Downloaded from http://journals.lww.com/nsca-jscr by BJUxp2M3YpfdwbM14xNmYUDU4IBtO6VyGYyK0PbipMALws AOB2MZBaYW/FIRDiGxSX0a4WW42tsjk2maoK3sv7d4nXmF1yQNYrPBow0tDGyXz3D0qfMzxj5ZBBJHc on 04/10/2023

# Relationship Between Muscle Swelling and Hypertrophy Induced by Resistance Training

**Tetsuya Hirono,[1,2] Tome Ikezoe,[1] Masashi Taniguchi,[1] Hiroki Tanaka,[1,3] Junya Saeki,[2,4] Masahide Yagi,[1] Jun Umehara,[1,2] and Noriaki Ichihashi[1]**

*[1]Human Health Sciences, Graduate School of Medicine, Kyoto University, Kyoto, Japan; [2]Japan Society for the Promotion of Science, Tokyo, Japan; [3]Rehabilitation Unit, Kyoto University Hospital, Kyoto, Japan; and [4]Faculty of Sport Sciences, Waseda University, Saitama, Japan*

**Abstract**

Hirono, T, Ikezoe, T, Taniguchi, M, Tanaka, H, Saeki, J, Yagi, M, Umehara, J, and Ichihashi, N. Relationship between muscle swelling and hypertrophy induced by resistance training. *J Strength Cond Res* 36(2): 359–364, 2022—Muscle swelling immediately after resistance exercise may be induced by metabolic stress. The accumulation of metabolic stress is considered to promote muscle hypertrophy after several weeks of resistance training (RT). The purpose of this study was to determine the relationship between muscle swelling immediately after the first session of RT and muscle hypertrophy after a 6-week RT using ultrasonography. Twenty-two untrained young men performed knee extension resistance exercise consisting of 3 sets with 8 repetitions at a load of 80% of one repetition maximum for 6 weeks (3 d·wk$^{-1}$). Muscle thickness of the quadriceps femoris was measured using ultrasonography device at 3 anatomical sites (proximal, medial, and distal sites) of the middle, lateral, and medial part of the anterior thigh. The sum of the muscle thickness at 9 measurement sites was used for analysis. Acute change in muscle thickness immediately after the first session of RT was used as an indicator of muscle swelling. Chronic change in muscle thickness after the 6-week RT was used as an indicator of muscle hypertrophy. A significant increase in muscle thickness was observed immediately after the first session of RT (8.3 ± 3.2%, $p < 0.001$). After the 6-week RT, muscle thickness increased significantly (2.9 ± 2.6%, $p < 0.001$). A significant positive correlation was found between muscle swelling and muscle hypertrophy ($\rho = 0.443$, $p = 0.039$). This study suggests that the greater the muscle swelling immediately after the first session of RT, the greater the muscle hypertrophy after RT.

**Key Words:** muscle hypertrophy, resistance training, knee extension, ultrasound, muscle thickness

## Introduction

Resistance training (RT) is effective in increasing muscle mass or preventing muscle atrophy. High-intensity RT using more than 60% of a one repetition maximum (1RM) load for more than 6 weeks has been recommended to obtain the effect of muscle hypertrophy (1,4). Regarding the mechanisms of increases in muscle mass, mechanical and metabolic stress caused by muscle tension or muscle damages has been reported to initiate anabolic signaling pathways, which lead to muscle hypertrophy (23). The regular performance of progressive RT positively promotes anabolic signaling to cause a more positive balance of protein synthesis than protein degradation, facilitating gains in muscle mass in 6 weeks (19).

After resistance exercise, metabolic stress products such as growth hormone and reactive oxygen species are produced concurrently and play an important role in activating the mammalian target of rapamycin and muscle protein synthesis (5,28). Muscle swelling immediately after resistance exercise is also a more novel mechanism that might be involved in the hypertrophic response to metabolic stress (5,22,23,29). Muscle swelling occurs as a result of the following: (a) resistance exercise can increase phosphocreatine and hydrogen ion accumulations due to blood lactate and growth hormone production (8), and (b) the high lactate and hydrogen ion concentrations may accelerate water uptake in muscle cells according to cell permeability (21,31) because the molecular weights of the lactate and hydrogen ions are smaller than that of muscle glycogen. Peeze Binkhorst et al. (18) reported that exercise-induced muscle swelling is due to increased wet weight because of increased interstitial volume in an animal experiment. In vivo study, Sjogaard et al. (25) also reported that swelling is maximized during exercise that relies heavily on anaerobic metabolism, due to the osmotic changes caused by lactate accumulation. Previous studies that used bioimpedance spectroscopy suggested that changes in intracellular and extracellular water balance after changes in ion concentration were associated with metabolic changes in skeletal muscle cell after exercise (20,26). Thus, muscle swelling occurs due to the alteration of intracellular and extracellular water balance induced by increased vascular permeability, which can also mediate osmolytes (9,12,13,16). Therefore, muscle swelling can be an indirect indicator of the accumulation of metabolic stress.

Muscle hypertrophy is the result of cumulative periods of positive muscle protein synthesis. Considering that metabolic stress can contribute to muscle hypertrophy adaptations (23), the measurement of acute muscle swelling after resistance exercise may be a good predictor of subsequent muscle hypertrophy. For instance, Bellamy et al. (2) revealed that a significant correlation between acute satellite cell response assessed using muscle biopsies and muscle hypertrophy

*Address correspondence to Tetsuya Hirono, MSc, hirono.tetsuya.56x@st.kyoto-u.ac.jp.*

*Supplemental digital content is available for this article. Direct URL citations appear in the printed text and are provided in the HTML and PDF versions of this article on the journal's Web site (http://journals.lww.com/nsca-jscr).*

*Journal of Strength and Conditioning Research 36(2)/359–364*

*© 2020 National Strength and Conditioning Association*



Copyright © 2020 National Strength and Conditioning Association. Unauthorized reproduction of this article is prohibited.

Downloaded from http://journals.lww.com/nsca-jscr by BJUxp2M3Ypfdwb M14xNmYUDU4lBtO6VyGYyK0PbipMALws AOBzMZBaYW/FlRDiGxSX0a4WW42tsjk2tmaoK3sv7d4nXmF1yQNYrPBow0tDGyXz3D0qfMzxj5ZBBJHc on 04/10/2023

after RT. With regard to muscle cell swelling, resistance exercise with high training volume induced larger muscle swelling than resistance exercise with less training volume (10). Considering that high training volume causes more severe muscle hypertrophy (24), greater muscle swelling could induce a greater anabolic signaling response and promote muscle hypertrophy. In addition, regarding RT with blood flow restriction (BFR), Fahs et al. (6) and Farup et al. (7) investigated acute swelling and chronic muscle hypertrophy. The results revealed similar acute muscle swelling and chronic muscle hypertrophy between the 2 groups with and without BFR, even with low-load training intensity. Considering these BFR studies, muscle swelling could be related to chronic muscle hypertrophy. However, to the best of our knowledge, no study has examined the relationship between muscle swelling immediately after exercise and muscle hypertrophy induced by several weeks of RT. If greater muscle swelling immediately after resistance exercise can cause greater chronic effects of muscle hypertrophy, assessment of muscle swelling immediately after the first session of RT may predict future effects of muscle hypertrophy. Therefore, the assessment of muscle swelling might lead to more effective RT program prescriptions of physical training for sports athletes.

For measurement of muscle swelling, changes in muscle thickness or cross-sectional area were used in many studies (3,6,7,10,15,29,32). Ultrasound is a relatively inexpensive and noninvasive method for the assessment of skeletal muscle and can be used immediately after exercise. Thus, the purpose of this study was to investigate whether the immediate increase in muscle thickness after resistance exercise, i.e., muscle swelling, is related to muscle hypertrophy after a 6-week RT. We hypothesized that there would be a positive correlation between muscle swelling immediately after the first session of RT and muscle hypertrophy after the 6-week RT.

## Methods

### Experimental Approach to the Problem

The experimental design of this study was an observational study with an intervention for single group. The experimental protocol is shown in Figure 1. The RT of knee extension was performed on the dominant leg, which was determined by what they would use to kick a ball. All the subjects visited the laboratory for assessment of knee extension strength and muscle thickness of the quadriceps femoris muscle before (PRE) and after (POST) the training program that included 18 sessions of RT over a 6-week training period (RT1–RT18; Figure 1). The previous assessment session (PRE) was separated more than 1 week before the first session of RT (RT1). In the first session of RT (RT1), muscle thickness of the quadriceps femoris was measured before (baseline) and immediately (0 minutes), 5, 10, and 15 minutes after resistance exercise. The acute change in muscle thickness from baseline was determined as an index of muscle swelling. After these measurements, RT for knee extensors was performed in 18 sessions, 3 days per week for 6 weeks. The final assessment session (POST) was conducted 3–7 days after the last training session (RT18). The chronic change in muscle thickness from PRE to POST was determined as an index of muscle hypertrophy. We analyzed the relationship between the index of muscle swelling and the index of muscle hypertrophy.

### Subjects

The sample size was calculated using G*Power 3.1 software (Heinrich Hein University, Düsseldorf, Germany) with an $\alpha$ error = 0.05, power = 0.8, and effect size = 0.5, which showed that 26 subjects were necessary for the correlation analysis. Therefore, 26 healthy young men (24 ± 6.3 years, range; 20–35) participated in this study. None of the included subjects were athletes or in regular RT. Subjects with a history of neuromuscular disorders or surgery in a training leg were excluded.

The purpose and procedures were explained to the subjects before they gave informed written consent for participation in the study. The study was conducted in accordance with the Declaration of Helsinki and approved by the ethics committee of Kyoto University Graduate School and the Faculty of Medicine (C1294). This trial is registered with the UMIN Clinical Trials Registry.

### Procedures

*Measurements of Knee Extension Strength*. The 1RM test was performed using the isotonic mode of a dynamometer (Biodex System 4; Biodex Medical Systems, Inc., Shirley, NY) by increasing load every 5 N·m. The subjects sat on the dynamometer seat with belts fastened across their trunk and pelvis. The subjects were required to move their leg through the required full range of motion (knee

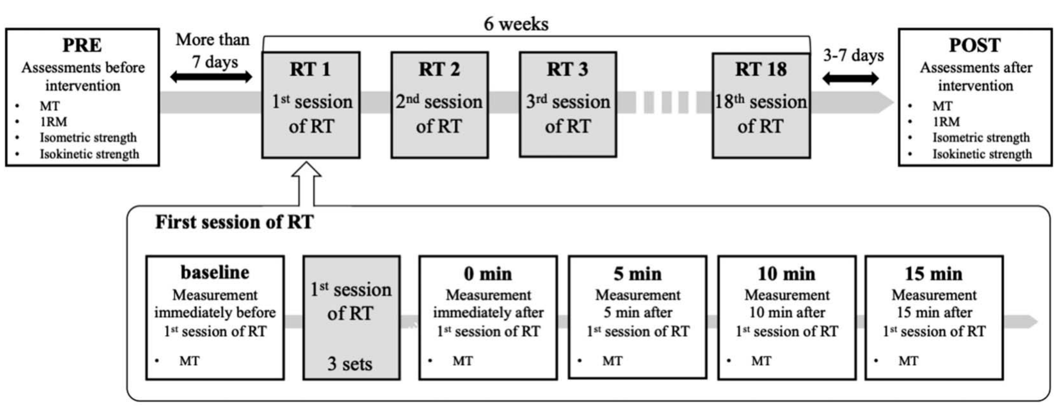


**Figure 1.** The resistance training of knee extension was performed for 6 weeks. All the subjects visited the laboratory for assessments of knee extension strength and muscle thickness before (PRE) and after (POST) 6-week resistance training. Eighteen sessions of resistance training over the 6-week training period were performed (RT1–RT18). In RT1, muscle thickness of quadriceps femoris was measured before (baseline) and immediately (0 minutes), 5, 10, and 15 minutes after resistance exercise to assess muscle swelling. MT, muscle thickness; 1RM = one repetition maximum; RT = resistance training.



Copyright © 2020 National Strength and Conditioning Association. Unauthorized reproduction of this article is prohibited.

Downloaded from http://journals.lww.com/nsca-jscr by BJUxp2M3YpfdwbM14xNmYUDU4IBt06VyGYyK0PbipMALwsAOBzMZBaYW/FIRDGxSX0a4WW42tsjk2tmaoK3sv7d4hXmF1yQNYrPBow0tDGyXz3D0qfMzjSZBBJHc on 04/10/2023

flexion 90–20°) against the set load. The 1RM was defined as the maximum load in which the subject could complete one repetition through the range of motion. Each trial was separated by adequate rest periods of more than 2 minutes. Maximum isometric strength with knee angles at 90 and 70° was measured using the isometric mode of the dynamometer. The subjects were instructed to hold maximum voluntary contraction for 3 seconds. Maximum isokinetic strength through a knee angle range of 110–20° with contraction speeds of 90° and 180·s$^{-1}$ was measured using the isokinetic mode of the dynamometer. Measurements of 1RM, isometric strength, and isokinetic strength were performed randomly one time with interval periods of more than 2 minutes.

*Measurements of Muscle Thickness*. Muscle thickness of the quadriceps femoris was measured using a B-mode ultrasonography device (Noblus; Hitachi Aloka Medical Systems, Tokyo, Japan) with a linear-array probe (4.0 cm). The subjects were instructed to lie in the supine position and relax completely. Based on a previous study (11), muscle thickness of the quadriceps femoris was obtained at 9 sites, which consisted of proximal, median, and distal sites on the middle, lateral, and medial part of the anterior thigh. Measurements of the middle part were taken at 30, 50, and 70% of the distance from the anterior superior iliac spine to the superior border of the patella. Measurements of the lateral part were taken at 30, 50, and 70% of the distance from the greater trochanter to the lateral condyle of the femur. Measurements of the medial part were taken at 70, 80, and 90% of the distance from the anterior superior iliac spine to the joint space in front of the anterior border of the medial collateral ligament. Wakahara et al. (30) reported that muscle hypertrophy occurred nonuniformly between the proximal and distal parts of the muscle. Therefore, 9 sites of the quadriceps were measured in this study, since muscle swelling might also differ between the proximal and distal parts of the muscle. Muscle thickness was determined as the distance between the muscle fasciae and bone interface, and the sum of measurements of the 9 sites was used in the analysis. To replicate the images between the baseline and after training, we verified that the distances between the landmarks were equal before the measurements. Interday reliability of measurement of muscle thickness was assessed by calculating the intraclass correlation coefficient (ICC) (1,1) using the values of the 2 measurements at baseline and before the first session. The ICC (1,1) value was 0.961, which was confirmed as having high reliability. In addition, the *SEM* of the difference in muscle thickness between baseline and immediately before first session was 1.06 mm. The percent change in muscle thickness after the first session of RT was the indicator of muscle swelling. The percent change in muscle thickness after the 6-week training intervention was the indicator of muscle hypertrophy. When we analyzed absolute changes in muscle thickness, we found that the results were similar to those based on percentage changes, indicating that using neither absolute changes nor relative changes influenced the interpretation (see Figure, Supplemental Digital Content 1, http://links.lww.com/JSCR/A175).

*Resistance Training*. The subjects performed resistance exercise on knee extension using a dynamometer (Biodex System 4; Biodex Medical Systems). The training load was set at 80% 1RM, based on the 1RM measurements at PRE session. The subjects sat on the dynamometer seat with belts fastened across their trunk and pelvis. The subjects performed knee extension through a knee flexion range of 90–20° with a speed of 1-second concentric contraction, 1-second eccentric contraction, and 1-second rest period according to 60 b·min$^{-1}$ made by a metronome. The session of resistance exercise consisted of 3 sets of 8 repetitions with a rest interval of 60 seconds. The RT was performed 3 days per week for 6 weeks.

### Statistical Analyses

All data were analyzed using SPSS version 22.0 software (IBM Japan, Inc., Tokyo, Japan). A one-way repeated-measures analysis of variance (ANOVA) with post hoc Bonferroni test was performed to analyze the acute changes in muscle thickness after the first session of RT. Paired *t*-tests were performed to investigate the effects of RT intervention on 1RM, maximum isometric strength, maximum isokinetic strength, and muscle thickness. The 95% confidence interval and effect size in baseline and after 6-week training were calculated. In addition, Spearman correlation coefficients were used to examine the association between percent changes in muscle thickness after the first session of RT (0, 5, 10, and 15 minutes) and percent changes in muscle thickness after the 6-week RT. Statistical significance was set at an alpha level of 0.05.

## Results

Twenty-five subjects completed the 6-week RT session. One subject dropped out, and the data of 3 subjects could not be obtained completely. Therefore, 22 young men (age; 25 ± 4 years, height; 172 ± 5 cm, body mass; 67 ± 10 kg) completed the analyses (Figure 2).

The one-way ANOVA showed a significant main effect of acute changes in muscle thickness of the quadriceps. Post hoc test revealed that muscle thicknesses at 0, 5, 10, and 15 minutes immediately after the first session of RT were significantly greater compared with baseline (Figure 3). As for time course of acute change from 0 to 15 minutes after exercise, significant decreases in muscle thickness were observed between all times.

The paired *t*-tests showed significant increases in 1RM, maximal isometric strength, maximal isokinetic strength, and muscle thickness after the 6-week RT (Table 1).

The Spearman correlation coefficient revealed the significant positive correlations between the change in muscle thickness after the 6-week RT and acute changes in muscle thickness at 0 minutes ($\rho = 0.443$, $p = 0.039$), 5 minutes ($\rho = 0.582$, $p = 0.004$), 10 minutes ($\rho = 0.596$, $p = 0.003$), and 15 minutes ($\rho = 0.443$, $p = 0.039$) immediately after the first session of RT (Figure 4).

## Discussion

This study investigated the relationship between muscle swelling immediately after the first session of RT and muscle hypertrophy after 6 weeks of RT. Our hypothesis was that muscle swelling in the first session of RT would be associated with muscle

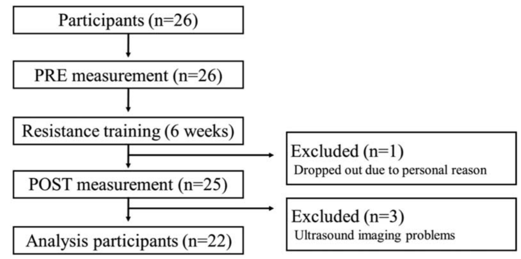


**Figure 2.** Twenty-six healthy young men participated in this study. Twenty-five subjects completed the 6-week RT session. One subject dropped out, and the data of 3 subjects could not be obtained completely. Therefore, 22 young men completed the analyses. RT = resistance training.



Copyright © 2020 National Strength and Conditioning Association. Unauthorized reproduction of this article is prohibited.

Downloaded from http://journals.lww.com/nsca-jscr by BJUxp2M3YpfdwbM14xNmYUDU4IBtO6VyGYyK0PbipMALwsAOBzMZBaYW/FIRDtGxSX0a4WW42tsjk2tmaoK3sv7d4hXmF1yQNYrPBow0tDGyXz3D0qf/MzxjSZBBJHc on 04/10/2023

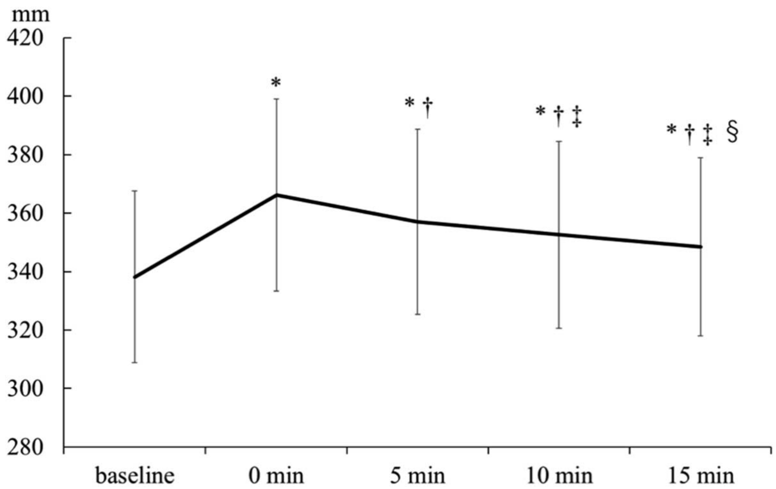


**Figure 3.** Acute changes in muscle thickness immediately after the first session of resistance training. The one-way ANOVA showed a significant main effect of acute changes in muscle thickness of the quadriceps. Post hoc test revealed that muscle thicknesses at 0, 5, 10, and 15 minutes immediately after the first session of RT were significantly greater compared with baseline. Values are mean ± *SD*: $n = 22$. Significance was set at $p < 0.05$. *Significant difference from baseline. †Significant difference from 0 minutes. ‡Significant difference from 5 minutes. §Significant difference from 10 minutes. ANOVA = analysis of variance; RT = resistance training.

hypertrophy. To determine the relationship between acute muscle swelling and chronic muscle hypertrophy, affecting factors should be eliminated as much as possible. As the aim of this study was to investigate the acute effects of the first session of RT on the chronic effects, training load was not changed from the first session. The results showed that resistance exercise with a load of 80% of 1RM caused muscle swelling, and that muscle hypertrophy was observed after the 6-week RT program, although the training load was not changed throughout the intervention. Furthermore, this study revealed that each muscle swelling obtained at 0, 5, 10, and 15 minutes after the first session of RT had significant positive correlations with the muscle hypertrophy caused by the 6-week intervention. These results support our hypothesis. This is the first study to reveal the relationship between muscle swelling immediately after resistance exercise and muscle hypertrophy after RT.

In our study, muscle thickness increased by 2.9 ± 2.6% and 1RM increased by 25.4 ± 9.6% after the 6-week RT. Tanimoto and Ishii (27) investigated the effect of a 12-week knee extension RT at 80% 1RM, which was similar to our RT protocol, and reported that the cross-sectional area (CSA) of the knee extensor muscle increased by 4.3 ± 2.1% and the 1RM increased by approximately 32% (from 104.9 ± 18.6 to 138.3 ± 18.6 kg). Since RT of this study was performed for only 6 weeks, magnitudes of improved muscle thickness and muscle strength were smaller than those of the previous study.

This study showed that muscle swelling immediately after the first session of RT was associated with muscle hypertrophy after the 6-week intervention. Muscle swelling immediately after exercise is a response to metabolic stress to the skeletal muscle (14,23). Although multiple metabolic stress markers such as hormonal release or reactive oxygen species production can be associated with muscle hypertrophy (5,23), the result of this study suggested a possibility that only the acute response assessed with the changes in muscle thickness using an ultrasonography device could affect the subsequent muscle hypertrophy. Acute muscle swelling is caused by water uptake in muscle cell according to phosphocreatine and hydrogen ion accumulation due to blood lactate and growth hormone production (8,21,31), which can promote anabolic protein synthesis. Therefore, greater acute muscle swelling might be associated with greater chronic muscle hypertrophy. Because muscle hypertrophy is caused by repeated sessions of RT (19), it is possible that the amount of mechanical or metabolic stress in the skeletal muscle induced by one session of RT could predict muscle hypertrophy after repeated sessions of RT for several weeks. In general, the effects of muscle hypertrophy can be obtained by more than 6 weeks of RT (1,4). Therefore, to evaluate the effect of muscle hypertrophy, a long-term

**Table 1**

**Changes in muscle strength and muscle thickness after the 6-week resistance training.*†**

| | Before RT | After RT | *p* | Percent changes [%] | Effect size (*r*) | 95% confidence intervals |
|---|---|---|---|---|---|---|
| 1RM (N·m) | 192.3 ± 35.3 | 240.7 ± 43.9 | <0.001 | 25.4 ± 9.8 | 0.93 | 40.0–56.9 |
| Maximum isometric strength at 90° (N·m) | 196.4 ± 44.9 | 237.0 ± 44.5 | <0.001 | 22.2 ± 15.3 | 0.87 | 30.2–50.9 |
| Maximum isometric strength at 70° (N·m) | 236.7 ± 47.7 | 266.2 ± 50.7 | <0.001 | 13.2 ± 12.0 | 0.74 | 17.2–41.9 |
| Maximum isokinetic strength at $90 \cdot s^{-1}$ (N·m) | 165.1 ± 32.8 | 199.3 ± 25.0 | <0.001 | 24.5 ± 25.9 | 0.80 | 22.5–46.0 |
| Maximum isokinetic strength at $180 \cdot s^{-1}$ (N·m) | 132.0 ± 24.0 | 151.4 ± 18.4 | <0.001 | 17.0 ± 18.7 | 0.74 | 11.5–27.3 |
| Muscle thickness of the quadriceps femoris (mm) | 340.1 ± 30.2 | 349.9 ± 29.6 | <0.001 | 2.9 ± 2.7 | 0.76 | 6.0–13.6 |

*1RM = one repetition maximum; RT = resistance training.

†Values are mean ± *SD*. Muscle thickness of the quadriceps femoris was calculated by the sum of 9 measurement sites.



Copyright © 2020 National Strength and Conditioning Association. Unauthorized reproduction of this article is prohibited.

Downloaded from http://journals.lww.com/nsca-jscr by BJUxp2M3YpfdwbM14xNmYUDU4IBtO6VyGYyK0PbipMALvws AOBzMZBaYW/FIRDtGxSX0a4WW42tsjk2tmaoK3sv7d4hXmF1yQNYrPBow0tDGyXz3D0qfMzxj5ZBBJHc on 04/10/2023

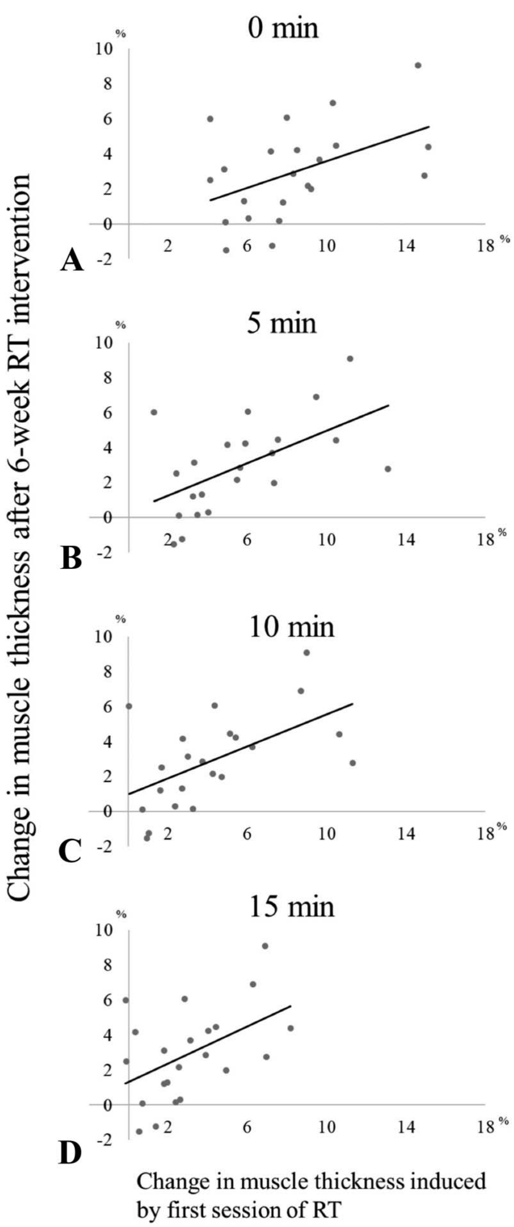


**Figure 4.** The relationship between changes in muscle thickness immediately after the first session of resistance training and after 6-week resistance training ($n$ = 22). The Spearman correlation coefficient revealed significant positive correlations between the change in muscle thickness after 6-week resistance training and acute changes in muscle thickness at 0 minutes (A; $\rho = 0.443$, $p = 0.039$), 5 minutes (B; $\rho = 0.582$, $p = 0.004$), 10 minutes (C; $\rho = 0.596$, $p = 0.003$), and 15 minutes (D; $\rho = 0.443$, $p = 0.039$) immediately after the first session of resistance training. RT = resistance training.

intervention period is required. This study revealed a positive relationship between muscle swelling immediately after resistance exercise and muscle hypertrophy induced by the 6-week RT. The results suggest that the assessment of muscle swelling immediately after resistance exercise could possibly predict an effect of muscle hypertrophy in the future. The noninvasive and immediate measurement of muscle swelling may be useful in the prescription of a more effective RT program.

In contrast to our findings, previous studies showed no relationship between acute and chronic effects of RT. Mitchell et al. (17) reported that acute effects of myofibrillar protein synthesis after initial exposure to resistance exercise were not correlated with muscle hypertrophy after chronic RT. Damas et al. (4) also reported that initial RT-induced muscle damage possibly drives myofibrillar protein synthesis toward muscle remodeling, not hypertrophy. The physiological mechanism in exercise-induced muscle damage and remodeling has been incompletely resolved. Although Mitchell et al. (17) investigated muscle biopsies obtained from one site of the vastus lateralis, the current study assessed muscle thickness from 9 sites on the anterior thigh using an ultrasonography device. There is a difference in the assessments between these studies, but this contradiction is not explained from our data. Further studies are necessary to investigate the mechanism.

This study had some limitations. First, we could not measure the volume of blood flow or blood test data; nevertheless, muscle swelling was affected by physiological functions such as blood flow or metabolic materials (22,23). In addition, the characteristics of the skeletal muscle such as muscle fiber size and muscle fiber type could also not be examined using muscle biopsy. However, our results showed a positive correlation between muscle hypertrophy and muscle swelling, which suggests that assessment of muscle swelling using ultrasonography images could predict the magnitude of muscle hypertrophy. The second limitation was the small sample size due to data availability. Finally, we examined only the training protocol with load of 80% 1RM and 6-week intervention. Thus, it is unclear whether other training protocols (e.g., low-load training or long duration of intervention) lead to a similar result of this study. Future studies are needed to examine various RT protocols such as low-load RT and high-repetition RT.

In conclusion, this study investigated the relationship between muscle swelling immediately after the first session of RT and muscle hypertrophy after a 6-week RT in untrained healthy young men. The results revealed a significant positive correlation between muscle swelling and muscle hypertrophy. The results of this study suggest that the assessment of changes in muscle thickness immediately after the first session of RT could predict the magnitude of chronic effects of muscle hypertrophy in the future.

## Practical Applications

This result suggested that an assessment of immediate change in muscle thickness in the first session of RT using ultrasonography device could be a possible predictor of the chronic effect of muscle hypertrophy. Evaluating the change in muscle thickness immediately after exercise may be useful for prescribing the effective training protocol in accordance with the subjects.

## Acknowledgments

The authors thank all the subjects for their cooperation in this study. This study was not funded by any institutions, agencies, or companies.

## References

1. American College of Sports Medicine. American College of Sports Medicine position stand. Progression models in resistance training for healthy adults. *Med Sci Sports Exerc* 41: 687–708, 2009.
2. Bellamy LM, Joanisse S, Grubb A, et al. The acute satellite cell response and skeletal muscle hypertrophy following resistance training. *PLoS One* 9: e109739, 2014.



Copyright © 2020 National Strength and Conditioning Association. Unauthorized reproduction of this article is prohibited.

3. Buckner SL, Dankel SJ, Counts BR, et al. Influence of cuff material on blood flow restriction stimulus in the upper body. *J Physiol Sci* 67: 207–215, 2017.
4. Damas F, Libardi CA, Ugrinowitsch C. The development of skeletal muscle hypertrophy through resistance training: The role of muscle damage and muscle protein synthesis. *Eur J Appl Physiol* 118: 485–500, 2018.
5. de Freitas MC, Gerosa-Neto J, Zanchi NE, Lira FS, Rossi FE. Role of metabolic stress for enhancing muscle adaptations: Practical applications. *World J Methodol* 7: 46–54, 2017.
6. Fahs CA, Loenneke JP, Thiebaud RS, et al. Muscular adaptations to fatiguing exercise with and without blood flow restriction. *Clin Physiol Funct Imaging* 35: 167–176, 2015.
7. Farup J, de Paoli F, Bjerg K, et al. Blood flow restricted and traditional resistance training performed to fatigue produce equal muscle hypertrophy. *Scand J Med Sci Sports* 25: 754–763, 2015.
8. Gonzalez AM, Hoffman JR, Townsend JR, et al. Intramuscular anabolic signaling and endocrine response following high volume and high intensity resistance exercise protocols in trained men. *Physiol Rep* 3: e12466, 2015.
9. Häussinger D, Lang F, Gerok W. Regulation of cell function by the cellular hydration state. *Am J Physiol* 267: E343–E355, 1994.
10. Jenkins ND, Housh TJ, Bergstrom HC, et al. Muscle activation during three sets to failure at 80 vs. 30% 1RM resistance exercise. *Eur J Appl Physiol* 115: 2335–2347, 2015.
11. Jenkins NDM, Miramonti AA, Hill EC, et al. Greater neural adaptations following high- vs. low-load resistance training. *Front Physiol* 8: 331, 2017.
12. Lambert IH, Hoffmann EK, Pedersen SF. Cell volume regulation: Physiology and pathophysiology. *Acta Physiol (Oxf)* 194: 255–282, 2008.
13. Lang F, Busch GL, Ritter M, et al. Functional significance of cell volume regulatory mechanisms. *Physiol Rev* 78: 247–306, 1998.
14. Loenneke JP, Fahs CA, Rossow LM, Abe T, Bemben MG. The anabolic benefits of venous blood flow restriction training may be induced by muscle cell swelling. *Med Hypotheses* 78: 151–154, 2012.
15. Loenneke JP, Fahs CA, Thiebaud RS, et al. The acute muscle swelling effects of blood flow restriction. *Acta Physiol Hung* 99: 400–410, 2012.
16. Low SY, Rennie MJ, Taylor PM. Signaling elements involved in amino acid transport responses to altered muscle cell volume. *FASEB J* 11: 1111–1117, 1997.
17. Mitchell CJ, Churchward-Venne TA, Parise G, et al. Acute post-exercise myofibrillar protein synthesis is not correlated with resistance training-induced muscle hypertrophy in young men. *PLoS One* 9: e89431, 2014.
18. Peeze Binkhorst FM, Slaaf DW, Kuipers H, Tangelder GJ, Reneman RS. Exercise-induced swelling of rat soleus muscle: Its relationship with intramuscular pressure. *J Appl Physiol (1985)* 69: 67–73, 1990.
19. Phillips SM, Tipton KD, Aarsland A, Wolf SE, Wolfe RR. Mixed muscle protein synthesis and breakdown after resistance exercise in humans. *Am J Physiol* 273: E99–E107, 1997.
20. Raja MK, Raymer GH, Moran GR, Marsh G, Thompson RT. Changes in tissue water content measured with multiple-frequency bioimpedance and metabolism measured with 31P-MRS during progressive forearm exercise. *J Appl Physiol (1985)* 101: 1070–1075, 2006.
21. Sahlin K, Harris RC, Nylind B, Hultman E. Lactate content and pH in muscle obtained after dynamic exercise. *Pflugers Arch* 367: 143–149, 1976.
22. Schoenfeld BJ. The mechanisms of muscle hypertrophy and their application to resistance training. *J Strength Cond Res* 24: 2857–2872, 2010.
23. Schoenfeld BJ. Potential mechanisms for a role of metabolic stress in hypertrophic adaptations to resistance training. *Sports Med* 43: 179–194, 2013.
24. Schoenfeld BJ, Ogborn D, Krieger JW. Dose-response relationship between weekly resistance training volume and increases in muscle mass: A systematic review and meta-analysis. *J Sports Sci* 35: 1073–1082, 2017.
25. Sjøgaard G, Adams RP, Saltin B. Water and ion shifts in skeletal muscle of humans with intense dynamic knee extension. *Am J Physiol* 248: R190–R196, 1985.
26. Taniguchi M, Yamada Y, Ichihashi N. Acute effect of multiple sets of fatiguing resistance exercise on muscle thickness, echo intensity and extracellular-to-intracellular water ratio. *Appl Physiol Nutr Metab*, 2019. 2020 Feb;45(2):213–219.
27. Tanimoto M, Ishii N. Effects of low-intensity resistance exercise with slow movement and tonic force generation on muscular function in young men. *J Appl Physiol (1985)* 100: 1150–1157, 2006.
28. Thannickal VJ, Fanburg BL. Reactive oxygen species in cell signaling. *Am J Physiol Lung Cell Mol Physiol* 279: L1005–L1028, 2000.
29. Vieira A, Blazevich A, Souza N, et al. Acute changes in muscle thickness and pennation angle in response to work-matched concentric and eccentric isokinetic exercise. *Appl Physiol Nutr Metab* 43: 1069–1074, 2018.
30. Wakahara T, Fukutani A, Kawakami Y, Yanai T. Nonuniform muscle hypertrophy: Its relation to muscle activation in training session. *Med Sci Sports Exerc* 45: 2158–2165, 2013.
31. Watson PD, Garner RP, Ward DS. Water uptake in stimulated cat skeletal muscle. *Am J Physiol* 264: R790–R796, 1993.
32. Yasuda T, Loenneke JP, Thiebaud RS, Abe T. Effects of blood flow restricted low-intensity concentric or eccentric training on muscle size and strength. *PLoS One* 7: e52843, 2012.

Downloaded from http://journals.lww.com/nsca-jscr by BJUxp2M3YpfdwbM14xNmYUDU4IBtO6VyGYyK0PbipMALvws AOBzMZBaYWIFlRDGxSX0a4WW42tsjk2tmaok3sv7d4nXmF1yQNYrPBow0tDGyXz3DDqfMzj5ZBBJHc on 04/10/2023



Copyright © 2020 National Strength and Conditioning Association. Unauthorized reproduction of this article is prohibited.