


Temporal increase in muscle cross-sectional area as an acute effect of resistance exercise in resistance-trained and untrained individuals

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ABSTRACT

The purpose of this study was to compare the temporal increase in muscle cross-sectional area (CSA) as the acute response of resistance exercise (RE) between resistance-trained and untrained groups and investigate the factors that affect the muscle CSA. Resistance-trained ($n = 14$) and untrained ($n = 14$) subjects performed four kinds of triceps brachii RE. Muscle CSA and intracellular hydration (IH), were measured prior to and 5-, 30-, and 60-minute after RE. Pearson's correlation coefficient was calculated to clarify the relationships among percent increases in muscle CSA and IH, area under the Oyx-Hb curve, blood lactate concentration, and % maximum voluntary contraction (MVC)-root-mean-square (RMS) of electromyogram (EMG). At 5-minute after RE, muscle CSA increased significantly to $120.2 \pm 6.3\%$ in the resistance-trained group and $105.5 \pm 2.3\%$ in the untrained group ($p < .01$). However, neither group showed a significant difference between the values before and 30-minute after RE. In the resistance-trained group, there was a significant increase in IH at 5-minute post-RH ($p < .01$), and correlations were found between percent increases in muscle CSA and IH ($r = 0.70$, $p < .01$), area under the Oxy-Hb curve ($r = 0.77$, $p < .01$), and % MVC-RMS of EMG ($r = 0.72$, $p < .01$). The findings of this study suggest that measurements of muscle CSA in studies of muscle hypertrophy should be performed 30-minute or more after the last resistance exercise session, and muscle pump exercises should be conducted just before participation in bodybuilding, and physique contests.

Keywords: Muscle hypertrophy; Oxygenated haemoglobin; Hypoxia; Intramuscular hydration; Muscle pump.

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INTRODUCTION

Previous studies suggest that multiple exercise, moderate to high load (65-85% of 1 repetition maximum), 6 to 12 repetitions, slower speed (2-4 seconds) for both concentric and eccentric contractions, 3 to 5 sets, and intervals between sets within 60-90 seconds are optional for a resistance exercise protocol targeting muscle hypertrophy (Schoenfeld, 2010). This resistance exercise protocol induces metabolic changes such as increased hydrogen ion concentration (Cheema et al., 2014), production of reactive oxygen species (Powers et al., 2011), promotion of intramuscular hypoxia, and increased blood lactate concentration (Goto et al., 2019). As these intramuscular metabolic changes disturb regular muscle contraction, interstitial fluid accumulates in the plasma membrane of the muscle to buffer these metabolites, increasing intracellular hydration (Sjogaard, 1998). This phenomenon, known as resistance exercise-induced muscle swelling (Vieira et al., 2018), or muscle pump (Schoenfeld, 2013), is believed to serve as a physiological regulator of cell function (Haussinger et al., 1994). Some studies have shown that resistance exercise-induced muscle swelling results in an increase in protein synthesis and a decrease in proteolysis (Lang et al., 1998).

There are some studies of acute changes in muscle thickness induced by resistance exercise. Vieira et al. (2018) reported that the muscle thickness of vastus lateralis increased by 11 to 14% as an acute effect of resistance exercise. Furthermore, they found that concentric contractions seem to be a more potent stimulus for inducing acute changes in muscle thickness. Wilson et al. (2013) investigated the acute effects of low-intensity leg press exercise with or without vascular blood flow restriction on muscle activation, thickness, and damage. They concluded that low-intensity exercise with vascular blood flow restriction increased muscle activation and thickness more than without blood flow restriction. Fink et al. (2018) investigated the acute effects of resistance exercises on the muscle thickness of the triceps brachii and reported that drop-sets increased the muscle thickness by 18%. In the studies mentioned above, untrained individuals were used as subjects. Smith et al. (2017) investigated the impact of ingesting an amino acid-electrolyte beverage during upper body resistance exercise on muscle thickness in resistance-trained males. They concluded that resistance exercise increased muscle thickness as an acute effect, but acute ingestion of an amino acid-electrolyte beverage did not alter acute muscle thickness.

In these acute effects, muscle thicknesses increased immediately after resistance exercise and returned to their original size within 24 hours. However, no study has investigated the temporal changes of muscle thickness or muscle swelling within an hour after resistance exercise. In addition, there might be differences in capillary density and energy metabolism among resistance-trained and untrained individuals (McCall et al., 1996), with a corresponding difference in muscle swelling, but there has been no muscle swelling study focusing on the difference in resistance exercise experience.

The aims of this study were to compare the temporal increase in muscle CSA as the acute response to resistance exercise between resistance-trained and untrained groups, and to investigate the factors that affect the muscle CSA. Muscle CSA and intramuscular hydration prior to and 5, 30, and 60 minutes after resistance exercise, blood lactate concentration prior to and 5 minutes after resistance exercise, and % maximum voluntary contraction (MVC)-root-mean-square (RMS) of electromyogram (EMG) and the area under the oxygenated haemoglobin (Oxy-Hb) curve during resistance exercise were measured. We expected the results to be useful for determining an appropriate period after the last resistance exercise session before measuring the muscle CSA in the study of muscle hypertrophy as a long-term effect of resistance exercise. Furthermore, confirmation of the degree and duration of muscle swelling might be useful information for participants in bodybuilding and physique contests where muscle volume determines the outcome.

MATERIAL AND METHODS

Experimental Approach

A two-group (resistance trained and untrained) pre- and post-test design was used to investigate temporal increase in muscle CSA as an acute effect of resistance exercise. Resistance-trained ($n = 14$) and untrained ($n = 14$) subjects performed four types of triceps brachii resistance exercise. Muscle CSA based on the circumference of the upper arm and muscle thickness, and intracellular hydration were measured four times: before and 5, 30, and 60 minutes after resistance exercise. Pearson's correlation coefficient was calculated to clarify the relationships among percent increase in muscle CSA, intracellular hydration, area under the Oyx-Hb curve, blood lactate concentration, and % MVC-RMS of EMG.

Subjects

Fourteen resistance-trained men who were members of a resistance training club (resistance-trained group) and 14 healthy young men who did not exercise regularly (untrained group) were recruited from among students and staffs at Aino University. The inclusion criteria for the resistance-trained subjects consisted of at least 1 year of resistance exercise experience, participating in a resistance exercise program at least 3 days a week, and performing triceps brachii exercises at least once a week. Physical characteristics of the two groups are shown in Table 1. Subjects who reported any musculoskeletal injuries of the upper extremities in the year before the test were excluded. All subjects were instructed to refrain from vigorous physical activity within 24 hours of an initial testing session (Maehlum et al., 1986). Before participating in the study, the subjects were informed about the study procedures and any possible risks both verbally and in writing before providing written informed consent. The study was approved by the ethics committees of Aino University.

Table 1. Physical characteristics of subjects.

	Trained ($n = 14$)	Untrained ($n = 14$)
Age (yr.)	26.1 ± 7.8	27.8 ± 7.9
Height (cm)	169.8 ± 2.7	171.3 ± 7.8
Body weight (kg)	71.5 ± 7.1	66.4 ± 8.9

Means ± SD ($n = 14$ for both group) are shown.

Procedures

Exercise protocols

Before the week of the testing session, a trial session was conducted to familiarize the subjects with the exercise methods. At both test and trial sessions, five minutes' light stretching as a warm-up was performed before starting resistance exercise. After the light stretching, subjects performed four kinds of triceps brachii resistance exercise continuously, in the following order: barbell lying elbow extension, dumbbell French press, triceps dumbbell kickback, and triceps pushdown; 8 repetitions per set and 4 sets, with 30-second intervals between sets. The exercise intensity was determined at the 8-repetition maximum (RM) for each exercise, but not by % of 1 RM, because this method is more commonly used during actual resistance exercise. They flexed and extended their elbow joint using the full range of motion. Eccentric /concentric contraction cycles of the triceps brachii were performed at a metronome-controlled tempo of one second per eccentric contraction and one second per concentric contraction.

Muscle CSA of triceps brachii muscle measurements

The muscle thickness (MT) of the right triceps brachii muscle and the circumference of the right upper arm at 60% proximal between the acromion and olecranon at of the right upper arm were measured using an ultrasound imaging unit (Noblus; Hitachi Medical Inc., Tokyo, Japan) and a tape measure at rest. Muscle

CSA was calculated as the product of MT and circumference (Akagi et al., 2008). A trained technician performed all the tests. Water-soluble transmission gel was applied to the measurement site, and a 2.5 MHz ultrasound probe was placed perpendicular to the tissue interface without depressing the skin. The images were saved to a hard drive. MT dimensions were obtained by measuring the distance from the subcutaneous adipose tissue-muscle interface to the muscle-bone interface. The muscle CSA of the triceps brachii muscle was compared between two groups, and before and 5, 30, and 60 minutes after resistance exercise.

Intracellular hydration measurements

Intracellular hydration of the right upper arm was measured using an Inbody S10 (Inbody Co., Ltd, Korea). Subjects wore shorts and a T-shirt and wiped both hands and feet with an antibacterial electrode wipe for conduction as part of MF-BIA pre-testing guidelines. In accordance with the manufacturer's recommendations, participants stood erect on the device with both arms extended and abducted from the trunk. The InBody S10 measured impedance at varying frequencies (1, 5, 50, 250, 500 and 1,000 kHz) across the legs, arms and trunk. All four extremities were in contact with the electrodes, and the subjects stood with bare feet on the device until completion of test. Intracellular hydration was compared between two groups, and before and 5, 30, and 60 minutes after resistance exercise. The relationship between percent increase in muscle CSA and intracellular hydration was also calculated.

Intramuscular oxygenation measurements

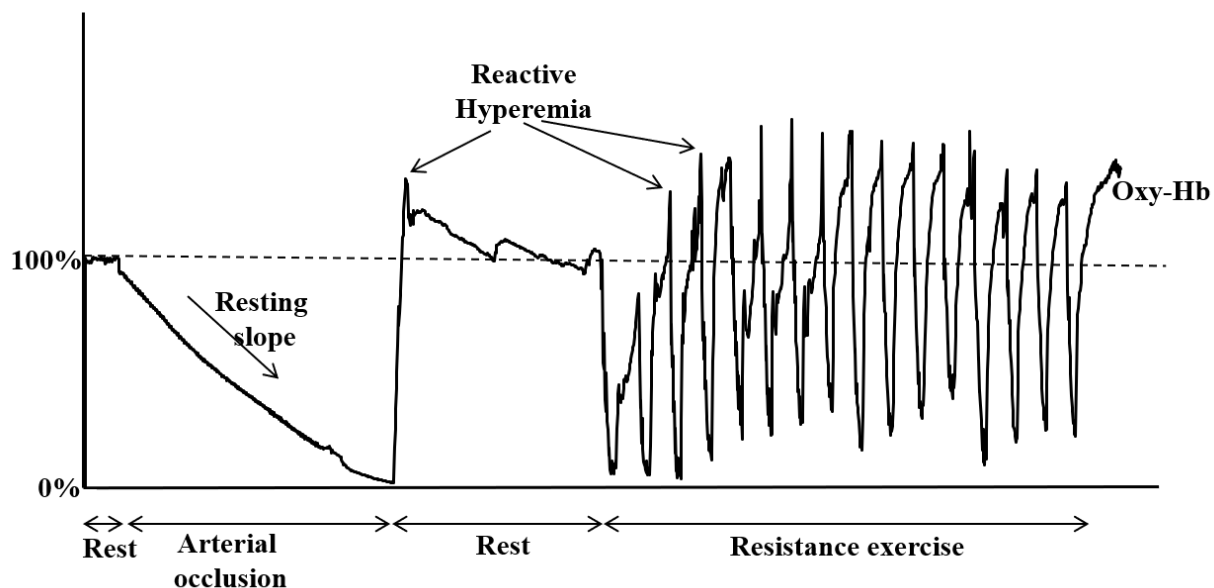


Figure 1. Typical example showing change in intramuscular oxidative metabolism in the right triceps brachii muscle from at rest to the end of resistance exercise.

A near-infrared continuous-wave spectrometer (NIRS: HB14-2; ASTEM Co., Ltd., Kanagawa, Japan) was used to measure peripheral muscle oxygenation and the area under the oxygenated haemoglobin (Oxy-Hb) curve in the right triceps brachii muscle during resistance exercise. Figure 1 shows a typical example of the Oxy-Hb dynamics detected in the right triceps brachii muscle from at rest to the end of resistance exercise. The wavelength of the emitted light ranged between 750-850 nm, and the relative concentration of Oxy-Hb in the target tissue was quantified according to the Beer-Lambert law (Chance et al., 1992). The distance between the incident point of the emitted light and the detector was 30 mm. The laser emitter and detector were fixed in place with adhesive tape. The NIRS signals were stored in a personal computer. NIRS signals

recorded during exercise do not always reflect the absolute levels of intramuscular oxygenation, so the changes in oxygenation of working skeletal muscles were expressed relative to the overall changes in the monitored signal, according to the arterial occlusion method (Hamaoka et al., 2007). In the present study, the Oxy-Hb level observed at rest was taken as 100%, and the minimum Oxy-Hb plateau level induced by arterial occlusion was defined as 0%. A pressure cuff was placed around the proximal portion of the upper arm and manually inflated to 250 mm Hg until the minimum plateau level of Oxy-Hb was obtained (Bae et al., 2000). The area under the Oxy-Hb curve was used to examine the reduction in the intramuscular oxygen level induced during each exercise, as described by Manfredini et al. (2015). The mean area under the Oxy-Hb curve during resistance exercise was compared between two groups, and the relationship between the percent increase in muscle CSA and mean area under the Oxy-Hb curve was investigated.

Blood lactate concentration measurements

Blood samples were collected at rest and 5 minutes after exercise, and the difference between them was calculated. Approximately 5 μ l of blood was taken from the fingertip with a needle and immediately analysed for blood lactate concentration using a lactate analyser (Lactate Pro; Kyoto Primary Science Inc., Kyoto, Japan). The mean blood lactate concentration 5 minutes after resistance exercise was compared between two groups. Furthermore, relationship between percent increase in muscle CSA and mean blood lactate concentration was calculated.

Electromyographic signal recording measurements

The muscle activity of the long head of the right triceps brachii was recorded at a sample rate of 1000 Hz using an EMG system (Myosystem 1200, Noraxon U.S.A. Inc., AZ, U.S.A.). Bipolar surface EMG electrodes (model: M-150Ag/AgCl, Nihon Kohden Inc., Tokyo, Japan) were used to measure EMG signals from the long head of the triceps brachii during exercise. Based on the Surface Electromyography for the Non-Invasive Assessment of Muscles (SENIAM) recommendations (Hermens et al., 2000), pairs of EMG electrodes were placed along the muscle midline. The bipolar surface EMG electrodes were placed in line with the muscle fibres. The centre-to-centre distance between each pair of electrodes was 2.5 cm. Prior to the placement, each subject's skin was shaved, wiped using skin preparation gel (Nihon Kohden Inc., Tokyo, Japan), and cleaned with alcohol wipes. A reference electrode was placed over the acromioclavicular joint. It was confirmed that all of the recorded inter-electrode resistance values were below 10 k Ω using an electrode impedance checker (Biopack Systems Inc, U.S.A.). Myoelectric signals were relayed from the bipolar electrodes to a TeleMyo device (TeleMyo 2400T, Noraxon U.S.A. Inc., AZ, USA). The raw EMG signals were rectified, band-pass-filtered, and integrated using commercially available software (MyoResearch XP, Noraxon U.S.A. Inc., AZ, U.S.A.). EMG amplitude was measured from EMG signals: (1) during MVC measurements, RMS of EMG was calculated based on a 500 ms time window centred on the highest force value, (2) during the exercise, RMS of EMG was calculated for each repetition based on a 500 ms time window centred on the highest value. All RMS of EMG measurements were normalized to pre-exercise MVC. Percent MVC-RMS of EMG during resistance exercise was compared between the two groups. The relationship between the percent increase in muscle CSA and the mean % MVC-RMS of EMG was also calculated.

Statistical analysis

All data are expressed as means \pm standard deviation. All statistical analyses were performed using SPSS for Windows version 21.0 (SPSS Statistics 21.0; IBM, Tokyo, Japan). The test-retest reliability of the circumference of the upper arm and muscle thickness measurements was evaluated using ICC. All tests and measurements were found to be reliable (ICCs ranged from 0.82 to 0.9, and no significant differences were detected between the mean test-retest values). A 2 \times 4 [resistance training experience (trained: $n = 14$ vs.

untrained: $n = 14$) × intervention of resistance training (before and 5, 30, 60 minutes after resistance exercise)] mixed-measures analysis of variance (ANOVA), with the Greenhouse-Geisser correction and Bonferroni pairwise comparisons, was used to analyse the differences in muscle CSA of the right triceps brachii and intracellular hydration. The unpaired t -test was used to compare the differences between two groups in area under the Oxy-Hb curve, blood lactate concentration 5 minutes after resistance exercise, and % MVC-RMS of EMG. Pearson's correlation coefficients were calculated for the relationships between muscle CSA, intracellular hydration, area under the Oxy-Hb curve during the exercise, blood lactate concentration, and % MVC-RMS of EMG. An alpha level of .05 was used to determine significance. The sample size was estimated using G*power. Effects sizes were calculated using means and SDs according to the methods of Cohen (1988). The effect size was assessed using the following criteria: < 0.10 = small; $0.10 - 0.4$ = moderate; and > 0.4 = large differences.

RESULTS

Changes in muscle CSA of triceps brachii muscle

Muscle CSA of the triceps brachii muscle before resistance exercise was 737.9 ± 132.3 cm² for the resistance-trained group and 336.5 ± 34.6 cm² for untrained group. Percent increases in muscle CSA in resistance-trained and untrained subjects at 5, 30, and 60 minutes after resistance exercise compared with the value before resistance exercise are shown in Figure 2. The percent increases in muscle CSA 5 minutes after resistance exercise were $120.2 \pm 6.3\%$ in trained and $105.5 \pm 2.3\%$ in untrained subjects. In both groups, there were significant increases in muscle CSA at 5 minutes after resistance exercise compared with the value before resistance exercise ($p < .01$). However, there was no significant difference between the values before and 30 minutes after resistance exercise. The percent increase in muscle CSA at 5 minutes after resistance exercise in the resistance-trained group was significantly larger than that in the untrained group ($p < .01$).

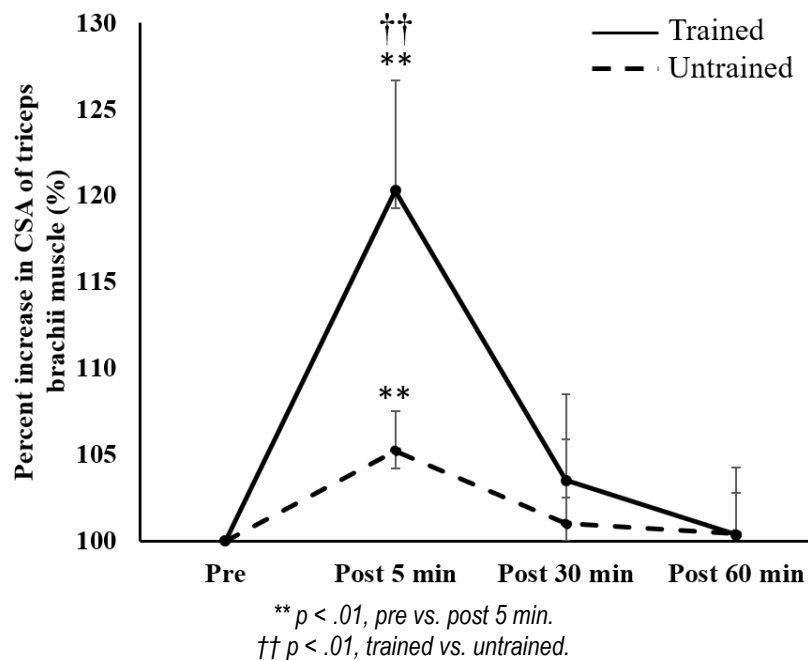


Figure 2. Percent increase in cross-sectional area (CSA) of triceps brachii muscle before (Pre), after (Post) 5 minutes, after 30 minutes, and after 60 minutes of resistance exercise.

Changes in intracellular hydration

Intracellular hydration values of the right upper limb before resistance exercise were 2.8 ± 0.2 L for the resistance-trained group and 2.0 ± 0.2 L for the untrained group. Intracellular hydration prior to resistance exercise was significantly larger in the resistance-trained group than in the untrained group. Percent increases in intracellular hydration of the two groups 5, 30, and 60 minutes after resistance exercise compared with the value before resistance exercise are shown in Figure 3. In the resistance-trained group, there was a significant increase in intracellular hydration at 5 minutes after resistance exercise compared with the value prior to resistance exercise ($p < .01$). However, there was no significant difference in the untrained group between the values before and 30 minutes after resistance exercise. The percent increase in intracellular hydration at 5 minutes after resistance exercise was significantly larger in the resistance-trained group than in the untrained group ($p < .01$). Furthermore, in the resistance-trained group there were significant correlations between the percent increase in muscle CSA at 5 minutes after resistance exercise and the percent increase in intracellular hydration at 5 minutes after resistance exercise ($r = 0.70$, $p < .01$). However, in the untrained group there was no significant correlation between the percent increase in muscle CSA at 5 minutes after resistance exercise and the percent increase in intracellular hydration at 5 minutes after resistance exercise ($r = 0.26$, $p = .35$) (Figure 4).

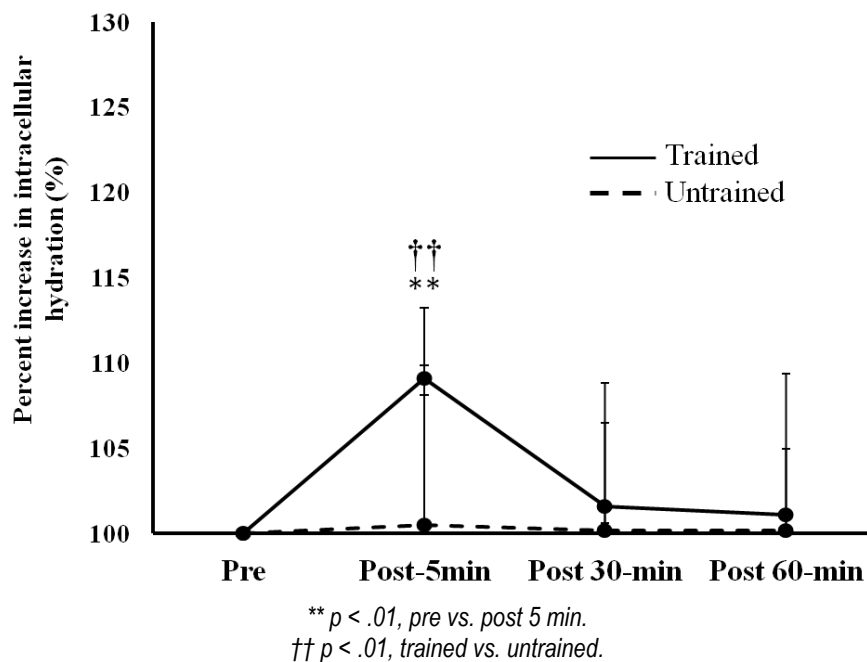


Figure 3. Percent increase in intracellular hydration of right upper arm before (Pre), after (Post) 5 minutes, after 30 minutes, and after 60 minutes of resistance exercise.

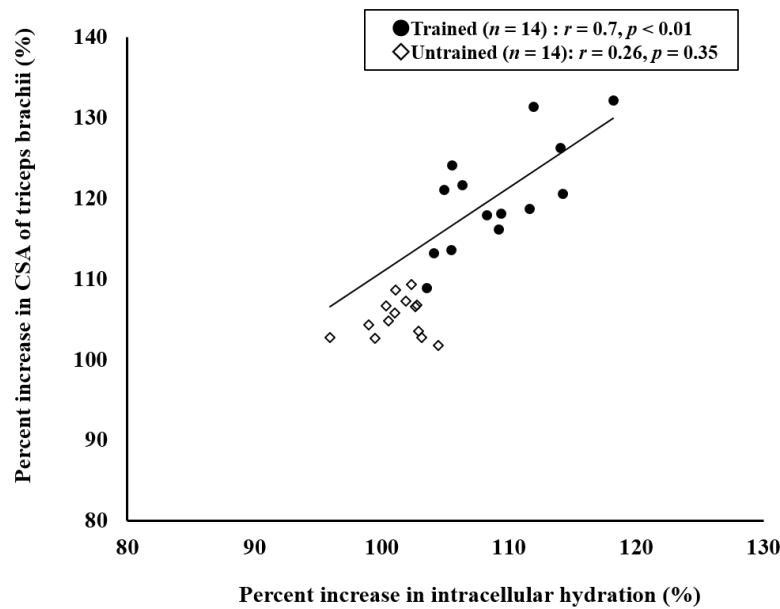


Figure 4. The relationship between percent increase in CSA of triceps brachii and intracellular hydration.

Area under the Oxy-Hb curve during resistance exercise

Figure 1 shows typical examples of changes in relative oxygenation levels in the right triceps brachii muscle before and during resistance exercise. Oxy-Hb levels decreased immediately as the exercise repetitions started, and then recovered quickly, followed by hyper compensation after the completion of the exercise repetitions. The value of the area under the OxyHb curve indicates the degree of sustained intramuscular hypoxia during resistance exercise. There was no significant difference in area under the Oxy-Hb curve between the resistance-trained and untrained groups ($p = .25$). The area under the Oxy-Hb curve was $42.0 \pm 5.1\% \cdot \text{sec}$ for the resistance-trained group and $39.8 \pm 4.6\% \cdot \text{sec}$ for the untrained group.

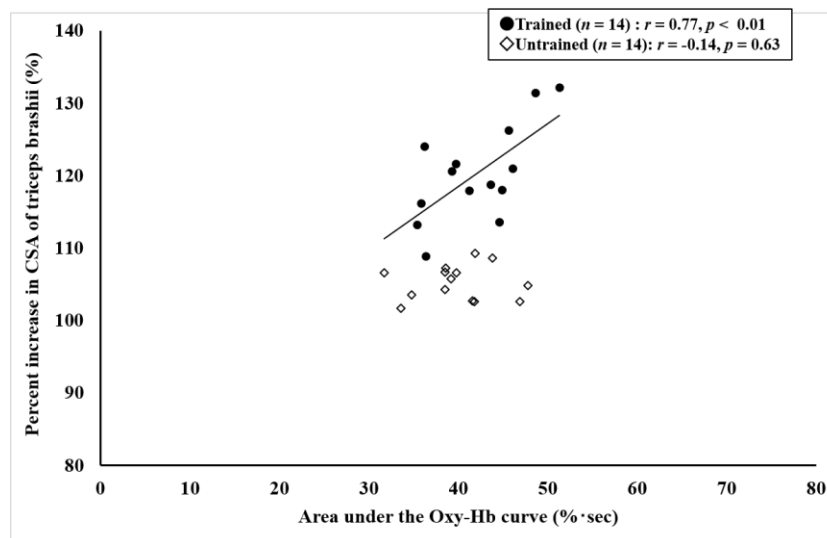


Figure 5. The relationship between percent increase in CSA of triceps brachii and area under the Oxy-Hb curve.

Furthermore, in the resistance-trained group there was a significant correlation between the percent increase in muscle CSA at 5 minutes after resistance exercise and area under the Oxy-Hb curve ($r = 0.77, p < .01$). However, in the untrained group there was no significant correlation between the percent increase in muscle CSA at 5 minutes after resistance exercise and area under the Oxy-Hb curve ($r = -0.14, p = .63$) (Figure 5).

Blood lactate concentration

Blood lactate concentrations were measured at rest and 5 minutes after resistance exercise, and the difference between them was calculated. Blood lactate concentration was 11.2 ± 1.2 mM for the resistance-trained group and 8.9 ± 0.9 mM for the untrained group. Blood lactate concentration was significantly higher in the resistance-trained group than in the untrained group ($p < .01$).

There were no significant correlations between the percent increase in muscle CSA at 5 minutes after resistance exercise and blood lactate concentration at 5 minutes after resistance exercise in either the resistance-trained ($r = 0.26, p = .36$) or untrained ($r = -0.07, p = .81$) groups (Figure 6).

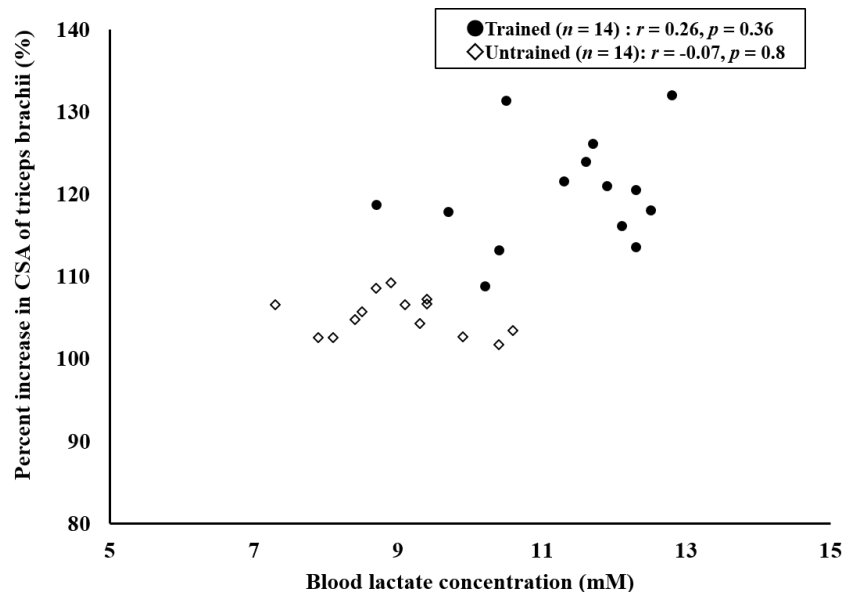


Figure 6. The relationship between percent increase in CSA of triceps brachii and blood lactate concentration after resistance exercise.

Electromyographic signal recording measurements

Percent MVC-RMS value of EMG recorded in the right triceps brachii muscle during resistance exercise were $78.7 \pm 2.8\%$ for the resistance-trained group and $67.8 \pm 2.5\%$ for untrained. Percent MVC-RMS of EMG was significantly higher in the resistance-trained than group in the untrained group ($p < .01$). Furthermore, in the resistance-trained group there was a significant correlation between the percent increase in muscle CSA at 5 minutes after resistance exercise and % MVC-RMS of EMG ($r = 0.71, p < .01$). However, in the untrained group there was no significant correlation between the percent increase in muscle CSA at 5 minutes after resistance exercise and % MVC-RMS of EMG ($r = -0.29, p = .31$) (Figure 7).

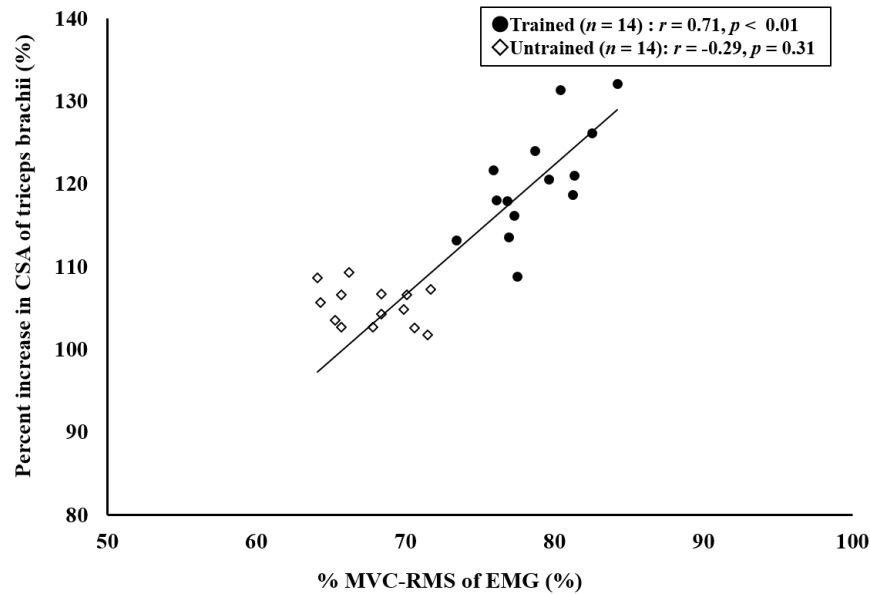


Figure 7. The relationship between percent increase in CSA of triceps brachii and % MVC-RMS of EMG during resistance exercise.

DISCUSSION

In the present study, changes in muscle CSA and intracellular hydration as acute effects of resistance exercise were compared between resistance-trained and untrained groups. The relationships between percent increase in muscle CSA at 5 minutes after resistance exercise, and intracellular hydration at 5 minutes after resistance exercise, blood lactate concentration at 5 minutes after resistance exercise, area under the Oxy-Hb curve during resistance exercise, and % MVC-RMS of EMG during resistance exercise were also examined.

At 5 minutes after resistance exercise, muscle CSA increased significantly to $120.2 \pm 6.3\%$ in the resistance-trained group and $105.5 \pm 2.3\%$ in the untrained group, compared with the values prior to resistance exercise. At 30 minutes after resistance exercise, the value of muscle CSA returned to the original size as at rest in both groups. There was a significant difference in the percent increase 5 minutes after resistance exercise between resistance-trained and untrained groups, and value in the resistance-trained were significantly greater than that in the untrained group. The intracellular hydration 5 minutes after resistance exercise in the resistance-trained group was significantly increased to $109.1 \pm 4.2\%$ compared with that before resistance exercise. Furthermore, there were positive correlations between the percent increase in muscle CSA at 5 minutes after resistance exercise and intracellular hydration at 5 minutes after resistance exercise ($r = 0.70$, $p < .01$), the area under the Oxy-Hb curve ($r = 0.67$, $p < .01$), and % MVC-RMS of EMG ($r = 0.71$, $p < .01$). The reason for muscle CSA and intracellular hydration at 5 minutes after resistance exercise in resistance-trained group being greater than that in untrained group might be due to differences in original muscle size, resistance exercise-induced metabolic responses, and motor unit activation between two groups. Sustained intramuscular hypoxia is facilitated by intramuscular capillary compression with greater muscle contraction (Goto et al., 2019). As a result, the glycolysis metabolism might be promoted and post resistance exercise intracellular hydration and muscle CSA might increase (Frigeri et al., 1998). As the Oxy-Hb wave of NIRS in Figure 1 shows, the reactive hyperaemia immediately after intramuscular hypoxia due to muscle contraction

might induce intracellular hydration. Blood lactate concentrations increased significantly 5 minutes after resistance exercise, but there was no correlation between the percent increase in muscle CSA and the blood lactate concentration at 5 minutes after resistance exercise. This lack of correlation may have been due to the resistance exercise being performed only on the triceps brachii muscle, which is a part of the upper limb. In the resistance-trained group, resistance exercise with greater intramuscular hypoxia and motor unit activation can make it possible to promote post resistance exercise intracellular hydration and may result in an increase in protein synthesis and a decrease in proteolysis (Lang et al., 1998).

On the other hand, muscle CSA and intracellular hydration in the untrained group increased less than in the resistance-trained group. There were also no correlations between the percent increase in muscle CSA at 5 minutes after resistance exercise and intracellular hydration ($r = 0.26, p = .35$), the area under the Oxy-Hb curve ($r = -0.14, p = .63$) or % MVC-RMS of EMG ($r = -0.29, p = .31$). Muscle CSA prior to resistance exercise in the untrained group was $336.5 \pm 34.6 \text{ cm}^2$, which was almost half the resistance-trained group muscle CSA, $737.9 \pm 132.3 \text{ cm}^2$. The smaller muscle volume of the untrained group might explain why the muscle CSA and intracellular hydration did not increase after resistance exercise as the resistance-trained group showed. It has been reported that the amounts of adenosine triphosphate, adenosine diphosphate, glycogen, and creatine phosphate in untrained individuals are smaller than those of resistance-trained peers (MacDougall et al., 1977). Limitations in high threshold motor unit activation (Adams et al., 1993), lower glycolytic energy metabolism, and the feature of the Inbody S10 that intracellular hydration is measured in each limb, not in each muscle, might explain the absence of increase in intracellular hydration after resistance exercise in the untrained group.

CONCLUSION

Acute increase in muscle CSA after resistance exercise, known as muscle swelling or muscle pump, increased significantly 5 minutes after resistance exercise in both resistance-trained and untrained groups. There was a difference in acute muscle CSA increase between the resistance-trained and untrained groups, with the resistance-trained group showing a greater percent increase in muscle CSA. Within 30 minutes, the increased muscle CSA returned to the original size before resistance exercise in both groups. There were positive correlations between the acute increase in muscle CSA after resistance exercise and sustained intramuscular hypoxia and % MVC-RMS of EMG. These results suggest that measuring muscle CSA in studies of muscle hypertrophy should be performed 30 minutes or more after the last resistance exercise session because of this muscle swelling as acute effect of resistance exercise. In contrast, at bodybuilding and physique contests, muscle pump exercises should be conducted just before performance. As it is assumed that weight-bearing and non-weight-bearing muscles react differently to a particular exercise (Zhang et al., 2010), the results of this study might be applicable only to upper limb muscles.

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