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ORIGINAL ARTICLE

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Muscle hypertrophy, hormonal adaptations and strength development during strength training in strength-trained and untrained men

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Abstract Hormonal and neuromuscular adaptations to strength training were studied in eight male strength athletes (SA) and eight non-strength athletes (NA). The experimental design comprised a 21-week strength-training period. Basal hormonal concentrations of serum total testosterone (T), free testosterone (FT) and cortisol (C) and maximal isometric strength, right leg 1 repetition maximum (RM) of the leg extensors were measured at weeks 0, 7, 14 and 21. Muscle cross-sectional area (CSA) of the quadriceps femoris was measured by magnetic resonance imaging (MRI) at weeks 0 and 21. In addition, the acute heavy resistance exercises (AHRE) (bilateral leg extension, five sets of ten RM, with a 2-min rest between sets) including blood samples for the determination of serum T, FT, C, and GH concentrations were assessed before and after the 21-week training. Significant increases of 20.9% in maximal force and of 5.6% in muscle CSA in NA during the 21-week strength training period were greater than those of 3.9% and −1.8% in SA, respectively. There were no significant changes in serum basal hormone concentrations during the 21-week experiment. AHRE led to significant acute decreases in isometric force and acute increases in serum hormones both at weeks 0 and 21. Basal T concentrations (mean of 0, 7, 14 and 21 weeks) and changes in isometric force after the 21-week period correlated with each other ($r=0.84$, $P<0.01$) in SA. The individual changes in the acute T responses between weeks 0 and 21 and the changes in muscle CSA during the 21-week training correlated with each other ($r=0.76$, $P<0.05$) in NA. The correlations between T and the changes in isometric strength and in muscle CSA suggest that both serum basal testosterone concentrations and training-induced changes in acute testosterone responses may be important factors for strength development and muscle hypertrophy.

Keywords Basal hormones · Hormonal responses · Magnetic resonance imaging · Resistance exercise

Introduction

Strength training, especially among initially untrained healthy subjects, leads to functional and structural adaptations in the neuromuscular system. Early training-induced increases in strength are accounted largely for by neural factors with a gradually increasing contribution of muscular hypertrophy of trained muscles as training proceeds (Moritani and DeVries 1979). The increase in the cross-sectional area of trained muscles comes primarily from the increase in size of individual muscle fibers (MacDougall et al. 1977). In well-trained subjects, such as strength athletes, further improvements in strength and training-induced muscle hypertrophy are much more limited than in previously untrained subjects (Häkkinen 1994a). Strength development and muscle hypertrophy is also dependent on the type and intensity of loading as well as volume of the strength training of each individual strength athlete at a given time.

The role of hormone regulation may become increasingly important for muscle hypertrophy and strength development in strength athletes with a long and intense training background. It has been suggested that the level of free testosterone (FT) may be of

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importance for trainability (Häkkinen et al. 1985; Kraemer et al. 1990). The changes in the volume of strength training have led to changes in serum total testosterone/cortisol (T/C) ratio with a concomitant change in serum LH concentrations. Furthermore, the T/SHBG ratio has been shown to correlate to strength performance in elite weightlifters in a previous study of Häkkinen et al. (1987). Periodical changes in T concentrations seem to occur during the most intense training periods of prolonged strength training (Häkkinen et al. 1988). These observations support the suggestion that the periodical adaptative responses in the endogenous hormone balance during training seem to have an increasing importance for changes in strength performance, especially in strength athletes. It is also possible that adaptations of the endocrine system in untrained subjects would not play such a limiting role for muscle hypertrophy in short training periods such as 6 months in strength athletes who already have a long and intense training background of several years.

Heavy resistance exercise is well known to be a potent stimulus for acute increases in circulating anabolic hormones in young men. It has been suggested that muscle hypertrophy may be due to, at least in part, exercise-induced acute increase in endogenous anabolic hormones which may increase the number of receptor interactions thereby mediating changes in muscle size and neuromuscular function (Kraemer et al. 1990). Since a single hypertrophic type of resistance exercise induces increases in serum hormone concentrations, it is also possible that the magnitude and/or duration of the acute hormone response may change due to prolonged strength training. This may be due to adaptation processes in the production and/or clearing mechanisms in the endocrine system (Kraemer et al. 1990). However, only a few studies have found evidence that acute hormonal responses would change due to long-term strength training. In a recent study of Häkkinen et al. (2001) it was showed that the acute GH response became significant and its duration lengthened due to the 21-week strength training period in older women. In the study by Kraemer et al. (1992) experienced weightlifters had a greater acute increase in testosterone response following heavy resistance exercise than that of unskilled weight trainers. The enhanced acute testosterone response due to strength training has been reported (Kraemer et al. 1998), but other previous studies have not found any significant changes in resistance exercise-induced acute testosterone responses due to long-term strength training in adult men (Craig et al. 1989; Hickson et al. 1994; McCall et al. 1999).

As far as is known, there are no previous studies that have examined both basal and acute hormone responses and changes in muscle mass and strength during prolonged strength training and compared the results between untrained and strength athletes. Therefore, the purpose of the present study was to investigate hormonal adaptations and their relationships to muscle hypertrophy and strength development during the 21-week strength-training period in male strength athletes and non-athletes. Hormonal adaptations were studied by the determination of basal serum hormonal concentrations at rest and those of acute hormonal responses to heavy resistance exercise.

Methods

Subjects

Eight physically active men (NA) [mean (SD); age 34.4 (4.4) years, height 177.1 (3.8) cm, weight 85.7 (16.4) kg, body fat 19.1 (4.3)%] and eight strength athletes (SA) [mean (SD); age 30.0 (6.5) years, height 177.2 (6.3) cm, weight 91.7 (10.0) kg, body fat 17.3 (3.6)%] volunteered to participate in this study. The group of strength athletes (five bodybuilders and three weightlifters/powerlifters) had several years experience with resistance training. No medication was being taken by the subjects, which would have been expected to affect physical performance.Each subject was informed of the potential risks and discomforts associated with the investigation and all the subjects gave their written informed consent to participate. The Ethics Committee of the University of Jyväskylä approved the study.

Experimental design

The total duration of the present study was 21 weeks. The basal hormonal and strength measurements were repeated during the actual experimental training period at 7-week intervals (i.e., weeks 0, 7, 14 and 21). Measurements were also made 1 week before the study in NA. The 1st week of the study was then used as a control period during which time no experimental training was carried out. The experimental design also comprised two acute heavy resistance-loading sessions (AHRE) (5×10 RM leg press) before and after the 21-week strength-training period at the same time of day for the examination of acute hormonal and neuromuscular responses.

Muscle strength measurements

An electromechanical dynamometer was used to measure maximal voluntary isometric force of the bilateral leg extension action at a knee angle of 107°. A minimum of three trials was completed for each subject and the best performance trial with regard to maximal peak force was used for the subsequent statistical analysis. The force signal was recorded on a computer (486 DX-100) and thereafter digitized and analyzed with a Codas TM computer system (Data Instruments). Maximal peak force was defined as the highest value of the force (N) recorded during the bilateral isometric leg extension.

A David 210 dynamometer (David Fitness and Medical) was used to measure maximal unilateral concentric force production of the leg extensors (hip, knee and ankle extensors) (Häkkinen et al. 1998). The subject was in a seated position so that the hip angle was 110°. On verbal command the subject performed a concentric right leg extension starting from a flexed position of 70° trying to reach a full extension of 180° against the resistance determined by the loads (kg) chosen on the weight stack. In the testing of the maximal load, separate 1-RM contractions were performed. After each repetition the load was increased until the subject was unable to extend the legs to the required full extension position. The last acceptable extension with the highest possible load was determined as 1 RM. This dynamic testing action was used in addition to that of the isometric one, since the strength training was also dynamic in nature.

Muscle cross-sectional area

The muscle cross-sectional area (CSA) of the right quadriceps femoris was assessed before and after the 21-week experimental training using magnetic resonance imaging (MRI) (1.5-Tesla, Gyroscan S15, Philips) at Keski-Suomen Magneettikuvaus, Jyväskylä, Finland. The length of the femur (Lf), taken as the distance from the bottom of the lateral femoral condyle to the lower corner of the femur head, was measured on a coronal plane. Subsequently, 15 axial scans of the thigh interspaced by a distance of 1/15 Lf were obtained from the level of 1/15 Lf to 15/15 Lf as described previously (Häkkinen et al. 2001). Great care was taken to reproduce the same individual femur length each time using the appropriate anatomical landmarks. All MRI images were then ported to a Macintosh computer for the calculation of muscle CSA. For each axial scan, CSA computation was carried out on the quadriceps femoris as a whole and for the final calculation of the CSA, slices 5/15–12/15 were used (slice 5 being closer to the knee joint of the thigh). CSA (measured as cm^2) was determined by tracing manually along the border of the quadriceps femoris. Muscle CSA is represented as mean of the values from 5/15 to 12/15 Lf.

Blood collection and analyses

During the loading session blood samples were drawn from the antecubital vein for the determination of T and FT, C and growth hormone concentrations before, immediately after (post) and 15 (post 15 min) and 30 min (post 30 min) after the loadings. Fingertip blood samples were drawn for the determination of blood lactate. Two blood samples were also drawn within 30 min without exercise at the same time of day that each subject would later undertake his heavy resistance-loading protocols to determine normal diurnal variation of serum hormone concentrations. Fasting blood samples were obtained at 7-week intervals throughout the experimental period in the mornings at 0730–0830 hours for the determination of T, FT and C concentrations.

Serum samples for the hormonal analyses were kept frozen at –20°C until assayed. T concentrations were measured by the Chiron Diagnostics ACS:180 automated chemiluminescence system using ACS:180 analyzer (Medfield, Mass., USA). The sensitivity of the testosterone assay was 0.42 nmol/l, and the intra-assay coefficient of variation was 6.7%. The concentrations of T were measured by RIAs using kits from Diagnostic Products (Los Angeles). The sensitivity of the FT assay was 0.52 pmol/l, and the intra-assay coefficient of variation was 3.8%. The assays of serum C were carried out by RIAs using kits from Farmos Diagnostica (Turku, Finland). The sensitivity of the C assay was 0.05 nmol/l, and the intra-assay coefficient of variation was 4.0%. Concentrations of growth hormone were measured using RIA kits from Pharmacia Diagnostics (Uppsala, Sweden). The sensitivity of the GH assay was 0.2 μg/l, and the intra-assay coefficient of variation was 2.5–5%. All the assays were carried out according to the instructions of the manufactures. All samples for each test subject were analyzed in the same assay for each hormone. Blood lactate concentrations were determined using a lactate kit (Roche, Germany).

Anthropometry

Body weight and body fat of the subjects were measured at weeks 0, 7, 14, and 21. The percentage of body fat was estimated by measuring skin-fold thickness at four different sites according to Durnin and Rahaman (1967).

Strength training

The supervised 21-week strength training for NA was carried out twice a week. Each training session included two exercises for the leg extensor muscles: the bilateral leg press exercise and the bilateral and/or unilateral knee extension exercise on the David 200 machine. In addition, each training session included four or five exercises for the other main muscle groups of the body. The training program has presented earlier elsewhere (Häkkinen et al. 2000).

Large interindividual variation was observed in the strength training programs among the present strength athletes. During the present 21-week follow-up period they continued training individually as they had been used to. The primary purposes of their strength training were to gain maximal strength and muscle mass. The training performed by this group was observed by training diaries. Their strength training typically included 3 training days per week. Different body parts were trained on different training days with multiple exercises; repetitions were 6–12 per exercise with 2–5 min rest between the sets. Exercises for the leg extensors included typically squat, leg presses and knee extension. The volume of the training in SA is expressed as total work (loads×sets×reps) in the above-mentioned leg exercises calculated from their training diary.

Statistical analyses

Standard statistical methods were used for the calculation of mean, standard deviation (SD), standard error (SE) and Pearson product-moment correlation coefficient. The changes in the variables over time from the pre-level were analyzed using general linear model (GLM) analysis of variance with repeated measures. Differences between the experimental groups within each time point were analyzed utilizing independent—samples of *t*-tests and within the experimental groups with dependent—samples of *t*-tests. The $P < 0.05$ criterion was used for establishing statistical significance.

Results

Anthropometry

No significant changes took place in the body mass or body fat percentage during the 21-week training period, except for the decrease in SA in body fat from 17.3 (3.6) to 16.4 (3.9) ($P < 0.05$).

Maximal bilateral isometric leg extension force

At 0 maximal isomeric force was larger ($P < 0.001$) in SA than in NA (Fig. 1). During the 21-week training period significant increases of 21 (22)% ($P < 0.05$) and 4 (10)% (ns) were recorded in the NA and SA groups, respectively.

Unilateral 1 RM right leg extension values

SA showed larger ($P < 0.001$) 1-RM strength than NA at 0 (Fig. 2). During the 21-week training period significant increases of 19% [from 91 (17) and 108 (16) kg; $P < 0.001$] and 7% [143 (18) and 152 (17) kg; $P < 0.05$) took place in the 1-RM load in the NA and SA groups, respectively.

Muscle CSA

SA showed larger ($P < 0.001$) CSA values than NA at 0 (Fig. 3). The CSA increased in NA throughout the

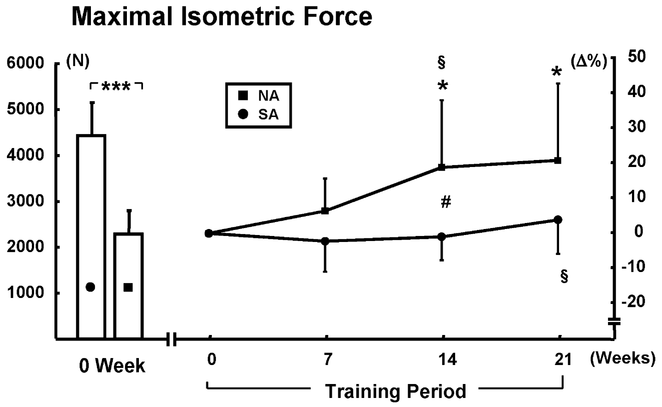


Fig. 1 The relative changes (mean; SD) in maximal isometric force during the 21-week strength-training period. *Asterisks*: significantly different ($*P<0.05$, $***P<0.001$) from the corresponding pre-training value. $^{\#}$Statistically significant difference ($P<0.05$) between the groups. §Statistically significant difference ($P<0.05$) from the preceding value. *NA* Non-athletes, *SA* strength athletes

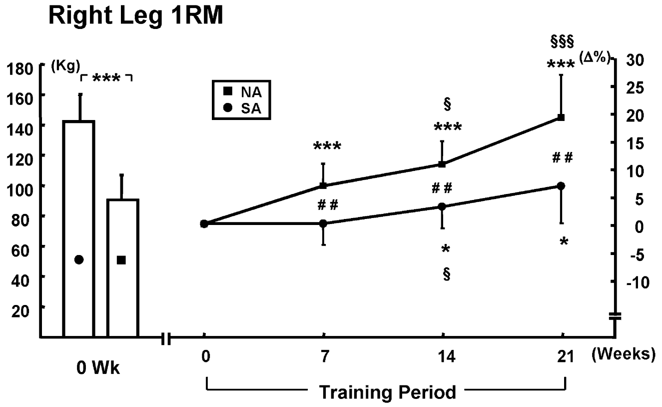


Fig. 2 The relative changes (mean; SD) in right leg 1 repetition maximum (RM) during the 21-week strength-training period. *Asterisks*: significantly different ($*P<0.05$, $***P<0.001$) from the corresponding pre-training value. $^{\#}$Statistically significant difference ($^{\#}P<0.05$, $^{\#\#\#}P<0.001$) between the groups. §Statistically significant difference ($^{\S}P<0.05$, $^{\S\S\S}P<0.001$) from the preceding value

length of the femur and significantly at 5/15 to 9/15 Lfs ($P<0.05$–0.001). No increases occurred in SA during the 21-week training period. Right leg 1 RM to muscle CSA ratio increased after the 21-week training period by 8.2 (6.1)% ($P<0.05$) in SA and 10.6 (6.5)% ($P<0.01$) in NA. Maximal isometric force to muscle CSA ratios were greater in SA than in NA before ($P<0.01$) and after ($P<0.001$) the strength training. In NA the maximal isometric force and right leg 1 RM as well as maximal isometric force and muscle CSA correlated with each other ($r=0.82$, $P<0.05$) and ($r=0.84$, $P<0.05$), respectively.

Basal hormone concentrations

There were no significant changes in T, FT or C concentrations or T/C or FT/C ratio during the 21-week strength training period in both groups. In SA serum basal testosterone and FT concentrations increased ($P<0.01$) throughout the first 14 weeks and decreased ($P<0.01$) during the last training cycle between weeks 14 and 21 (Fig. 4). In SA the changes in maximal isometric force after the 21-week training period correlated with the mean (averaged for the 0, 7, 14 and 21 weeks) serum basal total testosterone concentration ($r=0.84$, $P<0.01$) (Fig. 5) and T/C ratio ($r=0.88$, $P<0.01$). Also in SA the mean (averaged for the 0, 7, 14 and 21 weeks)

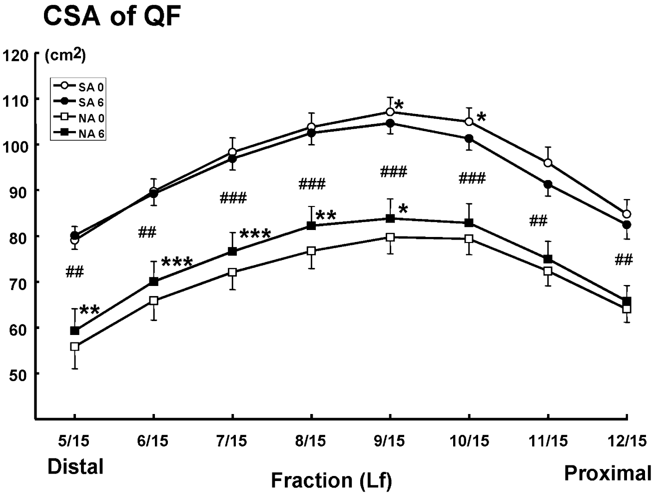


Fig. 3 A cross-sectional area of the quadriceps femoris (mean; SE) from 5/15 to 12/15 femur lengths (Lfs) before and after the 21-week strength-training period. *Asterisks*: significantly different ($*P<0.05$, $**P<0.01$, $***P<0.001$) from the corresponding pre-training value. $^{\#}$Statistically significant difference ($^{\#\#}P<0.01$, $^{\#\#\#}P<0.001$) between the groups ($n=7$ in NA and 7 in SA)

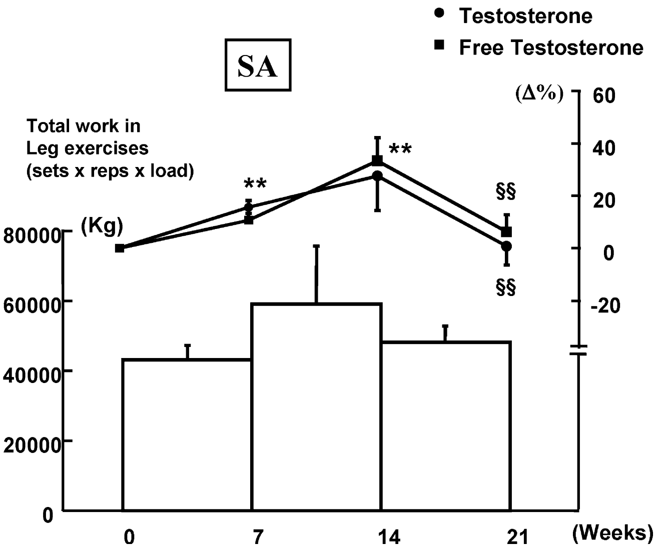
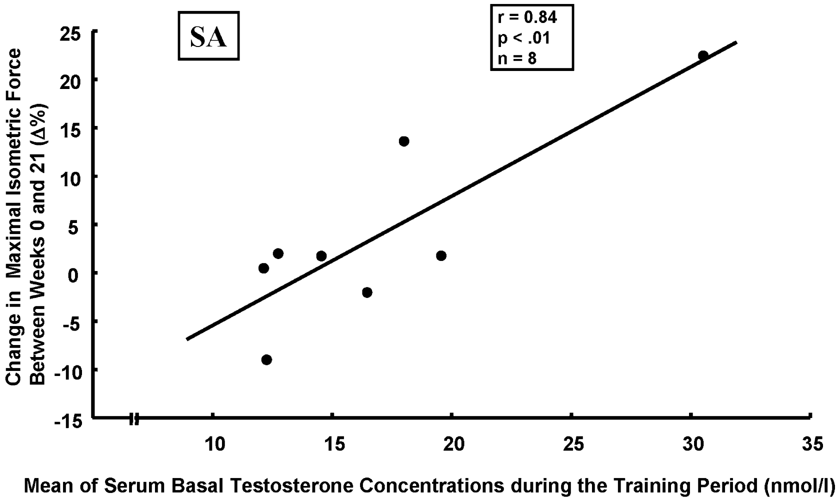


Fig. 4 The relative changes (mean; SE) in serum basal testosterone and free testosterone (FT) and total work in leg exercises (sets×reps×load) during the 21-week strength-training period in SA. *Asterisks*: significantly different ($**P<0.01$) from the corresponding pre-training value. §Statistically significant difference ($^{\S\S}P<0.01$) from the preceding value ($n=7$)

Fig. 5 A correlation between the individual changes in maximal isometric force after the 21-week strength-training period and the mean values of serum basal testosterone concentrations during the training period in SA ($r = 0.84$, $P < 01$, $n = 8$)



serum basal FT concentration correlated with maximal isometric values before ($r = 0.76$, $P < 0.05$) and after ($r = 0.82$, $P < 0.05$) the 21-week training period.

Acute heavy resistance loading

The total volume of the work (loads×sets×reps) in NA was 8,400 (1,084) kg and 9,800 (1,034) kg ($P < 0.001$) and in SA 11,700 (1,445) kg and 12,388 (733) kg ($P < 0.05$) before and after the 21-week training period, respectively. Significant acute decreases of 36–34% and 35–32%, ($P < 0.001$) occurred in maximal isometric force before and after the experimental strength training period in NA and SA, respectively. There were no significant differences in the blood lactate concentrations between the experimental groups in the AHREs before or after the strength training period.

Acute hormonal responses

There were no significant changes between the two control blood samples drawn within 30 min without exercise at the same time of day that each subject had performed his heavy resistance loading protocols except for the decrease in T in SA [from 12.6 (6.3) to 11.8 (6.4), $P < 0.05$) at week 21. Serum GH, T, FT, and C concentrations increased ($P < 0.05$–0.001) after the loadings both before and after the training period (Figs. 6, 7, 8). There were no significant differences in acute hormone responses between the groups or between the loading sessions except for GH concentrations ($P < 0.05$, post 30 min) between SA and NA recorded before the training period. Furthermore, the mean of the acute GH responses (averaged for 0 and 21 weeks) was greater ($P < 0.05$, post 15 min.) in SA than in NA. The difference in acute T responses between the heavy resistance loadings before and after training period and changes in muscle CSA (mean of 5/15 to 12/15 Lf) correlated with each other ($r = 0.76$, $P < 0.05$) in NA (Fig. 9).

Discussion

The present study included two experimental groups. As expected, the SA were stronger and had greater muscle mass than their age and height-matched controls, a group of NA with no previous strength training experience. Maximal isometric force and 1 RM strength as well as muscle CSA increased during the 21-week strength-training period more in NA than in SA.

The difference in the muscle CSA of the quadriceps femoris between the two groups was clear throughout the length of the femur before the experimental training period. In NA the training-induced muscle hypertrophy took place at all lengths but reached statistical significance at mid- and distal portions of the quadriceps femoris, while SA showed no further increase during the 21-week training period. The latter finding may in part be related to the slight decrease observed in the training volume during the last 7-week training period. In NA the increase in maximal isometric force was greatest during the first 14 weeks of training, but the 1 RM increased gradually throughout the training period. The 1 RM increased also significantly in SA but to a lesser degree than in NA. The increases observed in the 1 RM to muscle CSA ratio during the training indicates that neural adaptations might have occurred during the present training period in both groups. However, greater isometric force to muscle CSA ratio in SA indicates that SA might be able to produce greater maximal voluntary activation of the agonist muscles than NA. In addition to the increased neural drive to the activated muscles, it is also possible that the force to muscle CSA ratio would increase during the training due to architectural changes of leg extensor muscles (Aagaard et al. 2001).

Serum basal testosterone, FT and C concentrations remained unchanged in both groups during the present training period. However, basal testosterone and FT concentrations did increase during the first 14 weeks of the experimental training period in SA with the increase in the volume of the training (Fig. 5). Therefore, the

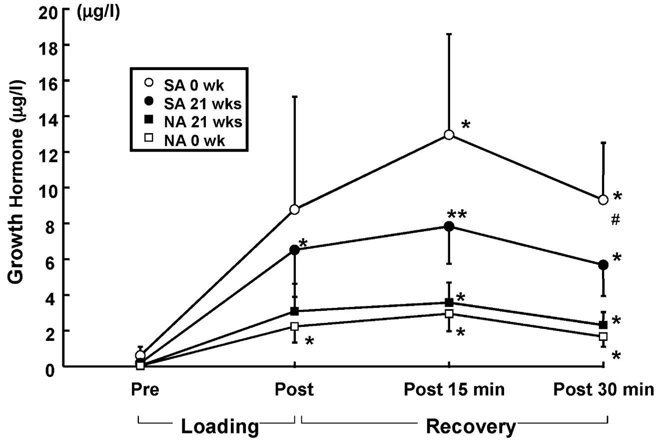


Fig. 6 Serum GH concentrations (mean; SE) during the heavy resistance loadings before and after the 21-week strengthtraining period. *Asterisks*: significantly different ($*P < 0.05$, $**P < 0.01$) from the corresponding pre-exercise value. #Statistically significant difference ($P < 0.05$) between the groups

decrease in basal testosterone and FT concentrations in SA during the last training cycle from week 14 to week 21 may be associated to the decrease observed in the training volume. These findings are in line with previous data by Häkkinen et al. (1987, 1988) showing serum testosterone concentrations to differ with regard to the volume and/or intensity of the strength training periods. The correlation observed between T concentrations and the changes in isometric strength (Fig. 4) suggest that serum basal testosterone concentrations may be an important factor for strength development in strength athletes. However, non-athletes may gain strength and muscle mass in the beginning of the strength training despite periodical changes in the level of serum testosterone concentration.

The present experimental design comprised the two acute heavy resistance loadings performed before and after the 21-week strength training period. As expected (Häkkinen 1994b), the loadings did lead to remarkable acute decreases in maximal isometric strength, but the magnitudes of the decreases were similar both before and after the training period as well as between the experimental groups. Therefore, the degree of acute neuromuscular fatigue produced by the loading was similar in both experimental groups before and after the strength-training period, when the relative intensity of the loadings was kept the same.

It has been proposed that the exercise-induced acute endocrine responses could reflect some other hormonal regulatory mechanism than those of the regulation of the resting hormonal concentrations (Fry et al. 1991). Exercise-induced acute increase in serum testosterone concentration may be due to the increased gonadal secretion (Metivier et al. 1980; Cumming et al. 1986), testosterone release by vasodilatation (Meskaitis et al. 1997), increases in LH pulsatility or production (Vermeulen et al. 1972; Longcope et al. 1990) and/or a direct (LH independent) stimulatory effect of lactate on the secretion of testosterone (Lu et al. 1997). The elevated exercise-induced symphatic activity may contribute to the augmented acute testosterone response (Jezova and Vigas 1981; Fahrner and Hackney 1998). Regardless of the mechanism(s) of exercise-induced increase of serum testosterone concentrations, the skeletal muscle will be exposed to an elevated peripheral testosterone concentration and thus the likelihood of possible interactions with potential muscle cell receptors could increase (Kraemer et al. 1990).

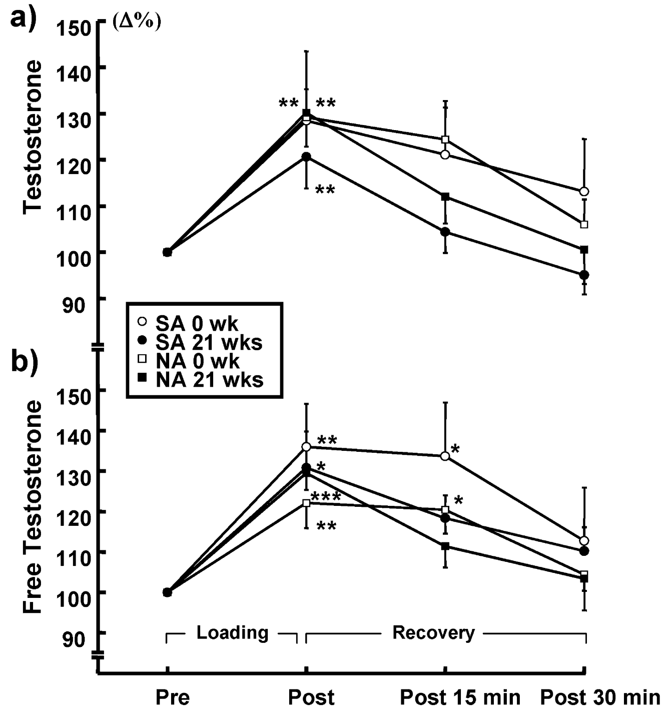


Fig. 7a, b The relative acute changes (mean; SE) in serum testosterone and FT concentrations during the heavy resistance loadings before and after the 21-week strength-training period. *Asterisks*: significantly different ($*P < 0.05$, $**P < 0.01$, $***P < 0.001$) from the corresponding pre-exercise value

The present heavy-resistance exercises before and after the training period did induce acute increases in serum testosterone and FT concentrations in both groups. The acute testosterone and FT responses (Fig. 7a, b) tended to decrease after the experimental training period as observed with the lowered concentrations during the 30-min recovery period after the exercises. It may be necessary to increase the volume of the resistance exercise to achieve similar testosterone and FT responses after the strength training than before the training period. Interestingly, those NA subjects who showed increased acute T response after the strength training period were also able to gain more muscle CSA than those with the lowered responses (Fig. 9). Great care has to be exercised with regard to interpretations of the results due to a limited number of subjects of the present study. However, the correlations observed between the changes in acute testosterone response and the changes in muscle CSA suggest that training-induced

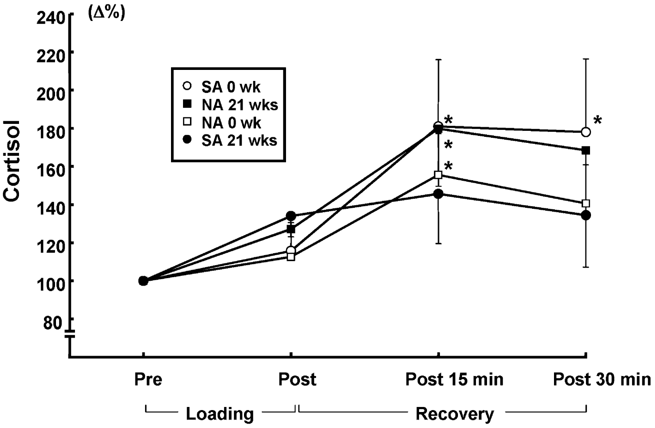


Fig. 8 The relative acute changes (mean; SE) in serum cortisol (C) concentrations during the heavy resistance loadings before and after the 21-week strength-training period. *Asterisk*: significantly different ($P < 0.05$) from the corresponding pre-exercise value

changes in the endocrine regulation do take place and that changes in acute testosterone responses may be an important factor for training-induced muscle hypertrophy.

The high-intensity, heavy-resistance exercise is well known to induce a great acute GH response. It has been suggested that exercise-induced acute increase in serum GH concentrations may be responsive to the central stimuli as brain motor center activity (Galbo et al. 1987; Kjaer et al. 1987, 1989) and/or changes in acid-base balance within the loaded muscles via afferent feedback from peripheral chemoreceptors (Gordon et al. 1994). However, the present study showed no significant correlations between the blood lactate concentrations and the acute GH responses. Nevertheless, the loadings performed in the present study before and after the experimental strength-training period did lead in both groups to the great acute increase in serum GH concentrations. The acute GH response (Fig. 6) induced by the single resistance exercise at week 0 was greater in SA than in NA. After the 21-week training period the acute GH response decreased in SA. The attenuated acute GH response in SA suggests that the exercise stimulus may have changed at week 21, even though it was performed with the same relative load as that of AHRE at 0, or alternatively the training may have changed the type of GH variant being produced leading to a lower concentration of the 22-kDa isoform (Hymer et al. 2001). It is also possible that it would be necessary to increase the absolute volume of the loading to produce similar GH response after the 21-week training period. However, there was an increased trend in the acute GH response in NA after the strength training period. This finding is in line with the previous study of Häkkinen et al. (2001) that showed a lengthened duration of the acute GH response due to the 21-week strength-training period in older women.

Cortisol is primarily related to catabolic processes, as the degradation of proteins from skeletal muscles. However, a prominent role of the acute C response is to meet the greater metabolic demands caused by the resistance exercise (Viru et al. 1994). In previous studies the acute C response has occurred when the overall stress of the exercise protocol has been very high (Häkkinen and Pakarinen 1993, Kraemer et al. 1993) and the response has been linked to the volume and/or intensity of total work to a given heavy-resistance exercise protocol (Kraemer et al. 1987, 1991, 1993, 1995; Gotshalk et al. 1997). Long-term resistance training may lead to an overall reduction of acute C responses to exercise stress in men (Staron et al. 1994; Kraemer et al. 1995, 1999). In the present study the acute exercise induced C response increased in NA and decreased in SA after the 21-week strength-training period, but these changes were not statistically significant (Fig. 8).

In conclusion, the present study suggest that serum basal testosterone concentrations and acute increases in serum testosterone concentrations due to a single resistance exercise session may be important factors for training-induced muscle hypertrophy as well as for strength development of the trained muscles.

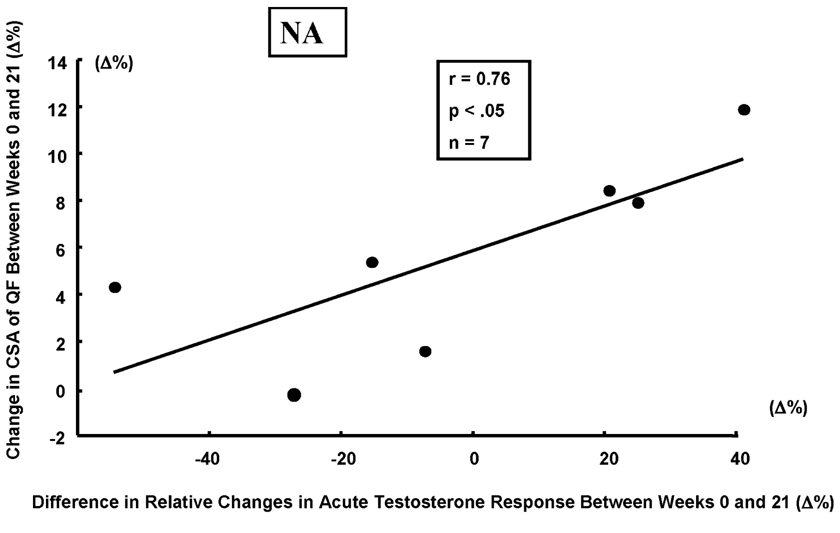


Fig. 9 A correlation between the relative acute changes in serum testosterone responses between the heavy resistance loadings performed before and after the 21-week strength-training period and the relative changes in cross-sectional area of the quadriceps femoris (mean of 5/15 to 12/15) after the 21-week training period in NA ($r = 0.76$, $P < 05$, $n = 7$)

The present study also suggests that adaptations in the endocrine system can take place, so that acute hormonal responses may change due to strength training. These results also suggest that one could try to optimize the volume and/or intensity of resistance exercises especially in previously strength-trained athletes to meet the level of adaptation of the neuromuscular and endocrine systems in order to further increase muscle mass and strength.

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