Effects of 4, 8, and 12 Repetition Maximum Resistance Training Protocols on Muscle Volume and Strength

Keitaro Kubo,[1] Toshihiro Ikebukuro,[1] and Hideaki Yata[2]

[1]Department of Life Science (Sports Sciences), the University of Tokyo, Tokyo, Japan; and [2]Department of Human and Environmental Well-being, Wako University, Tokyo, Japan

Abstract

Kubo, K, Ikebukuro, T, and Yata, H. Effects of 4, 8, and 12 repetition maximum resistance training protocols on muscle volume and strength. *J Strength Cond Res* 35(4): 879–885, 2021—The purpose of this study was to determine skeletal muscle adaptations (strength and hypertrophy) in response to volume-equated resistance training with divergent repetition strategies. Forty-two men were randomly assigned to 4 groups: higher load–lower repetition group performing 4 repetition maximum (RM) for 7 sets (4RM, $n = 10$), intermediate load–intermediate repetition group performing 8RM for 4 sets (8RM, $n = 12$), lower load–higher repetition group performing 12RM for 3 sets (12RM, $n = 10$), and nonexercising control group (CON, $n = 10$). The volume of the pectoralis major muscle (by magnetic resonance imaging) and 1RM of the bench press were measured before and after 10 weeks of training (2 times per week). No significant difference was observed in the relative increase in the muscle volume among the 4RM, 8RM, and 12RM groups. The relative increase in 1RM was significantly lower in the 12RM group than in the 4RM group ($p = 0.029$) and the 8RM group ($p = 0.021$). The relative increase in 1RM was significantly correlated with that in the muscle volume in the 12RM group ($r = 0.684$, $p = 0.042$), but not in the 4RM ($r = -0.265$, $p = 0.777$) or 8RM ($r = -0.045$, $p = 0.889$) groups. These results suggest that the increase in muscle size is similar among the 3 training protocols when the training volume was equated, whereas the increase in muscle strength is lower with the 12RM protocol than the other protocols.

Key Words: bench press, pectoralis major muscle, one repetition maximum, magnetic resonance imaging

Introduction

In the field of athletic training and exercise science, it is believed that a training protocol with a heavier load and fewer repetitions (1–5 repetition maximum [RM]) maximizes muscle strength, whereas a training protocol with a moderate load and more repetitions (8–12RM) maximizes muscle hypertrophy (11,22,28). To date, however, previous findings concerning the relationships between the outcome of training and training prescription have been conflicting (6,8,15,24). Several studies have shown that heavy load training is superior for the enhancement of muscle strength, whereas moderate load training is more suitable for hypertrophy (6,24). On the other hand, Mangine et al. (15) reported that high-intensity resistance training led to greater improvements in strength and hypertrophy than moderate-intensity (high-volume) resistance training, whereas Hisaeda et al. (8) showed similar effects on muscle strength and the cross-sectional area after 2 different modes of resistance training (4–6RM vs. 15–20RM).

It is widely accepted that the training volume (load × repetition × set) plays a significant role in both strength and hypertrophic adaptations after resistance training (11,21). Colquhoun et al. (7) demonstrated that there were no differences in increases in the muscle strength and size between low-frequency (3 times per week) and high-frequency (6 times per week) resistance training when the training volume was equated. Although only a few studies have evaluated the effects of load and repetition on training-induced muscular adaptations during volume-equated training between protocols, the results are conflicting (4,5,26). Chestnut and Docherty (5) reported no significant differences in the increases in the 1RM and muscle cross-sectional area between 4 and 10RM training protocols. Campos et al. (4) and Schoenfeld et al. (26) showed that strength improvement with a high-load and low-repetition training protocol was greater compared with a moderate-load and high-repetition training protocol, whereas increases in muscle size were similar between the 2 protocols.

As one of the reasons for the discrepancies among the previous findings, the muscle size might not have been evaluated correctly because the muscle thickness and cross-sectional area at the limited part were determined in previous studies (e.g., Refs. 5,15). According to the findings of several studies (18,29), muscle hypertrophy after resistance training did not occur equally throughout the entire length of the muscle. Therefore, we need to evaluate the muscle volume to precisely assess the effects of resistance training on the muscle size. Furthermore, if the prevailing theory as described earlier (a protocol with a heavier load and fewer repetitions increases strength, whereas that with a moderate load and repetitions promotes hypertrophy) is correct, the training-induced increase in muscle strength would be expected to correlate with that in muscle volume for the training protocol (with a moderate load and more repetitions) to maximize hypertrophy, but not for the training protocol (with a heavier load

Address correspondence to Keitaro Kubo, kubo@idaten.c.u-tokyo.ac.jp.

Journal of Strength and Conditioning Research 35(4)/879–885

and fewer repetitions) to maximize muscle strength. To the best of our knowledge, however, no studies have ever presented experimental data about these points.

In this study, we aimed to compare the effects of 3 different resistance training protocols designed to elicit either neural (4RM protocol), hypertrophic (12RM protocol), or moderate adaptations for muscle strength and size (8RM protocol) during volume-equated training. We hypothesized that the increase in the muscle strength would be greatest with the 4RM protocol, increase in muscle volume would be greatest with the 12RM protocol, and increases in muscle strength and volume would be intermediate with the 8RM protocol. In addition, we expected the relationship between the relative increase in muscle strength and volume to be closer with the 12RM protocol compared with the other 2 protocols.

Methods

Experimental Approach to the Problem

To investigate the effects of 3 different resistance training protocols with divergent repetition strategies on skeletal muscle adaptations, we determined changes in muscle size and strength after 10 weeks (2 days per week) of resistance training. All measurements were performed as almost the same time of day to minimize the effect of diurnal cycle. No difference in the training volume (calculated from the load × repetition × set) was found among the 3 training groups. Subjects were randomly assigned to the 3 training and control (untrained) groups (see below). In this study, we assessed the muscle volume (evaluated from all slices of magnetic resonance imaging from the origin to the insertion of muscle) to precisely evaluate the effects of the different training protocols on the muscle size.

Subjects

Forty-two healthy men (19.5–24.0 years) volunteered for this study. Subjects were divided into 4 groups: high load–low repetition (4RM) performing for 7 sets (4RM group, $n = 10$), intermediate load–intermediate repetition (8RM) performing for 4 sets (8RM group, $n = 12$), low load–high repetition (12RM) performing for 3 sets (12RM group, $n = 10$), nonexercising control (CON group, $n = 10$) by matching average baseline physical characteristics, and the 1RM of bench press among the 4 groups. The physical characteristics of all groups are shown in Table 1. Subjects were physically active but had not participated in any organized program involving regular exercise for at least 1 year before testing. During the experimental period, they were instructed to continue their daily routines and not to change their physical activity level and food and fluid intakes. They were fully informed of the procedures to be used, risks, and benefits as well as the purpose of the study. Written informed consent was obtained from all subjects. This study was approved by the Ethics Committee for Human Experiments, Department of Life Science (Sports Sciences), the University of Tokyo.

Procedures

1 Repetition Maximum of Bench Press. Subjects completed 2 familiarization sessions to receive instructions on the proper technique for the bench press exercise. The grip width was set at approximately 165% of the biacromial breadth (27). Subjects lowered the barbell until the bar touched the chest at nipple level (but not to bounce the weight off their chest) and then returned the barbell to the fully extended arm position. During the exercise, the shoulders, back, and buttocks of subjects were required to remain in contact with the bench. After a standardized warm-up (e.g., stretching of the major muscle groups), subjects performed 2 sets of 5 repetitions at approximately 50 and 70% of their estimated 1RM with a 2-minute rest between sets. The load was then progressively increased until subjects were unable to lift it with a correct bench press form. An average of 5–6 trials was required to complete the 1RM test.

The repeatability of 1RM measurements was investigated on 2 separate days with 10 young men. No significant differences were observed between the test and retest values for 1RM. The test–retest correlation coefficient and coefficient of variation were 0.95 and 1.5%, respectively.

Muscle Volume. A series of cross-sectional images of the pectoralis major muscle on the right side were obtained using 3T magnetic resonance imaging (Magnetom Prisma; Siemens, Munich, Germany). Before the measurement, subjects lay supine on the bed for 20–30 minutes to allow for body fluid shift stabilization (2). T1-weighted spin-echo imaging in the axial plane was performed with the following variables: TR 580 ms, TE 20 ms, matrix 256 × 192, field of view 250 mm, slice thickness 10 mm, and interslice gap 0 mm. Subjects lay supine in the body coil with their arms extended. Transverse scans were performed from the lateral epicondyle of the humerus to the epigastrium. Typical examples of magnetic resonance images of the mid portions of the chest are shown in Figure 1. The number of axial images obtained for each subject was the same before and after training. Images obtained with magnetic resonance imaging were transferred to a computer and analyzed using Osirix DICOM image analysis software (Pixmeo, Geveva, Switzerland). Muscle volumes were obtained by multiplying the anatomical cross-sectional area of each image by the thickness (10 mm). Unfortunately, we could not measure the muscle volume in one subject of the 12RM group because this subject has claustrophobia. Therefore, the number of samples for the muscle volume was 9 for the 12RM group.

Table 1

Age and physical characteristics of subjects.*†

	Age (y)	Height (cm)	Body mass (kg), before	Body mass (kg), after
4RM group ($n = 10$)	20.9 ± 0.4	173.3 ± 6.4	63.5 ± 11.2	63.0 ± 10.7
8RM group ($n = 12$)	20.9 ± 1.6	169.2 ± 5.0	64.0 ± 7.2	64.0 ± 7.6
12RM group ($n = 10$)	20.8 ± 0.8	172.8 ± 4.6	64.3 ± 4.8	64.1 ± 4.3
Control group ($n = 10$)	21.1 ± 1.1	170.7 ± 5.3	63.5 ± 6.2	63.8 ± 6.4

*RM = repetition maximum.
†Mean ± *SD*.

Figure 1. Typical magnetic resonance images showing transverse sections of the mid portions of the chest before (A) and after (B) training.

The repeatability of muscle volume measurements was investigated on 2 separate days with 10 young men. No significant differences were observed between the test and retest values for muscle volumes. The test–retest correlation coefficient and coefficient of variation were 0.97 and 1.7%, respectively.

Bench Press Training. The procedure of bench press training was described earlier (1RM of bench press). All groups completed 10 weeks (2 days per week) of bench press training. All training sessions were monitored and supervised to ensure the correct form by at least 1 experienced investigator. To become accustomed training and acquire the correct form, subjects of all training groups performed 3 sets of 60% 1RM × 10 repetitions in the first week and 3 sets of 70% 1RM × 8 repetitions in the second week. In the third week, subjects performed 5 sets of 90% 1RM × 3 repetitions in the 4RM group, 3 sets of 80% 1RM × 6 repetitions in the 8RM group, and 2 sets of 70% 1RM × 10 repetitions in the 12RM group. In the first session of the fourth week, the training protocol was 7 sets of 90% 1RM × 4 repetitions for the 4RM group, 4 sets of 80% 1RM × 8 repetitions for the 8RM group, and 3 sets of 70% 1RM × 12 repetitions for the 12RM group, respectively. If subjects were able to perform the prescribed training (number of repetitions and sets), the training load was increased by 2.5 kg for the next training session. The training volume was calculated from the load × repetition × set. In this study, subjects in all training groups took approximately 3-minute rest periods between sets to achieve the required repetitions in each set.

Statistical Analyses

Descriptive data included mean ± *SD*. Because of the absence of normality in most of the measured variables (checked by the Kolmogorov–Smirnov test), nonparametric statistical procedures were used and so described below. Baseline similarities among the 4 groups were determined by the Kruskal–Wallis test. The Wilcoxon signed-rank test was used to compare the measured variables before and after training in each group. Percent changes from the baseline were also compared among the 4 groups by the Kruskal–Wallis test using Mann–Whitney test. The effect size (ES) was calculated for all dependent variables between before and after training using Cohen's *d* formula: ES = (Mafter − Mbefore)/*SD*pooled, where Mafter is the mean variable after training, Mbefore is the mean variable before training, and *SD*pooled is the pooled *SD* of the measured variables of before and after training. In addition, 95% confidence intervals (95% CIs) for selected differences between mean values were calculated and were presented where appropriate. To assess the relationships among measured parameters, the Pearson product–moment correlation was computed. The significance levels for all analyses were set to $p \leq 0.05$. Statistical computations were performed using IBM SPSS Statistics (version 19).

Results

For all groups, the body mass did not change after 10 weeks of the intervention period (Table 1). From the fourth to 10th week, the mean number of repetitions in each set was 3.4 ± 0.3 in the 4RM group, 7.1 ± 0.4 in the 8RM group, and 10.5 ± 0.4 in the 12RM group. The load used significantly increased by 18.9 ± 7.1% in the 4RM group, 23.1 ± 6.6% in the 8RM group, and 18.6 ± 9.8% in the 12RM group. No significant difference in the total training volume (calculated from the fourth to 10th week) was found among the 4RM (16,933 ± 4,264 kg·repetitions), 8RM (16,732 ± 4,866 kg·repetitions), and 12RM (18,298 ± 2,858 kg·repetitions) groups ($p = 0.647$, Figure 2).

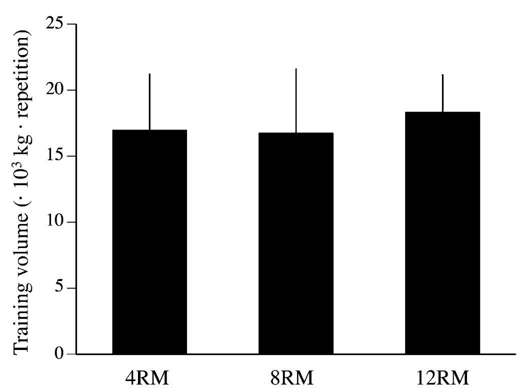

Figure 2. The total training volume (load × repetition × set) from the fourth to 10th week in the 4, 8, and 12RM groups. Values are mean ± *SD*.

Table 2
Volume of pectoralis major muscle and 1RM of bench press before and after 10 weeks of training.*†

	Muscle volume (cm^3)		1RM (kg)	
	Before	After	Before	After
4RM group	329.2 ± 104.9	363.6 ± 103.8**	54.5 ± 14.4	69.0 ± 15.0**
8RM group	345.6 ± 92.4	379.4 ± 95.9**	50.4 ± 14.7	64.4 ± 16.4**
12RM group	336.4 ± 46.2	373.0 ± 41.2**	56.0 ± 8.1	66.0 ± 6.9**
Control group	338.4 ± 40.2	333.7 ± 40.0	57.8 ± 6.2	57.0 ± 5.6

*RM = repetition maximum.
†Mean ± *SD*.
Significantly different from before (**$p < 0.01$).

The volume of the pectoralis major muscle significantly increased by 11.1 ± 4.3% in the 4RM group ($p = 0.005$, ES = 0.33, 95% CI 8.0–14.2), 10.1 ± 5.1% in the 8RM group ($p = 0.002$, ES = 0.36, 95% CI 6.8–13.3), and 11.3 ± 4.5% in the 12RM group ($p = 0.008$, ES = 0.85, 95% CI 7.9–14.7) (Table 2 and Figure 3A). No significant difference was observed in the relative increases in the muscle volumes among the 3 groups (Figure 3A). The 1RM of the bench press significantly increased by 28.4 ± 10.0% in the 4RM group ($p = 0.005$, ES = 0.99, 95% CI 21.3–35.6), 29.5 ± 11.6% in the 8RM group ($p = 0.002$, ES = 0.90, 95% CI 22.1–36.9), and 18.7 ± 10.1% in the 12RM group ($p = 0.005$, ES = 1.33, 95% CI 11.5–25.9) (Table 2 and Figure 3B). The relative increase in 1RM in the 12RM group was significantly lower than that in the 4RM ($p = 0.029$, ES = 0.97) and 8RM ($p = 0.021$, ES = 1.03) groups (Figure 3B). The relative change in 1RM was significantly correlated with that in the muscle volume in the 12RM group, but not in the 4RM or 8RM group (Figure 4).

In the control group, no significant changes in the muscle volume or 1RM were noted after the intervention period (Table 2).

Discussion

The main results of this study were that (a) there was no difference in the relative increase in the muscle volume among the 3 training groups, and (b) the relative increase in 1RM was significantly lower in the 12RM group than in the 4RM and 8RM groups.

When the training volume was equated, there was no difference in the relative increase in the muscle volume among the 4, 8, and 12RM groups. According to the findings of several studies (11,22,28), training programs consisting of moderate loads (70–75% of 1RM) and repetitions (10–12 repetitions) have been recommended to maximize muscle hypertrophy. To the best of our knowledge, a few studies have compared the training-induced hypertrophy among different volume-equated training protocols (4,5,26). Recent studies demonstrated that the total training volume performed during the intervention period was important for a training-induced increase in muscle size (7,23). Schoenfeld et al. (23) reported that the increase in muscle thickness was greater for a 5-set group than for 1- and 3-set groups, whereas there was no difference in strength gain among the 3 groups. In addition, we considered that change in muscle size was assessed correctly since we adopted gold-standard method (i.e., magnetic resonance imaging) to measure the muscle volume in this study. Taken together, it is reasonable to consider that training-induced hypertrophy depends on the training volume performed, as stated in previous studies (7,23).

The relative increase in 1RM was significantly lower in the 12RM group than in the other 2 groups. Campos et al. (4) reported that maximal strength improved significantly more in a lower repetition training group (3–5RM) compared with higher repetition training groups (9–11 and 20–28RM), whereas there was no difference in the training volume. Furthermore, several studies demonstrated that a high-load and low-repetition training protocol was more beneficial for strength enhancement compared with a low-load and high-repetition training protocol, even if the training volume was lower for the former (15,24). The present results for the 4RM group agreed with these findings. Moreover, the increase in 1RM in the 8RM group was equivalent to that in the 4RM group in this study. Therefore, the present results indicated that at least 80% of 1RM was needed to induce further neural and strength adaptations during resistance training, since 8RM corresponded to approximately 80% of 1RM (16). On the other hand, the results for 1RM in the 12RM group suggested that the resistance training using a load less than 80% of 1RM did not bring about changes in neuromuscular activities, although the muscle activation level was not measured in this study. In a future study, we need to assess muscle activation levels using electromyography and interpolated twitch techniques.

Training-induced changes in muscle strength are generally considered to be the results of neurological and musculoskeletal adaptations (17,18). An interesting finding of this study was that the relative change in 1RM was significantly correlated with that in the muscle volume in the 12RM group, but not in the 4RM and 8RM groups (Figure 4). Our hypothesis was supported in this study. These results indicated that increases in 1RM in the 12RM group were mostly due to muscle hypertrophy, whereas those in the 4RM and 8RM groups were facilitated by hypertrophy and changes in neuromuscular activity, which did not actually determine. To the best of our knowledge, this is the first study to demonstrate the contribution of neurological and muscular factors to training-induced changes in muscle strength, which was tested experimentally in humans.

According to the obtained results for 1RM, the training effects of the 4RM protocol (4RM × 7set) and 8RM protocol (8RM × 4 set) are almost the same, and those of the 12RM protocol (12RM × 3set) are inferior to the other protocols. However, we need to consider the time required for each training protocol. In this study, subjects in all groups took approximately 3-minute rest between sets. Therefore, the total duration of training (except for warmup) in the 4RM group (approximately 20 minutes) was markedly longer than that in the 8RM (approximately 11 minutes) and 12RM (approximately 8 minutes) groups. Given the similar muscle strength and hypertrophic gains between the 4 and 8RM groups, the 4RM protocol was not a time-efficient strategy for eliciting these increases. Schoenfeld et al. (26), who compared 3RM × 7 sets and 10RM × 3 sets, also pointed out the similar concern. If the number of sets performed by the 4RM group is decreased, the training-induced increase in the muscle volume may decline, although this has not been proven experimentally. Furthermore, a heavy load of training such as the 4RM (approximately 90% of 1RM) protocol is imposed on the musculoskeletal system and joints. Therefore, the 4RM protocol would cause degenerative changes in working joints, although subjects in this study did not drop out due to musculoskeletal or joint injuries. Considering these points, the 8RM protocol would be better to effectively achieve muscle strength gain and hypertrophy.

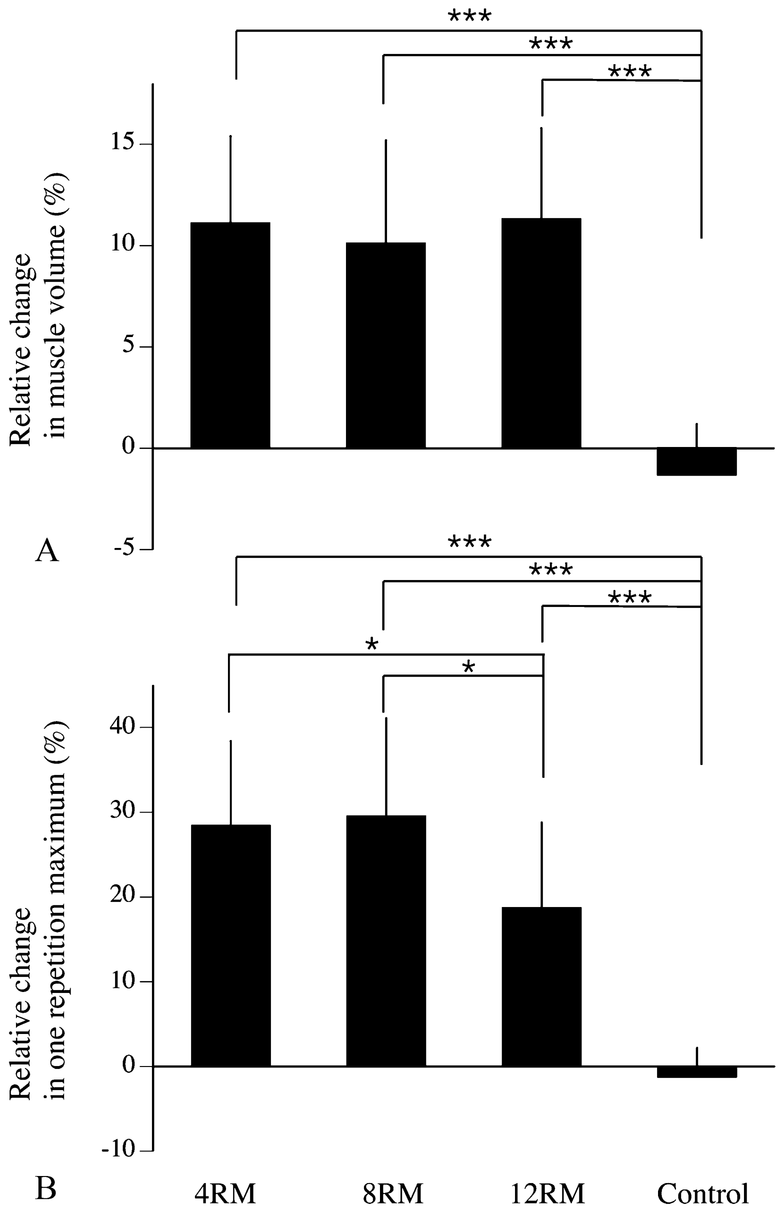

Figure 3. Relative increases in the pectoralis major muscle volume (A) and one repetition maximum for the bench press (B) in the 4, 8, 12, and control groups. Values are mean ± *SD*. $^{*}p < 0.05$, $^{***}p < 0.001$.

For the 3 training groups, the volume of the pectoralis major muscle increased by approximately 10% after 10 weeks of bench press training. More recently, we found that the volume of lower-limb muscles increased by 4.9% for the quadriceps femoris muscles, 6.2% for the adductor muscle, and 6.7% for the gluteus maximus muscle after 10 weeks of full-squat training (2 times per week) (12). According to previous findings on the training-induced hypertrophy, the volume of triceps brachii muscle increased by 12.4% after 12 weeks (3 times per week) of isometric training (9) and 31.7% after 16 weeks (3 times per week) of french press training (10), whereas the volume of quadriceps femoris and triceps surae muscles increased by approximately 5% after 12 weeks (4 times per week) of isometric and isotonic training (13,14). In addition, the cross-sectional area of the pectoralis major muscle increased by 22% after 9 weeks (3 times per week) of bench press training (19), whereas that of knee extensor muscles increased by approximately 6% after 12 weeks (3 times per week) of squat training (3). Abe et al. (1) also demonstrated that the relative increases in muscle thickness of upper-limb muscles (10–31%) were greater than those of lower-limb muscles (7–9%) after 12 weeks of resistance training. Considering these previous and the present results, the training-induced changes in muscle size would be more marked for upper-limb compared with lower-limb muscles.

In this study, we must draw attention to some limitations of the methodology followed. First, subjects in all training groups took approximately 3-minute rest periods between sets to achieve the required repetitions in each set. In several studies, however, the rest period between sets was relatively short (e.g., 1 minute) for low load-high repetition protocols to increase metabolic stress (4,15,26). This would be related to the lower increase in 1RM in the 12RM group. In addition, the relative increase in muscle

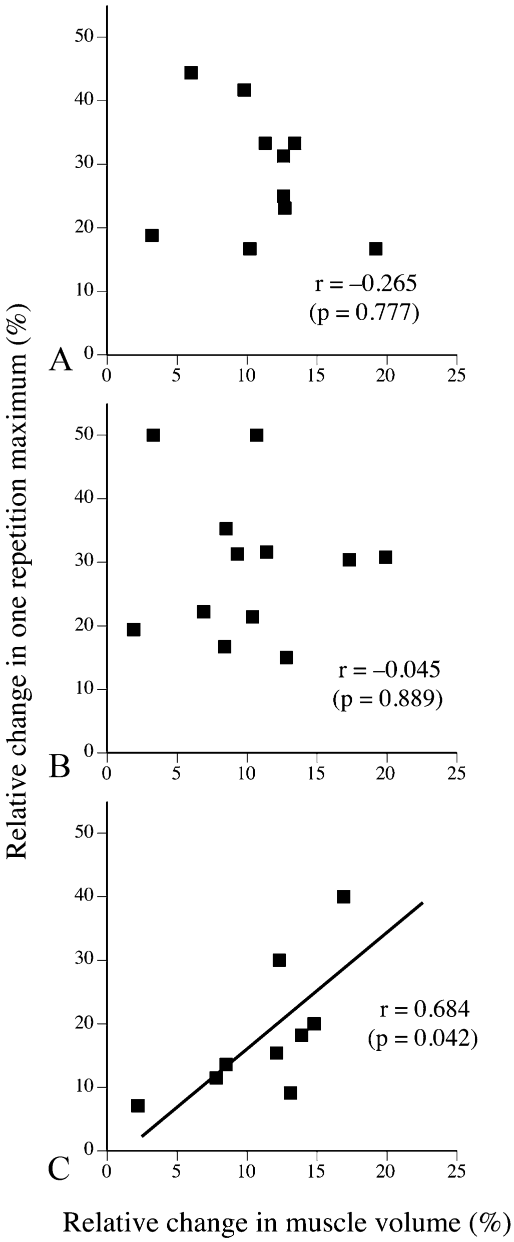

Figure 4. Relationship between relative change in one repetition maximum and muscle volume in the 4RM (A), 8RM (B), and 12RM (C) groups.

volume in the 12RM group would be higher with a shorter rest period between sets. However, Schoenfeld et al. (25) reported that taking short rest periods (1 minute) attenuated the hypertrophic response to resistance training. Second, we could not measure the volume of other muscles (e.g., triceps brachii and deltoid muscles) due to the size of the body coil used. However, Ogasawara et al. (19) reported that the relative increase in the cross-sectional area of the pectoralis major muscle (28.7%) was greater than that of the triceps brachii muscle (17.7%) after 15 weeks of bench press training. Therefore, we considered that this point did not affect the main results of this study. Third, we used untrained subjects in this study. It is known that the response to resistance training for trained individuals is different from that of those lacking training experience (20,24). However, if we used trained subjects, the effects of training experience would have affected the obtained results before the intervention period.

Practical Applications

These results suggested that there was no difference in the relative increase in the muscle volume among 4, 8, and 12RM protocols during volume-equated training, whereas the relative increase in 1RM for the 12RM (i.e., low-load and high-repetition) protocol tended to be lower than that for 4 and 8RM protocols. On the other hand, the 4RM protocol required the long duration of training and would cause the musculoskeletal injuries due to a heavy load of training. Considering these findings and from a practical point of view, the 8RM protocol would be useful for recreational and competitive athletes who require muscle strength gain and hypertrophy simultaneously. In a future study, we need to investigate the effects of various training protocols (combined different loads, repetitions, and sets) because competitive athletes performed these training practically.

Acknowledgments

This study was supported by a Grant-in-Aid for Scientific Research (B) (17H02149 to K. Kubo) from the Japan Society for the Promotion of Science. The authors have no conflicts of interest to disclose.

References

1. Abe T, DeHoyos DV, Pollock ML, Garzarella L. Time course for strength and muscle thickness changes following upper and lower body resistance training in men and women. *Eur J Appl Physiol* 81: 174–180, 2000.
2. Berg HE, Tedner B, Tesch PA. Changes in lower limb muscle cross-sectional area and tissue fluid volume after transition from standing to supine. *Acta Physiol Scand* 148: 379–385, 1993.
3. Bloomquist K, Langberg H, Karlsen S, et al. Effect of range of motion in heavy load squatting on muscle and tendon adaptations. *Eur J Appl Physiol* 113: 2133–2142, 2013.
4. Campos GER, Luecke TJ, Wendeln HK, et al. Muscular adaptations in response to three different resistance-training regimens: Specificity of repetition maximum training zones. *Eur J Appl Physiol* 88: 50–60, 2002.
5. Chestnut JL, Docherty D. The effects of 4 and 10 repetition maximum weight-training protocols on neuromuscular adaptations in untrained men. *J Strength Cond Res* 13: 353–359, 1999.
6. Choi J, Takahashi H, Itai Y. The difference between effects of "power-up" and "bulk-up" strength training exercises: With special reference to muscle cross-sectional area. *Jpn J Phys Fitness Sports Med* 47: 119–129, 1998.
7. Colquhoun RJ, Gai CM, Aguilar D, et al. Training volume, not frequency, indicative of maximal strength adaptations to resistance training. *J Strength Cond Res* 32: 1207–1213, 2018.
8. Hisaeda H, Miyagawa K, Kuno S, Fukunaga T, Muraoka I. Influence of two different modes of resistance training in female subjects. *Ergonomics* 39: 842–852, 1996.
9. Kanehisa H, Nagareda H, Kawakami Y, et al. Effects of equivolume isometric training programs comprising medium or high resistance on muscle size and strength. *Eur J Appl Physiol* 87: 112–119, 2002.
10. Kawakami Y, Abe T, Kuno S, Fukunaga T. Training-induced changes in muscle architecture and specific tension. *Eur J Appl Physiol* 72: 37–43, 1995.
11. Kraemer WJ, Ratamess NA. Fundamentals of resistance training: Progression and exercise prescription. *Med Sci Sports Exer* 36: 674–688, 2004.
12. Kubo K, Ikebukuro T, Yata H. Effects of squat training with different depths on lower limb muscle volumes. *Eur J Appl Physiol* 119: 1933–1942, 2019.

13. Kubo K, Ikebukuro T, Yaeshima K, et al. Effects of static and dynamic training on the stiffness and blood volume of tendon in vivo. *J Appl Physiol* 106: 412–417, 2009.
14. Kubo K, Morimoto M, Komuro T, et al. Effects of plyometric and weight training on muscle-tendon complex and jump performance. *Med Sci Sports Exer* 39: 1801–1810, 2007.
15. Mangine GT, Hoffman JR, Gonzalez AM, et al. The effect of training volume and intensity on improvements in muscular strength and size in resistance-trained men. *Physiol Rep* 3: e12472, 2015.
16. Mayhew JL, Johnson BD, LaMonte MJ, Lauber D, Kemmler W. Accuracy of prediction equations for determining one repetition maximum bench press in women before and after resistance training. *J Strength Cond Res* 22: 1570–1577, 2008.
17. Moritani T, deVries H. Potential for gross muscle hypertrophy in older men. *J Gerontol* 35: 672–682, 1980.
18. Narici MV, Hoppeler H, Kayser B, et al. Human quadriceps cross-sectional area, torque and neural activation during 6 months strength training. *Acta Physiol Scand* 157: 175–186, 1996.
19. Ogasawara R, Yasuda T, Sakamaki M, Ozaki H, Abe T. Effects of periodic and continued resistance training on muscle CSA and strength in previously untrained men. *Clin Physiol Func Imaging* 31: 399–404, 2011.
20. Peterson MD, Rhea MR, Alvar BA. Applications of the dose-response for muscular strength development: A review of meta-analytic efficacy and reliability for designing training prescription. *J Strength Cond Res* 19: 950–958, 2005.
21. Peterson MD, Rhea MR, Alvar BA. Maximizing strength development in athletes: A meta-analysis to determine the dose-response relationship. *J Strength Cond Res* 18: 377–382, 2004.
22. Sale DG, Martin JE, Moroz DE. Hypertrophy without increased isometric strength after weight training. *Eur J Appl Physiol* 64: 51–55, 1992.
23. Schoenfeld BJ, Contreras B, Krieger J, et al. Resistance training volume enhances muscle hypertrophy but not strength in trained men. *Med Sci Sports Exer* 51: 94–103, 2019.
24. Schoenfeld BJ, Contreras B, Vigotsky AD, Peterson M. Differential effects of heavy versus moderate loads on measures of strength and hypertrophy in resistance-trained men. *J Sports Sci Med* 15: 715–722, 2016.
25. Schoenfeld BJ, Pope ZK, Benik FM, et al. Longer interset rest periods enhance muscle strength and hypertrophy in resistance-trained men. *J Strength Cond Res* 30: 1805–1812, 2016.
26. Schoenfeld BJ, Ratamess NA, Peterson MD, et al. Effects of different volume-equated resistance training loading strategies on muscular adaptations in well-trained men. *J Strength Cond Res* 28: 2909–2918, 2014.
27. Simpson SR, Rozenek R, Garhammer J, Lacourse M, Storer T. Comparison of one repetition maximums between free weight and universal machine exercises. *J Strength Cond Res* 11: 103–106, 1997.
28. Stone MH, O'Bryant H, Garhammer J. A hypothetical model for strength training. *J Sports Med* 21: 342–351, 1981.
29. Wakahara T, Fukutani A, Kawakami Y, Yanai T. Nonuniform muscle hypertrophy: Its relation to muscle activation in training session. *Med Sci Sports Exer* 45: 2158–2165, 2013.