

# Reduced susceptibility to eccentric exercise-induced muscle damage in resistance-trained men is not linked to resistance training-related neural adaptations

**AUTHORS:** Ye X, Beck TW, Wages NP

Biophysics Laboratory, Department of Health and Exercise Science, University of Oklahoma, Norman, OK 73019, USA

**ABSTRACT:** The purpose of this study was to examine the acute effects of maximal concentric vs. eccentric exercise on the isometric strength of the elbow flexor, as well as the biceps brachii muscle electromyographic (EMG) responses in resistance-trained (RT) vs. untrained (UT) men. Thirteen RT men (age:  $24 \pm 4$  years; height:  $180.2 \pm 7.7$  cm; body weight:  $92.2 \pm 16.9$  kg) and twelve UT men (age:  $23 \pm 4$  years; height:  $179.2 \pm 5.0$  cm; body weight:  $81.5 \pm 8.6$  kg) performed six sets of ten maximal concentric isokinetic (CON) or eccentric isokinetic (ECC) elbow flexion exercise in two separate visits. Before and after the exercise interventions, maximal voluntary contractions (MVCs) were performed for testing isometric strength. In addition, bipolar surface EMG signals were detected from the biceps brachii muscle during the strength testing. Both CON and ECC caused isometric strength to decrease, regardless of the training status. However, ECC caused greater isometric strength decline than CON did for the UT group ( $p = 0.006$ ), but not for the RT group. Both EMG amplitude and mean frequency significantly decreased and increased, respectively, regardless of the training status and exercise intervention. Resistance-trained men are less susceptible to eccentric exercise-induced muscle damage, but this advantage is not likely linked to the chronic resistance training-induced neural adaptations.

**CITATION:** Ye X, Beck TW, Wages NP. Reduced susceptibility to eccentric exercise-induced muscle damage in resistance-trained men is not linked to resistance training-related neural adaptations. *Biol Sport*. 2015;32(3):199–205.

Received: 2015-01-11; Reviewed: 2015-02-23; Re-submitted: 2015-02-25; Accepted: 2015-02-27; Published: 2015-04-24.

Corresponding author:

**Xin Ye**

Department of Health and Exercise Science  
University of Oklahoma  
1401 Asp Ave. Room 104  
Norman, OK 73019  
405-325-5211 (phone)  
405-325-0594 (fax)  
E-mail: xin.ye-1@ou.edu

**Key words:**

resistance training  
training status  
eccentric exercise  
muscle damage  
electromyography  
neural adaptations

## INTRODUCTION

Chronic resistance training can induce adaptations in the endocrine system [1], the nervous system [2], as well as the muscular system [3]. The integration of these adaptations contributes to the improvement of all the aspects of muscular fitness, such as skeletal muscle strength, power, and endurance [4]. Generally speaking, resistance training consists of a combination of concentric, eccentric, and isometric muscle actions. Particular interests have been focused on eccentric muscle action over the last three decades. Unlike concentric and isometric muscle actions, a unique characteristic of this type of muscle action is that eccentric muscle action often induces muscle damage [5], which is believed to contribute to the extra voluntary strength loss when compared to other types of exercise [6]. In addition, the decline of strength or torque following a bout of eccentric exercise has been shown to be a generally reliable and valid muscle damage marker [7].

Most of the research studies have used untrained individuals who were not accustomed to eccentric exercise to examine the eccentric exercise-induced muscle damage. In the recent decade, there has been an increasing interest towards the physiological responses following eccentric exercise in athletic populations [8], especially in

those who are chronically resistance-trained. For example, Newton et al. [9] directly compared several muscle damage markers following a bout of maximal eccentric exercise protocol between resistance-trained and untrained individuals, and concluded that resistance-trained men are less susceptible to eccentric exercise-induced muscle damage. Indirectly, "repeated bout effect", a phenomenon that the previously exercised muscle appears to be more resistant to the damaging effects of a second bout of the same exercise [10], has also been examined in resistance-trained subjects [11-14]. Specifically, the rationale is that due to long-term exposure to repeated bouts of concentric and eccentric resistance training, the physiological responses to a bout of eccentric exercise in resistance-trained individuals would not be as drastic as in untrained individuals. However, controversial findings were reported [11-14].

The possible reduced susceptibility to eccentric exercise-induced muscle damage in resistance-trained individuals is most likely the consequence of the combination of training adaptations in various organ systems. Of all these changes associated with chronic resistance training, adaptations in the nervous system are as important as in others. By examining the summation of motor unit action potentials

under the pick-up area of the electrodes, surface electromyography (EMG) has been extensively used to examine muscle activity and to interpret neural strategies under certain circumstances [15, 16]. For example, Warren et al. [17] had their subjects perform two separate bouts of maximal eccentric exercise, and found that there was a reduction in EMG median frequency (MF) with no change in EMG amplitude during the second bout of eccentric exercise. Their results suggested an adaptation in the nervous system after the first bout of exercise: there was a greater reliance on low-threshold motor units (generally innervate slow-twitch muscle fibers) during the repeated bout, thereby potentially protecting fast-twitch muscle fibers which are innervated by high-threshold motor units [17]. Over the last few years, our laboratory has examined the acute responses of EMG amplitude and frequency following maximal concentric vs. eccentric exercise specifically in resistance-trained individuals [18-20]. However, no previous study has directly compared the acute responses of EMG parameters following a bout of high intensity eccentric exercise between resistance-trained and untrained individuals. Specifically, such information can be very useful because it may reveal the underlying neural mechanism(s) responsible for the possible different responses to eccentric exercise due to different training statuses.

Therefore, the purpose of this investigation was to examine the acute effects of a bout of maximal concentric (CON) vs. eccentric (ECC) exercise on the isometric strength of the elbow flexor, as well as the EMG amplitude and mean frequency (MNF) of the biceps brachii muscle in resistance-trained vs. untrained men. We expect that, when compared with concentric exercise, eccentric exercise may induce greater strength loss in untrained, but not necessarily in resistance-trained subjects. These different strength responses, in addition, may be partially explained by the neural factors. Specifically, due to chronic resistance training-induced neural adaptations, resistance-trained individuals may have a greater ability to maximally activate the elbow flexor even following the eccentric exercise intervention than untrained individuals do. In addition, selective damage to fast-twitch muscle fibers may also be attenuated in resistance-trained individuals.

## MATERIALS AND METHODS

This investigation used a within-subjects design: after a familiarization visit (1<sup>st</sup> visit), each subject went through different dynamic exercise interventions (CON vs. ECC) in separate visits (2<sup>nd</sup> and 3<sup>rd</sup> visits). Before and after the exercise intervention, isometric strength of the elbow flexor and EMG signals detected from the biceps brachii muscle were recorded.

### Subjects

Thirteen resistance-trained (RT) men (had at least five years of weight training experience with at least four resistance training sessions per week prior to the study; mean  $\pm$  SD: age = 24  $\pm$  4 years; height = 180.2  $\pm$  7.7 cm; body weight = 92.2  $\pm$  16.9 kg) and twelve untrained

(UT) men (engaging no more than one session of either resistance training, aerobic training, or recreational sports per week prior to the study; mean  $\pm$  SD: age = 23  $\pm$  4 years; height = 179.2  $\pm$  5.0 cm; body weight = 81.5  $\pm$  8.6 kg) volunteered to participate in this study. The experiments of the investigation were performed in accordance with the ethical standards of the Helsinki Declaration, and the study was approved by the university Institutional Review Board for Human Subjects. Before the investigation began, each subject read and signed an informed consent and completed a health status questionnaire which indicated that they had no current or recent neuromuscular or musculoskeletal disorders. During the entire investigation, all subjects were refrained from any upper-body resistance exercise. The experimental testing was always performed on the dominant arm based on throwing preference of each subject.

### Testing Procedures

#### Isometric Strength

At the beginning of both exercise intervention visits (2<sup>nd</sup> and 3<sup>rd</sup> visits), the testing for elbow flexor isometric strength was conducted in a custom-build strength testing apparatus. The elbow of the subject was fixed on the apparatus and the wrist was cuffed and connected with a load cell (Model SSM-AJ-5000; Interface, Scottsdale, AZ, USA). The subject's seating position was pre-determined during the familiarization visit to ensure that his arm and forearm were at a 90-degree elbow joint angle, where the highest isometric force is generally produced [21, 22]. After several submaximal isometric elbow flexion muscle actions as warm-up, subjects were then required to perform three separate five-second isometric maximal voluntary contractions (MVCs) of the elbow flexion exercise, with 2-minute breaks between consecutive MVCs. The value from the highest two-second portion of these maximal contractions was recorded as Pre-MVC. This allowed us to collect the maximal strength data from a relatively stable force production region, which properly represented the subjects' true maximal elbow flexion strength. Immediately after the exercise intervention, the testing for the Post-MVC was performed in the exactly same manner and order as the Pre-MVC testing procedures.

#### Exercise Interventions

After the Pre-MVC, subjects were required to sit in front of an isokinetic dynamometer (LIDO Multi-Joint; Loredan Biomedical, West Sacramento, CA, USA) based on the manufacturer's instructions for upper-body strength testing. The LIDO isokinetic dynamometer has been proved to be a reliable instrument to assess isokinetic strength [23]. The subjects then performed one of the randomly selected exercise interventions: (1) six sets of ten maximal concentric muscle actions of the elbow flexor at a velocity of 60 degrees per second on the isokinetic dynamometer for CON, or (2) six sets of ten maximal eccentric muscle actions of the elbow flexor at a velocity of 60 degrees per second on the isokinetic dynamometer for ECC. With the hand supinated, a range of motion of 100 degrees for elbow

flexion was set for both exercise interventions. This range of motion was close to the full range of motion of the elbow flexion for some of the subjects. One minute of rest was provided between the consecutive isokinetic muscle actions. These two exercise interventions were performed in a random order on the 2<sup>nd</sup> and 3<sup>rd</sup> visits, which were separated by at least one week. Extra care was taken to ensure that subjects did not have any muscle soreness before coming to the laboratory for the last visit testing (Visit 3), which minimized the potential influences from the previous exercise intervention.

### Measurements

During the isometric strength testing, force was detected by the tension applied to the load cell. The force signal was digitized with a 12-bit analog-to-digital converter (National Instruments, Austin, TX, USA) and stored in a personal computer for further analyses. Bipolar EMG signals were detected from the belly of the biceps brachii muscle with a preamplified surface EMG sensor (10 mm interelectrode distance DE 2.1 single differential surface EMG sensor; Delsys, Inc., Boston, MA, USA) during all the isometric MVCs. Before placing the surface EMG sensor, all skin sites were shaved and cleansed with rubbing alcohol. The EMG sensor was placed in accordance to the electrode placement recommendations from the SENIAM project [24], and the reference electrode (5.08 cm diameter; Dermatrod HE-R, American Imex, Irvine, CA, USA) was placed on the seventh cervical vertebra. The raw EMG signals were amplified (gain = 1000) with Bagnoli 16-channel EMG system (Delsys, Inc., Boston, MA, USA) and filtered with a bandpass of 10-500 Hz. The EMG signals were then digitized at a sampling rate of 20000 samples per second with a 12-bit analog-to-digital converter (National Instruments, Austin, TX, USA) and stored in a personal computer for subsequent analyses.

### Data Analyses

EMG Works 4.0 Analysis (Delsys, Inc., Boston, MA, USA) was used to analyze the force and EMG signals. Specifically, the system automatically selected and calculated the highest two-second portion from the five-second isometric MVC contractions. In addition, the corresponding EMG signal was selected from the same portion as where the isometric MVC was calculated. The EMG amplitude (root-mean-square (RMS)) and the MNF of each recorded EMG signal were calculated (EMG Works 4.0 Analysis, Delsys, Inc., Boston, MA, USA), and then normalized as a percentage of the values from the Pre-MVC.

### Statistical Analyses

Three separate three-way (time [Pre vs. Post] × condition [CON vs. ECC] × training status [RT vs. UT]) mixed factorial analyses of variance (ANOVAs) were used to compare the mean isometric strength, normalized EMG amplitude, and normalized EMG MNF values before and after different exercise intervention between two populations. When appropriate, follow-up analyses included two-way mixed factorial ANOVAs as well as paired-samples *t*-tests. IBM SPSS Statistics 20.0 (IBM Corp., Armonk, NY) was used for all the statistical analyses, with alpha level set less than 0.05.

## RESULTS

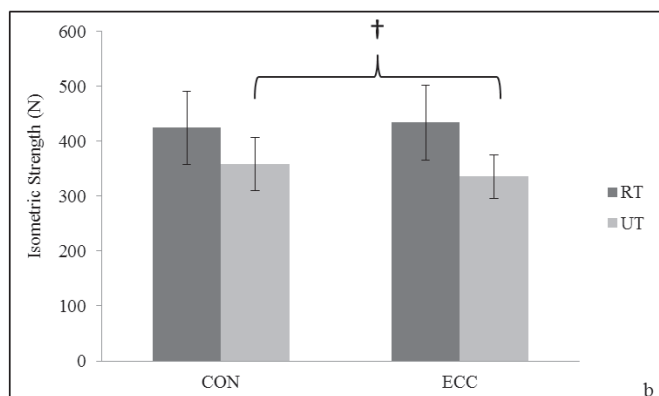
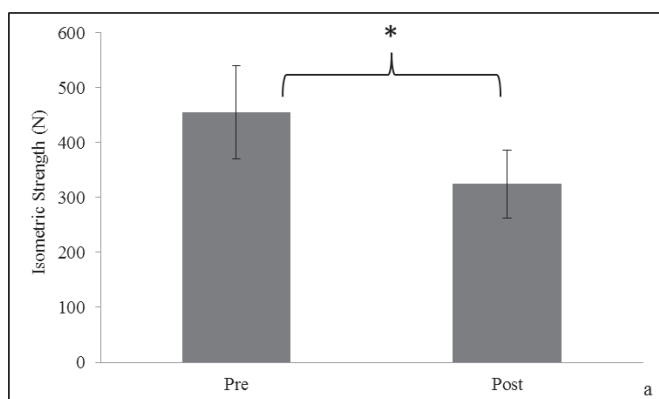
The test-retest reliability for the Pre-MVCs between the second and third visits was excellent, with intraclass correlation coefficient (ICC) greater than 0.95, and no significant difference between test and retest mean values. In addition, our data also showed that the ICCs for the EMG amplitude and MNF are both greater than 0.90, with no difference between mean values in different visits. Table 1 shows the isometric strength values for both RT and UT groups before and after the exercise interventions (CON and ECC). When compared the pre-exercise isometric strength between groups, the mean Pre-MVCs were significant greater in RT than those in UT group at both exercise intervention visits (CON visit:  $t = 2.675$ ,  $p = 0.007$ , Cohen's  $d = 1.07$ ; ECC visit:  $t = 2.914$ ,  $p = 0.004$ , Cohen's  $d = 1.17$ ).

The results from the three-way mixed factorial ANOVA for isometric strength indicated that there was no significant three-way (time × condition × training status) interaction ( $F = 3.970$ ,  $p = 0.058$ , partial eta squared  $\eta_p^2 = 0.147$ ). However, there were significant two-way interaction for condition × training status ( $F = 10.327$ ,  $p = 0.004$ ,  $\eta_p^2 = 0.310$ ) and main effect for time ( $F = 146.682$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.864$ ). When collapsed across both condition and training status, the marginal mean isometric strength decreased significant from Pre- to Post-exercise interventions (Figure 1a). When collapsed across time, follow-up paired samples *t*-tests showed that, for the marginal mean isometric strength, ECC caused greater strength decline than CON did for the UT group ( $t = 3.397$ ,  $p = 0.003$ , Cohen's  $d = 0.52$ ), but not for the RT group ( $t = 1.305$ ,  $p = 0.11$ , Cohen's  $d = 0.15$ ) (Figure 1b).

The three-way mixed factorial ANOVA for normalized EMG amplitude indicated that there was no significant three-way (time × condition × training status) interaction ( $F = 2.007$ ,  $p = 0.17$ ,  $\eta_p^2 = 0.080$ ). However, there was a main effect for time ( $F = 14.505$ ,

**TABLE 1.** Mean ± standard deviation (SD) of isometric strength values (N) for both resistance-trained and untrained subjects before (Pre) and after (Post) both exercise interventions.

	Resistance-trained group		Untrained group	
	Pre	Post	Pre	Post
Concentric exercise intervention Visit	492.21 ± 83.53	356.86 ± 54.64	414.86 ± 57.44	302.44 ± 53.39
Eccentric exercise intervention Visit	499.13 ± 92.73	369.66 ± 58.18	408.58 ± 56.77	262.96 ± 39.72



**FIG. 1.** a. Changes in elbow flexor isometric strength (N) (collapsed across both exercise condition and training status) between Pre- and Post-exercise interventions.

b. Differences in elbow flexor isometric strength (N) (collapsed across time) for concentric exercise intervention (CON) and eccentric exercise intervention between resistance-trained (RT) and untrained (UT) groups.

\* Statistically significant difference between Pre- and Post-isometric strength

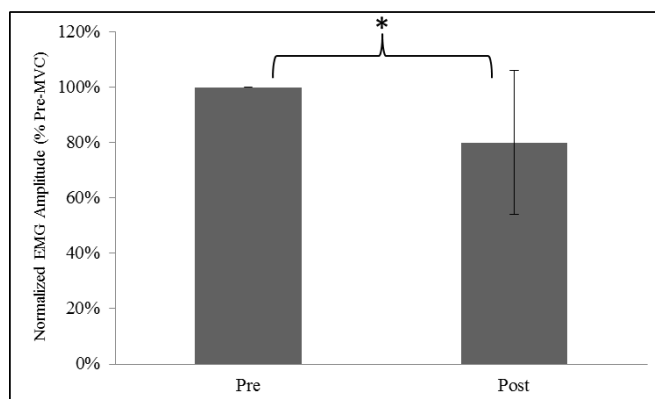
† Statistically significant difference between isometric strength between concentric exercise and eccentric exercise interventions in untrained subjects

$p < 0.001$ ,  $\eta_p^2 = 0.387$ ). When collapsed across both condition and training status, the marginal mean normalized EMG amplitude decreased significant from Pre- to Post-exercise interventions ( $t = 3.823$ ,  $p < 0.001$ , Cohen's  $d = 1.08$ ) (Figure 2).

The results from the three-way mixed factorial ANOVA for normalized EMG MNF indicated that there was no significant three-way (time  $\times$  condition  $\times$  training status) interaction ( $F = 0.263$ ,  $p = 0.613$ ,  $\eta_p^2 = 0.011$ ). However, there was a main effect for time ( $F = 9.402$ ,  $p = 0.005$ ,  $\eta_p^2 = 0.290$ ). When collapsed across both condition and training status, the marginal mean normalized EMG MNF increased significant from Pre- to Post-exercise interventions ( $t = 3.134$ ,  $p = 0.0025$ , Cohen's  $d = 0.89$ ) (Figure 3).

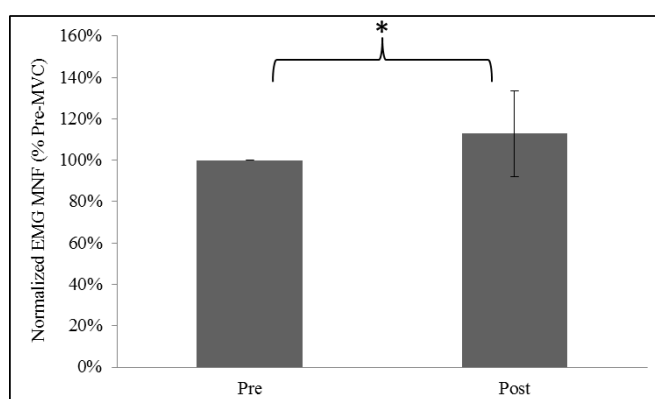
## DISCUSSION

The purpose of this study was to examine whether resistance-trained and untrained men have different responses in elbow flexor strength decline following a bout of maximal concentric vs. eccentric exercise.



**FIG. 2.** Changes in normalized EMG amplitude (collapsed across both exercise condition and training status) between Pre- and Post-exercise interventions.

\* Statistically significant difference



**FIG. 3.** Changes in normalized EMG mean frequency (MNF) (collapsed across both exercise condition and training status) between Pre- and Post-exercise interventions.

\* Statistically significant difference

More importantly, we tried to answer the question whether this potential difference is due to chronic training-induced neural adaptations by examining surface EMG parameters (amplitude and center frequency) of the biceps brachii. Obviously, our study is not the first to examine the acute effects of eccentric exercise on resistance-trained vs. untrained individuals. However, to our knowledge, this is the first research study examining the role of training-related neural adaptations on the susceptibility to eccentric exercise-induced muscle damage.

The major finding of this study is that same sets and repetitions of maximal concentric and eccentric muscle contractions caused significant decreases in the mean isometric strength of the elbow flexor for both trained and untrained subjects. In addition, as expected, training status did play an important role influencing the acute isometric strength responses following different exercise interventions: untrained individuals experienced greater strength loss following the ECC than that following the CON, which indicated that the ECC might have induced muscle damage in the elbow flexor, causing greater strength loss when compared with performing the concentric exercise intervention. However, resistance trained subjects had similar strength losses following both exercise interventions. These results, in general, are in agreement with previous studies from



our laboratory, where the authors have examined the acute responses of isometric strength following concentric versus eccentric interventions in resistance-trained [18-20, 25] and untrained subjects [26]. However, prior to this investigation, we have never directly compared the acute responses of isometric strength between groups with different training statuses. Newton et al. [9] had their subjects perform very similar eccentric exercise protocol (ten sets of six maximal isokinetic eccentric elbow flexion at an angular velocity of 90 degrees per second), and found that resistance trained subjects suffered less strength loss when compared with untrained subjects. Although isometric strength loss immediately after eccentric exercise may not be the most accurate indirect marker for muscle damage [27], consistent with the changes in strength decline, changes in other muscle damage markers such as range of motion, exercised arm circumference and plasma creatine kinase level were also smaller in resistance-trained men when compared to those in untrained men [9]. As mentioned earlier, a well-known characteristic of eccentric exercise is that muscle damage could occur following very strenuous eccentric exercise in subjects who are unaccustomed to this type of muscle action, thereby inducing more severe strength loss when compared to concentric exercise. Therefore, we believe that resistance-trained men are more resistant (less susceptible) to eccentric exercise-induced muscle damage, which is suggested by Newton et al. [9] as well.

With the finding of influence of training status on the acute responses of isometric strength, a more important question is what exactly the mechanisms are that can cause this attenuated susceptibility to eccentric exercise-induced muscle damage in resistance-trained men. As an important portion of chronic resistance training-induced physiological adaptations, changes in neural factors can be examined via EMG parameters. Based on our results, both groups (RT and UT) had similar decreases in the normalized EMG amplitude following both exercise interventions, suggesting that both groups of subjects reduced their ability to maximally activate their biceps brachii muscles [20]. Accompanying to the decreased EMG amplitude was the significantly increased EMG MNF. However, just like the decreased EMG amplitude, this altered EMG MNF was not specific to training status or exercise type. These results are generally in accordance with our previous observation of EMG parameters (amplitude and mean frequency) responses on resistance-trained men following both concentric and eccentric interventions [20], but different from others [6, 28, 29]. In general, the reduced ability to maximally contract a muscle may partially be due to the increased inhibition from free nerve endings in the exercised muscle that are sensitive to changes in temperature, pH, and mechanical damage [20]. Specifically, the accumulation of metabolites during the fatiguing contractions might have activated these free nerve endings, which then sent inhibitory input to alpha motor neuron pool, thereby influencing the amplitude of surface EMG signals [30]. In addition, it is also believed that eccentric muscle action can affect muscle spindle activity, which contributes to the altered force and position senses [31]. This disturbed muscle spindle activity, in addition, may

lead to the decreased afferent excitability of the motor neuron, thereby reducing the muscle activation [32].

Unlike what we expected, chronic resistance training-induced neural adaptations did not seem to account for the reduced susceptibility to eccentric exercise-induced muscle damage in resistance-trained men. In research studies that have examined the "repeated bout effect", it has been suggested that after a first bout of eccentric exercise, there was an increased reliance on low-threshold motor units to confer protection during the second (repeated) bout of the eccentric training session [17, 33]. Thus, one may hypothesize that, due to long-term resistance training (viewed as many repeated bouts of combination of concentric, eccentric, and isometric exercise), resistance-trained individuals may have a better ability to utilize low-threshold motor units during an eccentric exercise session, which can induce a less degree of damage to the fast-twitch muscle fibers, when compared with untrained individuals. However, this advantage was not shown from the result of our study. Caution should be taken though, when comparing the results from previous studies [17, 33] to the ones from current investigation. For example, Warren et al. [17] and Howatson et al. [33] had their subjects perform continuous 50 and 45 maximal eccentric muscle actions, respectively. While in the current study, although the total numbers of repetitions were similar to what Warren et al. [17] had, our subjects had one minute of rest following every 10 maximal muscle contractions, which might have helped the subjects to recover from the maximal exercises. In addition, unlike the previous studies [17, 33], the EMG measurement in the current study was taken immediately after the exercise interventions rather than during the exercise interventions. These factors might have contributed to the different responses in EMG variables between previous studies and the current investigation. In fact, not all "repeated bout effect" studies demonstrated improved neural factor-related protective mechanism following a single bout of eccentric exercise against eccentric exercise-induced muscle damage. For example, McHugh et al. [34] and Falvo et al. [12] showed unchanged EMG MF values between the initial and repeated bouts of eccentric exercise, which indicated that the "repeated bout effect" is not likely linked to neural adaptation, thereby indirectly supporting our results.

A question remains unanswered, however, is what other possible factors are that could cause the different isometric strength responses between groups with different training statuses, since neural factors are not likely the explanation. Many research studies have compared mechanical properties of muscle fibers and/or connective tissue in resistance-trained and untrained individuals. For example, when examined the properties of biceps brachii muscle between resistance-trained bodybuilders and control subjects, greater absolute amounts of connective tissue were found in bodybuilders, even though the number of muscle fibers were equal between these two populations [35]. In addition, it has also been suggested that the adaptation to the heat shock system may also be responsible for providing a more protective effect for skeletal muscles in resistance-trained subjects [9]. Specifically, heat shock protein activity can be slightly el-

evated following resistance exercise, and it is hypothesized that this small elevation in heat shock protein activity may interact with cytoskeletal system and/or the glutathione system, thereby protecting muscle cells [36]. Unfortunately, it is very difficult to determine how much these mechanisms could contribute to the different isometric strength responses between groups with different training statuses, because we were not able to quantify changes in these variables.

## CONCLUSIONS

Similar to what Newton et al. [9] have found in their study, we confirmed that resistance-trained men are less susceptible to eccentric exercise-induced strength loss. However, the collected data does not suggest that this advantage is associated with long-term resistance training-induced neural adaptations.

## Acknowledgements

The authors would like to thank the anonymous reviewers for their valuable comments and suggestions, which improved the quality of this manuscript. In addition, the authors also thank all test subjects for their time and effort. There were no conflicts of interest or funding declared from authors for the completion of this project and manuscript.

**Conflict of interests:** the authors declared no conflict of interests regarding the publication of this manuscript.

## REFERENCES

- Kraemer WJ, Ratamess NA. Hormonal responses and adaptations to resistance exercise and training. *Sports Med.* 2005;35(4):339-361.
- Sale DG. Influence of exercise and training on motor unit activation. *Exerc Sport Sci Rev.* 1987;15:95-151.
- Jones DA, Rutherford OM, Parker DF. Physiological-Changes in Skeletal-Muscle as a Result of Strength Training. *Q J Exp Physiol Cms.* 1989;74(3):233-256.
- American College of Sports Medicine. ACSM's Guidelines for exercise testing and prescription. 8th ed. Philadelphia: Lippincott Williams & Wilkins; 2009.
- Proske U, Morgan DL. Muscle damage from eccentric exercise: mechanism, mechanical signs, adaptation and clinical applications. *J Physiol.* 2001;537(Pt 2):333-345.
- Weerakkody N, Percival P, Morgan DL, Gregory JE, Proske U. Matching different levels of isometric torque in elbow flexor muscles after eccentric exercise. *Exp Brain Res.* 2003;149(2):141-150.
- Warren GL, Lowe DA, Armstrong RB. Measurement tools used in the study of eccentric contraction-induced injury. *Sports Med.* 1999;27(1):43-59.
- Falvo MJ, Bloomer RJ. Review of exercise-induced muscle injury: relevance for athletic populations. *Res Sports Med.* 2006;14(1):65-82.
- Newton MJ, Morgan GT, Sacco P, Chapman DW, Nosaka K. Comparison of responses to strenuous eccentric exercise of the elbow flexors between resistance-trained and untrained men. *J Strength Cond Res.* 2008;22(2):597-607.
- Clarkson PM, Tremblay I. Exercise-induced muscle damage, repair, and adaptation in humans. *J Appl Physiol.* 1988;65(1):1-6.
- Meneghel AJ, Verlengia R, Crisp AH, Aoki MS, Nosaka K, da Mota GR, et al. Muscle damage of resistance-trained men after two bouts of eccentric bench press exercise. *J Strength Cond Res.* 2014;28(10):2961-2966.
- Falvo MJ, Schilling BK, Bloomer RJ, Smith WA. Repeated bout effect is absent in resistance trained men: an electromyographic analysis. *J Electromyogr Kinesiol.* 2009;19(6):e529-535.
- Falvo MJ, Schilling BK, Bloomer RJ, Smith WA, Creasy AC. Efficacy of prior eccentric exercise in attenuating impaired exercise performance after muscle injury in resistance trained men. *J Strength Cond Res.* 2007;21(4):1053-1060.
- Bloomer RJ, Falvo MJ, Schilling BK, Smith WA. Prior exercise and antioxidant supplementation: effect on oxidative stress and muscle injury. *J Int Soc Sports Nutr.* 2007;4:9.
- Farina D, Merletti R, Enoka RM. The extraction of neural strategies from the surface EMG. *J Appl Physiol.* 2004;96(4):1486-1495.
- De Luca CJ. The use of surface electromyography in biomechanics. *J Appl Biomech.* 1997;13(2):135-163.
- Warren GL, Hermann KM, Ingalls CP, Masselli MR, Armstrong RB. Decreased EMG median frequency during a second bout of eccentric contractions. *Med Sci Sports Exerc.* 2000;32(4):820-829.
- Ye X, Beck TW, Wages NP. Acute effects of concentric versus eccentric exercise on force steadiness and electromyographic responses of the forearm flexors. *J Strength Cond Res.* 2015;29(3):604-611.
- Ye X, Beck TW, DeFreitas JM, Wages NP. An examination of the strength and electromyographic responses after concentric vs. eccentric exercise of the forearm flexors. *J Strength Cond Res.* 2014;28(4):1072-1080.
- Beck TW, Kasishke PR, 2nd, Stock MS, DeFreitas JM. Neural contributions to concentric vs. eccentric exercise-induced strength loss. *J Strength Cond Res.* 2012;26(3):633-640.
- Hansen EA, Lee HD, Barrett K, Herzog W. The shape of the force-elbow angle relationship for maximal voluntary contractions and sub-maximal electrically induced contractions in human elbow flexors. *J Biomech.* 2003;36(11):1713-1718.
- van Zuynen EJ, van Velzen A, Denier van der Gon JJ. A biomechanical model for flexion torques of human arm muscles as a function of elbow angle. *J Biomech.* 1988;21(3):183-190.
- Brown LE, Whitehurst M, Bryant JR. Reliability of the LIDO Active isokinetic dynamometer concentric mode. *Isokinet Exerc Sci.* 1992;2(4):191-194.
- Hermens H, Freriks B, Merletti R, Stegeman D, Blok J, Rau G, et al. SENIAM European recommendations for surface ElectroMyoGraphy: Result of the SENIAM Project. Enschede, The Netherlands: Roessingh Research and Development. 1999.
- Ye X, Beck TW, Wages NP. Influences of dynamic exercise on force steadiness and common drive. *J Musculoskelet Neuronal Interact.* 2014;14(3):377-386.
- Ye X, Beck TW, DeFreitas JM, Wages NP. Acute effects of dynamic exercises on the relationship between the motor unit firing rate and the recruitment threshold. *Hum Mov Sci.* 2015;40C(4):24-37.
- Nosaka K, Chapman D, Newton M, Sacco P. Is isometric strength loss immediately after eccentric exercise related to changes in indirect markers of muscle damage? *Appl Physiol Nutr Metab.* 2006;31(3):313-319.
- Zhou Y, Li Y, Wang R. Evaluation of exercise-induced muscle damage by surface electromyography. *J Electromyogr Kinesiol.* 2011;21(2):356-362.
- Semmler JG, Tucker KJ, Allen TJ, Proske U. Eccentric exercise increases EMG amplitude and force fluctuations during submaximal contractions of elbow

- flexor muscles. *J Appl Physiol.* 2007;103(3):979-989.
30. Bigland-Ritchie BR, Dawson NJ, Johansson RS, Lippold OCJ. Reflex origin for the slowing of motoneuron firing rates in fatigue of human voluntary contractions. *J Physiol.* 1986;379:451-459.
31. Proske U, Gandevia SC. The proprioceptive senses: their roles in signaling body shape, body position and movement, and muscle force. *Physiol Rev.* 2012;92(4):1651-1697.
32. Avela J, Kyrolainen H, Komi PV. Altered reflex sensitivity after repeated and prolonged passive muscle stretching. *J Appl Physiol.* 1999;86(4):1283-1291.
33. Howatson G, Van Someren K, Hortobagyi T. Repeated bout effect after maximal eccentric exercise. *Int J Sports Med.* 2007;28(7):557-563.
34. McHugh MP, Connolly DA, Eston RG, Gattman EJ, Gleim GW. Electromyographic analysis of repeated bouts of eccentric exercise. *J Sports Sci.* 2001;19(3):163-170.
35. MacDougall JD, Sale DG, Alway SE, Sutton JR. Muscle fiber number in biceps brachii in bodybuilders and control subjects. *J Appl Physiol Respir Environ Exerc Physiol.* 1984;57(5):1399-1403.
36. Koh TJ. Do small heat shock proteins protect skeletal muscle from injury? *Exerc Sport Sci Rev.* 2002;30(3):117-121.