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Comparison of Muscle Physiology and Performance Outcomes from Either Relative Intensity or Repetition Maximum Training

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Comparison of Muscle Physiology and Performance Outcomes from Either Relative Intensity or Repetition Maximum Training

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ABSTRACT

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The main purpose of this dissertation was to compare performance and physiological outcomes of between a repetition maximum (RM) and a relative intensity using sets-and-repetitions (RI_{SR}) resistance training (RT) program in well-trained lifters. Fifteen subjects underwent RT 3 $d \cdot wk^{-1}$ for 10-weeks in either a RM group (n=8) or RI_{SR} group (n=7). The RM group achieved a relative maximum each day while the RI_{SR} group trained based on percentages. Testing included percutaneous needle biopsies of the vastus lateralis, ultrasonography, unweighted (<1kg) and 20kg squat jumps (SJ) and counter-movement jumps (CMJ), and isometric mid-thigh pulls (IMTP). Major dependent variables were fiber type-specific cross-sectional area (CSA), anatomical CSA (ACSA), myosin heavy chain (MYH) isoforms, jump height (JH), allometrically-scaled peak power (PPa), isometric peak force (IPF), scaled IPF (IPFa), and rate of force development (RFD). Mixed design ANOVAs were used in addition to effect size using Hedge's *g* to assess within and between-group alterations. RI_{SR} from pre-to-post yielded statistically significant increases in Type I CSA (p=0.018), Type II CSA (p=0.012), ACSA (p=0.002), unweighted (p=0.009) and 20 kg SJ JH (p=0.012), unweighted (p=0.003) and 20kg SJ PPa (p=0.026), IPF (p<0.001), and IPFa (p<0.001). Additionally, RI_{SR} increased in unweighted (p=0.023) and 20kg SJ JH (p=0.014), and 20kg SJ PPa (p=0.026) from pre-to-post taper. RM yielded statistically significant increases from only pre-to-post taper for 20kg SJ JH

(p=0.003) and CMJ JH (p=0.031). Additionally, RM had a statistically significant pre-to-post decrease in RFD from 0-50ms (p=0.018) and 0-100ms (p=0.014). Between-group effect sizes supported RI_{SR} for Type I CSA (g=0.48), Type II CSA (g=0.50), ACSA (g=1.03), all MYH isoforms (g=0.31-0.87), all SJ variables (g=0.64-1.07), unweighted and 20kg CMJ JH (g=0.76-0.97), unweighted CMJ PPa (g=0.35), IPFa (g=0.20), and all RFD (g=0.31-1.25) time-points except 0-200ms; with all other effects being of trivial magnitude (g<0.20). Overall, this study demonstrated that RI_{SR} training yielded greater improvements in vertical jump, RFD and maximal strength compared RM training. These performances results may, in part, be explained mechanistically by the superior physiological adaptations observed in the RI_{SR} group within the skeletal muscle. Taken together, these data support the use of RI_{SR} training in well-trained populations.

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CHAPTER 1

INTRODUCTION

Previous research has established that proper resistance training implementation has a positive impact on strength (Abe, DeHoyos, Pollock, & Garzarella, 2000; Buford, Rossi, Smith, & Warren, 2007; Campos et al., 2002; Deschenes & Kraemer, 2002; Hakkinen et al., 1998), explosiveness (Aagaard, Simonsen, Andersen, Magnusson, & Dyhre-Poulsen, 2002; Bazyler et al., 2016), and sport performance (Abt et al., 2016; Alexander, 1989; Chelly et al., 2009; Christou et al., 2006; Suchomel, Nimphius, & Stone, 2016). Neuromuscular and performance adaptation to resistance training is in part based on the manipulation of one or more variables such as volume, intensity, and exercise selection (Bird, Tarpenning, & Marino, 2005; Fleck & Kraemer, 2014; Stone, Stone, & Sands, 2007; Verkoshansky, 1985). Within this context, a strategy to manipulate these variables becomes important to coaches attempting to elicit desired adaptations. Researchers have examined manipulation of resistance training variables and measured both physiological and performance outcomes (Fry, 2004; Kraemer et al., 2000; Painter et al., 2012). However, optimal methodologies for neuromuscular adaptation still require investigation.

The optimal method of selecting loads (intensities) for resistance training exercises has potentially large implications regarding adaptation (Stone et al., 2007). There are a number of prevalent strategies for load prescription, such as: percentage based on 1RM (Christou et al., 2006; Fink, Kikuchi, Yoshida, Terada, & Nakazato, 2016; J. R. Hoffman et al., 2009a), or repetition maximum (RM) (Campos et al., 2002; Tan, 1999). It has been suggested that using RM loading strategies are superior to percentage-based systems (Bird et al., 2005; Tan, 1999), although not all agree (B. H. DeWeese, Hornsby, Stone, & Stone, 2015b; Harris, Stone,

O'Bryant, Proulx, & Johnson, 2000; Painter et al., 2012). Additionally, training using the RM method may push lifters to or near muscular failure during training, which may not be an advantageous training method (Davies, Orr, Halaki, & Hackett, 2016; Stone, Chandler, Conley, Kramer, & Stone, 1996). Current research is not conclusive and further investigation is warranted to further explore the optimal methods of loading.

Several limitations of the existing literature confound the practical application of resistance training studies seeking to explore optimal loading strategies. One such limitation is the equating of work. Programs of vastly different workloads may interfere with results concerning the efficacy of a loading strategy. However, overly-ambitious efforts to equate workloads can also result in the loss of the program's intent and purpose. While an attempt to control workloads when comparing loading strategies is an important consideration, special attention should be given in order to retain the integrity of the programming style in question.

An additional concern in existing resistance training literature deals with the use of unrealistic training schedules for participants. Understandably, it is difficult to compare training strategies among competitive and elite athletes as an ethical dilemma exists concerning an athletic team segregating into distinct training groups. Thus, very few studies comparing loading strategy have included the training of actual athletes (J. R. Hoffman et al., 2009b; Kraemer et al., 2000; Painter et al., 2012). To extrapolate results to competitive athletes, researchers have recruited participants with higher levels of training experience and baseline strength levels (Coffey et al., 2006; Ronnestad, Hansen, & Raastad, 2010; Schoenfeld et al., 2014). Even with well-trained participants the training schedules often do not typically mimic the training schedule of actual athletes. Resistance training 2-3 times per week still does not account for other aspects of training such as sprint training or sport practice. Furthermore,

studies comparing training strategies should attempt to employ a more holistic training environment relatable to actual athletics.

Strength and power sports require that athletes are able to 1) produce high levels of force, and 2) produce force at fast work rates (Aagaard et al., 2002; Stone et al., 2003; Suchomel et al., 2016). A variety of neuromuscular factors are ultimately responsible for producing adaptations to force, power, and rate of force development capabilities. For example, changes in intramuscular protein accumulations may modulate specific cellular pathways designed to alter the morphology of skeletal muscle cells in response to resistance training (Ahtiainen et al., 2015; Glass, 2005; Gonzalez, Hoffman, Stout, Fukuda, & Willoughby, 2016). Morphological alterations in skeletal muscle may affect the force production capabilities of the muscle and subsequently performance capability (Aagaard et al., 2001; Maffiuletti et al., 2016; Schoenfeld, 2010). Thus, in depth examinations of skeletal muscle protein accretion, morphology, and subsequent physical performance provide useful and somewhat comprehensive information regarding the efficacy of specific training strategies on neuromuscular and athletic performance.

Dissertation Purposes

1. To compare RM (failure) to RI (non-failure) training prescriptions on training load, vertical jump, and maximal strength characteristics in well-trained lifters.
2. To compare skeletal muscle physiological outcomes between a RM (failure) or RI (non-failure) RT program. Specifically, to examine intramuscular protein accretion, muscle fiber cross-sectional area, and ultrasonography muscle size.

Operational Definitions

Anatomical cross-sectional area- the measured area within a whole muscle.

Fiber cross-sectional area- the measured area within a muscle fiber.

Maximal strength- greatest amount of force able to be produced by an individual for a given task.

Muscle architecture- the structural arrangement of muscle fibers respective to a specific whole muscle.

Muscular failure- the inability to complete a task as a result of momentary fatigue.

Protein synthesis- the creation of new protein as a result of translational activity in the ribosome, resulting from specific gene expression.

Rate of force development- force production over a given time period.

Repetition maximum- the greatest number of repetitions an individual can complete within a given repetition range.

Training intensity- within resistance training, the load of an exercise.

Training volume- within resistance training, the amount of work accomplished. Estimated by repetitions · sets · displacement.

CHAPTER 2

COMPREHENSIVE REVIEW OF LITERATURE

History of Training for Sport

Modern training practices originate from historical accounts of sport training. Although some would argue today's training regimens are more sophisticated and advanced compared to ancient methods, the core values of modern training have some astounding similarities to training in the earlier days of man. For example, during the Chou dynasty of ancient China (1122-249BC) citizens were required to demonstrate their ability through a series of weightlifting tests before admittance to the armed forces (Verkhoshansky & Siff, 2009). This is not drastically different than modern tests for admittance to a specific sport team (e.g. NFL combine, Olympic Trials). Furthermore, a basic knowledge of sporting history, especially as it related to resistance training may provide valuable insight for practitioners.

References to athletic competition and strength training have been observed as early as 2500 BC in the artwork within Egyptian tombs (Kraemer & Häkkinen, 2008). By the 6th century (referred to as the "Age of Strength") in ancient Greece athletics and feats of strength had become a major part of culture. The Greek physician Galen authored a revolutionary text, *Preservation of Health* in which he details the usefulness of resistance-style training for both athletic strength and human health (Kraemer & Häkkinen, 2008; Verkhoshansky & Siff, 2009). Throughout several centuries, training for sport and combat alike involved lifting weights and the enhancement of strength. John Paugh's 1728 publication, *A Physiological, Theoretical and Practical Treatise on the Utility of Muscular Exercise for Restoring the Power to the Limbs*

portrayed resistance training as a scientific process as opposed to just an effective tool for human performance and health (Verkhoshansky & Siff, 2009).

Modern resistance training theory developed further as a scientific discipline in the 20th century (Verkhoshansky & Siff, 2009). Several influential publications (Matveyev, 1964; Verkoshansky, 1985) have influenced an era of exploration into the planning of enhancing sport performance through targeted training strategies (e.g. resistance training, sport training, etc.) (Bompa & Haff, 2009; Stone et al., 2007; Verkhoshansky & Siff, 2009).

Periodization as a Training Strategy

Planned training for sport is arguably one of the most important concepts for coaches and sport scientists to consider. Careful planning and monitoring of the training process is imperative for understanding the effectiveness and efficiency of a specific training program (B. H. DeWeese, Hornsby, Stone, & Stone, 2015a; B. H. DeWeese et al., 2015b). One of the most used planning methods for sport training is based on the concept of "periodization" modeled in 1964 by the Russian sport scientist Lenoid P. Matveyev (Matveyev, 1964). Although the term periodization is relatively new, the planning of training prior to competition has likely been in practice since the ancient Olympic Games in Greece (Bompa & Haff, 2009). Periodization has been defined in a variety of ways (B. DeWeese, Gray, Sams, Scruggs, & Serrano, 2013), but perhaps most appropriately periodization is defined as "the logical, sequential, phasic method of manipulating training variables in order to increase the potential for achieving specific performance goals while minimizing the potential for overtraining and injury through the incorporation of planned recovery" (B. H. DeWeese et al., 2015a). Many authors have discussed and examined the periodization concept (Bompa & Haff, 2009; Issurin, 2010; Matveyev, 1964;

Stone et al., 2007; Verkhoshansky & Siff, 2009). However, Stone et al. (2007) points out periodization has been largely based on observation and practical knowledge due to the limited body of existing controlled research. The limited empirical evidence available limits periodization's integration into all performance and training formats, and thus should be investigated more thoroughly.

The search for optimal training strategies to enhance sport performance is of primary importance in strength and conditioning and sport science (Campos et al., 2002; Issurin, 2010; Painter et al., 2012; Rhea, Ball, Phillips, & Burkett, 2002). Typically, one or more programming variables are altered when comparing training strategies. It is sometimes suggested these training variable alterations represent differences in periodization models. However, periodization is an overall concept to a training strategy, while programming deals with sets, repetitions, exercise selection, etc. (B. H. DeWeese et al., 2015a; Stone et al., 2007). Training strategies should be employed based on how human physiology is altered in response to acute and chronic training stimuli. However, not all training responses and adaptations are equal, thus differing training strategies are likely to yield different performance outcomes. Therefore, training adaptations are largely specific to the type of stimuli encountered (Fry, 2004; Peterson, Rhea, & Alvar, 2004; Rhea, Alvar, Burkett, & Ball, 2003; R. S. Staron et al., 1994).

Some of the earliest modern training concepts, such as Yakovlev's supercompensation cycle (Issurin, 2010), were based on physiological responses to exercise and training. Fitness characteristics (e.g. strength, power, speed, endurance, etc.) may be enhanced through specific training stimuli and appropriate recovery paradigms (B. H. DeWeese et al., 2015a; Stone et al., 2007). Moreover, a variety of training strategies have been introduced in an effort to enhance sport performance (Campos et al., 2002; Issurin, 2016; Painter et al., 2012; Tan, 1999), yet there

is a lack of clarity in research as to which methods might provide superior adaptations and subsequently performance.

Block Periodization

What is commonly known as "traditional periodization" is largely based on the original work of Matveyev (1964). Similar to other forms of periodization, traditional periodization is broken into several phases (preparatory, competitive, and transitional). Traditional periodization employs a multidirectional loading approach in which a variety of fitness characteristics (strength, endurance, etc.) are trained concurrently during the preparatory phases while training emphases transition to more event-specific stimuli during competitive periods. However, concurrent emphasis of multiple characteristics has been to interfere with overall adaptation, specifically in strength-power training (Hakkinen et al., 2003). Also, characteristic of traditional periodization are peaking phases, which were designed to peak athletes for their most important competition each training cycle. This strategy was eventually modified for athletes who had up to three competitions per year. Unfortunately, multidirectional loading builds a foundation of many fitness characteristics early in the training cycle but does not apply stimuli to retain those characteristics during specific preparatory phases. Additionally, modern athletics often includes a relatively large number of important competitions that athletes must peak for, limiting the efficacy of multidirectional loading patterns and thus the traditional periodization approach (Issurin, 2010, 2016).

Block periodization is a training scheme characterized by specific training phases, or "blocks," with each emphasizing specific fitness characteristics (Verkhoshansky & Siff, 2009; Verkoshansky, 1985). Similar to traditional periodization, the training cycle progresses from

general preparatory, specific preparatory, competitive, transitional. However, in contrast to traditional periodization, block periodization employs unidirectional loading, or training stimuli directed towards a specific fitness characteristic, within each block of training. These unidirectional loads are commonly known as concentrated loads (Verkhoshansky & Siff, 2009). Concentrated loads are strategically implemented at certain time periods within a training cycle such that fitness characteristics more vital for performance in a given sport are expressed at a time of peaking. For example, a concentrated load for work capacity or strength endurance may be programmed during the early general preparation phase while an explosive strength concentrated load may be programmed nearer to an important competition. Utilizing unidirectional loading, for many sports, has been purported to be more effective in developing many types of athletic performance compared to multidirectional loading (B. H. DeWeese et al., 2015a; Stone et al., 2007; Verkhoshansky & Siff, 2009). Moreover, the logical sequencing of concentrated loads is potentially vital for the success of a particular program.

Conjugate Sequential Integration

The conjugate sequence system is an advanced periodization strategy originally developed by Dr. Yuri Verkhoshansky (Verkhoshansky & Siff, 2009). This system deals with the organizing, or sequencing, of concentrated loads (blocks) in a specific manner throughout a training cycle, which may result in the enhancement of specific fitness qualities. Execution of the conjugate sequence system is dependent on a target quality for which all training will be directed towards achieving. For example, conjugate sequencing for speed development (such as for a sprinter) may differ from the conjugate sequencing for maximal strength (such as for a

powerlifter). Therefore, conjugate sequencing can be used for a variety of disciplines and for the procurement of a variety of training goals.

Enhancing a desired fitness quality is achieved through three phases: accumulation, transmutation, realization. Accumulation deals with a concentrated load that supports the desired quality but may cause temporary fatigue and reduction in performance. The transmutation phase alters the concentrated load such that fatigue can be reduced, and training stimuli will be more specific to the desired characteristic. The major reason for a realization phase is to express the fitness quality all subsequent training phases have been building towards. Thus, realization increases performance readiness by altering the concentrated load to be very specific and reducing fatigue typically via reduction in training volume. The desired fitness quality is achieved via the accumulated training effects from previous blocks of training, known as the long-term delayed training effect (Stone et al., 2007). The long-term delayed training effect inherent within conjugate sequencing (and block periodization) is the premise of phase potentiation, which postulates that each training phase should enhance subsequent phases of training if the proper sequencing of previous training blocks is prescribed (Stone et al., 2007). Training studies often do not include a realization phase, possibly altering the performance results due to accumulated fatigue.

Even within the same periodization model, there are a variety of different programming strategies that can be employed. Many programming variables (volume, intensity, etc.) are typically altered throughout and between training phases and will combine to elicit a training effect. Intensity (i.e. load in resistance training) has been identified as a critically important programming variable (Fry, 2004). Therefore, the proper prescription of loading is essential to

the training process. The large influence intensity has on adaptation necessitates the exploration of the optimal methods by which to prescribe it.

Repetition Maximum Loading

Resistance training loading, or intensity, may be prescribed in a number of ways, perhaps the most common being Repetition Maximum Zones (RM loading or RM zones) or percentage-based programs (%1RM, etc.). RM loading prescribes an RM or range of RM (e.g. 4-6 RM) to guide training. Imperative to this loading strategy is truly reaching a maximum load for the given repetition range prescribed. RM loading uses the actual maximum number of repetitions performed as a guide for the load selection, in contrast to other methods which include a percentage of a maximum or estimated maximum (Tan, 1999). Thus, training at or near failure is one of the basic tenets of this strategy. Advantages of RM loading have been suggested to include: load increases are potentially more accurate because once an athlete is able to surpass the RM prescription with a given load, an increase is made- perhaps limiting the chance of underloading. Also, this strategy theoretically eliminates the need for 1RM or RM testing due to consistently training at RM values (Tan, 1999). However, training to failure may attenuate positive adaptations due to large amounts of fatigue or overtraining (Davies et al., 2016; Stone et al., 1996; Tan, 1999), although it has been suggested to be a potent stimulus for hypertrophy (Schoenfeld, 2010, 2013) or maximal strength (Tan, 1999). Additionally, training to failure may at best produce similar strength gains compared to non-failure methods (Izquierdo et al., 2006; Painter et al., 2012), questioning the efficiency of failure-methods. The potential negative effects confound the purported benefits of RM loading, although more research is needed to further explore this.

Much of the current resistance training research uses RM loading (Campos et al., 2002; Kerksick et al., 2009; Moss, Refsnes, Abildgaard, Nicolaysen, & Jensen, 1997; Prestes, De Lima, Frollini, Donatto, & Conte, 2009; Rhea et al., 2002), including when comparisons are drawn between different training groups (Campos et al., 2002; Juliano Spineti et al., 2013). These comparisons may be clouded by experimental groups consistently training at maximal relative intensities. Although these studies provide valuable information to the existing body of research on resistance training, it is currently unclear whether using this loading strategy may affect the training outcomes or not. While RM loading provides a popular and potentially beneficial loading strategy, other loading strategies may produce similar or superior performance enhancements while limiting the increased risk of increased of fatigue or overtraining syndrome.

Relative Intensity Based on Sets and Repetitions Loading

Relative intensity based on sets and repetitions (also referred to as the set-rep best method) is, in its most basic definition, an extension of the classic %1RM system. The set-rep best approach uses an athlete's maximum within a given set-rep range (i.e. 3x10, 3x5, and 3x3 all have different 'maximum loads') or an estimation based on previously achieved loads for a given set-rep range (B. DeWeese, Sams, & Serrano, 2014). While the initial training values may be rooted in %1RM, further adjustments are made with consideration of the estimated set-and-repetition maximums. While the maximum repetitions that can be completed varies between individuals and between exercises at a given %1RM (Hoeger, Hopkins, Barette, & Hale, 1990), the set-rep best approach seeks to limit that confounder by considering the best loads lifted within that given set-rep range and exercise.

Unlike RM loading (where maximal intensity is necessary to govern future load selection), a set-rep best approach uses a range of submaximal loads ranging from light to very heavy throughout training stages and phases (Stone & O'Bryant, 1987). Adequate management of accumulated fatigue while enhancing fitness qualities may also be achieved via incorporation of heavy and light days (B. H. DeWeese et al., 2015b; Stone, Pierce, Sands, & Stone, 2006; Stone et al., 2007). A comparison of a primarily maximal-intensity program (RM loading) to a more varied and submaximal intensity-based program (set-rep best) would provide valuable insight into performance outcomes and may aid future researchers when selecting appropriate training methods.

Outcomes of Training: Molecular Changes

Specific training modes (e.g. aerobic vs. anaerobic modes) indeed dictate the type and direction of adaptation (Baar, 2006; Hakkinen et al., 2003). Changes in the molecular environment of cells, specifically skeletal muscle fibers, in response to training stimuli are diverse and a well-known phenomenon (Coffey & Hawley, 2007; Glass, 2005; Schoenfeld, 2010). Some of these changes pertain to muscle fiber characteristics or other protein synthetic alterations. Changes in muscle fiber phenotypes have been observed following resistance training (Campos et al., 2002; Fry, 2004; R. Staron et al., 1990; R. S. Staron et al., 1994; R. S. Staron et al., 1991). Perhaps more importantly, resistance training has been shown to induce significant hypertrophy specific to faster phenotypes of muscle (i.e. preferential Type II fiber hypertrophy) (Campos et al., 2002; Trappe, Costill, & Thomas, 2000). For the purposes of this review MHC isoforms, mTOR, and AMPk proteins are considered. The importance of these proteins for muscle fiber adaptation and in the larger scheme of sport performance is considered.

Importance of Intracellular Signaling

Protein synthesis is a necessary contribution to overall training adaptation (Ahtiainen et al., 2015; Atherton et al., 2005; Coffey et al., 2006; Damas, Phillips, Vechin, & Ugrinowitsch, 2015). Although protein synthesis is involved in an astounding number of biological functions, each protein and subsequent function serve a specific purpose. Therefore, synthesis of specific proteins may be attributed to specific adaptations to a variety of specific stimuli, including exercise and training. In the past twenty years, our understanding of protein translation has accelerated, and a variety of up- and downstream targets have been identified that can lead to functional adaptations (e.g. cell growth, differentiation) (Bodine et al., 2001; Glass, 2005; Proud, 2007). These organizations of proteins within cells are known as intracellular signaling pathways. These signaling pathways are sensitive to various stimuli or changes in the extracellular environment. Additionally, signaling pathways may communicate (i.e. either inhibit or enhance) between one another via autocrine and paracrine mechanisms. The importance of this discovery is illustrated by the implications for disease, where dysfunction of a protein in a signaling pathway may result in a disease such as cancer. More specific to the current topic, the discovery of signaling pathways has prompted exercise and sport scientists to further explore this area as it pertains to human performance. Several proteins have been specifically identified to be involved in protein synthesis related to adaptations to specific training modes (i.e. endurance training vs. heavy resistance training).

Mammalian Target of Rapamycin (mTOR)

Mammalian Target of Rapamycin (mTOR) has been repeatedly implicated as a critically important regulator of protein synthesis and cell growth (Bodine et al., 2001; Drummond et al.,

2009; Golberg, Druzhevskaya, Rogozkin, & Ahmetov, 2014; Gonzalez et al., 2016; Goodman, 2014; Leger et al., 2006; Proud, 2007). Specifically, the first of two complexes containing mTOR (TORC1) is considered to be a major contributor to eventual skeletal muscle hypertrophy (Goodman, 2014). Studies have shown that sustained, low intensity muscle contraction (as occurs in aerobic-type training) inhibits mTOR activity via mechanisms to be later discussed in more detail (see section; "Adenosine Monophosphate-Activated Protein Kinase") (Atherton et al., 2005). Conversely, several upstream regulators of mTOR within the Insulin-Like Growth Factor-1 (IGF-1) signaling cascade such as Protein Kinase B (PKB, or Akt) and Tuberous Sclerosis Complex 2 (TSC2) have been shown to increase activity following high intensity muscle contraction (as occurs in resistance-type training). Several of mTOR's downstream targets, Ribosomal protein S6 kinase beta-1 (p70s6k), eIF4E binding protein (4E-BP1), and Eukaryotic Translation Elongation Factor 2 (eEF2) have also been shown to increase following high intensity muscle stimulation (Atherton et al., 2005). Although mTOR activation is controlled in part by Akt in the IGF-1 pathway, it is a necessary component of adaptive protein synthesis (Goodman, 2014; Ogasawara et al., 2013; Proud, 2007). Inhibition of mTOR activation via rapamycin administration *in vitro* resulted in blocking muscle protein synthesis, thus limiting cell growth (Drummond et al., 2009). Additionally, evidence suggests alternative methods of mTOR activation may be possible independent of a concomitant rise in Akt phosphorylation (Moller et al., 2013). The practical implications for this are an increase in synthesis of contractile proteins, facilitated by mTOR's downstream effects, may influence muscle phenotype and function (Bodine et al., 2001; Egerman & Glass, 2014; Glass, 2005). While mTOR has certainly been examined in humans (Dreyer et al., 2006; Mascher et al., 2008; Mayhew, Kim, Cross,

Ferrando, & Bamman, 2009; Moller et al., 2013; Vissing et al., 2013), much has yet to be uncovered concerning its responsiveness to resistance training programs, among other things.

Although mTOR's role in protein synthesis has been explored *in vitro,* in animal models, and in biological/medical reviews, very few studies have been conducted on humans measuring the mTOR response to chronic resistance training (Mayhew et al., 2009). Activated mTOR was shown to be significantly increased one and two hours post exercise (10x10 leg extensions at 70% 1RM) but not immediately following exercise in untrained subjects (Dreyer et al., 2006). This change was associated with increased muscle protein synthesis at the same time points. Interestingly, muscle protein synthesis immediately following exercise was significantly lower than basal values. This was concomitant with increased phosphorylation of AMPk, which has an interference effect on mTOR activation and muscle protein synthesis (Baar, 2006; Dreyer et al., 2006; Glass, 2005). Another study examining protein synthesis 30 min post exercise of up- and downstream of mTOR indicated that greater volumes of resistance training (10x10) resulted in greater activation of Akt and p70s6k compared to lower volumes (5x10). However, both resistance training modalities had statistically greater responses within the IGF-1 pathway compared to endurance exercise (Ahtiainen et al., 2015). This suggests greater volumes stimulate skeletal muscle protein synthesis to a larger extent than lesser volumes in acute RT, although this result has not been substantiated in the literature. Additionally, these results must be considered over chronic training stimuli as opposed to single dose.

Mascher et al. (2008) examined the repeated bout effect on mTOR activation using 4x10 repetitions of leg press using 80% 1RM (1RM determined prior to test). The training sessions, separated by 48 hours, induced statistically greater activations of mTOR 15 minutes, 1 hour, and 2 hours post-training for both training sessions. Although not statistically significant, mTOR

activation was greater at rest and after training at all time points during the second and final training session (Mascher et al., 2008). These increases were in the absence of Akt increases, suggesting increased mTOR activation in response to resistance training independent of Akt, thus furthering mTOR's influence on protein translation (Mascher et al., 2008). One such mechanism, inhibitor of nuclear factor kappa-B kinase subunit beta (IKK-β), whose activation has been shown to mirror that of mTOR in resistance-trained individuals following an acute resistance training stimulus, provides basis for an Akt-independent mechanism of mTOR activation (Moller et al., 2013). Although mTOR activation increases following an acute resistance training stimulus (Ahtiainen et al., 2015; Mascher et al., 2008; Moller et al., 2013), very little evidence exists concerning the chronic effects of resistance training on mTOR content and phosphorylation.

Although mechanisms have been elucidated previously, chronic resistance training adaptations to the Akt-mTOR pathway via enhanced mTOR translation and activation are currently not clear. Following eight weeks of lower body resistance training using repetition maximum loading (to muscular failure) activated levels of Akt, glycogen synthase kinase 3 beta (GSK3-β) and mTOR were increased at rest. Muscle biopsies were taken 48-72 hours following the final training session. After eight weeks of detraining levels of Akt and GSK3-beta were decreased while mTOR remained elevated (Leger et al., 2006). This may indicate an adaptive mechanism for preserving muscle mass gained during training, evidenced by detraining not resulting in a return to baseline cross-sectional area (CSA). In contrast to the findings of Leger et al. (2006), another study observed no changes in the total or activated levels of mTOR following sixteen weeks of resistance training (Mayhew et al., 2009), although data for mTOR were not specifically reported by the authors. This finding is peculiar due to observed increases in Type II

muscle fiber CSA. Notably, muscle biopsies taken by Mayhew et al. (2009) were obtained 24 hours after the initial training session, and 24 hours following the final training session. This is an important consideration as evidence demonstrates the acute training response of mTOR is muted following structured resistance training (Luo et al., 2013). Another study examining acute response of mTOR pre- and post- 8 weeks of training indicated a statistically greater acute mTOR activation response in the resistance-trained individuals, compared to a resting baseline (Vissing et al., 2013). A lack of sporting-relevant programming tactics, number of investigations, and subject trained states all limit the applicability of these findings to sporting populations. Therefore, more research is certainly warranted into mTOR translation/activation and its effect on muscle phenotype and performance in trained individuals.

Adenosine Monophosphate-Activated Protein Kinase (AMPk)

Decreased cellular energy levels in response to mechanical stimuli, symbolized by high levels of AMP compared to ATP (AMP:ATP ratio), is a potent stimulator of cellular processes directed towards supplying additional energy (Coffey & Hawley, 2007). AMP has affinity for a specific protein kinase as part of a signaling cascade resulting in catabolism, cellular survival and ultimately energy supply. This protein kinase, AMPk, has been implicated in typical aerobic adaptations such as mitochondrial biogenesis and subsequent increased aerobic capacity (Baar, 2006; Coffey & Hawley, 2007; Proud, 2007). AMPk activates TSC2, a regulator for mTORC1, thereby inhibiting mTOR's potential as a translational initiator. Thus, AMPk has been speculated to be the molecular culprit behind the interference effect observed during concurrent endurance and resistance-type training (Baar, 2006).

Although AMPk has been linked to aerobic stimuli (Vissing et al., 2013), its upregulation has been observed during resistance training as well as cellular energy levels become depleted (Atherton et al., 2005), limiting mTOR's effect on protein synthesis. This result has been supported in humans (Dreyer et al., 2006) and animal models (Atherton et al., 2005). Following training when energy levels have recovered, marked increases in protein synthesis and cellular mediators of synthesis (e.g. Akt, mTOR, etc.) are observed concomitantly with reductions in AMPk activation (Dreyer et al., 2006). Additionally, AMPk activation does not seem to be dependent solely on the type of stimulus, but also the training history of an individual (Coffey et al., 2006). A study comparing the effects of an acute resistance or endurance training bout on already resistance (powerlifters) or endurance (cyclists) trained athletes indicated a "familiarity effect" for AMPk. The resistance-trained athletes had no appreciable AMPk response to resistance training while endurance training caused greater AMPk activation. Conversely, AMPk was not significantly stimulated during endurance training for already endurance-trained athletes while resistance training caused AMPk to increase (Coffey et al., 2006). A possible explanation for these findings is the homogenization of muscle tissue that combine fast and slow skeletal muscle isoforms. Additionally, the training status of each group of participants may have suppressed the molecular response in the familiar intervention, while increasing the response in the unfamiliar intervention (Ogasawara et al., 2013).

Myosin Heavy Chain Isoforms

The functional units of the muscle, sarcomeres, are responsible for muscle contraction (Brooks, Fahey, & White, 1996) which are made up of several proteins, most notably the contractile proteins actin and myosin. Myosin is composed of both heavy chains (MHC), which

are determinants of ATPase activity and shortening velocity, and light chains (MLC), which modulate ATPase activity in the globular heads. MHC and MLC have different isoforms, each with unique properties relating to shortening velocity and especially ATPase activity (Brooks et al., 1996; Stone et al., 2007). These proteins, specifically MHC, have a major role in determining muscle fiber type (Behan, Cossar, Madden, & McKay, 2002). MHC isoforms in humans follow the same labels as the overall muscle fiber type classifications: Type I, IIa, and IIx, which are arranged from slowest to fastest speeds of contraction. The contraction speeds within the muscle fiber are largely a result of the amount of myosin ATPase activity present in the globular heads of the MHC. Thus, MHC isoform content is an important consideration when examining muscular adaptations to training.

Evidencing MHCs modulation of contractile characteristics, it has been shown that muscle fiber type transitions due to training are concomitant with changes in MHC isoform concentrations (Fry, 2004; Pette & Staron, 2000; Schiaffino, 2010). Additionally, MHC isoform content has been suggested to relate to muscular rate of force development and muscle activation (Aagaard et al., 2002). Due to the relationship of MHC content and muscle fiber type, adding analysis of these component may provide depth to investigations regarding hypertrophy.

Outcomes of Training: Architectural Changes

Molecular changes to skeletal muscle certainly play a major role in large scale morphological and architectural adaptations (Schoenfeld, 2010). Although molecular changes may be ultimately responsible for architectural adaptation, the manifestation of larger scale adaptive results (e.g. muscle fiber type, size, and thickness) are more closely linked with performance (Aagaard et al., 2001; J. L. Andersen & Aagaard, 2010). Therefore, a closer

examination into the architectural adaptations to training, specifically resistance training, should be conducted.

Fiber Type Distribution

Three predominant skeletal muscle fiber types (along with several intermediates) have been identified in humans: Type I, Type IIa, and Type IIx (Pette & Staron, 2000; Schiaffino, 2010). These muscle fiber types are differentiated by the contractile proteins (e.g. myosin and actin) present within the functional unit of each muscle cell, the sarcomere. Sarcomeres are responsible for muscle contraction (Brooks et al., 1996). Myosin is composed of both heavy chains (MHC), which are determinants of ATPase activity and shortening velocity, and light chains (MLC), which modulate ATPase activity in the globular heads. MHC and MLC have different isoforms, each with unique properties relating to shortening velocity and especially ATPase activity (Brooks et al., 1996; Stone et al., 2007). These proteins have a major role in determining muscle fiber type (Behan et al., 2002). In regard to the predominant human fiber types, ATPase activity can be ordered: IIX > IIA > I and the shortening velocity can be ordered: I < IIA < IIX (Pette & Staron, 2000; Stone et al., 2007). Furthermore, it has been shown that fiber types with greater ATPase activity and faster shortening velocities will likely have greater rates of force development and greater peak forces (J. L. Andersen & Aagaard, 2010; Fitts, McDonald, & Schluter, 1991; Harridge, 2007). This is practically important due to the reliance on fast movements in most sports, especially strength and power sports. However, these muscle fiber properties and proteins are largely governed via innervation with efferent motor neurons (Gabriel, Kamen, & Frost, 2006). The properties of these motor neurons (discharge rate, frequency, etc.) ultimately determine the phenotype of a given muscle fiber or group of fibers by

influencing contractile protein content. Thus, the question of whether specific training stimuli may affect the motor neuron, contractile protein content, and subsequently phenotype has been explored.

Muscle fiber types have been shown to shift phenotype in response to extreme stimuli. For example, spinal cord injury and paralysis has shown to exponentially increase Type IIX muscle fibers (Andersen, Mohr, Biering-Sørensen, Galbo, & Kjaer, 1996). It has been repeatedly shown that resistance training stimuli will result in reductions in Type IIX muscle isoforms and an increase in Type IIA (Campos et al., 2002; Fry, 2004; R. Staron et al., 1990; R. S. Staron et al., 1994; R. S. Staron et al., 1991). Reductions in faster isoforms of skeletal muscle resulting from resistance training seems counter-intuitive especially considering the improvements to maximal strength and explosiveness (i.e. RFD) observed following RT. It has been suggested that these positive adaptations to RT are largely a result of selective Type II muscle fiber hypertrophy and neural mechanisms (Campos et al., 2002; Fry, 2004). Therefore, a more applicable and relevant measurement may be to examine muscle fiber hypertrophy as a measurement of adaptations as opposed to fiber type alone.

Cross-Sectional Area

Cross-sectional area in skeletal muscle is typically defined as either 1) anatomical cross-sectional area (aCSA), the size of the whole muscle; or 2) fiber cross-sectional area (fCSA), the size of individual muscle fibers. aCSA is typically measured using ultrasound, MRI, CT, or DEXA. Conversely, fCSA can be determined through biopsy and appropriate analysis (Campos et al., 2002). Although muscle fiber types have specific qualities indicative of their exercise performance, cross-sectional area of those fibers and possibly the whole muscle may be a more

potent factor regarding performance capability. Anatomical CSA has been shown to increase following heavy resistance training and has been related to force production (Holm et al., 2008; Ronnestad et al., 2010), although not all research agrees (Mitchell et al., 2012). It has been observed that Type II fiber CSA is preferentially increased following resistance training compared to Type I fibers (Campos et al., 2002; Trappe et al., 2000). It has also been suggested that muscular failure may result in appreciable increases in cross-sectional area (Schoenfeld, 2010; Tan, 1999). However, the consequences of training to muscular failure (e.g. fatigue, overtraining, etc.) may limit the upside to its potential as a training stimulus overall (Davies et al., 2016; Schoenfeld, 2010). Still, a majority of research exploring CSA use RM values for loading (i.e. training to failure, albeit not in a traditional bodybuilding manner), thus limiting our understanding of more athlete-specific loading modalities and their effects on CSA. Understandably, more research is needed to elucidate the effects of these loading modalities on CSA.

Outcomes of Training: Performance Changes

An understanding of molecular and structural adaptations to resistance training is vitally important in sport physiology. However, exploring performance outcomes specific to sport (e.g. jumping, sprinting, etc.) are the culmination of physiological change and are arguably the most important metrics to measure. Consider an athlete who gains appreciable CSA in the quadriceps muscles but does not improve performance. While it is entirely plausible that performance effects lag behind molecular and structural adaptation, if peaking and preparedness are of importance than inherently the timing of performance change is critical. Thus, studies examining

adaptations to training with respect to athletic competition should put significant weight in the results of performance changes, such as strength, power, and RFD.

Maximal Strength

Increases in maximal strength have been repeatedly shown as a response to resistance training for many years (Abe et al., 2000; Buford et al., 2007; Campos et al., 2002; Deschenes & Kraemer, 2002; Hakkinen et al., 1998). In fact, maximal strength may be one of the most important variables in determining performance capability (Suchomel et al., 2016). Maximal strength is typically measured via dynamic repetition maximums (Banyard, Nosaka, & Haff, 2016; Campos et al., 2002; J. R. Hoffman et al., 2009a; Mangine et al., 2015), or isometric strength tests such as isometric mid-thigh pulls (Bailey, Sato, Burnett, & Stone, 2015; Beckham et al., 2013), isokinetic tests (Holm et al., 2008). Although strong support exists for resistance training mediated increases in maximal strength, evidence exists that different resistance training periodization or programming strategies have varying magnitudes of effect (Painter et al., 2012).

Rate of Force Development

Rate of force development (RFD) provides a key aspect of producing optimal performances (Aagaard et al., 2002; Maffiuletti et al., 2016). Rate of force development can be measured in a variety of ways (dynamic or isometric), but is most typically measured during maximal isometric contraction to alleviate methodological concerns over dynamic joint movement (Maffiuletti et al., 2016). It may also be measured indirectly using vertical jump or sprint performance. Maximal force (strength) provides an essential backbone to performance (Suchomel et al., 2016). However, sporting movements (e.g. jumping, kicking a ball, etc.) exist

in a time-sensitive manner. Development of the ability to rapidly produce force is therefore incredibly important. RFD could be considered the most important performance-determining factor especially for sports associated with extraordinarily short critical timeframes for sporting movements (e.g. boxing, high jump, etc.) (Aagaard et al., 2002; Maffiuletti et al., 2016; Taber, Bellon, Abbott, & Bingham, 2016). However, it should be noted that high RFD probably does not exist in the absence of at least reasonable maximal strength values (Suchomel et al., 2016). Moreover, the ability to produce high RFD is a central focus of nearly all physical training for strength and power sports.

RFD is influenced by a variety of factors such of muscle fiber type, size, strength, and rate coding (Maffiuletti et al., 2016). It has been shown that a block-periodized training program using percentage-based loading resulted in positive changes to RFD while a daily undulating program utilizing RM loading resulted in negative changes (Painter et al., 2012). While an overwhelming amount of literature does not exist, Painter and colleauges (2012) provide evidence to warrant further studies comparing the effects of maximum (RM loading) and submaximal (percentage-based, relative intensity) loading on RFD.

Summary

Surely resistance training provides a robust stimulus for increasing athletic abilities. Adaptations to resistance training may exist on a continuum ranging from molecular (protein accretion), cellular (morphology and architecture), to performance outcomes. Human performance is multifactorial and therefore physiological and physical adaptations are culminations of each other and should be considered as factors when interpreting results of any resistance training program. Alterations in muscle protein content such as myosin heavy chains,

stimulated by cellular mechanisms governing translation, may result in shifts in muscle fiber characteristics, sometimes leading to a shift in phenotype. More notably, greater content of contractile proteins results in enlargement of muscle fibers, hypertrophy. This hypertrophy may be selective based on the training stimuli encountered and thus may influence strength, explosiveness, and subsequent performance. Indeed, the method in which resistance training is prescribed is important for these adaptations and worth further investigation.

CHAPTER 3

RESISTANCE TRAINING USING REPETITION MAXIMUMS OR RELATIVE INTENSITY RESULTS IN DIVERGENT PERFORMANCE AND PHYSIOLOGICAL OUTCOMES: PART 1- PERFORMANCE

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Abstract

Purpose: The purpose of our investigation was to compare repetition maximum (RM) to relative intensity using sets and repetitions (RI_{SR}) resistance training (RT) on measures of training load, vertical jump, and maximal strength in well-trained lifters. **Methods:** Fifteen well-trained males underwent RT 3 $d \cdot wk^{-1}$ for 10-weeks in either an RM group (n=8) or RI_{SR} group (n=7). The RM group achieved a relative maximum each day while the RI_{SR} group trained based on percentages. Testing at five time-points (A-B-C-D-E) included unweighted (<1kg) and 20kg squat jumps (SJ) and counter-movement jumps (CMJ). Isometric mid-thigh pulls (IMTP) were also performed. Dependent variables were: volume load x displacement (VLd), training monotony (TM), training strain (TS), jump height (JH), scaled peak power (PPa), isometric peak force (IPF), scaled IPF (IPFa), and rate of force development (RFD) from 0-50ms, 0-100ms, 0-150ms, and 0-200ms. Mixed design ANOVAs were used in addition to effect size using Hedge's *g* to assess within and between-group alterations. **Results:** Weekly VLd was statistically similar between groups. TS was statistically greater in the RM group throughout a majority of the intervention. Post-hoc testing revealed statistically significant A-E increases for RI_{SR} in unweighted (p=0.009) and 20 kg SJ JH (p=0.012), unweighted (p=0.003) and 20kg SJ PPa (p=0.026), IPF (p<0.001), and IPFa (p<0.001); and D-E increases for unweighted (p=0.023) and 20kg SJ JH (p=0.014), 20kg SJ PPa (p=0.026). Conversely, the RM group statistically increased D-E 20kg SJ JH (p=0.003) and CMJ JH (p=0.031). Statistically significant reductions were observed in the RM group for RFD 0-50ms (p=0.018) and 0-100ms (p=0.014). **Conclusions:** Overall, this study demonstrated that RI_{SR} training yielded greater improvements in vertical jump, RFD and maximal strength compared RM training, which may

partly be explained by the differences in the imposed training stress and the use of failure/non-failure training in a well-trained population.

Key Words: maximal strength, rate of force development, vertical jump, isometric mid-thigh pull

Introduction

Resistance training (RT) has repeatedly shown the capability to enhance physical performance characteristics such as maximal strength (Campos et al., 2002; Harris, Stone, O'Bryant, Proulx, & Johnson, 2000; Hoffman et al., 2009a; Stone et al., 2000) and rate of force development (RFD) (Aagaard, Simonsen, Andersen, Magnusson, & Dyhre-Poulsen, 2002). Maximal strength and RFD are critically important for athletes, particularly in strength-power sports (Maffiuletti et al., 2016; Suchomel, Nimphius, & Stone, 2016). While RT has been shown to enhance these and other physical traits, exercise or training intensity seems to play a major role in facilitating these improvements (Fry, 2004). Both high load/high force and low load/high velocity loading prescriptions have been shown to enhance jump performance (Cormie, McCaulley, & McBride, 2007; Tricoli, Lamas, Carnevale, & Ugrinowitsch, 2005). However, a combination of high force and high velocity training may provide superior results (Cormie et al., 2007; Harris et al., 2000; Toji & Kaneko, 2004; Toji, Suei, & Kaneko, 1997; Tricoli et al., 2005). Toji et al. (2004) observed greater peak power output increases (52.9%) in the elbow flexors when varying heavy-and-light training loads (i.e. greater load ranges throughout study). Similarly, Cormie et al. (2007) showed that the combination of "optimally" loaded jump squats with heavy squats were superior to only jump squat training in producing increases in peak jump power and height. These observations indicate that a broad range of loading is necessary for superior improvements in ballistic movements. Therefore, loading strategies should be carefully considered when designing RT programs for athletes requiring high rates of force development.

There are a number of prevalent strategies for load prescription in RT. Two popular strategies include using a percentage of a one-repetition maximum (%1RM) (Christou et al.,

2006; Fink, Kikuchi, Yoshida, Terada, & Nakazato, 2016; Harris et al., 2000; Hoffman et al., 2009b) or repetition maximum (RM) zones (Campos et al., 2002; Tan, 1999). Proponents of RM zone training suggest it is superior to %1RM due to acute fluctuations in daily strength levels. Therefore, by completing repetition maximums in training, it has been suggested that practitioners can account for these perturbations in strength levels and more accurately prescribe training loads (Tan, 1999). Converse to RM zones, training programs based on %1RM (often referred to as relative intensity, RI) use mostly submaximal training intensities or percentages. RI loading is a popular method for prescribing a more undulated training approach using heavy-and-light training days within each training week. Further, due to fluctuations in 1RM values (e.g. due to daily fatigue levels), a variant of relative intensity loading has been developed (RI_{SR}) using percentages of set and repetition combination maximums instead of %1RM to prescribe training loads. Using the RI_{SR} strategy, each set and repetition combination (e.g. 3x10 vs 3x5) has a specific 100% value, as opposed to constantly being related back to a 1RM. This also allows for more consistent relative load descriptions, regardless of the set and repetition combination. Proponents of RI_{SR} suggest that using submaximal training intensities and heavy-and-light training days results in better fatigue management and superior adaptations compared to RM training (B. H. DeWeese, Hornsby, Stone, & Stone, 2015a, 2015b; Harris et al., 2000; Stone et al., 2000).

Differences in physiological and performance changes between these two RT load prescription strategies have not been compared. Therefore, the purpose of our investigation was to compare RM to RI_{SR} training on measures of training load, vertical jump, and maximal strength in well-trained lifters. We hypothesized that the greater variations in training intensity

and attention to fatigue management in RI_{SR} would result in superior performance changes compared to RM training.

Methods

Subjects

Eighteen well-trained males volunteered to participate in the study, however one withdrew prior to beginning the training protocol due to time conflicts and two others withdrew due to injury during the study (one from each group). Therefore, fifteen subjects participated in and completed the study (age = 26.94 + 3.95 yrs, body mass = 86.21 + 12.07 kg, BMI = 27.07 + 3.08). All subjects were required to have been actively resistance training, including the performance of squats, for at least 1 year at a minimum frequency of 3 days/wk. Experience was confirmed based on a questionnaire and careful questioning by the investigators. Subjects were considered well-trained based on their baseline isometric mid-thigh pull peak force (IPF) (4403.61 $\pm$ 664.69 N) and allometrically scaled isometric peak force (IPFa) (226.04 $\pm$ 25.81 $N/kg^{0.67}$), which were similar or greater than previously reported values for collegiate athletes (Kawamori et al., 2006; McGuigan & Winchester, 2008; Thomas, Comfort, Chiang, & Jones, 2015). Subjects were ranked based on initial IPFa and matched pairs were randomly assigned into either a RI_{SR} group (RI_{SR}, n=7) or an RM zone group (RM, n=8). It should be noted that the matching was performed with the initial eighteen subjects, prior to any dropouts. All subjects read and signed an informed consent document prior to participating in the study, as approved by the university's Institutional Review Board.

Training Programs

Following baseline testing, subjects completed resistance training 3 $d \cdot wk^{-1}$ for 10 weeks (Table 1). Resistance training was completed on Mondays, Wednesdays, and Fridays

(Table 2) while a rudimentary sprint program was completed on Tuesdays and Thursdays. The sprint program consisted of 2-3 sets of three 20m sprints with 2 minutes of rest between repetitions and 4 minutes of rest between sets. It is important to note that the sprint training was exactly the same for both groups. The purpose of the sprint program was to provide a stimulus more similar to what a typical athlete (e.g. throwers, baseball/softball players) would encounter. Where most RT studies only provide a stimulus on RT days, we attempted to more closely mimic training that occurs in the real world. Subjects in the study were highly motivated and completed 100% of the training sessions. All training sessions were supervised by trained and certified strength and conditioning coaches. Strength coaches were rotated periodically to reduce potential coaching bias. Both groups performed the same dynamic warm-up preceding each training session. Additionally, subjects were encouraged to give maximal effort for all repetitions throughout each training session. All subjects trained within the same 3-hour window each day. Work was estimated by volume load displacement from all warm-up and working sets (VLd = sets · repetitions · vertical displacement) (B. H. DeWeese et al., 2015a) and session rating of perceived exertion (sRPE). Vertical displacement was measured using a linear position transducer (Open Barbell, Brooklyn, NY, USA). To further interpret the workloads experienced during each group's RT, training monotony (TM) and training strain (TS) were calculated for each week using sRPE multiplied by session duration. TM was calculated by dividing the mean weekly sRPE by the standard deviation of the week; and TS was calculated as the product of the mean weekly sRPE and the TM score for the week (Foster, 1998; McGuigan & Foster, 2004).

Table 3.1 Resistance Training Programs

			RI_{SR}		RM Zone
Training Block	Week	(sets)x(reps)	Day 1 and 2	Day 3	
(A) VJ and IMTP testing					
Strength-Endurance	1	3x10	80.0%	70.0%	3x8-12
	2	3x10	85.0%	75.0%	3x8-12
	3	3x10	90.0%	80.0%	3x8-12
(B) VJ and IMTP testing					
Max-Strength*	4	3x5	85.0%	70.0%	3x4-6
	5	3x5	87.5%	72.5%	3x4-6
	6	3x5	92.5%	75.0%	3x4-6
	7	3x5	80.0%	65.0%	3x4-6
(C) VJ and IMTP testing					
Overreach	8	5x5	85.0%	75.0%	5x4-6
(D) VJ and IMTP testing					
Speed-Strength	9	3x3	87.5%	67.5%	3x2-4
	10	3x2	85.0%	65.0%	3x1-3
(E) VJ and IMTP testing					

*Symbolizes down set at 60% of working weight (RI_{SR} only), RI_{SR}= relative intensity based on sets and repetitions, RM= repetition maximum, VJ= vertical jump, IMTP= isometric mid-thigh pull

Table 3.2 Training Exercises for all subjects

Training Block	Day 1	Day 2	Day 3
Strength-Endurance	Back Squat, Overhead Press, Bench Press, DB Tricep Ext.	CG MTP, CG SLDL, BB Bent-Row, DB Bent Lateral Raise	Back Squat, Overhead Press, Bench Press, DB Tricep Ext.
Max-Strength	Back Squat, Push Press, Incline Bench Press, Wtd. Dips	CG MTP, Clean Pull, SG SLDL, Pull-Ups	Back Squat, Push Press, Incline Bench Press, Wtd. Dips
Overreach	Back Squat, Push Press, DB Step Up, Bench Press	CG CM Shrug, Clean Pull, CG SLDL, SA DB Bent-Row	Back Squat, Push Press, DB Step Up, Bench Press
Speed-Strength	Back Squat + Rocket Jump, Push Press, Bench Press + Med Ball Chest Pass	CG MTP, CG CM Shrug, Vertical Med Ball Toss	Back Squat + Rocket Jump, Push Press, Bench Press + Med Ball Chest Pass

*DB= dumbbell, CG= clean grip, MTP= mid-thigh pull, BB= barbell, Ext= extension, Wtd= weighted, SG= snatch grip, SLDL= stiff-legged deadlift, SA= single arm, CM= counter-movement

Both groups followed a block-periodized program consisting of three main phases: strength-endurance, maximum strength, and speed-strength (B. H. DeWeese et al., 2015a). This phase progression, which has been used similarly by other training studies (Harris et al., 2000; Painter et al., 2012), was applied to both training groups simultaneously. However, RI_{SR} training used mostly submaximal intensities (i.e. percentages of set-and-rep maximums), heavy-and-light training days within each week, and down-sets (where appropriate). The maximums for each set and repetition combination were: 100% is very heavy, 90-95% is heavy, 85-90% is moderately heavy, 80-85% is moderate, 75-80% is moderately light, 70-75%

is light, and 65-70% is very light (B. H. DeWeese et al., 2015b; Stone, Stone, & Sands, 2007). Heavy-and-light training days consisted of a specific intensity reduction from Day 1 to Day 3 in the RI_{SR} group: 10% for strength-endurance and overreach, 15% for maximum strength, and 20% for speed-strength (Table 1). Loads were adjusted weekly based on estimated set-rep bests within each set-rep combination (3x10, 3x5, 5x5, 3x3, 3x2) (B. DeWeese, Sams, & Serrano, 2014; B. H. DeWeese et al., 2015b).

Unlike RI_{SR} training, the RM training group used maximal loads within each training session and RM zone prescription (3x8-12, 3x4-6, 5x4-6, 3x2-4, 3x1-3). The goal of the RM zone prescription was that each subject would reach muscular failure on the final set of the exercise, indicating a maximum had been achieved. If the failed set resulted in repetitions fewer than were prescribed, the load was subsequently reduced by a minimum of 2.5%. However, if the repetitions achieved surpassed the prescription, the load was increased by a minimum of 2.5%. All other factors not pertaining to the loading strategy (i.e. training times, rest intervals, training volumes, etc.) were controlled between groups to the best of our ability. Both groups performed the same standardized dynamic warm-up prior to each training session. Maximum efforts were encouraged for all sets throughout each training session. Rest periods between RT sets were 3-5 minutes for both groups. Throughout the intervention, subjects were instructed to refrain from excess physical activity outside of training and on rest days. Subjects were also instructed to maintain their typical dietary habits throughout the intervention and to abstain from taking stimulants prior to any testing or training sessions.

Vertical Jump Assessments

Static jumps (SJ) and counter-movement jumps (CMJ) were assessed at five time-points as indicated in Table 1 using unweighted (<1kg) and weighted (20kg) conditions. Jump

height (JH) and allometrically scaled peak power (PPa) were measured during each jump condition. All performance testing was completed 72 hours following the most recent training stimulus. Baseline testing was considered time point A and all other time points were in order: B, C, D, and E (where E is the post-test). Following a standardized dynamic warm-up (Kraska et al., 2009), each subject performed two warm-up SJs with a plastic pipe (<1kg) rested on the trapezius muscles just below the seventh cervical vertebrae. The plastic pipe was used to eliminate arm swing and to standardize testing conditions between subjects. Static jumps were performed from an internal knee angle of 90° measured using a goniometer. Following 50% and 75% effort warm-up jumps, two maximal-effort SJs were performed on dual-force plates (2 x 91cm x 45.5 cm) sampling at 1000Hz (Rice Lake Weighing Systems, Rice Lake, WI). Following the SJs, CMJ testing was performed using identical procedures. Data were collected and processed using a LabView program (LabView 8.6, and 2010, National Instruments Co., Austin, TX). Sixty-seconds of rest were given between each jump trial and between jump types. Jump height was estimated from flight time as described previously (Linthorne, 2001). The force-time trace was converted to an acceleration-time trace, which was then differentiated to obtain a velocity-time trace. Peak power was the maximal value obtained from the product of the velocity-time and force-time trace, and was allometrically scaled to account for differences in body mass. The mean of the two best trials within a 2 cm difference in JH was used for analysis. Additional trials were performed when the difference between two trials was greater than 2 cm. Reliability was assessed by intraclass correlation coefficients (ICC) and coefficient of variation (CV) for JH (ICC = 0.99, CV = 1.96%) and PPa (ICC = 0.92, CV = 2.24%).

Isometric Mid-Thigh Pull Assessments

Isometric peak force (IPF), allometrically scaled IPF (IPFa), and rate of force development (RFD) were assessed from isometric mid-thigh pulls (IMTP) performed at each testing time point. Specifically, RFD from 0-50ms (RFD50), from 0-100ms (RFD100), from 0-150ms (RFD150), and from 0-200ms (RFD200) were considered. Following a standardized warm-up (Kraska et al., 2009), each subject was positioned in a custom-built power rack with an affixed bar. Subject internal knee and hip angles were measured manually using a goniometer and were required to be 130 $\pm$ 5° and 150 $\pm$ 5°, respectively. Each power rack contained dual force plates (2 x 91cm x 45.5 cm) sampling at 1000 Hz (Rice Lake Weighing Systems, Rice Lake, WI). Subjects were secured to the bar using straps and athletic tape to eliminate grip strength as a confounding variable during testing. Prior to maximal effort trials, a 50% and a 75% warm-up effort was completed, separated by sixty seconds of rest. Three minutes of rest was given following the final warm-up effort. Each subject completed two maximal-effort IMTP trials and were instructed to "pull as fast and as hard" as they could. Additional trials were completed if the IPF differed between trials >250N or if there was a >200N counter-movement in any trial. Verbal encouragement was provided during every IMTP effort. Again, three minutes of rest were given between trials. Kinetic data were processed using a commercially available software (ForceDecks, NMP Technologies Ltd., London, UK). Within-subject, between-trial reliability assessed by ICC and within-subject CV were as follows: IPF (ICC = 0.95, CV = 2.83%), IPFa (ICC = 0.95, CV = 2.83%), RFD50 (ICC = 0.74, CV = 24.16%), RFD100 = (ICC = 0.81, CV = 21.24%), RFD150 (ICC = 0.83, CV = 16.55%), RFD200 (ICC = 0.83, CV = 12.01%). The two IMTP trials were averaged together for statistical analysis.

Statistical Analysis

After verifying that there were no between group differences for SJ, CMJ, and IMTP ($p > 0.05$) at baseline, a 2x5 (group x time) mixed-design analysis of variance (ANOVA) was conducted. Additionally, VLd, TM, and TS were compared using a 2x10 (group x time) mixed ANOVA. Homogeneity of variance using Levene's test and Mauchly's test of sphericity were calculated prior to performing ANOVA tests. Alpha level was set at $p \leq 0.05$. Significant main effects were followed by post-hoc tests using a Holm-Bonferroni adjustment. Specific interest was given to post-hoc tests between the A and E (pre-to-post) time points and the D to E (before and after the taper). These points of interest were chosen due to the importance of both 1) the changes from baseline to post study, and 2) the changes associated with a taper period, which has been shown to be an important aspect of training (Bazyler et al., 2016; Murach et al., 2014; Trappe, Costill, & Thomas, 2000). Statistical analyses were performed on a commercially available statistics software (JASP version 0.8.1.1) and Microsoft Excel 2016 (Microsoft Corporation, Redmond, WA, USA). To assess practical significance, effect size using Hedge's *g* was calculated for pre-post measures. Within-group effect sizes were calculated using pre and post mean and standard deviation values for each group. Between-group effect sizes were calculated using change scores between groups. 90% confidence intervals were calculated for each of these effects. Effect size magnitude was assessed using the following scale: 0.0-0.2 (trivial); 0.2-0.6 (small); 0.6-1.2 (moderate); 1.2-2.0 (large); 2.0-4.0 (very large); 4.0-∞ (nearly perfect) (Hopkins, Marshall, Batterham, & Hanin, 2009).

Results

ANOVA revealed a statistically significant interaction (group x time) effect for VLd ($p < 0.001$), and TS ($p = 0.005$); a significant main effect for time was observed for TM ($p =$

0.033). Further analysis revealed simple time effects for VLd ($p < 0.001$) and TS ($p < 0.001$) in both groups. Post hoc testing revealed no statistically significant between-group VLd difference for any week ($p > 0.05$) (Figure 1). However, there was statistically greater TS for the RM group in weeks 3-10 (Figure 2). Body mass and BMI resulted in statistically significant main effects for time ($p < 0.001$). Post hoc testing revealed a statistically significant increase in body mass for both the RI_{SR} group ($p = 0.007$) and the RM group ($p = 0.002$). Additionally, BMI increased significantly for the RI_{SR} group ($p = 0.008$) and the RM group ($p = 0.002$).

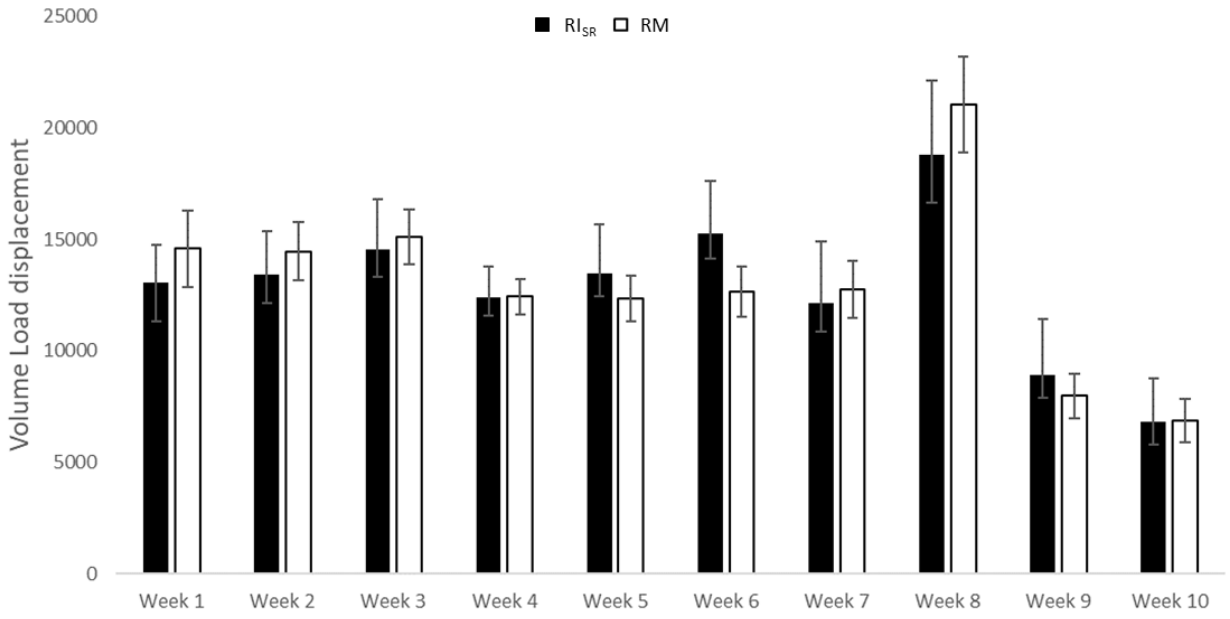

Figure 3.1 Weekly volume load displacement for relative intensity (RI) and repetition maximum (RM) groups were similar for all weeks ($p > 0.05$).

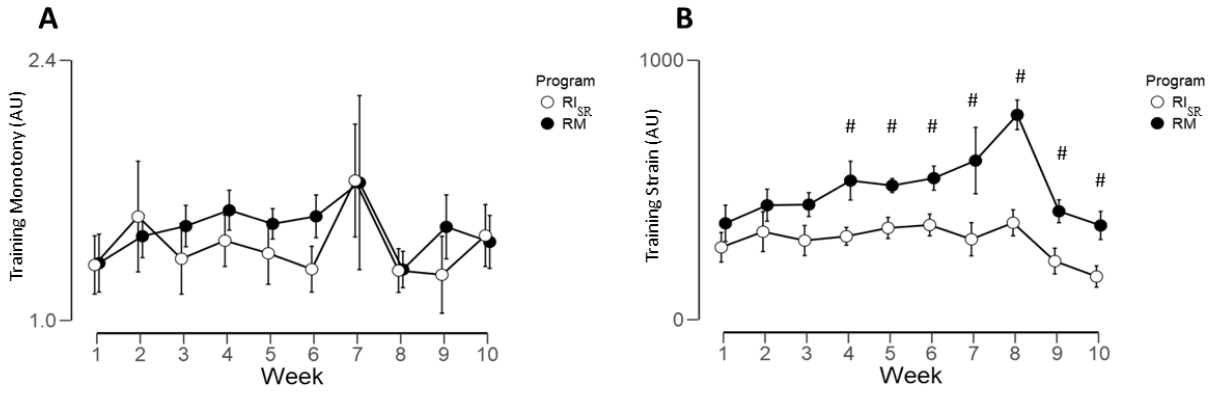

Figure 3.2 # = between-group difference at specific time-point. A) Training monotony and B) training strain were statistically higher for repetition maximum (RM) at week 3. These measures were also higher than relative intensity (RI) for all other weeks, although without statistical significance.

Unweighted SJH yielded a statistically significant main effect for time ($p = 0.006$). Post-hoc analysis revealed statistically significant increases for the RI_{SR} group from A-to-E ($p = 0.009$) and from D-to-E ($p = 0.023$). Alternatively, no statistical significance was reached for the RM group ($p > 0.05$) (Figure 3). A significant interaction ($p = 0.046$) was observed for SJH with 20kg. Simple main time effects were observed for RI_{SR} ($p = 0.021$) and for RM ($p = 0.036$). The RI_{SR} group improved significantly in SJH 20kg from A-to-E ($p = 0.012$) and from D-to-E ($p = 0.014$), while the RM group only improved from D-to-E ($p = 0.003$). There were no statistically significant differences between groups at any time point for either SJ condition. Significant interaction effects occurred for both CMJH conditions ($p = 0.006$ and $p < 0.001$, respectively). Simple main effects for time were significant only for RM CMJH 20kg ($p = 0.001$). Post-hoc comparisons revealed no statistically significant differences between groups

at any time point for unweighted CMJH ($p > 0.05$) while for CMJH at 20kg a difference was observed at time point D ($p = 0.033$) (Figure 3). Additionally, the RM group significantly improved CMJH 20kg between D-and-E ($p = 0.031$). Between-group effect magnitudes supported the RI_{SR} group for all measures of JH with moderate effects ($g = 0.76 – 1.07$) (Table 3).

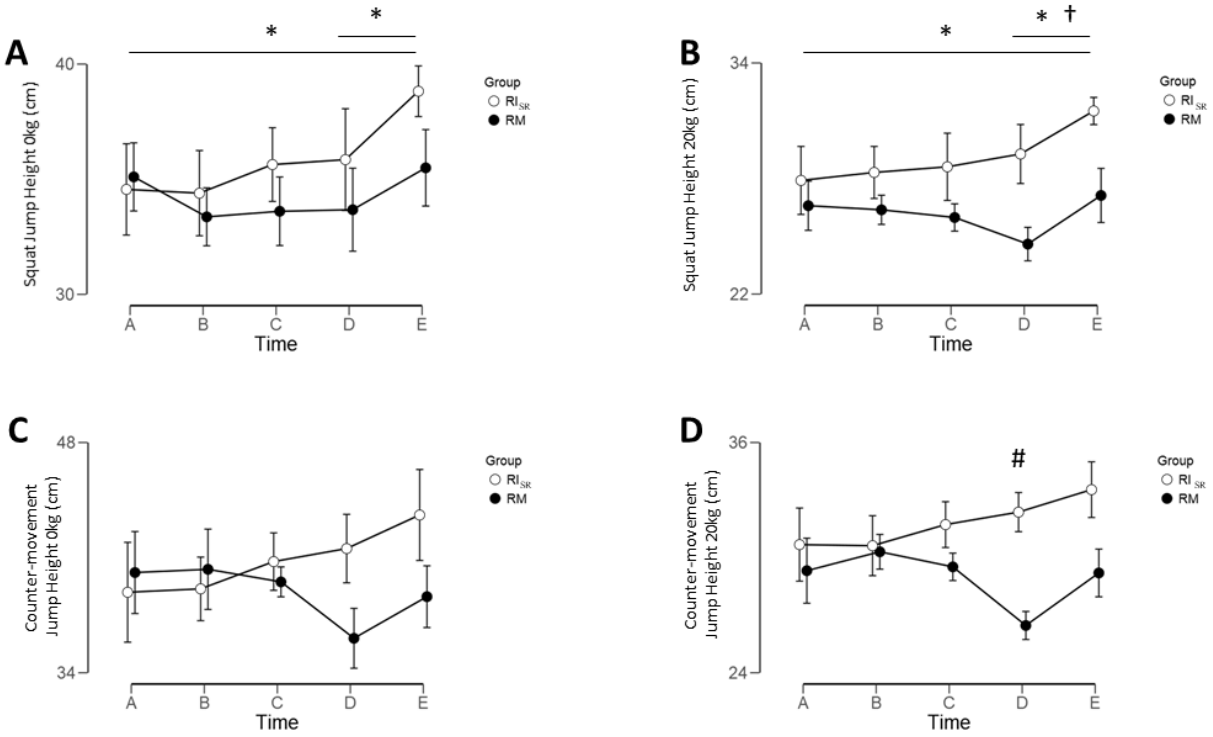

Figure 3.3 * = statistically significant change for relative intensity (RI) group only, † = statistically significant change for repetition maximum (RM) group only, # = between-group difference at specific time-point. Alterations in squat jump height (A & B) and counter-movement jump heights (C & D) for both unweighted and 20kg conditions. RI resulted in statistically significant increases in squat jump height from A-to-E and D-to-E while RM only increased squat JH significantly from D-to-E. No within-group differences existed for counter-movement jump variables but there was a statistically significant between-group difference for 20kg counter-movement jump height at time point D.

Allometrically scaled peak power revealed statistical main effects for time at unweighted SJ and 20kg SJ conditions ($p < 0.001$ and $p = 0.02$, respectively). The RI_{SR} group statistically increased unweighted SJ PPa from A-to-E ($p = 0.003$) and from D-to-E ($p = 0.026$) while no statistical change was present for RM ($p > 0.05$). The RI_{SR} group statistically increased 20kg SJ PPa from A-to-E ($p = 0.024$) but all other post-hoc tests revealed no significant differences for either group ($p > 0.05$). A significant interaction effect ($p = 0.024$) was observed for 20kg CMJ PPa, with post-hoc tests revealing a significant between-group difference at the D time point ($p = 0.045$). For all scaled peak power measures, both within- and between-group effect magnitudes supported the RI_{SR} group (Table 3).

Table 3.3 Effect size using Hedge's *g* and 90% Confidence Intervals for within-group and between-group effects

	Relative Intensity Effects			Repetition Maximum Effects			Between Group Effects
Variable	*g* ± CI	pre ± SD	post ± SD	*g* ± CI	pre ± SD	post ± SD	*g* ± CI
SJ 0kg JH	0.82±0.42	0.35±0.05	0.39±0.04	0.05±0.30	0.35±0.07	0.35±0.07	1.07±0.83
SJ 20kg JH	0.89±0.49	0.28±0.04	0.32±0.03	0.08±0.32	0.27±0.07	0.27±0.06	0.91±0.83
CMJ 0kg JH	0.69±0.70	0.39±0.05	0.44±0.07	-0.2±0.47	0.40±0.07	0.39±0.07	0.97±0.84
CMJ 20kg JH	0.58±0.54	0.31±0.05	0.34±0.05	-0.02±0.43	0.29±0.05	0.29±0.05	0.76±0.83
SJ 0kg PPa	0.96±0.39	246±25	270±20	0.21±0.26	229±45	239±42	0.81±0.82
SJ 20kg PPa	0.71±0.46	246±29	265±20	0.14±0.29	224±45	230±40	0.64±0.83
CMJ 0kg PPa	0.29±0.63	258±27	266±27	-0.01±0.35	240±35	240±42	0.35±0.84
CMJ 20kg PPa	0.20±0.48	254±30	260±22	0.08±0.33	231±35	234±35	0.15±0.83
IPF	1.05±0.23	4,382±648	5,161±733	0.83±0.67	4,500±621	5,159±864	0.18±0.81
IPFa	1.26±0.26	219±26	254±24	0.98±0.86	235±18	263±33	0.20±0.81
RFD50	0.37±0.72	3,646±2,034	4,613±2,768	-0.94±0.58	5,534±2,060	3,466±2,118	1.25±0.84
RFD100	0.12±0.68	7,778±4,061	8,374±5,068	-0.61±0.36	10,577±4,754	7,682±4,274	0.89±0.84
RFD150	-0.02±0.62	8,925±3,728	8,821±4,580	-0.34±0.39	9,982±2,865	8,743±3,922	0.31±0.84
RFD200	0.01±0.06	8,364±2,623	8,398±3,475	-0.19±0.94	8,813±1,681	8,307±3,058	0.13±0.82

**g*= Hedge's *g* effect size, CI= 90% confidence interval, SD= standard deviation, SJ= squat jump, CMJ= counter-movement jump, JH= jump height, PPa= allometrically-scaled peak power, IPF= isometric peak force, IPFa= allometrically-scaled isometric peak force, RFD= rate of force development

Statistically significant main effects for time were observed for IPF and IPFa (p < 0.001). Statistically significant increases in IPF and IPFa were observed from A-to-E for the RI_{SR} group only (p < 0.001), while no other statistical effects were observed between any other time points for either group (p > 0.05). A statistically significant time interaction (p = 0.049) was observed for RFD50. A statistically significant decrease in RFD50 from A-to-E was observed for the RM group only (p = 0.018), with no other statistical changes for either group (p > 0.05) (Figure 4). No statistical difference for RFD50 existed between groups at any time point. A statistically significant main effect for time was observed for RFD100 (p = 0.014). A statistically significant decrease in RFD100 from A-to-E was observed in the RM group only (p = 0.014). No statistically significant main effects were observed for either RFD150 or RFD200. However, effect magnitudes were negative for the RM group at all RFD time points (Table 3). Both within- and between-group effect magnitudes supported the RI_{SR} group for all IMTP variables.

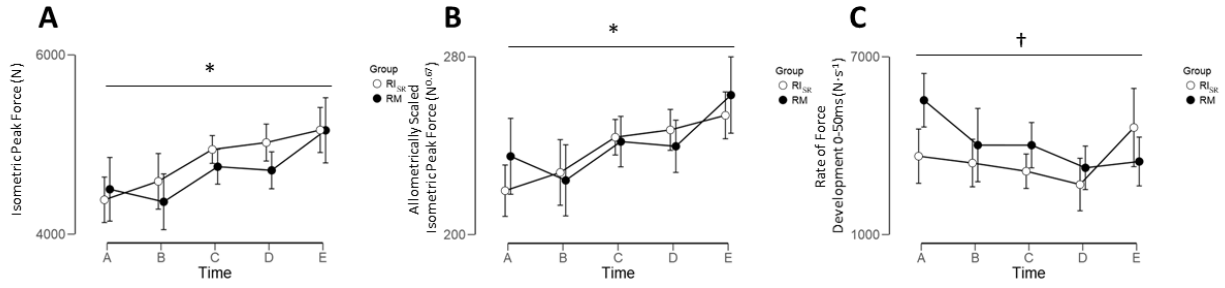

Figure 3.4 * = statistically significant change for relative intensity (RI) group only, † = statistically significant change for repetition maximum (RM) group only. RI resulted in statistically significant increases from A-to-E for A) isometric peak force and B) allometrically-scaled isometric peak force. RM resulted in a statistically significant decrease in C) rate of force development from 0-50ms.

Discussion

The purpose of our investigation was to compare RM to RI_{SR} training on measures of training load, vertical jump, and maximal strength in well trained lifters. The main findings of the study were, 1) Work, estimated as VLd, was similar throughout the intervention with the exception of a single day. TS was consistently greater for RM compared to RI_{SR}. 2) In support of our hypothesis, the RI_{SR} training group achieved superior improvements in vertical jump height and peak power outputs compared to the RM group throughout the intervention. 3) While both groups improved maximal strength, as measured by IPF and IPFa, only the RI_{SR} group reached statistical significance and showed larger effect sizes. Interestingly, RFD50 did not reach a statistically significant increase for the RI_{SR} group, however the RM group statistically decreased RFD50 throughout the intervention. Further inspection of the within- and between-group effect magnitudes (Table 3) revealed virtually all performance variables within the current study supported the RI_{SR} group. Our findings suggest that training with RM zones may be disadvantageous for athletes who aim to improve performance.

While the work completed by each group was similar across the intervention (Figure 1), the imposed stress demands differed. For example, the TS was significantly greater in the RM group compared to the RI_{SR} group throughout the majority of the intervention (Figure 2). As TS is a measure of the total stress imposed on an individual (Foster, 1998), this suggests that the RM group was exposed to high levels of training stress even given the similar external workloads (VLd). By contrast, the RI_{SR} group had comparatively low TS scores, most likely as a function of heavy-and-light training days during each week. The greater TS observed in the RM group likely contributed to their inability to increase performance to the degree of the RI_{SR} group. This concept is not new, as high levels of monotony and strain have been suggested to

impair adaptation and may potentially contribute to poor fatigue management and overtraining (Foster, 1998; McGuigan & Foster, 2004). These findings demonstrate that differences in imposed training stress between training programs can impact performance outcomes despite similarities in total work completed.

Positive relationships have been observed between changes in SJ performance with type II fiber content, and cross-sectional area (Andersen et al., 2005; Mero, Jaakkola, & Komi, 1991). Therefore, the greater SJH and SJ PPa improvements in the RI_{SR} group may suggest a mechanically advantageous phenotype shift or a greater hypertrophic response compared to the RM group. CMJ performances were also superior in the RI_{SR} group from pre-to-post, suggesting favorable enhancements in stretch-shortening cycle (SSC) function. In contrast, the decreases in CMJH in both loads for the RM group indicate impaired SSC function likely resulting from the residual fatigue of repeated training to failure. In support of this, Moran-Navarro et al. (2017) recently demonstrated that performing bench press and back squats to failure delays recovery of CMJ performance by up to 24-48 hours post-exercise (Moran-Navarro et al., 2017). Therefore, RI_{SR} training may stimulate greater CMJ performance improvements than RM training by permitting shorter recovery times between training sessions.

Both maximal strength and RFD can be impacted by fatigue (Chiu, Fry, Schilling, Johnson, & Weiss, 2004). Previous research has shown increases in maximal strength following RM training (Campos et al., 2002; Spineti et al., 2013). This is supported by our results, as both groups increased IPF and IPFa (RI_{SR} g = 1.05 – 1.26, RM g = 0.83 – 0.98), while only the RI_{SR} group reached a statistically significant increase ($p < 0.001$). Rate of force development seems to have greater sensitivity to fatigue compared to maximal strength

(Hornsby et al., 2017), possibly due to neural factors. Indeed, early RFD measures (25-75ms) have been linked to motor unit discharge rates (Maffiuletti et al., 2016). The statistically significant reductions in early RFD observed in the RM group (RFD50 $p = 0.018$, RFD100 $p = 0.014$) seem to suggest impaired neural drive. These findings have major implications for athletes, as RFD is critically important for performing time-sensitive tasks in sport (Aagaard et al., 2002; Maffiuletti et al., 2016). Therefore, RM training may result in inferior training adaptations to RI_{SR} training, particularly as it relates to rapid force production.

A taper was prescribed for both groups between time points D-and-E. The taper consisted of reduced volume, relatively high intensity, and more explosive exercises (e.g. down-sets of ballistic med ball throws for both groups). An interesting observation was a noticeable increase in performance following the taper, regardless of group. These data are particularly intriguing as the "D" and "E" time points were only separated by two weeks. Although RM training also benefited from a taper, this does not obviate the inferior performance adaptations observed throughout the intervention. Even with a taper, the RM group was unable to return to their baseline values for several variables (CMJH and early RFD). These depressed performance variables observed in the RM group provide further support for RI_{SR} as an efficacious training strategy. However, these data suggest regardless of training strategy, a taper should be used when optimal performances are the goal.

Conclusion

Overall, this study demonstrated that RI_{SR} training resulted in consistently greater improvements in vertical jump, RFD and maximal strength compared RM training, which may partly be explained by the differences in the imposed stress and design of RT workloads and the use of failure/non-failure training. Further, the similar workloads but drastically different

TS experienced between groups highlight the importance of tactics within the training process. Although RM training resulted in an increase in maximal strength, the obvious impairments to vertical jump and early RFD performance bring into question the efficacy of monotonous training and training to failure in populations where optimal performance enhancement is the goal, such as in competitive athletes. We recognize the limitations associated with small sample sizes, and this should be considered when interpreting the results of the study. However, in a well-trained and highly-motivated subject pool, the sample size seemed adequate. Our results support the use of RI_{SR} training with the inclusion of adequately varied training stimuli, such as heavy-and-light training days and a variety of high force and velocity outputs. Part 2 of this investigation will explore some of the underlying mechanisms behind these results. Particularly, we will compare our training groups on changes in muscle cross-sectional area, fiber cross-sectional area, and several key proteins within skeletal muscle.

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CHAPTER 4

RESISTANCE TRAINING USING REPETITION MAXIMUMS OR RELATIVE INTENSITY RESULTS IN DIVERGENT PERFORMANCE AND PHYSIOLOGICAL OUTCOMES: PART 2- PHYSIOLOGY

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Abstract

Purpose: The purpose of the study was to compare skeletal muscle physiological outcomes between a repetition maximum (RM) to relative intensity using sets and repetitions (RI_{SR}) resistance training (RT) program in well-trained lifters. **Methods:** Fifteen well-trained males underwent RT 3 $d \cdot wk^{-1}$ for 10-weeks in either an RM group (n=8) or RI_{SR} group (n=7). The RM group achieved a relative maximum each day while the RI_{SR} group trained based on percentages. Percutaneous needle biopsies of the vastus lateralis were obtained before and after the training intervention, along with ultrasonography measures of the same site. Dependent variables were: fiber type-specific cross-sectional area (CSA), anatomical CSA (ACSA), muscle thickness (MT), mammalian target of rapamycin (mTOR), adenosine monophosphate protein kinase (AMPK), and myosin heavy chains (MYH) specific for Type I (MYH7), Type IIA (MYH2), and Type IIX (MYH1). Mixed design ANOVAs were used in addition to effect size using Hedge's *g* to assess within and between-group alterations. **Results:** RI_{SR} statistically increased Type I CSA (p=0.018), Type II CSA (p=0.012), ACSA (p=0.002), and MT (p<0.001). RI_{SR} also yielded a significant reduction in mTOR (p=0.031). Conversely, RM statistically increased MT (p=0.003). Between-group effect sizes supported RI_{SR} for Type I CSA (g=0.48), Type II CSA (g=0.50), ACSA (g=1.03), MT (g=0.72), MYH1 (g=0.31), MYH2 (g=0.87), and MYH7 (g=0.59); with all other effects being of trivial magnitude (g<0.20). **Conclusions:** Our results demonstrated superior adaptations to fiber size, whole-muscle size, and several key contractile proteins in the RI_{SR} group compared to RM. Taken together with previously-published performance results, these data support the use of RI_{SR} training in well-trained populations.

Key Words: hypertrophy, cross-sectional area, contractile protein, skeletal muscle, mTOR

Introduction

From Carroll et al. (Part 1), performance outcomes clearly favored relative intensity (RI_{SR}) resistance training (RT) compared to repetition maximum (RM) training. We hypothesized that these preferential benefits of RI_{SR} training were, in part, due to superior fatigue management through the use of heavy-and-light training days and non-failure training sessions used throughout the intervention. Conversely, RM training consisted of very high intensity (i.e. failure) training every session with little variability, possibly impacting the group's ability to recover and adapt appropriately. Performance outcomes, such as those measured previously (Part 1), are certainly critical in understanding any training program's efficacy. However, a more thorough investigation of underlying mechanisms within the skeletal muscle tissue is warranted.

Sarcomeres, the functional units of skeletal muscle, are central contributors to the activity and capability of the cell. Alterations in protein isoforms within the sarcomere give rise to skeletal muscle plasticity, or changes in phenotype. Myosin heavy chain (MYH) isoforms are directly related to the muscle fiber type (Adams, Hather, Baldwin, & Dudley, 1993; Fry, Allemeier, & Staron, 1994) and the shortening velocity of the fiber (Pette & Staron, 2000; Reiser, Moss, Giulian, & Greaser, 1985). Alterations and synthesis of MYH isoforms provide a great deal of information regarding training outcomes. Further, the addition of more sarcomeres and the MYHs which they contain is the basis for muscle hypertrophy (Schoenfeld, 2010). Because of their degree of involvement in contraction dynamics, these factors are often considered when examining training outcomes or comparing training programs (Adams et al., 1993; J. L. Andersen & Aagaard, 2000; Campos et al., 2002).

Stimulation of myofibrillar or mitochondrial protein synthesis is, in part, controlled by a complex network of cellular signaling pathways (Baar, 2006; Wilkinson et al., 2008). Much of

the divergence in myofibrillar vs mitochondrial protein synthesis has been attributed to the interaction between the Protein Kinase B (PKB, or Akt)-mammalian target of rapamycin (mTOR) pathway and the adenosine monophosphate kinase (AMPK)-peroxisome proliferator-activated receptor gamma coactivator 1-alpha (PGC1α) pathway (Coffey & Hawley, 2007; Glass, 2005). Activation of the Akt-mTOR pathway has been shown to increase following RT and plays a key role in the synthesis of myofibrillar proteins (such as MYH isoforms), while AMPK-PGC1α activation has increased following both RT and endurance training and is considered a primary regulator of mitochondrial protein synthesis (Petriz et al., 2017; Vissing et al., 2013; Wilkinson et al., 2008). Additionally, Atherton and colleagues (2005) demonstrated that the mTOR pathway was inhibited via AMPK activation of tuberous sclerosis complex 2 (TSC2). These findings highlight the importance of the Akt-mTOR and AMPK-PGC1α pathway in training adaptations.

Due to differences in load prescription (e.g. failure vs non-failure), RI_{SR} and RM training may result in divergent cellular signaling responses, which may affect adaptations to the skeletal muscle tissue and ultimately performance. Thus, the purpose of the study was to compare skeletal muscle physiological outcomes between a RM or RI_{SR} resistance training program. We hypothesized that RI_{SR} would result in superior gains in muscle size, contractile protein, and mTOR accretion.

Methods

Subjects

Eighteen well-trained males volunteered for the study, however, one subject withdrew prior to beginning the training intervention and two others (one from each group) withdrew due to minor injuries during the study. Fifteen subjects completed the entire training intervention. To

be included in the study, subjects were required to have been training consistently (at least 3 days·wk^{-1}) for at least one year prior to beginning the study. This experience was confirmed by 1) an exercise-history questionnaire, and 2) careful questioning by the investigators. We considered our subjects to be well trained based on their baseline isometric mid-thigh pull peak force (IPF) (4403.61 $\pm$ 664.69 N) and allometrically-scaled isometric peak force (IPFa) (226.04 $\pm$ 25.81 N/kg$^{0.67}$). These values are in line with previously-published data in well-trained, competitive athletes (Kawamori et al., 2006; McGuigan & Winchester, 2008; Thomas et al., 2015). The study groups were formed by matching for baseline IPFa and assigned into either a RI_{SR} group using %set-rep best (RI, n = 7) or an RM zone group (RM, n = 8). It should be noted that the matching was performed with the initial eighteen subjects, prior to any dropouts. All subjects read and signed an informed consent document prior to participating in the study, as approved by the university's Institutional Review Board.

Resistance Training

Training methodology for the current study was extensively outlined in "Part 1" of this study. In brief, both training groups completed resistance training 3 d·wk^{-1} for 10-wk on Mondays, Wednesdays, and Fridays. Additionally, sprint training was conducted 2 d·wk^{-1} throughout the intervention on Tuesdays and Thursdays and was identical for both groups.

Both group programs were based on a block-periodized approach (B. H. DeWeese et al., 2015a; Harris et al., 2000; Painter et al., 2012), however the difference was in the loading strategy used. The RI_{SR} group used submaximal intensities (i.e. percentages) to guide the training process while the RM group used maximal loads within each training session with the set and repetition prescription. Loads were adjusted for the RI_{SR} group based on estimated set-rep bests within each set-rep combination (e.g. 3x10, 3x5, etc.). Conversely, the RM group adjusted loads

based on the maximal load lifted in each training session, within the RM zone prescription (e.g. 3x8-12, 3x4-6, etc.). The RM zone training approach necessitated that each subject would reach muscular failure on the final set of the prescription, indicating a maximum effort had been achieved. These daily-maximums were then used to adjust training loads for subsequent session. If the failed set resulted in fewer repetitions than were prescribed, the load was reduced by a minimum of 2.5% for the next training session. However, if the repetitions achieved on the failed set exceeded the prescription, the load would be increased by a minimum of 2.5%. All other training factors not pertaining to the loading strategy were controlled to the best of our ability (e.g. coaching, training time, etc.).

Both groups performed the same dynamic warm-up preceding each training session, and performed the same lift-specific warm-up procedures during resistance training. Specifically, each subject performed three progressive sets of warm-ups for each of the major lifts (squats, pulls, and presses). Maximum effort was encouraged on every set of every exercise throughout the intervention. Subjects were highly-motivated and completed 100% of the prescribed training. Subjects were instructed to refrain from excess physical activity outside of training and on rest days. Lastly, every training session was closely supervised by multiple certified strength and conditioning coaches throughout the intervention.

Muscle Biopsy Sampling and Processing

Muscle biopsies were sampled at least 72 hours before any study activity and 72 hours after the final training session. Following an overnight fast, a percutaneous needle biopsy of the VL was obtained using a 5mm Bergstrom-Stille needle under suction (Bergström, 1962; Stuart et al., 2006) and local anesthetic. The specimen was obtained in the superficial region of the VL at a depth of approximately 3 cm for both pre- and post-testing. Additionally, care was taken to

obtain the post-sample at a distance 0.5 cm distal of the pre-sample and at the same tissue depth. About half of the 50-100 mg sample was mounted on cork, quickly frozen in isopentane, and cooled in liquid nitrogen for later sectioning on a cryostat (Leica, Wetzlar, Germany) and immunohistochemical analysis. The remainder of the sample was placed in a container and frozen in an isopentane slurry cooled over liquid nitrogen. All samples were then promptly stored at -80°C until they were needed for analysis.

The cork-mounted biopsy samples were removed from the -80°C freezer and allowed to thaw to -20°C. Serial sections were obtained of each sample at a thickness of 14 μm and affixed to a microscope slide. Following this, tissues were fixed with acetone at -20°C for five minutes. All samples were blocked for two hours in a 10% normal goat serum and incubated overnight in monoclonal antibodies specific to myosin heavy chain (MYH) isoforms: MHY1 for Type IIX fibers (IgM, 1:10 dilution), MYH2 for Type IIA fibers (IgG1, 1:100 dilution), and MYH7 for Type I fibers (IgG2b, 1:200 dilution). Each of these antibodies were obtained from the Developmental Studies Hybridoma Bank (DSHB, University of Iowa, Iowa, USA). The following day, sections were incubated for two hours using goat anti-mouse AlexaFluor 488 (IgM), AlexaFluor 350 (IgG1), and AlexaFluor 555 (IgG2b), each at 1:200 dilution (Invitrogen, Carlsbad, California). Following mounting with OCT, a series of photographs were taken at 10x magnification. Images were processed in the ImageJ software (National Institute of Health, USA). A total of 3018 fibers were measured using the software's tracing tool (100.6 fibers/sample on average), and the average circularity of the measured fibers was 0.77 ± 0.09. Fiber types we identified and sized objectively based on the staining intensity within each fiber (i.e. the most predominant staining intensity) (Figure 1). Of the thirty biopsy samples (pre-and-post), only thirteen of them were positive for Type IIX muscle fibers (of those thirteen, only five

had greater than ten Type IIX fibers). Therefore, Type IIX and Type IIA fiber sizes were not separated for statistical analyses.

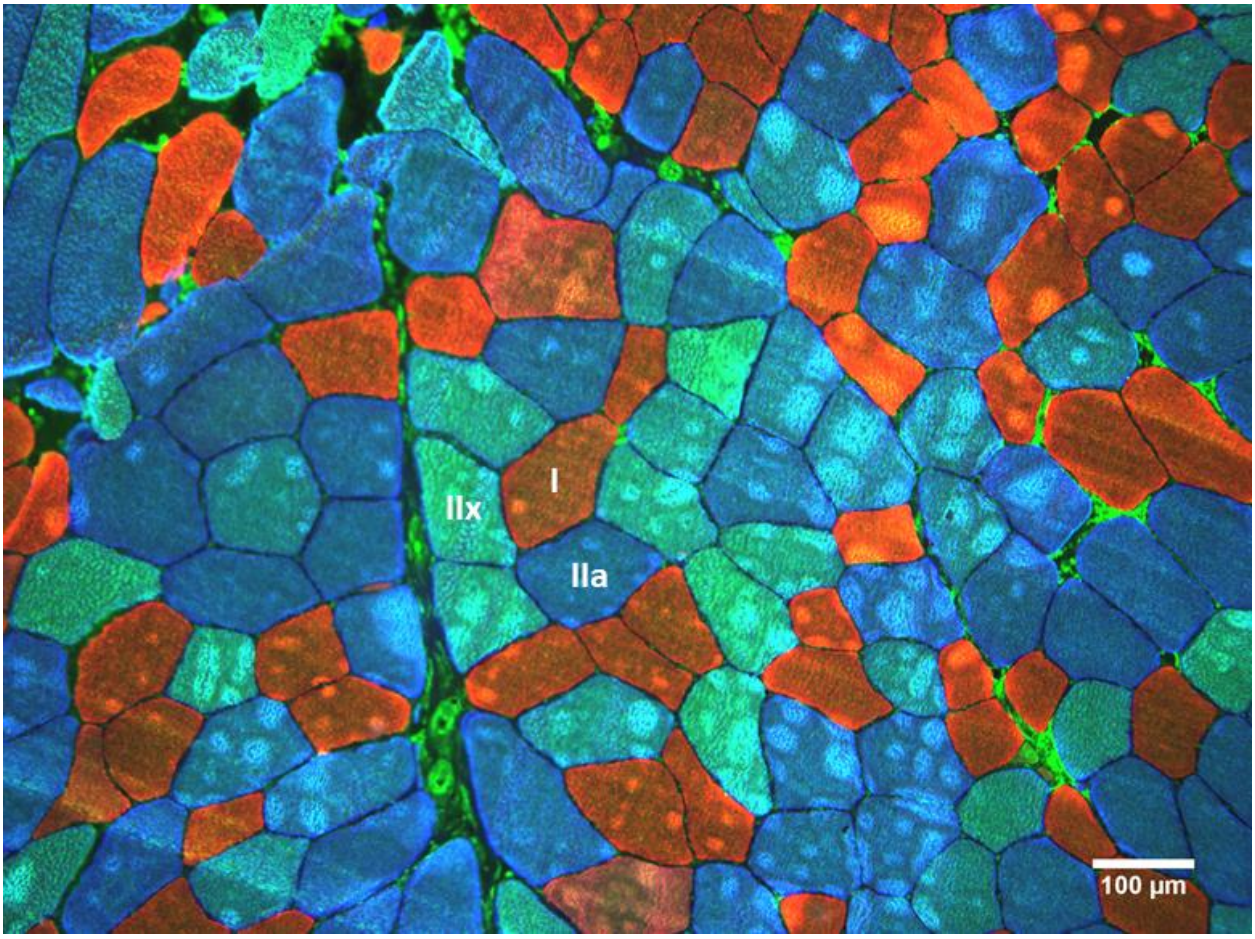

Figure 4.1 Example of histochemical stains for myosin heavy chain (MYH) isoforms: MYH1 (Type IIX; green), MYH2 (Type IIA; blue), and MYH7 (Type I; red). Scale= 100µm.

Prior to immunoblot processing, a small piece of tissue was removed from -80°C storage and kept on dry ice. Muscle homogenates were prepared by separating 25-50mg of muscle into a solution consisting of 500 µl 0.25M sucrose, 20mM HEPES buffer, and protease inhibitors (Halt Protease Inhibitor Cocktail Kit; Pierce, Rockford, IL). This solution was then homogenized with 2-3 fifteen second bursts of a homogenizer (Pellet Pestle Motor; Kontes, Vineland, NJ) as

previously described (Layne et al., 2011). Antibodies raised against mTOR and AMPK were purchased from Cell Signaling (Danvers, MA, USA) while MYH1 and MYH7 were purchased from Sigma Aldrich (St. Louid, MO, USA). Antibodies for MYH2 were obtained from the DSHB as mentioned above. For mTOR and AMPK analysis, samples containing 10 µg of protein were applied to 3-8% polyacrylamide gradient gels for immunoblotting, while 5 µg of protein were used for MYH1, MYH2, and MYH7. Following one hour of electrophoresis at 150V, each gel was transferred to a polyvinylidene difluoride membrane. This transfer was performed for ninety minutes at 80V. Each immunoblot was blocked in 5% nonfat dry milk for two hours prior to overnight incubation in the primary antibody. The following day, appropriate secondary antibodies were used at 1:5000 dilution for two hours prior to chemiluminescent imaging. Each of the samples were run in duplicate and the pre-and-post samples for each subject were run on the same gel (Figure 2). The odd numbered lanes on each gel contained the pre-samples while the next even numbered lane contained the post samples for each respective subject.

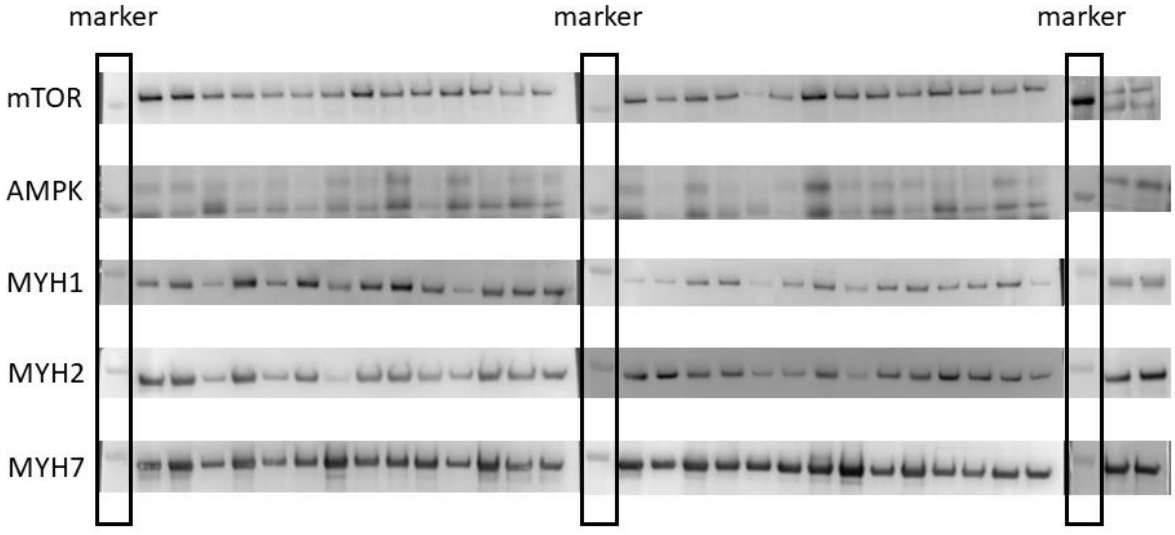

Figure 4.2 Immunoblots for mammalian target of rapamycin (mTOR), adenosine monophosphate kinase (AMPK), and the myosin heavy chain (MYH) isoforms: MYH1, MYH2, and MYH7. Immunoblots were performed with a marker in the first lane, followed by the first subject's pre-value and their post-value. This was repeated for all subjects and proteins.

Ultrasonography

Anatomical cross-sectional area (ACSA) and muscle thickness (MT) of the right leg, mid-vastus lateralis (VL) was assessed using ultrasonography (LOGIQ P6, General Electric Healthcare, Wauwatosa, WI) on each subject before and after the intervention. Ultrasonography was performed 48-72 hours following the most recent training session to ensure minimal alterations due to muscle swelling (Damas et al., 2016). Prior to measurement, each subject's hydration status was determined using refractometry (Atago, Tokyo, Japan) to ensure level of hydration would not affect the ultrasonography measures. Each subject began the ultrasonography session by lying on their left side with an internal knee angle of 170 $\pm$ 5°. To determine measurement site, landmarks were found and marked at the greater trochanter and lateral epicondyle of the femur. The length between these landmarks was the femur length, and 50% of this length was marked and used as the measurement site. Additionally, another marking was placed 5 cm medial to the 50% femur mark for MT measurement. The athlete's femur length was recorded and used for subsequent testing sessions to ensure proper placement of the probe. Additionally, probe placement and orientation were verified by comparing adipose and connective tissue markings from previous images to the current image.

Following application of a water-soluble transmission gel, a 16 Hz ultrasonography probe was oriented perpendicular to the VL at 50% femur length. ACSA Images were obtained using a panoramic sweep in the transverse plane of the VL using the LOGIQView function of the

ultrasound device. For MT, the probe was oriented 5 cm medial to the mid-femur marking parallel with the VL. Utmost care was given to not depress the skin or tissues during measurement. Vastus lateralis ACSA was measured by tracing the inter-muscular interface in the cross-sectional images and MT was measured as the distance between subcutaneous adipose tissue-muscle interface and inter-muscular interface. Three images were taken for each subject and were analyzed on the ultrasonography instrument. Nearly perfect reliability was observed using intraclass correlation coefficient (ACSA ICC = 0.99, CV = 1.75%; MT ICC = 1.00, CV = 0.77%), therefore, the three images were averaged together for statistical analysis.

Statistical Analysis

Data were assessed for normality using a Shapiro-Wilks test and for homogeneity of variance using a Levene's test. A 2x2 (group x time) mixed design analysis of variance (ANOVA) was used to examine main effects for each of the variables derived from the muscle biopsy samples and ultrasonography. Statistically significant main effects were further examined using a Bonferroni-Holm post-hoc adjustment. Effect size using Hedge's *g* with 90% confidence intervals (CI) was calculated for each pre-post variable for both within-group and between-group effects. Effect size values of 0.0, 0.2, 0.6, 1.2, 2.0, and 4.0 were interpreted as trivial, small, moderate, large, very large, and nearly perfect, respectively (Hopkins et al., 2009). The alpha level before post-hoc adjustments was set as $p \leq 0.05$. Statistical analyses were performed on a commercially available statistics software (JASP version 0.8.1.1) and Microsoft Excel 2016 (Microsoft Corporation, Redmond, WA, USA).

Results

For measurement of muscle size, Type I CSA, Type II CSA, and MT each resulted in statistically significant main effects for time ($p < 0.001$), while there was a statistically

significant interaction effect for ACSA (p = 0.046). There were no between-group differences at pre- or post for ACSA; however, post-hoc tests revealed statistically significant increases for the RI_{SR} group in Type I CSA (p = 0.018), Type II CSA (p = 0.012), ACSA (p = 0.002), and MT (p < 0.001). With the exception of MT (p = 0.003), none of these measurements reached statistical significance for the RM group (p > 0.05) (Figures 3 and 4). However, effect sizes for muscle size measurements revealed small-large effect sizes for the RI_{SR} group and small-moderate changes for the RM group. Between-group effect sizes favored the RI_{SR} group with small-moderate effect magnitudes (Table 1).

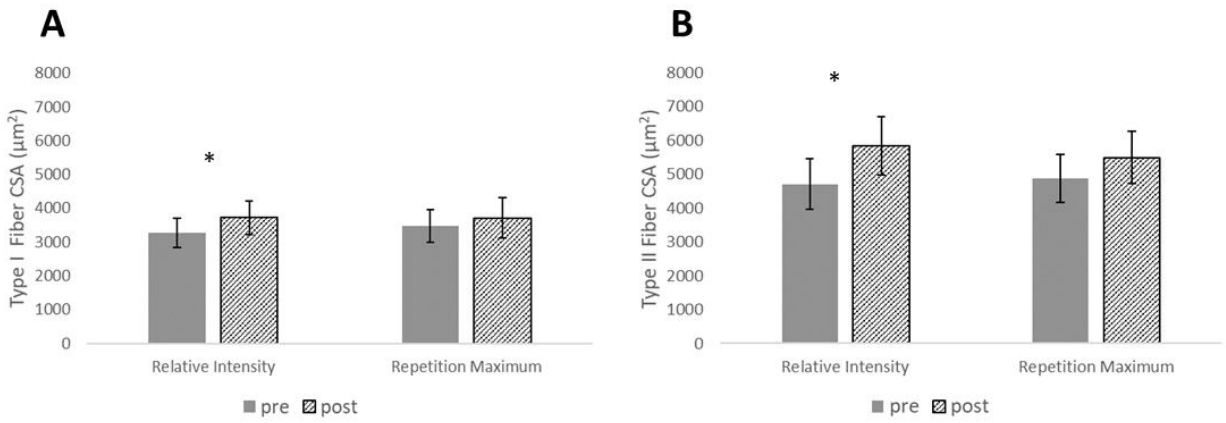

Figure 4.3 Changes in A) Type I and B) Type II cross-sectional area (CSA) pre-to-post intervention. *denotes significance for relative intensity group, $p \leq 0.05$.

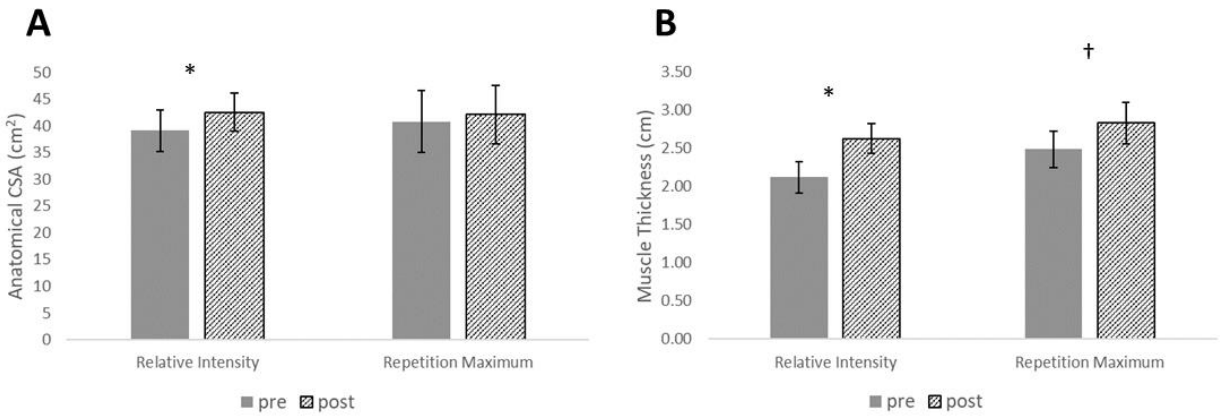

Figure 4.4 Changes in A) anatomical cross-sectional area (ACSA) and B) muscle thickness measured by ultrasonography pre-to-post intervention. *denotes significance for relative intensity group, $p \leq 0.05$. † denotes significance for RM group, $p \leq 0.05$.

Basal levels of mTOR decreased from pre-to-post, indicated by a statistically significant main effect for time ($p = 0.007$). Post-hoc tests revealed a statistically significant decrease in mTOR for the RI_{SR} group ($p = 0.031$) but not for the RM group ($p = 0.08$). No statistically significant main effects for time were observed for AMPK ($p = 0.792$), MYH1 ($p = 0.072$), MYH2 ($p = 0.055$), or MYH7 ($p = 0.090$) (Figure 5). Effect size statistics for the RI_{SR} group suggested a large decrease in mTOR, trivial changes in AMPK, and moderate increases for MYH1, MYH2, and MYH7. For the RM group, moderate decreases in mTOR were observed, no change in AMPK, and small increases in each of the myosin heavy chains. Between-group effect sizes again favored the RI_{SR} group for each of the myosin heavy chains with effect magnitudes ranging from small-moderate. mTOR and AMPK each had trivial between-group effects (Table 1).

Table 4.1 Effect size using Hedge's *g* and 90% Confidence Intervals for within-group and between-group effects

	Relative Intensity Effects			Repetition Maximum Effects			Between Group Effects
Variable	*g* ± CI	pre ± SD	post ± SD	*g* ± CI	pre ± SD	post ± SD	*g* ± CI
Type I CSA (μm^2)	0.56±0.34	3,277±692	3,720±793	0.26±0.28	3,470±789	3713±974	0.48±0.83
Type II CSA (μm^2)	0.81±0.44	4709±1,195	5,839±1,399	0.49±0.54	4,883±1,137	5,493±1,241	0.50±0.83
ACSA (cm^2)	0.53±0.20	39.10±6.25	42.53±5.76	0.14±0.14	40.77±9.22	42.09±8.75	1.03±0.83
MT (cm^2)	1.47±0.48	2.12±0.33	3.62±0.32	0.80±0.34	2.48±0.38	2.83±0.43	0.72±0.83
mTOR (AU)	-1.40±0.97	0.00	-0.22±0.21	-0.97±0.89	0.00	-0.23±0.33	0.02±0.82
AMPK (AU)	-0.19±0.97	0.00	-0.10±0.70	-0.01±0.89	0.00	-0.01±0.81	-0.11±0.83
MYH1 (AU)	0.93±0.97	0.00	1.22±1.74	0.44±0.90	0.00	0.61±1.85	0.31±0.83
MYH2 (AU)	0.96±0.97	0.00	1.70±2.34	0.24±0.90	0.00	0.13±0.70	0.87±0.86
MYH7 (AU)	0.78±0.97	0.00	0.50±0.85	0.37±0.90	0.00	0.10±0.36	0.59±0.85

**g*= Hedge's *g* effect size, CI= 90% confidence interval, SD= standard deviation, CSA= cross-sectional area, ACSA= anatomical cross-sectional area, MT= muscle thickness, mTOR= mammalian target of rapamycin, AMPK= adenosine monophosphate protein kinase, MYH= myosin heavy chain

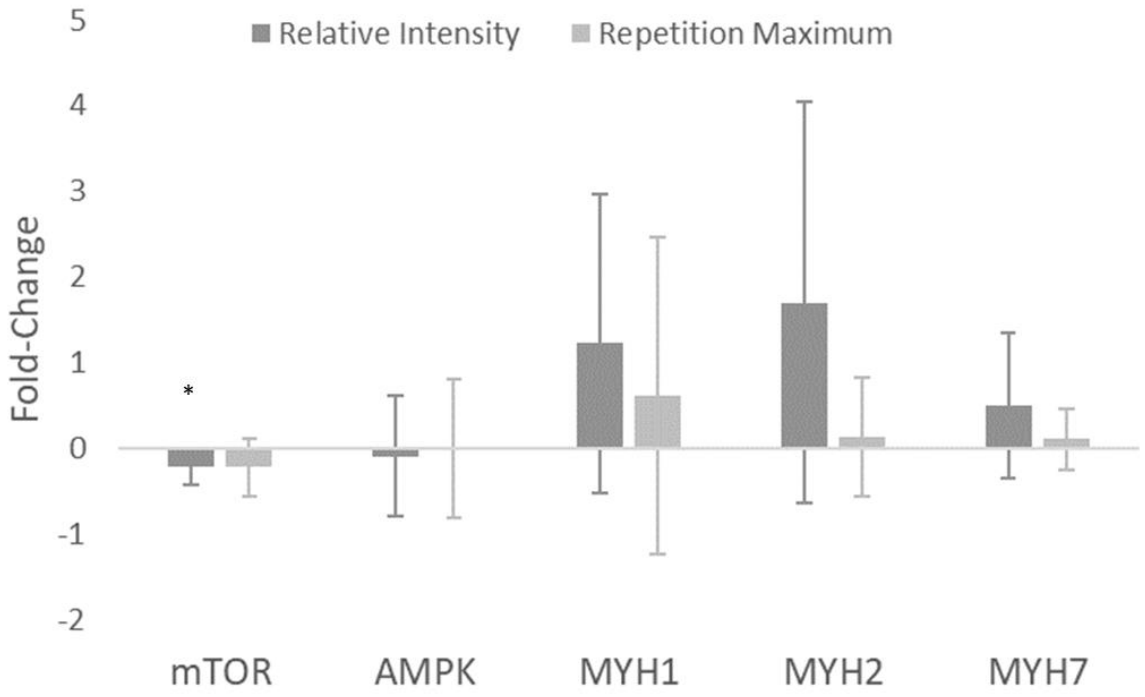

Figure 4.5 Fold-change results from immunoblotting for mammalian target of rapamycin (mTOR), adenosine monophosphate kinase (AMPK), and the myosin heavy chain (MYH) isoforms: MYH1, MYH2, and MYH7. *denotes significance for relative intensity group, $p \leq 0.05$.

Discussion

The main purpose of this study was to compare the skeletal muscle physiological alterations following either a relative intensity or repetition maximum program. In agreement with our hypothesis, the results of our investigation indicate that RI_{SR} training was superior to RM training for measures of whole muscle size, fiber size, and yielded greater increases in key myofibrillar proteins. Both groups trained using the same periodization scheme with no statistical differences in volume load (Part 1), yet the results convincingly favored the RI_{SR} group. We propose that a major contributor to the result was superior fatigue management in the

RI_{SR} group. Consistent training to failure in the RM group possibly led to a reduced ability to adapt in our well-trained sample.

Hypertrophic adaptations at both the whole muscle and single fiber level favored the RI_{SR} over RM training group evidenced by the small-to-moderate between-group effect magnitudes (g = 0.48 – 1.03). Higher volume loads have been associated with greater increases in muscle size (Schoenfeld, 2010), yet even with similar volume loads (Part 1) the RI group resulted in superior size gains. This is possibly due to a lack of recovery allowed by virtue of consistently training to failure in the RM group, rather than insufficient stimuli. In support of this, Moran-Navarro et al. (2017) recently demonstrated that performing bench press and back squats to failure delays recovery of neuromuscular performance by up to 24-48 hours post-exercise (Moran-Navarro et al., 2017). Further, the greater hypertrophy in the RI_{SR} group supports the use of a broader loading spectrum (e.g. heavy-and-light days, down sets) within a training week. Indeed, there is a paucity of data in well-trained individuals comparing the RI_{SR} and RM. Thus, to our knowledge this study is the first to demonstrate the superiority of RI_{SR} compared to RM for muscle hypertrophy in strength-trained subjects.

Small-to-moderate between-group effect magnitudes supported the RI_{SR} group for MYH1 (g = 0.31), MYH2 (g = 0.87), MYH7 (g = 0.59). Although statistical significance (p-value) was not attained for any MYH isoform, the effect magnitudes support the RI_{SR} group. The accretion of myofibrillar proteins is an important component of muscular performance (Pette & Staron, 2000; Reiser et al., 1985). The greater enhancements in MYH isoforms in the RI_{SR} group may provide information to why the RI_{SR} group also improved muscular performance more so than the RM group (Part 1). Conversely, the RM group's lesser accretion of MYHs could be due to the increased fatigue and delayed recovery associated with RT to failure. As previous research

has demonstrated failure training to induce greater levels of fatigue compared to non-failure training (Moran-Navarro et al., 2017), which may impact the ability for meaningful accretion of myofibrillar proteins. MYH1 and MYH2 showed greater increases for both groups compared to MYH7, with the former being expressed in Type IIX and Type IIA muscle fibers, respectively. This suggests the RT stimulus, particularly in the RI_{SR} group, may have selectively enhanced production of faster isoforms of MYH. Although beyond the scope of the current study, tapering has been shown to produce an increase in fast MYH expression (Luden et al., 2010; Murach et al., 2014). Thus, the taper performed by both groups during the last training phase may have influenced these alterations.

Alterations in the signaling proteins of interest were somewhat small in magnitude compared to MYH (Figure 5). However, there was a large, statistically significant decrease in mTOR in the RI_{SR} group (g = -1.40), and a moderate, non-statistically significant decrease for the RM group (g = -0.97). These decreases are interesting and oppose our hypothesis, as intuitively there would be an increase in mTOR given its role in protein synthesis. However, most research examines mTOR alterations within an acute exercise window (i.e. 0-72 hours post-exercise) and usually measures the level of mTOR (or its targets) activation (Ahtiainen et al., 2015; Atherton et al., 2005; Coffey et al., 2006; Dreyer et al., 2010). Research is sparse examining the changes in basal total mTOR following RT interventions (Layne et al., 2011). Additionally, acute mTOR increases are suppressed following repeated RT stimuli (Ogasawara et al., 2013). This suggests the decreases in basal mTOR in the current study may have been a result of a molecular adaptation. Additionally, there are various other, potentially mTOR-independent, mechanisms by which protein translation may be initiated such as via the costamere and focal adhesion kinase (Klossner, Durieux, Freyssenet, & Flueck, 2009). Although mTOR is a

critical protein for cellular growth, it is also important note that there are many interacting and competing signals within the *in vivo* environment of a skeletal muscle cell (N. J. Hoffman et al., 2015; Potts et al., 2017). The combinations of these signals are likely the ultimate contributor to fiber and whole-muscle hypertrophy.

No significant changes were observed for basal AMPK levels in either the RI_{SR} (g = -0.19) or the RM (g = -0.01) groups. Resistance exercise and electrical muscle stimulation have been shown to increase the activation of AMPK (Ahtiainen et al., 2015; Atherton et al., 2005). As AMPK is an energy-sensing protein kinase (Coffey & Hawley, 2007), it is selectively activated in times where energy is being depleted, such as during exercise (Dreyer et al., 2006). Our results seem to support this, as muscle specimens were collected under resting conditions. However, acute AMPK activation may be an avenue for future research comparing RM to RI_{SR} training strategies. Indeed, it is possible that RM training yielded stronger immediately post-exercise AMPK responses, possibly impacting the mTOR signaling pathway and ultimately protein synthesis (Nader, 2006).

Conclusion

Our results demonstrated a superior effect for fiber and whole-muscle CSA following RI_{SR} compared to RM training in well-trained males. Along with superior muscle hypertrophy, the RI_{SR} group increased the content of several key MYH isoforms to a greater extent than the RM group, which may be explained by the superior workload distribution in the RI_{SR} group through the use of heavy and light training and non-failure training sessions. These results, taken together with the performance results (Part 1), support the use of RI_{SR} training in well-trained populations.

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Conflict of Interest

The authors of this manuscript have no conflicts of interest.

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CHAPTER 5

SUMMARY AND FUTURE DIRECTIONS

The purposes of this dissertation were: 1) to compare RM (failure) to RI (non-failure) training prescriptions on training load, vertical jump, and maximal strength characteristics in well-trained lifters; and 2) to compare skeletal muscle physiological outcomes between a RM (failure) or RI (non-failure) RT program. Specifically, to examine intramuscular protein accretion, muscle fiber cross-sectional area, and ultrasonography muscle size. Our results demonstrated that RI_{SR} training resulted in consistently greater improvements in vertical jump, RFD and maximal strength compared RM training, which may partly be explained by the differences in the distribution of RT workload and the use of failure/non-failure training. Although RM training resulted in an increase in maximal strength, the obvious impairments to vertical jump and early RFD performance bring into question the efficacy of monotonous training and training to failure in populations where optimal performance enhancement is the goal, such as in competitive athletes. Additionally, this study has demonstrated a superior effect for fiber and whole-muscle CSA following RI_{SR} compared to RM training in well-trained males. Along with superior muscle hypertrophy, the RI_{SR} group increased the content of several key MYH isoforms to a greater extent than the RM group, which may be explained by the superior workload distribution in the RI_{SR} group through the use of heavy-and-light training and non-failure training sessions. These results, taken together with the performance results support the use of RI_{SR} training in well-trained populations.

Future investigations should examine these results over longer training periods and in different sets of populations. Additionally, a more thorough analysis of the intracellular protein

network is warranted. Although the results of our selected proteins yielded interesting results, there are thousands of other proteins in the muscle sample which may provide meaningful information regarding the divergent responses observed in our investigation.

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