EFFECT OF TIME-UNDER-TENSION DURING RESISTANCE EXERCISE ON AUTONOMIC, NEUROMUSCULAR, AND PERCEIVED MEASURES OF FATIGUE AND RECOVERY: A CROSS-OVER STUDY

by

JACOB EISENREICH ERICKSON

(Under the Direction of Michael D. Schmidt)

ABSTRACT

Participation in exercise has long been recommended to improve health outcomes and overall quality of life. Resistance training (RT) is a mode of exercise shown to improve muscular endurance, muscular strength, and muscular hypertrophy. A great deal of research has been conducted assessing RT prescription as well as the recovery necessary between RT bouts. Measures of autonomic recovery, neuromuscular recovery, and perceived recovery are among the most common methods of recovery assessment.

The first portion of this study assessed whether acute RT sessions with differing time-under tension (TUT) influence autonomic function recovery over a 48-hour period as indicated by RMSSD, LF, HF, and LF/HF ratio in resistance-trained males. Results showed that significant differences in internal load did not lead to significant differences in heart rate variability (HRV) when comparing the two exercise sessions. In addition, there were significant decreases in LnRMSSD from baseline to immediately-post, but no difference was seen between exercise sessions. Furthermore, LnRMSSD was not significant from baseline measures by 24-hours after the RT bout.

The second portion of this study aimed to assess the agreement between alternative non-invasive measures of recovery (RMSSD, perceptual fatigue and energy, perceived recovery and soreness, and neuromuscular fatigue) up to 48-hours after acute bouts of RT at differing TUT. Results from this study showed that the higher volume session resulted in multiple recovery markers being significantly different from baseline after 24-hours and others that were significantly different after 48-hours post-exercise. In contrast, the lower volume session also had recovery markers that were significantly different from baseline, but no significant differences were seen after that. A primary finding of this study is that many of the recovery markers recovered at different time-points, and some never fully recovered with the 48-hour follow-up period. Therefore, one recovery marker may not be sufficient to illustrate the recovery status of the body as a whole. Overall, future research should focus on the impact of different RT variables on HRV metrics and individual systems within the body to improve exercise prescription and the recovery required between RT bouts.

INDEX WORDS: Heart rate variability, resistance exercise, time-under-tension, fatigue, perceived exertion

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by

JACOB EISENREICH ERICKSON

B.S., Minnesota State University Moorhead, 2012

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JACOB EISENREICH ERICKSON

Major Professor:	Michael D. Schmidt
Committee:	Nathan T. Jenkins Robert C. Lynall Patrick J. O'Connor

Electronic Version Approved:

Ron Walcott
Vice Provost for Graduate Education and Dean of the Graduate School
The University of Georgia
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DEDICATION

I dedicate this dissertation to my family. Your continued support is the reason I have achieved all that I have in life.

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CHAPTER 1

INTRODUCTION

1.1 Significance

Regular physical activity and exercise are associated with numerous physical and mental health benefits in men and women. Regarding physical health, exercise and physical activity decrease the risk of developing coronary heart disease, stroke, type 2 diabetes and some forms of cancer. They have also been shown to lower blood pressure, improve lipoprotein profile, C-reactive protein, enhance insulin sensitivity, and play an important role in weight management [1]. From a mental health standpoint, depressive disorders and anxiety can be prevented or improved upon through participation in exercise, and cognitive function, feelings of energy, well-being, and quality of life can also be enhanced [1].

The specific benefits reaped are often dictated by the mode of exercise in which each individual chooses to participate. Resistance training (RT) is a mode of exercise designed to increase strength, power, and muscular endurance [2, 3] and can be completed using multiple types of equipment such as free weights, weight machines, and resistance bands, as well as any other piece of equipment or object that can create external resistance, including the human body. In addition to improving performance measures, a significant amount of evidence has shown correlations between higher levels of muscular fitness and cardiometabolic risk factor profiles, lower risk of all-cause mortality, fewer cardiovascular disease events, lower risk of developing functional limitations, and non-fatal disease, although currently there are insufficient data on the dose-response characteristics between muscular fitness and health outcomes [1]. Nevertheless, there has been a great deal of research conducted on RT prescription focused on the manipulation of RT program variables to achieve optimal performance and health outcomes. These variables include choice of resistance (i.e., intensity), exercise selection and order, number of sets and repetitions, frequency, and rest period length [3].

A crucial factor associated with any exercise program is the recovery needed between exercise sessions. Recovery from RT varies based on the magnitude, duration, and mode of training, with typical mechanical and biochemical restoration occurring within three hours of moderate-intensity RT or 24-96 hours after intense RT where muscular failure is achieved and/or muscle damage has occurred [4]. The ACSM recommends ≥48 hours between RT sessions for any single muscle group [5], though this is a broad recommendation considering the number of variables that can be manipulated within a RT program. The primary goal of monitoring and regulating RT is to more closely match the intended training stress with readiness and recovery to optimize adaptation on an individual basis [6]. Individuals recover from RT at different rates [6] and a lack of recovery has been associated with non-functional overreaching, overtraining, and overtraining syndrome [7].

Non-functional overreaching occurs when the intensification of a training stimulus continues without adequate recovery and regeneration, which can lead to overtraining [8]. Overtraining refers to that point at which an athlete experiences physiological maladaptation and chronic performance decrements [2]. Most symptoms that result from overtraining, collectively referred to as overtraining syndrome, are subjective and identifiable only after the individual's performance and physiological function have suffered [2], although psychological symptoms can occur as a result of overtraining as well. Common symptoms associated with overtraining include change in appetite, weight loss, sleep disturbances, loss of motivation and vigor, lack of mental concentration, feelings of depression, and lack of appreciation for things that are normally enjoyable [2].

Due to the adverse effects which can result from non-functional overreaching and overtraining, it is critical that a non-invasive measure is established that gives a valid and reliable measure of recovery. One measure hypothesized to indicate recovery status is heart rate variability (HRV) [9]. HRV consists of changes in the time intervals between consecutive heartbeats called interbeat intervals and can be expressed using three different types of metrics: time-domain, frequency-domain, and non-linear [10]. Time-domain indices (e.g., root mean square of successive differences (RMSSD)) quantify the amount of HRV observed during specific monitoring periods (e.g., 1-minute). Frequency-domain metrics (e.g., low frequency (LF), high frequency (HF), and low frequency/high frequency ratio (LF/HF)) calculate the absolute or relative amount of signal energy within component bands. Non-linear measurements (e.g., SD1) quantify the unpredictability and complexity of a series of interbeat intervals [10].

Because HRV metrics give an indication as to how the autonomic nervous system responds to sudden physical and psychological challenges [10], recent studies have utilized HRV to assess recovery after RT [11-13]. Specifically, HRV is reflective of sympathetic and parasympathetic modulation, both of which can be impacted by acute

RT [14]. Previous studies have reported that acute RT bouts increase cardiac sympathetic modulation while decreasing cardiac parasympathetic modulation indicating stress on the body [14]. Prolonged stress from regular RT bouts without adequate recovery can lead to overtraining syndrome. However, by monitoring the recovery status of the cardiac autonomic modulation (i.e., HRV), health and fitness professionals could optimize exercise prescription, thereby increasing adaptation and performance, while simultaneously avoiding injuries and overtraining [14].

In addition to HRV, several other markers have been proposed as non-invasive measures to determine recovery after RT [4, 11]. Examples of perceptual markers that have been utilized to assess recovery include perceived recovery and perceived soreness scales [13, 15]. Performance markers, such as vertical jump height, have also been examined, as have grip strength and velocity measures [11]. Finally, biochemical markers, such as testosterone, cortisol, and creatine kinase have also been analyzed [15], but evidence is mixed as to whether these markers are valid and reliable measures of recovery.

The RT variable that has been shown to be most strongly correlated with increased sympathetic modulation and delayed recovery, as illustrated by low HRV measures, is volume. Volume is most commonly expressed as “volume load” and is calculated as repetitions multiplied by external resistance (i.e., reps x weight) [16]. Multiple studies have illustrated that RT sessions utilizing higher volume loads decrease HRV to a greater extent than RT sessions completed with lower volume loads [12, 17], but there is more than one way to calculate the volume of a RT session. Volume determination using time-under-tension (TUT) involves monitoring the time to perform each phase of a repetition including the eccentric, transition, concentric, and resting phases [18]. For example, when completing a repetition with a 1/0/1/0 TUT, the eccentric contraction is one second, there are zero seconds between the eccentric and concentric phases of the repetition, the concentric contraction is one second, and there are zero seconds of rest between repetitions. TUT is a useful variable when creating a RT program as different TUTs have been shown to elicit differing psychological and physiological responses [3, 19, 20].

Multiple TUTs have been utilized in research including 1.5/0/1.5/0, 4/0/1/0, 1/0/4/0 [21], 2/0/2/0, 1/0/1/0/ [22-25], 1/0/5/0, 5/0/1/0, 3/0/3/0, 1/0/1/0 [26], as well as "super slow" tempos such as 10/0/10/0 [27]. Research has shown that eccentric muscle actions require less motor unit activation per specific load, are less metabolically demanding, and are conducive to promoting hypertrophic adaptation yet result in more pronounced delayed onset muscle soreness as compared with concentric actions [3]. Regarding strength gains, faster repetition tempos (i.e., 1/0/1/0) have been shown to be more effective than slower repetition tempos (i.e., 3/0/3/0) [28, 29]. Finally, two effective strategies that have been utilized to improve muscular endurance via prolonged set durations include utilizing a moderate repetition number using an intentionally slow velocity or a high repetition number using moderate to fast velocities [3]. In either case, increasing the TUT with sufficient loading can increase muscular fatigue [30], and fatigue is important to eliciting muscular endurance enhancement [3].

To further our exercise prescription knowledge, it is critical to evaluate the effect of differing TUTs on recovery time and to identify sensitive, but non-invasive, measures of recovery status. To date, multiple studies have been conducted assessing specific RT volume loads and their relationships to various measures of recovery [11, 13, 31]. Holmes et al. [11] compared measures of HRV, lactate, IL-6, handgrip strength, countermovement jump, and mean propulsive velocity at baseline and post a moderate load RT session. Their results showed that the magnitude of change and full recovery of training load variables, such as neuromuscular performance and fatigue biomarkers, may differ greatly from HRV patterns. Flatt et al. compared measures of HRV, countermovement jump, squat and bench press velocity, and perceived soreness and recovery for 48-hours after a high-volume exercise protocol and once again found that health professionals should be specific with their post-RT recovery testing and not use the status of a given physiological system (e.g., cardiac-autonomic) to infer the status of another (e.g., neuromuscular or perceived psychological). They also stated that each of these appear to be independent recovery markers that may offer unique strengths offering information on differing aspects of post-RT recovery and adaptation [13]. Lastly, Thamm et al. compared resistance exercise sessions with two different volume loads and assessed HRV, lactate, serum creatine kinase, and muscle pain pre- and post-48-hours after each session. They too found no associations between HRV or any of the other recovery markers [31].

Due to the lack of evidence establishing a valid, reliable, and accurate measure of recovery, more research must be conducted to close the gap in the literature.

To date, each study comparing volume load to recovery measures found that HRV was most affected by higher volumes, but only in the traditional measure of volume (i.e., repetitions x external resistance). To our knowledge, no studies have been conducted assessing the effect of volume expressed as TUT on measures of HRV, perceptual, and neuromuscular measures of recovery. In addition, there is a lack of evidence as to whether there is a relationship between HRV, perceptual, and neuromuscular measures of recovery when RT with different TUT.

1.2 Specific Aims

Study 1

Primary Aim: To assess whether acute RT sessions with differing TUT, but identical exercise order, sets, reps, weight, and rest intervals influence autonomic function over a 48-hour period as indicated by RMSSD, LFnu, HFnu, and LF/HF ratio in resistance-trained males.

Hypothesis: The exercise session with the longest TUT (4/0/4/0), and therefore greatest volume, will decrease RMSSD and HF while increasing LF/HF ratio and LF to a greater extent than the lower volume session (1/0/1/0), but all HRV indices will recover back to baseline within 24-hours post-exercise after both sessions.

Study 2

Primary Aim: To assess the agreement between alternative non-invasive measures of physiological recovery (RMSSD, perceptual fatigue and energy, soreness, subjective recovery, and neuromuscular fatigue) up to 48-hours after acute bouts of RT at differing TUT.

Hypothesis: The higher volume exercise session (SLOW) will lead to greater increases in fatigue for all measures assessed when compared to the lower volume session (FAST). In addition, each measure of recovery will recover at different time-points.

1.3 Public Health Significance

There is significant variability in the tempo that individuals perform RT exercises, and it is unclear how these differences in tempo influence recovery times. This is an important gap in knowledge since inadequate recovery can lead to overtraining syndrome. By understanding the impact TUT has on physiological and psychological stress within the human body, health and fitness professionals can better assess recovery, and as a result manipulate exercise program variables to optimize performance and health outcomes while minimizing injuries and overtraining. An overarching goal in this area would be to find a single, quick, non-invasive measure of recovery that could be used in any setting to provide feedback regarding recovery status and assist individuals in avoiding overtraining.

1.4 Limitations

One limitation of this study was the use of weight machines, each of which had a weight stack with a maximal amount of weight that could be utilized. Thus, the research team utilized a one-repetition maximum equation if the participant could successfully lift the maximum amount of weight for more than one repetition. Although validated, this equation could estimate a different one-repetition maximum than what may be seen if a true one-repetition maximum was found. This study was conducted in a small sample of resistance-trained male participants of similar age, so the results of this study may not apply to dissimilar populations. Lastly, the exercise protocol utilized a small number of exercises and may not be generalizable to other forms of resistance exercise equipment or different exercise types.

1.5 Delimitations

The current study was delimited to male subjects who were resistance-trained and had completed exercises working the same muscles utilized in the study at least once a week for the previous six months directly preceding the study. Subjects had to be between the ages of 18-40 years old and not taking medications, drugs, or supplements that could alter cardiovascular responses to exercise. They could not have any current cardiovascular, metabolic, or renal disease signs or symptoms, any cardiac arrythmias, or any physical limitations, health problems, or musculoskeletal injuries/disorders that would hinder them from completing the exercise protocol required. Additionally, the findings of this study may only apply to the exercises and measures used in this study.

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CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This review of literature will discuss resistance exercise prescription, volume calculations, time-under-tension (TUT), heart rate variability (HRV), and perceptual and neuromuscular measures of energy and fatigue, as well as how each of these content areas are related to recovery. A great deal of literature has attempted to establish a valid, reliable, and accurate method of assessing recovery utilizing various autonomic, neuromuscular, and perceived markers after a bout of resistance exercise, but research has yet to agree on which measure of recovery is best [1, 2]. Furthermore, each of the body's systems often influence one another, making the process of establishing a gold-standard for recovery complex. Finally, there are a large number of variables that can be manipulated within a resistance exercise program and influence recovery characteristics, further compounding the issue.

2.2 Resistance Training

Resistance training (RT) is a mode of exercise designed to increase strength, power, and muscular endurance and is a critical component to every exercise program [3, 4]. To meet the needs of the general population, the American College of Sports Medicine (ACSM) has created RT recommendations using the "FITT-VP" (frequency, intensity, time, type, volume, and progression) principles [5]. Frequency refers to how often an individual exercises and is most often expressed in the number of days per week exercise is completed (e.g., 2-3 days per week). Intensity is most commonly expressed as a percentage of one-repetition maximum (e.g., 50% of one-repetition maximum), but terms such as “very light-intensity”, “light-intensity”, “moderate-intensity”, and “vigorous-intensity” are also used. Time is prescribed as a measure of the amount of time exercise is performed (e.g., time per session, per day, and per week), but the ACSM gives no specific time recommendation for RT programs. Type refers to the mode of exercise being completed such as RT involving each major muscle group, multi-joint or single-joint exercises, or the type of RT equipment being utilized. The ACSM calculates volume as a product of sets, repetitions, and intensity [5]. Finally, progression can be accomplished in a variety of ways, but the most common approach is increasing the amount of resistance lifted during training [5].

2.3 Time-Under-Tension and Recovery

Training volume and intensity are the most important variables in RT program design [6]. Volume load is most commonly calculated as “repetitions x external load” but can be calculated as the cumulative time that a muscle group is under tension or contraction during a training session, which is referred to as TUT [7]. When training load (e.g., repetitions x external load) is equated, the major determinant of muscle fatigue is TUT. This is attributable to the fatigue mechanisms in the muscle contractile components which result in a reduction in the force generating capacity of the muscle [7].

Mazetti et al. [8] revealed slow RT as the most fatiguing method when compared to a faster RT tempo, possibly due to increased levels of lactate production interfering with the mechanics of muscle contraction. This is important as the fatigue from a longer TUT might prompt hormonal and metabolic changes that are crucial for acute and chronic adaptation like hypertrophy and strength gain [9]. In addition, repetitions performed with a slower tempo, and therefore longer TUT, may need to be completed with a lower intensity (e.g., <50% 1RM) [6] which may be beneficial for those with the goal of hypertrophy, but not for those who have the goal of increasing muscular power [10]. Finally, utilizing a longer TUT may be beneficial for individuals wanting to expend less energy during RT as research has shown faster contractions expend more energy [8]. TUT impacts training volume and, consequently, the level of post-exercise muscular fatigue and adaptation patterns. The effect of a stronger training stimulus as a result of the slower repetition tempo can be observed even if the slower tempo leads to a decline in RT volume computed in the traditional sense (i.e., repetitions x external load) [10].

Perceived exertion may also be affected by TUT as evidenced by a study conducted by Hatfield et al. [11] that compared the rating of perceived exertion (RPE) of a RT bout with a very slow velocity to that of a self-selected velocity. In this study, each individual completed one session with a 10/0/10/10 tempo while the other session consisted of the individual being able to self-select the movement velocity they would utilize during their normal training days. Both exercise sessions utilized the shoulder press and squat, and the results of the study illustrated that the very slow session led to a significantly higher RPE than the session performed with a self-selected tempo.

Overall, fatigue can be assessed using both subjective and objective measures. Proposed subjective methods of assessing fatigue resulting from RT include perceived soreness scales [12-15], perceived recovery scales [13], and perceived energy and fatigue scales [16-18]. In contrast, objective measures such as measures of neuromuscular fatigue [19-21] and neurocardiac function [1, 2, 22-56] have also been proposed. To date, most research has analyzed these measures separately, but a select few have made an effort to gather a better understanding as to whether each of these are related and if they can be utilized to assess overall recovery [1, 2, 57].

Volume and Time-Under-Tension

Volume is considered to be one of the most important RT variables, especially in regard to hypertrophic adaptations as well as improvements in force generation [58] and can be calculated in a variety of ways. Volume expressed as “volume load” (repetitions x external load) has been used to monitor athletes and to equate resistance exercise volumes between experimental conditions [59]. As previously stated, volume is most commonly calculated in this fashion with the assumption that all repetitions are performed through the same range of motion [7]. The maximum dynamic strength volume load method (repetitions [no.] x [body mass - shank mass (kg) + external load (kg)] gives researchers and practitioners a way to quantify volume during resistance exercise when no external load is present. The shank mass refers to the lower legs and feet, which is approximately 12% of body mass [60]. The total work method (force [N] x displacement [m]) has also been used to quantify resistance exercise volume. This method accounts for the actual force exerted and displacement of the center of mass or barbell during the exercise [59]. However, training volume can also be calculated as the cumulative time that a muscle group is under tension or contraction during a training session, referred to as TUT [7, 59]. TUT refers to the cadence at which each repetition is performed [10]. Changes in TUT can result from the effect of the external resistance, with an increase in the external load leading to a decline in maximal movement speed in the concentric phase or conscious control of individual movement cadences [61].

Cadence is most often defined by means of several digits which correspond to particular movement phases. For example, 4/0/2/0 denotes a 4-second eccentric phase, no break in the transition phase, a 2-second concentric phase, and no rest before the next repetition [10]. Research has shown that consciously manipulating the TUT of each repetition or set of repetitions may impact neuromuscular adaptations [58, 62], perceived exertion [63], hormonal [62, 64, 65], and metabolic [62] responses.

It is suggested that mechanical stimuli are essential and represent the major determinant of RT adaptation. Changes in the mechanical stimulus generated by different TUT and the number of muscle contractions may influence the production of force. Muscle strength depends on the central nervous system and the modulation between recruitment and the frequency of motor unit activation [66]. For this reason, some middle-high intensity RT exercises with different concentric and eccentric duration times have been introduced [6]. Recent studies indicate that low-intensity RT induces muscle strength and hypertrophy when performed at slow velocity [6]. Tanmito and Ishii conducted a study assessing the effect of low-intensity resistance exercise with slow movement and tonic force generation on muscular function in young men [67]. These authors utilized three experimental groups with eight participants each. The protocols consisted of a 3/0/3/1 tempo with 50% of one-repetition maximum (1RM), 80% 1RM at a 1/0/1/1 tempo, and 50% 1RM with a 1/0/1/1 tempo. Their results reported that slow RT with low-intensity showed similar increases in strength and hypertrophy as the high-intensity group [67]. In contrast, Munn et al. [68] assessed whether number of sets or TUT produced the greatest increases in strength utilizing one and three set protocols, and 1/0/1/0/ and 3/0/3/0 TUT. After six weeks of training, the group training at fast speeds had greater strength gains than the group training at slow speeds. However, the effect of repetition velocity on strength was smaller than the effect the number of sets had on strength gains.

When focusing purely on TUT, it appears that training at moderate velocities produces the greatest strength increases across all testing velocities [69]. Compared with slow velocities, moderate (1/0/2/0) and fast (<1/0/1/0) velocities have been shown to be more effective for enhanced muscular performance capacities (e.g., number of repetitions performed, work and power output, and volume) [70, 71] and for increasing the rate of strength gains [72]. Keeler et al. [73] showed that traditional velocity (e.g., 4/0/2/0) RT produced significantly greater strength increases over 10 weeks than super slow (5/0/10/0) training in five of eight exercises trained. However, a study by Neils et al. [74] showed statistically similar increases in strength between super slow (5/0/10/0) and traditional velocity (4/0/2/0) training when assessing 1RM on the squat and bench press exercises after eight weeks of RT.

Less is known concerning the effect of repetition velocity on hypertrophy [4]. One study was able to illustrate that fast (1/0/1/0) and moderate to slow (3/0/3/0) velocities of training produced similar changes in elbow flexor girth after 6 weeks of RT in untrained individuals [68]. In contrast, Mohamad et al. [75] found that when low-load, high-velocity and high-load, low-velocity schemes were equated by volume, utilizing a lighter load and higher velocity resulted in kinematics more beneficial to increases in hypertrophy. More recently, Costa et al. [76] conducted a study which assessed hypertrophy and strength of the pectoralis major and triceps brachii muscles after 10 weeks of RT in two groups. The two protocols utilized were 1.5/0/1.5/0 for 12 repetitions and 3/0/3/0 for six repetitions to ensure overall TUT was equal between them. To further equate the protocols, the intensity, frequency, rest between sets, and number of sets were identical. The results of the study showed that both protocols produced similar increases in cross-sectional area and strength of each muscle group [76].

In regards to muscular endurance, it seems that the type of RT dictates the TUT that should be utilized for improvements in muscular endurance [4]. Studies examining isokinetic exercise have shown that a fast-training velocity was more effective than a slow-training velocity for improving muscular endurance [77, 78]. In contrast, both fast and slow velocities are equally effective for improving muscular endurance during dynamic constant RT [4]. Increasing the TUT with sufficient loading can increase muscular fatigue, and fatigue is important to improvements in muscular endurance [58]. This was illustrated by Tran et al. [58], who compared three sets of 10 repetitions at a 5/0/5/0 tempo, 10 repetitions at a 2/0/2/0 tempo, and 5 repetitions at a 4/0/10/0 tempo and reported that the highest volume load and TUT resulted in the largest magnitude of peripheral fatigue, which would lead to greater improvements in endurance. To conclude, there have been multiple studies conducted assessing TUT and its effect on muscular strength, hypertrophy, and endurance, but evidence is mixed as to which TUT is most effective for each of these goals.

2.4 Measures of Recovery from Resistance Training

Recovery

The manipulation of various RT variables (exercise type and order, loading, number of repetitions and sets, rest durations, and TUT) determines the acute responses of the neural, endocrine, and musculoskeletal systems, which have pivotal influences on the magnitude of long-term training adaptation [79]. To ensure these adaptations are gained, adequate recovery is needed between RT bouts. The term recovery is often contextual in nature and typically pertains to either physiological, subjective, or performance-based measures [80]. Specifically, autonomic recovery refers to HRV features representative of parasympathetic activity, which are usually reported in literature as high frequency power and the root mean square of successive RR differences (RMSSD) [81]. From a practical perspective, neuromuscular recovery is defined as the ability to meet or exceed performance in a particular activity [82]. Lastly, perceptual recovery can be defined in a variety of ways, but based on a commonly utilized perceived recovery scale, perceived recovery refers to a numerical value relating to how well a person would expect to perform at that time if they were to participate in a specific activity [83]. Nonetheless, the recommended recovery time between sessions for any single muscle group is ≥48 hours [5], but the recovery course may be increased as the repetition number approaches failure [19]. In fact, previous studies have shown reductions in the ability to rapidly apply force for up to 48-hours after RT to failure against 70 and 80% of 1RM, and up to 96-hours after intense RT where muscular fatigue and/or muscle damage has occurred [84] which could negatively interfere with other components of training [19-21].

While a single overloading RT bout results in acute fatigue and a relative decrease in performance, short-term periods of accumulated training above the habitual level followed by subsequent recovery can lead to functional overreaching, or a diminished adaptive response and long-term performance decrement, known as nonfunctional overreaching if sufficient recovery is not gained [84]. Furthermore, prolonged exposure to nonfunctional overreaching may lead to overtraining syndrome. Studies that have investigated high-volume, high-intensity RT-based conditioning suggest that these practices can lead to endocrinological alteration [85], increased inflammatory response [86], performance decline, and increased risk for non-functional overreaching and possibly overtraining syndrome if the balance between training and recovery is not adhered to [12, 85].

To complicate the issue, individuals recover from RT at different rates [87]. For advanced athletes, an effective RT approach may require individualization based on the dynamic state of recovery and performance of the athlete. According to Selye's General Adaptation Syndrome, a stressor is required for adaptation. However, to adapt to stress, an individual must be able to recover, which is impacted by outside stressors. In the context of exercise, if a stressor is beyond the capacity for adaptation (defined by Seyle as "exhaustion"), improvements in performance can cease or regress. The amount of time it takes for positive adaptations to return and continue, determines whether this regression was considered non-functional overreaching (shorter and less severe) or overtraining (longer and more severe) [87, 88]. In addition, factors such as sleep [89], nutrition [90], and psychological stress [91] can all impact adaptation and recovery. To date, an agreed upon valid, reliable, and accurate measure of recovery after a bout of RT has yet to be agreed upon, but many have been proposed [1, 2].

Perceived Measures of Recovery

Fatigue is a complex and multifactorial phenomenon and much is still unknown about why an individual becomes fatigued under various exercise conditions [92]. Multiple research studies have been conducted in an attempt to better understand how exercise and fatigue are correlated. Many of these studies utilized perceived measures of recovery and fatigue, such as perceived soreness [1, 12-14], recovery [1, 13, 15, 17], and perceived energy and fatigue [16-18]. In addition, research has utilized measures of neuromuscular fatigue [1, 2, 19-21, 57] as an objective measure since fatigue has been implicated in long-term neuromuscular adaptations with greater fatigue being associated with increased strength and hypertrophy [58].

Perceived soreness, sometimes called perceived pain, has been obtained using a 0-10 scale where a response of 0 means the participant is "normal, not sore at all" and a response of 10 means the participant is "severely sore" [1]. Sikorski et al. assessed soreness using the 0-10 scale for the legs, chest, and arms where 0-1 represented little to no pain, 2 represented slight pain, 3-4 represented mild pain, 5-6 represented moderate pain, and 7-8 and 9-10 were indicative of severe to the worst pain that the subject had experienced in their lives. Other studies have used similar scales to assess soreness [12, 14, 16]. For example, Chen et al. [14] utilized a 0-10 scale where the even numbers of the scale had the following verbal anchors: 0, no pain; 2, uncomfortable; 4, very uncomfortable; 6, painful; 8, very painful; and 10, extremely painful.

Perceived recovery is another subjective measure that has been researched in relation to recovery. The perceived recovery status scale utilized by Sikorski et al. [13] is based on the subjective physical and mental feelings of the athlete, as it pertains to their body either before or after a training session and has demonstrated itself as an effective mechanism to determine the performance in a particular training session before a subject commences training. In this study, each participant's recovery status was taken before each RT bout and consisted of values between 0 and 10, with 0–2 being very poorly recovered with anticipated declines in performance, 4–6 being low-to-moderately recovered and expected similar performance, and 8–10 representing high perceived recovery with expected increases in performance. Each participant's recovery status was taken 48-hours after each bout as well since this scale may be well suited for the determination of overtraining syndrome and the prevention of overtraining [93]. Furthermore, the results of the study suggest that the perceived recovery status scale may indicate the magnitude of damage done at the level of the muscle and/or the degree of recovery after a difficult bout of exercise [13].

Unfortunately, few studies have been conducted assessing the effect of acute RT on feelings of energy and fatigue, but the few that have been completed each utilized a different instrument to assess energy and fatigue [16-18]. A study published by Herring and O'Connor [16] quantified the intensity of feelings of energy and fatigue using 5-item scales from the Profile of Mood State-Brief Form Questionnaire before a bout of RT, as well as every 11 minutes and 40 seconds during each RT bout, and 20 and 30 minutes after each RT bout was complete.

Santos et al. [17] conducted a study assessing the impact of RT on fatigue attributed to work-related physical, organizational, psychosocial demands, and stress in the workplace utilizing the Need for Recovery Scale (Br-NFR). This Likert-type scale has 11 questions with 4 possible responses (0 = never; 1 = sometimes; 2 = often; and 3 = always). The answer "always" indicates an unfavorable situation and receives 3 points, except for item 4, which has a reversed score. The total score is obtained by adding all of the scores and converting them into a scale ranging from 0 (lowest) to 100 (maximum) by means of a simple rule of three. The higher the score, the greater the number of symptoms and the greater the need for recovery.

Lastly, Ward-Ritacco et al. [18] completed a study assessing the effect of RT on pregnant women from weeks 23-35 of pregnancy utilizing the Mental and Physical State Energy and Fatigue Scales which assess current subjective feelings of physical energy, physical fatigue, mental energy, and mental fatigue on a series of 100mm visual analog scales. Three items for each dimension of energy and fatigue were presented and added together for a score ranging from 0 to 300 where higher scores indicated more intense feelings.

Neuromuscular Measures of Recovery

Neuromuscular fatigue is defined as an exercise-induced reduction in the force/power-generating capacity of a muscle or muscle group [94] and can be inflicted via RT [50]. Neuromuscular responses are influenced by central (e.g., inhibited central motor drive due to metabolite activation of group III and IV afferent fibers) and peripheral factors (e.g., muscle damage and inflammation) [1]. Isometric handgrip (IHG) [2] and countermovement jump (CMJ) [2, 95] are both established indirect indicators of neuromuscular fatigue.

IHG can be measured using a variety of devices including cable tensiometers and handgrip dynamometers [5]. To successfully assess IHG, a person squeezes the dynamometer as hard as possible twice on each hand without holding their breath. The total grip strength score is calculated by summing the highest of the two readings for each hand [5]. Multiple studies have used this technique to assess neuromuscular fatigue due to its quick, simple, and non-invasive nature [2, 96].

The CMJ is a jump test administered on a force plate [1, 2], through utilization of a smart device app [34] or an infrared platform [97], and is used to determine lower body muscular power capacity [34]. To successfully perform a CMJ, an individual fixes their hands on their hips, flexes their hips and knees to a self-selected depth and then jumps as high as possible landing in the same spot they started [1]. Traditionally, a warm-up is completed before CMJ testing is conducted. Benitez-Flores et al. [34] had each participant complete a 2 minute warm-up on a cycle-ergometer at a rate of 50 rpm and an intensity of ~50W before CMJ testing was conducted with the My Jump app. Flatt et al. [1] had each participant complete three warm-up jumps at 50%, 70% and 90%, followed by three maximal effort CMJ on a force plate with 60 seconds rest between. Holmes et al. [2] utilized a similar method, except each participant was given 180 seconds between jumps rather than 60 seconds. Lastly, Jimenez-Reyes et al. [97] assessed CMJ using an Optojump infrared platform where each participant completed three CMJ attempts with 30 seconds rest between, but no warm-up was needed since the participants of the study completed a 60-meter sprint 10 seconds before the first CMJ.

Heart Rate Variability

Numerous studies have been conducted assessing the impact RT has on HRV. HRV indexes neurocardiac function and is generated by heart-brain interactions and dynamic non-linear autonomic nervous system processes [98]. HRV reflects regulation of autonomic balance, blood pressure, gas exchange, gut, heart, and vascular tone, which refers to the diameter of the blood vessels that regulate blood pressure [98]. HRV can be assessed in the long-term (24 hours), the short-term (~ 5 minutes), and the ultra-short-term (<5 min) [98]. Exercise studies have traditionally used short-term and ultra-short-term measures [1, 2, 44]. Two distinct but overlapping processes influence short-term HRV. The first source is a complex and dynamic relationship between the sympathetic and parasympathetic branches [99]. The second source includes the regulatory mechanisms that control HR via respiratory sinus arrhythmia (respiration-driven speeding and slowing of the heart via the vagus nerve). When you inhale, heart rate increases. Blood pressure rises about 4-5 s later. Baroreceptors detect this rise and fire more rapidly. When you exhale, heart rate decreases, blood pressure falls 4-5 s later [100]. The baroreflex makes this acceleration and deceleration of the heart possible [101] and also links heart rate, blood pressure, and vascular tone [98]. Baroreceptor firing due to blood pressure changes activates mechanisms that change heart rate and vascular tone. Rising blood pressure triggers decreases in heart rate and vascular tone, while falling blood pressure causes increases in both [98]. In contrast, long-term HRV measures are affected by circadian rhythms, core body temperature, metabolism, the sleep cycle, and the renin–angiotensin system [98]. Since slower regulatory mechanisms contribute to HRV metrics recorded over longer measurement periods, 24-hour, short-term, and ultra-short-term values are not interchangeable [98].

Heart Rate Variability Metrics

There are a variety of metrics available to analyze HRV. Time-domain indices quantify the amount of HRV observed during monitoring periods that may range from <1 min to >24 hours [98]. Frequency-domain values calculate the absolute or relative amount of signal energy within component bands and non-linear measurements quantify the unpredictability and complexity of a series of interbeat intervals [98]. RMSSD is an HRV time-domain metric and one of the variables most commonly adopted in scientific studies with physical exercise [36] as it is usually utilized as a measure of parasympathetic cardiac modulation [2, 39] and recovery status [102].

Indeed, RMSSD appears promising as an internal indicator of training load [103] as well as a predictor of nonfunctional overreaching [104, 105], though its use to assess recovery is still in question [1, 2, 57]. Recently, research has utilized ultra-short-term RMSSD measures that have been converted to the natural logarithm of RMSSD (LnRMSSD) to avoid outliers [29] and ensure a normal distribution of data [20, 44]. Ultra-short-term measures of LnRMSSD have been shown to be no different from criterion 5-min measures, require only a brief stabilization period, and are sensitive to training-induced changes [106].

Common frequency-domain metrics utilized in exercise-based research to address recovery status include normalized units low-frequency (LFnu), normalized units high-frequency (HFnu), and low-frequency/high frequency ratio (LF/HF) [102]. HFnu indicates the level of cardiac parasympathetic modulation, and is generally correlated with measures of RMSSD, while LFnu provides the degree of cardiac sympathetic modulation [102]. Furthermore, the LF/HF ratio presents the extent of sympathicovagal balance [102]. Each of the previously discussed time-domain and frequency-domain metrics have been shown to be altered following an acute RT bout [102]. Finally, non-linear measures of HRV have been analyzed in relation to RT, but these are beyond the scope of this review. To conclude, HRV may be a useful metric in assessing recovery, but other non-invasive methods must also be considered.

2.5 Resistance Training, Heart Rate Variability, and Measures of Recovery

Early research assessing the impact of exercise on HRV compared RT to endurance training [107]. This research described HF oscillations of HRV (0.15–0.40 Hz) as almost entirely mediated by the vagus nerve and thus represented parasympathetic nervous activity, while LF power (0.04–0.15 Hz) was attributed to both the vagus and cardiac sympathetic nerves, and represented both parasympathetic and sympathetic nervous activity [107]. In addition, the authors stated the LF/HF ratio was an indicator of sympathovagal balance. After comparing a bout of RT that utilized eight exercises for three sets of ten to 30-minutes of continuous stationary cycling at 65% of peak oxygen uptake, Heffernen et al. [107] illustrated that autonomic cardiovascular control of the heart is not fully regained within 30 minutes of either acute endurance exercise or RT. This study was also able to show there were similar reductions in HFnu power and similar increases in LFnu power after both bouts of exercise. The LF/HF ratio increased similarly after both bouts, suggesting a comparable shift towards a state of sympathetic predominance [107]. After the completion of this study, there was a great deal of research conducted assessing the effect of RT on HRV [1, 2, 22-56].

In a review by Kingsley and Figueroa [108] that examined 10 studies published before 2014, the authors stated cardiac parasympathetic modulation decreases (i.e. decreased HFnu) and cardiac sympathetic modulation increases (i.e., increased LFnu and LF/HF ratio) following a RT session in healthy young men and women [102]. This review paper also stated that the LFnu component of HRV is mediated by both sympathetic and parasympathetic activities of the autonomic nervous system. Over time, other studies compared the impact of RT on measures of HFnu, LFnu, and HF/LF to better understand their relationships and if they are correlated in any way [14, 52, 109, 110]. In general, studies were in agreement that an acute RT bout resulted in a decrease in HFnu and a short-term increase in LFnu and LF/HF, but the length of this autonomic change following the bout was still in question as three of the studies showed this change for between 5-25 minutes [52, 109, 110], while the other study illustrated that it may last up to 24 hours [14] when omitting the LF/HF measure. The early research conducted in this area led to a new time-domain metric that has been shown to be correlated with HFnu and indicative of the level of cardiac parasympathetic modulation, RMSSD, which has been hypothesized as a metric that could be used to monitor recovery status after a RT bout [102]. Since this metric was established, many studies have also utilized RMSSD and LnRMSSD as measures of cardiac autonomic activity [1, 2, 22-25, 32, 37, 39, 41, 43, 44].

Three key studies conducted by Figueiredo et al. [23-25] attempted to delineate which RT variable most impacted HRV: load intensity, rest interval length, or volume load. The results of these studies concluded that rest-interval length and volume load (repetitions x external load) altered cardiac autonomic activity most, and of these two, volume load altered HRV to a greater extent. Other research is in agreement with these findings as a review and meta-analysis showed that performing ≥3 sets and higher training volumes had the greatest effect on RMSSD, HFnu, and LFnu, whereas performing <3 sets and lower training volumes had the least effect when comparing subgroups following RT [102]. Measures of LF/HF were not different between subgroups when volume or any other RT variable was taken into account [102]. Following these findings, researchers attempted to find correlations between HRV and other measures of fatigue and recovery to further close the gap on improving exercise prescription [1, 2, 57]

Holmes et al. [2] conducted a study that assessed the impact of a moderate load RT session on HRV, which was the internal marker of fatigue, as well as two external markers of fatigue, IHG and CMJ. The aim of this study was to determine the relationship between baseline, immediately-post-exercise, and 30-min post-exercise changes in HRV, neuromuscular performance, and fatigue biomarkers in response to a full-body, hypertrophic-style resistance exercise bout. In this study, HRV, IHG and CMJ were assessed before the RT session, which consisted of six sets of ten repetitions in the back squat and three sets of ten repetitions in both the bench press and bent-over row, all at 70% 1RM with 120 seconds of rest between sets and 180 seconds of rest between each exercise, as well as after the RT session was completed. From this study, the authors concluded that the magnitude of the change and full recovery of training load variables, such as neuromuscular performance and fatigue biomarkers, may differ greatly from HRV patterns. Therefore, practitioners should look to incorporate multiple methods of monitoring fatigue and recovery to assess an athlete's readiness to perform more effectively [2].

In a similar study by Thamm et al. [57], the authors expanded on previous findings by assessing whether the type of exercise loading (i.e., maximal strength and hypertrophy) acutely affects HRV assessed immediately after, as well as up to 48-hours following each protocol utilizing ten healthy men in a randomized cross-over design. In this study, each participant completed both hypertrophy (five sets of ten repetitions, 80% 1RM) and maximal strength (15 sets of one repetition, 100% 1RM) RT bouts on the leg press separated by seven days. HRV was taken pre-, immediately-post, 30-minutes-post, 60-minutes-post, and 24- and 48-hours post each RT session. RMSSD, LFnu, HFnu, and LF/HF ratio were all assessed at each time-point. Rate of force development and muscle pain were each assessed immediately before, 24- and 48-hours post each RT bout as well. Results showed that RMSSD significantly decreased immediately following both protocols but returned to the baseline values within 30 minutes post-exercise. LF, HF, and LF/HF remained unaltered during the acute recovery period up to one-hour post-RT. Lastly, rate of force development from pre- to post-RT in each condition was statistically significantly associated with changes in RMSSD.

Finally, Flatt et al. [1] aimed to quantify associations between changes in HRV, neuromuscular, and perceptual measures of recovery for 48-hours following an intense RT bout. The RT session for each of the ten participants in this study consisted of completing six sets of squat, bench press, and pull-down to failure utilizing 90% of 10 repetition maximum as the external load. Changes from pre- to immediately-, 24- and 48-hours post-RT were calculated for CMJ and perceived recovery and soreness scales. Pre-measures of HRV, specifically LnRMSSD, were calculated from a five-day baseline, and post-measures were taken immediately-, 24-, and 48-hours post-RT. Results of this study were similar to that of the Holmes [2] study where HRV, neuromuscular, and perceptual markers of fatigue showed varying timeframes of recovery. Specifically, LnRMSSD measures were not different from baseline by 24-hours post-RT, neuromuscular makers were not different from pre-RT by 48-hours post-RT, and perceptual measures remained suppressed at 48-hours post-RT. In addition, no significant associations among change scores in variables were observed, but IHG was moderately associated with CMJ (r = 0.38, P = 0.040). Overall, these three studies [1, 2, 57] illustrate that RT bouts utilizing moderate-to-high volumes alter various measures of fatigue, each of which recover at different time-points, but only when volume is calculated as "repetitions x external load".

2.6 Gaps in the Literature

There is now a strong foundation of evidence illustrating RT bouts completed with high volumes result in decreased HRV, but to date, this is only true when volume is calculated as "repetitions x external load". To our knowledge, research has yet to assess the impact of RT bouts with differing TUT on measures of HRV. In addition, no studies to date have compared changes in HRV metrics (LFnu, HFnu, LF/HF) to measures of neuromuscular fatigue or perceived soreness after RT bouts with differing TUT. Furthermore, no study has compared measures of HRV to perceived energy and fatigue utilizing the Mental and Physical State Energy and Fatigue Scales. Lastly, assessing multiple recovery metrics for 48-hours post-RT is needed to evaluate whether the recommended 48-hour minimum recovery period is appropriate for RT sessions using different TUT.

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CHAPTER 3

THE EFFECT OF DIFFERING TIME-UNDER-TENSION DURING RESISTANCE TRAINING ON AUTONOMIC FUNCTION RECOVERY OVER 48-HOURS IN TRAINED MEN [1]

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3.1 Abstract

Resistance training (RT) has become one of the most popular forms of exercise for enhancing physical fitness and well-being. Participation in RT can lead to increases in strength, hypertrophy, and muscular endurance, as well as improvements in other physiological aspects of overall health. To fully achieve the effects of RT, recovery after exercise needs to be monitored to avoid overtraining. Heart rate variability (HRV) has been proposed as an instrument to assess recovery after an exercise bout. This study aimed to assess whether acute RT sessions with differing volumes via altered time-under tension (TUT) influences autonomic function over a 48-hour period as indicated by commonly used measures of HRV (LnRMSSD, LnLFnu, LnHFnu, and LnLF/HF ratio) in resistance-trained males. HRV was assessed once before (baseline) and three times after (immediately-post-RT, 24-hours post-RT, and 48-hours post-RT) the completion of both a slow repetition tempo (SLOW) and fast repetition tempo (FAST) RT bout utilizing a Polar H10 Heart Rate Strap and Kubios HRV Premium software. Results from the study showed that there were significant decreases in LnRMSSD from baseline to immediately-post-RT in both RT protocols, but no other differences were seen when assessing change scores. In contrast, the SLOW session resulted in a greater internal load evidenced by significantly higher ratings of perceived exertion (RPE) on the leg press, chest press, and lat pulldown, as well as a significantly higher RPE for the session overall. In the FAST session, there were significant correlations from baseline to immediately-post between measures of LnRMSSD and mean and peak HR, and between LnRMSSD and mean HR 24-hours post-exercise. The SLOW session resulted in significant correlations between three HRV metrics, LnRMSSD, LnLF, and LnLF/HF, and mean HR from baseline to immediately-post, but no other correlations were seen. Overall, varying volumes through differing TUT did not result in significant differences in HRV metric changes across time-points between conditions and all HRV metrics returned to near or above baseline values by 24-hours post-exercise.

Index Words: heart rate variability, time-under-tension, resistance exercise, recovery

3.2 Introduction

Regular physical activity and exercise are associated with numerous physical and mental health benefits [1]. Resistance training (RT) is a mode of exercise designed to increase strength, power, and muscular endurance [2, 3] and can be completed using multiple types of equipment such as free weights, weight machines, and resistance bands, as well as any other equipment or object that can create external resistance, including the human body. A crucial factor associated with any exercise program is the recovery time needed between exercise sessions.

Recovery from RT varies based on the magnitude, duration, and mode of training, with typical mechanical and biochemical restoration occurring within three hours of moderate-intensity RT or 24-96 hours after intense RT where muscular failure is achieved and/or muscle damage has occurred [4]. The American College of Sports Medicine recommends ≥48 hours between sessions for any single muscle group [5], though this is a broad recommendation considering the number of variables that can be manipulated within a RT program. The primary goal of monitoring and regulating RT is to more closely match the intended training stress with readiness and recovery to optimize adaptation on an individual basis [6]. Individuals recover from RT at different rates [6] and a lack of recovery has been associated with non-functional overreaching, overtraining, and overtraining syndrome [7]. Overtraining refers to that point at which an athlete experiences physiological maladaptation and chronic performance decrements [2]. Most symptoms that result from overtraining, collectively referred to as overtraining syndrome, are subjective and identifiable only after the individual's performance and physiological function have suffered [2], although psychological symptoms can occur as a result of overtraining as well.

Due to the adverse effects that can result from overtraining, it is critical that an objective, non-invasive measure is established that gives a valid and reliable measure of recovery, and one possible measure is heart rate variability (HRV) [8]. HRV consists of changes in the time intervals between consecutive heartbeats called interbeat intervals and can be expressed using time-domain or frequency-domain metrics [9]. A time-domain metric commonly utilized in exercise studies is the root mean square of successive RR interval differences (RMSSD) [10] as it can be utilized as a measure of parasympathetic cardiac modulation [11, 12] and recovery status [13, 14]. Frequency-domain metrics can also be used in exercise-based research to address recovery status and include normalized units low-frequency (LFnu), normalized units high-frequency (HFnu), and low-frequency/high-frequency ratio (LF/HF) [13]. HFnu indicates the level of cardiac parasympathetic modulation and is generally correlated with measures of RMSSD, while LFnu provides the degree of cardiac sympathetic modulation [13]. Furthermore, the LF/HF ratio presents the extent of sympathovagal balance [13]. Each of these time-domain and frequency-domain metrics have been shown to be altered following an acute RT bout [13].

The RT variable that has been shown to be most strongly correlated with increased sympathetic modulation and delayed recovery, as illustrated by low HRV measures, is volume [15]. Volume is most commonly expressed as “volume load” and is calculated as repetitions multiplied by external resistance (i.e., repetitions x weight). However, there is more than one way to calculate the volume of a RT session. Volume determination using time-under-tension (TUT) involves monitoring the time to perform each phase of a repetition including the eccentric, transition, concentric, and resting phases [16]. For example, when completing a repetition with a 1/0/1/0 TUT, the eccentric contraction is one second, there are zero seconds between the eccentric and concentric phases of the repetition, the concentric contraction is one second, and there are zero seconds of rest between repetitions. TUT is a useful variable when creating a RT program as different TUTs have been shown to elicit different psychological and physiological responses [3, 17, 18].

To date, studies comparing RT volume to recovery measures have found that HRV is most affected by higher volumes, but only when volume is expressed as "volume load" (i.e., repetitions x weight). To our knowledge, no studies have been conducted assessing the effect of volume expressed as TUT on alternative measures of HRV. Therefore, the primary aim of this study was to assess whether acute RT sessions with differing TUT, but identical exercise order, sets, reps, weight, and rest intervals influence autonomic function over a 48-hour period as indicated by RMSSD, LFnu, HFnu, and LF/HF ratio in resistance-trained males. We also assessed whether there were any correlations between each of these HRV metrics and measures of internal load.

3.3 Methods

Participants

Twelve healthy, resistance-trained males participated in the study (Table 3.1). The participants were classified as being resistance-trained if they had participated in six months of RT directly preceding their participation in the study, with completion of leg, chest, and back exercises at least once a week during that time. Inclusion criteria for all participants: (a) to be a male between 18-40 years old; (b) not taking medications, drugs, or supplements that could alter cardiovascular response to exercise; (c) free of signs and symptoms of cardiovascular, metabolic, and renal disease as evidenced by completion of the PAR-Q; and (d) to have no physical limitations or musculoskeletal injuries/disorders that would hinder the participant from completing the exercise protocol. This project was approved by the University of Georgia Institutional Review Board.

Experimental Design

A counterbalanced, cross-over design was used to assess the influence of TUT on measures of HRV over 48-hours. Initially, each participant was required to complete an online pre-screening survey to ensure their eligibility for the study. After eligibility was confirmed, each participant visited the lab seven times over a three-to-four-week period. During the first visit, each participant completed informed consent, after which height was assessed utilizing a stadiometer (Novel Products, Rockton, Ill) and weight was recorded using a digital scale (A&D Co., San Jose, CA). After height and weight were recorded, one-repetition maximum (1RM) testing was conducted. The RT exercises utilized in this study were the leg press, chest press, and lat pulldown, in that order. After completion of the first visit, each participant was scheduled for their next six visits, which were all scheduled at the same time of day.

During the second visit, HRV was assessed, the participant completed a warm-up and the RT bout, and then HRV was taken once more immediately after the exercise session was complete. The third and fourth visits consisted of the participant coming to the lab for follow-up HRV measures 24- and 48-hours after the exercise session. Visits five, six, and seven were identical to visits two, three, and four, only a different volume (e.g., TUT) was used for the RT bout. The sequence of protocol completion was determined by alternating allocation of participants upon study enrollment to ensure balanced sequences and to avoid any period effects. Throughout the study, participants were instructed not to exercise within 72 hours of the 1RM and exercise sessions, not to drastically change their diet or sleep patterns, and to refrain from ingestion of alcohol for 24 hours, caffeine for 12 hours, and any heavy meals for two hours before each session. In addition, no aerobic or anaerobic exercise was allowed between the RT session and the 48-hour follow-up session.

Heart Rate Variability

Measures of HRV were collected using a Polar H10 Heart Rate Strap (Polar Electro, Kemple, Finland) at a sampling rate of 130 Hz [19, 20] and a cost-free mobile application (Elite HRV Version 5.5.4, Ashville, NC, USA) [21] at baseline, immediately-post-RT, as well as 24- and 48-hours post-RT for both exercise sessions. All HRV readings were collected in an identical fashion. To obtain an HRV reading, the participant was seated, quiet, and still for a 1-minute stabilization period, after which they would inhale and exhale at the pace instructed through the mobile app for 1-minute. After all HRV measures were collected, they were exported via email to the researchers for R-R filtering using Kubios HRV Premium software (Version 3.5, Kuopio, Finland). RMSSD values were converted to the natural log of RMSSD (LnRMSSD) as ultra-short (i.e., 1-minute) LnRMSSD measures have been shown to be no different from criterion 5-minute measures, require only a brief stabilization period, and are sensitive to training-induced changes [14]. The natural log of all HRV measures was used to promote a normal distribution and minimize the influence of extreme values [8, 15, 22].

One-Repetition Maximum Testing

1RM testing for the leg press, chest press, and lat pulldown was completed during the first visit using Cybex resistance exercise machines (Franklin Park, Ill) after a brief warm-up. The warm-up consisted of a 5-minute walk on a treadmill at 3 mph, 10 bodyweight squats, 10 push-ups, and self-selected dynamic stretching of the upper and lower body. After the warm-up, participants completed 1RM testing for each of the exercises [23]. First, they completed ten repetitions at a self-selected light resistance, followed by a 1-minute rest period. They then completed five repetitions at a self-selected moderate resistance, followed by a 2-minute rest period. Next, participants completed a near-maximal load for three repetitions, followed by a 3-minute rest period. Finally, participants completed one-repetition at an estimated maximal load, followed by a three-minute rest period. After this attempt was complete, resistance was increased 10 to 20 pounds for upper body exercise or 30 to 40 pounds for lower body exercise for each successive attempt until a 1RM was successfully completed with correct form.

If a participant was unable to complete an attempt, the last successful attempt was recorded as their 1RM. If a participant could complete the maximum amount of weight allowed by the machine, the participant completed as many repetitions as possible with correct form at that weight and the Epley equation (1RM = [(0.033 x number of repetitions) x (weight)] + weight) was used to estimate 1RM. The Epley equation uses the maximum number of repetitions performed using a given weight to provide an estimate of 1RM and is one of the most popular prediction equations for estimating 1RM [24].

Resistance Exercise Protocol

The RT protocol was performed after baseline measures of HRV and a warm-up that was identical to that used in the 1RM session. Each RT protocol utilized 50% of 1RM for each of the three exercises (i.e., leg press, chest press, and lat pulldown, in that order) for three sets of eight repetitions with one-minute of rest between sets and exercises. The lone difference between the two exercise sessions was the volume being utilized as one session utilized a 1/0/1/0 TUT (FAST) and the other a 4/0/4/0 TUT (SLOW) (Table 3.2). To ensure the correct cadence was maintained throughout each repetition, a smart device metronome application was utilized (Soundbrenner, version 1.24, Hong Kong, China). If a participant became too fatigued to continue at the required cadence, a researcher would give assistance to ensure the cadence was maintained throughout each set of repetitions without manipulating any of the other components of the RT bout including rest between sets and exercises.

Statistical Analysis

Data were analyzed with IBM SPSS version 28.0.0.0. for Windows and Microsoft Excel version 2202. Data normality was assessed visually using histograms and statistically with Shapiro-Wilks tests. One participant had HF, LF, and LF/HF values that were > 3 SD from the mean which induced extreme non-normality in overall study data. A 2 (session) × 4 (time) repeated measures ANOVA was used to assess differences between baseline and post-exercise LnRMSSD, LnHF, LnLF, and LnLF/HF values at four time-points within and between conditions. Sphericity was assessed using Mauchly's test and, if violated, the Greenhouse-Geisser correction was utilized to adjust for a lack of sphericity. Pearson's correlations were calculated between change scores of

HRV and measures internal load separately for the SLOW and FAST conditions and defined as weak (0.10-0.30), moderate (0.30-0.50), or strong (0.50-1.0). Percent change scores were calculated using the equation (post-baseline)/baseline x 100. The sample a priori power was calculated using G*Power 3.1.9.7. With an ES of 0.5, a significance level of .05, and a power (β) of 0.80 for two sessions (SLOW, FAST) with repeated-measures at four time points (baseline, immediately-post, 24h, and 48h). This resulted in an estimated minimum sample size of eight participants [15]. Data are presented as mean ± standard deviation, unless otherwise stated, and statistical significance was set at an alpha level of 0.05.

3.4 Results

There were no significant differences at baseline for RPE (Table 3.3). There were no significant differences in Mean HR values between sessions, but Peak HR was significantly higher in the SLOW session ($p < 0.01$) (Table 3.3). In addition, the SLOW session resulted in significantly higher RPE leg press ($p < 0.001$), RPE chest press ($p < 0.001$), RPE lat pulldown ($p < 0.001$), and overall RPE ($p < 0.001$) measures when compared to the FAST protocol (Table 3.3). These differences in Peak HR and measures of RPE reflect the higher volume of the SLOW session when compared to the FAST session.

There were no statistically significant interactions between TUT and time (Table 3.4). However, we observed significant main effects of time on LnRMSSD ($p < 0.001$) (Table 3.4), such that LnRMSSD measures immediately-post-RT were significantly lower in both the FAST ($p = 0.028$) and SLOW ($p < 0.01$) sessions when compared to baseline (Table 3.5). In pairwise comparisons, LnRMSSD immediately-post-exercise (mean ± SD) was significantly different from LnRMSSD values at baseline with mean differences ranging from -.96 to -1.15 (all $p < 0.01$) but returned to baseline levels by 24-hours post-exercise, regardless of the TUT (Table 3.5).

Strong significant correlations were seen in the FAST session between measures of LnRMSSD and mean and peak HR from baseline to immediately-post (Table 3.6). Measures of LnRMSSD, LnLF, and LnLF/HF were significantly correlated to mean HR from baseline to immediately-post in the SLOW session as well. The only significant correlation observed from baseline to 24-hours post-exercise was of LnRMSSD in the FAST session. There were no significant correlations from baseline to 48-hours post-exercise between measures of internal load and the HRV metrics assessed.

3.5 Discussion

We investigated whether acute RT sessions with differing TUT influence autonomic function over a 48-hour period as indicated by LnRMSSD, LnLFnu, LnHFnu, and LnLF/HF ratio in resistance-trained males. Key findings in the study include the SLOW session resulting in higher internal load measures than the FAST session. We also saw significant decreases from 15-30% across time-points for LnRMSSD in both sessions, but no other significant findings were observed. Mean HR was strongly correlated to LnRMSSD in both sessions, whereas it was only correlated to LnLF and LnLF/HF in the SLOW session. Lastly, all measures of HRV returned to near or above baseline within 24-hours post-exercise.

Changes in LnRMSSD following an acute RT bout was explored in depth by a recent literature review and meta-analysis which compared 26 papers published since 2006 on the impact of RT on the autonomic nervous system [13]. This paper concluded that there was a withdrawal of cardiac parasympathetic activity and activation of cardiac sympathetic modulations following acute RT, and that these changes are greater when higher training volumes are performed, though none of the papers cited varied their volume through changes in TUT. The current study is in agreement with this literature review, as well as with a study by Holmes et al. [12] which showed decreased LnRMSSD for up to 30 minutes after the completion of a moderate load RT bout in 30 young, resistance-trained males and females. However, longer duration changes in LnRMSSD were not examined in this study.

Although we did not see a significant difference in HRV metrics between protocols (e.g., FAST or SLOW) at any time-point, the decrease in LnRMSSD immediately-post-RT was approximately twice as large in the SLOW condition compared to the FAST condition. This is in agreement with other research which concluded higher volume loads do indeed lead to greater decreases in parasympathetic activity and increases in sympathetic activity [15]. Holmes et al. [15] conducted a study comparing RT sessions with three different volume loads (low-volume, moderate-volume, and high-volume) on LnRMSSD in ten, young, resistance-trained males and females. In this study, each participant was required to either complete two sets, four sets, or six sets of ten repetitions on the back squat, one set, two sets, or three sets of ten repetitions on the bench press, and one set, two sets, or three sets of ten repetitions on the bent-over row with all other variables being controlled. This study illustrated that the protocols utilizing the moderate- and high-volume loads led to greater decreases in LnRMSSD for up to 30 minutes after completion of the exercise session, but no further comparisons to the current study can be made as they did not collect data past 30 minutes.

Figueiredo et al. [25] conducted a similar study on 11 young men with strength-training experience and assessed whether RT sessions utilizing one set, three sets, or five sets on eight different exercises led to alterations in RMSSD, HFnu, and LFnu. Their results showed that the highest volume RT session (e.g., 5 sets) promoted the greatest alterations on cardiac autonomic control when compared to lower volumes evidenced by decreases in RMSSD and HFnu, as well as increases in LFnu after each bout. In contrast, Santos et al. [26] conducted a study with 27 healthy men between 20-40 years of age comparing a German Volume Training session to a Sarcoplasm Stimulating Training protocol. They assessed HRV for 50-minutes after each protocol and found that both RT protocols produced similar responses despite the German Volume Training protocol having a significantly higher volume. In this study, there were similar increases in LF and LF/HF ratio and similar decreases in RMSSD and HF post-RT despite the different volume loads.

Lastly, we assessed correlations between changes in HRV metrics and measures of internal load to better understand if greater TUT leads to greater changes in HRV and if measures of internal load reflected these changes. The results of the current study showed that mean HR was most correlated with LnRMSSD, but only from baseline to immediately-post and baseline to 24-hours post-exercise in the FAST group. Kassiano et al. [27] conducted a study comparing the acute effects of multiple sets of RT with and without concentric muscle failure, inter-repetition rest, and rest pause on HRV indices and internal training load in 29 young, resistance-trained men and women. In this study RMSSD and RPE were taken before and after a RT session. Their results showed that internal load, calculated by RPE, was highest when the highest external training loads were performed and that these loads also led to the greatest decrease in RMSSD. The results of the current study did not align with these results as we did not see significant correlations between RPE and HRV, but did see moderate to strong correlations between LnRMSSD and overall measures of internal load from baseline to immediately-post-exercise in both conditions.

Strengths and Limitations

A strength of the current study included the use of a counterbalanced, cross-over design since many measures of HRV are individualized. Therefore, using separate groups rather than one group may show significant differences, or no significant differences, between HRV metrics leading to inaccurate results. Another strength was the use of identical exercise protocols in a controlled environment, with only TUT being different. The current study also completed follow-up measures at 24- and 48-hours post-exercise.

Limitations of the study include a small sample size of participants which may have impacted the precision of the correlations between the different HRV metrics. Additionally, we needed to estimate 1RM for some participants, which may not accurately reflect a true 1RM. Only young, healthy, resistance-trained males participated in the study, so results may not be reflective of what may be seen in other populations. Lastly, RT sessions utilizing differing TUT, number or sets, repetitions, exercises, rest intervals, and/or equipment could result in findings different than that of the current study as manipulating each of these RT variables can independently impact the physiology of the body.

3.6 Conclusion

The findings of this study illustrate that RT programs utilizing identical exercises, intensities, and weight, but different repetition tempos decrease measures of HRV in a similar fashion. The study also showed that all HRV metrics had returned to near or above baseline values by 24-hours post-exercise. In addition, the internal load achieved during the SLOW session was significantly higher than that of the fast session, illustrated by significantly higher measures of peak HR, leg press, chest press, lat pulldown, and overall RPE scores. We also saw a moderate correlation between LnRMSSD and mean HR in the SLOW session from baseline to immediately-post-exercise. We saw the same correlation in the FAST session, but it was stronger, illustrating that the relationship between parasympathetic withdrawal and internal load (e.g., heart rate), may be different than that of parasympathetic withdrawal and external volume (e.g., TUT). To conclude, more research must be conducted using differing TUT, types of resistance exercise equipment, exercise order, rest interval times, and populations to better understand the relationship between internal and external volume load, calculated as TUT, and their effect on HRV.

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Table 3.1 Participant Demographics, (n=12)

Characteristic	Mean ± SD
Age (years)	21.6 ± 0.8
Height (cm)	178.6 ± 4.8
Body mass (kg)	83.9 ± 7.6
1RM leg press (kg)	227.0 ± 45.0
1RM chest press (kg)	129.4 ± 27.9
1RM lat pulldown (kg)	102.6 ± 18.0

SD = standard deviation

Table 3.2 Total Volume for Each RT Protocol, (n=12)

Protocol	Sets	Repetitions	Concentric Phase (s)	Eccentric Phase (s)	TUT per repetition (s)	Total TUT (s)
FAST	9	8	1	1	2	144
SLOW	9	8	4	4	8	576

RT = resistance training; s = seconds; total TUT calculated as "sets x repetitions x TUT per repetition"

Table 3.3 Comparison of Internal Load Measures Between Sessions, (n=12)

Variable	FAST	SLOW	p-value
Mean HR (bpm)	110.17 ± 21.52	121.42 ± 17.03	0.065
Peak HR (bpm)	134.67 ± 22.55	151.50 ± 22.31	<0.01**
Baseline RPE	6.00 ± 0.00	6.00 ± 0.00	-
RPE leg press	10.81 ± 1.52	14.19 ± 2.45	< 0.001**
RPE chest press	11.63 ± 1.27	15.78 ± 1.98	< 0.001**
RPE lat pulldown	11.28 ± 1.31	15.22 ± 2.02	< 0.001**
Overall RPE	11.58 ± 1.38	15.83 ± 1.85	< 0.001**

HR = heart rate; bpm = beats per minute; RPE = rating of perceived exertion; The baseline RPE p-value cannot be calculated because the standard error of the difference is 0; *Significant difference between conditions ($p < 0.05$); **Significant difference between conditions ($p < 0.01$).

Table 3.4 Main Effects and Interactions of Each HRV Metric, (n=12)

Variable	F-statistic	Degrees of Freedom	Error	p-value
LnRMSSD				
Main effect of TUT	0.42	1	11	0.841
Main effect of time	14.72	1.84	20.26	< 0.001**
Interaction	2.67	3	33	0.063
LnHFnu				
Main effect of TUT	0.58	1	11	0.464
Main effect of time	1.02	3	33	0.396
Interaction	0.50	3	33	0.688
LnLFnu				
Main effect of TUT	0.70	1	11	0.422
Main effect of time	0.81	1.46	16.09	0.425
Interaction	1.07	1.43	15.75	0.343
LnLF/HF				
Main effect of TUT	0.62	1	11	0.449
Main effect of time	0.99	3	33	0.409
Interaction	0.55	3	33	0.650

LnRMSSD = natural logarithm of the root mean square of successive RR differences; LnHFnu = natural logarithm of the normalized units high-frequency; LnLFnu = natural logarithm of the normalized units low-frequency; LnLF/HF ratio = natural logarithm of the low-frequency/high-frequency ratio; TUT = time-under-tension; *Significant main effect or interaction at ($p < 0.05$); **Significant main effect or interaction at ($p < 0.01$)

Table 3.5 Changes in HRV from Baseline to Post-Exercise, (n=12)

Variable	FAST Mean ± SD	Δ (%)	SLOW Mean ± SD	Δ (%)
LnRMSSD				
Baseline	4.20 ± 0.84	-	4.34 ± 0.52	-
IP	3.54 ± 1.01	-15.71*	3.08 ± 0.91	-29.03**
24h	4.35 ± 0.72	3.57	4.52 ± 0.46	4.15
48h	4.34 ± 0.71	3.33	4.59 ± 0.52	5.76
LnHFnu				
Baseline	2.02 ± 0.80	-	2.16 ± 0.85	-
IP	1.96 ± 1.05	-2.97	1.84 ± 0.60	-14.81
24h	2.06 ± 0.79	1.98	2.33 ± 0.78	7.87
48h	2.21 ± 0.76	9.41	2.22 ± 0.92	2.78
LnLFnu				
Baseline	4.51 ± 0.06	-	4.48 ± 0.09	-
IP	4.49 ± 0.10	-0.44	4.53 ± 0.04	1.12
24h	4.49 ± 0.09	-0.44	4.46 ± 0.10	-0.45
48h	4.48 ± 0.08	-0.67	4.42 ± 0.27	-1.34
LnLF/HF				
Baseline	2.48 ± 0.85	-	2.32 ± 0.94	-
IP	2.52 ± 1.14	1.61	2.68 ± 0.64	15.52
24h	2.43 ± 0.87	-2.02	2.14 ± 0.87	-7.76
48h	2.28 ± 0.84	-8.06	2.20 ± 1.16	-5.17

HRV = heart rate variability; SD = standard deviation; Δ (%) = percent change from baseline calculated as ((post-baseline)/baseline*100); LnRMSSD = natural logarithm of the root mean square of successive RR differences; LnHFnu = natural logarithm of the normalized units high-frequency; LnLF = natural logarithm of the normalized units low-frequency; LnLF/HF = natural logarithm of the low-frequency/high-frequency ratio; IP = immediately-post-exercise; 24h = 24-hours post-exercise; 48h = 48-hours post-exercise; *Significant difference compared to baseline ($p < 0.05$); *Significant difference compared to baseline ($p < 0.01$)

Table 3.6 Pearson Correlations Between HRV Metric Change Scores and Measures of Internal Load, (n=12)

Variable	Slow TUT			Fast TUT		
Baseline to IP	Mean HR	Peak HR	Overall RPE	Mean HR	Peak HR	Overall RPE
LnRMSSD	-0.639*	-0.478	-0.444	-0.803**	-0.746**	-0.158
LnHF	-0.488	-0.317	-0.100	0.050	0.120	0.371
LnLF	0.669*	0.422	-0.008	0.132	-0.032	0.108
LnLF/HF	0.672*	0.430	0.080	0.374	0.250	0.014
Baseline to 24h						
LnRMSSD	-0.213	-0.307	-0.079	0.646*	0.570	0.006
LnHF	-0.509	-0.513	-0.244	0.102	0.161	0.388
LnLF	0.291	0.176	0.029	-0.436	-0.314	-0.446
LnLF/HF	0.354	0.247	0.079	-0.451	-0.366	-0.385
Baseline to 48h						
LnRMSSD	-0.248	-0.288	-0.079	0.076	-0.213	-0.193
LnHF	-0.486	-0.492	-0.174	0.134	-0.125	-0.110
LnLF	0.470	0.428	0.088	0.326	0.176	0.372
LnLF/HF	0.505	0.472	-0.034	-0.469	-0.065	-0.199

HRV = heart rate variability; HR = heart rate; RPE = rating of perceived exertion; LnRMSSD = natural logarithm of the root mean square of successive RR differences; LnHFnu = natural logarithm of the normalized units high-frequency; LnLFnu = natural logarithm of the normalized units low-frequency; LnLF/HF ratio = natural logarithm of the low-frequency/high-frequency ratio; IP = immediately-post; 24h = 24-hours post-exercise; 48h = 48-hours post-exercise; *Significant correlation at ($p < 0.05$); **Significant correlation at ($p < 0.01$)

CHAPTER 4

CHANGES IN AUTONOMIC, NEUROMUSCULAR, AND PERCEIVED MEASURES OF RECOVERY RESULTING FROM RESISTANCE EXERCISE WITH DIFFERING TIME-UNDER-TENSION [1]

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[1] Erickson, J.E., Lynall, R.C., O'Connor, P.J., Jenkins, N.T., Schmidt, M.D. To be submitted to *Journal of Strength and Conditioning*.

4.1 Abstract

Habitual participation in a resistance training (RT) program has been shown to result in multiple short-term and long-term benefits. One key aspect of acquiring these positive health outcomes is achieving the needed recovery between RT sessions. The recommended recovery time between RT sessions utilizing the same muscle group is ≥48 hours, but research has shown that individuals recover from RT at different rates. If adequate recovery is not gained between RT bouts, nonfunctional overreaching may occur, and in more severe cases, overtraining syndrome. Therefore, it is crucial that a non-invasive, simple, quick, and effective measure of recovery is established. To date, research has been conducted on a variety of autonomic, neuromuscular, and perceived markers of recovery, but a single, valid measure of recovery has yet to be established. In addition, time-under-tension (TUT) has yet to be used as a measure of volume in research assessing recovery markers. Therefore, the aim of this study was to assess the agreement between alternative non-invasive measures of recovery (LnRMSSD, neuromuscular fatigue, and perceptual fatigue, energy, and recovery) up to 48-hours after acute bouts of RT at differing TUT. To do this, subjects performed two different RT protocols (SLOW and FAST) with only TUT being different between them. Within each of these protocols, each measure was assessed at baseline, immediately-post-exercise, 24-hours post-exercise, and 48-hours post-exercise. Results showed that the SLOW session had a significantly higher internal load and that many measures of autonomic, neuromuscular, and perceived recovery were more impacted in this condition than from the lower internal load of the FAST session. Additionally, change scores indicated many of the recovery markers increased or decreased independently of one another, meaning multiple recovery markers may need to be utilized to assess the recovery of each body system. Finally, no matter the condition, HRV showed few correlations to other variables and was recovered by 24-hours post-exercise, further illustrating that recovery of the cardiac autonomic nervous system may not indicate recovery of other body systems.

Index Words: heart rate variability, recovery, fatigue, resistance training, time-under-tension, volume

4.2 Introduction

Resistance training (RT) programs provide health benefits for people across a range of ages and fitness levels, especially those with the goal of improving body composition, muscular strength, and muscular endurance [1]. The main variables associated with a RT prescription include volume (repetitions x external load), intensity (percentage of maximum voluntary strength), and rest time between sets, exercises, and training sessions [2]. Each of these variables can be manipulated to align with an individual's goals, fitness level, and limitations.

One aspect of a RT regimen that has recently come under investigation is the recovery period required after each exercise session as an imbalance between training and recovery can lead to non-functional overreaching and, possibly, overtraining syndrome [3]. The American College of Sports Medicine recommends a recovery period of ≥48 hours between RT sessions utilizing any single muscle group [4], regardless of the type of RT performed. However, there is evidence that RT bouts with moderate-to-high volume loads require a longer recovery time than those with lower volume loads [3, 5]. In contrast, other research has shown that recovery is similar for high volume load (hypertrophy) and low volume load (maximal strength) RT sessions [6]. Therefore, it is unclear whether RT sessions with differing volume loads and intensities require different recovery periods [7].

It is likely that the recovery time necessary following a RT bout is affected by both volume and intensity of the given exercise program [6]. RT with higher volume loads, such as hypertrophy training, has been shown to elicit greater muscle damage, which has been identified as a mechanism of skeletal muscle adaptations [8, 9]. RT sessions that result in greater muscle damage may require longer recovery periods as excessive training volume and load for prolonged periods may result in chronic fatigue, diminished readiness to perform, and decreased fitness levels [5]. In contrast, RT with lower volume loads and intensities, such as endurance training, may not result in muscle damage to the same extent as seen in higher load RT programs, therefore, the recovery period necessary following a lower volume session may not need to be as long.

A variety of methods have been utilized to assess the impact RT has on short-term (~50 minutes) and prolonged (~48 hours) recovery, but many are invasive, require expensive equipment, and/or trained technicians. Simple, non-invasive, less expensive methods of assessing recovery following a RT session are needed; one such option is heart rate variability (HRV), which reflects beat-to-beat changes in heart rate (HR) [10]. HRV is a non-invasive physiological marker of cardiac autonomic nervous system activity and can be measured via HR straps, finger sensors, smart devices, and mobile applications. HRV has become a popular tool for monitoring autonomic responses to exercise-induced stress and as a marker for internal training load [8] and recovery status [11]. A reduced HRV value after an exercise bout indicates a poor recovery status, whereas an increased HRV is indicative of a better recovery status [11]. Those with a higher HRV may be more suited to perform higher load and/or higher intensity workouts without the risk of crossing over into nonfunctional overreaching or overtraining. HRV can be measured using frequency-domain or time-domain indices over the course of long-term (24 hours), short-term (~ 5-10 minutes), or ultra-short-term (< 5 minutes) time periods. An HRV metric commonly used in exercise studies is the root mean square of successive RR interval differences (RMSSD) [12] as it can be used as a measure of parasympathetic cardiac modulation [8, 13] and recovery status [11].

Neuromuscular measures of fatigue, including countermovement jump (CMJ) and isometric handgrip (IHG) assessments, which assess maximal and rapid force production [6], have also been utilized when assessing recovery after an acute RT bout, but haven't shown agreement to other non-invasive measures of recovery, such as autonomic function [8]. Lastly, perceptual markers, such as perceived recovery scales and perceived soreness scales [5] have been used to assess recovery after an acute RT bout due to their ease and feasibility, but haven't been shown to be in agreement with measures of neuromuscular fatigue or autonomic recovery [14]

To date, studies assessing the impact of RT on measures of recovery have calculated volume as volume load (i.e., repetitions x weight), but no studies have assessed the impact of volume, calculated as time-under-tension (TUT), on these recovery measures. TUT refers to the cadence at which each repetition is performed [15] and is most often defined using several digits which correspond to particular movement phases. For example, 4/0/2/0 denotes a 4-second eccentric phase, no break in the transition phase, a 2-second concentric phase, and no rest before the next repetition [15]. Research has shown that consciously manipulating the TUT of each repetition or set of repetitions may impact neuromuscular adaptations [16, 17], perceived exertion [18], hormonal [17, 19, 20], and metabolic [17] responses. Therefore, the aim of this study was to assess the agreement between alternative non-invasive measures of physiological recovery (RMSSD, perceptual fatigue and energy, soreness, recovery, and neuromuscular fatigue) up to 48-hours after acute bouts of RT at differing TUT. We also assessed whether the differing TUT resulted in longer recovery periods for each recovery marker when comparing between conditions. We hypothesized that the higher volume exercise session (SLOW) would lead to greater increases in fatigue for all recovery measures compared to the lower volume session (FAST). In addition, autonomic, neuromuscular, and perceived measures of recovery would regain near or above baseline values at different time-points (e.g., immediately-post, 24-hours post, and 48-hours post-RT).

4.3 Methods

Experimental Approach to the Problem

This study utilized a counterbalanced, cross-over design where each participant completed a total of seven visits to the lab. To compare HRV, neuromuscular, and perceptual measures of fatigue and recovery, subjects performed two different RT protocols (SLOW and FAST) with 24- and 48-hour follow-up sessions after each over a three-to-four-week period. The SLOW protocol consisted of performing the leg press, chest press, and lat pulldown, in that order, with a 4/0/4/0 cadence, whereas the FAST protocol was completed utilizing the same exercises in the same order with a 1/0/1/0 cadence.

After each participant's eligibility was confirmed via an online pre-screening survey, the participant came to the lab for their first visit and completed a one-repetition maximum (1RM) session where informed consent was obtained, height was assessed using a stadiometer (Novel Products, Rockton, Ill), weight was collected using a digital scale (A&D Co., San Jose, CA), and 1RM was assessed on the leg press, chest press, and lat pulldown. After completion of the first visit, each participant was scheduled for the next six visits, which were all scheduled at the same time of day.

During the second visit, HRV, rating of perceived exertion (RPE), perceived recovery and soreness, perceived energy and fatigue, IHG, and CMJ measures were collected before the RT protocol began. During the RT protocol, mean and peak heart rate (HR) were collected, as was RPE after each set of each exercise. After completion of the RT bout, HRV, RPE, perceived recovery and soreness, perceived energy and fatigue, IHG, and CMJ measures were assessed once more.

The third and fourth visits served as the 24-hour and 48-hour follow-up sessions and consisted of assessing HRV, perceived recovery and soreness, perceived energy and fatigue, IHG, and CMJ. Visit five, the second RT session, was identical to visit two, except the participant completed the RT protocol they had not yet performed (e.g., SLOW or FAST). Visits six and seven were 24- and 48-hour follow-up sessions and identical to visits three and four. The sequence of protocol completion was determined by alternating allocation of participants upon study enrollment to ensure balanced sequences and to avoid any period effects.

Subjects

13 healthy, resistance-trained males participated in the study (Table 4.1). They were classified as being resistance-trained if they had participated in six months of RT directly preceding their participation in the study, with completion of leg, chest, and back exercises at least once a week during that time. Inclusion criteria for all participants: (a) to be a male between 18-40 years old; (b) not taking medications, drugs, or supplements that could alter cardiovascular response to exercise; (c) free of signs and symptoms of cardiovascular, metabolic, and renal disease as evidenced by completion of the PAR-Q; and (d) to have no physical limitations or musculoskeletal injuries/disorders that would

hinder the participant from completing the exercise protocol. This project was approved by the University of Georgia Institutional Review Board.

One-Repetition Maximum Determination

1RM testing for the leg press, chest press, and lat pulldown were assessed during the first visit using Cybex resistance exercise machines (Franklin Park, Ill) after a brief warm-up. The warm-up consisted of a 5-minute walk on a treadmill at 3 mph, 10 bodyweight squats, 10 push-ups, and self-selected dynamic stretching of the upper and lower body. After the warm-up, participants completed 1RM testing for each of the exercises [7]. First, they completed ten repetitions at a self-selected light resistance, followed by a 1-minute rest period. They then completed five repetitions at a self-selected moderate resistance, followed by a 2-minute rest period. Next, participants completed a near-maximal load for three repetitions, followed by a 3-minute rest period. Finally, participants completed one-repetition at an estimated maximal load, followed by a three-minute rest period. After this attempt was complete, resistance was increased 10 to 20 pounds for upper body exercise or 30 to 40 pounds for lower body exercise for each successive attempt until a 1RM was successfully completed with correct form.

If a participant was unable to complete an attempt, the last successful attempt was recorded as their 1RM. If a participant could complete the maximum amount of weight allowed by the machine, the participant completed as many repetitions as possible with correct form at that weight and the Epley equation (1RM = [(0.033 x number of repetitions) x (weight)] + weight) was used to estimate 1RM. The Epley equation utilizes the maximum number of repetitions performed using a given weight to provide an estimate of 1RM and is one of the most popular prediction equations for estimating 1RM [21].

Resistance Training Sessions

The RT protocol was performed after baseline measures of HRV, RPE, perceived recovery and soreness, perceived energy and fatigue, IHG, and CMJ were recorded. Once again, a warm-up was completed identical to that of the 1RM session before the IHG and CMJ measures. Each RT protocol utilized 50% of 1RM for each of the three exercises (e.g., leg press, chest press, and lat pulldown, in that order) for three sets of eight repetitions with one minute of rest between sets and exercises. The lone difference between the two exercise sessions was the volume being utilized as one session utilized a 1/0/1/0 TUT (i.e., FAST) and the other a 4/0/4/0 TUT (i.e., SLOW) (Table 4.2). To ensure the correct cadence was maintained throughout each repetition, a smart device metronome application was used (Soundbrenner, version 1.24, Hong Kong, China). If a participant were to become too fatigued to continue at the required cadence, a researcher would give assistance to ensure the cadence was maintained throughout each set of repetitions without manipulating any of the other components of the RT bout including rest between sets and exercises.

Measures of Heart Rate Variability and Heart Rate

Measures of HRV were collected using a Polar H10 Heart Rate Strap (Polar Electro, Kemple, Finland) at a sampling rate of 130 Hz [22, 23] and a cost-free mobile application (Elite HRV Version 5.5.4, Ashville, NC, USA) [24] at baseline, immediately-post-RT, as well as 24- and 48-hours post-RT for both exercise sessions. All HRV readings were collected in an identical fashion. To obtain an HRV reading, the participant was seated, quiet, and still for a 1-minute stabilization period, after which they would inhale and exhale at the pace instructed through the mobile app for 1-minute. After all HRV measures were collected, they were exported via email to the researchers for R-R filtering using Kubios HRV Premium software (Version 3.5, Kuopio, Finland). RMSSD values were converted to the natural log of RMSSD (LnRMSSD) as ultra-short (i.e., 1-minute) LnRMSSD measures have been shown to be no different from criterion 5-minute measures, require only a brief stabilization period, and are sensitive to training-induced changes [14].

HR was collected during each RT bout using a Polar H10 Heart Rate Strap (Polar Electro, Kemple, Finland) and a cost-free mobile application (Polar Beat version 3.5.2, Kemple, Finland). At the start of the first exercise (e.g., leg press) the researcher would begin collecting HR data on a smart device and continuously collect data until completion of the final repetition of the final exercise (e.g., lat pulldown). The mean and peak HR collected on the app would then be recorded for analysis.

Rating of Perceived Exertion

RPE was assessed using the Borg Scale (6-20) and was recorded at baseline and immediately-post each exercise session as well as during the RT protocol. For measures of RPE during the RT protocol, participants were instructed to report the level of effort they experienced after each set of each exercise [25]. The three values were averaged to calculate an overall RPE for each exercise. At the conclusion of each RT protocol, participants would report their RPE for the RT session as a whole.

Perceived Recovery and Soreness

Perceived recovery and soreness were assessed at baseline, immediately-post, as well as 24- and 48-hours post-RT. A 0-10 scale was administered to assess recovery where 0 = “no recovery at all” and 10 = “most complete recovery imaginable”. Soreness of the legs, chest, back, and arms were all assessed individually utilizing a 0-10 scale where 0 = “no soreness at all” and 10 = “most soreness imaginable”.

Perceived Energy and Fatigue Assessment

The Mental and Physical State Energy and Fatigue Scales were utilized to assess mood states at baseline, immediately-post, and 24- and 48-hours post each exercise session. Participants indicated their current subjective feelings of physical energy, physical fatigue, mental energy, and mental fatigue on a series of 0-10 visual analog scales. Three items for each dimension of energy and fatigue were presented and added together for a score ranging from 0 to 30. Higher scores indicated more intense feelings [26].

Neuromuscular Performance

CMJ and IHG were used as assessments for neuromuscular fatigue. These measures were assessed immediately before each RT bout, immediately-post each RT bout, and 24-hours and 48-hours after each exercise session. Before each CMJ assessment, the participant completed three warm-up jumps at 50%, 70%, and 90% of maximum effort, followed by three maximal jumps with 60 seconds rest between attempts. To perform the CMJ, subjects were instructed to fix their hands on the hips, flex their hips and knees to a self-selected depth and jump as high as possible. Height and power for each CMJ were collected using a portable force plate (OR6, AMTI, Watertown, MA, USA) sampling at 1000 Hz [14] using AMTI Netforce acquisition software (Netforce, AMTI, Watertown, MA, USA). The three CMJ attempts at each time-point were then averaged to calculate measures of height and power for that collection period.

Power and jump height were calculated as previously described [14] using custom Matlab (Mathworks, Natick, MA) code. Vertical ground reaction force data were filtered with a zero-phase lag Butterworth filter at 50 Hz. Each participant's body weight was subtracted from the vertical ground reaction force time curve, then divided by their body mass, and integrated relative to time using the trapezoidal rule. Power was then calculated as maximum vertical ground reaction force times velocity. Jump height was calculated using the formula [jump height = (9.81 x ((time in air during jump)^2)) / 8] [27].

IHG was assessed using a Jamar dynamometer (G.E. Miller, Inc., Yonkers, New York). To collect measures of IHG, participants were in a standing position with the grip bar under the second joint of their fingers. While holding the dynamometer in line with the forearm at the level of the thigh, away from the body, the participant squeezed as hard as they could without holding their breath or letting their hand nor the dynamometer touch their body. This test was repeated twice with each hand and the scores that were the highest of the three readings for each hand were added together and recorded as their grip strength score in kilograms [4].

Statistical Analyses

All data were analyzed with IBM SPSS version 28.0.0.0. for Windows and Microsoft Excel version 2202. Data normality was assessed visually using histograms and statistically with Shapiro-Wilks tests. Outliers were identified as having a value that was > 3 SD from the mean. No outliers were identified. A 2 (session) × 4 (time) repeated measures analysis of variance (ANOVA) was used to assess differences between baseline and post-exercise LnRMSSD, physical energy, physical fatigue, mental energy, mental fatigue, recovery, leg soreness, chest soreness, back soreness, arm soreness, IHG, and CMJ power and height values at four time-points within and between conditions. Sphericity was assessed using Mauchly's test and, if violated, the Greenhouse-Geisser correction was utilized to adjust for a lack of sphericity. For variables where there was a significant TUT*time interaction, separate one-way ANOVAs were run separately for SLOW and FAST conditions to assess the significance of time effects. Pearson's correlations were calculated between change scores of HRV and other non-invasive measures of recovery separately for the SLOW and FAST conditions and defined as weak (0.10-0.30), moderate (0.30-0.50), or strong (0.50-1.0). Percent change scores were calculated using the equation (post-baseline)/baseline x 100. The sample a priori power was calculated using G*Power 3.1.9.7. With an ES of 0.5, a significance level of .05, and a power (β) of 0.80 for two sessions (SLOW, FAST) with repeated-measures at four time points (baseline, immediately-post, 24h, and 48h). This resulted in an estimated minimum sample size of eight participants [5]. Data are presented as mean ± standard deviation, unless otherwise stated, and statistical significance was set at an alpha level of 0.05.

4.4 Results

Measures of internal load, including mean HR ($p = 0.032$), peak HR ($p < 0.001$), RPE leg press ($p < 0.001$), RPE chest press ($p < 0.001$), RPE lat pulldown ($p < 0.001$), and overall RPE ($p < 0.001$) were significantly higher in the SLOW session (Table 4.3).

Significant interactions between TUT and time were seen for LnRMSSD ($p = 0.014$), physical energy ($p < 0.01$), physical fatigue ($p < 0.001$), mental fatigue ($p < 0.01$) and soreness ($p < 0.001$) (Table 4.4 and Table 4.5), which was calculated by averaging all measures of soreness (leg, chest, back, arm) at each time-point within each condition into one value. Among recovery markers without a significant interaction, there were significant main effects of time for subjective recovery ($p < 0.001$) and CMJ height ($p < 0.014$) (Table 4.6) and significant main effects of TUT for subjective recovery ($p = 0.015$) (Table 4.7).

Mean values of multiple markers of recovery changed significantly from baseline to post-exercise in both sessions (Table 4.8 and 4.9). Within the SLOW condition, there were significant changes from baseline to immediately-post-exercise for LnRMSSD ($p < 0.001$), physical energy ($p < 0.01$), physical fatigue ($p < 0.001$), mental fatigue ($p < 0.01$), subjective recovery ($p < 0.001$), soreness ($p < 0.001$), and CMJ height ($p < 0.01$). Among these, only subjective recovery ($p < 0.001$) was significantly different from baseline until 24-hours post-exercise. In addition, physical fatigue ($p < 0.01$) and soreness ($p < 0.001$) were significantly different from baseline until 48-hours post-exercise. IHG ($p = 0.049$) was significantly different from baseline at 24-hours post-exercise as well, but not immediately-post.

The FAST session resulted in significant change scores from baseline to immediately-post-exercise for LnRMSSD ($p < 0.01$), subjective recovery ($p < 0.001$), soreness ($p < 0.001$), and CMJ height ($p < 0.01$), but no change scores were significantly different from baseline by 24-hours post-exercise in this condition. We also observed significant time effects within the SLOW condition for LnRMSSD ($p < 0.001$), physical energy ($p < 0.001$), physical fatigue ($p < 0.001$), mental fatigue ($p < 0.001$), subjective recovery ($p < 0.001$) soreness ($p < 0.001$), and CMJ height ($p < 0.001$). In the FAST condition, significant time effects were seen for measures of LnRMSSD ($p < 0.026$), physical fatigue ($p < 0.046$), and soreness ($p < 0.01$).

The length of recovery needed to regain near or above baseline values, if achieved during the 48-hour follow-up sessions, illustrates the effect the higher volume (i.e., SLOW) session had on the objective and subjective measures of recovery when compared to the lower volume session (i.e., FAST). When comparing correlations between LnRMSSD and other measures of recovery within the FAST condition, only physical fatigue had a significant correlation (Table 4.10), and only immediately-post. Within the SLOW condition, LnRMSSD was significantly correlated with physical fatigue 48-hours post-RT (Table 4.10), but no other significant correlations were seen.

4.5 Discussion

The primary aim of this study was to assess the agreement between alternative non-invasive measures of physiological recovery (RMSSD, perceptual fatigue and energy, soreness, recovery, and neuromuscular fatigue) up to 48-hours after acute bouts of RT at differing TUT. The study showed that the SLOW session resulted in a greater internal load and that change scores from baseline to post-exercise were larger within the SLOW condition. The SLOW session also resulted in multiple recovery markers being significantly different from baseline after 24-hours and others that were significantly different after 48-hours post-exercise. The FAST session also had recovery markers that were significantly different from baseline, but no significant differences were seen after that. Another important finding is that many of the recovery markers recovered at different time-points, and some never fully recovered within the 48-hour follow-up period. Therefore, one recovery marker may not be sufficient to illustrate the recovery status of the body as a whole. Finally, only physical fatigue was correlated to LnRMSSD within each condition, but at different time-points.

While external measures of load provide important information, they may not accurately reflect internal load, making the prediction and assessment of physiological training outcomes very difficult [28]. Our results showed significantly higher values of mean HR, peak HR, RPE leg press, RPE chest press, RPE lat pulldown and overall RPE during the SLOW TUT condition, confirming that the SLOW sessions did indeed result in a greater internal load. Hiscock et al. [29] performed a study assessing session RPE on 12 young, male athletes with at least 12 months of RT experience and found that session RPE is sensitive to power, strength, and hypertrophy exercise and may also reflect the magnitude and duration of reduced neuromuscular performance following an exercise session. The authors stated that hypertrophy training, which had the highest volume load (calculated as repetitions x external resistance), led to longer durations of reduced CMJ performance. In the current study, there was a significant decrease in CMJ height from baseline to immediately-post-exercise for the both the SLOW and FAST protocols, therefore, we cannot conclude that differing TUTs result in greater neuromuscular fatigue based on measures of CMJ height.

The current study showed significant differences between baseline measures of HRV and those immediately-post-exercise in both conditions, but they were no longer significant by 24-hours post-exercise. Our results are in agreement with Thamm et al. [6] who compared a hypertrophy session to a maximal strength session in ten healthy young men. Their study showed there was a significant decrease in HRV for both sessions and that HRV recovered within 24-hours of each exercise bout. Additionally, Holmes et al. [5] conducted a study comparing the HRV response between low-volume, moderate-volume, and high-volume RT sessions in ten young, resistance-trained males and females. Their results showed significant differences in that the moderate- and high-volume sessions led to significantly greater decreases in HRV than the low-volume session, which was in agreement with the results of our study as the SLOW session resulted in decreases in LnRMSSD twice as large as what was seen in the FAST session immediately-post-exercise. However, their study only assessed HRV for 30-minutes post-exercise, so no comparisons can be made with the current study in relation to time to recovery.

When assessing measures of neuromuscular recovery, CMJ height was the only variable significantly different from baseline at immediately-post-exercise. A study by Holmes et al. [8] using thirty healthy, resistance-trained males and females was in agreement as they saw a significant decrease in CMJ height from baseline to 30-minutes post a moderate load RT bout, but since no other follow-up measures were recorded, no other comparisons can be made. Furthermore, results from a study by Flatt et al. [14] on ten young males with at least one year of resistance training experience found a significant decrease in CMJ power from baseline at 24-hours post-exercise, which is not in agreement with the current study as no significant differences were seen between baseline and post-measures of CMJ power in either condition.

We also observed significant differences in perceived measures of subjective recovery and soreness when compared to baseline. This is in agreement with Flatt et al.

[14] who found significant decreases in measures of perceived recovery up to 48-hours post-exercise, although in the current study subjective recovery was not significantly different from baseline by 24-hours post-exercise in the FAST session or by 48-hours post-exercise in the SLOW session. Flatt et al. [14] also saw significant increases in soreness up to 48-hours post-exercise, which the current study observed in the SLOW session, but in the FAST session soreness was no longer significantly different from baseline by 24-hours post-exercise Furthermore, Sikorski et al. [30] used 0-10 scales to assess perceived soreness in 35 highly resistance-trained young participants and found significant increases in soreness post-exercise when compared to baseline measures, which is in agreement with the current study, but no further follow-up measures of soreness were recorded so no further comparisons can be made. The extent as to how much the exercise volume and intensity of these studies are related to their subjective recovery and soreness outcomes are difficult to compare to the current study as Flatt et al. [14] had their participants perform to momentary failure using 90% of 10 repetition maximum whereas the current study did not have participants exercise to failure. Additionally, Sikorski et al. [30] had each participant complete nine exercises for three sets of 10- to 12-repetition maximum, which was far more than was required for the current study. Finally, neither of these studies recorded the TUT utilized, so comparisons of volume between these two studies and the current study cannot be done.

The current study saw significant decreases in perceived physical energy and mental fatigue from baseline to immediately-post-exercise in the SLOW session, as well as a significant increase in perceived physical fatigue up to 48-hours post-exercise. A study by Ward-Ritacco et al. [26] contradicts our findings as they assessed the impact of

RT on 26 pregnant women and saw increases in perceived energy and decreases in perceived fatigue after a single bout of RT, although the RT session used in the study was low-to-moderate intensity. Herring et al. [31] used the Profile of Mood States-Brief Form questionnaire to assess feelings of fatigue and energy in 14 young, sedentary women 11 minutes and 40 seconds after each set of an acute RT bout and 20 and 30 minutes after the completion of the exercise bout. The authors reported no significant differences in perceived fatigue during or after each condition compared to baseline levels, but measures of perceived energy were increased during and after the exercise bout compared to baseline measures, which is not in agreement with the current study. The extended TUT of the SLOW session may be why the current study saw significant decreases in physical energy and increases in mental fatigue while the studies by Ward-Ritacco and Herring did not as they utilized a 2/0/2/0 tempo compared to the current study's 4/0/4/0 tempo.

Finally, only physical fatigue was significantly correlated to measures of LnRMSSD, and only in the FAST session between baseline and immediately-post-exercise and the SLOW session between baseline and 48-hours post-exercise. This indicates that LnRMSSD may not be a good measure of overall recovery after an acute bout of RT. To add to this, many of the recovery markers were significantly different long after LnRMSSD had returned to above baseline levels. Other studies have shown evidence for this as well and stated that the recovery status for one system should not infer the recovery status of another as each marker appears to be independent of the others. [8, 14]. To date, evidence is limited as to whether measures of objective and subjective recovery are more sensitive to volume, intensity, rest periods between sets and exercises, or other RT variables.

Strengths and Limitations

A strength of the study included the use of a counterbalanced, cross-over design since many measures of recovery are individualized. Therefore, using separate groups rather than one group may show significant differences, or no significant differences between markers of recovery leading to inaccurate results. Another strength was the use of identical exercise protocols with only TUT being different in a controlled environment.

Limitations of the study include a small sample size of participants which may have impacted the precision of the correlations between the different recovery measures. Additionally, we needed to estimate 1RM for some participants, which may not accurately reflect a true 1RM. In addition, only young, healthy, resistance-trained males participated in the study, so results may not be reflective of what may be seen in other populations. Lastly, RT sessions utilizing differing TUT, number or sets, repetitions, exercises, rest intervals, and/or equipment could result in findings different than that of the current study as manipulating each of these RT variables can independently impact the physiology of the body.

4.6 Conclusion

Many of the recovery markers assessed were impacted more by the SLOW session than the FAST, as evidenced by the comparison of change scores between the two conditions. Additionally, each recovery marker within each condition seemed to be independent of the others as some of them were unaffected, while others were significantly different up to 48-hours post-exercise. For this reason, our results agree with most other studies and suggest that practitioners should use a variety of recovery measures to assess each aspect of recovery (e.g., autonomic, neuromuscular, perceived) after RT with a slow or fast repetition cadence as each marker of recovery may be influenced to a different extent than the others, and the magnitude to which each is impacted may be based on different RT variables. Future research should focus on assessing the impact of various RT variables on markers of recovery to better understand the relationship between exercise prescription variables and the body systems they effect.

4.7 References

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Table 4.1 Participant Demographics, (n=13)

Characteristic	Mean ± SD
Age (years)	21.6 ± 0.8
Height (cm)	178.6 ± 4.7
Body mass (kg)	84.0 ± 7.3
1RM leg press (kg)	223.8 ± 44.7
1RM chest press (kg)	131.4 ± 27.7
1RM lat pulldown (kg)	102.7 ± 17.3

SD = standard deviation

Table 4.2 Total Volume for Each Resistance Training Protocol, (n=13)

Protocol	Sets	Repetitions	Concentric Phase (s)	Eccentric Phase (s)	TUT per repetition (s)	Total TUT (s)
FAST	9	8	1	1	2	144
SLOW	9	8	4	4	8	576

s = seconds; total TUT calculated as “sets x repetitions x TUT per repetition”

Table 4.3 Comparison of Internal Load Measures Between Sessions, (n=13)

Variable	FAST	SLOW	p-value
Mean HR (bpm)	107.8 ± 22.4	120.6 ±16.6	0.032*
Peak HR (bpm)	131.7 ± 24.1	150.5 ± 21.6	< 0.001**
Baseline RPE	6.0 ± 0.0	6.1 ± 0.3	0.337
RPE leg press	10.6 ±1.7	13.9 ± 2.6	< 0.001**
RPE chest press	11.4 ± 1.6	15.7 ± 1.9	< 0.001**
RPE lat pulldown	11.0 ± 1.5	15.2 ± 1.9	< 0.001**
Overall RPE	11.4 ± 1.5	16.1 ± 2.0	< 0.001**

HR = heart rate; bpm = beats per minute; RPE = rating of perceived exertion; *Significant difference between conditions ($p < 0.05$); **Significant difference between conditions ($p < 0.01$).

Table 4.4 Baseline and Post-Training Values (Mean ± SD) for Objective Measures of Recovery, (n=13)

Recovery Metric	Protocol	Baseline	IP	24-hours post	48-hours post	TUT * Time	
						F-statistic	p-value
LnRMSSD	FAST	4.25 ± 0.82	3.61 ± 1.00	4.35 ± 0.69	4.36 ± 0.68	4.03	0.014*
	SLOW	4.33 ± 0.50	2.97 ± 0.96	4.47 ± 0.49	4.62 ± 0.51		
IHG (kg)	FAST	84.46 ± 14.50	83.15 ± 16.28	82.92 ± 14.03	80.62 ± 15.30	0.765	0.521
	SLOW	80.85 ± 16.63	79.46 ± 17.71	76.38 ± 16.32	78.08 ± 15.41		
CMJ power (W)	FAST	4937.61 ± 1120.13	4850.18 ± 1551.69	5076.59 ± 1377.37	5229.82 ± 1554.34	0.89	0.413
	SLOW	4700.16 ± 810.92	4608.63 ± 896.52	5440.60 ± 1981.73	4942.04 ± 1582.53		
CMJ height (m)	FAST	0.36 ± 0.06	0.35 ± 0.06	0.36 ± 0.06	0.34 ± 0.07	3.60	0.051
	SLOW	0.36 ± 0.06	0.34 ± 0.05	0.36 ± 0.05	0.36 ± 0.05		

TUT = time-under-tension; IP = immediately-post; LnRMSSD = natural logarithm of the root mean square of successive RR differences; IHG = isometric handgrip; kg = kilograms; CMJ = countermovement jump; W = watts; m = meters; *Significant difference between TUT protocols across time-points ($p < 0.05$)

Table 4.5 Baseline and Post-Training Values (Mean ± SD) for Subjective Measures of Recovery, (n=13)

Recovery Metric	Protocol	Baseline	IP	24-hours post	48-hours post	TUT * Time	
						F-statistic	p-value
Physical energy (0-30)	FAST	20.85 ± 4.26	19.62 ± 4.86	20.69 ± 5.66	20.31 ± 5.77	5.38	< 0.01**
	SLOW	19.31 ± 5.72	13.62 ± 6.46	19.23 ± 4.09	19.54 ± 4.33		
Physical fatigue (0-30)	FAST	5.46 ± 3.89	8.15 ± 4.60	6.00 ± 3.76	5.92 ± 3.75	15.37	< 0.001**
	SLOW	4.54 ± 3.46	17.46 ± 6.08	9.92 ± 5.91	8.23 ± 3.70		
Mental energy (0-30)	FAST	19.54 ± 5.72	19.15 ± 5.19	20.31 ± 5.15	18.69 ± 5.81	1.24	0.308
	SLOW	17.85 ± 5.90	15.92 ± 6.75	18.77 ± 5.12	18.62 ± 5.92		
Mental fatigue (0-30)	FAST	7.92 ± 5.25	9.00 ± 4.67	7.15 ± 4.51	8.85 ± 5.26	4.83	< 0.01**
	SLOW	7.85 ± 6.88	13.54 ± 6.28	9.15 ± 5.54	8.46 ± 4.33		
Subjective recovery (0-10)	FAST	8.62 ± 1.33	6.85 ± 1.73	7.69 ± 2.29	8.23 ± 2.39	3.24	0.055
	SLOW	8.23 ±1.96	4.23 ± 2.01	6.15 ± 1.68	7.77 ± 1.09		
Soreness (0-10)	FAST	0.62 ± 0.13	1.75 ± 0.45	0.90 ± 0.17	0.52 ± 0.07	26.79	< 0.001**
	SLOW	0.40 ± 0.30	4.62 ± 0.72	3.54 ± 0.66	1.77 ± 0.49		

TUT = time-under-tension; IP = immediately-post; **Significant difference between TUT protocols across time-points (p < 0.01).

Table 4.6 Time Effects for Both Conditions Combined for Each Variable without a Significant Interaction, (n=13)

Variable	Mean ± SD	Δ (%)	(p-value)
Mental energy			
Baseline	18.69 ± 5.76	-	-
IP	17.54 ± 6.13	-6.15	0.267
24h	19.54 ± 5.09	4.55	0.276
48h	18.65 ± 5.75	-0.21	0.967
Time effects (p-value)	0.120		
Subjective recovery			
Baseline	8.42 ± 1.65	-	-
IP	5.54 ± 2.27	-34.20	< 0.001**
24h	6.92 ± 2.12	-17.81	< 0.01**
48h	8.00 ± 1.83	-4.99	0.343
Time effects (p-value)	< 0.001**		
IHG (kg)			
Baseline	82.65 ± 15.40	-	-
IP	81.31 ± 16.78	-1.62	0.222
24h	79.65 ± 15.28	-3.63	0.063
48h	79.35 ± 15.10	-3.99	0.032*
Time effects (p-value)	0.247		
CMJ power (W)			
Baseline	4818.88 ± 965.96	-	-
IP	4729.41 ± 1247.97	-1.86	0.343
24h	5258.59 ± 1682.31	9.12	0.109
48h	5085.93 ± 1543.80	5.54	0.199
Time effects (p-value)	0.192		
CMJ height (m)			
Baseline	.36 ± 0.06	-	-
IP	.34 ± 0.05	-5.56	< 0.001**
24h	.36 ± 0.05	-0.001	0.928
48h	.35 ± 0.06	-2.78	0.430
Time effects (p-value)	0.014*		

SD = standard deviation; Δ calculated as ((post-baseline)/baseline*100); IHG = static handgrip; kg = kilograms; CMJ = countermovement jump; W = watts; m = meters; IP = immediately-post-exercise; 24h = 24-hours post-exercise; 48h = 48-hours post-exercise; *Significant difference between time-points or time effects (p < 0.05); **Significant difference between time-points or time effects (p < 0.01).

Table 4.7 TUT Effects for All Time-Points Combined Within Each Condition for Each Variable without a Significant Interaction, (n=13)

Variable	Mean ± SD	Comparison to Baseline (p-value)
Mental energy		
FAST	19.42 ± 5.35	0.015*
SLOW	17.79 ± 5.89	
TUT effects (p-value)	0.073	
Subjective recovery		
FAST	7.85 ± 2.03	< 0.001**
SLOW	6.60 ± 2.30	
TUT effects (p-value)	0.015*	
IHG (kg)		
FAST	82.79 ± 14.67	< 0.01**
SLOW	78.69 ± 16.13	
TUT effects (p-value)	0.109	
CMJ power (W)		
FAST	5023.55 ± 1377.57	0.597
SLOW	4922.86 ± 1401.22	
TUT effects (p-value)	0.700	
CMJ height (m)		
FAST	0.35 ± 0.06	0.759
SLOW	0.35 ± 0.05	
TUT effects (p-value)	0.814	

SD = standard deviation; Δ calculated as ((post-baseline)/baseline*100); IHG = static handgrip; kg = kilograms; CMJ = countermovement jump; W = watts; m = meters; *Significant difference between conditions or TUT effects ($p < 0.05$); **Significant difference between conditions or TUT effects ($p < 0.01$).

Table 4.8 Changes from Baseline HRV, Physical and Mental Energy and Fatigue, and Perceived Recovery within Protocols, (n=13)

Variable	FAST Δ (%)	SLOW Δ (%)
LnRMSSD		
IP	-15.06**	-31.18**
24h	2.59	3.47
48h	2.59	6.93
Time effects (p-value)	0.026*	< 0.001**
Physical energy		
IP	-5.90	-29.46**
24h	-0.71	-0.41
48h	-2.59	1.19
Time effects (p-value)	0.427	< 0.001**
Physical fatigue		
IP	49.26	284.58**
24h	9.89	118.50**
48h	8.42	81.27**
Time effects (p-value)	0.046*	< 0.001**
Mental energy		
IP	-1.94	-10.75
24h	3.94	5.15
48h	-4.35	4.31
Time effects (p-value)	0.453	0.145
Mental fatigue		
IP	13.64	72.48**
24h	-9.72	16.68
48h	11.62	7.90
Time effects (p-value)	0.163	< 0.001**
Subjective recovery		
IP	-20.53**	-48.60**
24h	-10.67	-25.27**
48h	-4.41	-5.58
Time effects (p-value)	0.095	< 0.001**

HRV = heart rate variability; Δ calculated as ((post-baseline)/baseline*100); LnRMSSD = natural logarithm of the root mean square of successive RR differences; IP = immediately-post-exercise; 24h = 24-hours post-exercise; 48h = 48-hours post-exercise; *Significant difference between measures ($p < 0.05$); **Significant difference between measures ($p < 0.01$).

Table 4.9 Changes from Baseline Perceived Soreness and Neuromuscular Measures within Protocols, (n=13)

Variable	FAST Δ (%)	SLOW Δ (%)
Soreness		
IP	184.38**	1042.99**
24h	46.88	776.29**
48h	-15.63	338.14**
Time effects (p-value)	< 0.01*	< 0.001**
IHG (kg)		
IP	-1.55	-1.71
24h	-1.82	-5.52*
48h	-4.56	-3.43
Time effects (p-value)	0.509	0.135
CMJ power (W)		
IP	-1.77	-1.94
24h	2.81	15.75
48h	5.92	5.15
Time effects (p-value)	0.524	0.196
CMJ height (W)		
IP	-2.78**	-5.63**
24h	-0.83	0.85
48h	-5.56	2.82
Time effects (p-value)	0.193	< 0.001**

Δ calculated as ((post-baseline)/baseline*100); IHG = isometric handgrip; CMJ = countermovement jump; IP = immediately-post exercise; 24h = 24-hours post-exercise; 48h = 48-hours post-exercise; *Significant difference between measures ($p < 0.05$); **Significant difference between measures ($p < 0.01$).

Table 4.10 Pearson Correlations Between Measures of HRV, Perceived Energy and Fatigue, Perceived Recovery, Perceived Soreness, and Neuromuscular Recovery, (n=13)

Baseline to IP	LnRMSSD (FAST)	LnRMSSD (SLOW)
P energy	0.096	0.011
P fatigue	-0.658*	0.181
M energy	0.450	-0.048
M fatigue	-0.493	0.350
Subjective recovery	0.147	-0.135
Soreness	-0.372	-0.100
IHG	-0.186	0.070
CMJ power	0.045	-0.058
CMJ height	-0.033	0.279
Baseline to 24h	LnRMSSD (FAST)	LnRMSSD (SLOW)
P energy	0.043	0.092
P fatigue	0.212	-0.311
M energy	-0.358	-0.024
M fatigue	0.160	-0.205
Subjective recovery	0.256	0.163
Soreness	0.073	-0.278
IHG	-0.415	-0.354
CMJ power	0.438	0.386
CMJ height	-0.145	-0.104
Baseline to 48h	LnRMSSD (FAST)	LnRMSSD (SLOW)
P energy	-0.135	-0.071
P fatigue	0.266	0.745**
M energy	-0.350	0.370
M fatigue	0.148	0.409
Subjective recovery	0.200	-0.346
Soreness	-0.069	0.285
IHG	-0.217	-0.155
CMJ power	0.419	0.043
CMJ height	0.075	0.141

HRV = heart rate variability; LnRMSSD = natural log of the root mean square of successive RR differences; IHG = isometric handgrip; P = physical; M = mental; IP = immediately-post; 24h = 24-hours post-exercise; 48h = 48-hours post-exercise; *Significant correlation at ($p < 0.05$); **Significant correlation at ($p < 0.01$)

CHAPTER 5

SUMMARY AND CONCLUSIONS

The findings of the current study add to the body of exercise literature in multiple ways. It is well-established that the completion of resistance training (RT) can benefit an individual through improvements in muscular strength, power, and muscular endurance. In addition to improving performance, RT can help improve an individual’s cardiometabolic risk profile, which is why it has become one of the most popular modes of exercise. In order to reap the full benefits of RT, one must adhere to appropriate recovery between RT sessions. The recovery necessary is dependent on the magnitude, duration, and mode of training, making it difficult to assess. Without adequate recovery, an individual risks non-functional overreaching and overtraining, which can lead to decrements in performance, injury, and other physiological and psychological consequences. Therefore, recent research has focused on finding non-invasive, quick, and simple methods for assessing recovery status after a RT bout.

One metric that has been researched in depth in this area is that of heart rate variability (HRV). Multiple researchers have manipulated a variety of RT variables to better understand their impact on HRV. Furthermore, previous studies have assessed HRV along with measures of neuromuscular fatigue, perceived soreness, and perceived recovery to see if there is agreement among them. By closing the gaps within the area of RT and recovery, we can better suit all those who participate in RT.

The first portion of this study attempted to close a gap surrounding the effect of time-under-tension (TUT) on different metrics of HRV over a 48-hour period. In addition, we assessed whether there were any correlations between each of these HRV metrics and measures of internal load including mean and peak heart rate, and rating of perceived exertion. Key findings included the SLOW session (e.g., 4/0/4/0) resulting in higher internal load measures than the FAST session (e.g., 1/0/1/0). We also saw significant decreases from 15-30% from baseline to immediately-post-exercise for LnRMSSD in both sessions, but there were no significant differences between groups. Furthermore, there were no significant within or between group differences for other measures of HRV. Mean HR was strongly correlated to changes in LnRMSSD in both sessions, whereas it was only correlated to changes in LnLF and LnLF/HF in the SLOW session. Lastly, all measures of HRV returned to near or above baseline within 24-hours post-exercise. These findings are in agreement with other studies that observed significant decreases in RMSSD from baseline to immediately-post-exercise. These studies also had similar results regarding the recovery of HRV, in that RMSSD was not significantly different from baseline by 24-hours.

The second portion of the study assessed the agreement between alternative non-invasive measures of physiological recovery (LnRMSSD, perceptual fatigue and energy, perceived recovery and soreness, and neuromuscular fatigue) up to 48-hours after acute bouts of RT at differing TUT. Our findings showed that the SLOW session resulted in a greater internal load and that change scores of LnRMSSD, countermovement jump height, physical energy, physical fatigue, mental fatigue, subjective recovery, and soreness were significantly different from baseline immediately-post RT. The SLOW session also resulted in measures of isometric handgrip strength, physical fatigue, subjective recovery, and soreness being significantly different from baseline after 24-hours. Lastly, physical fatigue and soreness measures were significantly different from baseline 48-hours post-exercise. The FAST session also had recovery markers that were significantly different from baseline, including LnRMSSD, countermovement jump height, subjective recovery, and soreness, but all measures were not significantly different from baseline by 24-hours post-exercise.

Another important finding is that many of the recovery markers recovered at different time-points, and some never fully recovered within the 48-hour follow-up period. Therefore, one recovery marker may not be sufficient to illustrate the recovery status of the body as a whole. Finally, only physical fatigue was significantly correlated to LnRMSSD within each condition, but at different time-points. Specifically, change in physical fatigue was significantly correlated to the change in LnRMSSD immediately-post-exercise in the FAST session and 48-hours post-exercise in the SLOW session. Overall, our results agree with most other studies and suggest that practitioners should use a variety of recovery measures to assess each aspect of recovery (e.g., autonomic, neuromuscular, perceived) after RT.

To conclude, our research illustrates that each marker of recovery may be influenced to a different extent after a bout of RT, no matter the TUT. Perceived measures of recovery, such as physical energy, physical fatigue, mental energy, mental fatigue, subjective recovery, and soreness differed in the duration needed to return to baseline levels. In the same fashion, neuromuscular measures had different patterns of recovery as well. Finally, LnRMSSD was recovered at 24-hours post-exercise in both conditions and correlations between change in LnRMSSD and changes in other measures of recovery varied substantially across measures and across time-points. The evidence from the current study suggests that the ACSM guidelines recommending a rest of ≥48 hours between sessions for any single muscle group may be too broad and that the duration of rest required between sessions should be individualized based on an individual's specific exercise bout and training status.

Future research should assess how HRV changes with chronic training and whether different volumes, intensities, and exercise orders influence the time needed for recovery of the autonomic nervous system. Furthermore, measures of neuromuscular and perceived recovery should be included in future research to better understand how each is related to HRV with chronic training and whether there is a measure of recovery that is more sensitive to changes in performance, overtraining, and psychological well-being. Finally, the utility of measures of neuromuscular, perceived, and autonomic recovery may vary across individuals, therefore, relying on a single measure of recovery may not be warranted at this time.