Journal of Strength and Conditioning Research, 2005, 19(3), 572–582

SHORT VS. LONG REST PERIOD BETWEEN THE SETS IN HYPERTROPHIC RESISTANCE TRAINING: INFLUENCE ON MUSCLE STRENGTH, SIZE, AND HORMONAL ADAPTATIONS IN TRAINED MEN

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ABSTRACT. Ahtiainen, J.P., A. Pakarinen, M. Alen, W.J. Kraemer, and K. Häkkinen. Short vs. long rest period between the sets in hypertrophic resistance training: Influence on muscle strength, size, and hormonal adaptations in trained men. *J. Strength Cond. Res. 19(3):572–582. 2005.*—Acute and long-term hormonal and neuromuscular adaptations to hypertrophic strength training were studied in 13 recreationally strength-trained men. The experimental design comprised a 6-month hypertrophic strength-training period including 2 separate 3-month training periods with the crossover design, a training protocol of short rest (SR, 2 minutes) as compared with long rest (LR, 5 minutes) between the sets. Basal hormonal concentrations of serum total testosterone (T), free testosterone (FT), and cortisol (C), maximal isometric strength of the leg extensors, right leg 1 repetition maximum (1RM), dietary analysis, and muscle cross-sectional area (CSA) of the quadriceps femoris by magnetic resonance imaging (MRI) were measured at months 0, 3, and 6. The 2 hypertrophic training protocols used in training for the leg extensors (leg presses and squats with 10RM sets) were also examined in the laboratory conditions at months 0, 3, and 6. The exercise protocols were similar with regard to the total volume of work (loads × sets × reps), but differed with regard to the intensity and the length of rest between the sets (higher intensity and longer rest of 5 minutes vs. somewhat lower intensity but shorter rest of 2 minutes). Before and immediately after the protocols, maximal isometric force and electromyographic (EMG) activity of the leg extensors were measured and blood samples were drawn for determination of serum T, FT, C, and growth hormone (GH) concentrations and blood lactate. Both protocols before the experimental training period (month 0) led to large acute increases ($p < 0.05$–0.001) in serum T, FT, C , and GH concentrations, as well as to large acute decreases ($p < 0.05$–0.001) in maximal isometric force and EMG activity. However, no significant differences were observed between the protocols. Significant increases of 7% in maximal isometric force, 16% in the right leg 1RM, and 4% in the muscle CSA of the quadriceps femoris were observed during the 6-month strength-training period. However, both 3-month training periods performed with either the longer or the shorter rest periods between the sets resulted in similar gains in muscle mass and strength. No statistically significant changes were observed in basal hormone concentrations or in the profiles of acute hormonal responses during the entire 6-month experimental training period. The present study indicated that, within typical hypertrophic strength-training protocols used in the present study, the length of the recovery times between the sets (2 vs. 5 minutes) did not have an influence on the magnitude of acute hormonal and neuromuscular responses or long-term training adaptations in muscle strength and mass in previously strength-trained men.

KEY WORDS. serum hormones, resistance exercise, muscle strength, electromyography, cross sectional area, dietary intake

INTRODUCTION

It has been well known that systematic strength training has a potent effect in promoting increases in size and strength of skeletal muscle due to combinations of multiple factors, i.e., mechanical stress, neuromotor control, metabolic demands, and endocrine activities. A heavy-resistance–exercise protocol performed with the progressive overload principle leads to acute responses observed as increases in serum anabolic hormone concentrations and temporary decreases in neuromuscular performance (5, 13, 20, 22, 24). Therefore, the magnitude of acute hormonal and neuromuscular responses can be considered important indicators of training effects of various heavy-resistance exercises. Actually, it has been hypothesized that during long-term strength training, acute hormonal responses induced by the single-resistance exercises are important contributors to muscle hypertrophy (22).

Heavy-resistance exercise has been shown to induce acute hormone responses, which are dependent on the type of exercise protocol, i.e., intensity (load) of exercise, number of sets and repetitions per set, length of rest periods between sets, and muscle mass involved (e.g., 12, 22). According to the previous study by Kraemer et al. (22), the acute endocrine response in heavy-resistance exercise was greater in 10 repetition maximum (10RM) sets with shorter compared with longer rest periods (1 minute vs. 3 minutes). In addition, Gotshalk et al. (8) found that the acute growth hormone and testosterone responses were greater after a total-body resistance-exercise protocol performed with 3 sets per exercise than after the single-set exercise. These previous studies suggest that the greatest exercise-induced stimulus to the endocrine system is produced when the resistance exercise is performed with multiple sets per exercise and short rest periods between the sets.

For the purpose of ultimate training-induced muscle hypertrophy, it has been generally recommended to use multiple sets per exercise, a moderately high number of repetitions (e.g., 8–12RM) per set, and short rest periods (i.e., 60–120 seconds) between the sets (5). Short rest periods between the sets (i.e., 60 seconds) are used with moderate resistance (8–10 RM) to achieve a longer duration of time under tension along with a great anabolic hormonal response to induce increases in muscular hypertrophy (22, 23). However, training protocols emphasizing somewhat higher intensity (load) with longer rest periods between the 8–10RM sets have been recommended in the practical type of strength-training publications. Briefly, the basic recommendations in these kinds of high-intensity hypertrophic training systems have been that only a few training sets to a momentary concentric failure (i.e., a set until exhaustion) with several minutes recovery time between the sets would be needed per exercise to progressively overload the muscles and stimulate training-induced muscle hypertrophy. In spite of the popularity of those training systems, no previous studies on physiological and/or long-term training responses to high-intensity hypertrophic training systems have been published so far.

The purpose of the present study was to investigate acute hormonal and neuromuscular responses and recovery to 2 hypertrophic heavy-resistance protocols performed with a similar overall volume of exercise; a higher intensity and longer rest periods between the sets in comparison with that of somewhat lower intensity but shorter rest periods between the sets. Furthermore, the present study also investigated hormonal and neuromuscular adaptations to training using these 2 hypertrophic heavy-resistance training protocols over a 3-month period.

Methods

Experimental Approach to the Problem

The acute hormonal and neuromuscular responses of 2 loading protocols differing by rest periods between the sets (2 vs. 5 minutes) were studied with 13 recreationally strength-trained men. Both loading protocols were expected to lead to large acute hormonal responses. According to previous studies, we hypothesized that when using shorter rest periods between the sets, the endocrine response should be larger along with a greater metabolic stress (i.e., lactic acid) than that of longer rest periods between the sets. This may result in greater tissue catabolism stimulating muscle tissue remodeling and protein synthesis at a greater rate (26, 27). The long-term adaptations to strength training were additionally examined with the two 3-month experimental training periods by using the crossover design. The training protocols and the total load performed by the subjects were similar in both 3-month training periods, but the rest periods between the sets were modified to 2 or 5 minutes according to the experimental design. Because both exercise protocols were hypertrophic in nature and similar with regard to total load used, the differences in acute hormonal responses may, at least in part, explain the possible differences in the gains of muscle mass and strength during the strength training.

Subjects

Thirteen recreationally strength-trained men (mean ± *SD*; age = 28.7 ± 6.2 years; height = 181.4 ± 5.5 cm; weight = 83.9 ± 11.7 kg; 14.8 ± 3.9% fat; with an experience of 6.6 ± 2.8 years of continuous strength training) volunteered as subjects. None of the subjects were competitive strength athletes. Twenty subjects volunteered for the study, but 13 of them completed the whole 6-month investigation. Because the training and measurement protocols were physically very demanding, 7 of the subjects had to discontinue the study during the experimental training period, mostly due to training-induced aches in the knees and back. No medication was being taken by the subjects, which would have been expected to affect physical performance. Each subject was informed of potential risks and discomforts associated with the investigation, and all subjects gave their written, informed consent to participate. The Ethics Committee of the University of Jyväskylä approved the study.

Experimental Design

Familiarization Session. The subjects were familiarized with the experimental testing procedures during a control day about 1 week before the actual measurements. Resistance-load verifications for the experimental leg press and squat exercises were also determined. During the control day, 3 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 for the determination of basal serum-hormone concentrations. Two blood samples were also drawn within ½ hour without exercise at the same time of day that each subject would later undertake his heavy-resistance loading protocols.

Acute Resistance-Exercise Responses. The experimental design comprised 2 heavy-resistance loading sessions within 1 week: (a) lower intensity with shorter rest periods between the sets (SR) and (b) higher intensity with longer rest periods between the sets (LR) before the experimental strength-training period as well as after 3-month and after 6-month strength training at the same time of day for the examination of acute hormonal and neuromuscular responses (Figure 1). The first of the loading sessions (SR) was a traditional type of resistance exercise and included 5 sets of leg presses (David 210, David Fitness and Medical Ltd, Vantaa, Finland; from a knee angle of 60–180° = knee straight) and 4 sets of squats in the Smith-machine (from a knee angle of 70–180° = knee straight) with a 2-minute recovery between the sets and 4 minutes between the exercises. The knee angle of the squats was controlled by an electronic goniometer with a sound signal.

The second loading session (LR) was a high-intensity type of resistance exercise. The loading protocol was the same as in the first one, but 4 sets of leg presses and 3 sets of squats were done with a 5-minute recovery between the sets and 4 minutes between the exercises. The loads in all sets were approximately 15% higher than in the first loading. All the sets in both loading were performed with the maximum load possible for 10 10RM. The loads were adjusted during the course of the session due to fatigue so that each subject would be able to perform 10 repetitions at each set. In the LR loading, when necessary, the subject was assisted slightly during the last few repetitions of the set to complete the 10-repetition sets. The loadings were designed to be as similar as possible to be used during the experimental training periods and similar to those in normal strength training of experienced strength athletes for further gains in muscle

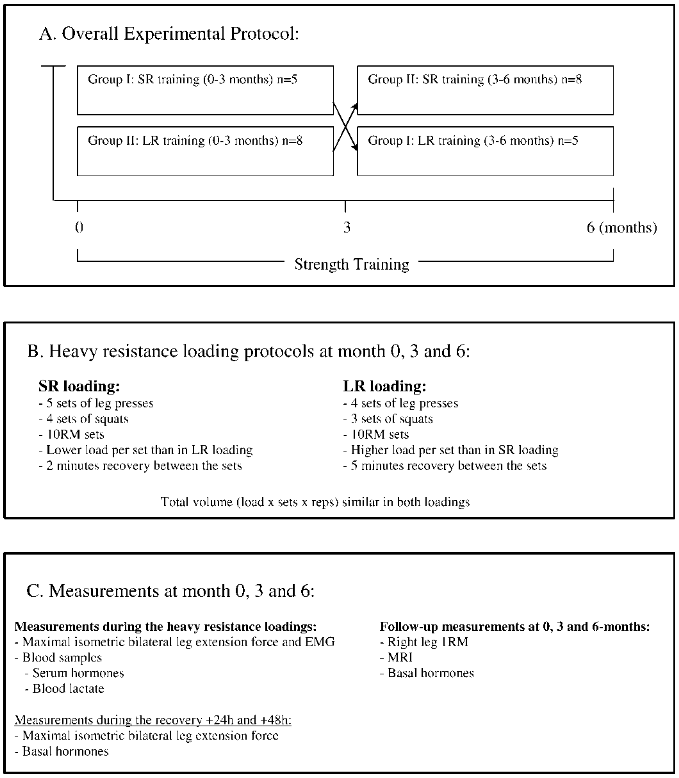

FIGURE 1. Experimental design of the study (A), the heavy-resistance loading protocols (B), and measurements during the loading protocols and during the experimental training period (C).

mass and strength. The loadings were planned to be comparable so that the total volume, as presented by multiplication of load, sets, and repetitions in both protocols would be as identical as possible (14). Thus, the number of the sets was lower and the exercise intensity (i.e., loads) was greater in the LR loading.

Strength Training. The total duration of the present training period was 6 months, which comprised 2 different kinds of 3-month training periods in a randomized order (Figure 1). After the measurements at month 0, the subjects were randomly divided into 2 training groups. No statistically significant differences were observed in the anthropometric characteristics, maximal isometric and dynamic leg extension force, or cross-sectional area (CSA) of the quadriceps femoris between the experimental training groups. Group I (n = 5) trained the first 3-month training period with shorter rest between the sets (2 minutes) and multiple sets (i.e., traditional resistance training) followed by a 3-month experimental strength-training period with longer rest between the sets (5 minutes) and fewer sets (i.e., high-intensity resistance training). Therefore, the first training period was called lower intensity with shorter rest periods between the sets training (SR training) and the second training period higher intensity with longer rest periods between the sets training (LR training). Group II (n = 8) performed the experimental training periods using the opposite order. The resistance training protocols the subjects performed during the experimental training periods were similar to the loading protocols used in the heavy-resistance loading sessions in the laboratory.

During the present 6-month experimental period, the subjects continued their training individually as they had previously. The subjects had several years (6.6 ± 2.8) of experience in strength training and their primary purpose in their strength training was to gain maximal strength and muscle mass. Therefore, the exercise protocols of the subjects before the experimental training period had been similar as used in the present strength training of this study. Therefore, they did not need to make drastic changes in the training programs they had previously used. The main intervention to their training was the change and control of the length of the rest periods between the sets. The strength-training sessions were carried out approximately 4 times per week. Different body parts were trained on different training days with multiple exercises and sets with 8–12 repetitions per sets. The training load of the exercises was increased progressively by trying to increase the load for every exercise session. Exercises for the leg extensors were carried out once per week and typically included squat, leg presses, and knee-extension exercises. The subjects performed their strength training for every muscle group with the same training protocol according to the training period. The training performed by the subjects was controlled by training diaries, and especially leg training was partly supervised.

Muscle Strength and Electromyographic 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 3 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 and thereafter digitized and analyzed with a Codas TM computer system (Dataq Instruments, Inc.; Akron, OH). Maximal peak force was defined as the highest value of the force (N) recorded during the bilateral isometric leg extension. Electromyographic (EMG) activity 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; Beckman Coulter, Inc., Fullerton, CA) with the 20-mm interelectrode distance were placed longitudinally over the muscle belly, and 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 entire experimental period (16). The EMG signals were recorded telemetrically (Glonner Biomes 2000; Glonner Electronic, Munich, Germany) and stored on magnetic tape (Racall 16; Recall-Thermionic, Hythe, United Kingdom) and in the computer with the CODAS computer system (Dataq Instruments, Inc.). EMG signal was amplified (by a multiplication factor of 200, low-pass cut-off frequency of 360 Hz 3 dB^{-1}) and digitized at a sampling frequency of 1,000 Hz. The EMG was full-wave rectified, integrated (iEMG in mV·s), and time normalized. The EMG activity of the VL and VM was averaged and analyzed in the maximal force phase (500–1,500 milliseconds) of the isometric muscle actions (9).

A David 210 dynamometer (David Fitness and Medical Ltd) was used to measure maximal unilateral concentric force production of the leg extensors (hip, knee, and ankle extensors) (17). 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 1RM contractions were performed. After each repetition, the load was increased until the subject was unable to extend the leg to the required full-extension position. The last acceptable extension with the highest possible load was determined as 1RM. This dynamic testing action was used in addition to that of the isometric one because the present strength training was also dynamic in nature.

Muscle CSA. The muscle 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, Eindhoven, The Netherlands) at the Keski-Suomen Magneettikuvaus Ltd., 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 (15). Great care was taken to reproduce the same individual femur length each time using the appropriate anatomical landmarks. All MR 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 6/15–11/15 were used (slice 5 being closer to the knee joint of the thigh). The CSA (measured as cm^2) was determined by tracing manually along the border of the quadriceps femoris. Muscle CSA was expressed as a mean of the values from 6/15 to 11/15 Lf.

Blood Collection and Analyses. During the loading session, blood samples were drawn from the antecubital vein for the determination of serum total and free testosterone, cortisol, and growth-hormone concentrations before, immediately after (post), and 15 (post-15 min) and 30 minutes (post-30 min) after the loadings. Fingertip blood samples were drawn for the determination of blood lactate. Two blood samples were also drawn within ½ hour without exercise during the control day at the same time of day that each subject would later undertake his heavy-resistance loading protocols. Fasting blood samples were obtained at 3-month intervals throughout the experimental period in the mornings at 0730–0830 hours, before the acute heavy-resistance loadings, as well as on the first and second mornings after the loadings for the determination of basal serum testosterone, free testosterone, and cortisol concentrations.

Serum samples for the hormonal analyses were kept frozen at −20° C until assayed. Serum testosterone concentrations were measured by the Chiron Diagnostics ACS:180 automated chemiluminescene system using ACS:180 analyzer (Medfield, MA). The sensitivity of the testosterone assay was 0.42 nmol·L^{-}, and the intraassay coefficient of variation was 6.7%. The concentrations of serum free testosterone were measured by radioimmunoassays using kits from Diagnostic Products Corp. (Los Angeles, CA). 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 Farmos Diagnostica (Turku, Finland). The sensitivity of the cortisol assay was 0.05 nmol·L^{-}, and the intraassay 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 intraassay coefficient of variation was 2.5–5%. All the assays were carried out according to the instructions of the manufacturers. 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, Mannheim, Germany).

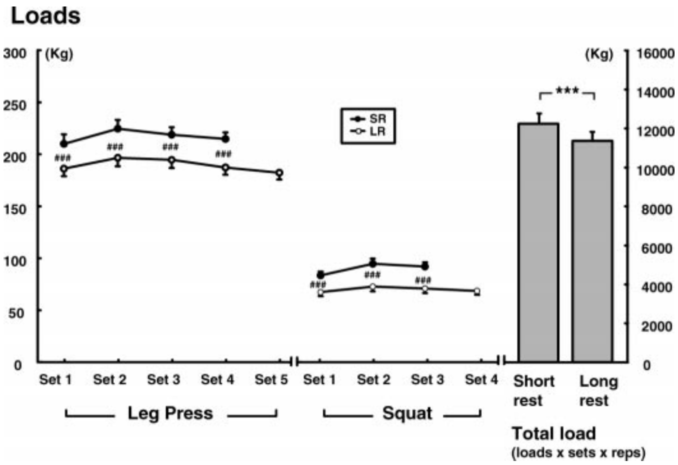

Figure 2. The loads in the short rest (SR) and long rest (LR) (mean ± *SE*) in the group 1 + 2 before the 6-month experimental training period. * = significantly different (* = $p < 0.05$, ** = $p < 0.01$) from set 2 value of each exercise. # = statistically significant difference (### = $p < 0.001$) between the SR and LR loadings.

Anthropometry. The percentage of body fat was estimated by measuring skinfold thickness at 4 different sites according to Durnin and Rahaman (3).

Dietary Analysis. Dietary intake was obtained from a food diary and analyzed (Nutrica 3.11; Kansaneläkelaitos, Helsinki, Finland) during a 3-day period before the heavy-resistance loading sessions. Subjects were encouraged to eat similar diets, which resulted in similar caloric and nutrient intakes throughout the experimental training period.

Statistical Analyses

Standard statistical methods were used for the calculation of means, *SD*, *SE*, and Pearson product moment correlation coefficients. The changes in the variables over time from the prelevel 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 $p \leq 0.05$ criterion was used for establishing statistical significance.

Results

Heavy-Resistance Loadings

Loads and Neuromuscular Responses. The total volumes of the work (loads × sets × reps) was 7.5 ± 3.5% ($p < 0.001$) greater in the SR (12,235 ±1,770 kg) than in the LR loading (11,362 ± 1,459 kg) at month 0 (Figure 2) and

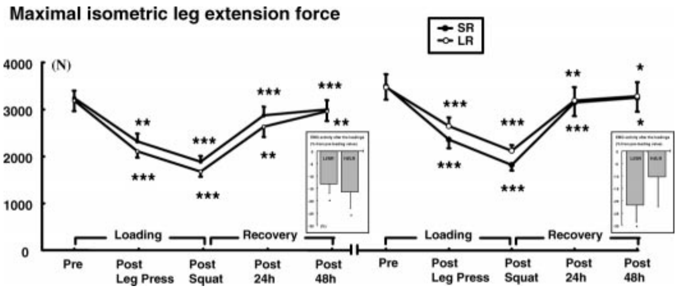

FIGURE 3. Maximal voluntary isometric leg extension force (mean ± *SE*) before, during, and after the short rest (SR) and long rest (LR) loadings before the experimental training period. In the inner figure, maximal integrated electromyographic activity (mean ± *SE*) during the isometric muscle action after the SR and LR loadings (percentage from preloading value). * = significantly different (* = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$) from the corresponding pre-exercise value.

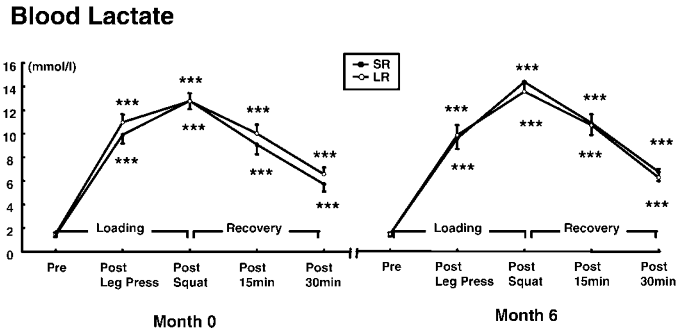

FIGURE 4. Blood lactate concentrations (mean ± *SE*) before, during, and after the short rest (SR) and long rest (LR) loadings before the experimental training period. * = significantly different (*** = $p < 0.001$) from the corresponding pre-exercise value.

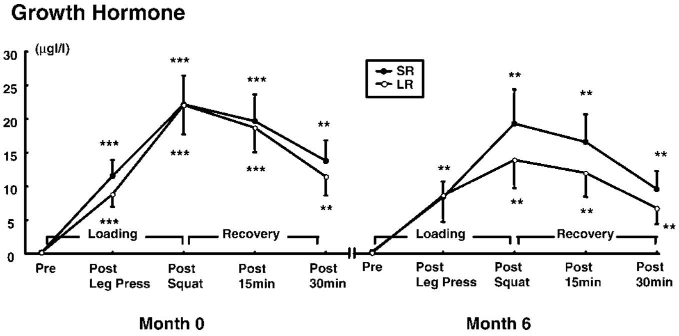

FIGURE 5. Serum growth hormone concentrations (mean ± *SE*) before, during, and after the short rest (SR) and long rest (LR) acute heavy-resistance loadings before and after the 6-month experimental training period. * = significantly different (** = $p < 0.01$, *** = $p < 0.001$) from the corresponding pre-exercise value.

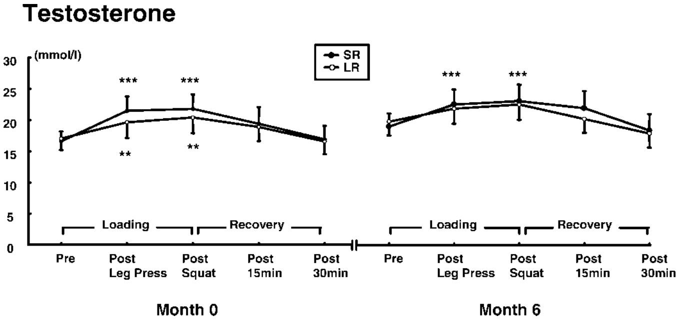

FIGURE 6. Serum testosterone concentrations (mean ± *SE*) before, during, and after the short rest (SR) and long rest (LR) acute heavy-resistance loadings before and after the 6-month experimental strength-training period. * = significantly different (** = $p < 0.01$; *** = $p < 0.001$) from the corresponding pre-exercise value.

increased up to 15,500 ± 2,141 kg ($p < 0.01$) and 143,17 ± 1,736kg ($p < 0.01$) in the SR and LR loadings after the 6-month strength training, respectively. The loads in the leg press sets were 14% ($p < 0.001$) and in the squat sets 30% ($p < 0.001$) higher in the LR than in the SR loading at month 0. The subjects needed assistance in 3.2% (199 out of 6240) of all repetitions performed during the LR loadings at 0-, 3-, and 6-month loading sessions.

No statistically significant differences were observed in the maximal bilateral isometric leg extension force between the SR and LR loading sessions at the 0-, 3-, or 6-month measurements. Large acute decreases of 36% (from 3,242 ± 566 N to 1,888 ± 445 N, $p < 0.001$) and 35% (from 3,188 ± 809 N to 1,674 ± 380 N, $p < 0.001$) occurred in maximal isometric force at month 0 after the SR and LR loadings, respectively (Figure 3). The relative decreases of maximal isometric force after the loadings remained the same during the 6-month training period. Maximal isometric force recovered, but remained lowered during the 48-hour recovery period after both loading protocols. The EMG activity of the VL and VM muscles during the isometric action decreased by 13 ± 14% ($p < 0.05$) and 17 ± 24% ($p < 0.05$) after the SR and LR loading protocols, respectively, with no differences between the protocols. The relative decreases also remained the same during the loadings at month 6. Blood-lactate concentrations increased up to 12.8 ± 3.1 $\text{mmol}\cdot\text{L}^{-}$ ($p < 0.001$) after both loading protocols, with no significant differences between the loadings at month 0 (Figure 4). This was also true at month 6.

Acute Hormonal Responses

No significant changes were observed in serum hormone concentrations between the 2 control blood samples drawn within ½ hour without exercise during the control day. Serum GH, testosterone, free testosterone, and cortisol concentrations increased ($p < 0.05$–0.001) after the loadings both before and after the experimental training period, except for testosterone concentrations in the LR loading at month 6 (Figures 5–8). No statistically significant differences were observed in the acute hormone responses between the loading sessions at 0-, 3-, or 6-month measurements. The relative changes in the integrated area under the curve (AUC) analysis in acute testosterone and free testosterone responses in the SR loadings during the first 3-month training period and the changes in muscle CSA of the quadriceps femoris correlated with each other ($r = 0.63$, $p < 0.05$ and 0.74, $p < 0.01$, respectively) in the total group of subjects. A trend toward attenuated hormone responses was observed independently of the training type during the 6-month experimental training period, especially in the LR protocol. There were no sta-

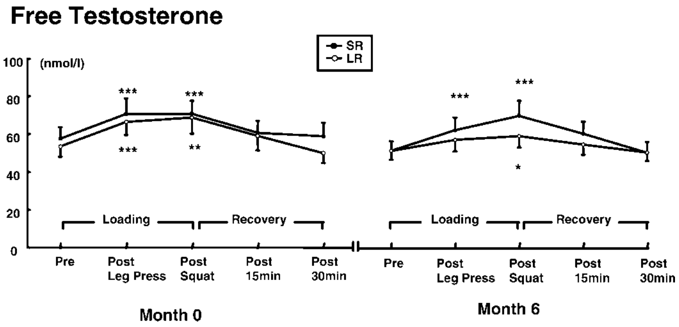

Figure 7. Serum free testosterone concentrations (mean ± *SE*) before, during, and after the short rest (SR) and long rest (LR) acute heavy-resistance loadings before and after the 6-month experimental strength-training period. * = significantly different (** = $p < 0.01$; *** = $p < 0.001$) from the corresponding pre-exercise value.

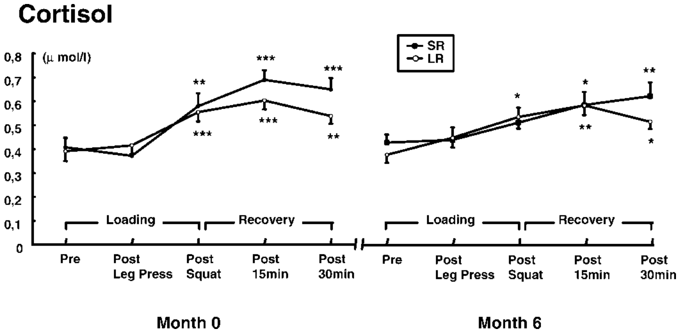

Figure 8. Serum-cortisol concentrations (mean ± *SE*) before, during, and after the short rest (SR) and long rest (LR) acute heavy-resistance loadings before and after the 6-month experimental strength-training period. * = significantly different (** = $p < 0.01$; *** = $p < 0.001$) from corresponding pre-exercise value.

tistically significant changes in the basal total testosterone, free testosterone, or cortisol concentrations at the first and second morning after the loading protocols or between the loading protocols at months 0 and 6 except for testosterone, at the second morning after the SR loading at month 6 (Table 1).

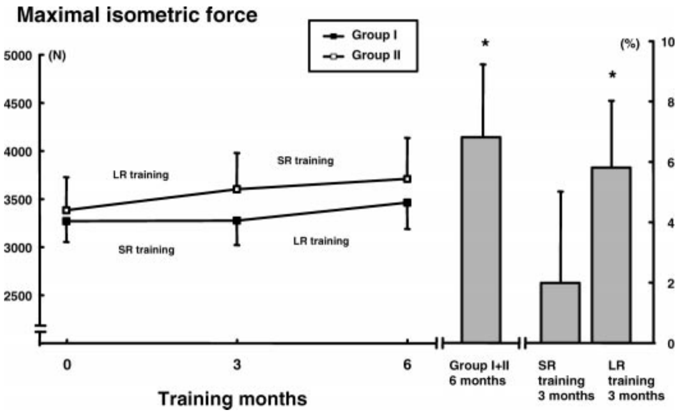

Figure 9. Changes (mean ± *SE*) in maximal isometric force during the experimental 6-month strength-training period in both groups and the relative changes (mean ± *SD*) after the short rest (SR) and long rest (LR) training periods. * = significantly different (* = $p < 0.05$) from the corresponding pre-training value.

Follow-Up Measurements

Anthropometry. No significant changes took place in the body mass (from 83.9 ± 11.7 kg to 84.6 ± 12.9 kg) or body fat percentage (from 14.8 ± 3.9% to 15.3 ± 3.6%) during the 6-month experimental training period in the total group of subjects.

Strength Training. The training for the quadriceps femoris muscles included squat, leg press, and/or knee extension exercises. Six out of 13 subjects kept the training diary throughout the 6-month experimental training period. There were no statistically significant differences in the total training load (7,065 ± 2,180 kg and 7,043 ± 2,208 kg) for the quadriceps femoris per exercise between the SR and LR training periods, respectively.

Maximal Bilateral Isometric Leg Extension Force. During the 6-month training period, a significant increase of 6.8 ± 8.7% (from 3,370 ± 748 to 3,613 ± 949 N) ($p < 0.05$) was recorded in the maximal isometric leg extension force in the total group of subjects (Figure 9). During the 3-month SR training period, maximal isometric force increased by 2.0 ± 10.9% (not significant) and during the

Table 1. Basal hormone concentrations (mean ± *SD*) on the first and second mornings after the loadings at month 0 and 6.

Month	Control day morning (−1 week)		First morning after the loading	Second morning after the loading
0				
Testosterone (nmol·L^{-1})	23.9 ± 9.7	SR	23.8 ± 9.4	21.4 ± 7.9
		LR	23.5 ± 8.4	22.9 ± 8.8
Free testosterone (pmol·L^{-1})	74.8 ± 21.7	SR	80.5 ± 25.4	73.0 ± 27.5
		LR	71.7 ± 21.1	70.7 ± 25.6
Cortisol (µmol·L^{-1})	0.51 ± 0.16	SR	0.44 ± 0.21	0.41 ± 0.21
		LR	0.44 ± 0.17	0.45 ± 0.18
6				
Testosterone (nmol·L^{-1})	22.0 ± 8.9	SR	23.4 ± 7.1	25.4 ± 7.5*
		LR	24.3 ± 7.5	26.4 ± 7.1
Free testosterone (pmol·L^{-1})	68.8 ± 24.6	SR	70.6 ± 21.5	70.0 ± 23.7
		LR	64.6 ± 18.4	71.6 ± 24.3
Cortisol (µmol·L^{-1})	0.55 ± 0.19	SR	0.50 ± 0.12	0.50 ± 0.11
		LR	0.46 ± 0.12	0.52 ± 0.14

*Significantly different ($p < 0.05$) from the control day morning value. (SR = short rest; LR = long rest).

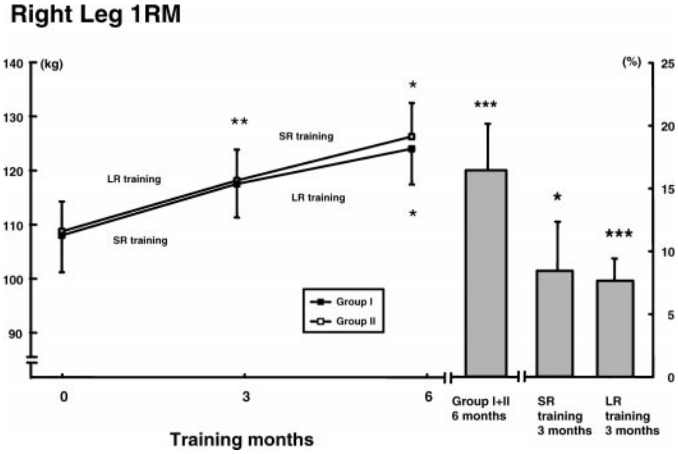

FIGURE 10. Changes (mean ± *SE*) in right leg 1RM during the experimental 6-month strength-training period in both groups and the relative changes (mean ± *SD*) after the short rest (SR) and long rest (LR) training periods. * = significantly different (* = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$) from the corresponding pre-training value.

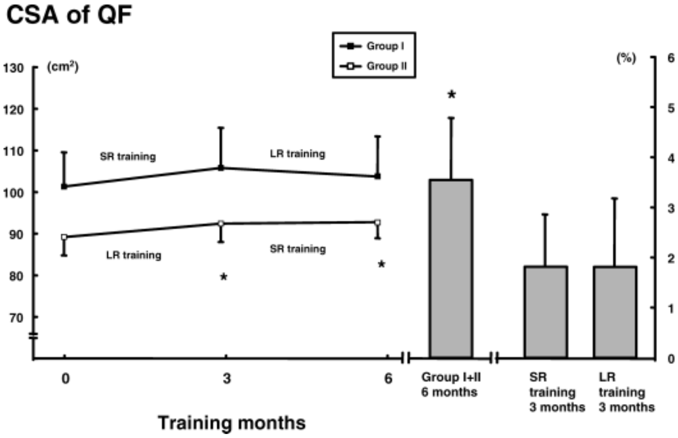

FIGURE 11. Changes (mean ± *SE*) in the cross-sectional area of the quadriceps femoris during the experimental 6-month strength-training period in both groups and the relative changes (mean ± *SD*) after the short rest (SR) and long rest (LR) training periods. * = significantly different (* = $p < 0.05$) from the corresponding pretraining value.

3-month LR training period by 5.8 ± 8.0% ($p < 0.05$), with no significant differences between the training protocols.

Unilateral 1RM Right Leg Extension. During the 6-month training period, a significant increase of 16.4 ± 13.3% (from 108.5 ± 14.8 to 125.4 ± 16.0 kg) ($p < 0.01$) took place in the 1RM load in the total group of subjects (Figure 10). During the 3-month SR training period, maximal isometric force increased by 8.4 ± 13.9% ($p < 0.05$) and during the LR by 7.7 ± 6.4% ($p < 0.001$), with no significant differences between the training protocols.

Muscle CSA. The CSA of the quadriceps femoris (mean of 6/15 to 11/15 Lfs) increased by 3.5 ± 4.3% (from 9,139 ± 1,238 to 9,448 ± 1,257 mm^2) ($p < 0.05$) during the experimental 6-month training period in the total group of subjects (Figure 11). The muscle CSA increased by 1.8 ± 4.7% (not significant) and 1.8 ± 3.6% (not significant) during the 3-month SR and LR training periods, respectively. The relative changes in maximal isometric force and the relative changes in muscle CSA correlated with each other ($r = 0.69$, $p < 0.05$) during the experimental 6-month training period in the total group of subjects.

Basal Hormone Concentrations. No statistically significant changes were observed in serum basal testosterone, free testosterone, or cortisol concentrations or in the testosterone-to-cortisol ratio during the 6-month strength-training period (Table 2).

Dietary Analysis. No statistically significant changes were observed in total energy consumption or macronutrient intake during the experimental training period (Table 3). The relative changes in total energy consumed and relative changes in the quadriceps femoris cross-sectional area correlated between each other ($r = 0.65$, $p < 0.05$) during the 6-month strength-training period in the total group of subjects.

DISCUSSION

Hypertrophic heavy-resistance exercise is known to induce the greatest acute hormone responses when per-

TABLE 2. Basal hormone concentrations (mean ± *SD*) during the 6-month experimental training period.

	Month		
	0	3	6
Testosterone (nmol·L^{-1})	23.9 ± 9.7	27.3 ± 8.2	22.9 ± 8.8
Free testosterone (pmol·L^{-1})	74.8 ± 21.7	81.3 ± 20.9	69.3 ± 23.3
Cortisol (μmol·L^{-1})	0.51 ± 0.16	0.54 ± 0.21	0.54 ± 0.18

TABLE 3. Total energy and macronutrient intake per day (mean of 3 days before the short-rest loading session) during the experimental training period ($n = 12$).

	Month		
	0	3	6
Total energy (kJ)	10,551 ± 2,012	11,100 ± 2,226	10,010 ± 1,728
Protein (%)	21 ± 7	22 ± 8	22 ± 8
Fat (%)	28 ± 9	26 ± 5	27 ± 7
Carbohydrate (%)	50 ± 12	51 ± 7	48 ± 8
Protein intake/body weight (g·kg^{-1})	1.6 ± 0.7	1.8 ± 0.7	1.7 ± 0.8
Carbohydrate intake/body weight (g·kg^{-1})	3.7 ± 0.6	3.8 ± 0.9	3.5 ± 1.1

formed by multiple sets per exercise (e.g., 3–5 sets) with short rest periods (e.g., 60–120 seconds) between the sets and with a moderately high number of (e.g., 8–12RM) repetitions per set (e.g., 12, 19, 20). Some previous data also suggest that the magnitude and/or duration of the acute hormone responses might be in relationship with the gains in muscle mass or strength during strength training (1, 15, 18). The role of the acute hormone responses becomes important because anabolic hormones, e.g., testosterone (4) and growth hormone (7), increase protein synthesis in muscle cells. Therefore, exercise-induced stimulation of the endocrine system may be a trigger for adaptation processes in skeletal muscle cells, leading to increases of the contractile proteins. Heavy-resistance exercise also induces acute neuromuscular responses observed as temporary decreases in maximal force production and EMG activity of the loaded muscles associated with increases in blood-lactate concentrations. The acute decreases in maximal isometric force and EMG activity were rather similar in magnitude after the hypertrophic-resistance exercise performed with the 10RM protocol for 10 sets (10) as compared with the respective acute decreases after the neural high-loading 1RM protocol of 20 sets (12). However, the acute hormonal responses (e.g., GH) were drastically greater after the 10RM loading protocol with only minor hormonal responses observed after the 1RM protocol. Therefore, the data of these previous studies suggest that the training mode seems to have a critical influence on the magnitude and/or duration of acute hormonal responses.

In the present study, recreationally strength-trained young men performed 2 typical hypertrophic strength-training protocols, similar with regard to the total volume but differing in terms of the length of recovery between the sets for the leg muscles: a high intensity with shorter rest periods between the sets (SR), and a somewhat higher intensity with the longer rest periods between the sets (LR). It was hypothesized that these 2 heavy-resistance–exercise protocols would lead to significantly different acute hormonal responses due to different metabolic demands of the exercises. Consequently, we hypothesized that long-term adaptations to hypertrophic strength training would also differ to some extent when training with the SR compared with LR protocol.

The present loadings were designed to be as similar as possible to those used in practice in strength training among experienced strength athletes, such as bodybuilders, to gain muscle mass and strength. The acute loading sessions were also planned to be comparable so that the total volume, expressed by the multiplication of load, sets, and repetitions, in both protocols would be as identical as possible. The present data showed that, as planned, significantly greater absolute loads in all sets were performed during the higher-intensity loading protocol before the experimental training period (Figure 2). There was a statistically significant, but only slight, difference of 7% in the total volume between the loadings. Although this difference can be considered physiologically rather minor, it cannot be totally excluded, but this might not have had any influences on the physiological responses measured.

The exercise protocols performed at month 0 led to significant acute decreases in maximal isometric force with no differences between the 2 loadings (Figure 3). Isometric force decreased down to 54 and 59% of the preloading maximum after the SR and LR loadings, respectively. The maximal isometric force had not recovered completely after 2 days of rest after the loadings. The EMG activity of the loaded muscles also decreased after both protocols. Blood-lactate concentrations increased up to about 13 $\text{mmol}\cdot\text{L}^{-1}$ during both protocols, with no significant differences between the protocols (Figure 4). The present 2 loading protocols led to surprisingly similar blood-lactate responses. The present results indicate that for young men who are experienced in strength training, even the 5-minute rest periods between the sets may not be sufficient time to recuperate between the multiple 10RM sets for the large muscle groups, such as leg muscles. We were able to collect heart-rate data from a subgroup of subjects ($n = 9$, data not shown). As expected, heart rate during the recovery periods between the sets were significantly greater ($p < 0.05$–0.001) in the SR than in the LR loading, suggesting a greater metabolic demand in the SR compared with the LR loading.

Contrary to our hypothesis, we did not find any statistically significant differences in the acute hormonal responses between the 2 loading protocols before the experimental training period. Both loading protocols led to significant acute increases in serum total and free testosterone concentrations. However, the acute testosterone responses were very similar, with no statistically significant differences between the present loadings. Both protocols led also to large acute increases of similar magnitude in serum growth-hormone concentrations. The 3 loading protocols led also to acute increases in serum-cortisol concentrations. However, the acute response was slightly greater after the SR loading. Nevertheless, these results indicate that there were no systematic differences in the physiological variables measured between the SR and LR loadings at month 0.

Because no systematic differences were observed in the acute hormonal or neuromuscular responses between the present hypertrophic-loading protocols, the results indicate that a lower-intensity protocol with shorter rest periods between the sets seems to produce similar acute hormonal responses to a protocol performed with a higher intensity with longer rest periods between the sets, when typical hypertrophic sets of 10RM are used. Although the present study examined only these 2 protocols, the results suggest that the length of the rest periods between the sets and the number of sets may not have an influence on acute exercise responses. This seems to be true at least in young strength-trained men, if several sets are performed, and if the training intensity of the exercise is kept high, as in the present study. In the previous studies of Kraemer et al. (19, 20, 22), the short rest between the sets (1 minute) elicited greater anabolic hormone responses than that of longer rest periods between the sets (3 minutes). Contrary to the present study, those studies included recreationally strength-trained men as well as women and the experimental loading protocol was carried out with a total of 24 sets of exercises to all muscle groups of the body. Whether the shorter rest periods between the sets (i.e., 60 seconds) would produce different acute hormonal responses compared with the exercise protocols used in the present study remains unanswered. However, the data of the present study indicate that various modifications of hypertrophic protocols with a sufficient volume and within high-intensity levels, such as the 10RM protocol, can lead to large acute hormonal and neuromuscular responses. It could be hypothesized that after the certain threshold level in the hypertrophic training stimuli, the length of the rest periods between the sets and number of sets would not make a systematic contribution to the magnitude of acute hormonal and neuromuscular responses. In the LR loading, assistance was given to the subject if he could not complete the 10RM set. This may have influenced the acute hormonal responses, because the forced repetitions protocol may increase the acute hormone responses (2). However, assistance was given only occasionally, when necessary, and not systematically during the study.

Adaptation of the human body to prolonged strength training takes place by various neuromuscular and hormonal mechanisms. Neural factors are important for increases in muscle strength, especially in earlier phases of strength training, while the changes in the muscle mass also contribute to strength development during prolonged strength training (11, 30). It is well known that the progressive increase and the modifications in the training intensity, volume, and frequency are the only way to manipulate the training load over several years of strength training for further increases in muscle mass and strength. While it is not possible endlessly to increase the training volume, frequency, or intensity, periodic changes in these training variables, such as used, e.g., in periodizing, become important for optimal training stimulus (6, 32).

In addition to acute hormonal and neuromuscular responses, the present study was also designed to examine long-term hormonal and neuromuscular adaptations to 2 hypertrophic training protocols that differed mainly by the training intensity and length of the rest periods between the sets, while the total volume between the training protocols was as similar as possible. The similarities observed in the acute hormonal and neuromuscular responses in both our exercise protocols before the experimental training period would not necessary mean that the present exercise protocols would lead to similar muscle strength or mass increases during long-term training. It cannot be totally excluded that the previous training protocols used by these subjects before the present study may have had some influence on the gains in muscle mass and strength recorded during the study period. However, the subjects were experienced strength trainers and the present 2 training periods were as long as 3 months. The maximal bilateral isometric leg extension force and the right leg 1RM increased throughout the 6-month experimental strength-training period, with no significant differences between training groups 1 and 2 or between the training protocols (Figures 9 and 10). The quadriceps femoris CSA increased during the first 3-month training period, but no further increase in the CSA was observable during the latter training period from 3 to 6 months. When comparing the training periods independently, the present study showed no differences in the changes in the maximal isometric force, right leg 1RM, or CSA of the quadriceps femoris between the 2 training protocols during the 3-month training periods. During the SR training, maximal isometric force increased only slightly, but during the LR training, the increase in maximal isometric force was statistically significant. Although the relative increase in the 1RM strength was similar in magnitude, the increase in the LR training was more systematic than in the SR training. Therefore, the results of the present study suggest that LR training may create more optimal training stimuli for maximal strength development than SR training.

The significant acute total testosterone, free testosterone, cortisol, and growth-hormone responses were observable in both loading protocols at months 0, 3, and 6 (except for the total testosterone response at month 6). In general, a trend of attenuated acute hormone responses was observed during the 6-month training period. Similar findings have been reported, especially in the acute GH and cortisol responses, due to prolonged strength training in previously untrained young men (21, 31) and in male strength athletes (1). In the present study, the decreased acute hormonal responses seemed to be slightly greater in the LR than in the SR loading after the 6-month experimental training period. If the magnitude of acute hormone responses is expected to be crucial for optimal adaptation to strength training, the results of the present study suggest that the LR exercise protocol in long-term training may create less favorable conditions for gains in muscle mass. However, there were no statistically significant differences in the development of the muscle mass between the 2 training protocols.

Interestingly, in the present study, significant relationships were observed between the increases of the acute testosterone and free testosterone responses and the increase in the muscle CSA of the quadriceps femoris in the SR loadings during the first 3-month training period when both experimental groups were combined. Our previous study (1) supports this finding, when the increase in the acute testosterone response correlated with the increases in the muscle CSA of the quadriceps femoris in previously untrained men during the 6-month training period. Because testosterone can stimulate protein synthesis after resistance exercise (34), these findings suggest that the increase in acute testosterone response after the heavy-resistance loadings due to prolonged strength training may be an important factor for training-induced muscle hypertrophy.

It could be speculated that the hormone system adapted to the present systematic hypertrophic strength training by diminishing the acute hormonal responses. This could be due to the decreased stress response and/or decreased hormone production. It may be necessary, e.g., to increase exercise volume to some extent to achieve similar acute hormonal responses after the 6-month strength-training period than in the beginning of the training period. However, it is also possible that subjects of the present study were slightly overreached due to several months of very strenuous strength training. Actually, our subjects reported some difficulties in carrying out intensive resistance exercises as planned in the training program. Therefore, it could be speculated that the attenuated acute hormone responses could be, at least in part, consequences of too-intensive strength training for too long a training period. However, there were no signs of systematic decrements in maximal muscle strength during the study. Moreover, basal testosterone, free testosterone, and cortisol concentrations did not change during the 6-month training period to indicate a possible overtraining condition. However, the exact time course of the decrements in muscle strength and the changes in basal hormone concentrations during long-term overtraining are not well known. It is possible that a trend toward a decreased acute hormone response observed in the present subjects may be a preliminary sign of an overtraining condition.

The nourishment of the present subjects was close to the Scandinavian countries dietary recommendations, except for the relative carbohydrates intake of total energy consumption, which was somewhat lower, and protein intake greater than the recommendations (28). Therefore, one could assume that total protein intake of the subjects (approximately 1.7 g·kg^{-1} body weight) was adequate for the present strength training (25, 33). Interestingly, the relative changes in the total energy consumption and relative changes in the CSA of the quadriceps femoris correlated between each other during the 6-month experimental training period. This is in line with a suggestion that, when the individual protein requirements are met, energy content of the diet has the largest effect on the changes of body composition (29). Therefore, the results of the present study suggest the importance of the sufficient total caloric intake as the requirement for the training-induced muscle hypertrophy.

In conclusion, the present study shows that the present hypertrophic SR and LR protocols induced similar acute hormonal and neuromuscular responses and that the length of the recovery times (i.e., 2 and 5 minutes) between the sets did not influence the magnitude of these responses. The results of the present study suggest that there may be several different ways to create exercise conditions leading to large acute hormonal responses, at least when several sets within the hypertophic loading intensity such as the 10RM are performed. The present study also shows that long-term training adaptations in muscle strength and mass did not differ between the 2 hypertrophic strength-training protocols examined in the group of young men with a background in strength training. Nevertheless, the results of the present study further suggest that strength training induced changes in the acute total and free testosterone responses after the heavy-resistance exercise may contribute to muscle hypertrophy of the trained muscles.

Practical Applications

The present study shows that, in hypertrophic heavy-resistance exercise, the 2- vs. 5-minute length of the rest periods between the sets did not lead to systematic differences in the acute exercise-induced metabolic, hormonal, or neuromuscular responses. Furthermore, training-induced adaptations over the 3-month period in muscle mass and strength were similar in magnitude in both the short- and long-rest protocols. Therefore, the length of the rest periods between the sets may not be a crucial factor in hypertrophic types of training protocols as long as muscles are overloaded with several sets to the concentric failure. In practice, the present study suggests that, in hypertrophic exercise, large exercise stimulus could be attained either with multiple training sets with short rest periods between the sets or with somewhat fewer sets with longer recovery period between the sets but with somewhat higher intensity. Therefore, it could be hypothesized that there is a certain kind of threshold of work to be performed in order to create exercise-induced physiological responses and that there may be various training protocols to stimulate the muscles to lead to increased muscle mass and strength during long-term strength training. However, the gains in muscle mass and strength in already-trained men take time (several months), and it may be important to design training programs systematically so that muscles will be exposed to various kinds of training stimuli of sufficient intensity and volume.

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Acknowledgments

This study was supported in part by a grant from the Ministry of Education, Finland.

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