THE DOSE-RESPONSE OF WEEKLY RESISTANCE TRAINING VOLUME ON SKELETAL MUSCLE ADAPTATIONS IN TRAINED MALES

by

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Abstract

Purpose: Previous literature is unclear on the dose response relationship between resistance training (RT) volume and skeletal muscle adaptations when weekly sets exceed 10-12. The present study compared the effects of various weekly RT volume on skeletal muscle thickness and strength in young RT trained males over 6 weeks. **Methods:** RT trained young (aged 18-21) males (n=21) were randomly allocated to a low (LOW, n=7) moderate (MOD,n=7) or high (HIGH,n=7) group. Participants undertook RT of the biceps over a 6-week period. LOW performed 1 RT session per week consisting of 9 sets (9 weekly sets), MOD performed 2 RT sessions per week consisting of 9 sets (18 weekly sets), HIGH performed 2 RT sessions per week consisting of 14 and 13 sets (27 weekly sets). All participants consumed 40g whey protein post RT session, whilst recording dietary intake and external RT volume throughout the 6-week period. Pre and Post training period assessments of muscle thickness (MT; Ultrasound), isometric maximal voluntary contraction and one repetition maximum strength was completed by all groups. Data was analysed using a mixed design ANOVA to examine within and between group pre-post changes. **Results:** MT significantly increased pre-post in LOW (9.3 ± 5.5%, p<.001) and MOD (14.3 ± 10.4%, p<.001) but not in HIGH (5.59 ± 4.0%, p=.054). All groups experienced significant increases in 1RM strength but no significant increase in isometric strength. There were no significant differences between groups for MT, 1RM and isometric strength. **Conclusion:** The findings of this study suggest that moderate and high weekly RT volumes, performed twice per week, provide minimal further benefit to skeletal muscle adaptations over lower weekly RT volumes performed once per week for 6 weeks.

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List of Abbreviations

ANOVA	Analysis of variance
BW	Bodyweight
CSA	Cross-sectional area
CT	Computed tomography
DEXA	Dual x-ray absorptiometry
ES	Effect size
GH	Growth hormone
HIGH	High weekly volume experimental group
IGF1	Insulin like growth factor 1
LOW	Low weekly volume experimental group
MAPK	Mitogen activated protein kinase
MOD	Moderate weekly volume experimental group
MPB	Muscle protein breakdown
MPS	Muscle protein synthesis
MRI	Magnetic Resonance imaging
MT	Muscle thickness
mTORC1	Mammalian target of rapamycin complex 1
MVC	Maximal voluntary contraction
RIR	Repetitions in reserve

RM	Repetition maximum
ROM	Range of motion
RPE	Rating of perceived of exertion
RT	Resistance training
SD	Standard deviation
SEM	Standard error of mean

1. Introduction

The development of skeletal muscle mass and strength are desirable adaptations from physical exercise for both health and performance benefits. High levels of lean muscle mass and function are becoming increasingly important for the well-being of the general public. There is a growing body of evidence to support the consensus that individuals with higher levels of muscle mass maintain superior quality of life as they age and decrease their risk of the development of associated diseases such as sarcopenia (Wolfe et al., 2006; Seguin et al., 2003; Liu et al., 2009). In addition to decreasing disease risk, the use of physical exercise to develop muscle mass and strength has been shown to assist in the improvement of health in individuals suffering from type 2 diabetes (Son et al., 2017; Pesta et al., 2017). The relative amount of muscle mass an individual has, has been negatively associated with risk of type 2 diabetes, possibly due to the ability of skeletal muscle mass to uptake large amounts of glucose (Hong et al, 2017) Finally, outcomes of developing muscle mass, specifically increased leg strength, has been shown to be a strong predictor of mortality (Singh et al., 2010).

Besides the importance for general health and longevity, high levels of muscle strength and size are key attributes to physical performance in most sports. Muscle size and strength share a strong relationship, with increases in strength often being largely (though not solely) attributed to increases in size (Maughan et al., 1983). These qualities also form a strong base to develop other desirable physical qualities such as power, speed and the ability to quickly change direction (Hojka et al., 2016), alongside associated injury prevention benefits (Fleck et al., 1986). Given these adaptations, athletes in sports such as throwing, sprinting and rugby will dedicate considerable training time to develop muscle mass and strength to the highest possible level for the individual. Therefore, the health and performance benefits of strength training for muscle mass development are well documented.

However, the correct physical training prescription to elicit these adaptations, as well as aspects of the underpinning physiology, remain contested.

2. Literature Review: Skeletal Muscle Remodelling

2.1. Types of Skeletal Muscle Remodelling

Increases in muscle mass are thought to be defined by two processes, hyperplasia and hypertrophy. Hyperplasia refers to the addition of new cells and in regard to skeletal muscle, an increase in the total number of myofibrils. Although this process may occur, evidence for hyperplasia in humans as an adaptation of physical exercise is lacking considerably. The latter of these two processes, hypertrophy, is the predominant cause of increases in muscle size in humans from physical exercise. Hypertrophy refers to the increase in the cross-sectional area of myofibrils. This increase in size is a result of an increase in the number and size of contractile filaments (actin and myosin), leading to an increase in the number of sarcomeres. These sarcomeres are added either in series or parallel (Tesch et al., 1982; Paul et al., 2002). This process results in a myofiber which is larger than previous.

2.2. Mechanisms of Skeletal Muscle Hypertrophy

The physiological underpinning of hypertrophy is multi-faceted, however, the main mechanism underpinning this process is the balance between muscle protein synthesis (MPS) and muscle protein degradation (MPB) (Toigo et al., 2006). Synthesis leads to the addition of new proteins, whilst degradation results in the breakdown of existing proteins, both of which are necessary processes during skeletal muscle remodelling. For hypertrophy to occur, levels of MPS must be greater than MPB, resulting in a net positive protein balance. Over time, this net positive balance results in the accretion of muscle mass. There are several other mechanisms, including myogenic signalling pathways, hormonal interactions and satellite cell activity, that can either influence the protein balance in favour of synthesis or produce other effects leading to hypertrophy.

2.2.1. Molecular underpinnings of hypertrophy. The key myogenic pathway in this process is the mammalian target of rapamycin complex 1 (mTORC1). This complex is considered the master regulator of skeletal muscle growth (Bodine et al., 2001) by being an effector of anabolic signals, of which result in positive effect on MPS and inhibitory effects on catabolic signals. mTORC1 responds to physiological stimuli such as mechanical stress, energy status and amino acids. The activation of mTORC1 is increased following resistance training (RT; Song et al., 2017) and is well correlated with RT-induced hypertrophy (Terzis et al., 1999). The critical importance of this signalling pathway is evidenced in studies which have examined the effects of inhibiting the activity of mTORC1 following RT, resulting in a blunting effect of muscle protein synthesis (Drummond et al., 2009).

Alongside the mTORC1 pathway, hypertrophy may also be affected by alterations in the Mitogen activated protein kinase (MAPK) pathway and calcium dependent pathways. MAPK is regarded as a master regulator of gene expression and metabolism (Kramer et al., 2007). This signalling molecule has been shown to sense cellular stress, modulate cell growth, and be sensitive to eccentric based RT (Schoenfeld et al., 2010). Calcium dependent pathways may also play a role. Calcinecurin has been identified as a key regulator of this pathway and has been linked to hypertrophy. The inhibition of this pathway has been shown to result in inhibition of muscle growth during periods of muscular loading (i.e. resistance training; Dunn, 1999).

2.2.2. Hormones and hypertrophy. The influence of several hormones may play an anabolic role in the muscular adaptation to RT. These hormones include testosterone, Insulin like growth factor 1 (IGF-1) and growth hormone (GH). The possible roles in which these hormones have in influencing hypertrophy may include 1) increasing protein synthesis through affecting upstream molecular signalling pathways, directly mediating gene transcription (Vingren et al., 2010), 2) inhibition of catabolic signals, and 3) influencing satellite cell activity (Goodman et al., 2011). Following RT, these hormones will typically transiently increase, particularly following RT that involves a large amount of muscle mass, short rest periods, moderate intensities and high volume (Kraemer et al., 2005). Some research suggests that these RT protocols which maximise acute increases in hormonal concentrations are vital for maximum hypertrophy. Ahtiainen and colleagues (2003) found a strong correlation (r^2=.76) between these acute increases and increases in cross-sectional area (CSA) over 21 weeks of RT. McGall and colleagues (1999) have also demonstrated a similar strength of correlation between elevations in GH and hypertrophy. However, the extent to which these correlations are important is highly debated. West and Phillips (2012) have found, with larger sample sizes, a far weaker correlation (r=.28). These authors have also demonstrated through specific experimental designs with RT to increase acute elevations in hormones, that increases between groups of high hormonal elevations and low conditions do not cause significant differences in MPS (West et al., 2009). West and colleagues (2010) have also continued this design over 15 weeks of RT and observed no differences in hypertrophy. A key consideration of this research is that it was carried out in untrained participants. Kraemer and colleagues (2005) suggests that the role of these anabolic hormones may be more important for trained participants. Therefore, the role of these hormones remains slightly unclear when considering RT adaptations, especially for resistance trained individuals.

2.2.3 Cell swelling. The cellular hydration of a muscle cell can also play a role as a mechanism of hypertrophy, known as cell swelling. This process is associated with RT training that relies heavily on glycolysis to produce energy, which has been suggested to cause changes in intra- and extracellular water balance. The accumulation of lactate resulting from anaerobic metabolism serves as a contributor to osmotic changes inside the cell (Sjoogard et al., 1987). It is thought that due to this increase in fluid, the increased pressure against the cellular membrane and resulting stretch is considered harmful to cellular integrity, and results in a signalling response leading to the reinforcement of the cell (Schoenfeld et al., 2010).

2.2.4. Hypoxia. A hypoxic intramuscular environment is also considered to be a contributor to hypertrophy. Hypoxic environments have been shown to increase lactate and reduce its clearance, which may lead to an increase in cell swelling and cause alterations in anabolic hormones (Takarada et al., 2000). Alongside the metabolic effect on lactate accumulation, it is considered to cause an increase in reactive oxygen species, which may play a role in hypertrophy by effecting satellite cell proliferation and activation of MAPK (Takarada et al., 2000). The potency of the hypoxic stimuli for hypertrophy has been evidenced using vascular occlusion. Takardada and colleagues (2000) saw that occlusion by itself reduced muscular atrophy in patients during bed rest, a scenario that in normal conditions would result in significant muscle loss. This has been further supported by the combination of occlusion and RT, known commonly as “blood flow restriction training”. Blood flow restriction training has been shown to result in hypertrophic gains greater than RT alone (Loenneke et al., 2012).

2.2.5. Satellite cells. The activity of satellite cells is another mechanism thought to facilitate increases in muscle size. Satellite cells are located between the basal lamina and sarcolemma (Hawke et al., 2001) behaving as myogenic stem cells that remain dormant until activated by sufficient mechanical loading (Vierck et al., 2000). Once activated, these cells proliferate and can fuse to existing cells or to themselves, forming new myofibers to provide the necessary tools required for cellular repair and growth. During hypertrophy, the muscle fiber to nuclear ratio, known as the myonuclear domain remains constant. The myonuclear domain regulates mRNA production for contractile apparatus and any increases in fiber size must result in a corresponding increase in myonuclear domain. Changes to this over time require an external source of active cells. Satellite cells can play a critical role in this process and serve as an extra pool of myonuclear domain to support continued muscle growth by either increasing the number of myonuclear domain or the size of existing domains (Barton-Davis et al., 1999).

2.3 Mechanisms of Exercise Induced Skeletal Muscle Hypertrophy

The use of RT is the most commonly used form of exercise and can be considered the most potent for bringing about increases in muscle size. This form of exercise is characterised by the execution of muscular contractions against an external resistance. In relation to RT exercise, there are three main factors that regulate the mechanisms that underpin hypertrophy. These are 1) mechanical tension, 2) metabolic stress and 3) muscle damage.

2.3.1 Mechanical tension. Mechanical tension is characterised by the force generation and stretch exhibited by muscles during RT. The intramuscular tension associated with mechanical loading during RT results in a disturbance in the integrity of the skeletal muscle, which is then translated into chemical signals that lead into molecular and cellular responses effecting protein synthesis (Baar et al., 1999). When loading is combined with stretching of the muscle, a greater response is typically seen (Vandenburgh et al., 1987). However, mechanical loading by itself is not solely indicative of hypertrophy. For example, the brief high levels of mechanical tension that are associated with training for muscular strength result in neural adaptations with minimal changes in hypertrophy.

2.3.2 Metabolic stress. Metabolic stress is characterised by the accumulation of a number of metabolites such as lactate, hydrogen ion, inorganic phosphate, creatine and others

(Tesch et al, 1986). The accumulation of these metabolites is a product of anaerobic glycolysis for energy production. The resultant metabolic stress can provide signals for molecular signalling, hormonal increases, cell swelling and increased activity of growth factors. In addition to this, the acidic environment developed may potentially lead to fiber degradation. The ischemic nature of mechanical loading during RT may further enhance this metabolic stress developed during certain forms of RT (Toigo et al., 2006; Pierce et al., 2006). At a relatively moderate loading intensity, venous return is inhibited during muscular contractions. This results in a trapping and further accumulation of metabolites. Therefore, RT of a moderate intensity (65-75%) and moderate repetition range (6-12) may provide an ideal symphony between both mechanical loading and metabolic stress, to maximise hypertrophy.

2.3.3 Muscular damage. During some forms of RT or under specific circumstances, muscular damage can occur. This muscular damage and level of damage can range from small molecular damage to larger tears in the tissue (Vierck et al., 2000). The response to this muscle damage and resulting trauma is similar to the response to infection, with the involvement of immune cells to clear damage. The activation of these immune cells can lead to the release of growth factors, which may in turn regulate satellite cell proliferation (Hill et al., 2003).

2.3.4 Training response and status. The individual response to RT varies considerably between participants and is an important factor to consider with RT programs. Individuals may experience extremely high levels of hypertrophy following RT (responders), however other individuals may not experience any improvements and may possibly even see decreases (non-responders). Within these categorisations, the level of response is very broad. Hubal and colleagues (2005) examined the training response in 585 male and female participants following 12 weeks of RT. Changes following this training ranged from increases over 59% in muscle size to 2% decreases in muscle size. Changes in muscle strength showed even more variability with changes varying from 0% improvement to 250%. This varied response may be due to differences in factors such as lifestyle behaviours, training status and genetics. The time it takes to recover from RT may also play a role. Baurmert and colleagues (2016) suggests individuals that are genetically predisposed to increased muscle damage may take longer to recover from training. Building upon these genetics differences, Jones and colleagues (2016) have suggested that matching individuals to specific training modalities based on their genotype may lead to superior improvements in performance, as opposed to not matching. This evidence suggests that when examining and conducting RT studies the participants involved may vary individually in their response to training due to innate factors.

The training status of participants is also a key factor in the level of adaptation observed in RT programs. Following RT, untrained participants will exhibit a sustained whole body increase in MPS of up to 48 hours (Phillips et al., 1987) regardless of the muscle mass exercised. However, a trained participant will display a far shorter duration of increased MPS, which will be specific to the region of muscle mass exercised (Damas et al., 2015). In addition to this, untrained individuals typically experience rapid increases in neural adaptations to RT (Mulligan et al., 1996), which may affect the measurement of other forms of muscle adaptation (i.e. strength). Schoenfeld (2010) also suggests that mechanisms of adaptation may differ between trained and untrained individuals, suggesting that the activity of satellite cells may be of greater importance to participants with a longer resistance training history. Therefore, the comparison of studies varying in the training status of individuals can greatly affect the level of application of the results to other populations.

2.4. Assessing Skeletal Muscle Hypertrophy

There are a number of ways to measure exercise-induced skeletal muscle development to provide insight into hypertrophic adaptations. The most common measurements are skeletal muscle cross-sectional area (CSA) and muscle thickness (MT) and volume (most often used when directly examining the result of RT programs). However, changes in limb girth and lean body mass may also be used. Changes in muscle volume, thickness and cross-sectional area are typically measured via the use of magnetic resonance imaging (MRI; deemed the gold standard; Sato et al., 2005), computed tomography (CT) or ultrasonography. Changes in lean body mass can be measured using dual-energy X-ray absorptiometry (DEXA) scans. The use of MRI, CT and DEXA all provide highly detailed information, although, are limited by financial implications, such as running costs, when collecting a large number of samples. Ultrasonography is a typically more convenient method for measuring hypertrophy and widely used in RT studies. The measure has been validated and considered an accurate measure of hypertrophic adaptations (Lixandrao et al., 2014). The measurement of muscle thickness from ultrasound has been shown to correlate with CSA measurements via MRI to determine RT-induced hypertrophy (Franchi et al, 2018). However, a consideration and potential short coming of ultrasound measurements is the skill level of the operator. To minimise variance in measurements and potential errors, the proficient operator must remain the same during all measurements. Limb girth can be measured via tape measurements, however it is the least accurate of all measures when used as the sole measure, and may overestimate increases in hypertrophy (Sato et al., 2005).

2.5 Influence of Resistance Training Variables on Skeletal Muscle Hypertrophy

Resistance training is influenced by a variety of training variables such as volume, intensity, exercise selection and rest time. Each training variable can have a significant effect on the training adaptation, and therefore an understanding of the influence of their training variables on hypertrophy is needed.

2.5.1 Exercise selection. The selection of exercises is a critical component of constructing RT programmes for training adaptations. Exercises can vary on the number of joints involved during their movements, most broadly categorised into single joint or multi joint movements and the variation of similar movements based on joint angles. Typically, multi-joint exercises involve a larger number of active muscles in comparison to single joint exercise that may specifically isolate one muscle. These two types of exercise movement will greatly affect the total level of activation in the active muscles, Gentil et al, (2007) Brenneckle et al, (2007) suggest that the activation of distal muscles is lower than proximal prime movers during a multi-joint exercise. However, these findings are opposed by Clemons and Aaaron (1997) who suggest the level of activation was higher in the distal muscles of the triceps than the prime movers of the pectorals major, in the bench press exercise. The differences in the findings of these studies may be due to individual differences, such as limb lengths and the exercise technique and execution. Alongside this, higher levels of activation during multi-joint exercises may be a product of a greater total load that is possible with larger mutli-joint exercises. In untrained participants Gentil et al, (2015) have demonstrated no difference between single joint and multi-joint exercises for increasing muscle thickness, with similar findings in trained participants (Silverstre De Franca et al., 2015).

The variety of exercises for the same muscle group may be supported by the concept of regional hypertrophy. Due to differences in levels of muscle activation and ROM between exercises, different regions of the same muscle group may be exposed more so than others (Mendigucha et al, 2015). Therefore, the use of a large variety of exercises during a RT program may lead to greater overall hypertrophy; this is supported by work by Fonseca et al,

(2014) which demonstrates a greater variety of multi joint exercises was superior for muscular development.

2.5.2. Rest period. The amount of rest used between sets and exercises during RT can have both beneficial and adverse effects on both the adaptation and performance during a session. Rest periods can be categorised into short (less than 60s) moderate (1-3 mins) or long (> 3 mins) periods. When considering typical hypertrophy training that is glycolytic in nature, short rest periods will typically produce greater levels of fatigue during the RT session due to the shortened recovery time and therefore greater accumulation of metabolites. These short periods have been suggested to be key for increasing metabolic stress inside the muscle which may drive hypertrophic adaptation. In addition to this, shorter rest periods are also associated with greater acute post exercise hormonal increases, however these increases may decrease throughout the duration of the RT program (Buresh et al.,2009). A negative to short rest periods and benefit to moderate and long is that the level of fatigue generated in short rest periods will limit the amount of repetitions performed with a given load (Miranda et al., 2009, Senna et al., 2009), which may result in a decreased stimulus for mechanical loading. Moderate and longer rest periods typically allow for greater recovery and therefore avoid the reduction in training volume that would occur with fatigue. The superiority of longer rest periods over shorter rest periods is supported by McKendry et al, (2016), which suggests that a shorter rest period may lead to a blunting of the acute increase in MPS following RT. Over the course of a RT program, in both untrained and training participants, longer rest periods have been shown to produce superior hypertrophic adaptations (Schoenfeld et al., 2015, Athtiainen et al., 2005, Buresh et al., 2009).

2.5.3 Muscle contraction type. The use of concentric, isometric, eccentric and isokinetic contractions can all be utilised during RT to bring about increases in hypertrophy. The eccentric contraction, however, is regarded as the most potent contraction for improving hypertrophy (Roig et al., 2009). The use of eccentric only training firstly allows a greater load to be lifted in comparison to regular isotonic (both concentric and eccentric contractions) exercises. This may lead to an increase in the amount of mechanical tension in the active muscles (Flanagan et al., 2013). In addition to this, eccentric based exercises induce greater levels of muscular damage due their lengthening nature (Proske et al.,2001), which may result in greater muscle hypertrophy through the role of muscle damage to improve hypertrophy (Schoenfeld, 2010). Moore et al, (2005) and Cutherbesrston et al, (2006) also suggest that eccentric contractions may lead to greater levels of MPS. This has also been supported by Seger et al, (1998) which demonstrate superior training adaptations with eccentric exercise in both trained and untrained participants.

2.5.4 Range of motion. Range of motion (ROM) in RT can be considered as the range that a joint will move through during the exercise. When considering the effect of ROM on hypertrophy, the net joint moment must be considered. For example, It is a commonly practiced RT principle to employ a smaller ROM exercise due to the increased load that can be used and potentially cause a mechanical overload. Although a greater load may produce greater mechanical loading and tensile force through a muscle, this may be countered by a smaller external moment arm length. This in turn may lead to a smaller net joint moment in comparison to a lesser loading, larger ROM exercise which may result in less tensile force in the muscle (McHananon et al.,2014). With a larger ROM, more work may be performed by the active muscles due to a greater distance in which the load is moved. In addition to this, a larger ROM may evoke a greater stretch on the active muscle which may be more beneficial for hypertrophy. Goldspink et al, (1999) and Russ et al, (2008) suggest that the phosphorylation of mtorc1 is greater during both passive stretch and active stretch, which may encourage the use of full ROM over shorter partial ROM during RT pograms.

2.5.5 Intensity. The intensity of RT can be measured in various ways. The most common measurement of intensity is the load of the barbell expressed as the percentage of a repetition maximum (1RM, 5RM) which can also be referred to as intensity load/relative load. However, the level of physical exertion must also be considered. The intensity load can be categorised into light load (below 50%) and heavy load (60% and above) (Schoenfeld et al., 2013, ACSM, 2009). For hypertrophic adaptations a minimum intensity threshold of 65% 1RM (McDonagh et al.,1984) is considered necessary for RT, with loads less than 65% insufficient to recruit and fatigue high threshold motor units. However, when light loads are combined with muscular failure, hypertrophy can be achieved (Morton et al.,2016). Aside from this, an intensity range of 65-75% 1RM is deemed optimal for hypertrophy due to several reasons. Increases beyond this intensity > 75% 1RM, may elicit hypertrophy but are more suitable for increases in muscular strength. This is due to the greater load and decrease in the total possible number of repetitions and therefore will typically produce very high levels of mechanical tension but with very low levels of metabolic stress. Intensity loads in the range of 65-75% enable both enough mechanical tension and metabolic stress due to the moderate number of repetitions that can be performed per set (6-12). During this range, a high number of metabolites can be generated, along with increases in cellular swelling and post exercise increases in anabolic hormones. This intensity range and number of repetitions performed per set is recommended and deemed optimal for hypertrophy.

2.5.6 Muscular failure. Training to muscular failure is a commonly used RT variable and can be defined as *"the inability to perform any more concentric contractions without significant changes to posture or repetition duration against a given resistance*" (Fisher, 2011). The rationale for the use of training to failure to maximise hypertrophy can be partly explained by the neural mechanisms of motor unit recruitment. Under normal conditions, Henneman's size principle (Mendell et al.,2005) states that the smallest and weakest motor units are recruited first, with larger, stronger motor units recruited further on as the magnitude of the neural signal increases. It is theorised that when training to failure, a larger number of motor units are recruited, which may not have been recruited under normal conditions due to fatigue. However, this concept is debated (Stone et al., 1996, Schoenfeld et al., 2014). The potential benefit to hypertrophy has been supported by (Schoenfeld et al., 2015) which has demonstrated that regardless of training intensity, when exercised to failure, loads as low as 30% may induce hypertrophy. This has also been supported by Burd et al, (2012) who has shown that the level of molecular signalling and MPS are increased when training close to failure. In trained and untrained participants, training to failure shows greater benefits (Pareja-Blanco et al.,2016, Goto et al., 2005). However, recent research by (Nobrega et al., 2017) suggests that training close, but not to failure may produce the same results. This is of great importance due to the potential injury risk/overreaching that may be associated with training under high levels of fatigue experienced when training to failure.

2.5.7 Frequency. Training frequency refers to the number of RT sessions that are performed in a week, and in particular, the number of sessions that a specific muscle will be exercised. When considering training frequency and adaptations to RT, it is important to consider that molecular responses to RT increase following RT sessions and remain elevated for up to 48h (Phillips,1997). Therefore, the concept of frequent training with sufficient recovery periods may allow participants to accumulate greater adaptational responses to RT by increasing their exposure to the RT stimulus. The use of this training variable is very closely linked with training volume, if a theoretical volume threshold per session exists then increasing training frequency becomes a method to increase overall training volume. This change in volume, however, must be considered by examining different training frequencies. Multiple research studies (Hakkinen et al., 1994, McLester et al., 2000, Schoenfeld et al., 2015) suggest that when volume is matched between groups, increasing training frequency results in greater increases in hypertrophy in trained participants. These findings do not seem to be conclusive in untrained participants with some research suggesting no advantage to increased training frequency. This may be due to the potential increases in muscle damage experienced by untrained participants and longer time course of adaptational responses.

2.6.8 Volume. Training volume is often regarded as one of the key training variables that drives hypertrophy. Volume can be considered as the total amount of work completed in a specific time frame such as one session, one week and so on. Volume can be quantified in several ways, however, the use of volume load (Stone et al., 1998) is typically most common and defined as the product of sets x reps x load lifted. Volume may also be measured by the amount of sets performed by a muscle group in one week (Schoenfeld et al, 2016). The idea behind the superiority of RT that contains greater volumes is that the stimulus for mechanical tension will be increased due to the fact that the muscle will be exposed to this loading for a greater period of time. This has been supported by meta-analysis by Krieger (2010) suggesting that multiple set training programs were associated with a 40% greater hypertrophic adaptation than programs using single sets. Building upon this, multiple studies have shown that greater training volumes result in increased myogenic signalling and increases in MPS (Burd et al., 2010, Terzis et al., 2010). Although these studies support the use of multiple sets, it is important to note that the overall training volume is low when considered to those often used in an applied setting; therefore the concept of a linear increase in this signalling response is unclear. Although examined in rodents, Souza et al, (2011, 2014) suggests that this positive increase is not linear with increasing volume, rodents exhibited to high training volumes have shown that atrophy begins to occur and that the relationship between skeletal muscle adaptation and volume may be hormetic. In regard to studies directly examining the response to long term RT programs, a meta-analysis by Schoenfeld et al, (2016) suggests that higher volume has a greater effect on hypertrophy than lower volume, with the practical guidance of 10 weekly sets per muscle group as an optimal training volume for the majority of individuals. However, due to the nature of meta-analysis, the studies included must be considered when examining the strength of the analysis. A large number of studies that have investigated the response to varying levels of training volumes are limited to due to methodological issues such as variance in participants training status and age, lack of dietary control and more. For example, research by Cannon and Marino et al, (2005), Galvao and Taaffe et al, (2005), Radaelli, Botton et al, (2014) and Ribeiro et al (2015) have examined varying RT volumes over long term RT programs in untrained elderly populations. This is problematic when extrapolating results to other populations such as young, trained populations. Even though relative increases in hypertrophy in response to RT may be similar between elderly and young participants (Lambert et al, 2002), although lacking evidence, the ability to perform high amounts of RT volume may be impeded/not advised in elderly populations due to potential risk of injury. A large number of RT studies examining RT volume involve participants training with a repetition maximum (RM) load, for example 12RM (Ostrowski et al, 1997, Rhea et al, 2002, Radaelli, Fleck et al, 2014). This detail in the training protocols suggests that participants would be training with muscular failure due to the nature of RM. As previously eluded to, training to muscular failure can promote superior hypertrophic adaptations, however, when examining RT volume, training to failure may be a potential confounding variable and limit the clarity of the RT volume effect on hypertrophy. Several studies suggests the superiority of higher RT volumes in untrained participants (Radaelli and Fleck et al, 2014, Ronnestad et al, 2007, Sooneste et al, 2013), however, research in trained participants suggests no additional benefit to higher volumes (Ostrowski et al, 1997, Rhea et al, 2002). A potential reason for the differences observed between studies may be due to the varying RT responses between untrained and trained participants. Furthermore, the majority of RT studies examining volume randomly allocate participants into experimental groups. This could potentially be a limiting factor to the findings of these studies, for example, trained participants may be randomly allocated into a volume group that is drastically greater or lesser than their habitual training volumes. This may potentially cause participants to over/undershot their current recovery abilities to RT and may lead to errors in findings. Table 1 outlines the results of the studies involved in Schoenfeld et al, (2016) analysis. Based on current findings, it is unclear whether higher RT volumes may lead to greater muscle adaptations and a dose response is unclear, especially due to the low levels of training volumes studied along with their methodological limitations.

Table 1. Details of studies included in Schoenfeld et al., (2016)

	Sample size (n)	Participant information	Duration (weeks)	RT volume (weekly sets)	Measure	Results
Bottaro et al., (2011)	30	Untrained males	12	High: 6 Low: 2	Ultrasound	No significant difference in muscle thickness between groups
Cannon and Marino (2010)	31	Untrained, young and elderly women	10	High: 9 Low: 3	MRI	No significant differences in muscle volume between groups
Correa et al., (2015)	36	Untrained women	11	High: 9 Low: 3	Ultrasound	Significantly greater increase in muscle thickness for high volume group.
Galvao and Taaffe (2005)	28	Untrained elderly men and women	20	High: 20 Low: 5	DEXA	No significant differences between lean body mass in groups.
McBride et al., (2003)	28	Untrained young men and women	12	High: 12 Low: 2	DEXA	No significant differences between lean body mass in groups.
Mitchell et al., (2012)	18	Untrained young men	10	High: 9 Low: 3	MRI and biopsy	No significant differences in CSA between groups
Ostrowski et al., (1997)	27	Trained young men	10	High: 12-28 Med: 6-14 Low: 3-7	Ultrasound	No significant differences in muscle thickness between groups

Table 1., *continued*

	Sample size	Participant information	Duration (weeks)	RT volume (Weekly sets)	Measure	Results
Radelli, Fleck et al., (2014)	48	Recreationally trained young men	6 months	High: 30 Med: 18 Low: 6	Ultrasound	Significantly greater increases in muscle thickness for the high-volume group.
Radelli, Wilhelm et al., (2014b)	27	Untrained elderly women	6	High: 12 Low: 4	Ultrasound	No significant differences in muscle thickness between groups
Radelli, Botton et al., (2014)	20	Untrained elderly women	20	High: 12 Low: 4	Ultrasound	Significantly greater increases in muscle thickness for the high-volume group.
Rhea et al., (2002)	18	Trained young men	12	High: 5 Low: 3	BodPod	No significant differences in lean body mass between groups.
Ribeiro et al., (2015)	30	Untrained elderly women	12	High: 10 Low: 4	DEXA	No significant differences in lean body mass between groups.
Ronnestead et al., (2007)	21	Untrained young men	11	High: 9-18 Low: 3-6	MRI	Significantly greater increases in CSA for high-volume group.
Sooneste et al., (2013)	8	Untrained young men	12	High: 6 Low: 2	MRI	Significantly greater increases in CSA for high-volume group.
Starkey et al., (1996)	48	Untrained mixed age, men and women	14	High: 9 Low: 3	Ultrasound	No significant differences in muscle thickness between groups.

RT, resistance training; MRI, magnetic resonance imaging; DEXA, dual-energy x-ray absorptiometry; CSA, cross-sectional area

3. Aims and Hypothesis

As a result of the limitations of the current research into RT volume, the aim of the present study was to examine the relationship between weekly RT volume and skeletal muscle thickness and strength, in resistance trained individuals. The specific aim of this study was to examine the differences in adaptations between low, moderate and high weekly RT volumes. It was predicted that skeletal muscle adaptations would increase in a linear fashion with weekly RT volume.

4. Methods

4.1. Ethical Approval

Ethical approval was obtained by the Science, Technology, Engineering and Mathematics Ethical Review Committee, University of Birmingham, UK, code ERN_16-1084 in accordance with the 7th version of the declaration of Helsinki.

4.2. Participants

20 male participants were recruited and participated in the study. All participants were aged 18-35 years and were deemed resistance trained, participating in frequent RT (> 3 per week) for more than 1 year. Participants with a RT experience of 1 year were recruited to control for possible variations in RT response and adaptations. These participants would most likely be familiar with the RT exercise and therefore aimed to limit any large effects of learning on the training performance.

All participants completed a general health questionnaire (General Health Questionnaire, School of Sport, Exercise and Rehabilitation Sciences, University of Birmingham, UK) and were ineligible for participation from the study if they were of general ill-health, regularly smoking or consuming any medication/supplementation deemed inappropriate by the ethical approval and participant information sheet. Participants were informed to refrain from the consumption of alcohol within 24hrs of a RT session due to the potential acute lose in performance resulting from alcohol consumption (Vella et al, 2010). In addition, participants were informed to not train their elbow flexors outside of the study, to avoid alterations in training volume.

Participants were informed of the study details via the participant information sheet and verbally informed of the details of their participation by the lead investigator. All participants gave written informed consent to participate.

Table 2. Participant characteristics. Data are presented as mean ± SD.

	LOW	MOD	HIGH
Age (years)	20.1 ± 1.2	19.5 ± 1.4	20.5 ± 1.2
Bodyweight (kg)	80.8 ± 6.7	72.5 ±8	84.2 ± 14
Height (cm)	179.8 ± 4.3	175.2 ±7.4	179.8 ± 7.7
Body Fat (%)	21 ± 5.7	18.1 ± 8.3	17.7 ± 7.5

LOW, low training volume group; MOD, moderate training volume group; HIGH, high training volume group

4.3 Study Design.

Participants were randomly assigned to 1 of 3 training conditions, a low (LOW; n=7), moderate (MOD; n=7) or high (HIGH; n=7) weekly RT volume. The RT volume was defined as the total number of weekly sets performed by the training group. LOW completed 9 weekly sets, MOD completed 18 weekly sets and HIGH completed 27 weekly sets over a 6-week training period. The weekly sets used for each group were derived from the findings of previous literature concerning RT volume (Schoenfeld et al, 2016), recommending 10 weekly sets per muscle group as adequate RT volume for hypertrophy. Therefore, the exercise volumes of the LOW, MOD and HIGH represented a stepwise progression and two-fold and threefold increase in recommended RT volumes. All participants completed the same exercise session focusing on training of the biceps brachii at a moderate intensity.

One week prior to the start of training, all participants undertook pre-training assessments of anthropometric characteristics, muscle thickness, isometric and isotonic strength. Following all sessions participants were given post-exercise protein supplementation and informed to record their dietary intake. Post-exercise protein was given to participants to control for the acute responses in MPS following RT. Participants were given a 40g dose of whey protein, which has been demonstrated to be a sufficient protein intake to maximise increases in post exercise MPS (Macnaughton et al, 2016). Participants were permitted to partake in physical activity including RT outside of the study but were informed to record this activity. Participants were informed to restrain from any external RT involving the elbow flexor muscles. Participants were informed to refrain from the training of the elbow flexors outside of the study to limit the influence of external volume on the responses to the RT program. One week after the completion of the 6-week training period all participants repeated pre-training assessments. The overall study design is depicted in Figure 1.

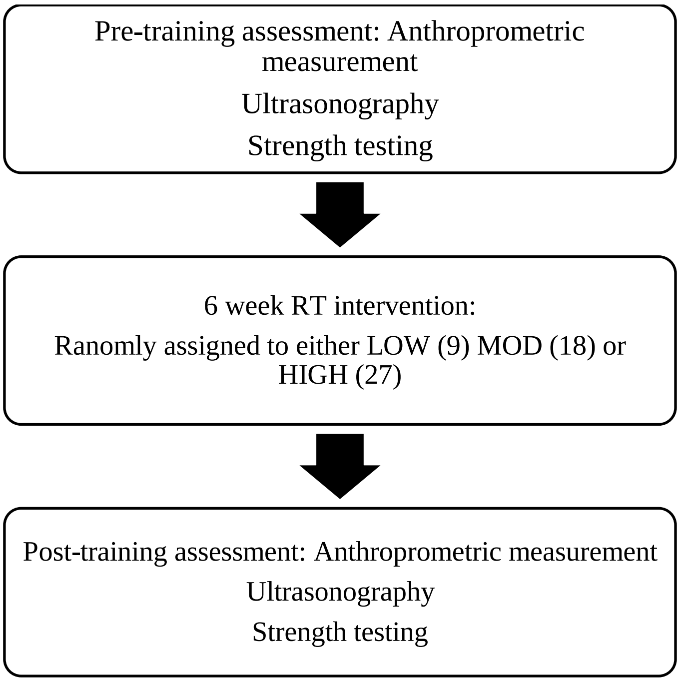

Figure 1. Study design

4.4. Resistance Training Program

All participants completed 6 weeks of RT exercise. The LOW training group performed one RT session per week, with the MOD and HIGH completing two sessions per week. The LOW and MOD group performed an identical training RT session consisting of 9 total sets of seated supine biceps curl (3), supine grip bent over row (3) and supine grip pulldown (3), described in Table 3. The HIGH group performed one RT session consisting of 14 total sets of seated supine biceps curl (5), supine grip bent over row (5) and supine grip pulldown (4), followed by a second RT session consisting of 13 total sets of seated supine biceps curl (4), supine grip bent over row (4) and supine grip pulldown (5), described in Table 3. These exercises were chosen due to the high levels of activation in the elbow flexors. In addition, the exercise variations were also chosen due to the considerable contributions from the back musculature, to limit the possibility of external training of exercises such as the bent over row and pulldown which would involve a large contribution of the elbow flexors and would therefore confound the volumes within the RT program.

Table 3. Resistance training protocol for LOW, MOD, and HIGH volume groups.

LOW
Day one
Seated barbell curl 3x10-12 70% 1RM 7.5-8 RIR
Seated supine grip pulldown 3x10-12 70% 1RM 7.5-8 RIR
Supine grip bent over row 3x10-12 70% 1RM 7.5-8 RIR
Total weekly sets: 9

MOD	
Day one	Day two
Seated barbell curl 3x10-12 70% 1RM 7.5-8 RIR	Seated barbell curl 3x10-12 70% 1RM 7.5-8 RIR
Seated supine grip pulldown 3x10-12 70% 1RM 7.5-8 RIR	Seated supine grip pulldown 3x10-12 70% 1RM 7.5-8 RIR
Supine grip bent over row 3x10-12 70% 1RM 7.5-8 RIR	Supine grip bent over row 3x10-12 70% 1RM 7.5-8 RIR
Total weekly sets: 18	

HIGH	
Day one	Day two
Seated barbell curl 5x10-12 70% 1RM 7.5-8 RIR	Seated barbell curl 4x10-12 70% 1RM 7.5-8 RIR
Seated supine grip pulldown 5x10-12 70% 1RM 7.5-8 RIR	Seated supine grip pulldown 4x10-12 70% 1RM 7.5-8 RIR
Supine grip bent over row 4x10-12 70% 1RM 7.5-8 RIR	Supine grip bent over row 5x10-12 70% 1RM 7.5-8 RIR
Total weekly sets: 27	

LOW, low training volume group; MOD, moderate training volume group; HIGH, high training volume group; 1RM, one repetition maximum; RIR, repetitions in reserve

Following a standardised warmup, all participants performed 10-12 repetitions per set on all exercises, with load modulated by the repetitions in reserve (RIR) model (Zourdos et al, 2016). Training intensity was measured after each set using the Borg category ratio scale (Buckley et al., 2011) with 0 indicating rest and 10 indicating maximal effort. Participants were informed to complete their sets with a 2 RIR indicating a target score of 8 on the CR-10. In the first set of the first training session for all training groups a load of 75% 1RM was utilised. This load for subsequent sets and training sessions was altered in accordance with the RIR achieved in the set. If the RIR score was below the target score of 8, a suitable load increase was used, if the RIR score exceeded the target score, load was decreased to avoid failure. The RIR scale was implemented due to the limitations of 1 repetition max (1RM) testing and thus the effect on prescribed percentages for subsequent RT sessions. 1RM testing can be influenced by many factors including time of day and motivation of participants, therefore the validity of 1RM scores may be questionable. The use of the RIR scale allowed for alterations in the training load to achieve the required intensity. In addition, the RIR scale accounted for participants daily fluctuations in RT performance due to external lifestyle factors such as fatigue. This allowed for the correct training load to be used to avoid training to failure, due to the possible interference training to failure may have on the results of the RT program.

Participants were informed on the correct lifting technique and received instruction throughout the training period to maintain the correct form and tempo of the repetition (3-1 eccentric-to-concentric contraction). A timed rest period of 3 minutes was given between all sets, due to the benefit of longer rest periods of muscle mass adaptations (McKendry, 2016).

Training sessions were performed at times convenient with the participant however were encouraged to maintain consistency in this time throughout the course of the training period. Participants received verbal encouragement and could listen to music. Following the completion of all training sessions, all participants immediately consumed 40g unflavoured whey protein isolate (MyProtein, UK) in 250ml water provided by the research team.

4.5. External Training Control

Participants were permitted to perform external RT outside of the study, however, exclusion of exercise involving the elbow flexors was requested. Participants were given a list of exercises that would be excluded due to the involvement of the elbow flexors in these exercises. External training logs were given to participants, instructing them to self-record their external training throughout and submitted every two weeks, these logs were actively analysed by members of the research team to ensure participants were not confounding the excluded exercise list. These training logs were further used to examine external RT volume.

4.6. Dietary Control

All participants were instructed to maintain normal dietary habits throughout the duration of the study. Dietary intake was recorded due to the influence of nutrition on muscle mass adaptations, particularly protein intake (Morton et al, 2018). Recordings of dietary intake were used in an attempt to ensure adequate nutritional intakes required for muscle mass adaptations and control for any potential confounding impacts of individual dietary habits. Participants were informed that if taking diet supplements, to maintain this throughout and not alter intake. This information was given to participants to limit the influence of supplements which may positively affect skeletal muscle adaptations following RT such as creatine (Cribb, 2007). Dietary intake was measured via self-reported food diaries supplied by the research team. Participants were instructed with the correct details for competition and recorded every two weeks over 3 days (2 weekdays and 1 weekend). Analysis of food diaries was carried out using DietPlan6 (Forestfield Software Ltd, Horsham, UK) to acquire values of total caloric and macronutrient intake.

4.7. Testing Protocol

4.7.1. Anthropometric measurements. Participants height and weight were using a stadiometer (Marsden Leicester Height Measure, Marsden, UK) and digital weighing scales (Seca 877, Secca, Hamburg, Germany).

4.7.2. Muscle thickness. Biceps brachii muscle thickness of both participants' arms was measured via ultrasound (Diasus Application Ultrasound, Dynamic Imaging Ltd, Livingston, UK). Participants sat in an upright position with their arm relaxed in the supinated extended position. Participants supraglenoid tubercle and radial tuberosity were identified and 50% of the distance between these landmarks was measured and marked. An ultrasound probe (7.5mHz transducer) covered in transmission gel (Henleys Medical Supplies, Hertfordshire, UK) was placed parallel to the muscle fibres at the 50% mark. This site of measurement was remarked weekly and photographed to ensure accuracy of repeated measurements. Five images were taken by the operator with the highest quality image – defined as the clearest, most parallel aponeuroses was used for analysis to determine muscle thickness. Images were analysed in Image J (Image J) for muscle thickness, defined as the perpendicular distance between the superficial and deep aponeuroses. The operator remained the same throughout the study period and was the lead investigator, performing all scans and analysis. Coefficient of variation based on obtained images was 2%.

4.7.3. Maximal isometric strength. Maximal isomeric strength of the Biceps Brachii was assessed using a KinCom dynamometer (Chattanooga Group Inc, Hixson, Tennessee, USA) which was calibrated by the lead investigator to attain measures of peak torque of the elbow flexors during a maximal voluntary isometric contraction. Participants informed the lead investigator of their dominant arm and were sat in the seated position and secured by straps across their waist, torso and shoulders. The arm was placed in a flexed position at 55°

using the machines elbow attachment, arm lever length for each participant was recorded for post-training testing. The arm was secured with strapping across the elbow joint. Participants were informed of the testing procedure and proceeded to perform three 3s submaximal isometric contractions with 2 minutes rest between contractions as a warm up and familiarisation. Participants then followed this with three 3s maximal isometric contractions for a total of 6 total contractions, the highest maximal score was recorded. Participants were instructed and verbally encouraged to "push up as hard as possible" against the lever padding. Participants received on screen instructions and verbal commands to begin and cease contractions.

4.7.4. Maximal isotonic strength. Maximal isotonic strength was measured via the performance of a single repetition maximum (1RM) for seated supinated biceps curl, supinated bent over row and supinated seated pulldown. Prior to the competition of all tests, participants were given demonstrations of each exercise informing them of the correct technique required for a successful repetition. For seated supinated biceps curl and supinated bent over row, participants completed a warm up of 3 sets of 10 repetitions with a 9kg barbell. Participants were then instructed to self-select a load that would elicit volitional fatigue at 4-5 repetitions. The load was then adjusted in the same manner for 3-4 repetitions, 2-3 repetitions and ending on 1 repetition for a 1RM. Participants were given up to 3 minutes rest between sets, repetition attempts that failed to lift the load throughout the entire range of motion or with the incorrect demonstrated technique were deemed failed attempts and were not recorded. Verbal encouragement was provided throughout the duration of the testing. 1 participant in the LOW group did not complete post-intervention maximal isotonic strength testing due to illness.

4.8. Statistical Analysis

All data was analysed using SPSS (version 22, IBM Statistics, Chicago, Illinois, USA). To assess the significance of each measure between groups, between pre- and post-testing, a mixed design analysis of variance was used. Where significant effects were found, Bonferroni post hoc tests were used. Mauchly's test of sphericity was used to determine within-subject effects. Significance was set at $p < 0.05$. Effect size (ES), using Cohens d, was used to assess the magnitude of effect from pre- to post-intervention between groups for muscle thickness and strength measurements. Effect size thresholds were set at 0.2, small, 0.5 moderate and 0.8, large. All data is expressed as mean ± SD.

5. Results

5.1. Muscle Thickness

Following 6 weeks of training all groups increased MT. A 2 x 3 group mixed-design ANOVA revealed there was a significant main effect for time (F (1,18) = 42.1, $p < 0.001$) and no significant main effect for group (F(2,18) = 0.18 $p = 0.837$). There was no significant time x group interaction (F (2,18) = 2.8, $p = 0.87$). Post-hoc analysis revealed that MT significantly increased following 6 weeks of training in the LOW (9.3 ± 5.5%, $p < 0.001$) and MOD groups (14.3 ± 10.4, $p < 0.001$). The increase in the HIGH group was not significant (5.5 ± 4.0, $p = 0.054$). There were no significant differences between groups in MT over the 6-week training period. The average absolute values and percentage changes of combined (left and right arm) MT of the biceps is presented in Table 4. Figure 2 represents average absolute values of combined MT. Figure 3 represents the individual variance in percentage change in combined MT. Effect scores are presented in Table 11.

Table 4. Absolute values and percentage change of combined muscle thickness of the biceps, pre- and post-intervention. Data are presented as mean ± SD.

Group	Pre-Intervention MT (cm)	Post-Intervention MT (cm)	Percentage Change (%)
LOW (n=7)	3.4 ± 0.4	3.7 ± 0.4	+9.3 ± 5.5
MOD (n=7)	3.3 ± 0.4	3.7 ± 0.3	+14.3 ± 10.4
HIGH (n=7)	3.4 ± 0.6	3.6 ± 0.7	+5.5 ± 4.0

LOW, low training volume group; MOD, moderate training volume group; HIGH, high training volume group; MT, muscle thickness

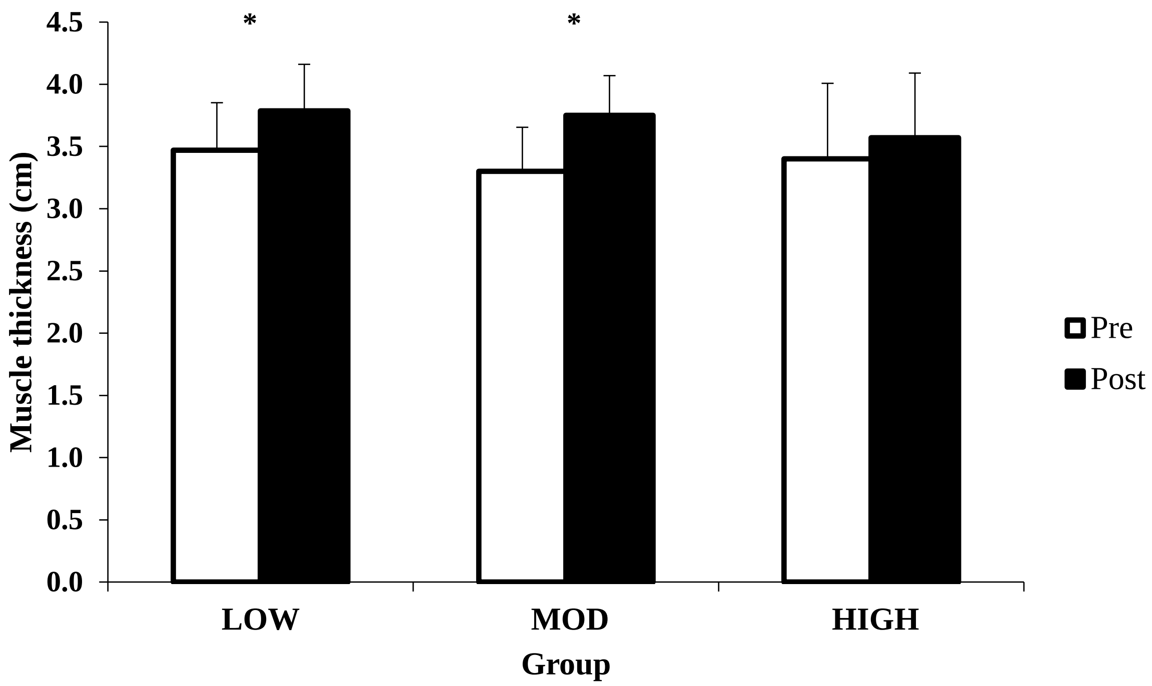

Figure 2. Combined average muscle thickness of the biceps by group. Data are presented as mean ± SEM. * Indicates significantly greater than pre-intervention (p < 0.05).

5.2. Maximal Isometric Strength

Following 6 weeks of training maximal isometric strength did not significantly increase in all groups. A 2 x 3 group mixed-design ANOVA revealed there was no significant main effect for time (F(1,18) F = 4.2, p = 0.054, np^2 = 0.2) and no significant effect for group (F(2,18) F = 0.7, p = 0.5, np^2 = 0.07). There was no significant time x group interaction (F(2,18) F = 0.1, p = 0.95, np^2 = 0.01). Post hoc analysis revealed no significant increase in isometric strength in LOW (5.9 ± 13.3%, p = 0.36), MOD (9.0 ± 15.3%, p = 0.23) or HIGH (10.3 ± 15.4%, p = 0.18). The average absolute values and percentage changes of isometric maximal voluntary contraction is presented in Table 5. Figure 4 represents average absolute values of isometric maximal voluntary contraction. Figure 5 represents the individual variance in percentage change in isometric maximal voluntary contraction. Effect scores are presented in Table 11.

Table 5. Absolute values and percentage change of isometric strength of the biceps, pre- and post-intervention. Data are presented as mean ± SD.

Group	Pre-Intervention (N)	Post-Intervention (N)	Percentage change (%)
LOW (n=7)	247.7 ± 46.5	261.6 ± 56.5	+5.9 ± 13.3
MOD (n=7)	254.7 ± 37.8	273 ± 24.4	+9.0 ± 15.3
HIGH (n=7)	278.1 ± 86.8	299 ± 72.7	+10.3 ± 15.4

LOW, low training volume group; MOD, moderate training volume group; HIGH, high training volume group

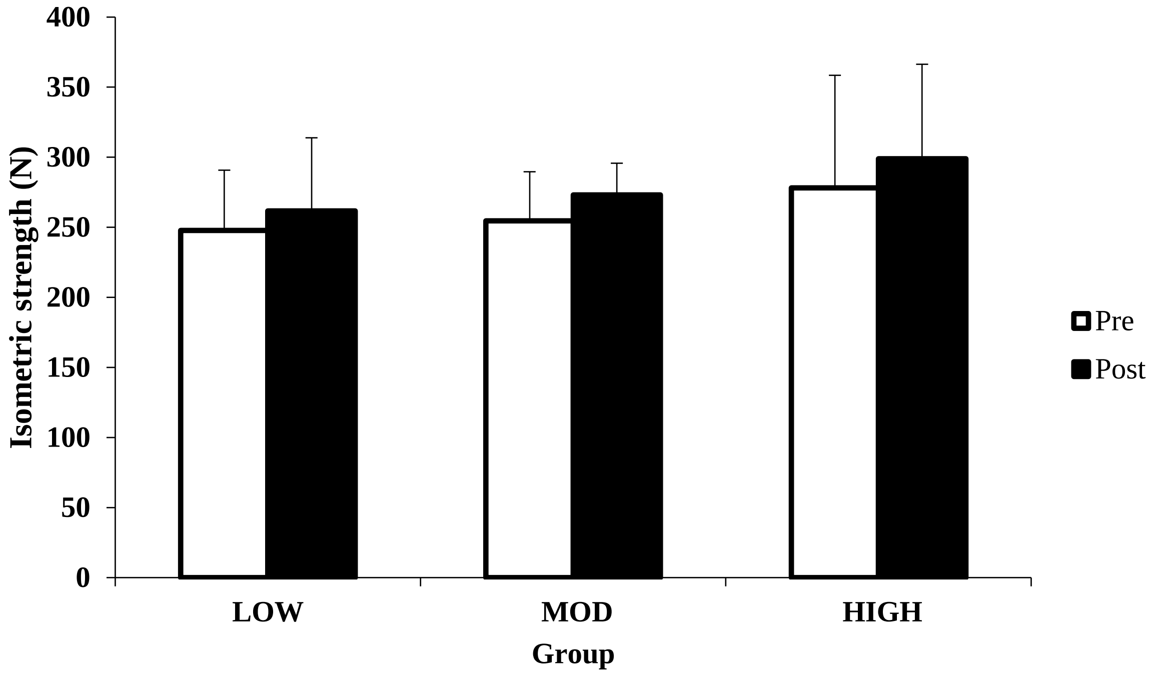

Figure 3. Isometric strength of the biceps by group. Data are presented as means ± SEM. LOW, low training volume group; MOD, moderate training volume group; HIGH, high training volume group.

5.3. Maximal Isotonic Strength

5.3.1. Supine biceps curl. Following 6 weeks of training, all groups increased supine biceps curl 1RM strength. A 2 x 3 group mixed-design ANOVA revealed there was a significant main effect for time (F(1,17) = 22.9 $p < 0.001$, $np^2 = 0.6$) and no significant effect for group (F(2,17) = 0.3 $p = 0.8$, $np^2 = 0.03$). There was no significant time x group interaction (F(2,17) = 0.7, $p = 0.52$, $np^2 = 0.07$). Post-hoc analysis revealed that participants in the MOD (15.6 ± 10.4%, $p = 0.003$) and HIGH (12.2 ± 5.9%, $p = 0.005$) groups significantly increased supine biceps curl strength after 6 weeks of training compared to before 6 weeks of training. There was no significant increase for LOW group (10.4 ± 14.5%, $p = 0.11$). The average absolute values and percentage changes of supine biceps curl 1RM is presented in Table 6. Figure 6 represents average absolute values of supine biceps curl 1RM.

Figure 7 represents the individual variance in percentage change supine biceps curl 1RM.

Effect scores are presented in Table 11.

Table 6. Absolute values and percentage change of supine biceps curl one-repetition maximum, pre- and post-intervention. Data are presented as mean ± SD.

Group	Pre-Intervention 1RM (kg)	Post-Intervention 1RM (kg)	Percentage change (%)
LOW (n=6)	34.7 ± 7.8	37.3 ± 4.4	+10.4 ± 14.5
MOD (n=7)	34 ± 6.6	39 ± 6.1	+15.6 ± 10.4
HIGH (n=7)	36.5 ± 7.9	41.1 ± 10.4	+12.2 ± 5.9

LOW, low training volume group; MOD, moderate training volume group; HIGH, high training volume group; 1RM, one-repetition maximum

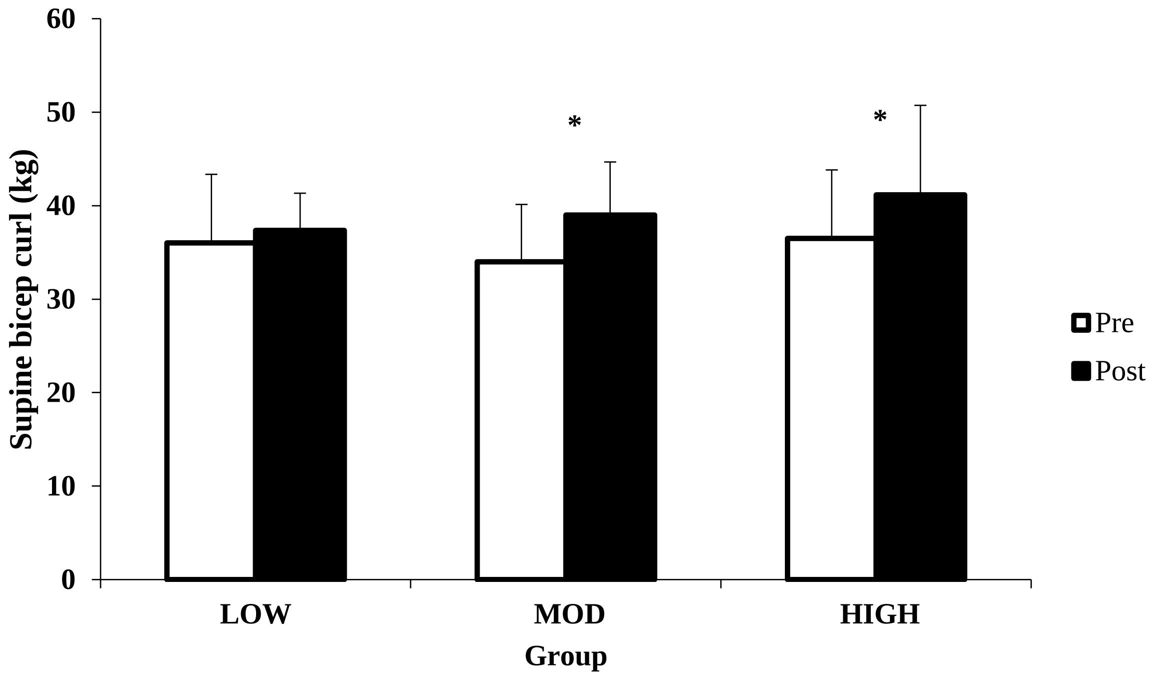

Figure 4. Supine biceps curl one repetition maximum by group. Data are presented as means ± SEM. * Indicates significantly greater than pre-intervention ($p < 0.05$).
LOW, low training volume group; MOD, moderate training volume group; HIGH, high training volume group.

Supine grip pulldown. Following 6 weeks of training all groups increased Supine grip pulldown 1RM strength. A 2 x 3 group mixed-design ANOVA revealed there was a significant main effect for time ($F(1,17) = 29.9$, $p < 0.001$, $np^2 = 0.64$) and no significant effect for group ($F(2,17) = 0.5$, $p = 0.6$, $np^2 = 0.1$). There was no significant time x group interaction ($F(2,17) = 0.23$ $p = 0.8$, $np^2 = 0.03$). Post-hoc analysis revealed that participants in the LOW (8.1 ± 7.6%, $p = 0.015$), MOD (8.0 ± 5.9%, $p = 0.008$) and HIGH (9.8 ± 6.9%, $p = 0.001$) group significantly increased supine pulldown strength after 6 weeks of training compared to before 6 weeks of training. The average absolute values and percentage changes of supine grip pulldown 1RM is presented in Table 7. Figure 8 represents average absolute values supine grip pulldown 1RM. Figure 9 represents the individual variance in percentage change supine grip pulldown 1RM. Effect scores are presented in Table 11.

Table 7. Absolute values and percentage change of supine grip pulldown one one-repetition maximum, pre- and post-intervention. Data are presented as mean ± SD.

Group	Pre-Intervention 1RM (kg)	Post-Intervention 1RM (kg)	Percentage change (%)
LOW (n=6)	108.5 ± 19.1	116.8 ± 18.6	+8.1 ± 7.6
MOD (n=7)	109.4 ± 8	117.8 ± 5.7	+8.0 ± 5.9
HIGH (n=7)	113.1 ± 10.4	123.7 ± 9.5	+9.8 ± 6.9

LOW, low training volume group; MOD, moderate training volume group; HIGH, high training volume group; 1RM, one-repetition maximum

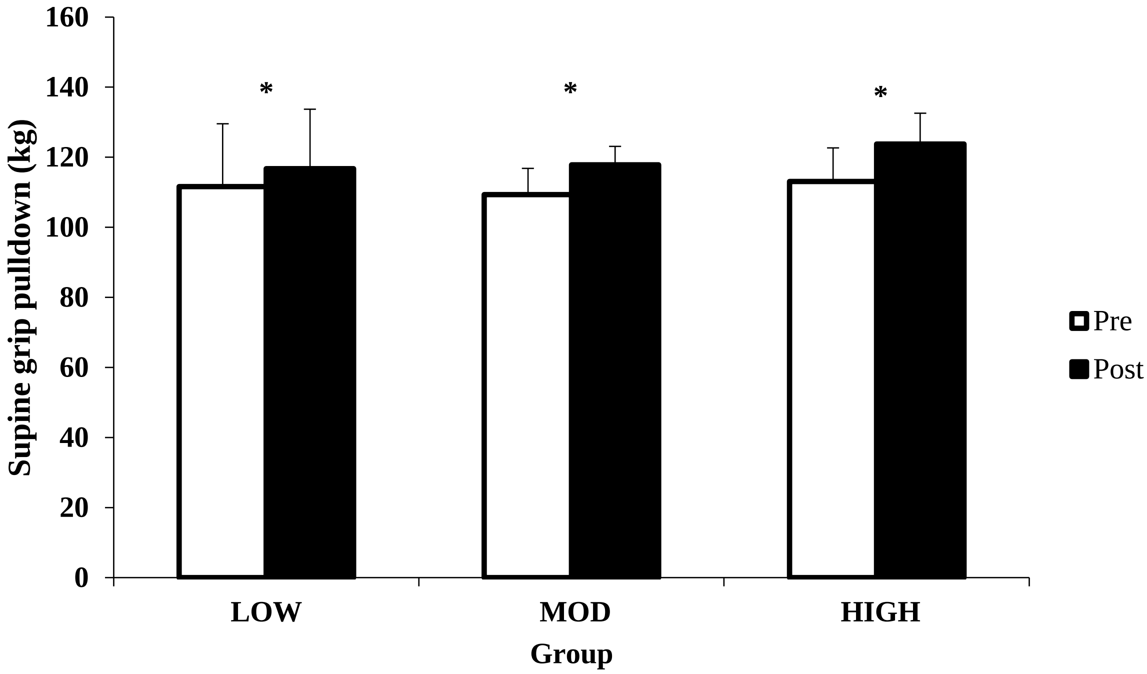

Figure 4. Supine grip pulldown one repetition maximum by group. Data are presented as means ± SEM. * Indicates significantly greater than pre-intervention (p < 0.05). LOW, low training volume group; MOD, moderate training volume group; HIGH, high training volume group.

Supine grip row. Following 6 weeks of training all groups increased Supine grip row 1RM strength. A 2 x 3 group mixed-design ANOVA revealed there was a significant main effect for time (F(1,17) = 27.6 p < 0.001, $np^2 = 0.6$) and no significant effect for group (F(2,17) = 1.9, p = 0.2, $np^2 = 0.2$). There was no significant time x group interaction (F(2,17) = 1.9 p = 0.2, $np^2 = 0.2$). Post-hoc analysis revealed that participants in the MOD (10.0 ± 5.1%, p = 0.019) and HIGH (15.3 ± 7.0, p < 0.001) group significantly increased supine row strength after 6 weeks of training compared to before 6 weeks of training. There was no significant increase in the LOW group (8.9 ± 14.7%, p = 0.074). The average absolute values and percentage changes of supine grip row 1RM is presented in Table 8. Figure 10 represents average absolute values supine grip row 1RM. Figure 11 represents the individual variance in percentage change supine grip row 1RM. Effect scores are presented in Table 11.

Table 8. Absolute values and percentage change of supine grip row one one-repetition maximum, pre- and post-intervention. Data are presented as mean ± SD.

Group	Pre-Intervention 1RM (kg)	Post-Intervention 1RM (kg)	Percentage change (%)
LOW (n=6)	81.9 ± 13.9	84.4 ± 13.1	+8.9 ± 14.7
MOD (n=7)	81.1 ± 13.9	89 ± 14	+10.0 ± 5.1
HIGH (n=7)	91.1 ± 17.4	105.4 ± 23.7	+15.3 ± 7.0

LOW, low training volume group; MOD, moderate training volume group; HIGH, high training volume group; 1RM, one-repetition maximum

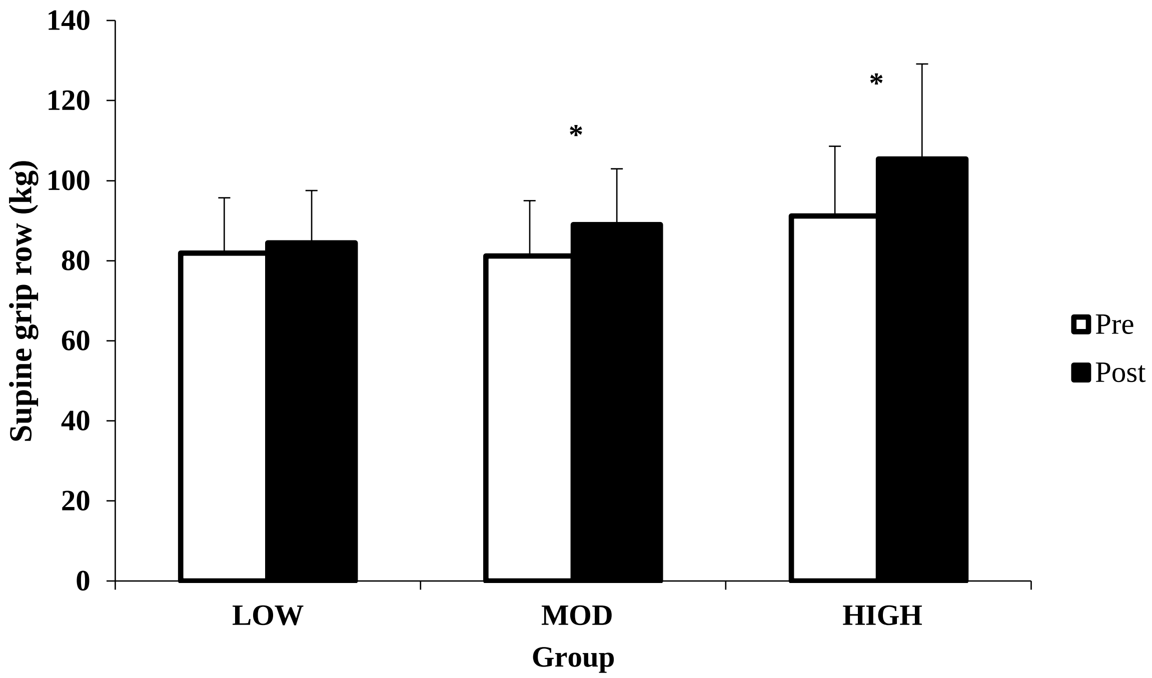

Figure 6. Supine grip row one repetition maximum by group. Data are presented as means ± SEM. * Indicates significantly greater than pre-intervention ($p < 0.05$).
LOW, low training volume group; MOD, moderate training volume group; HIGH, high training volume group.

5.4. Dietary Intake

Over the course of the 6-week training period, pre to post measures of dietary intake did not significantly differ between groups. Table 9 represents average dietary intakes between groups.

5.5. Caloric Intake

There was no significant effect for time ($p = 0.82$) or group ($p = 0.86$) Post hoc analysis revealed that caloric intake did not significantly differ between groups during the study period.

5.4.1. Protein intake.

There was no significant effect for time ($p = 0.60$) or group ($p = 0.60$). Post hoc analysis revealed that protein intake did not significantly differ between groups during the study period.

5.4.2. Carbohydrate intake.

There was no significant effect for time ($p = 0.57$) or group ($p = 0.84$). Post hoc analysis revealed that carbohydrate intake did not significantly differ between groups during the study period.

5.4.3. Fat intake.

There was no significant effect for time ($p = 0.61$) or group ($p = 0.64$). Post hoc analysis revealed that fat intake did not significantly differ between groups during the study period.

Table 9. Dietary macronutrient intake at pre- and post-intervention of 6 weeks of resistance training. Data are measured over three days of a one week period. Data are presented as mean ± SD

	LOW (n=7)		MOD (n=7)		HIGH (n=7)	
	Pre	Post	Pre	Post	Pre	Post
Energy intake (Kcal)	2432.4 ± 711.1	2693.5 ± 439.1	2583.8 ± 492.8	2391.7 ± 390.4	2648.0 ± 454.6	2641.7 ± 312.5
Protein (g/kg BW)	1.6 ± 0.4	1.7 ± 0.3	1.8 ± 0.3	1.7 ± 0.1	1.7 ± 0.4	1.6 ± 0.3
Carbohydrates (g/kg BW)	3.6 ± 1.0	3.9 ± 0.6	3.6 ± 0.6	3.5 ± 0.8	3.7 ± 0.7	3.7 ± 0.7
Fat (g/kg BW)	0.9 ± 0.4	1.1 ± 0.3	1.3 ± 0.2	1.3 ± 0.1	1.3 ± 0.2	1.3 ± 0.2

LOW, low training volume group; MOD, moderate training volume group; HIGH, high training volume group; Pre, three day average over one week period pre-intervention; Post, three day average over one week period post-intervention; BW, bodyweight

5.5 Internal Study Resistance Training Volume

Over the 6 weeks of RT, all groups increased study RT volume load (sets x reps x load). A 6 x 3 group mixed-design ANOVA revealed there was a significant main effect for time ($F(1.5,21.7) = 25.2$, $p < 0.001$, $np^2 = 0.62$) and a significant effect for group ($F(2,15) = 19.9$, $p < 0.001$, $np^2 = 0.73$). There was a significant time x group interaction ($F(2.9, 21.7) = 4.7$, $p = 0.01$, $np^2 = 0.38$). Post-hoc analysis revealed that RT volume significantly differed between groups, with HIGH doing significantly greater RT volume than MOD and LOW and MOD doing significantly greater RT volume than LOW. Table 10 represents average RT volume load for each week of the 6 weeks of RT. Figure 12 represents average RT volume load for each week of the 6 weeks of RT

Table 10. Resistance training volume load each week of a 6 week of resistance training intervention. Data are presented as mean ± SD

	Weekly Training Volume (kg)					
	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6
LOW (n=7)	4469 ± 657	4541 ± 694	4806 ± 801	4598± 775	4861 ± 729	4898 ± 699
MOD (n=7)	8957 ± 1218	9105 ± 1532	9575 ±1571	10073 ± 1619	10557 ± 1788	10444 ± 1899
HIGH (n=7)	14398 ± 3756	14675 ± 4042	15624± 4511	16576 ± 4970	17345 ± 5813	17311 ± 6154

LOW, low training volume group; MOD, moderate training volume group; HIGH, high training volume group

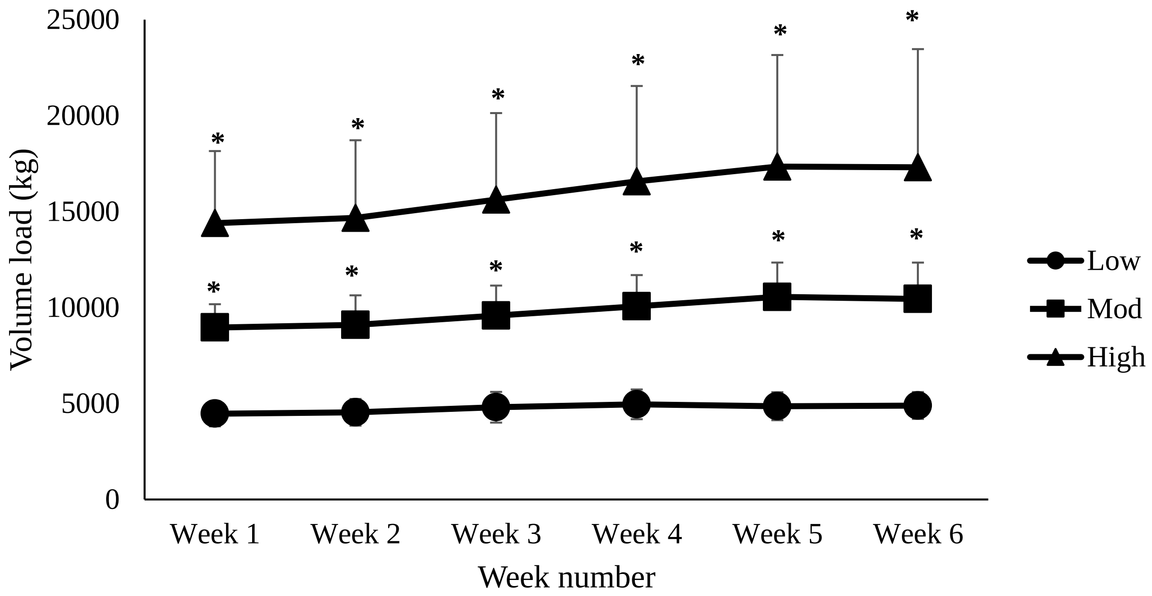

Figure 7. Within group resistance volume load. Data are presented as means ± SEM. * Indicates significantly difference between groups ($p < 0.001$).
LOW, low training volume group; MOD, moderate training volume group; HIGH, high training volume group

Table 11. Effect size of within and between group changes in muscle thickness and strength. Data are presented as mean ± SD

	Pre *vs* Post (within group)			Absolute Change (between group)		
	LOW	MOD	HIGH	LOW *vs* MOD	LOW *vs* HIGH	MOD *vs* HIGH
Biceps MT	0.83	1.33	0.30	0.10	0.47	0.41
Isometric Force	0.29	0.63	0.28	0.29	0.62	0.51
Curl 1RM	0.23	0.85	0.54	0.34	0.52	0.27
Pulldown 1RM	0.29	1.30	1.16	0.08	0.52	0.83
Row 1RM	0.19	0.57	0.69	0.34	1.10	0.84

LOW, low training volume group; MOD, moderate training volume group; HIGH, high training volume group; MT, muscle thickness; 1RM, one-repetition maximum

6. Discussion

The present study aimed to examine the dose response between skeletal muscle adaptations and RT volume. Previous literature (Schoenfeld et al., 2016, Burd et al., 2010, Krieger,2010) suggests that increases in RT volume promote a graded, beneficial muscular response; however, the volumes examined are low and limited by experimental design. The present study aimed to investigate the validity of this linear response in training volumes around two-fold and three-fold greater than those currently recommended by Schoenfeld et al, (2016). Our results suggest that in trained participants, over a short-term training period, low weekly RT volume performed once per week produced increases in muscle thickness and strength that were not statistically different to the increases observed in moderate and high weekly RT volumes. Therefore, our results suggest that there was not a graded dose response between low, moderate and high RT volumes and skeletal muscle adaptations, indicating a possible volume threshold whereby increases in RT volume do not provide further beneficial gains in skeletal muscle adaptations.

6.1 Muscle Thickness

The findings of our study are in agreement with previous research in trained individuals. Ostrowski et al (1997) examined MT changes of the upper body and lower body in trained participants, following RT volumes of 3-7, 6-14. 12-28 weekly sets. Ostrowski et al, (1997) reported no differences between the groups suggesting no additive benefit for higher RT volumes. Meta-analysis by Schoenfeld et al, (2016) has suggested that weekly RT volumes of around 10 sets per week are optimal for hypertrophy, our results agree with this finding and that based on current evidence, RT volumes greater than this seem not to provide further benefit. The data in our study suggest no significant increase in muscle thickness for high volumes over the training period. In opposition to this, our results contrasted to those by

Radelli et al. (2015), who demonstrated that higher weekly RT volumes lead to greater increases in MT of the elbow flexors. A limitation of this study and possible explanation of the difference in results, is that participants in Radelli et al (2015) were untrained, therefore changes in the molecular mechanisms between trained and untrained participants may explain why the untrained participants may have demonstrated a greater response to increased RT volumes.

When considering the underlying mechanisms, there is evidence to suggest that acute increases in molecular signalling and MPS increase linearly with RT volume (Burd et al.,2010). However, these studies have only examined differences in very low RT volumes and currently no investigation has examined molecular signalling and high training volumes, like those in the present study, in humans. Therefore, due to the lack of mechanistic measurements used in this study and the lack of literature investigating the underlying mechanisms at training volumes similar to the ones used in this study, it is unclear how these mechanisms may have been affected by the increases in the training volume. It may be possible to speculate a threshold of exercise volume whereby the observed linear increases in molecular signalling and MPS do not continue to increase despite increased training volume.

6.2. Maximal Strength Measurements

When considering the effect of RT volume on strength, our findings demonstrate that the training period was able to elicit increases from pre-post in isotonic strength but not isometric. The current data suggests that there may have been a moderate to large effect for RT volume on strength between groups, with the MOD and HIGH groups both significantly increasing isotonic strength over the training period. However, between groups there was no statistically significant differences. In previous research, a dose response relationship has been demonstrated in low weekly RT volumes (Ralston et al.,2017) however it is unclear if this relationship continues with higher RT volumes. Most of the research carried out suggesting this dose response at low volumes has been conducted on untrained participants, which is a limitation to the findings. As previously eluded to, differences between trained and untrained participants may be even greater when considering muscular strength due to the enhanced neural adaptations that occur in individuals with a low RT history (Mulligan et al.,1996). The increases in strength observed in our data for isotonic strength may be partially explained by an enhanced learning effect and skill execution for the exercises. The moderate and higher volume groups demonstrated significant increases in isotonic strength, however the lower volume group did not. Although this could be attributed to the increased training frequency and familiarity to the isotonic exercises, no significant differences between groups was observed. The magnitude of the isotonic strength increase observed in the current study, may be small when considering RT studies. However, the current RT program employed loading that was designed to improve structural changes in skeletal muscle and not neurological changes, which are considered the key driver of muscle strength adaptations. Schoenfeld et al (2014) has compared two differing volume matched loading parameters. A higher repetition program comprising of 3 sets of 10RM compared to a lower repetition program comprising of 7 sets of 3RM on strength and hypertrophy. The results of this suggest that the lower repetition program was superior for increasing strength adaptations, due to the increased load used and the enhanced neurological adaptations observed with heavier, lower repetition training. No significant increase in isometric strength was observed, however the RT program employed during the present study included dynamic, isotonic exercises and not isometric exercises. This may explain the lack of significant increases in isometric strength, due to the specific structural and neurological adaptations that occur in relation to the specific mode of contraction. Oranchuk et al, (2018) suggests that muscular adaptations from isometric training differ depending on the length of the muscle in the isometric contraction. In addition, previous research (Kitai and sale et al, 1989) also suggest highly angle-specific adaptations with isometric training. Therefore, the current RT program may have not provided enough loading in the specific joint angle testing occurred at, to result in significant training adaptations.

6.3. Limitations and Considerations

Although our present study suggests no potential benefit for MOD and HIGH RT volumes over LOW for skeletal muscle adaptations, the findings must be considered in line with the limitations of the current study. The participants included in the current study were considered resistance trained and had been participating in RT for at least 1 year prior, however due to individual differences in training responses and variations in training methodology employed it is unclear the details of this RT history. Therefore, it may have been possible that differences in RT history between participants may have affected their training response to the training program in the current study. For example, participants who were randomly allocated in the MOD training group may have been experiencing less RT volume than their regular habitual levels. Participants were also permitted to train outside of the study but were monitored through the use of external training diaries and prohibited to external training of the elbow flexors. Although, we controlled for this with exercise selection in the training program and the collection of external training diaries demonstrated no confounding external training, misreporting is common and the possibility in the present study cannot be ruled out. In previous training studies examining RT volume, there has been a lack of dietary control, which is problematic due to the requirement of adequate protein intakes for optimal hypertrophy. In the present study, participants were required to report dietary intake via the use food diaries. On examination of the results of these diaries, the average protein intake for all training groups was above 1.2g/kg bodyweight, which is deemed adequate for hypertrophy (Stark et al.,2012). Alongside this, all participants consumed 40g of whey protein immediately following RT. This level of protein intake has been shown to be more than suitable to maximise the post exercise signalling response (Macnaughton et al.,2016), ensuring that participants were in suitable protein balance following all training sessions. A potential consideration is the fact that participants in the MOD group were considerably lighter, in terms of bodyweight than the other two groups. This may have effected results due to differing levels of muscle mass prior to the training period. However, no valid measurement of body composition was used during the study due to financial cost of these measurements, therefore it is unclear on the body composition of participants and how differences in bodyweight were composed of. In addition to this, average muscle thickness was similar between groups at pre-intervention testing, which indicates similar levels of muscle mass in the biceps brachii between all groups.

A potential confounding factor in the application of the results of our study is the design of the RT protocol. Although the RT protocol used, controlled for speed of movement, muscular failure, rest time and range of motion, the duration and frequency may be noted as confounding factors. Firstly, the RT protocol lasted for 6 weeks, which has been shown to be enough time to elicit hypertrophy (DeFreitas et al,.2011, Seynnes et al.,2007). However, due to possible individual differences between participants in training response alongside the trained status of participants, this time period may have not been long enough to detect significant changes between groups. Previous research by (Radelli et al.,2013) has shown that a longer training period of 20 weeks was ample time to detect changes between high and low weekly RT volumes. Secondly, the training frequency between groups was not the same. The LOW group performed one RT session per week as opposed to the two RT sessions per week completed by MOD and HIGH. This increased training frequency may have exposed the MOD and HIGH groups to more optimal molecular signalling responses over the LOW group. However, previous literature (Schoenfeld et al.,2015) has only shown that increased frequency can improve hypertrophy when volume is matched, which was not the case with our study. Building upon this, the increased frequency of the higher volume groups was used as the method to increase the overall RT volume of the training groups. In the practical aspect of the training protocol, the LOW group performed sessions lasting ~45 minutes in duration. Considering that the MOD and HIGH group had a 2x and 3x weekly RT volume than the LOW group, it was necessary to split this increased work load over multiple sessions. To have achieved the total weekly RT volume of the MOD and HIGH groups in one session, the duration would have increased to ~90 minutes and 135 minutes respectively. Such an increase in the session duration would have been problematic for participant participation and may have drastically increased the injury risk to participants. Alongside this, it is suggested that the optimal RT session duration is ~60 minutes and that increased duration may have led to negative training adaptations (Zatsiorsky,1995). Overall the increased frequency in the 6-week training period did not seem to enhance the training response of the higher volume groups, however it is unclear whether this would have changed over a longer training period.

6.4. Practical Applications

From the results of the present study, it appears that significant increases in weekly RT volume does not enhance the muscular adaptations from RT over a 6-week period in trained participants. Therefore, it is recommended that for recreational individuals, of who are participating in RT for health and personal well-being, low volumes are suitable to maximise hypertrophy. For coaches and athletes, our results provide insightful data and a resource for the structuring of RT programs. The short-term nature of the RT protocol reflects the time demands that a coach/athlete may have access to for the needs of increasing muscular hypertrophy during a training period. Therefore, it may not be necessary to employ commonly used high RT volumes to increase hypertrophy over a short-term period. In conjunction with this, this may offer a benefit to athletes/coaches by not requiring a high training load which may decrease the likelihood of injury or overtraining which can occur during periods of high training volume. It is also important to consider that training volume is a variable training principle and may be affected by an individual’s lifestyle, nutrition and recovery ability. Therefore, it is recommended that individuals utilise ~9 weekly RT sets to optimise hypertrophy, whilst evaluating and manipulating their RT programs based off the individual response to the training.

7. Conclusion

In conclusion, the present study shows no significant differences between muscular adaptations over a 6-week training period between 9, 18 and 27 weekly RT sets. The findings suggest that in trained individuals, a low weekly RT volume can increase muscular hypertrophy and that further increases do not seem to offer further benefit. Future research should continue to build upon these findings and examine the relationship between RT volume and muscular adaptations over a longer training period and whether the RT volume is affected by the specific muscle group that is examined.

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