THE EFFECTS OF 4 WEEKS OF BLOOD FLOW RESTRICTION AND LOW-LOAD RESISTANCE TRAINING ON MUSCLE STRENGTH, POWER, HYPERTROPHY, AND NEUROMUSCULAR ADAPTATION

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The purposes of this study were to examine the effects of 4-wks of forearm flexion and extension blood flow restriction (BFR) resistance training versus non-BFR resistance training versus BFR without resistance training on: 1) muscle strength; 2) muscle power; 3) muscle size; and 4) neuromuscular adaptation. Forty women (mean±SD; 22±3 years) volunteered to participate in this investigation and were randomly assigned to either the resistance training with BFR (RT+BFR) (n=10), resistance training only (RT) (n=10), BFR without resistance training (n=10), or control (n=10) group. Resistance training included 75 (1×30, 3×15) repetitions of reciprocal isokinetic forearm flexion-extension muscle actions performed at 30% of concentric peak torque relative to forearm flexion and forearm extension peak torque, respectively. Blood flow restriction was applied using a KAATSU training device and was applied at a pressure that corresponded to 40% of arterial occlusion. Training was performed 3 times per week for 4-wks and all training and testing procedures were performed on a calibrated isokinetic dynamometer at a velocity of 120°·s^{-1}. The results of the present study indicated that there were similar mean increases in concentric peak torque, maximal voluntary isometric contraction (MVIC), muscle cross-sectional area, and muscle thickness for the forearm flexors and forearm extensors as a result of RT+BFR and RT. As a result of BFR only, there were smaller, but significant mean increases in concentric peak torque, but there were no changes in MVIC torque, muscle thickness

or muscle cross-sectional area. In addition to the increases in muscle strength, there were also training-induced increases (collapsed across Group) in forearm flexion peak power and mean power and forearm extension mean power, but no changes in forearm extension peak power. There were training-induced changes in the electromyographic (EMG) and mechanomyographic (MMG) responses that, in general, included increases (collapsed across Group) in EMG mean power frequency, MMG amplitude, and MMG mean power frequency, but no changes in EMG amplitude. The simultaneous increases in EMG mean power frequency and MMG mean power frequency may have reflected increases in motor unit firing rate, while the training-induced increases in MMG amplitude likely reflected the increases in muscle size.

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CHAPTER I: INTRODUCTION

The American College of Sports Medicine and the National Strength and Conditioning Association recommend resistance training loads of 60-85% of one-repetition maximum (1RM) to increase muscle strength and size (53, 58). Recent studies (4, 52, 83), however, have demonstrated increases in muscle strength and size as a result of blood flow restriction (BFR) training at lower intensities. For example, 1-wk of low-load (20% of 1RM) BFR leg extension resistance training increased 1RM and muscle cross-sectional area by 6.7% and 3.5%, respectively (52). Low-load non-BFR resistance training using the same training load, however, had no effects on 1RM or muscle cross-sectional area (52). In addition, 8-wks of low-load (20% of 1RM) BFR leg extension resistance training increased 1RM and muscle cross-sectional area by 40.1% and 6.3%, respectively, while low-load non-BFR resistance training at the same load resulted in smaller increases of 20.7% for 1RM and no significant changes in muscle cross-sectional area (83).

Previous investigations (40, 75, 137) have also demonstrated that low-load (≤ 50% of 1RM) BFR resistance training elicited comparable increases in muscle strength and size as high-load (≥ 50% of 1RM) non-BFR resistance training. For example, Takarada et al. (137) reported no differences for training-induced increases in muscle strength (18.4-22.6%) and muscle cross-sectional area (18.4-20.3%) following 16-wks of low-load (30-50% of 1RM) BFR versus high-load (50-80% of 1RM) non-BFR forearm flexion resistance training. In addition, Ellefsen et al. (40) found no differences between 12-wks of low-load (30% of 1RM) BFR leg extension resistance training and high-load (60-80% of 1RM) non-BFR resistance training for increases in 1RM (10-12%) or muscle cross-sectional area (6-7%).

It has been hypothesized that the increases in muscle strength and size associated with low-load BFR resistance training are related to cell swelling (86) and/or metabolite accumulation (87) that stimulate the mTOR pathway (61). Hoffmann et al. (66) suggested that the changes in intracellular pH associated with cell hydration and/or swelling likely affect the anabolic responses by enhancing the activity of ion exchange pumps. In addition, unlike high-load non-BFR resistance training (100, 114, 128), the early-phase increases in muscle strength as a result of low-load BFR resistance training appear to be driven primarily by hypertrophy and to a lesser extent, neuromuscular adaptations (90).

During high-load non-BFR resistance training, however, the early-phase increases in muscle strength are due primarily to neuromuscular adaptations and the effects of hypertrophy become a more prominent contributor to strength increases around 4-wks of resistance training. For example, Moritani and deVries (100) reported that the relative contributions of neuromuscular and hypertrophic adaptations to the increases in muscle strength were approximately 85% and 15% at 2-wks, 45% and 55% at 4-wks, 20% and 80% at 6-wks, and 15% and 85% at 8-wks, respectively. Moritani and deVries (100) delineated neuromuscular and hypertrophic adaptations across the 8-wks of high-load (66% of 1RM) non-BFR resistance training using the assessment of efficiency of electrical activity (EEA) that involves plotting the integrated electromyographic (iEMG) amplitude across submaximal intensities of the pretraining maximal voluntary isometric contraction (MVIC) value. Using the EEA technique, Moritani and deVries (100) suggested that neuromuscular adaptations were reflected by increases in voluntary activation (iEMG), while decreases in the slope coefficients of the iEMG versus torque relationship reflected muscle hypertrophy.

Using a similar approach, DeFreitas et al. (36) described the time-course of muscle hypertrophy by plotting the amplitude of the mechanomyographic (MMG) signal across submaximal intensities of the pretraining MVIC value prior to, and after 4- and 8-wks of high-load (60-80% of 1RM) non-BFR resistance training. MMG amplitude is affected by the number of activated motor units and increases linearly to approximately 60-80% of MVIC in men, but increases linearly to 100% of MVIC in women (13). DeFreitas et al. (36) hypothesized that a decrease in the slope coefficient of the MMG amplitude versus torque relationship reflects muscle hypertrophy because fewer motor units would be required to produce pretraining force levels. DeFreitas et al. (36) hypothesized that the decreases in slope coefficients for the MMG amplitude versus torque relationship after 4-wks (0.0074 to 0.0049 $m \cdot s^{-2}/kg^{-1}$) and 8-wks (0.0074 to 0.0048 $m \cdot s^{-2}/kg^{-1}$) of resistance training were likely the result of muscle hypertrophy. Together, Moritani and deVries (100) and DeFreitas et al. (36) applied EEA and MMG amplitude versus force relationship to examine neuromuscular and hypertrophic adaptations as a result of high-load non-BFR resistance training and found that the initial (<4-wks) changes in muscle strength were largely due to neuromuscular adaptations, but muscle hypertrophy became the primary mechanism promoting increases in muscle strength beyond 4-wks of resistance training.

No previous investigations, however, have examined the effects of BFR without resistance training on changes in muscle strength or size. This has important implications as BFR without resistance training has been demonstrated to maintain muscle strength during a period of detraining (82). Furthermore, no previous investigations have examined the time-course of changes in neuromuscular versus hypertrophic adaptations associated with low-load BFR resistance training using EEA or the MMG amplitude versus force relationship. Therefore,

the purposes of this study were to examine the effects of 4-wks of forearm flexion and extension BFR resistance training versus non-BFR resistance training versus BFR without resistance training on: 1) muscle strength; 2) muscle power; 3) muscle size; and 4) neuromuscular adaptation.

Hypotheses

Based on previous investigations (4, 52, 82, 83), we hypothesized that there would be increases in muscle strength, power, and size as a result of low-load BFR resistance training, low-load non-BFR resistance training, and BFR without resistance training, but there would be no changes for the control group. The increases in muscle strength, power, and size, however, would be greater as a result low-load BFR resistance training compared to low-load non-BFR resistance training and BFR without resistance training. In addition, we hypothesized that the increases in muscle strength and power would be due to increases in muscle size as reflected by increases in muscle cross-sectional area and muscle thickness, but decreases in the slope coefficients of the EMG amplitude and MMG amplitude versus force relationships (36, 40, 75, 90, 137).

CHAPTER II: REVIEW OF LITERATURE

2.1. Time Course of Neuromuscular and Hypertrophic Adaptations to Non-Blood Flow Restriction Resistance Training

2.1.1. Jenkins et al. (71)

The purpose of this investigation was to examine the effects of low- versus high-load resistance training on muscle strength and hypertrophy. Twenty-six men (mean age ± SD = 23.1 ± 1.7 yrs) were randomly assigned to low-load (30% of 1RM) or high-load (80% of 1RM) resistance training that was performed 3 times per weeks for 6 weeks. Resistance training consisted of 3 sets to failure of leg extension muscle actions. At 0, 3, and 6 weeks of training, muscle strength and hypertrophy were assessed. As a result of both training interventions, there were similar increases in muscle thickness at 3 weeks (approximately 3%) and 6 weeks (approximately 7%) of training. In addition, there were increases in 1RM and MVIC increased at 3 weeks (approximately 19% and 12%, respectively) and 6 weeks (approximately 31% and 31%, respectively) as a result of high-load training. There were smaller increases in 1RM (approximately 9%) and MVIC (approximately 15%) at 6 weeks as a result of low-load training, but there were no changes at 3 weeks. The larger increases in strength observed as a result of the high-load training were associated with increases in voluntary activation and increases in EMG amplitude. Together, these findings indicated that high- and low-load training induced similar increases in muscle hypertrophy, but there were greater increases in muscle strength as a result of high-load training. The greater increases in muscle strength associated with the high-load may have been due to neural adaptations that included increases in voluntary activation and muscle activation (EMG amplitude).

2.1.2. DeFreitas et al. (37)

The purpose of this study was to examine the time-course of muscle hypertrophy in response to resistance training. Twenty-five sedentary men (mean age ± SD = 21.5 ± 3.6 yrs) completed 8 weeks of high-load (80% 1RM) resistance training 3 times per week. Each training session consisted of 3 sets to failure of leg press, leg extension, and bench press performed at 80% of 1RM. Muscle cross-sectional area and MVIC strength were assessed at the end of each week of training and the minimal difference (MD) needed for a change to be considered "real" was determined. The results indicated that the changes in muscle thickness exceeded the MD within 2 training sessions that may have reflected muscle hypertrophy during the early-phase of resistance training. It should be noted, however, that the authors were not able to distinguish the changes in muscle thickness apart from potential increases in exercise-induced muscle edema that may have occurred. To account for this, the authors adjusted for the initial increases in muscle thickness and demonstrated that there were significant increases in muscle thickness at 3 weeks of training. Furthermore, there were increases in MVIC at 4 weeks of training that may have been due to muscle hypertrophy. Together, these results suggested that muscle hypertrophy may contribute to the early-phase increases in muscle strength as indicated by the concomitant increases in muscle size.

2.1.3. Stock et al. (131)

The purpose of this study was to examine the time-course of muscle hypertrophy as a result of concentric resistance training. Thirteen untrained men (mean age ± SD = 23 ± 4 yrs) performed 4 weeks of concentric-only dumbbell curls and dumbbell shoulder press 2 times per week. Training consisted of 4 sets to failure during the initial week of training and then progressed to 5 sets to failure during weeks 2-4 performed at 70% of 1RM. To describe the

time-course of muscle hypertrophy, muscle thickness, flexed arm circumference, relaxed arm circumference, and echo intensity were assessed from the trained arm at 8-time points throughout the 4 weeks of training and the MD for a change in muscle thickness to be considered "real" was determined. The results of this study indicated that "real" changes in muscle hypertrophy were evident after testing session 6 (at the end of week 3) as indicated by the increases in muscle thickness and flexed arm circumference without changes in exercise-induced edema (as indicated by echo intensity). These findings indicated that concentric-only training was sufficient to elicit increases in muscle hypertrophy within 4 weeks of training.

2.1.4. Moritani and deVries (100)

This investigation sought to describe the time course of neural and hypertrophic adaptations as they relate to training-induced increases in muscle strength. Seven men (mean of 22.0 yrs) and 8 women (mean of 18.2 yrs) completed 8 weeks of resistance training 3 times per week, 2 times per day. Resistance training consisted of 1 set of 10 forearm flexion muscle actions performed at 66% of 1RM. At 0, 2, 4, 6, and 8 weeks of training the subjects performed MVIC muscle actions and performed submaximal muscle actions at various increments of the 0-week MVIC value to determine the EMG:force relationship (iEMG:force). Neural changes were assessed by increases in iEMG, while hypertrophic adaptations were reflected by decreases in the slope of the iEMG:force relationships (i.e. fewer motor units required to produce submaximal intensities of the 0-week MVIC). The results indicated that the early-phase increases in MVIC were driven primarily by neural contributions and to a lesser extent, hypertrophic adaptations. Specifically, that the relative contributions of neuromuscular and hypertrophic adaptations to the increases in muscle strength were approximately 85% and 15% at 2 weeks, 45% and 55% at 4 weeks, 20% and 80% at 6 weeks, and 15% and 85% at 8 weeks, respectively. These findings

indicated that the initial increases in muscle strength were driven primarily by neural adaptations, while later increases in muscle strength were largely due to muscle hypertrophy.

2.1.5. DeFreitas et al. (37)

This investigation examined the MMG:force relationship as a result of resistance training. Twenty-two men (mean age ± SD = 21.7 ± 3.7 yrs) performed 8 weeks of bench press, bilateral leg extension, and bilateral incline press exercise 3 times per week. All resistance training was performed for 3 sets to failure (approximately 8-12 repetitions) at 80% of 1RM. MVIC strength was determined at 0, 4, and 8 weeks of training. To determine the MMG:force relationship, intensities of 10-90% of the 0-wk MVIC value were performed at 0, 4, and 8 weeks of training. The authors suggested the a decrease in the MMG:force relationship would be indicative of hypertrophic adaptations as fewer motor units would be required to produce a given level of force (i.e. 10-90% of 0-wk MVIC). The results indicated that MMG amplitude increased to approximately 66% of MVIC force and then plateaued at 0 weeks, while at 4 and 8 weeks of training MMG amplitude increased to approximately 85% of MVIC. The slope of the MMG:force relationship decreased similarly at 4 and 8 weeks from 0 weeks of training and was likely due to muscle hypertrophy. In addition, during the MVIC muscle actions at 4 and 8 weeks, MMG amplitude was lower compared to 0 weeks which may have been due to increases in muscle stiffness. These findings indicated that the MMG:force relationship may be used to describe the time course of muscle hypertrophy as a result of resistance training.

2.1.6. Ogasawara et al. (105)

This investigation examined the time-course of muscle hypertrophy as a result of bench press training. Seven previously untrained men (mean age ± SD = 25 ± 3 yrs) performed 24

weeks of bench press training at 75% of 1RM for 3 sets of 10 repetitions. Muscle thickness of the pectoralis major, biceps brachii, and triceps brachii were assessed weekly. There were increases in muscle thickness at 1 week for the pectoralis major and at 5 weeks for the triceps brachii, but there were no changes in the biceps brachii at any of the time points. In addition, there were increases in 1RM strength at 3 weeks of training that continued to increase throughout the remainder of the study. It is not possible, however, to determine if the initial increases in muscle thickness were due to muscle hypertrophy or exercise-induced muscle damage. However, muscle thickness continued to increase throughout the remainder of the study and was associated with increases in 1RM strength at 3 weeks. Together, these findings indirectly suggested that muscle hypertrophy may begin during the early-phases of a resistance training program and may occur prior to increases in strength.

2.1.7. Krentz and Farthing (81)

This study examined the time-course of muscle hypertrophy and neural adaptations as a result of resistance training. Twenty-two previously untrained men (mean age ± SD = 21.4 ± 0.6 yrs) performed 20 consecutive days of maximal eccentric muscle actions of the forearm flexors and extensors followed by 5 days of detraining. Training consisted of 6 sets of 8 repetitions at a velocity of $90°\cdot s^{-1}$. Muscle strength, muscle thickness, and muscle activation were assessed every 2 days of training and after 5 days of detraining. The results indicated that eccentric peak torque decreased at 8 days of training and did not return to baseline levels after training or detraining. Muscle thickness increased at 8 days of training and continued to increase to throughout the training (3.66 cm to 3.97 cm), but muscle thickness decreased after 5 days of detraining (3.97 cm to 3.80 cm). Muscle activation increased in the biceps brachii at 14 days of training, while muscle activation of the triceps brachii decreased at 20 days of training. These

findings indicated that high-load eccentric training continuously for 20 days decreased eccentric peak torque that did not recover throughout the training. There were, however, changes in muscle hypertrophy and neural adaptations for both the agonist and antagonist muscle groups, despite no improvements in muscle strength. Collectively, these findings suggested that neural and hypertrophic adaptations may begin during the early-phase of resistance training without changes in muscle strength.

2.1.8. Staron et al. (129)

The purpose of this study was to examine the effects of detraining and training on muscle strength, muscle fiber-type, and muscle fiber cross-sectional area. Six previously trained women (mean age ± SD = 21.4 ± 1.4 yrs) and 7 untrained women (mean age ± SD = 20.8 ± 1.0 year) performed 30 weeks of detraining followed by 6 weeks of training. Training was performed 2 times per week and consisted of 3 sets to failure performed at 80-85% of 1RM or 3 sets to failure performed at 70-75% of 1RM. Training included back squat, leg press, and leg extension exercises. The results indicated that there were no changes in muscle fiber-type cross-sectional area during the detraining phase, but the proportion of type IIb fiber-type increased. After the 6-week training, muscle fiber-type cross-sectional area increased for all fiber types, while the proportion of type IIb muscle fibers decreased. Together, these findings indicated that detraining resulted in gradual fiber-type changes to more fatigue type IIb motor units, but no changes in fiber-type cross-sectional area. Training-adaptations, however, occurred within 6 weeks of training that included increases in muscle fiber-type cross-sectional area and muscle strength.

2.1.9. Abe et al. (3)

The purpose of this study was to examine the time-course of strength and hypertrophy as a result of resistance training in men and women. Seventeen men (mean age ± SD = 37.7 ± 7.2 yrs) and 20 women (mean age ± SD = 41.0 ± 4.1 yrs) participated in 12 weeks of resistance training 3 days per week. In addition, 6 men (mean age ± SD = 42.5 ± 7.2 yrs) and 7 women (mean age ± SD = 44.6 ± 5.7 yrs) were assigned to a control group. Resistance training consisted of leg extension, leg flexion, chest press, seated row, forearm flexion, and forearm extension exercises performed for 3 sets to failure at 60% of 1RM. For only the chest press and leg extension exercise, the load progressed to 70% of 1RM after the 2-4 weeks of training. In addition, 1RM strength was only reported for the chest press and leg extension exercise as a result of the training. Muscle thickness values were assessed from the biceps brachii, triceps brachii, pectoralis major, anterior thigh (rectus femoris), and poster thigh (biceps femoris). As a result of the resistance training, leg extension 1RM strength increased at 2 weeks for the men, but not until 4 weeks for the women. Chest press 1RM increased at 6 weeks for the men, but at 4 weeks for the women. Following 20 weeks of training, however, both the men and women increased 1RM leg extension strength by 19%, and chest press 1RM increased by 19% and 27% for the men and women, respectively. Furthermore, muscle thickness increased for the pectoralis major, and biceps and triceps brachii for both the men and women at 6 weeks of training, but there were no changes in muscle thickness of the anterior thigh for either the men or women. For the posterior thigh, however, muscle thickness increased at 8 weeks for both the men and women. Collectively, these findings indicated that men and women responded similarly to resistance training of the upper and lower body. In addition, there were increases in muscle strength prior to observable changes in muscle size (hypertrophy).

2.1.10. Staron et al. (128)

The purpose of this investigation was to examine the time-course of changes in muscle strength and muscle hypertrophy in men and women. Thirteen men (mean age ± SD = 23.5 ± 3.2 yrs) and 8 women (mean age ± SD = 20.6 ± 1.5 yrs) participated in 8 weeks of resistance training, while 7 men (mean age ± SD = 20.7 ± 1.4 yrs) and 5 women (mean age ± SD = 20.6 ± 1.6 yrs) were randomly assigned to the control group. Training was performed 2 times per week and consisted of 3 sets to failure performed at 80-85% of 1RM or 3 sets to failure performed at 70-75% of 1RM. Training included back squat, leg press, and leg extension exercises. For the men, 1RM strength increased significantly at 4 weeks of training for squat, leg press, and leg extension exercises. For the women, 1RM strength for the leg press increased at 2 weeks and the squat and leg extension 1RM increased at 4 weeks. The largest increases in muscle strength occurred after 2 weeks of training for both men and women. The were no changes in muscle fiber-type cross-sectional area, but there were significant decreases in the proportion of type IIb muscle fibers and increases in type I muscle fibers. In addition, there were greater training-induced increases and decreases in resting testosterone and cortisol, respectively, for the men. These findings indicated that, despite different training-induced hormonal responses, men and women experienced similar early-phase increases in muscle strength.

2.1.11. Narici et al. (102)

The purpose of this investigation was to examine the time-course of muscle hypertrophy and neuromuscular adaptation. Four men (mean age ± SD = 28.3 ± 5.1 yrs) participated in 60 days of resistance training followed by 20 days of detraining. Training was performed 4 times per week and consisted of 6 sets of 10 maximal concentric isokinetic leg extension muscle actions performed at $120°\cdot s^{-1}$. Every 20 days throughout the training and detraining period, MVIC, concentric peak torque (at velocities of 0, 60, 120, 180, 240, and $300°\cdot s^{-1}$), muscle cross-

sectional area, and iEMG were assessed from the vastus lateralis, vastus medialis, and rectus femoris muscles. After 60 days of training, MVIC increased by 20.8 ± 5.4% and concentric peak torque increased 20.9, 23.8, 22.5, 14.5, 3.6, and 2.8% at 0, 60, 120, 180, 240, and 300°·s^{-1}, respectively. Muscle cross-sectional area increased by 8.5 ± 1.4 across the quadriceps muscles. In addition, iEMG increased by 42.4 ± 16.5% as a result of the resistance training. After 20 days of detraining, all indices of muscle strength, hypertrophy, and neuromuscular adaptations were reduced. These findings indicated that resistance training of the leg extensors increased muscle strength that was attributable to increases in muscle hypertrophy and iEMG. Following a period of detraining, however, these favorable adaptations were reduced.

2.1.12. Aagaard et al. (2)

This investigation examined the changes in motor neuron inhibition following concentric and eccentric resistance training. Fifteen men (mean age ± SD = 23.5 ± 3.4 yrs) competed 38 resistance training sessions over a 14-week period. Training consisted of 4-5 sets of 6-15 repetitions performed at an intensity that corresponded to 60-80% of 1RM. Training exercises included hack squat, incline leg press, leg extension, and leg flexion exercises. Motor neuron inhibition was quantified as the reduction in voluntary activation and torque production performed at slow to fast velocities. All values were normalized to the fast velocity concentric isokinetic muscle actions. As a result of resistance training, there were increases in concentric (15% and 8%) and eccentric (15-17%) isokinetic leg extension strength at 30°·s^{-1} and 240°·s^{-1}. In addition, iEMG increased 16-52% across the muscles of the quadriceps, but was lower during the eccentric muscle actions. These findings indicated that training increased iEMG and decreased motor neuron inhibition, but there were mode- (eccentric versus concentric) and velocity-specific (30°·s^{-1} versus 240°·s^{-1}) training responses.

2.1.13. Knight and Kamen (77)

This study examined the effects of resistance training on voluntary activation in young and older adults. Eight young (mean age ± SD = 21.4 ± 1.0 yrs) and 7 older adults (mean age ± SD = 77.0 ± 2.0 yrs) participated in 6 weeks of resistance training. Training was performed 3 times per week and consisted of 3 sets of 10 leg extension muscle actions performed at 85% of 1RM. MVIC strength and voluntary activation as assessed by interpolated twitch were determined prior to and after 6 weeks of training. There were similar increases of 36% and 30% in MVIC for the young and older adults, respectively, that were associated with 2% increases in voluntary activation. The young adults were, on average, 50% stronger than the older adults prior to and after training. For both the young and older adults, voluntary activation was greater than 95% of the interpolated twitch. These findings indicated that both young and older adults were equally responsive to the initial changes in strength and neuromuscular adaptations associated with resistance training.

2.2. Assessments of Neuromuscular and Hypertrophic Adaptations to Non-Blood Flow Restriction Resistance Training

2.2.1. Jenkins et al. (70)

The purpose of this study was to examine the reliability of ultrasound assessments of muscle thickness, muscle cross-sectional area, and echo intensity. Fourteen men (mean age ± SD = 21.8 ± 2.5 yrs) participated in this investigation consisting of 2 separate visits. During visits 1 and 2, ultrasound images were taken from the biceps brachii muscle at 66% of the distance from the medial acromion of the scapula to the fossa cubit. Both single and panoramic

images were obtained to determine muscle thickness and muscle cross-sectional area, respectively. The results indicated that both muscle thickness and muscle cross-sectional area could be reliably assessed between days (ICC 0.97-0.99) from the biceps brachii. Similarly, the ICC for echo intensity ranged 0.78-0.99. These findings suggested the both single or panoramic images could be used to reliably assess changes in muscle thickness, muscle cross-sectional area, and echo intensity.

2.2.2. Mitchell et al. (99)

The purpose of this study was to examine the effects of exercise volume on strength and hypertrophic adaptations. Eighteen men (mean age ± SD = 21 ± 1 yrs) completed 10 weeks of resistance training performed 3 times per week. The dominant and non-dominant legs of each subject were randomly assigned to 1 of 3 resistance training protocols: 1) 1 set to failure at 80% of 1RM; 2) 3 sets to failure at 80% of 1RM; 3) 3 sets to failure at 30% of 1RM. All resistance training consisted of isotonic leg extension muscle actions. Strength was assessed by 1RM and MVIC that was determined prior to training and after 10 weeks of training. Muscle hypertrophy was assessed using magnetic resonance imaging assessed prior to training and after 10 weeks of training. In addition, muscle biopsies were performed to quantify the changes in the phosphorylation of myogenic proteins. The results of this study indicated that 1 and 3 sets to failure at 80% of 1RM increased 1RM strength to a greater extent that performing 3 sets to failure at 30% of 1RM, but MVIC strength increased similarly across all resistance training protocols. The 80% protocols were associated with increased phosphorylation of $p70S6K^{Thr389}$, but there were no changes as a result of the 30% protocol. Despite increased phosphorylation in the 80% protocols, there were no differences in the magnitudes of muscle hypertrophy among 1 and 3 sets to failure at 80% of 1RM (3.2% and 7.2%, respectively) or 3 sets to failure at 30% of

1RM (6.8%). These findings indicated that muscle volume, which was greater in 3 sets to failure at 30% and 80% of 1RM compared to 1 set to failure at 80% of 1RM, was not a mediating factor of the hypertrophic responses associated with resistance training. In addition, these findings supported the use of low-load resistance training to elicit comparable increases in muscle hypertrophy as high-load resistance training.

2.2.3. Popov et al. (116)

This investigation examined the effects of exercise intensity on myogenic gene expression. Ten resistance-trained men (mean age = 21.1 yrs) randomly performed 3 resistance training protocols on separate days: 1) 74% of 1RM; 2) 54% of 1RM; and 3) 54% of 1RM without relaxation between repetitions (6 seconds of rest was allocated between repetitions during protocols 1 and 2). During all resistance training sessions, 8 sets of 12 bilateral isotonic leg extension muscle actions were performed with 6 minutes between sets. To examine acute responses in myogenic gene expression, muscle biopsies were taken prior to exercise, and 45 min, 5 hours, and 22 hours after the resistance exercise. In addition, blood lactate and glucose concentrations were assessed prior to exercise and 30 second after sets 3, 5, and 8. Testosterone, insulin, and insulin-like growth factor were also assessed prior to exercise and 15 minutes after exercise. There were increases in 5'-AMP-activated protein kinase as a result of the 74% 1RM protocol, and increases in ERK1/2$^{Thr202/Tyr204}$ as a result of the 54% protocol without rest between repetitions. In addition, there were decreases in myostatin mRNA expression as a result of the 74% (20-fold decrease) and 54% protocol without rest between repetitions (6-fold decrease). For all exercise conditions, blood glucose decreased following the 3rd set of exercise, although blood glucose was not different than pre-exercise conditions after sets 5 and 8. Blood lactate increased after all conditions, but the magnitudes of increase were greatest for the 54% protocol without

rest between repetitions. There were, however, no changes in testosterone, insulin, or insulin-like growth factor for any of the conditions. These findings suggested that both a high-load (74% of 1RM) and low-load (54% of 1RM) training performed without rest between repetitions resulted in similar changes in myogenic gene expression following exercise, but the magnitude of changes was greater for high-load resistance exercise. Together, these findings suggested that exercise intensity and rest periods between repetitions affected the anabolic responses associated with resistance exercise.

2.2.4. Burd et al. (24)

The purpose of this study was to examine the effects of exercise volume and training load on myogenic gene expression and muscle protein synthesis. Fifteen men (mean age ± SD = 21 ± 4 yrs) performed 4 sets of unilateral isotonic leg extension muscle actions using 2 of 3 conditions: 1) 90% of 1RM performed to failure (high-load); 2) 30% of 1RM in which the external work was matched to the work completed in the 90% to failure condition (work-matched low-load); or 3) 30% of 1RM performed to failure (low-load performed to failure). Muscle biopsies were obtained from the vastus lateralis muscle at rest and 4 hours and 24 hours after exercise. There were no differences in exercise volume between protocols 1 or 2, but exercise volume and time under tension were greater during protocol 3 (30% of 1RM performed to failure). Myofibrillar protein synthesis increased in all conditions 4 hours post exercise, but were greater as a result of high-load and low-load exercise performed to failure. In addition, phosphorylation of ERK1/2$^{Tyr202./204}$, p70S6K^{Thr389}, and 4E-BP1$^{Thr37/46}$ increased for only the low-load exercise performed to failure, while phosphorylation of Akt^{ser473} and in mTOR^{ser2448} increased for all conditions at 4 hours and 24 hours, respectively. Myogenic mRNA expression increased at 24 hours for the high-load exercise and low-load exercise performed to failure, but