Strength Athletes Are Capable to Produce Greater Muscle Activation and Neural Fatigue During High-Intensity Resistance Exercise Than Nonathletes

Juha P. Ahtiainen and Keljo Häkkinen

Department of Biology of Physical Activity and Neuromuscular Research Center, University of Jyväskylä, Jyväskylä, Finland

Abstract

Ahtiainen, JP and Häkkinen, K. Strength athletes are capable to produce greater muscle activation and neural fatigue during high-intensity resistance exercise than nonathletes. J Strength Cond Res 23(4): 1129–1134, 2009—Acute neuromuscular responses to maximum versus forced repetition (FR) knee extension resistance exercises (4 sets of 12 repetitions [reps] with a 2-minute recovery between the sets) were examined in 4 male strength athletes (SAs) and 4 nonathletes. Maximum repetition (MR) sets were performed to voluntary exhaustion (12 repetition maximum [RM]), whereas in the FR sets, the load was greater (8RM) and the set was continued after voluntary fatigue with 4 additional assisted reps. Maximal isometric force and electromyogram (EMG) activity of the knee extensors were measured before and after the exercise, as well as 2 recovery days after the exercise. Electromyogram activity was also measured during the actual concentric phases of the knee extensions. Both loading protocols in both groups led to decreases in isometric force, but no significant changes were observed in EMG activity during isometric actions at any time points. However, the difference between the 2 loading protocols and experimental groups was observed in muscle activity during the concentric phases of the knee extensions. As expected, EMG activity increased in both groups throughout the MR sets when compared with the first repetitions of the sets. Only in SAs, EMG activity decreased significantly at the end of the FR sets. The results suggest that experienced SAs were capable to activate their muscles to a greater extent than their non–strength-trained counterparts indicated by neural fatigue during the FR exercise. Greater motor unit activation in SAs than in nonathletes may be due to training-induced neural adaptation, which manifested during fatiguing exercise. The present study suggests that FRs are an efficient training protocol to overload the neuromuscular system especially in SAs.

Keywords: EMG, knee extension, isometric force, recovery

Introduction

Training programs are highly specific to the types of adaptation. For maximizing muscle hypertrophy, it typically recommended multiple-set programs with loads corresponding to 8 to 12 repetition maximum (RM) using 1- to 2-minute rest periods between sets at a moderate contraction velocity (21). To gain muscle mass and strength during resistance training, it is also commonly recommended to perform exercise sets to momentary concentric failure. Especially experienced strength athletes (SAs) who are already well adapted to resistance training may need high exercise intensity to promote further development in muscle strength and size. Exercise intensity in hypertrophic resistance training can be increased by using different kinds of exercise systems. One such system is called “forced repetitions (FRs).” After performing a set to exhaustion, a training partner would provide enough assistance to aid the lifter through a weaker range of movement to continue the set for a few additional repetitions (=FRs). When used properly, it is an extremely intense method of training. 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 (11). However, no scientific data have been published to support this suggestion. Changes in surface electromyogram (EMG) signal amplitude are often used as a practical indicator to estimate exercise- or training-induced changes in total efferent neural drive to working muscle, attributed by the alteration in motor unit activation patterns (1,9,22,15,16,13,14). To get information of immediate and short-term responses of FR resistance exercise on the neuromuscular system, we examined muscle activation...
during and after the exercise performed with FRs in comparison to that of the maximum repetition (MR) exercise in strength-trained and strength-untrained men. Based on the previous studies (1,9,22,15,16), we hypothesize that FR loading induces greater neuromuscular fatigue than traditional maximum repetition loading, and the responses are greater in SAs than in nonathletes.

**METHODS**

**Experimental Approach to the Problem**

The experimental design comprised MR and FR loading sessions separated by 2 weeks and performed in a randomized order. In addition, recovery of maximal isometric force after the loadings was examined for 2 days after both loadings. All measurements were performed at the same time of day. Single-joint knee extension exercise was used to study isolated quadriceps femoris activation during the loadings. The aim of the present study was to examine hypertrophic resistance exercise in which the FR training system is primarily used and, therefore, submaximal 12 repetitions (reps) per set were used in the experimental loadings. The subjects were instructed to eat their normal but similar diets before both loading sessions. Strenuous exercises were not allowed during 2 preceding days of the loading sessions and during recovery days after the loadings.

Maximum repetition included 4 sets of bilateral knee extensions with a 2-minute recovery between the sets. The exercise was performed with the maximum load possible to achieve 12 repetitions (12RM) in each set. In FR, the loading protocol was same as in MR, but the initial load was set higher than in MR so that the subject could lift approximately 8 reps by himself and 4 additional reps with assistance. The assistant was the same researcher in all measurements. The assistance was applied only during the concentric phases of the exercise without affecting the rate of the exercise. The experimental exercises were performed with variable load knee extension exercise machine (David 200; David Fitness and Medical, Vantaa, Finland) with a full range of movement allowed by the machine from a knee angle of approximately 60° to a fully extended knee angle (180°). The range of movement was controlled by a light signal.

**Subjects**

Four male strength athletes (SAs) and 4 physically active but non-athletes (NAs) volunteered as subjects (Table 1). To increase validity of the present study, only experienced high-level competitive powerlifters and weightlifters were accepted to the experimental group of SAs, whereas nonathletes had no experience in resistance training. No medication was taken by the subjects, which would have been expected to affect physical performance. Each subject was informed of the potential risks and discomforts associated with the investigation, and all the subjects gave their written informed consent to participate. The Ethics Committee of the University of Jyväskylä approved the study.

| Table 1. Descriptive characteristics of subjects (mean ± SD).†‡ |
|----------------|----------------|
|                | SA (n = 4)     | NA (n = 4) |
| Age (y)        | 32 ± 7         | 27 ± 4     |
| Height (cm)    | 175 ± 4        | 182 ± 5    |
| Weight (kg)    | 87.7 ± 12.0    | 80.0 ± 4.2 |
| Fat (%)        | 13.3 ± 3.6     | 16.8 ± 5.1 |
| LBM (kg)       | 75.8 ± 7.9     | 66.7 ± 6.5 |
| Thigh circumference (cm) | 55.6 ± 2.7* | 50.7 ± 2.9 |
| Weight training experience (y) | 17.3 ± 8.5 | n.a.       |
| Squat (kg)     | 220 ± 45       | n.a.       |
| Bench press (kg) | 160 ± 18    | n.a.       |

†‡ Statistically significant difference (*p < 0.05) between the experimental groups.

**Procedures**

The subjects were familiarized with the experimental testing procedures on the control day 1 week before the actual measurements. Anthropometrical measurements and resistance load verifications for the experimental exercise were also determined for each subject at this time. Training years and squat and bench press 1RM were reported by the SAs. The circumference of the middle thigh was determined by tape measures. The percentage of body fat was estimated from the measurements of skinfold thickness (10).

**Neuromuscular Measurements.** The David 200 apparatus used in the loadings was also modified with the dynamometer for strength testing. Maximal voluntary isometric torque of the bilateral knee extensor action was measured with a knee angle of 107° before and after the loadings and 24 and 48 hours after the loadings. The measurements during the recovery days were done at the corresponding time of the day as the subject performed the heavy resistance loading protocols. The force dynamometer was used to measure the accurate force produced by the subject against to the foot support while he was extending the knees. The lever arm was adjusted individually for each subject. On verbal command, the subject performed a maximum isometric knee extension. The subjects were instructed to exert their maximal force as fast as possible during a period of 3 to 4 seconds. A minimum of 3 maximal actions were recorded except immediately after the loadings, when 2 maximal isometric actions were measured within 45 seconds after the preceding exercise bout. The best maximum was used for the subsequent statistical analysis. The force signal was recorded on a computer and thereafter digitized and analyzed with a CODAS computer system (Dataq Instruments, Inc., Akron, OH). Maximal peak force was defined as the highest value of
force (N) recorded during the bilateral isometric knee extension (N). The force-time analysis on the absolute scale included the calculation of average force (N) produced during the first 500 milliseconds from the start of the contraction. Maximal rate of isometric force development (RFD) (N s⁻¹) was also analyzed and defined as the greatest increase in force in a given 50-millisecond period (16).

Surface EMG activity was recorded from the agonist muscles’ vastus lateralis (VL), vastus medialis (VM), and rectus femoris (RF) of the right leg. Bipolar surface electrodes (Beckman miniature-sized skin electrodes 650437; Beckman Coulter, Inc., Fullerton, CA) 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; Siemens). 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. Electromyogram signals were recorded telemetrically (Glonner Biomes 2000; Glonner Electronic, Munich, Germany) and stored on a magnetic tape (Recall 16; Recall-Thermionic, Hythe, UK) and to the computer with a CODAS computer system. Electromyogram signal was amplified (by a multiplication factor of 200, low-pass cutoff frequency of -3 dB at 360 Hz) and digitized at a sampling frequency of 1,000 Hz. Electromyogram was full-wave rectified, integrated (integrated electromyogram [iEMG] in millivolts/second), and time normalized. The activity (iEMG) of the VL, VM, and RF was averaged and analyzed in the maximal force phase (500-1,500 milliseconds) of the isometric muscle actions and during the actual concentric phases of the knee extensions of the loadings. The range of movement and duration of the concentric phases of dynamic muscle actions was measured by an electronic goniometer attached to the side of knee joint. Electronic goniometer data were also collected with the CODAS system and analyzed together with iEMG data with special software.

Blood Collection and Analyses. Fingertip blood samples were drawn for the determination of blood lactate concentration before, immediately after (post), and 15 (post 15 minutes) and 30 minutes (post 30 minutes) after the loadings. All blood samples were obtained at the same body position of the subject. Blood lactate concentrations were determined using a Lactate kit (Roche, Mannheim, Germany).

Statistical Analyses
Regardless of possible low statistical power due to the low number of the subjects in the experimental groups, standard statistical methods were used for the calculation of mean, SDs, and Pearson product moment correlation coefficients (SPSS version 15.0; SPSS Inc., Chicago, IL). Differences between the experimental groups were analyzed using Mann-Whitney U-test. When no differences were observed between SA and NA, the differences within the total group of subjects (SA + NA) were analyzed using dependent samples of t-tests. For 3 or more time points, the changes over time were analyzed using the general linear model analysis of variance with repeated measures. Intraclass correlation coefficients between premeasurements of forced and maximum loading sessions were in maximal isometric force of 0.927 and EMG activity during maximal isometric force of 0.727. The p ≤ 0.05 criterion was used for establishing statistical significance.

Figure 1. The loads in the forced repetition (FR) and maximum repetition (MR) knee extension sets (mean ± SE) in strength athletes (SA, n = 4) and nonathletes (NA, n = 4). Figure 2. Maximal bilateral isometric knee extension force and maximal integrated electromyogram (iEMG) activity (mean ± SE) during and after the maximal repetition (MR) versus forced repetition (FR) loading (% from preloading value) in strength athletes (SA, n = 4) and nonathletes (NA, n = 4). Maximal isometric force decreased significantly during the MR and FR loadings in both groups (p < 0.05–0.001).
Neuromuscular Responses to High-Intensity Resistance Exercise

**RESULTS**

**Loadings**
The average load was 23% (p < 0.001) and 9% (p < 0.05) higher in all FR sets than in MR sets in NA and SA, respectively (Figure 1). In FR sets, 79 ± 0.8 and 83 ± 1.2 reps were performed without assistance in NA and SA, respectively. The duration of the concentric phases increased gradually throughout the sets from 865 ± 125 to 1,403 ± 565 milliseconds. The average duration of the concentric phases was 975 ± 356 milliseconds in MR and 1,142 ± 441 milliseconds in FR (p < 0.001). The mean force produced by the subjects against the foot support of the exercise machine during the concentric phases of the FR did not change significantly compared with the preceding repetitions or the first repetitions of the sets (data not shown).

**Neuromuscular Responses**

**Maximal Isometric Force.** Preloading absolute maximal isometric forces were 29% (p < 0.001) larger in SA than in NA. Significant decreases (p < 0.05-0.001) occurred in isometric force after the loadings (Figure 2). The decrease in maximal isometric force was the greatest in SA for the FR loading (down to 69.5 ± 4.3% of the pre-level), although no statistical differences were observed in the isometric force data between the experimental groups. In combined SA and NA, maximal isometric force decreased 34 ± 20% (from 2,470 ± 409 to 1,867 ± 366 N, p < 0.001) in MR and 44 ± 17% (from 2,462 ± 414 to 1,723 ± 261 N, p < 0.001) in FR compared with the pre-level. The mean force during the first 500 milliseconds of the maximal isometric muscle action decreased by 27 ± 12% (from 1,367 ± 333 to 983 ± 182 N, p < 0.01) in MR and 39 ± 14% (from 1,274 ± 346 to 747 ± 141 N, p < 0.01) in FR compared with the pre-level. The decrease was greater in FR compared with MR (p < 0.05). The RFD during the maximal isometric muscle action decreased by 28 ± 23% (from 18,777 ± 7,743 to 12,504 ± 4,164 N/s, p < 0.05) in MR and 35 ± 28% (from 16,802 ± 7,585 to 9,301 ± 2,131 N/s, p < 0.05) in FR compared with the pre-level. No statistically significant differences were observed in maximal isometric force during recovery at 24 and 48 hours after the loadings compared with the pre-level or between the loading protocols.

**Electromyogram Activity.** No significant differences were observed in the changes in EMG activity during the maximal isometric action between the experimental groups or at any time points compared with pre-level (Figure 2). During the concentric phases of the knee extensions, the EMG activity (mean of all 4 sets) increased gradually (p < 0.05-0.001) in MR sets in both groups due to the submaximal load of rep 1 of the 12RM sets (Figure 3). In FR loading, the EMG activity in NA increased significantly (p < 0.05-0.001) throughout the loading up to 120.1 ± 6.7% compared with rep 1 of set 1, whereas in SA, the EMG activity increased through the first 6 reps but then decreased significantly (p < 0.01-0.001) during the last 3 reps from its highest value.

**Blood Lactate.** No statistically significant differences were observed in blood lactate concentrations between the loading protocols or experimental groups. In the total group of subjects, blood lactate concentrations increased up to 6.1 ± 1.6 mmol/L (p < 0.001) and 6.9 ± 1.4 mmol/L (p < 0.001) in MR and FR, respectively.
**DISCUSSION**

This study investigated acute neuromuscular responses and recovery during the exercise performed with the FRs in comparison to that of the MR exercise. Typically heavy resistance exercise induces acute decreases in strength and EMG of the loaded muscles. These acute responses are dependent on the type of exercise protocol, that is, number of sets and reps per set (e.g., (13,14)). The present loading protocol included multiple sets with submaximal load (12RM), but exercise sets were performed until exhaustion was achieved (i.e., a momentary concentric failure) with moderately short rest periods between the sets. Thus, the loading protocol was similar as used by SAs for training-induced muscular hypertrophy. Furthermore, the FR exercise protocol used in the present study is a special resistance training system, which is especially used by bodybuilders to increase training intensity.

Although great care needs to be exercised due to the low number of subjects used in the present study, both maximum and FR loading protocols in both experimental groups led to acute fatigue observable with decreases in maximal isometric force associated with increases in blood lactate concentrations. Furthermore, decreases in rapid force production, that is, the mean force during the first 500 milliseconds of maximal isometric muscle action, were greater in the FR loading, indicating that higher exercise intensity and, consequently, greater recruitment of fast-twitch motor units were achieved during the FR than in MR loading. Interestingly, in the present study, the EMG activity during the isometric action did not decrease after the loadings. In our previous studies, a similar loading protocol has led to the acute decrease in maximal EMG activity in isometric action, when the loading has taken place using the multijoint exercise such as leg press or squat (4,5). This finding suggests that the present isolated single-joint knee extension resistance exercise did not lead to neural (i.e., central) fatigue, but the temporary decrease in muscular performance was of peripheral origin in nature. This is supported by the present finding of increased blood lactate concentrations after the loadings in both groups. Nevertheless, the data further indicated that only SAs were capable for increased motor unit activation of the leg extensors during the actual dynamic loading, which in turn led later to a considerable neural fatigue observed by decreased EMG activity during the concentric phases of the actual dynamic fatiguing loading (Figure 3). This finding underlines the specificity of the training adaptations, which should be taken into account when choosing research or testing methods. As expected, EMG activity increased in both groups throughout the MR and FR sets, which were not observed in nonathletes. This may indicate that nonathletes are not able to voluntarily activate their muscles and achieve neural fatigue during the present loading such as SAs. Greater muscle activation due to repetition failure may lead to higher mechanical stress of muscle tissue associated with muscle cell disruption and enhanced gene expression of growth factors related to muscle growth and regenerative processes (12). Therefore, the training stimulus might be greater in SAs than in nonathletes during the same exercise. We have also previously observed statistically greater increases in EMG activity during the FR compared with MR squat exercises of 4 sets of 12 reps with strength-trained men (3). However, the changes in EMG activity during the multijoint squat exercise and differences between maximal and FR exercises were not as clear as in the present single-joint knee extension exercise possibly because of gradually increased activation of synergist muscles during the squat exercise sets.

A unique finding in the present study was that neural fatigue occurs during the loading in SAs, and it can be observed as decreased EMG activity during fatiguing high-intensity dynamic resistance exercise. There might be several explanations why especially strength-trained men were able to produce greater muscle activation during voluntary command than nonathletes and achieved neural fatigue during the present FR exercise. Strength training may cause adaptive changes within the nervous system that allow a trainee to more fully activate prime mover muscles in specific movements and to better coordinate the activation of all relevant muscles. Training-related neural adaptations that occur during long-term strength training include increased neural drive to agonist muscles, resulting in higher discharge rates of motor units (22,25,23,19). Also, improved intermuscular coordination between agonist, antagonist, and synergist muscles, which can be observed, for example, as a reduction in antagonist coactivation due to resistance training, would allow increased expression of agonist muscle force during the dynamic muscle actions and consequently greater neuromuscular fatigue (15,7). Bilateral limb deficit (i.e., the maximum force generated during simultaneous bilateral contraction is less than the sum of the forces produced by unilaterally, separately) can decrease or reverse due to resistance training, allowing greater force production during bilateral exercise movements (17,24,18). Strength-trained men may be able to activate a greater proportion of muscle tissue and to perform resistance exercise very intensively, which is associated with greater excitatory input and recruitment of fast-twitch fibers (1,6,20,8). Furthermore, it can be speculated that the changes in afferent input and the sensory receptors (i.e., Golgi tendon organs) in SAs may lead to disinhibition and an increased ability of the nervous system to appropriately activate the muscles (9,2). Some of these factors may explain the greater neural fatigue observed during the FR loading in SAs.

**PRACTICAL APPLICATIONS**

The results of the present study showed that knee extension maximum and FR loading protocols led to similar decreases in...
Neuromuscular Responses to High-Intensity Resistance Exercise

in maximal isometric force and increases in blood lactate with SAs and nonathletes. However, only SAs demonstrated considerable neural fatigue during the actual dynamic FR loading protocol. This finding suggests that the use of the FR exercise system especially in isolated single-joint exercises increases exertion of the neural system possibly due to the greater recruitment of motor units during the exercise. Therefore, resistance training with the FR exercise system may be advantageous especially for SAs when targeting muscular hypertrophy. When aiming development in maximum muscular strength or power, the exercise-induced neural fatigue may hinder the ability to maximal muscular contractions and increasing the time needed for recovery during the exercise session, and therefore, the FRs should be applied in training program with caution. Based on the present findings of dynamic loading–induced changes in muscle activation, further studies are needed to determine the supraspinal and spinal origin of the neural fatigue and adaptations during high-intensity resistance training.

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References


