limited potential for strength increase in elite-strength athletes. Despite continuous training, strength levels periodically increased and sometimes decreased (see Figs. 2 and 4). Thus the response of the neuromuscular system among these athletes is highly variable. Assessment of these periodic and/or individual responses requires a more detailed examination of the possible deficiencies in the individual train-
NEUROMUSCULAR AND HORMONAL ADAPTATIONS TO TRAINING

FIG. 6. Serum luteinizing hormone (LH) and follicle-stimulating hormone (FSH) in elite weightlifters during a 24-mo follow-up study of weight-lifting training and annual levels of measurements performed during 1st and 2nd follow-up yr (means ± SE). * P < 0.05; ** P < 0.01; *** P < 0.001.

FIG. 7. Relationship between individual changes in mean level of serum testosterone-to-cortisol ratio and individual changes in mean level of maximal isometric leg-extension force in elite weightlifters between 1st and 2nd follow-up yr during a 24-mo follow-up study of weight-lifting training.

FIG. 8. Relationship between individual annual mean level of serum testosterone-to-serum sex hormone-binding globulin (SHBG) ratio during 2nd follow-up yr and individual changes in averaged concentric power of leg extensor muscles during 2nd follow-up yr in elite weightlifters during a 24-mo follow-up study of weight-lifting training.

The limited muscular hypertrophy of both fiber types (Fig. 1), despite the prolonged follow-up, characterizes the difference in the magnitude and the time course of training-induced hypertrophy between elite-strength athletes and that observed in less-trained or previously untrained subjects (12, 19, 22). Because muscular hypertrophy contributes to the increase in maximal strength, it was expected that the average change in maximal strength in the present elite-strength athletes would not be of greater magnitude. The magnitude of fiber growth, however, is specifically dependent on the type of strength-training regimen, and increased muscular mass may not necessarily lead to a corresponding increase in maximal strength (8).

It is reasonable to expect that androgens may play an important role in physical conditioning, such as strength training. It has been demonstrated that serum testosterone levels might not change during a few months of strength training (6, 13, 14). However, during the most intensive training weeks, testosterone levels may change, and as has been observed (13) the individual changes in the serum testosterone-to-SHBG ratio are positively related to the changes in strength of the trained muscles. These observations seem to indicate that androgens have an important role in strength training, and the changes in the testosterone-to-SHBG ratio may reflect the differences in the individual trainability status of athletes at a given time during vigorous training periods. Serum testosterone concentrations increased during the present 2-yr follow-up period (Fig. 5); however, the values remained well within the normal range. These changes could be demonstrated in athletes who had already reached the high level of training adaptation before these experimental measurements. This long-term increase in serum testosterone concentration, with the simultaneous long-term increases in serum LH and FSH (Fig. 6) may reflect training-induced adaptations to the increasing demands of prolonged intensive training stress. The present observation has additional interest, because an overintense stressful training period of a few weeks decreased serum testosterone levels with a simultaneous decrease in strength performance (13). In these conditions the rise in serum LH levels found appear to result from the reduced serum testosterone concentrations (13). Therefore, intensive strength training seems to influence the pituitary and possibly hypothalamic levels regulating the production of testosterone.

The periodic changes in serum testosterone concentrations (Fig. 5) during the course of the 2-yr follow-up have
some similarities to those observed in periodic strength development (Figs. 2 and 4). The changes in the serum testosterone to SHBG ratio (Fig. 5), which reflects the changes in the levels of free testosterone, followed even more closely the courses of strength performances. The 2nd yr of the follow-up was characterized by the increased annual level in the serum testosterone-to-SHBG ratio. During this training period some athletes were able to increase their overall muscular concentric power, whereas even decreases in this performance capacity may be important during vigorous strength training. No changes have been reported in the basic level of serum cortisol levels have been observed in elite-strength athletes with concomitant decreased testosterone concentrations (13). In these types of stressful training conditions, large individual variations were observed also in the serum testosterone-to-cortisol ratio and in strength development. The individual changes in the serum testosterone to cortisol ratio correlated significantly with the concomitant individual changes in muscle strength (14). This suggests that a balance between androgenic-ana-bolic status and the catabolizing effects of glucocorticoids may be important during vigorous strength training. No changes have been reported in the basic level of serum cortisol after prolonged strength training of several months (6, 13, 14). The present findings demonstrated that serum cortisol concentrations were not altered by a very prolonged training period. The changes in the serum testosterone-to-cortisol ratios were largely individual, and no significant change was found in this ratio between the annual mean values of the 1st and 2nd follow-up yr (Fig. 5). However, the individual changes in the annual mean level of this hormone ratio correlated positively with the individual changes in the mean level of maximal strength (Fig. 7). The present observations in elite athletes support the suggested importance of this hormone balance and its relevance during a very prolonged training period.

In conclusion, the present findings support the concept that neuromuscular adaptations in elite-strength athletes during prolonged weight training are largely individual, varying with respect to their time courses, and much more limited than adaptations reported for less-trained and especially for initially untrained subjects. Intensive, very prolonged strength training in elite-strength athletes may influence the pituitary and possibly hypothalamic hormone levels, leading to increased serum levels of testosterone. The present results additionally suggest that increased testosterone levels may create more optimal conditions for intensive weight training to lead to increased strength development in elite-strength athletes.

This study was supported in part by grants from the Ministry of Education, Finland, The Finnish Olympic Committee, The Finnish Central Sports Federation, and the Finnish Weightlifting Association. Address for reprint requests: K. Häkkinen, Dept. of Biology of Physical Activity, Univ. of Jyväskylä, SF-40100 Jyväskylä, Finland.

Received 4 September 1987; accepted in final form 12 July 1988.

REFERENCES

20. KOMI, P. V., P. LAHTANEN, AND K. VILJAMASE. Measurement of Instantaneous Contact Forces on the Force-Platform. Jyväskylä,


