

Acute Hormonal Responses to Heavy Resistance Exercise in Strength Athletes Versus Nonathletes

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Mots-clés: répétitions forcées, récupération, EMG, force isométrique

Abstract/Résumé

The aim of the present study was to investigate acute hormonal and neuromuscular responses and recovery in strength athletes versus nonathletes during heavy resistance exercise performed with the forced and maximum repetitions training protocol. Eight male strength athletes (SA) with several years of continuous resistance training experience and 8 physically active but non-strength athletes (NA) volunteered as subjects. The experimental design comprised two loading sessions: maximum repetitions (MR) and forced repetitions (FR). MR included 12-RM squats for 4 sets with a 2-min recovery between sets. In FR the initial load was higher than in MR so that the subject could lift approximately 8 repetitions by himself and 4 additional repetitions with assistance. Before and after the loading protocols, blood samples were drawn to determine serum testosterone, free testosterone, cortisol and growth hormone concentrations, and blood lactate. Maximal voluntary isometric force and EMG activity of the leg extensors was measured before and after the loading as well as 24 and 48 hrs after the loading. The concentrations of the hormones measured increased significantly ($p < .01-.001$) after both loadings in both groups. The responses tended to be higher in FR than the MR loading and the increases of testosterone concentrations were significantly ($p < .01$) greater in both loadings in SA than in NA. Both loading protocols in

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both groups also led to neuromuscular fatigue observable with significant acute decreases in isometric strength by 32–52% ($p < .001$) and in maximal iEMG ($p < .05-.01$) associated with large increases in blood lactate. These data suggest that, at least in experienced strength athletes, the forced-repetition protocol is a viable alternative to the more traditional maximum-repetition protocol and may even be a superior approach.

Cette recherche se propose d'étudier les ajustements hormonaux et neuromusculaires ainsi que la récupération chez des athlètes de force comparativement à des individus physiquement actifs durant une séance de musculation constituée de répétitions usuelles et forcées. Huit athlètes de force (SA) ayant quelques années d'entraînement continu et 8 personnes physiquement actives, mais pas dans le domaine de la force (NA), se portent volontaires. Le devis expérimental inclut deux séances d'entraînement: une séance MR (répétitions maximales) et une séance FR (répétitions forcées). La séance MR comporte 4 séries de flexions accroupies à 12 RM intercalées d'une période de repos de 2 min. La séance FR débute avec une charge initiale supérieure à la MR: les sujets ne font donc que 8 répétitions, mais ils en ajoutent 4 autres avec l'aide d'un assistant. Avant et après chacune des séances, des échantillons de sang sont prélevés pour l'évaluation des concentrations de testostérone sérique, de testostérone libre, de cortisol, d'hormone de croissance, et de lactate. La force isométrique maximale et l'activité myoélectrique des extenseurs de la jambe sont également évaluées avant et après chacune des séances ainsi que 24 et 48 h plus tard. La concentration des hormones augmente significativement ($p < 0,01-0,001$) après chacune des séances chez les deux groupes. Les ajustements semblent plus importants durant la séance FR que pendant la séance MR. De plus, les augmentations de concentration des testostérones sont significativement plus fortes ($p < 0,01$) chez le groupe SA que chez le groupe NA, et ce, après les deux types de séance. La fatigue neuromusculaire est observable après les deux séances et chez les deux groupes, il y a diminution significative de la force isométrique de 32 à 52% ($p < 0,001$) et de l'activité myoélectrique intégrée ($p < 0,05-0,01$) doublée d'une forte augmentation de lactate sanguin. Ces observations suggèrent, à tout le moins chez les athlètes de force, qu'une séance de FR constitue une solution de rechange solide comparativement aux séances traditionnelles de MR et peut même s'avérer une approche préférable.

Introduction

Single heavy resistance exercise leads to acute neuromuscular responses (e.g., temporary muscle fatigue) and induces acute increases in serum anabolic hormone concentrations (i.e., testosterone and growth hormone). The magnitudes of acute neuromuscular and hormonal responses are influenced by exercise variables such as the volume and intensity of the resistance exercise and recovery between the sets (Ahtiainen et al., 2003b; Häkkinen, 1993; Kraemer et al., 1990). These acute responses are supposed to be primary stimuli for neuromuscular and hormonal adaptations that lead to muscle tissue hypertrophy and strength development during prolonged strength training (Kraemer et al., 1999). Therefore, it is possible that the manipulation of acute exercise variables may lead to specific adaptation processes and appropriate training effects.

One basic principle of strength training is the progressive increase in the training load used. To increase maximal strength, experienced weight trainers need to train with very high loads (e.g., 80–100% of 1 RM). On the other hand, in strength training that aims mainly for muscle hypertrophy, the intensity of the

exercises is only submaximal (e.g., 60–80% of 1 RM), but multiple repetitions are performed until concentric failure, i.e., considerable temporary muscle fatigue (Tesch and Larsson, 1982). Because of the risk for overtraining, it is not appropriate for long-term training purposes to increase repeatedly the volume or frequency of training to obtain progressive increases of the exercise load. It is inappropriate to increase the training intensity by increasing the magnitude of the load (e.g., load of the 1 RM) *or* the rate of the work performed.

To resolve this problem of training programs, strength athletes, especially bodybuilders, may increase exercise intensity using different kinds of exercise systems. One such system is called “forced repetitions.” The forced repetitions means that after the trainee has achieved a momentary concentric failure (i.e., a set until exhaustion), a training partner will assist by lifting or pushing the load just enough to allow the trainee to complete three to four additional repetitions. It has been suggested that during the sets to exhaustion more motor units will be recruited during the exercise, leading to a more effective training stimulus than when sets are not performed to exhaustion (Fleck and Kraemer, 1997). Due to the great stress to the activated muscles, the forced-repetition exercise system is thought to be an effective method for achieving greater exercise responses compared to exercise performed without the forced repetitions (Ahtiainen et al., 2003b).

To promote further development of muscular strength and size with heavy resistance training, optimal conditions for recovery from each exercise session are necessary. Physiological processes related to the recovery (e.g., remodeling processes of disrupted muscle fibers) are influenced by the availability and actions of anabolic and catabolic hormones (Staron et al., 1994). Examination of the rate of recovery of the neuromuscular and hormonal systems after heavy resistance exercise may be advantageous for estimating a proper strength training frequency and/or intensity and/or volume in order to avoid the overtraining syndrome.

The purpose of the present study was to examine acute hormonal and neuromuscular responses and recovery to the maximum and the forced-repetitions resistance protocols in strength athletes versus nonathletes.

Methods

SUBJECTS AND EXPERIMENTAL DESIGN

Eight physical education students (nonathletes, NA) and 8 strength athletes (SA) volunteered to participate in this study (Table 1). Strength athletes had several years (9.3 ± 6.9) experience with resistance training but none was a competitive lifter. None of the subjects were taking any medication that would have been expected to affect physical performance. Each subject was informed of the potential risks and discomforts associated with the study, and all gave their written informed consent to participate. The Ethics Committee of the University of Jyväskylä approved the study.

The subjects were familiarized with the experimental testing procedures on the control day about 1 week before the actual measurements (Figure 1). Anthropometrical measurements and resistance load verifications for the experimental exercise were also determined for each subject at this time. The percentage of body fat was estimated from measurements of skinfold thickness (Durmin and

Table 1 Physical Characteristics of Subjects (mean ± SD)

	Non-Athletes (NA) (n = 8)	Strength Athletes (SA) (n = 8)
Age (yrs)	26.0 ± 4.3	27.0 ± 4.8
Stature (cm)	183.3 ± 4.9	177.3 ± 7.3*
Mass (kg)	79.4 ± 6.5	86.2 ± 4.3
Fat %	12.9 ± 2.3	14.2 ± 2.7
BMI	23.6 ± 1.7	27.4 ± 2.0***
Weight training experience (years)	–	9.3 ± 6.9
Max voluntary isometric force (N)	2748 ± 482	3252 ± 482*
Thickness of vastus lateralis (mm)	26.2 ± 3.0	32.2 ± 2.1***

Note: Difference between experimental groups: **p* < 0.05; ****p* < 0.001.

Experimental design:

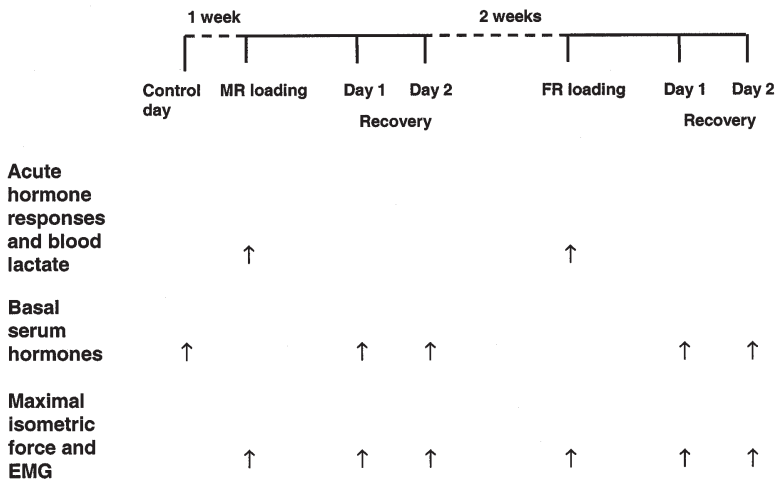


Figure 1. Experimental design.

Rahaman, 1967). The thickness of the m. vastus lateralis was measured by ultrasound (SSD 280ls, Aloka, Japan) from the level of 50% of the thigh length (Ahtiainen et al., 2003b).

During the control day three blood samples were obtained from each subject. One blood sample was drawn in the morning after 12 hours of fasting and approximately 8 hours of sleep so that basal serum hormone concentrations could be determined. For the determination of normal diurnal variation of serum hormone concentrations, two additional blood samples were also drawn within 1/2 hr without exercise at the same time of day that each subject would later undertake his heavy resistance loading protocols.

Loading Protocols. The experimental design comprised two loading sessions separated by 2 weeks performed at the same time of day. In addition, recovery of the loading sessions was examined for 2 days after both loadings. The first loading session was a maximum repetition (MR) protocol. MR included 4 sets of squats (Smith machine, from the knee angle of $79.0 \pm 1.1^\circ$ to 180°) with a 2-min recovery between sets. The deepness of the squats was controlled by a sound signal. The sets were performed with the maximum load possible to achieve 12 repetitions (12 RM). The load used in the first set had been determined during the laboratory visit a week earlier. The second loading session was a forced repetition (FR) protocol. In FR the loading protocol was same as in MR, but the initial load was assessed higher than in MR so that the subject could lift approximately 8 reps by himself and 4 additional reps with assistance. Force plates were used to measure the accurate force of the assistance given by the assistants while “lifting” the barbell with their own hands during the concentric phase of the squat, when necessary. The foot positions were identical in both loadings. The legs were 42.8 ± 1.7 cm apart from each other and the heels were 13.4 ± 1.4 cm in front of the bar path.

The subjects were encouraged to eat their normal but similar diets before the loading sessions. Fluid intake was limited just to moistening the mouth during the loadings. Strenuous exercises were not allowed during the 2 days preceding the loading sessions and during recovery days after the loadings.

Blood Collection and Analyses. Blood samples were drawn from the antecubital vein for determination of serum total and free testosterone, cortisol, and growth hormone concentrations. Fingertip blood samples were drawn for determination of blood lactate. During the loading session blood samples were drawn before, immediately after (post), and 15 (post 15 min) and 30 minutes (post 30 min) after the loadings. After 12 hours of fasting and approximately 8 hours of sleep, the morning of the first and second day after the loadings, fasting blood samples were obtained for the determination of basal serum hormone concentrations. All blood samples were obtained at the same body position of the subject.

Serum samples for hormonal analyses were kept frozen at -20°C until assayed. Serum testosterone concentrations were measured by the Chiron Diagnostics ACS:180 automated chemiluminescence system using an ACS:180 analyzer (Medfield, MA). The sensitivity of the testosterone assay was 0.42 nmol/L, and the intra-assay coefficient of variation was 6.7%. The concentration of serum free testosterone was measured by radioimmunoassays using kits from Diagnostic Products Corp. (Los Angeles). The sensitivity of the free testosterone assay was 0.52 pmol/L, and the intra-assay coefficient of variation was 3.8%. The assays of serum

cortisol were carried out by radioimmunoassays using kits from Farnos Diagnostica (Turku, Finland). The sensitivity of the cortisol assay was 0.05 nmol/L, and the intra-assay coefficient of variation was 4.0%. Concentrations of growth hormone were measured using radioimmunoassay 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 samples for each test subject were analysed in the same assay for each hormone. Blood lactate concentrations were determined using a Lactate kit (Roche, Mannheim, Germany).

Neuromuscular Measurements. An electromechanical dynamometer was used to measure maximal voluntary isometric force of the bilateral leg extension action at a knee angle of 107° before and after (within 45 seconds) the loadings as well as 24 and 48 hours after the loadings. The measurements during the recovery days were done at the same time of the day as when the subject performed the heavy resistance loading protocols.

Electromyographic activity (EMG) was recorded from the agonist muscles vastus lateralis (VL) and vastus medialis (VM) of the right leg during the maximal isometric action. Bipolar surface electrodes (Beckman miniature-sized skin electrodes 650437, Schiller Park, Illinois) with 20-mm interelectrode distance were employed. The electrodes were placed longitudinally over the muscle belly on the motor point area determined by an electrical stimulator (Neuroton 626). The positions of the electrodes were marked on the skin by small ink dots to ensure the same electrode positioning in each test during the experimental period (Häkkinen and Komi, 1983). EMG signals were recorded telemetrically (Glonner Biomes 2000) and stored on magnetic tape (Racall 16) and on the computer with a CO-DAS computer system (Dataq Instruments, Inc.). EMG signal was amplified (by a multiplication factor of 200, low-pass cut-off frequency of 360 Hz 3dB⁻¹), and digitized at a sampling frequency of 1000 Hz. EMG was full-wave rectified, integrated (iEMG in mV*s), and time normalized. The activity (iEMG) of the VL and VM was averaged and analysed in the maximal force phase (500–1500 ms) of the isometric muscle actions (Häkkinen et al., 1985).

Statistical Analyses. Standard statistical methods were used to calculate means, standard deviations (*SD*), standard errors (*SE*), and Pearson bivariate correlation coefficients. The changes in the variables over time from the prelevel were analysed using general linear model (GLM) analysis of variance with repeated measures. Differences between the experimental groups within each time point were analysed utilizing independent samples of *t*-tests, and within the experimental groups with dependent samples of *t*-tests. The $p < .05$ criterion was used to establish statistical significance.

Results

LOADING

The average load was higher (12% in SA, 30% in NA, $p < .001$) in all FR sets than in MR sets in both groups (Figure 2). In general, assistance was given for 4.4 ± 1.7 repetitions during the 12-rep sets in the FR loading in NA, and for 4.3 ± 1.4 repetitions in SA. The averaged force of the assistance in the last four reps was 100 ± 10 N, 103 ± 10 N, 128 ± 12 N, and 139 ± 13 N, respectively. The total volume of the

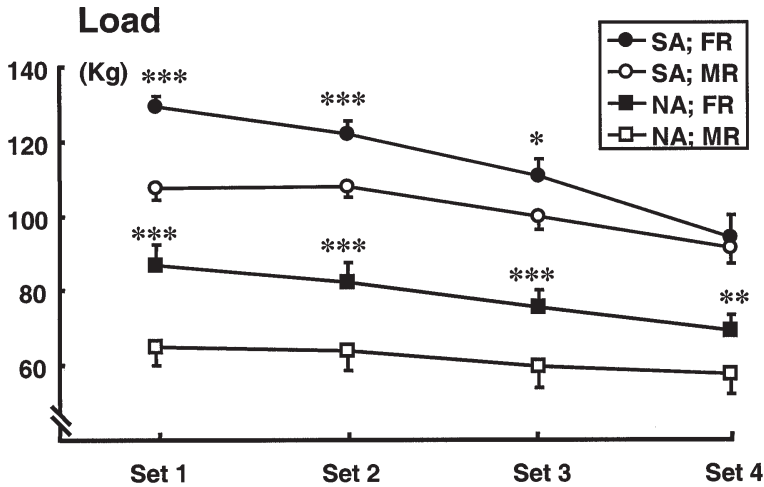


Figure 2. The loads in FR and MR sets (mean \pm SE) in SA and NA. Statistically significant difference (* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$) between the MR and FR loadings of the experimental groups.

work (loads*sets*reps) was greater ($p < .01$ in SA and $p < .001$ in NA) in the FR than in the MR loading in both groups. However, when the amount of external force produced by the assistant during the concentric phases of the FR repetitions was taken into account, the actual total volumes of the FR loadings did not differ from those of the MR loadings in both groups.

Control Blood Samples. There were no significant differences in the concentrations of serum hormones examined between the two control blood samples during the control day, with no exercise drawn at the corresponding time of the day as the subject's heavy resistance loading protocols.

Acute Hormonal Responses. Serum testosterone concentrations increased after the MR and FR loadings (post) in NA from 22.3 ± 6.0 nmol/L up to 28.1 ± 6.4 nmol/L ($p < .001$), and from 20.9 ± 5.3 nmol/L up to 26.9 ± 6.1 nmol/L ($p < .001$), respectively (Figure 3). In SA the serum testosterone concentrations increased after the MR and FR loadings from 15.7 ± 4.5 nmol/L up to 21.6 ± 5.3 nmol/L ($p < .001$), and from 14.4 ± 7.9 nmol/L up to 21.1 ± 7.5 nmol/L ($p < .001$), respectively. The increase in serum testosterone concentrations in SA were greater ($p < .01$) than in NA during both the MR and FR loadings. Furthermore, the testosterone response remained increased throughout the recovery period of 30 minutes after the FR loading in SA.

Serum free testosterone concentrations increased in NA after the MR and FR loadings (post) from 81.1 ± 24.2 pmol/L up to 111.2 ± 28.9 pmol/L ($p < .001$), and from 75.0 ± 23.5 pmol/L up to 112.0 ± 34.6 pmol/L ($p < .001$), respectively (Figure 4). In SA the serum free testosterone concentrations increased after the MR and FR loadings from 61.7 ± 15.3 pmol/L up to 86.5 ± 22.0 pmol/L ($p < .001$), and from 51.2 ± 14.4 pmol/L up to 79.6 ± 24.2 pmol/L ($p < .001$), respectively. The

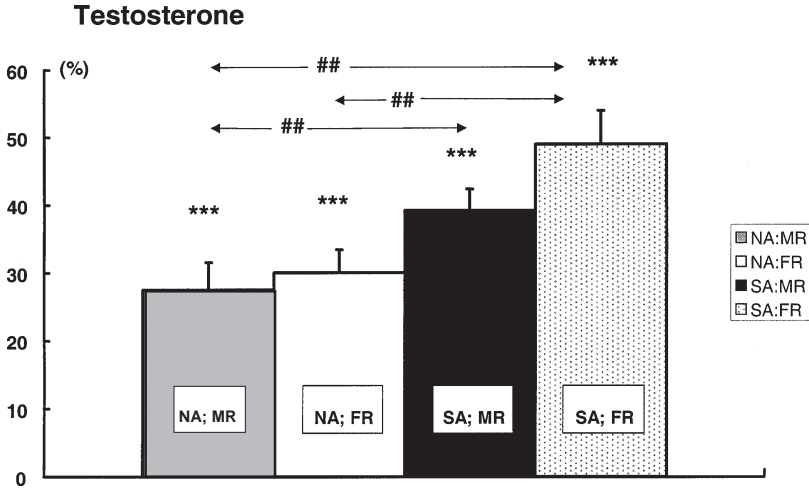


Figure 3. Relative changes in serum testosterone concentrations (mean \pm SE) before and immediately after the FR and MR loadings in SA and NA. Statistically significant difference (***) $p < 0.001$ from the corresponding preexercise value. Statistically significant difference (## $p < 0.01$) between the loading protocols and experimental groups.

changes in SA during the FR loading were greater ($p < .05$) than in NA during the MR loading. Serum free testosterone concentrations remained increased throughout the recovery period of 30 minutes after the FR loading in SA.

Serum GH concentrations increased in NA from $1.3 \pm 3.2 \mu\text{g/L}$ up to $12.8 \pm 8.3 \mu\text{g/L}$ (post 15 min) ($p < .001$), and from $1.5 \pm 2.6 \mu\text{g/L}$ up to $13.2 \pm 7.9 \mu\text{g/L}$ ($p < .001$) after the MR and FR loadings, respectively (Figure 5). In SA the serum GH concentrations increased from $0.2 \pm 0.3 \mu\text{g/L}$ up to $10.8 \pm 6.9 \mu\text{g/L}$ ($p < .001$), and from $0.1 \pm 0.2 \mu\text{g/L}$ up to $15.9 \pm 9.9 \mu\text{g/L}$ ($p < .001$) after the MR and FR loadings, respectively.

Serum cortisol concentrations increased in NA after the MR and FR loadings (post 15 min) from $0.37 \pm 0.13 \mu\text{mol/L}$ up to $0.54 \pm 0.18 \mu\text{mol/L}$ ($p < .01$), and from $0.41 \pm 0.16 \mu\text{mol/L}$ up to $0.63 \pm 0.16 \mu\text{mol/L}$ ($p < .01$), respectively (Figure 6). In SA the serum cortisol concentrations increased after the MR and FR loadings from $0.43 \pm 0.06 \mu\text{mol/L}$ up to $0.59 \pm 0.08 \mu\text{mol/L}$ ($p < .01$), and from $0.39 \pm 0.13 \mu\text{mol/L}$ up to $0.68 \pm 0.15 \mu\text{mol/L}$ ($p < .001$), respectively. The acute responses in cortisol ($p < .05$) were larger during the FR than during the MR loading in SA.

Basal Hormone Concentrations. There were no significant differences between the experimental groups in the basal hormone concentrations drawn on the control day. There were no significant changes in basal serum hormone concentrations on the first and second day after the loadings as compared to the control day values (data not shown).

Blood Lactate. The blood lactate concentration increased in NA up to $12.7 \pm 3.2 \text{ mmol/L}$ ($p < .001$) and to $14.2 \pm 4.0 \text{ mmol/L}$ ($p < .001$), and in SA up to 15.4

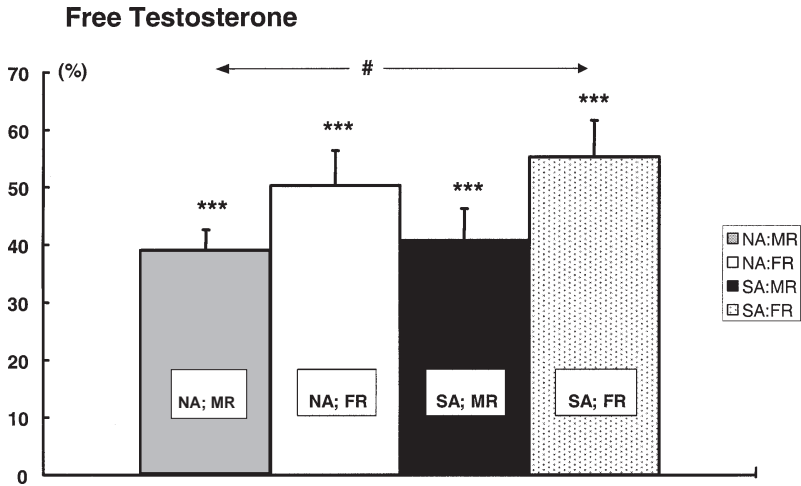


Figure 4. Relative changes in serum free testosterone concentrations (mean \pm SE) before and immediately after the FR and MR loadings in SA and NA. Statistically significant difference (***) $p < 0.001$ from the corresponding preexercise value. Statistically significant difference (# $p < 0.05$) between the SA:FR and NA:MR loadings.

± 1.8 mmol/L ($p < .001$) and to 16.3 ± 1.3 mmol/L ($p < .001$) after the MR and FR loadings, respectively.

Acute Neuromuscular Responses. Significant decreases of 32–52% ($p < .001$) occurred in maximal isometric force in both loading protocols in both groups (Figure 7a). The decreases in isometric force were greater ($p < .05$, post) during the FR than during the MR loadings in both groups. The decrease in isometric force remained lowered ($p < .05$) in NA during the MR loading for 24 hrs. In SA during the MR loading, and in NA during the FR loading, maximal isometric force was still lowered ($p < .05$) at the second day after the loading. In SA the changes in isometric force (post) and the changes in serum GH concentrations correlated with each other during the FR loading ($r = -.71$, $p < .05$).

Significant decreases of 15–19% ($p < .001$) occurred in the maximum integrated EMG of the isometric action after both loading protocols (post) in both groups (Figure 7b). The changes in EMG (post) and the changes in serum free testosterone concentrations correlated with each other in SA during the MR loading ($r = -.93$, $p < .01$). The changes in EMG (post) and the changes in serum GH concentrations (post 15 min) correlated with each other in NA during the FR loading ($r = -.73$, $p < .05$).

Discussion

The primary finding of this study was that the present heavy resistance exercise-induced acute testosterone responses were greater in strength athletes than in non-strength athletes. This was true especially when the resistance exercise was per-

Growth Hormone

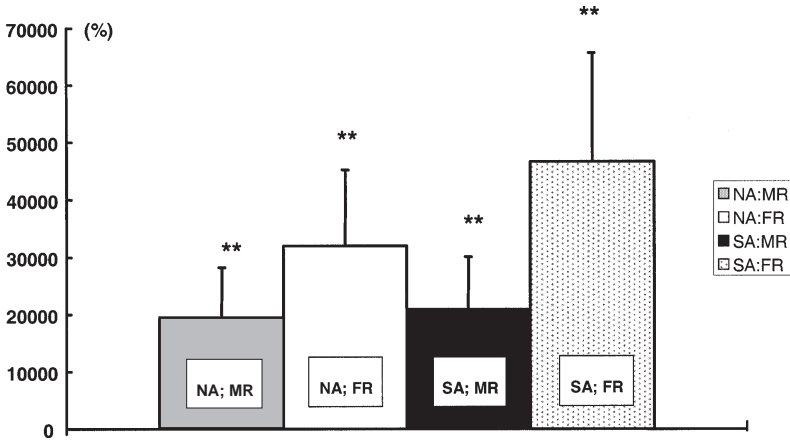


Figure 5. Relative changes in serum GH concentrations (mean ± SE) before and after (post 15 min) the FR and MR loadings in SA and NA. Statistically significant difference (** $p < 0.01$) from the corresponding preexercise value.

Cortisol

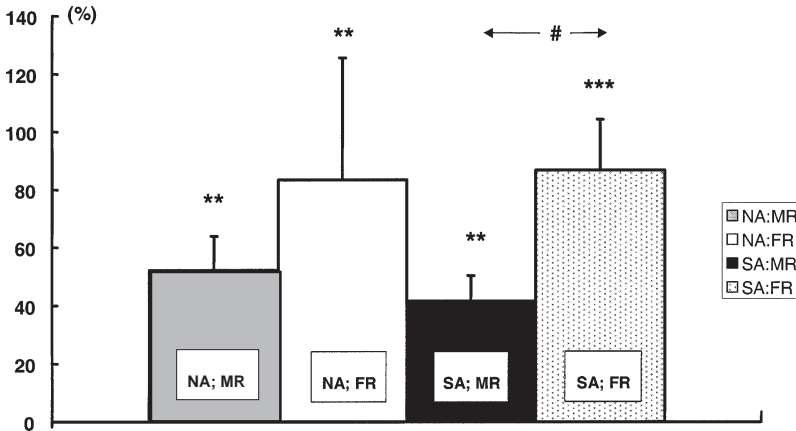


Figure 6. Relative changes in serum cortisol concentrations (mean ± SE) before and after (post 15 min) the FR and MR loadings in SA and NA. Statistically significant difference (** $p < 0.01$; *** $p < 0.001$) from the corresponding preexercise value. Statistically significant difference (# $p < 0.05$) between the SA:FR and SA:MR loadings.

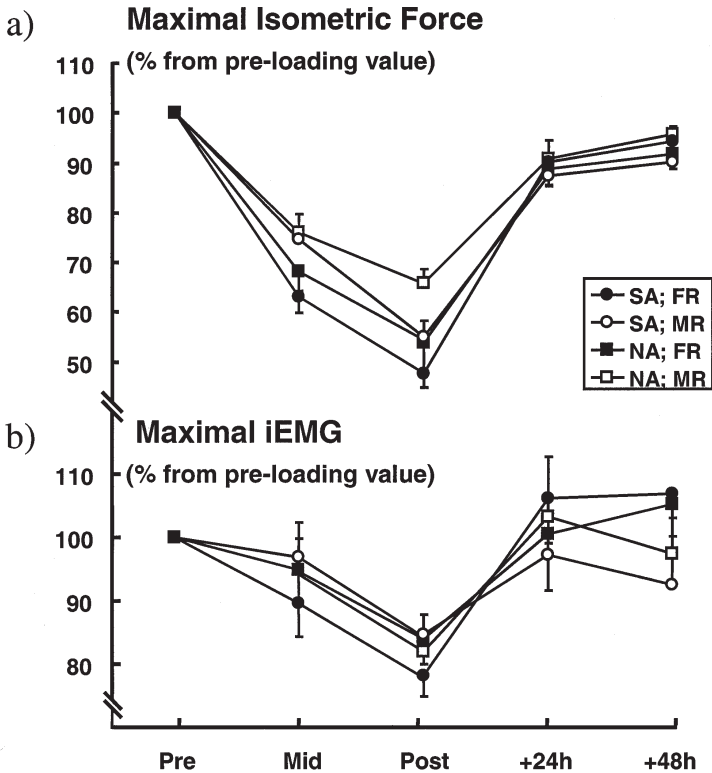


Figure 7. Relative changes (mean \pm SE) in maximal isometric force and EMG activity during and 2 days after the FR and MR loadings in SA and NA.

formed with the forced-repetitions protocol. The FR loading protocol also tended to produce greater acute free testosterone, GH, and cortisol responses in both groups. Both loading protocols in both groups also led to great neuromuscular fatigue. This was observable with the acute decreases in maximal voluntary isometric force associated with the decreases in maximal EMG of the loaded muscles recorded during the isometric muscle action as well as with high blood lactate concentration. The greatest decrease in isometric force took place in SA after the FR loading, while it was smallest in NA after the MR loading. The recovery of isometric force after the present loading protocols in both groups was almost completed during the two recovery days.

Testosterone is an anabolic hormone that exerts a potent effect on skeletal muscle (Spratt et al., 1988). Exercise-induced increases in serum testosterone concentration may be due to increases in LH pulsatility or production (Vermeulen et al., 1972), increased gonadal secretion (Cumming et al., 1986; Metivier et al., 1980), and testosterone release (Meskaitis et al., 1997), a direct (LH-independent) stimulatory effect of lactate on the secretion of testosterone (Lu et al., 1997), a

reduction in clearance rates (Cadoux-Hudson et al., 1985; Weiss et al., 1983), and/or changes in plasma volume (Cadoux-Hudson et al., 1985; Metivier et al., 1980; Weiss et al., 1983; Wilkerson et al., 1980). The elevated exercise-induced sympathetic activity may contribute to the augmented acute testosterone response (Jezova and Vigas, 1981) and direct catecholamine-mediated release of stored testosterone from the testes (Eik-Nes, 1969).

Due to the 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. It could be speculated that trained muscle tissue requires—as highly as possible—hormone-hormone receptor interactions to start the recuperation and adaptation processes optimally after the resistance exercises. Therefore it may also be possible that great heavy resistance exercise-induced hormone responses are physiologically very important for adaptation processes during prolonged strength training. Our previous study (Ahtiainen et al., 2003a) has indicated that, in particular, changes in the magnitude of acute exercise-induced testosterone responses during strength training seem to be related to the gains in muscle mass.

Serum testosterone concentrations increased significantly more in SA during the FR loading as compared to the responses in NA during both loading protocols. The testosterone response in SA during the MR loading was also greater than in NA during the MR loading. Furthermore, in the case of serum free testosterone, which represents the amount of bioactive testosterone, the response was greater in SA during the FR loading than in NA during the MR loading. These findings suggest that SA were able to produce greater testosterone and free testosterone responses, and these responses were further enhanced by the forced-repetitions training protocol. These findings are consistent with previous studies, which have indicated a relationship between total work (Gotshalk et al., 1997; Häkkinen and Pakarinen, 1993; Kraemer et al., 1990, 1993) and intensity (Hickson et al., 1994; Jezova et al., 1985) of the exercise and the degree of acute testosterone response. However, when the total volume of heavy resistance loading was higher (4 sets of leg presses, 2 sets of squats, and 2 sets of knee extensions), no differences could be observed in the testosterone responses between the FR and MR loading (Ahtiainen et al., 2003b).

Some previous studies of acute testosterone responses have shown contradictory results with regard to the subjects' training background. The resistance training background had no influence on the acute testosterone response produced by heavy resistance exercise (Fahey et al., 1976). On the other hand, experienced weightlifters showed a greater increase in testosterone response following the heavy resistance exercise than did the unskilled weight trainers (Kraemer et al., 1992). Kraemer et al. (1998) reported an enhanced acute testosterone response due to short-term strength training, while other previous studies have not shown any significant changes in resistance-exercise-induced acute testosterone responses due to long-term strength training (Craig et al., 1989; Häkkinen et al., 2000; Hickson et al., 1994; McCall et al., 1999).

High intensity heavy resistance exercise is known to induce a great acute GH response. In the present study, both loading protocols in both groups led to the great acute increase in serum GH concentrations. In line with the previous study of

Vanhelder et al. (1984) between exercise intensity and GH response, the present study also showed a trend to the greater GH response after the FR loading in both groups. Actually, when the volume of heavy resistance loading has been higher, the FR loading protocol did produce a larger GH response than that of MR loading (Ahtiainen et al., 2003b). It has been suggested that exercise-induced acute increases in serum GH concentrations may be responsive to the changes in acid-base balance in loaded muscles via afferent feedback from peripheral chemoreceptors (Gordon et al., 1994). Despite that, the present study found no relationship between blood lactate concentrations and changes in serum growth hormone concentrations. However, with afferent mechanisms the efferent activity of the brain motor center has also been connected to the exercise-induced GH response (Few and Davies, 1980; Galbo et al., 1987; Kjaer et al., 1987, 1989). This phenomenon is supported by the present study because the changes in GH concentrations were related to the changes in EMG in NA after the FR loading, and to the changes in isometric force in SA after the FR loading.

Cortisol is a catabolic hormone which among its other functions also plays a role in the degradation of proteins from skeletal muscles. However, a prominent role of acute cortisol response is to meet the greater metabolic demands of resistance exercise. In previous studies the acute cortisol response occurred when the overall stress of the exercise protocol was very high (Häkkinen and Pakarinen, 1993; Kraemer et al., 1993), and the response has been linked to the volume of total work or in magnitude to a given heavy-resistance exercise protocol (Gotshalk et al., 1997; Kraemer et al., 1987, 1991, 1993, 1995). In previous studies the strength training experience of young athletes did not have an influence on the acute cortisol response (Kraemer et al., 1992). However, long-term resistance training in adult men has had an overall reduction of cortisol responses to exercise stress (Kraemer et al., 1995, 1999; Staron et al., 1994).

In overtraining conditions the cortisol response has been attenuated due to the increase in resistance-training volume (Fry et al., 1994, 1998). In the present study the serum cortisol concentrations increased in both loadings in both groups. The higher volume of heavy resistance loading from the FR protocol produced a larger cortisol response than that of MR loading (Ahtiainen et al., 2003b). The present study showed that in SA during the FR loading the cortisol response was greater than during the MR loading. This indicates that the cortisol response is also enhanced by resistance exercise intensity in addition to the magnitude of total work. This result is in line with endurance exercise studies in which the acute cortisol response was related to exercise intensity (Farrell et al., 1983; Kindermann et al., 1982; Kuoppasalmi et al., 1980). The exact mechanism remains unclear, but the greater acute cortisol response during FR loading may be due to the greater metabolic demands which mediate some of the response via glycolytic and catecholamine stimulatory mechanisms (Kraemer et al., 1987, 1993; Van Helder et al., 1986). Also the neural control of adrenal cortex activity (Holzwarth et al., 1987) and nervous feedback from working muscles (Kjaer et al., 1989) are involved in regular mechanisms of exercise-induced cortisol response. However, there were no significant differences in blood lactate concentrations between the loadings or experimental groups. The decreased EMG activity during the actual FR loading in SA supports the presumption of neural control in the acute cortisol response.

As expected, the present heavy resistance exercise produced acute neuromuscular fatigue as observed by the decrease in maximal voluntary isometric force and maximal EMG activity during the isometric action. Both loading protocols led to a great decrease in isometric force, but the decreases were greater in SA during the FR loading than in NA during the MR loading. That may have been caused by the neural fatigue and/or metabolic factors in muscle cells (Häkkinen, 1993). However, there were no significant differences between the decreases in maximal EMG activity during the isometric actions or within blood lactate concentrations between the loading protocols or between the experimental groups.

The MR loading was performed first and its influence on the responses of the FR loading cannot be totally excluded. For that reason as much as 2 weeks of recovery was required between the loading sessions. The FR loading was performed as a second protocol, since it could be very difficult to assess the appropriate load for the present inexperienced subjects without performing the MR loading as the first loading protocol. Therefore, starting with the FR loading could create a high risk for the subjects. The results of the present study showed there were no major differences in recovery from the exercises. However, the overall volume of the exercise regimen in the present study (4 sets of squats) was lower than in a typical hypertrophic type of the strength training. Therefore, the present volume of loading might be insufficient to produce differences between loading protocols or experimental groups during the recovery. Actually, maximal isometric force has remained significantly lowered for as long as 3 recovery days after the exercise, when the overall volume of the session was much higher than in the present study (Ahtiainen et al., 2003b).

In conclusion, this study showed that the present MR and FR loading protocols in both groups led to great acute hormonal responses, and that the testosterone responses during the FR and MR loading were greater in SA than in NA. Furthermore, the free testosterone response was greater in SA during the FR loading than in NA during the MR loading, and the cortisol response was greater in SA during the FR loading than during the MR loading. Both loading protocols in both groups also led to great neuromuscular fatigue, as observed with the acute decreases in maximal voluntary isometric force associated with the decreases in EMG activity of the activated muscles during the isometric muscle action as well as with high blood lactate concentration. There were no major differences in the recovery of maximal isometric force or basal hormonal concentrations between loadings or between groups after the present low volume heavy-resistance loading protocols.

The data of the present study suggest that the forced-repetition exercise system may be an efficient training protocol for maximal strength and muscle mass development, especially in strength athletes. To what extent the larger acute endogenous hormone responses created by the FR loading protocol are related to training-induced muscle hypertrophy and strength development is unknown and remains to be examined.

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References

- Ahtiainen, J.P., Pakarinen, A., Alen, M., Kraemer, W.J., and Hakkinen, K. (2003a). Muscle hypertrophy, hormonal adaptations and strength development during strength training in strength-trained and untrained men. **Eur. J. Appl. Physiol.** 89: 555-563.
- Ahtiainen, J.P., Pakarinen, A., Kraemer, W.J., and Häkkinen, K. (2003b). Acute hormonal and neuromuscular responses and recovery to forced vs. maximum repetitions multiple resistance exercises. **Int. J. Sports Med.** 24: 410-418.
- Cadoux-Hudso, T.A., Few, J.D., and Imms, F.J. (1985). The effect of exercise on the production and clearance of testosterone in well trained young men. **Eur. J. Appl. Physiol. Occup. Physiol.** 54: 321-325.
- Craig, B.W., Brown, R., and Everhart, J. (1989). Effects of progressive resistance training on growth hormone and testosterone levels in young and elderly subjects. **Mech. Ageing Dev.** 49: 159-169.
- Cumming, D.C., Brunsting, L.A., 3rd., Strich, G., Ries, A.L., and Rebar, R.W. (1986). Reproductive hormone increases in response to acute exercise in men. **Med. Sci. Sports Exerc.** 18: 369-373.
- Durnin, J.V., and Rahaman, M.M. (1967). The assessment of the amount of fat in the human body from measurements of skinfold thickness. **Br. J. Nutr.** 21: 681-689.
- Eik-Nes, K.B. (1969). An effect of isoproterenol on rates of synthesis and secretion of testosterone. **Am J. Physiol.** 217: 1764-1770.
- Fahey, T.D., Rolph, R., Mounghmee, P., Nagel, J., and Mortara, S. (1976). Serum testosterone, body composition, and strength of young adults. **Med. Sci. Sports** 8: 31-34.
- Farrell, P.A., Garthwaite, T.L., and Gustafson, A.B. (1983). Plasma adrenocorticotropin and cortisol responses to submaximal and exhaustive exercise. **J. Appl. Physiol.** 55: 1441-1444.
- Few, J.D., and Davies, C.T. (1980). The inhibiting effect of atropine on growth hormone release during exercise. **Eur. J. Appl. Physiol. Occup. Physiol.** 43: 221-228.
- Fleck, S.J., and Kraemer, W.J. (1997). **Designing Resistance Training Programs** (2nd ed.). Champaign, IL: Human Kinetics.
- Fry, A.C., Kraemer, W.J., and Ramsey, L.T. (1998). Pituitary-adrenal-gonadal responses to high-intensity resistance exercise overtraining. **J. Appl. Physiol.** 85: 2352-2359.
- Fry, A.C., Kraemer, W.J., Stone, M.H., Warren, B.J., Fleck, S.J., Kearney, J.T., and Gordon, S.E. (1994). Endocrine responses to overreaching before and after 1 year of weightlifting. **Can. J. Appl. Physiol.** 19: 400-410.
- Galbo, H., Kjaer, M., and Secher, N.H. (1987). Cardiovascular, ventilatory and catecholamine responses to maximal dynamic exercise in partially curarized man. **J. Physiol.** 389: 557-568.
- Gordon, S.E., Kraemer, W.J., Vos, N.H., Lynch, J.M., and Knuttgen, H.G. (1994). Effect of acid-base balance on the growth hormone response to acute high-intensity cycle exercise. **J. Appl. Physiol.** 76: 821-829.
- Gotshalk, L.A., Loebel, C.C., Nindl, B.C., Putukian, M., Sebastianelli, W.J., Newton, R.U., Häkkinen, K., and Kraemer, W.J. (1997). Hormonal response of multiset versus single-set heavy-resistance exercise protocols. **Can. J. Appl. Physiol.** 22: 244-255.
- Häkkinen, K. (1993). Neuromuscular fatigue and recovery in male and female athletes during heavy resistance exercise. **Int. J. Sports Med.** 14: 53-59.
- Häkkinen, K., and Komi, P.V. (1983). Electromyographic changes during strength training and detraining. **Med. Sci. Sports Exerc.** 15: 455-460.
- Häkkinen, K., Komi, P.V., and Alen, M. (1985). 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.
- Häkkinen, K., and Pakarinen, A. (1993). Muscle strength and serum testosterone, cortisol and SHBG concentrations in middle-aged and elderly men and women. **Acta Physiol. Scand.** 148: 199-207.
- Häkkinen, K., Pakarinen, A., Kraemer, W.J., Newton, R.U., and Alen, M. (2000). Basal concentrations and acute responses of serum hormones and strength development during heavy resistance training in middle-aged and elderly men and women. **J. Gerontol. A, Biol. Sci. Med. Sci.** 55(2): B95-B105.
- Hickson, R.C., Hidaka, K., Foster, C., Falduto, M.T., and Chatterton, R.T., Jr. (1994). Successive time courses of strength development and steroid hormone responses to heavy-resistance training. **J. Appl. Physiol.** 76: 663-670.
- Holzwarth, M.A., Cunningham, L.A., and Kleitman, N. (1987). The role of adrenal nerves in the regulation of adrenocortical functions. **Ann. NY Acad. Sci.** 512: 449-464.
- Jezova, D., and Vigas, M. (1981). Testosterone response to exercise during blockade and stimulation of adrenergic receptors in man. **Horm. Res.** 15: 141-147.
- Jezova, D., Vigas, M., Tatar, P., Kvetnansky, R., Nazar, K., Kaciuba-Uscilko, H., and Kozlowski, S. (1985). Plasma testosterone and catecholamine responses to physical exercise of different intensities in men. **Eur. J. Appl. Physiol. Occup. Physiol.** 54: 62-66.
- Kindermann, W., Schnabel, A., Schmitt, W.M., Biro, G., Cassens, J., and Weber, F. (1982). Catecholamines, growth hormone, cortisol, insulin, and sex hormones in anaerobic and aerobic exercise. **Eur. J. Appl. Physiol. Occup. Physiol.** 49: 389-399.
- Kjaer, M., Secher, N.H., Bach, F.W., and Galbo, H. (1987). Role of motor center activity for hormonal changes and substrate mobilization in humans. **Am. J. Physiol.** 253(5 Pt 2): R687-R695.
- Kjaer, M., Secher, N.H., Bach, F.W., Sheikh, S., and Galbo, H. (1989). Hormonal and metabolic responses to exercise in humans: Effect of sensory nervous blockade. **Am. J. Physiol.** 257(1 Pt 1): E95-E101.
- Kraemer, W.J., Fleck, S.J., Dziados, J.E., Harman, E.A., Marchitelli, L.J., Gordon, S.E., Mello, R., Frykman, P.N., Koziris, P.L., and Triplett, T.N. (1993). Changes in hormonal concentrations after different heavy-resistance exercise protocols in women. **J. Appl. Physiol.** 75: 594-604.
- Kraemer, W.J., Fry, A.C., Warren, B.J., Stone, M.H., Fleck, S.J., Kearney, J.T., Conroy, B.P., Maresh, C.M., Weseman, C.A., Triplett, N.T., et al. (1992). Acute hormonal responses in elite junior weightlifters. **Int. J. Sports Med.** 13: 103-109.
- Kraemer, W.J., Gordon, S.E., Fleck, S.J., Marchitelli, L.J., Mello, R., Dziados, J.E., Friedl, K., Harman, E., Maresh, C., and Fry, A.C. (1991). Endogenous anabolic hormonal and growth factor responses to heavy resistance exercise in males and females. **Int. J. Sports Med.** 12: 228-235.
- Kraemer, W.J., Häkkinen, K., Newton, R.U., Nindl, B.C., Volek, J.S., McCormick, M., Gotshalk, L.A., Gordon, S.E., Fleck, S.J., Campbell, W.W., Putukian, M., and Evans, W.J. (1999). Effects of heavy-resistance training on hormonal response patterns in younger vs. older men. **J. Appl. Physiol.** 87: 982-992.
- Kraemer, W.J., Marchitelli, L., Gordon, S.E., Harman, E., Dziados, J.E., Mello, R., Frykman, P., McCurry, D., and Fleck, S.J. (1990). Hormonal and growth factor responses to heavy resistance exercise protocols. **J. Appl. Physiol.** 69: 1442-1450.
- Kraemer, W.J., Noble, B.J., Clark, M.J., and Culver, B.W. (1987). Physiologic responses to heavy-resistance exercise with very short rest periods. **Int. J. Sports Med.** 8: 247-252.

- Kraemer, W.J., Patton, J.F., Gordon, S.E., Harman, E.A., Deschenes, M.R., Reynolds, K., Newton, R.U., Triplett, N.T., and Dziados, J.E. (1995). Compatibility of high-intensity strength and endurance training on hormonal and skeletal muscle adaptations. **J. Appl. Physiol.** 78: 976-989.
- Kraemer, W.J., Staron, R.S., Hagerman, F.C., Hikida, R.S., Fry, A.C., Gordon, S.E., Nindl, B.C., Gothshalk, L.A., Volek, J.S., Marx, J.O., Newton, R.U., and Häkkinen, K. (1998). The effects of short-term resistance training on endocrine function in men and women. **Eur. J. Appl. Physiol. Occup. Physiol.** 78: 69-76.
- Kuoppasalmi, K., Naveri, H., Harkonen, M., and Adlercreutz, H. (1980). Plasma cortisol, androstenedione, testosterone and luteinizing hormone in running exercise of different intensities. **Scand. J. Clin. Lab. Invest.** 40: 403-409.
- Lu, S.S., Lau, C.P., Tung, Y.F., Huang, S.W., Chen, Y.H., Shih, H.C., Tsai, S.C., Lu, C.C., Wang, S.W., Chen, J.J., Chien, E.J., Chien, C.H., and Wang, P.S. (1997). Lactate and the effects of exercise on testosterone secretion: Evidence for the involvement of a cAMP-mediated mechanism. **Med. Sci. Sports Exerc.** 29: 1048-1054.
- McCall, G.E., Byrnes, W.C., Fleck, S.J., Dickinson, A., and Kraemer, W.J. (1999). Acute and chronic hormonal responses to resistance training designed to promote muscle hypertrophy. **Can. J. Appl. Physiol.** 24: 96-107.
- Meskaitis, V.J., Harman, F.S., Volek, J.S., Nindl, B.C., Kraemer, W.J., Weinstock, D., and Deaver, D.R. (1997). Effects of exercise on testosterone and nitric oxide production in the rat testis. **J. Androl.** p. S37.
- Metivier, G., Gauthier, R., De la Chevrotiere, J., and Grymala, D. (1980). The effect of acute exercise on the serum levels of testosterone and luteinizing (LH) hormone in human male athletes. **J. Sports Med. Phys. Fitness** 20: 235-238.
- Spratt, D.I., O'Dea, L.S., Schoenfeld, D., Butler, J., Rao, P.N., and Crowley, W.F., Jr. (1988). Neuroendocrine-gonadal axis in men: Frequent sampling of LH, FSH, and testosterone. **Am. J. Physiol.** 254(5 Pt 1): E658-E666.
- Staron, R.S., Karapondo, D.L., Kraemer, W.J., Fry, A.C., Gordon, S.E., Falkel, J.E., Hagerman, F.C., and Hikida, R.S. (1994). Skeletal muscle adaptations during early phase of heavy-resistance training in men and women. **J. Appl. Physiol.** 76: 1247-1255.
- Tesch, P.A., and Larsson, L. (1982). Muscle hypertrophy in bodybuilders. **Eur. J. Appl. Physiol. Occup. Physiol.** 49: 301-306.
- VanHelder, W.P., Casey, K., Goode, R.C., and Radomski, W.M. (1986). Growth hormone regulation in two types of aerobic exercise of equal oxygen uptake. **Eur. J. Appl. Physiol. Occup. Physiol.** 55: 236-239.
- Vanhelder, W.P., Radomski, M.W., and Goode, R.C. (1984). Growth hormone responses during intermittent weight lifting exercise in men. **Eur. J. Appl. Physiol. Occup. Physiol.** 53: 31-34.
- Vermeulen, A., Rubens, R., and Verdonck, L. (1972). Testosterone secretion and metabolism in male senescence. **J. Clin. Endocrinol. Metab.** 34: 730-735.
- Weiss, L.W., Cureton, K.J., and Thompson, F.N. (1983). Comparison of serum testosterone and androstenedione responses to weight lifting in men and women. **Eur. J. Appl. Physiol. Occup. Physiol.** 50: 413-419.
- Wilkerson, J.E., Horvath, S.M., and Gutin, B. (1980). Plasma testosterone during treadmill exercise. **J. Appl. Physiol.** 49: 249-253.