Eur J Appl Physiol
DOI 10.1007/s00421-014-2976-9

ORIGINAL ARTICLE

Muscle activation during low- versus high-load resistance training in well-trained men

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Received: 23 February 2014 / Accepted: 1 August 2014

Abstract
Purpose It has been hypothesized that lifting light loads to muscular failure will activate the full spectrum of MUs and thus bring about muscular adaptations similar to high-load training. The purpose of this study was to investigate EMG activity during low- versus high-load training during performance of a multi-joint exercise by well-trained subjects.
Methods Employing a within-subject design, 10 young, resistance-trained men performed sets of the leg press at different intensities of load: a high-load (HL) set at 75 % of 1-RM and a low-load (LL) set at 30 % of 1-RM. The order of performance of the exercises was counterbalanced between participants, so that half of the subjects performed LL first and the other half performed HL first, separated by 15 min rest. Surface electromyography (EMG) was used to assess mean and peak muscle activation of the vastus medialis, vastus lateralis, rectus femoris, and biceps femoris.
Results Significant main effects for trials and muscles were found ($p < 0.01$). Significantly greater peak EMG activity was found during the HL set ($M = 177.3$, $SD = 89.53$) compared to the LL set ($M = 137.73$, $SD = 95.35$). Significantly greater mean EMG activity was found during the HL set ($M = 63.7$, $SD = 37.23$) compared to the LL set ($M = 41.63$, $SD = 28.03$).
Conclusions Results indicate that training with a load of 30 % 1-RM to momentary muscular failure does not maximally activate the full motor unit pool of the quadriceps femoris and hamstrings during performance of multi-joint lower body exercise.

Keywords Muscle recruitment · Low-load resistance training · Light weights · Momentary muscular failure

Abbreviations

MPS	Muscle protein synthesis
RM	Repetition maximum
MU	Motor unit
EMG	Electromyography
RF	Rectus femoris
VL	Vastus lateralis
VM	Vastus medialis
BF	Biceps femoris
MVIC	Maximal voluntary isometric contraction

Introduction

Skeletal muscle size is regulated by the dynamic balance between muscle protein synthesis (MPS) and proteolysis (Sandri 2008). When synthesis is greater than breakdown, there is an accretion of contractile and/or non-contractile proteins, and a corresponding increase in muscle mass.

Communicated by William J. Kraemer.

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Accordingly, hypertrophy can be achieved by increasing MPS, reducing breakdown, or a combination of both. Mechanical loading is a key variable in maximizing the hypertrophic response. This is accomplished by a phenomenon called mechanotransduction, whereby sarcolemmal-bound mechanosensors, such as integrins and focal adhesions, convert musculoskeletal stress from mechanical loading into chemical signals that stimulate intracellular anabolic and catabolic pathways that ultimately leads to an enlargement of myofibers (Zou et al. 2011).

In humans, resistive exercise is the primary method of mechanical loading used to shift muscle protein balance in favor of anabolism. MPS is increased more than two-fold in the immediate post-exercise period and remains elevated upwards for 48 h thereafter (Phillips et al. 1997). When resistance exercise is performed at regular intervals every few days, the overall magnitude of protein accretion is greater than that of degradation, resulting in muscle hypertrophy. Indeed, marked increases in muscle mass have been reported across a wide variety of populations after relatively short periods of regimented resistance training (Wernbom et al. 2007). The extent of tissue growth has been shown to vary by fiber type, with type II fibers displaying an approximately 50 % greater capacity for growth in comparison to type I fibers (Adams and Bamman. 2012; Kosek et al. 2006).

Current resistance training guidelines espouse that a load of at least 65–70 % of one repetition maximum (1-RM) is necessary for maximizing gains in muscle mass (American College of Sports Medicine 2009). This recommendation is largely based on the theory that maximal hypertrophy of a given muscle can only be achieved by activating higher threshold motor units (MUs). Consistent with Henneman's size principle of recruitment; muscle fibers are recruited progressively according to the force requirements of the task, so that smaller, lower threshold MUs are recruited prior to larger, higher threshold MUs. Since substantial force production is required when lifting heavy loads, both lower and higher threshold motor units are recruited to meet force requirements. This is in contrast to lifting light loads whereby force production requirements are low and thus fewer MUs are needed to complete a given lift. Since a fiber must be recruited to initiate an adaptive response (21), it seems logical to conclude that training with heavy loads is necessary to maximize recruitment and therefore muscular adaptations.

The assertion that heavy weights are necessary for optimizing the post-exercise muscular response has recently been challenged, however, with some researchers claiming that light loads lifted to muscular failure can promote adaptations similar to heavy load training (Burd et al. 2012). This theory is based on the contention that simply training to momentary muscular failure, regardless of the magnitude of load, will result in recruitment of the full spectrum of available MUs, and thereby increase the potential for overall hypertrophy. While there is evidence that fatiguing contractions do in fact result in a corresponding increase in electromyography (EMG) activity, presumably resulting from an increased contribution of higher threshold MUs recruited to maintain force output (Spiering et al. 2008), it is not clear whether the level of recruitment during exercise performed with relatively light loads equals to that of heavy loads.

To the authors' knowledge, only two studies have directly compared muscle activation when training with lower versus higher loads performed to repetition failure. Cook et al. (2013) showed that EMG amplitude of the vastus lateralis, vastus medialis, and rectus femoris during knee extension exercise to failure was significantly greater at a higher intensity load (70 % 1-RM) versus a lower intensity (20 % 1-RM) load despite similar decrements in torque. Similarly, Akima and Saito (2013) found that knee extension repetitions to failure at 70 % of 1-RM elicited greater normalized EMG amplitude versus fatiguing repetitions at 50 % of 1-RM. Limitations of these studies include the lack of resistance training experience in subjects, and the use of a single-joint exercise to evaluate muscle recruitment. Therefore, the purpose of this study was to investigate EMG activity during low- versus high-load training during performance of a multi-joint exercise by well-trained subjects.

Materials and methods

Subjects

Ten young men (age = 21.3 ± 1.5 years; height = 176.9 ± 2.5 cm; weight = 79.9 ± 10.1 kg) were recruited from a university population to participate in this study. All subjects were experienced with resistance training, defined as having consistently performed at least two lifting sessions per week for 1 year or more with regular performance of lower body exercise. Inclusion criteria required that subjects were able to read and speak English as well as pass a Physical Activity Readiness Questionnaire (PAR-Q). Those receiving care for any lower body musculoskeletal disorder at the time of the study or those with an amputation of a lower extremity limb were excluded from participation. Each subject provided written informed consent prior to participation. The research protocol was approved by the institutional review board at Lehman College, Bronx, NY. Power analysis was performed a priori to determine the number of subjects required to produce an effect size of 0.80, a power of 0.80, at an α level of 0.05. A sample of at least ten subjects was determined to be sufficient to achieve adequate statistical power.

1-RM testing

Prior to EMG analysis, one repetition maximum (1-RM) testing was carried out on a plate-loaded angled leg press (Life Fitness, Westport, CT). Subjects reported to the lab having refrained from any lower body exercise other than activities of daily living for at least 48 h prior to testing. Repetition maximum testing was consistent with recognized guidelines as established by the National Strength and Conditioning Association (Baechle and Earle 2008). In brief, subjects performed a general warm-up prior to testing that consisted of light cardiovascular exercise lasting approximately 5–10 min. A specific warm-up set of the leg press of 5 repetitions was performed at 50 % of an estimated 1-RM followed by one to two sets of 2–3 repetitions at a load corresponding to 60–80 % of 1-RM. Subjects then performed sets of 1 repetition with increasing weight until a 1-RM was determined.

Successful performance of the leg press was determined as follows: Subjects sat upright on the angled legpress machine, placed their feet on the footplate with a hip-width stance, straightened their legs with toes angled 10° outward, and then unlocked the carriage-release bars located on the sides of the machine. Keeping their backs pressed firmly against the padded seat, subjects lowered carriage by bringing the knees towards the chest until the thighs and lower leg formed a 90° angle. Without bouncing at the bottom, the weight was pushed up in a controlled fashion until the knees were fully extended. Three to 5 min rest was provided between each successive attempt. All 1-RM determinations were made within 5 attempts. All testing sessions were supervised by a fitness professional to determine success on each attempt.

Procedure

Approximately 1 week after 1-RM testing, EMG analysis was conducted on each subject. Subjects were prepped by lightly shaving and then wiping the skin with an alcohol swab in the desired areas of electrode attachment to ensure stable electrode contact and low skin impedance. After preparation, self-adhesive disposable silver/silver chloride pre-gelled dual snap surface bipolar electrodes (Noraxon Product #272, Noraxon USA Inc, Scottsdale, AZ) with a diameter of 1 cm and an inter-electrode distance of 2 cm were attached parallel to the fiber direction of the rectus femoris (RF), vastus lateralis (VL), vastus medialis (VM), and biceps femoris (BF). Electrode placement was made on the right leg of each subject.

The RF electrodes were placed at 50 % on the line from the anterior spina iliaca superior to the superior aspect of the patella. The VL electrodes were placed at 2/3 on the line from the anterior spina iliaca superior to the lateral side of the patella. The VM electrodes were placed at 80 % on the line between the anterior spina iliaca superior and the joint space in front of the anterior border of the medial ligament. The BF electrodes were placed at 50 % on the line between the ischial tuberosity and the lateral epicondyle of the tibia. A neutral reference electrode was placed over the patella. These methods were consistent with the recommendations of surface EMG for non invasive assessment of muscles (SENIAM) (SENIAM Project 2005). After all electrodes were secured, a quality check was performed to ensure EMG signal validity.

Instrumentation

Raw EMG signals were collected at 2,000 Hz by a Myotrace 400 EMG unit (Noraxon USA Inc, Scottsdale, AZ), and filtered by an eighth order Butterworth band-pass filter with cutoffs of 20–500 Hz. Data was sent in real time to a computer via Bluetooth and recorded, and analyzed by MyoResearch XP Clinical Applications software (Noraxon USA, Inc., Scottsdale, AZ). Signals were rectified [by root mean square (RMS) algorithm] and smoothed in real time.

Maximal voluntary isometric contraction

For the purpose of normalizing EMG signals, maximal voluntary isometric contraction (MVIC) data were obtained for the quadriceps muscles by performing a resisted isometric contraction as outlined by Hislop and Montgomery (2002). Testing was carried out as follows: after an initial warm-up consisting of 5 min of light cardiovascular exercise and slow dynamic stretching in all three cardinal planes, subjects sat upright on a high bench with the knees flexed to 90° and hands grasping the edges of the bench for stabilization. Resistance was applied on the anterior aspect of the right leg just above the ankle. Subjects were asked to extend the knee by slowly increasing the force of the contraction so as to reach a maximum effort after 3 s. Subjects then exerted maximal force against resistance for another 3 s before slowly reducing force over a final period of 3 s.

For MVIC of the hamstrings, subjects lied prone on a floor mat with lower limbs extended. Resistance was applied on the right leg at the posterior surface of the leg just above the ankle. Subjects were asked to flex the knee by slowly increasing the force of the contraction so as to reach a maximum effort after approximately 3 s. Subjects then exerted maximal force against resistance for another 3 s before slowly reducing force over a final period of 3 s. The highest MVIC EMG value was used as the reference with which to normalize EMG signals. All data were reported as a percentage of MVIC.

Exercise description

Five minutes after MVIC testing, subjects performed sets of the leg press at different intensities of load: a high-load (HL) set at 75 % of 1-RM and a low-load (LL) set at 30 % 1-RM. The order of performance of the exercises was counterbalanced between participants so that half of the subjects performed LL first and the other half performed HL first. Fifteen minutes of rest was provided between exercise bouts to ensure that fatigue did not confound results (Willardson 2006). Cadence of repetitions was controlled by a metronome, so that both concentric and eccentric actions were performed at a count of 1 s each. Sets were carried out to the point of momentary muscular failure—the inability to perform another concentric action with proper form. Technique instruction and verbal inducements were provided to each subject before and during performance by the primary investigator who is a certified trainer to ensure that exercise was carried out in the prescribed manner.

Statistical analysis

Separate 2 (trials) X 4 (muscles) two-way ANOVAs with repeated measures on the first factor were used to compare peak and mean EMG activity on the selected muscles. To correct for the use of separate ANOVAs, the Bonferroni adjustment procedure was used and p value was set at 0.025. The trials consisted of high-load (75 % of 1-RM) and low-load (30 % of 1-RM) sets. The muscles assessed were the rectus femoris, vastus lateralis, vastus medialis, and biceps femoris. Effect size (partial Eta squared) and observed power statistics were computed for significant main effects and interactions. The Scheffe procedure was used to follow-up significant main effects for muscles. A dependent t test was used to compare the number of repetitions performed in the high-load and low-load exercise sets. Cohen's d was used to indicate effect size. Statistical analysis was carried out using SPSS 16 (SPSS Inc., Chicago, IL).

Results

Peak EMG activity

Significant main effects were evident for trials ($F_{1,36} = 28.64$; $p < 0.01$; $\eta_p^2 = 0.44$; $1 - \beta = 0.99$) and muscles ($F_{3,36} = 7.01$; $p < 0.01$; $\eta_p^2 = 0.37$; $1 - \beta = 0.97$). Significantly greater peak EMG activity was evident during the HL set ($M = 177.3$, SD $= 95.35$) versus the LL set ($M = 137.73$, SD $= 95.35$). Scheffe follow-up analysis indicated significantly lower mean activity for the BF ($M = 71.6$, SD $= 49.68$) versus the VM ($M = 209.95$, SD $= 91.54$; $p < 0.01$) and VL muscles ($M = 195.1$, SD $= 83.5$; $p < 0.01$) Fig. 1.

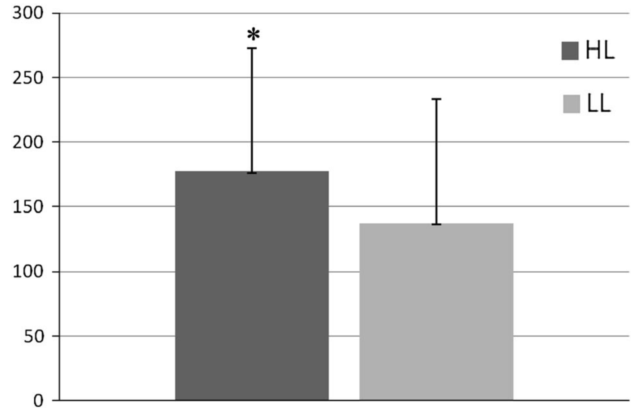

Fig. 1 Graphical representation of peak muscle activation in HL versus LL, mean (±SD). An *asterisk* indicates a significant difference

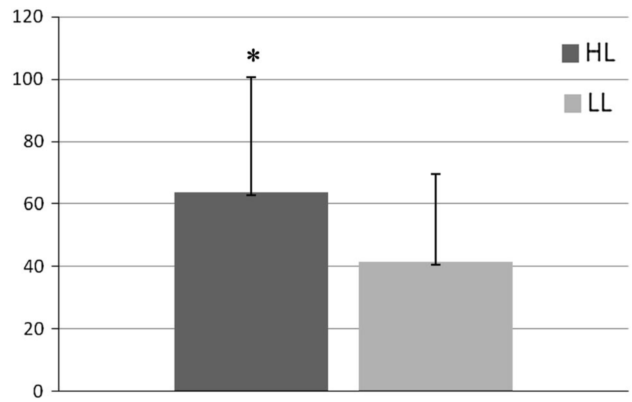

Fig. 2 Graphical representation of mean muscle activation in HL versus LL, mean (±SD). An *asterisk* indicates a significant difference

Mean EMG activity

Significant main effects were evident for trials ($F_{1,36} = 106.28$; $p < 0.01$; $\eta_p^2 = 0.75$; $1 - \beta = 1.00$) and muscles ($F_{3,36} = 11.1$; $p < 0.01$; $\eta_p^2 = 0.48$; $1 - \beta = 1.00$). Significantly, greater mean EMG activity was evident during the HL set ($M = 63.7$, SD $= 37.23$) versus the LL set ($M = 41.63$, SD $= 28.03$). Scheffe follow-up analysis indicated significantly lower mean activity for the BF ($M = 18.56$, SD $= 14.56$) versus the VM ($M = 73.35$, SD $= 31.38$; $p < 0.01$) and VL muscles ($M = 70.1$, SD $= 32.97$; $p < 0.01$) Fig. 2.

Repetitions

A significantly greater number of repetitions ($p < 0.01$) were performed during the low-load set ($M = 44.9$, SD $= 13.5$) versus the high-load set ($M = 14.3$, SD $= 5.8$).

Discussion

To the authors' knowledge, this is the first study to investigate muscle activation in low- versus high-load resistance training during multi-joint exercise when carried out to muscular failure. The study produced several important findings. First, both mean and peak muscle activity were markedly and significantly higher when training with heavy loads compared to light loads. Moreover, although peak muscle activity tended to spike on the last few repetitions of the low-load set, the level of muscle activation achieved did not approach that seen during the heavier lifting condition. Taken together, these results indicate that training with a load of 30 % of 1-RM does not maximally activate the full motor unit pool of the quadriceps femoris during performance of multi-joint lower body exercise.

Previous studies have found significantly greater activation of the quadriceps femoris during knee extension exercise to failure when using a load equating to 70 % of 1-RM versus lower intensity loads ranging from 20 to 50 % of 1-RM (Akima and Saito 2013; Cook et al. 2013). The results of the present study build on previous work, showing that quadriceps and hamstrings MU activation is suboptimal when training at 30 % of 1-RM during performance of multi-joint lower body exercise even when repetitions are carried out to momentary muscular failure. This would seem to refute the contention that fatigue ultimately necessitates near maximal motor unit recruitment to sustain muscle tension irrespective of the magnitude of load lifted (Mitchell et al. 2012). Taken in the context of the body of literature, the findings have important implications for resistance training loading prescriptions with respect to muscular adaptations.

Muscle hypertrophy pursuant to resistance training is predicated on recruiting as many MUs as possible in working muscles and achieving high firing rates in the associated MUs for a sufficient length of time (Wernbom et al. 2007). There is compelling evidence that low-load training promotes significant increases in whole muscle cross sectional area (CSA), in many cases similar to that of training with heavy loads (Leger et al. 2006; Mitchell et al. 2012; Ogasawara et al. 2013; Popov et al. 2006; Tanimoto and Ishii 2006; Tanimoto et al. 2008). The results of the present study may indicate that the hypertrophic equality between protocols could be attributed at least in part to relatively greater type I fiber growth when training with light loads given that activation of higher threshold MUs did not approach that of heavy load exercise. Since type I fibers have a high fatigue-threshold, the greater time under tension associated with low-load exercise would conceivably maximize their stimulation and thus promote a greater hypertrophic response.

This hypothesis is consistent with the findings of Mitchell et al. (2012), who compared knee extension training at 80 % of 1-RM versus 30 % of 1-RM over 10 weeks. Results showed both groups achieved similar increases in whole muscle hypertrophy of the quadriceps as assessed by magnetic resonance imaging. However, tissue analysis from muscle biopsy revealed clear fiber-specific differences between protocols, with the low-load condition showing increased type I fiber area (~23 versus ~16 % in low versus high-load, respectively) while the high-load condition favored greater type II fiber area (~15 versus ~12 % in high versus low-load, respectively). Although results did not reach statistical significance, this was likely a result of the study being underpowered to detect significant differences between protocols. Further research is needed to clarify the fiber type-specific response pursuant to low-load resistance training over time.

Maximal strength is optimized by a combination of increased muscle CSA and enhanced neural efficiencies (Cormie et al. 2011; Duchateau et al. 2006). Studies comparing muscular adaptations between low- versus high-load exercise have generally shown greater increases in 1-RM for those training with heavier loads (Campos et al. 2002; Mitchell et al. 2012; Ogasawara et al. 2013). It has been hypothesized that the superiority of high-load exercise is related to neural improvements; as such training allows the lifter to get practice at the performance of heavy lifts (Mitchell et al. 2012). While neural enhancements certainly may help to explain differences in strength acquisition between protocols, the present findings suggest that fiber-specific hypertrophy may also play a role in the process. Fast-twitch fibers are innervated by larger motor neurons compared to their slow-twitch counterparts, allowing for enhanced high force production. Because of the smaller size of the neurons associated with type I fibers, they simply cannot cycle fast enough to carry out tasks involving high levels of force. If low-load training does in fact result in a greater hypertrophy of type I as opposed to type II fibers as hypothesized, strength gains would be compromised as a result of the inherent differences in the abilities of the respective fibers to produce force per unit of CSA.

In the performance of single-joint exercise, loads of 30 % have been reported to correspond to a mean of ~24 repetitions (Burd et al. 2012). In our study using the leg press, a multi-joint lower body exercise, the mean number of repetitions lifted at 30 % was ~45. This indicates that low-load training during multi-joint exercise results in a substantially greater number of repetitions performed at a given percentage of 1-RM.

Another interesting finding was that both mean and peak hamstring activation were significantly lower compared to the vasti muscles. These results are consistent with other studies that have investigated muscle activation during multi-joint lower body exercise (Wilk et al. 1996; Wright et al. 1999). Conceivably this is related to the biarticular structure of the muscle complex. Since the hamstrings function both as hip extensors and knee flexors, their length remains fairly constant throughout the performance and thus force output is compromised. Another potential factor is related to the design of the leg press machine, where the moment arm of the resistance acts close to the axis of the hip joint throughout the range of motion; whereas, the moment arm of the resistance acts progressively further from the axis of the knee joint through the eccentric phase of the exercise. Because the quadriceps controls extension of the knee joint and the hamstrings controls the hip joint, the greater resistive torque at the knee joint results in correspondingly greater quadriceps versus hamstrings recruitment, respectively. This suggests that targeted single-joint exercise is required to optimally work the hamstrings.

Although surface EMG is widely regarded as a valid estimate of the neural activation sent to muscle, the technique does have its limitations. These limitations include the observation that the magnitude of a motor unit action potential at the skin surface is only partly related to the size of the motor neuron and that the relative contribution of action potentials to EMG amplitude may vary across conditions (Farina et al. 2010). Thus, the extent of motor unit output from the spinal cord may be underestimated by EMG amplitude. However, it appears unlikely that these limitations significantly impacted the results of our study, since the outcome measure was the delta change between conditions in terms of percent MVC. Seemingly, any underestimation would be equally reflected between conditions and results would hence remain constant regardless. Nevertheless, it remains possible that the inherent limitations of surface EMG differentially influenced findings and caution should therefore be taken into account when extrapolating results to real-world application.

Conclusion

The results of this study indicate that muscle activation during multi-joint lower body exercise resistance exercise at 30 % 1-RM does not rise to the same level as when using loads of 75 % 1-RM. This calls into question the theory that full activation of the high-threshold MU pool can be achieved at very low loads provided training is carried out to momentary muscular failure. Therefore, if hypertrophic gains are indeed similar between low- and high-load training as some studies suggest, it would seem that results would be attributed to fiber type-specific adaptations. This hypothesis requires further study. In addition, future research should seek to determine the minimum loading threshold at which full activation of the MU pool occurs during multi- and single-joint exercise performed for both the upper and lower body musculature.

Acknowledgments We gratefully acknowledge the contributions of Robert Harris and Gabriel Irizarry for their indispensible roles as research assistants in this study.

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