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Original Research

Low-Load x High-Load Resistance Exercise: Greater Cell Swelling After a Training Session

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ABSTRACT

International Journal of Exercise Science 16(3): 513-524, 2023. Cell swelling caused by resistance training is proposed to provide an anabolic stimulus for muscle growth and it is believed that these effects are heightened with the use of low loads. The purpose of this study was to compare the acute effects of two volume-equated resistance training (RT) protocols, low-load (LL) versus high-load (HL), on elbow flexor muscles thickness, arm circumference, and blood lactate concentration in well-trained individuals. Eight resistance-trained males performed the following two RT protocols involving unilateral elbow flexion of the dominant arm: i) LL, four sets with 50% 1 repetition-maximum [1 RM] and ii) HL, ten sets with 85% 1 RM until failure, and equated volume. Pre- and post-session measurements included muscle thickness of the elbow flexors (biceps brachii and brachialis), upper arm circumference, and blood lactate concentration. Significant pre- to post-session increases were found in both protocols for muscle thickness (F (1, 28) = 11.74, p = 0.0019), and blood lactate (F (1, 28) = 35.55, p < 0.0001); no statistically significant differences were observed between conditions, however, the magnitude of increases favored LL. Significant between-condition differences favoring LL were observed for total repetitions (p = 0.007), time under tension (p = 0.007), and training density (p = 0.007). These results suggest that LL training promotes superior post-session increases in muscle thickness, indicating that RT protocols with longer times under tension and densities are beneficial when the goal is to promote acute cell swelling.

KEY WORDS: Muscle hypertrophy, skeletal muscle, ultrasound imaging, muscle turgescence

INTRODUCTION

Resistance training (RT) is commonly prescribed as an intervention to induce skeletal muscle hypertrophy and strength development. Several mechanisms are hypothesized to be responsible for initiating the hypertrophic response to RT (26). Mechanical tension elicits hypertrophy via mechanotransduction-induced activation of anabolic signaling pathways, and/or satellite cell activation and proliferation (26). Metabolic stress also has been hypothesized to be a factor in RT-induced muscle growth (25). Some evidence indicates that an RT protocol designed to heighten metabolic stress promotes greater increases in muscle cross-sectional area compared to a protocol that induces less metabolic stress, suggesting a direct link between metabolic stress and muscle hypertrophy (6).

It is well established that high-load (HL) RT induces significant muscle hypertrophy in humans when performed consistently over time. However, evidence indicates that low-load (LL) training can promote similar hypertrophic adaptations to the use of heavier loads (29), which may be at least in part mediated by metabolite accumulation (24). From a mechanistic standpoint, it has been hypothesized that acute cell swelling associated with metabolic stress (i.e., "the pump") may be a contributing factor in the hypertrophic response to LL training (5, 28).

The cell swelling induced by RT promotes alterations in intra- and extracellular water balance, the extent of which is dependent on the type of exercise and intensity of training (26, 28). In vitro evidence indicates that cell swelling results in an increase in protein synthesis and a decrease in proteolysis in a variety of tissues (17, 26). These effects are believed to involve activation of protein-kinase signaling pathways, which in turn mediate autocrine effects on growth factors that are initiated in response to membrane stretch (27). Cell swelling-induced membrane stretch may also have a direct effect on the amino acid transport systems mediated through an integrin-associated volume sensor (19). However, the acute response to different loading schemes remains poorly understood, particularly for individuals experienced in RT.

Elevated blood lactate levels may promote anabolic effects on muscle tissue independent of mechanisms related to ischemia/hypoxia (22). LL training that increases lactate accumulation is associated with metabolites accumulation, which may play a role in RT-induced hypertrophy (33). The cellular balance of organic substances, such as amino acids, has been shown to upregulate protein synthesis in a variety of different cell types (17).

The aim of this study was to compare the acute effects of volume-equated resistance training protocols employing LL and HL on the thickness of the arm flexor muscles, arm circumference, and blood lactate concentration in men with previous RT experience. We hypothesized that the LL protocol would induce greater muscle swelling and blood lactate concentrations compared to the HL protocol.

METHODS

Participants

Participants were a convenience sample recruited from a university population of eight male healthy volunteers (age: 24.8 ± 3.4 years; body mass: 87.3 ± 12.8 kg; height: 180 ± 6 cm; resistance training experience: 6.7 ± 2.8 years; unilateral dumbbell arm curl 1 RM: 29.4 ± 6.8 kg). Participants had no existing musculoskeletal disorders in the 12 months prior to the intervention and possessed an arm circumference between 35-40 centimeters, measured with the elbow extended and muscles relaxed. Participants reported that they were free from consumption of anabolic steroids, ergogenic aids, or any type of nutritional supplements or other illegal agents known to increase muscle size or muscle performance for the previous year and during the period of this study. Participants were experienced resistance training practitioners (i.e., defined as consistently lifting weights at least three times per week for a minimum of one year and regularly performing the arm curl exercise). The study was approved by the Research Ethics Committee of the University of Campinas (#1.795.283). All procedures conformed to the Declaration of Helsinki. Before providing written informed consent, participants were fully informed of the nature and risks of the study. This research was carried out fully in accordance with the ethical standards of the International Journal of Exercise Science (21).

Protocol

This study employed a randomized crossover research design whereby all participants performed two resistance training protocols separated by a one-week period. The protocols consisted of the unilateral curl for the dominant arm under the following two conditions: i) LL, four sets with 50 % 1 RM, and ii) HL, ten sets with 85 % 1 RM. All sets for both protocols were performed until concentric failure with 90 seconds rest provided between sets (7). Pre- and post-session assessments included muscle thickness of the elbow flexors (combination of the biceps brachii and brachialis), circumference of the exercised arm, and blood lactate concentration. Therefore, all participants visited the laboratory three times, with each visit separated by one week. During the first visit, we obtained measurements of body mass, height, and repetition-maximum test (1 RM). In the subsequent two visits, participants performed the respective exercise protocols in a randomized manner.

Training for both protocols involved the performance of the unilateral dumbbell arm curl exercise for the dominant arm. All sets were performed until concentric failure (i.e., the inability to perform another concentric repetition while maintaining proper form). A 90-second rest period was afforded between sets for both protocols. The LL RT protocol involved the performance of four sets at 50 % 1 RM, whereas the HL protocol consisted of ten sets at 85 % 1 RM. A greater number of sets for HL vs LL was necessary to equate volume load (protocol volume = sets x repetitions x load) between conditions. The time under tension (i.e., time of each repetition x total repetitions), and exercise density (i.e., amount of exercise performed per total time of the training session) were monitored to provide insight into the type of stimulus imposed by each protocol (2, 4). One week before the first exercise bout, all participants were tested for 1 RM in the unilateral arm curl exercise to determine individual training loads for each protocol (LL and HL). Subjects were instructed to refrain from performing any additional resistance-type or high-intensity aerobic-type exercise during the two weeks spanning the initial testing session

and the final exercise session. All routines were directly supervised by the research team, which included physical education professionals with extensive experience in strength training.

The variables measured in the present study (i.e., muscle thickness and arm circumference) are particularly sensitive to alterations from nutrition and hydration status (16). Muscle glycogen levels are directly related to an individual's performance during exercise and, given that each gram of glycogen attracts approximately three grams of water into the cell, variations in the magnitude of storage can change the cell size (23). Muscle swelling is related to the amount of fluid inside the fiber, a condition that varies according to the hydration of the individual (32). Therefore, to avoid potential dietary confounding of results, participants were advised to maintain their habitual nutritional regimen. Self-reported food records were collected in written form one week before the initiation of exercise protocols. Participants were provided with a booklet and instructed how to properly record all food items consumed along with their respective portion sizes. The Interactive Healthy Eating Index (Center for Nutrition Policy and Promotion, United States Department of Agriculture; https://www.fns.usda.gov/cnpp) was used to analyze food records. Each item of food was individually entered into the program, and the program provided relevant information as to total energy consumption and the amount of energy derived from proteins, fats, and carbohydrates over the reference day. In addition, participants were instructed to consume a standardized breakfast on the morning of the intervention, two hours before the exercise protocol, consisting of the following: four slices of whole wheat bread, four slices of white cheese, four slices of ham, and 250ml of orange juice. Participants were advised to avoid consumption of any product containing caffeine and alcohol as well as the use of any diuretic-inducing drug in the 24h preceding the intervention; water consumption was allowed ad libitum. All measurements were carried out during the same period of the day (between 900AM and 1100AM) in an environment controlled for temperature and air humidity.

Elbow flexors strength was assessed by 1 RM testing in the unilateral dumbbell arm curl exercise. The 1 RM testing was performed one week prior to the exercise protocols (LL and HL) to determine the individual loads for use in use in each participant. The repetition-maximum test was consistent with recognized guidelines as established by Brown and Weir (1). Participants performed a general warm-up before testing that consisted of light cardiovascular exercise lasting approximately five minutes. Thereafter, a specific warm-up set of the given exercise was performed consisting of ten repetitions at ~50 % 1 RM, followed by a set of three repetitions at ~70%1 RM. Three minutes after the warm-up, participants performed sets of one repetition of increasing weight for 1 RM determination. A rest interval between three and five minutes was provided between each successive attempt. All 1 RM determinations were made within five attempts. The research staff supervised each 1 RM test; an attempt was deemed successful by a consensus of all those present.

Ultrasound imaging was used to obtain measurements of muscle thickness (MT). A trained technician performed all testing using a B-mode ultrasound-imaging unit (Nanomaxx, Sonosite, Bothell, Washington, USA). All measurements were taken on the exercised arm, before and

within ten minutes after the exercise protocol to evaluate the thickness of elbow flexors (biceps brachii and brachialis). The participants were placed on the stretcher in dorsal decubitus, anatomical position, with relaxed muscles. To ensure consistency in the evaluation pre-and post-session, the body position of each subject was demarcated on the stretcher. Measurements were taken 60% distally between the acromion and the radial fossa using a vinyl measuring tape. The anatomical sites were identified and marked with a semi-permanent pen to ensure precision between pre-and post-session measurements. The technician applied a water-soluble transmission gel (Aquasonic 100 Ultrasound Transmission Gel; Parker Laboratories Inc., Fair-field, NJ, USA) to the measurement site, and a 7.5 MHz ultrasound probe was placed perpendicular to the tissue interface without depressing the skin. When the quality of the image was deemed satisfactory, the technician saved the image to a hard drive and obtained MT dimensions by measuring the distance from the subcutaneous adipose tissue-muscle interface to the muscle-bone interface using freely available image scanning software (Madena 3.2.5, EyePhysics, Los Paladino's, USA). To further ensure the accuracy of measurements, at least two images were obtained for each site. If measurements were within a percentage of ten of one another, the figures were averaged to obtain a final value. If measurements exceeded a percentage of ten of one another, a third image was obtained and the closest of the measures were then averaged.

The circumference of the exercised arm was measured using a constant tension measuring tape. All measurements were taken before and within ten minutes after the exercise protocol by the same trained technician. The participants stood in anatomical position with muscles relaxed. The measurements were made at 60% distal between the acromion and the radial fossa, as in the MT evaluation, using a vinyl measuring tape. The anatomical sites were identified and marked with a semi-permanent pen to ensure precision between pre-and post-session measurements. To further ensure accuracy, at least three measurements were obtained and then averaged to determine the arm circumference as proposed by Guedes (8).

To evaluate the lactate blood concentration of each exercise protocol and the percentage of change in blood lactate concentration (ΔLactate), a small blood sample was collected from the middle finger with a disposable lancet before and within ten minutes after each exercise protocol. The samples were placed in labeled microtubules (Eppendorf®) containing 50 µl of a sodium fluoride solution (1%) and stored at approximately 4°C for 30 min and subsequently placed in a refrigerator. All samples were analyzed using the YSI 2300 Lactate Analyzer (YSI Life Sciences®).

Statistical Analysis

Normality and homogeneity of variance of the data were confirmed by the Shapiro-Wilk test. Data were expressed as mean ± standard deviation (*SD*), and relative changes (i.e., % change) between protocols. Non-parametric statistics were adopted for between and within-group comparisons when data violated the assumption of normality. Wilcoxon matched-pairs signed-rank tests were used to examine differences between conditions (LL vs. HL) for volume, time under tension, total repetitions, and density. A two-way repeated-measures analysis of variance

(time x condition) was employed to compare conditions (LL vs. HL) for muscle thickness, arm circumference, and blood lactate. The effect size (*ES*) with 95% confidence intervals was calculated in pre-and post-measurements and between conditions (LL vs. HL) according to Cohen's *d* (3,14). The ES was interpreted as "small" (*d* = 0.20 to 0.49), "medium" (*d* = 0.50 to 0.79), and "large" (*d* = 0.80) (3,14). An alpha of 0.05 was set a priori to determine statistical significance. All statistical tests were carried out using GraphPad-Prism version 8 (GraphPad Software, Inc, USA).

RESULTS

Means and standard deviation of volume, total repetitions, time under tension, and training density are presented in Table 1. The total number of repetitions was significantly different between LL and HL, as was the time under tension and training density.

Table 1. Characteristics of the exercise protocols.

Training Variable	Exercise protocol		*p*-value (between protocols)	*ES* (between protocols)
	Low-Load	High-Load		
Volume (kg)	1582.4 ± 907.8	1495.9 ± 777.1	0.148	0.10
Total Repetitions (rep)	107.5 ± 32.5	57.5 ± 16.5	0.007*	1.95
Time under tension (sec)	322.5 ± 97.7	172.5 ± 49.5	0.007*	1.94
Exercise Density (reps/rest)	0.63 ± 0.24	0.21 ± 0.06	0.007*	2.41

ES: effect size. * Significant difference between protocols, $p < 0.05$.

Muscle thickness values are presented in Figure 1. Ultrasound imaging of the elbow flexors showed a significant pre- to post-session increase in muscle thickness in both conditions. In LL, muscle thickness increases by 18.9 ± 5.74% (42.08 ± 4.62 mm to 50.06 ± 5.95 mm; F (1, 28) = 11.74, p = 0.0019), with a large *ES* (1.50). In HL, muscle thickness increased by 11.53 ± 5.96% (41.04 ± 4.47 mm to 45.81 ± 5.82 mm; F (1, 28) = 11.74, p = 0.0019), with a large *ES* (0.92). No statistically significant interaction was observed between conditions (F (1, 28) = 0.7443, p = 0.3956) with a medium *ES* (0.73).

Arm circumference values are shown in Figure 2. In LL, arm circumference increased by 5.38 ± 2.36% (351.6 ± 26.33 mm to 370.9 ± 33.57 mm; F (1, 28) = 2.222, p = 0.1472) with a medium *ES* (0.64). In HL, arm circumference increased by 3.27 ± 1.79% (351.6 ± 26.33 mm to 363.4 ± 31.72 mm; F (1, 28) = 2.222, p = 0.1472) with a medium *ES* (0.40). No statistically significant interaction was observed between conditions (F (1, 28) = 0.1292, p = 0.7219) with a small *ES* (0.23).

Blood lactate concentration values are presented in Figure 3. Both protocols showed a significant pre- to post-session increase in blood lactate concentration. In LL, blood lactate increased by 163.6 ± 78.51 % (1.61 ± 0.47 mmol/l to 4.08 ± 1.36 mmol/l; F (1, 28) = 35.55, $p < 0.0001$) with a large *ES* (2.42). In HL, blood lactate increased by 105.48 ± 102 % (1.85 ± 0.61 mmol/l to 3.5 ± 1.56 mmol/l; F (1, 28) = 35.55, $p < 0.0001$), with a large *ES* (1.39). No statistically significant interaction was observed between conditions (F (1, 28) = 1.435, p = 0.2411) with a small *ES* (0.40).

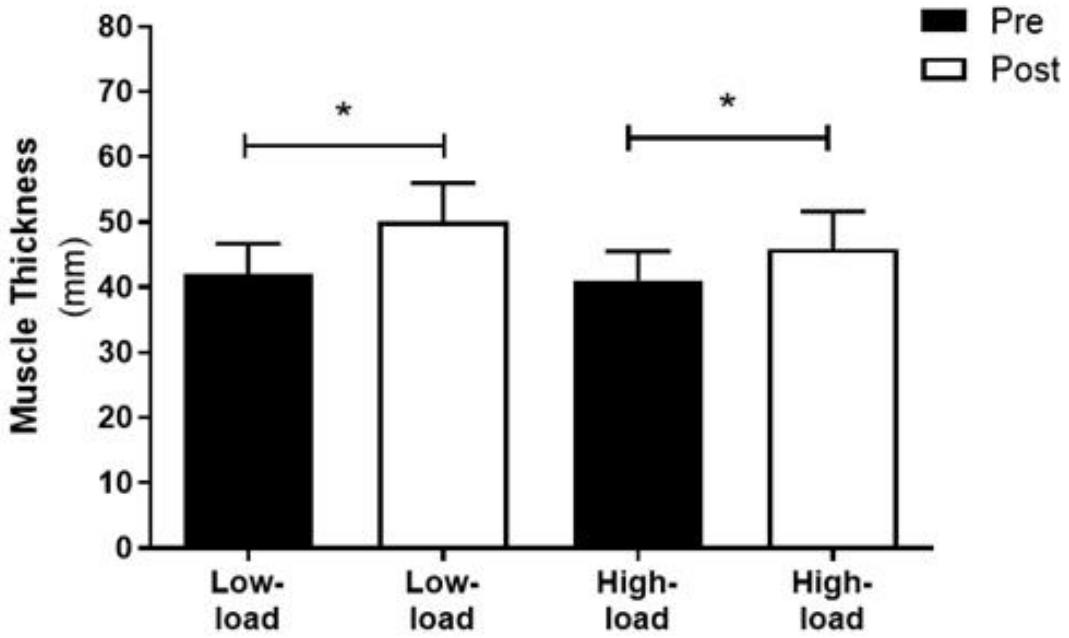

Figure 1. Muscle thickness values of elbow flexors (biceps brachii and brachialis) before (pre) and after (post) intervention for low-load and high-load, mean (± *SD*). Values expressed in millimeters (mm). * Significantly greater than the pre-training value ($p < 0.05$).

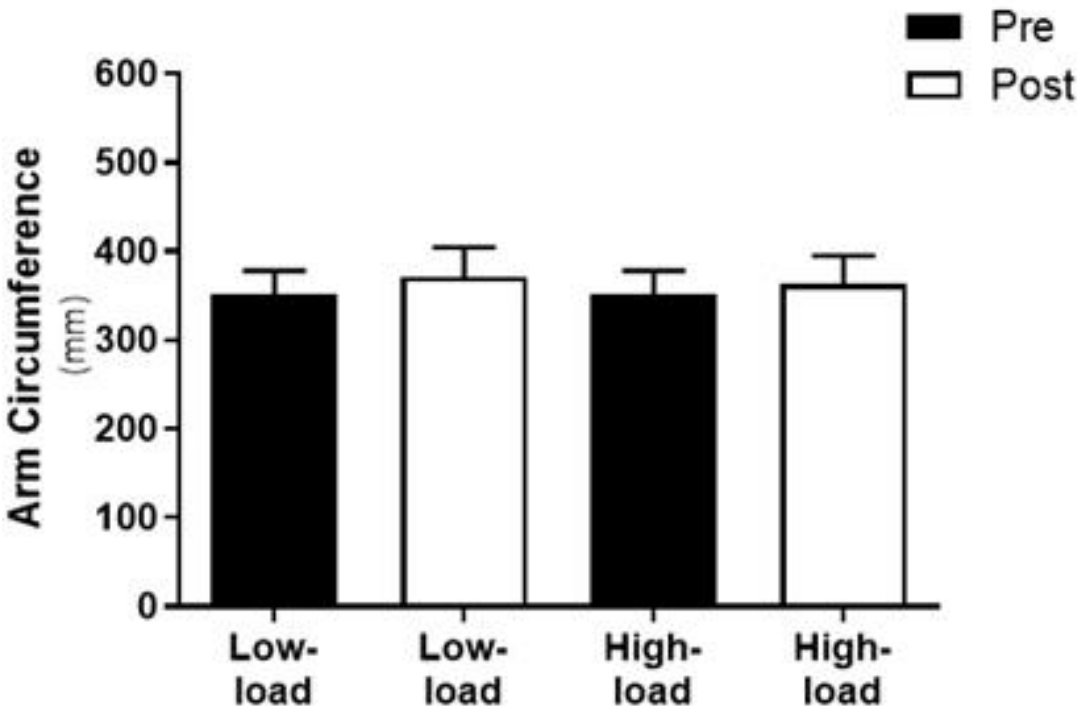

Figure 2. Arm circumference values of exercised arm before (pre) and after (post) intervention for low-load and high-load, mean (±SD). Values expressed in millimeters (mm).

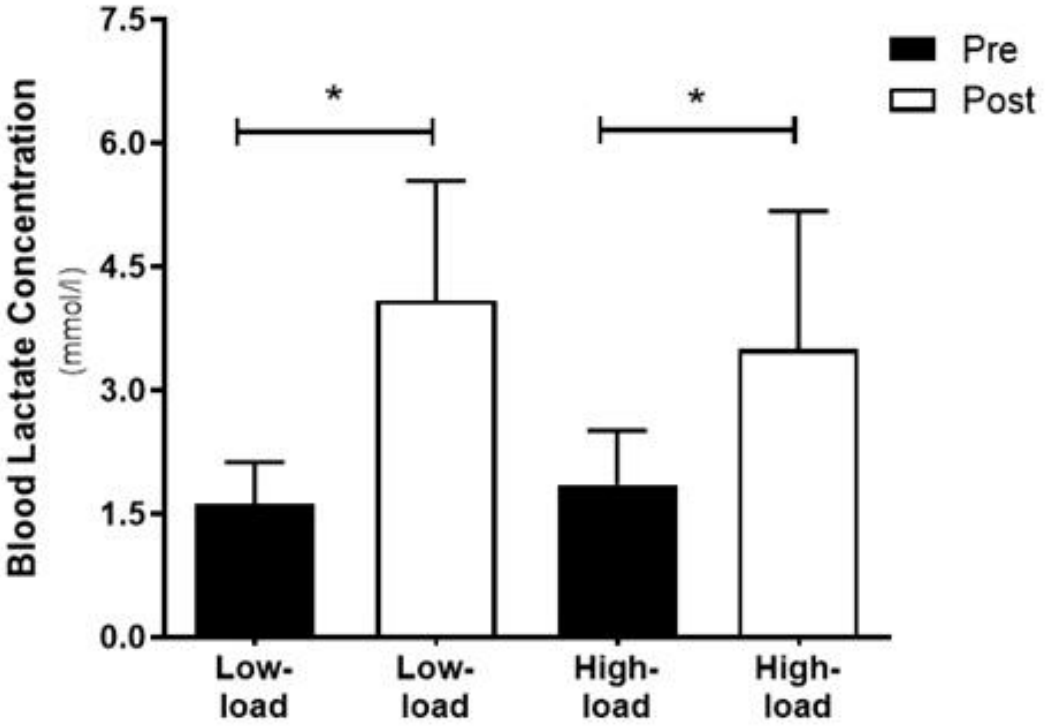

Figure 3. Blood lactate concentration values before (pre) and after (post) intervention for low-load and high-load, mean (± *SD*). Values expressed in mmol/l. * Significantly greater than the pre-training value ($p < 0.05$).

DISCUSSION

This study aimed to compare the acute effects of two volume-equated RT protocols, LL (50% 1 RM) and HL (85% 1 RM), on the thickness of the arm flexor muscles, arm circumference, and blood lactate concentration in well-trained men. To the authors' knowledge, this is the first study to evaluate these outcomes in this population. Our findings showed a significant increase in muscle thickness, and blood lactate regardless of condition, demonstrating that both protocols (LL – 50% 1 RM and HL protocol – 85% 1 RM) promote acute alterations in these variables. These results were contrary to our hypothesis that the LL protocol would induce greater muscle swelling and blood lactate concentrations compared to the HL protocol. Our findings provide evidence that RT carried out with different configurations can generate a favorable environment for the entry of water into the muscle cells and potentially stimulate anabolic effects resulting from the associated cell swelling (15, 26).

Although we equated volume load between protocols, the LL condition performed a significantly greater number of repetitions compared to HL given the markedly lighter loads used in LL. This in turn resulted in a significant difference in the time under tension between LL and HL. An increased time under tension and a greater number of contractions conceivably promote an environment conducive to alterations in the state of water concentration in the interstitial spaces, thus potentiating the effects of reactive hyperemia and a corresponding increase in intracellular hydration (11, 30). In addition, the training session density in the LL protocol was significantly higher than HL, since more repetitions were performed through the

sets, a greater mechanical stimulus is provided over time, promoting a greater accumulation of metabolites due to ATP resynthesis, thus increasing cytosolic osmolarity (13, 31).

Our results showed a significant increase in muscle thickness and blood lactate for both protocols (LL vs. HL) comparing pre- to post-session. Similarly, Kim et al. (12) evaluated acute changes in muscle thickness of the elbow muscle flexors and blood lactate after two blood flow restriction training protocols (LL vs. HL) in untrained individuals. Results showed a significant post-session increase in muscle thickness and lactate concentration in both protocols, with no differences between conditions. Although causality cannot necessarily be inferred, this suggests that resistance exercise that produces high levels of metabolic stress may provide a favorable milieu for changes in intracellular hydration (5). The acute increase in muscle thickness after an RT session has been attributed to increased intracellular hydration (5, 18, 35), commonly referred to as RT-induced cell swelling (18, 35). Evidence indicates that intracellular hydration is associated with increased protein synthesis and attenuated proteolysis in a variety of tissues including liver cells, bone cells, and muscle fibers (9, 10).

Although we did not observe statistically significant differences in lactate concentration between protocols, the ES markedly favored LL suggesting a potentially meaningful effect on this outcome. Given the moderate- to higher repetition schemes employed in our study, we anticipated that both protocols would strongly rely on the glycolytic pathway for energy utilization (25) and therefore induce a large lactate accumulation, as indeed was observed (LL = 163.6 ± 78.51 %, *ES* 2.42; HL = 105.48 ± 102 %, *ES* = 1.39). However, evidence shows a large variation in the individual response to blood lactate production and removal (12), which explains the fact that no statistical differences were observed between the protocols regarding this variable. However, the magnitude of the variation demonstrates that both protocols led to lactate accumulation, which in turn may have influenced the uptake of water from the extracellular environment to the intracellular environment, as previously reported in the literature (12, 33). Takarada et al. (33) demonstrated that the increased lactate accumulation and reduced lactate clearance rate seen with LL training combined with vascular occlusion is associated with increased accumulation of metabolites. Moreover, elevated lactate levels may promote anabolic effects on muscle tissue independent of mechanisms related to ischemia/hypoxia (22).

This study had several limitations that must be considered when attempting to extrapolate conclusions from the data. First, research constraints resulted in a relatively small sample size, which limited statistical power to draw strong inferences. Second, the participants were young, well-trained men, thereby limiting generalizability to other populations such as women and older adults. Third, although participants were advised to maintain their usual and customary diets throughout the study and provided self-reported dietary records, we cannot rule out the possibility that misreporting of either energy or macronutrient consumption may have influenced the results, especially post-session; the nutritional intake is one of the critical elements for muscle anabolism (20, 34). Fourth, subjective responses (RPEs - Rating of Perceived Exertion scales) of the participants was not collected and this information would be useful

regarding the exercise tolerance of the two protocols. Finally, the short-term crossover design of the study does not necessarily reflect what responses may occur over longer periods.

In conclusion, the findings of this study show that both LL (50 % 1 RM) and HL (85% 1 RM) RT cause a significant production of lactate, and a significant increase in elbow flexor muscle thickness, suggesting that intensities across a wide spectrum of loading zones can generate appreciable cell swelling. However, when comparing the magnitude of the protocols, LL showed greater post-session increases in muscle thickness and lactate, indicating that training protocols with longer times under tension and higher density (relation to exercise and rest) are preferable when the goal is to promote cell swelling. Although total RT volume has been established as a primary driver of strength and hypertrophy, our findings indicate that variables such as intensity, time under tension, the total number of repetitions, and the density of the training session are important considerations when the aim is to optimize cell swelling.

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