HIGH INTENSITY INTERVAL TRAINING VERSUS

MODERATE INTENSITY CONTINUOUS TRAINING

TO MAXIMIZE NEUROMUSCULAR ADAPTATIONS

By

MASOUD MOGHADDAM

Bachelor of Science in Physical Education
Imam Reza International University
Mashhad, IRAN
2014

Master of Science in Exercise Science
Texas A&M University-Commerce
Commerce, Texas
2016

Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
DOCTOR OF PHILOSOPHY
May, 2020

HIGH INTENSITY INTERVAL TRAINING VERSUS

MODERATE INTENSITY CONTINUOUS TRAINING

TO MAXIMIZE NEUROMUSCULAR ADAPTATIONS

Dissertation Approved:

Dr. Bert H. Jacobson
_____
Dissertation Adviser

Dr. Douglas B. Smith
_____

Dr. Nathaniel D.M. Jenkins
_____

Dr. Brenda J. Smith
_____

ACKNOWLEDGEMENTS

Undertaking doctoral research has been a truly rewarding and life-changing experience for me thanks to the outstanding support and guidance I received from many individuals.

I am immensely grateful to my doctoral advisor, Dr. Bert Jacobson, who constantly provided me with support and inspiration throughout my time at Oklahoma State University. I would like to thank and express my gratitude to the respected members of my dissertation committee, Dr. Doug Smith, Dr. Nathaniel Jenkins, and Dr. Brenda Smith, for their constant encouragement and feedback. I have been genuinely fortunate to be advised by the committee members, who have always had my best interest in mind.

I would like to acknowledge and express my gratitude to the Graduate College at Oklahoma State University for supporting my doctoral research through the Robberson Summer Dissertation Fellowship Award. I would also like to thank the Graduate College review panel for taking the time to review and select my application to be the recipient of this prestigious award. Moreover, I would like to thank all the faculty and staff at the Health and Human Performance Department as well as the Department of Wellness at Oklahoma State University for their incredible efforts in helping me advance towards my academic goals.

I would like to thank and acknowledge my wonderful parents, Eshrat and Ahmad, who have always provided me with their unconditional love and support through every stage of my life. Words are not enough to express my love for them. If there was one lesson, I ever learned from them, that would be to always do my best and never give up. I would like to thank my supportive siblings, Maryam, Mohsen, and Mahdi for the constant love, support, and encouragement ever since I can remember. I would also like to express my gratitude to my family and friends, especially Mamita and Carmina, for their unlimited love and support. Last but not least, I would like to express a special acknowledgement to my lovely wife, Montserrat, who has always supported me with her love and encouraged me to push the boundaries, do the best I can do, and be the best I can be. I love you.

Name: MASOUD MOGHADDAM

Date of Degree: MAY, 2020

Title of Study: HIGH INTENSITY INTERVAL TRAINING VERSUS MODERATE INTENSITY CONTINUOUS TRAINING TO MAXIMIZE NEUROMUSCULAR ADAPTATIONS

Major Field: HEALTH, LEISURE, AND HUMAN PERFORMANCE

Abstract: High intensity interval training (HIIT) is defined as a group of vigorous intensity bouts separated by periods of rest. Although many studies have been conducted on the effects of HIIT, few investigations have focused on neuromuscular adaptations in response to HIIT versus moderate intensity continuous training (MICT). The purpose of this study was to investigate the neuromuscular adaptations following low-volume HIIT designs (i.e., ultrashort-HIIT, Tabata-HIIT) compared to high-volume MICT on an air-resistance fan bike. Forty-seven recreationally active individuals volunteered to participate, and were randomly assigned to ultrashort-HIIT, Tabata-HIIT, and MICT. The intervention was performed 3 days per week for 4 weeks. MICT sessions included 30 min of cycling at 75% of maximal heart rate reserve, while HIIT protocols consisted of 3 sets of 8 intervals at maximal effort intensity. Ultrashort-HIIT and Tabata-HIIT protocols were performed with 10s:5s and 20s:10s work-to-rest ratios and provided with 2.5- and 5-min recovery periods between sets, respectively. Testing procedures were completed pre and post intervention, consisting of rate of torque development (RTD); peak torque (PT) during maximal voluntary isometric contraction (MIVC) and submaximal contractions leg extension; rectus femoris (RF) and vastus lateralis (VL) early phase and maximal activations during PT (i.e., PT-RMS) and entire contraction (i.e., pRMS); RF and VL muscle cross-sectional area (mCSA) and echo intensity (EI). Two-way mixed factorial ANOVAs were calculated for statistical analyses. There was a significant Time × Group interaction effect in RF PT-RMS during 70% MVIC ($p = 0.015$) and VL EI ($p = 0.023$). Tabata-HIIT elicited greater improvements in RF PT-RMS during 70% MVIC, while ultrashort-HIIT showed greater decreases in VL EI than other groups. Significant main effect of Time was observed in RTD_{50} ($p = 0.010$), RTD_{75} ($p = 0.044$), RTD_{100} ($p = 0.040$), $RTD_{100-200}$ ($p = 0.027$), pRMS MVIC ($p = 0.001$), PT-RMS ($p = 0.003$), pRMS ($p = 0.012$), PT-RMS ($p = 0.017$), pRMS 70% MVIC ($p = 0.009$), pRMS 100% MVIC ($p = 0.001$), r-pRMS 100% ($p = 0.047$), RF mCSA ($p < 0.001$), VL mCSA ($p < 0.001$), and RF EI ($p = 0.035$). No significant interactions nor main effects ($p > 0.05$) were observed in PT, RF and VL early phase activations, and VL maximal activation. These findings concluded that low-volume HIIT designs are "time-efficient" exercise mode to induce neuromuscular and muscular morphological adaptations compared to high-volume MICT. Furthermore, HIIT has the potential to elicit greater neuromuscular adaptations in comparison to traditionally prescribed MICT.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

1.1. Introduction

High intensity interval training (HIIT) is defined as a group of short bursts of vigorous intensity physical activity separated by periods of rest or low intensity exercise (8). Despite its popularity among athletes and coaches since the early 1900s, HIIT has recently become popular among fitness professionals. Since 2014, HIIT has been among top three fitness trends, while it was the top fitness trend worldwide for 2014 and 2018 (112). In comparison to high-volume moderate intensity continuous training (MICT), HIIT elicits similar physiological and performance adaptations such as enhanced aerobic metabolism, despite less exercise volume and duration (8). Hence, HIIT is known as a more "time-efficient" exercise alternative to traditionally prescribed MICT (8). Recently, HIIT has received significant attention in the scientific community regarding its impact on neuromuscular adaptations (75). Although many studies have been conducted regarding the effects of HIIT on health-related factors such as body composition and cardiorespiratory fitness, few studies have focused on the neuromuscular adaptations in response to HIIT versus MICT (75). Research has consistently shown that neuromuscular adaptations are highly specific and vary due to the exercise regime (117). Therefore, it is of utmost importance to investigate the differences between the neuromuscular adaptations of HIIT and MICT, which have different intensities, volumes, and likely motor unit recruitment patterns.

It has been suggested that the intensity and duration of both exercise and rest portions of each set are the most significant factors for optimizing adaptations to HIIT (8). Nevertheless, many studies use different intensities, durations, or various work-to-rest ratios (i.e., 2:1, 1:1, and 1:2) for their HIIT protocols (8). Therefore, it is hard to compare the adaptations to different studies on HIIT, because the physiological responses may vary due to differences in the nature of the exercise regime. For example, a HIIT protocol with shorter work periods performed at a supramaximal intensity may elicit greater adaptations specific to high-threshold motor units and the ATP-PCr system in comparison to a HIIT protocol with longer work periods performed a maximal intensity (8). However, it has been reported that a 2:1 work-to-rest ratio causes a higher accumulated oxygen deficit than other ratios (69). For example, the recent HIIT study implementing 1:1 work-to-rest ratio reported that obese individuals desiring to improve muscular strength should perform more intense HIIT protocols (14). In addition, the authors suggested future investigations determine if a single HIIT protocol can modify cardiorespiratory, body composition, and muscular strength due to their relationship with health status (14).

Regarding 2:1 work-to-rest ratio, the shortest yet effective HIIT protocol was performed at 20s:10s work-to-rest ratio, known as Tabata-HIIT, which induced improvements in cardiorespiratory fitness (109). The present study, however, incorporated a 10s:5s work-to-rest ratio protocol, called ultrashort-HIIT, which was performed at supra-maximal effort, with the goal of establishing a shorter yet effective HIIT protocol. Since the ultrashort-HIIT can be performed at supramaximal intensity, it may have potentials to elicit greater adaptations in neuromuscular system and improve torque production to a greater degree. To the best of our knowledge, the neuromuscular adaptations of low-volume HIIT designs were not previously studied and this was the first study investigating the neuromuscular adaptations of ultrashort-HIIT and Tabata-HIIT.

In order to investigate neuromuscular adaptations, it is important to understand the components of neuromuscular system providing communications between central nervous system and muscles. The neuromuscular system is composed of motor units. Each motor unit (MU) is consisted of one alpha motor neuron and the muscle fibers innervated by the axon terminals of the neuron, which act together as a single unit that is the basic functional element for force production (44). Increasing force production during a muscle contraction can be regulated by an increase in either the number of MUs activating (i.e., MU recruitment) or rate of electrical impulses firing (i.e., rate coding). The alpha motor neurons and MUs have different sizes and thresholds (95). Smaller motor neurons innervate relatively smaller number of muscle fibers to form smaller MUs generating small forces. Whereas, the larger alpha motor neurons innervate larger muscle fibers, known as larger MUs, to produce larger amount of force (95). In most skeletal muscles, the smaller MUs activated at lower thresholds innervate slow-twitch muscle fibers, which are more resistant to fatigue and contract slowly. This is while larger MUs, associated with fast-twitch fatigable muscle fibers, have higher threshold to be activated in order to generate strength and power movements (95). According to Henneman's size principle (46), MUs are recruited in the order of size and threshold to increase force production (Figure 1). In
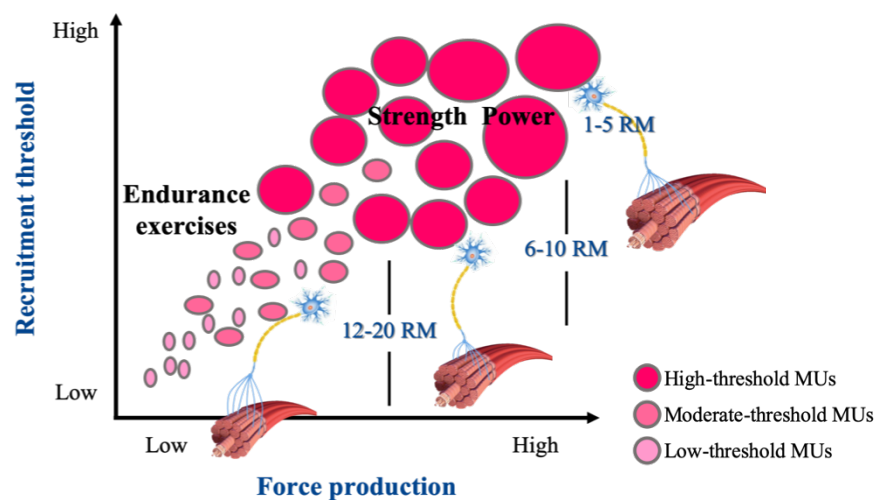
Figure1 – Henneman's size principle: Motor units are recruited in the order of size and threshold to increase force production.

other words, the small lower-threshold MUs are initially recruited, as the demand for force production increases, the large higher-threshold MUs are the last to be activated (39, 83).

High-intensity exercise activates higher-threshold MUs, thought to be composed primarily of fast-twitch muscle fibers (104). Since HIIT is performed at high-velocity and high-loads, higher-threshold MUs are likely recruited during each bout (104). In contrast, MICT likely results in the recruitment of low- to moderate-threshold MUs. According to a study using muscle biopsy and glycogen depletion techniques (101), it takes 20 minutes before some type IIa muscle fibers are recruited, and 2 hours before all three muscle fiber types (i.e., type I, IIa, and IIb) are activated during cycle ergometer exercise at 75% of VO_2max. Therefore, performing short-duration HIIT protocols have the potentials to maximize the recruitment of higher-threshold MUs, which are associated with greater anaerobic capacity and force generation capabilities, during each bout (104). Hence, short-duration HIIT protocols (e.g., ultrashort-HIIT, Tabata-HIIT) have the potentials to lead to greater neuromuscular responses regarding the adaptation of higher-threshold MUs, and consequently force production, compared to the MICT due to the routine activation during training.

To investigate neuromuscular adaptations, it has been previously established that surface electromyography (sEMG) is a non-invasive technique to monitor the activation of MUs (25). The sEMG signal is the algebraic summation of the electric potential differences within a muscle, which is detected by sEMG sensors placed on the skin overlying the muscle (31). The amplitude of the sEMG signal indicates muscle activation that is influenced by MU recruitment and rate coding, which can be taken as a global measure of MU activity (25). The amplitude of sEMG signal and its force-related pattern of responses reflect the concurrent MU recruitment and rate coding, which regulate the muscle force output (25). Furthermore, the muscle activation indicated by sEMG signal is the result of both facilitatory and inhibitory activities, which may occur at

different levels of the nervous system (85). The sEMG signal amplitude has commonly been utilized to evaluate neural adaptations to training interventions (28, 65, 85).

To the best of our knowledge, only one study examined cardiorespiratory and neuromuscular adaptations of interval versus continuous training and found that 6 session of HIIT on a cycle ergometer elicited similar improvements in cardiorespiratory fitness as MICT, despite significant differences in total training volume and intensity (75). Regarding the neuromuscular adaptations, however, HIIT improved MU activation during higher intensity maximal voluntary contractions, while MICT increased time to task failure without changing MU activities (75). The HIIT group performed high intensity cycling with 60s:75s work-to-rest ratio at 100% peak power, whereas MICT consisted of 90-120 min continuous cycling at 65% of VO_2max. Given the increase in MU activations observed for the HIIT group, these findings suggest greater neuromuscular adaptations for various HIIT protocols compared to MICT (75). Consequently, studies are needed to further investigate the neuromuscular and performance adaptations of interval versus continuous training by studying sEMG amplitude, muscular strength, and muscle size and quality.

1.2. Purpose of the Study

The purpose of this study was to investigate the neuromuscular adaptations following 4 weeks of the low-volume HIIT designs (i.e., ultrashort-HIIT, Tabata-HIIT) compared to the high-volume MICT on an air-resistance stationary fan bike.

1. The neural measurements included the examination of:
    a. Maximal sEMG amplitude
    b. Electromechanical delay

  c. Early phase muscle activation of Rectus Femoris and Vastus Lateralis during a ballistic maximal voluntary isometric contraction

    i. 0 – 30ms, 0 – 50ms, and 0 – 100ms

2. The muscular strength measurements included the examination of:

  a. Peak torque

  b. Rate of torque development

    i. 0-30 ms, 0-50 ms, 0-100 ms, 0-200 ms, and 100-200 ms

  c. Peak rate of torque development

3. The muscular morphological measurements included the assessment of:

  a. Muscle cross-sectional area and echo intensity

    i. Rectus Femoris

    ii. Vastus Lateralis

1.3. Specific Aims

1. The first aim was to examine whether the HIIT protocols (i.e., ultrashort-HIIT, Tabata-HIIT) lead to greater neuromuscular adaptations than MICT, despite different exercise volumes and durations.

2. The second aim was to examine whether the ultrashort-HIIT is able to elicit similar neuromuscular adaptations as Tabata-HIIT, despite different overall exercise time.

1.4. Research Questions

1. Does ultrashort-HIIT elicit greater neural adaptations in comparison to MICT?

2. Does Tabata-HIIT elicit greater neural adaptations in comparison to MICT?

3. Does ultrashort-HIIT elicit greater increases in strength performance in comparison to MICT?

4. Does Tabata-HIIT elicit greater increases in strength performance in comparison to MICT?

5. Does ultrashort-HIIT elicit greater neural adaptations in comparison to Tabata-HIIT?

6. Does ultrashort-HIIT elicit greater increases in strength performance in comparison to Tabata-HIIT?

7. Will there be a greater relationship between strength changes and neural adaptations, or strength changes and muscle cross sectional area (mCSA) following training?

1.5. Hypotheses

1. H_0: There will be no differences in neural adaptations between ultrashort-HIIT and MICT as indicated by sEMG.

   H_A: There will be significant differences in neural adaptations between ultrashort-HIIT and MICT as indicated by sEMG.

2. H_0: There will be no differences in neural adaptations between Tabata-HIIT and MICT as indicated by sEMG.

   H_A: There will be significant differences in neural adaptations between Tabata-HIIT and MICT as indicated by sEMG.

3. H_0: There will be no differences in strength between ultrashort-HIIT and MICT as indicated by maximal voluntary isometric contraction (MVIC).

   H_A: There will be significant differences in strength between ultrashort-HIIT and MICT as indicated by MVIC.

4. H_0: There will be no differences in strength between Tabata-HIIT and MICT as indicated by MVIC.

   H_A: There will be significant differences in strength between Tabata-HIIT and MICT as indicated by MVIC.

5. H_0: There will be no differences in neural adaptations between ultrashort-HIIT and Tabata-HIIT as indicated by sEMG.

   H_A: There will be significant differences in neural adaptations between ultrashort-HIIT and Tabata-HIIT as indicated by sEMG.

6. H_0: There will be no differences in strength between ultrashort-HIIT and Tabata-HIIT as indicated by MVIC.

   H_A: There will be significant differences in strength between ultrashort-HIIT and Tabata-HIIT as indicated by MVIC.

7. H_0: There will be no relationships between strength changes and neural adaptations.

   H_A: There will be significant relationships between strength changes and neural adaptations.

8. H_0: There will be no relationships between strength changes and mCSA.

   H_A: There will be significant relationships between strength changes and mCSA.

1.6. Significance of the Study

According to a recent study, the percentages of the U.S. adults (aged 18 and over) who meet the recommended physical activity for aerobic exercise and combination of aerobic and resistance trainings are 51.7% and 21.7%, respectively (118). Not surprisingly, middle-aged individuals mostly tend to participate in traditionally prescribed MICT. The lack of performing high intensity movements combined with aging results in a significant atrophy in fast-twitch muscle fibers in this age group (68). Specifically, the higher-threshold MUs are the first to be denervated due to aging and lack of high intensity activity (68). Prolonged disuse of fast-twitch muscle fibers causes loss of higher threshold MUs, and eventually loss of type II muscle fibers (68). Dysfunction of type II muscle fibers has been reported as one of the main reasons to increase the risks of falling to the ground in adults (107). When a fall is not fatal, it often results in hip fracture, brain damage, or loss of independence, which add up to a $31 billion annular healthcare cost (17). Recently, HIIT has become popular among fitness professionals and scientific communities, which is known as a "time-efficient" mode of exercise. As an alternative for MICT, performing HIIT not only has the potential to elicit similar cardiorespiratory adaptations, it also has potentials to induce greater neuromuscular responses than MICT. Regarding athletic performance, the results of this study have the potential to provide a new perspective for coaches and fitness professional to use HIIT more often in their program designs as a great tool for improving efficiency in their training programs. In collegiate sports, for example, coaches have limited time for countable athletic activities due to the new rules and regulations of the National Collegiate Athletic Association (NCAA) (5). Hence, implementing HIIT may assist coaches to bring more time-efficiency in their training programs by improving both anaerobic and aerobic performances in a shorter time. Furthermore, the findings of this study

may provide new information for the research community, to possibly delay the effects of early neuromuscular aging and reduce the risks of falling in older adults.

1.7. Delimitations

1. Participants were limited to 18-39 years of age.

2. This investigation required the recruitment of approximately 45 males and females to complete the study.

3. All participants required to be healthy and free from any sign or symptom of disease, and be without any musculoskeletal injury (i.e., broken bone, sprained ligament, and/or strained muscle) within the previous 6 months, as self-reported on a questionnaire.

4. This investigation required the participants to be recreationally active by participating in an exercise program for at least 30 minutes, 3 times per week, during the previous 3 months.

5. This investigation required the participants to refrain from participating in any strenuous exercise or physical activity program during the training intervention days.

6. Only two muscles of the quadriceps muscle group (i.e., rectus femoris, vastus lateralis) had to be investigated to complete the data collection.

1.8. Limitations

1. Participants were recruited through responding to a posted flyer, classroom visit announcement, and/or word of mouth on a volunteer basis. Therefore, the subject recruitment was not truly random.

2. The investigators were not truly able to control for any influence such as activity, diet, and/or sleep outside of the visits, which may have impacted the results of the study.

3. The investigators were not able to control for participants' level of motivation during each visit, which could have a direct influence on level of effort and/or ability to perform the tasks.

4. There were many restrictions for the technology and equipment utilized for data collection that may be different from a real-life situation, which include:

   a. Muscular contractions had to be isometric.

   b. There was a slow linear incline and a decline at the beginning and end of the trapezoidal-shaped trajectories of maximal and submaximal contractions, which may had influenced the performance.

1.9. Assumptions

1. Participants provided honest and accurate answers to complete the health and exercise history questionnaire.

2. Participants performed maximal voluntary effort to complete the pre- and post-testing tasks as well as the training protocols.

3. The technology and equipment utilized for data collection were calibrated and properly functioned as intended by the manufacturers.

4. There had been no error occurred during the data collection, data analysis, data entry, and/or statistical processing.

CHAPTER II

REVIEW OF LITERATURE

The aim of the following review of literature was to provide insights into the previous investigations that are relevant to the purpose of this study. Every section included the summary of each study and the results along with the interpretation of the authors. The purpose of this literature review was to emphasize the neuromuscular adaptations to exercise as well as physiological adaptations of HIIT compared to MICT.

2.1. *Comparison of High Intensity Interval Training and Moderate Intensity Continuous Training*

2.1.1. *Cardiorespiratory Adaptations*

<u>Kong et al., 2016 (66)</u>

The purpose of this investigation was to compare the impacts of HIIT versus moderate-to-vigorous intensity continuous training (MVCT) on cardiometabolic health outcomes and exercise enjoyment after 5 weeks in obese young females. Thirty-one obese females, 18-39 years

of age, were randomly assigned to either HIIT or MVCT group to participate in the 5-week interventions for 4 days per week. The HIIT protocol consisted of 20 minutes of repeated cycling at 8s:12s work-to-rest ratio, while the participants of MVCT group performed 40 minutes of continuous cycling at 60-80% of peak oxygen consumption. The participants' peak oxygen consumption, body composition, blood lipids, and serum sexual hormones were measured at pre- and post-testing. The score of Physical Activity Enjoyment Scale (PAES) was collected from each participant during exercise. After 5 weeks of training, both groups similarly improved peak oxygen consumption (HIIT: 9.1%, MVCT: 10.3%). Despite the fact that the MVCT group significantly decreased total body weight (-1.8%), fat mass (- 4.7%), and body fat percentage (-2.9%), there were no significant between-group differences for these variables from pre- to post-intervention measures. The HIIT group had higher scores of PAES during exercise compared to the MVCT group. Although both groups showed a decline in resting testosterone and estradiol levels, there was not significant change regarding blood lipids. Due to these findings, Kong and colleagues concluded that both HIIT and MVCT are effective tools to improve cardiorespiratory fitness and to reduce sexual hormones in obese young females, while HIIT was more enjoyable as well as time-efficient compared to MVCT.

Helgerude et al., 2007 (45)

The primary goal of this study was to compare the effects of aerobic endurance training at different intensities and with different methods matched for total work and frequency. The pre- and post-testing included maximal oxygen uptake, stroke volume of the heart, blood volume, lactate threshold, and running economy. Forty recreationally active males were randomly assigned to one of four groups. The first training protocol consisted of moderate intensity continuous running at 70% heart rate max for 45 minutes. The second training protocol was completed by moderate intensity continuous running at lactate threshold (85% heart rate max) for 24-25 minutes. The third training protocol consisted of 47 interval running sets with 15-second

sprints at 90– 95% heart rate max followed by 15-second active rest periods at 70% heart rate max. The fourth training protocol was completed by performing 4 sets of 4-minute running at 90– 95% heart rate max with 3-minute of active rests at 70% heart rate max after each bout. The training interventions were performed 3 times per week for 8 weeks. The findings of the study indicated that both HIIT protocols significantly improved maximal oxygen uptake compared to the moderate intensity continuous protocols. The 15s:15s and 4×4min groups increased VO_2max from 60.5 to 64.4 mL·kg^{-1}·min^{-1} (5.5%) and 55.5 to 60.4 mL·kg^{-1}·min^{-1} (7.2%), respectively. In addition, the interval training protocols resulted in increasing the stroke volume by approximately 10% following the intervention. These finding suggested that HIIT protocols are more effective compared to continuous training protocols at lactate threshold or at 70% heart rate max. In conclusion, the authors stated that the percentage of improvements in VO_2max is associated with the individuals' fitness level. In fact, there was no improvement in VO_2max for trained individuals, while youth and untrained individuals increased VO_2max by 5-10% and 17.9%, respectively. Furthermore, the authors suggested that stroke volume, improved in HIIT groups, was a key factor to enhance cardiorespiratory fitness that can be achieved through performing HIIT.

Daussin et al., 2007 (20)

The goal of this investigation was to determine whether continuous (CT) and interval training (IT) might develop the peripheral or the central cardiorespiratory components. Ten males (n = 5; Age: 46 ± 6 years; body mass index: 26.1 ± 1.4 kg.m^{-2}; body fay: 25.0 ± 1.5 percentage) and females (n = 5; Age: 47 ± 2 years; body mass index: 23.1 ± 2.4 kg.m^{-2}; body fay: 33.2 ± 1.7 percentage) were randomly ascribed to either the IT or CT program. Following three months of deconditioning, each subject was asked to complete the alternative type of training (i.e., IT or CT) with the order of the two training programs randomized. The testing procedures before and after each training intervention were performed on a cycle ergometer to determine maximal oxygen

14

uptake (VO_2max), cardiac output (Qmax), and maximal arteriovenous oxygen difference (Da-VO_2max). Every participant performed three exercise sessions per week over 8 weeks. The total mechanical work (kJ) and training duration were identical in both IT and CT protocols. The CT program was initially started by 20 minutes of moderate intensity exercise and progressed by 5 minutes every 2 weeks to achieve 35 minutes during the last 2 weeks. The IT protocol included series of 5-minute blocks, performing 4 minutes at lactate threshold followed by 1-minute at 90% of peak power. The results of the study indicated that both VO_2max and Qmax were significantly improved following the IT protocol (26.3 ± 1.6 to 35.2 ± 3.8 mL.min^{-1}.kg^{-1}; 17.5 ± 1.3 to 19.5 ± 1.8 L.m^{-1}, respectively; $p < 0.01$). Moreover, the Da-VO_2max measurements were significantly improved after both IT (11.0 ± 0.8 to 12.1 ± 1.0 mL.100mL^{-1}; $p < 0.05$) and CT (11.0 ± 0.8 to 12.7 ± 1.0 mL.100mL^{-1}; $p < 0.01$) programs. Finally, the investigators concluded that the central and peripheral adaptations in oxygen transportation and utilization were associated with the training modality for isoenergetic training. Furthermore, the IT program developed both central and peripheral components of Da-VO_2max, whereas the CT protocol was primarily associated with higher rates of oxygen extraction.

Daussin et al., 2008 (21)

The aim of this study was to investigate the effects of continuous (CT) versus intermittent (IT) training yielding identical mechanical work and training duration on skeletal muscle and cardiorespiratory adaptations in sedentary individuals. Eleven participants (males = 6, females = 5) were randomly assigned to either of the CT or IT programs in a cross-over design, separated by 12 weeks of deconditioning. The training programs were performed 3 times per week over an 8-week period (24 sessions). The CT protocol consisted of 20-35 minutes of continuous cycling, while the IT group performed blocks of 5 minutes exercise, including 4 minutes at the power associated with the first ventilatory threshold followed by 1 minute at 90% of maximal power. The maximal oxygen uptake was improved for both CT and IT groups, while only the participants

of the IT group showed faster VO_2 kinetics during time to exhaustion, and improved maximal cardiac output. Moreover, both groups increased capillary density, while only IT group improved skeletal muscle mitochondrial oxidative capacity, which was correlated with the maximal oxygen uptake and time to exhaustion for IT. The findings of the study suggested that the fluctuations of oxygen uptake, heart rate, and workload during exercise had greater impacts on improving skeletal muscle oxidative capacities compared to exercise duration or total energy expenditure. Finally, the investigators of this study suggested that IT seemed to be an optimal strategy to maximize both peripheral muscle and central cardiorespiratory adaptations, enhancing functional movement.

Tabata et al., 1996 (108)

The purpose of this study was to compare two different training protocols, MICT that is not supposed to depend on anaerobic metabolism versus HIIT, which recruits the maximal anaerobic energy metabolism. Fourteen young recreationally active males participated in this study to complete the 6-week intervention on mechanically braked cycle ergometer. Anaerobic capacity and maximal oxygen uptake were measured to compare the effects of MICT versus HIIT. The MICT group performed 60 minutes of continuous cycling at 70% of VO_2max, 5 days per week, whereas the HIIT protocol consisted of 7-8 sets of 20 seconds of high intensity cycling at 170% of VO_2max with 10 seconds rest between bouts. The maximal oxygen uptake was similarly improved for both MICT and HIIT, while the anaerobic capacity significantly increased for HIIT group. In conclusion, the authors stated that MICT improving aerobic performance does not increase anaerobic capacity, while HIIT may enhance both anaerobic and aerobic energy supplying systems due to the intensive stimuli on both systems during HIIT.

Esfandiari, Sasson, & Goodman, 2014 (29)

The goal of this study was to examine the effects of short-term high-intensity interval training (HIT) and continuous moderate-intensity training (CMT) on cardiac function in young, healthy men. Sixteen untrained males were randomly assigned to either or CMT to complete the 6-session intervention over a 12-day period. The protocol was performed by eight to twelve sets of 60-second sprint cycling at 95-100% of pre-training maximal aerobic power (VO_2max), separated by 75-second rest periods at 10% VO_2max. The CMT protocol, however, consisted of 90-120 minutes of cycling at 65% of VO_2max. Pre- and post-testing included measuring the left ventricular (LV) function at rest and during submaximal exercise using two-dimensional and Doppler echocardiography. The results of the investigation showed significant ($p < 0.001$) improvements in calculated plasma volume (PV), as well as the VO_2max in both (39.5 ± 7.1 to 43.9 ± 5.5 mL.kg^{-1}.min^{-1}) and CMT (39.9 ± 5.9 to 41.7 ± 5.3 mL.kg^{-1}.min^{-1}) groups. Although resting LV function did not change, increased exercise stroke volume ($p = 0.02$) and cardiac output ($p = 0.02$) were observed, secondary to increases in end-diastolic volume ($p < 0.001$). Furthermore, numerous Doppler and speckle tracking indices of diastolic function were similarly improved during exercise in both and CMT groups and were related to changes in PV. The investigator recommended that performing both short-term and CMT may be beneficial to elicit rapid improvements in VO_2max and LV filling without global changes in cardiac performance at rest.

Macpherson et al., 2011 (74)

The purpose of the study was to assess the effects of sprint interval training (SIT) and endurance training (ET) on body composition, 2000-m run time trial, maximal oxygen uptake (VO_2max), and maximal cardiac output (Qmax). Twenty males and females (n = 10 per group; mean $\pm$ SD: age = 24 ± 3 years) were randomly assigned to either SIT or ET groups to complete the intervention 3 times per week for six weeks. The SIT protocol consisted of four to six sets of 30-second all-out run sprints (manually driven treadmill) followed by a 4-minute recovery per

bout. The ET protocol was performed 30-60 minutes of continuous running at 65% of VO_2max. The findings of the study showed that both training protocols similarly improved ($p < 0.05$) body composition, 2000-m run time trial performance, and VO_2max. The fat mass was significantly decreased in SIT by 12.4% (mean ± SEM; 13.7 ± 1.6 to 12.0 ± 1.6 kg) and ET by 5.8% (13.9 ± 1.7 to 13.1 ± 1.6 kg), while the lean mass increased by 1% in both groups. In addition, time trial performance was enhanced by 4.6% for the SIT (-25.6 ± 8.1 s) and 5.9% for ET (-31.9 ± 6.3 s). Moreover, the VO_2max values were significantly improved in SIT by 11.5% (46.8 ± 1.6 to 52.2 ± 2.0 ml.kg^{-1}.min^{-1}) and ET by 12.5% (44.0 ± 2.0 to 49.5 ± 2.6 ml.kg^{-1}.min^{-1}). However, there were no significant differences between the groups in body composition, 2000-m run time trial performance, and VO_2max. In contrary, the Qmax measurements were only improved in the ET group by 9.5% (22.2 ± 2.0 to 24.3 ± 1.6 L·min^{-1}). In summary, the authors concluded that the SIT running elicited body composition, VO_2max, and performance adaptations to a similar extent as the ET protocol, despite a fraction of time commitment, while there was no significant impact on Qmax. Furthermore, they stated that adaptations with the ET protocol were of central origin primarily, whereas those with the SIT running were more peripheral.

McKay, Paterson, and Kowalchuk, 2009 (79)

The goal of this study was to examine the effects of high intensity interval (HIT) and low-intensity continuous endurance (END) training on pulmonary O_2 uptake (VO_2p) that reflects muscle O_2 consumption, and muscle deoxygenation kinetics that reflects the rate of O_2 extraction. Twelve males were randomly assigned to either or END groups to complete the 8-session interventions. The protocol was completed by eight to twelve sets of 1-minute sprint cycling at 120% of pre-training VO_2p followed by 1 minute of load-less cycling. The number of intervals progressed from eight in the first 2 sessions to 12 sets by the eighth session. The END protocol consisted of 90-120 minutes of continuous cycling at 65% of pre-training VO_2p. The participants of both groups completed step transitions to a moderate-intensity work rate (approximately 90%

18

estimated lactate threshold) on five occasions throughout training, and ramp incremental and constant-load performance tests were conducted at pre-, mid-, and post-training periods. The VO_2p test was conducted breath-by-breath by mass spectrometry and volume turbine. In addition, the deoxygenation (change in deoxygenated hemoglobin concentration; Delta-HHb) of the vastus lateralis muscle was monitored by near-infrared spectroscopy. Moreover, the fundamental phase II time constants for VO_2p (tauVO_2) and deoxygenation kinetics [effective time constant, tau' = (time delay + tau), Delta-HHb] during moderate-intensity exercise were estimated using nonlinear least-squares regression techniques. The findings of the investigation demonstrated that the tauVO_2 was reduced by approximately 20% ($p < 0.05$) after only two training sessions and by approximately 40% ($p < 0.05$) after eight training sessions (i.e., post-training), while there were no significant differences between the and END groups. The tau'-Delta-HHb (approximately 20 s) did not significantly change over the course of eight training sessions. The investigators interpreted that faster activation of muscle O_2 utilization was an early adaptive response to both and lower-intensity END training protocols. That Delta-HHb kinetics (a measure of fractional O_2 extraction) did not change despite faster VO_2p kinetics, which indicated that faster kinetics of muscle O_2 utilization were accompanied by adaptations in local muscle (microvascular) blood flow and O_2 delivery, resulting in a similar "matching" of blood flow to O_2 utilization. The investigators stated that the faster VO_2p kinetics during the transition to moderate-intensity exercise occurred after 2 days and END training and without changes to muscle deoxygenation kinetics, regardless of the type of exercise training program. Furthermore, both and END protocols elicited similar training-induced adaptations in exercise performance, VO_2p kinetics, heart rate kinetics, measured lactate threshold, and estimated lactate threshold, despite no significant differences between training programs.

2.1.2. Cardiometabolic Adaptations

The purpose of this study was to investigate the effects of HIIT versus MICT to improve body composition, insulin sensitivity, blood pressure, blood lipids, and cardiovascular fitness in young overweight or obese males. It was hypothesized that HIIT would result in similar enhancements in body composition, cardiovascular fitness, blood lipids, and insulin sensitivity compared to the MICT group, despite significant difference in time commitment. The HIIT group required one hour of activity per week, whereas the participants in the MICT group engaged in five hours continuous exercise during a week. Twenty-eight sedentary young overweight or obese individuals (Age: 20 ± 1.5 years, body mass index 29.5 ± 3.3 kg.m^{-2}) were randomly assigned into either HIIT or MICT group. The pre- and post-testing consisted of body composition evaluated by DXA, cardiovascular fitness measured by graded treadmill exercise test, insulin resistance assessed by oral glucose tolerance test, lipoprotein particles measured by nuclear magnetic resonance spectroscopy, and blood pressure evaluated by automatic auscultation. The training protocols were performed on an electronically braked cycle ergometer. The HIIT protocol consisted of 4 sets of 30-second sprint cycling at 85% of peak power with 4-minute recovery between sets, performing 3 times per week. Whereas, the MICT training included 45-60 minutes of continuous cycling at 55-65% of VO$_2$peak, performed 5 days per week. The results of this study showed greater improvements in cardiovascular fitness in MICT (11.1%) compared to HIIT (2.83%). Despite no significant difference was found between the groups, both HIIT and MICT significantly improved body fat percentage, total cholesterol, triglycerides, and cardiovascular fitness. The authors stated that participants in both groups similarly 1) improved insulin resistance, 2) reduced blood lipids, 3) decreased body fat percentage, and 4) increased cardiovascular fitness. These observations suggested that a relatively short duration of either HIIT or MICT may lead to improvements of cardiometabolic risk factors in overweight or obese males.

Burgomaster et al., 2008 (10)

The purpose of this investigation was to study the effects of sprint interval training (SIT) compared to traditional endurance training (ED) on metabolic adaptations during exercise. It was hypothesized that SIT and ET would elicit similar adaptations in markers of skeletal muscle carbohydrate (CHO) and lipid metabolism and metabolic control during exercise after 6 weeks of training, despite significant differences in training volume and duration. Twenty young healthy males and females (5 males and 5 females per group) performed a constant load cycling challenge, including 1 hour of cycling at 65% of VO_2peak) before and after the training interventions. The SIT protocol was completed by 4-6 sets of 30-second sprint intervals followed by 4.5 minutes recovery in 3 days per week, while the ET protocol was performed by 40-60 minutes of continuous cycling at 65% of VO_2peak in 5 days per week. Despite the significant differences in time commitment (SIT: ~1.5 hour, ET: ~4.5 hours) and total work (SIT: ~225 kJ, ET: ~2250 kJ) per week, both protocols elicited similar increases ($p < 0.05$) in mitochondrial markers for skeletal muscle CHO and lipid oxidation. Given significantly lower training volume and duration for the SIT group, the authors suggested that high intensity interval training was a time-efficient strategy to enhance skeletal muscle oxidative capacity and to induce specific metabolic adaptations during exercise compared to traditionally prescribed ET.

Cocks et al., 2013 (15)

The aim of this investigation was to compare the structural and endothelial enzymic changes in skeletal muscle microvessels following 6 weeks of SIT or ET. Sixteen young sedentary individuals (Age: 21 ± 0.7 years, BMI: 23.8 ± 0.7 kg.m^{-2}) were randomly assigned to either SIT or ET group. The SIT protocol consisted of four to six 30-second Wingate bouts with 4.5 minutes recovery after each set, performed 3 times per week. The ET group completed 40-60 minutes of continuous cycling at 65% of VO_2peak, trained 5 times per week. Prior to start the training, muscle biopsies were obtained from the vastus lateralis muscle in order to measure muscle microvascular endothelial nitric oxide synthase content using quantitative

immunofluorescence microscopy. The participants' whole-body insulin sensitivity, arterial stiffness, and blood pressure were also evaluated. The results of the study demonstrated that the SIT and ET groups significantly increased the muscle microvascular endothelial nitric oxide synthase content following the 6-week interventions. Furthermore, the participants of both groups significantly reduced aortic stiffness and improved whole-body insulin sensitivity to a similar extent. The investigators emphasized that SIT and ET were effective tools to similarly improve muscle microvascular density and endothelial nitric oxide synthase content in sedentary young males.

Burgomaster et al., 2005 (11)

The purpose of this study was to investigate the aerobic adaptations following six sessions of SIT. Sixteen recreationally active participants were randomly assigned to either SIT or control group. The pre- and post-testing sessions were performed on a stationary cycle ergometer, including the maximal oxygen uptake (i.e., aerobic capacity) and endurance capacity (at ~80% of VO$_2$peak) tests. Moreover, muscle biopsy samples were obtained from vastus lateralis muscles of SIT group to measure the levels of citrate synthase, adenosine triphosphate (ATP), phosphocreatine (PCr), and glycogen. The peak power, mean power, and fatigue index were assessed during training sessions. The SIT protocol was performed on an electronically braked cycle ergometer consisted of four to seven 30-second Wingate tests with four minutes of rest after each trial. During each bout of exercise, the participants were verbally encouraged to pedal as fast as possible against a load equivalent to 7.5% of their body weight. The training sessions were completed 3 times per week in two weeks. The number of Wingate bouts was four in day 1, five in day 2, six on days 3-4, seven on day 5, and four in the last session.

The results of the study showed significant increases in endurance capacity test only for the SIT group, while there was no change for the control group. In addition, the maximal oxygen

uptake was not significantly improved in either group. The peak power and fatigue index were significantly increased only in the SIT group, while mean power did not change. Furthermore, there were significant improvements in maximal activity of citrate synthase (by 38%) and glycogen concentrations (by 26%) in the SIT group, whereas no significant changes were observed in ATP and PCr levels. The authors of the study stated that that the 2-week short-duration intensive SIT protocol can positively impact the skeletal muscle metabolism as well as endurance capacity in recreationally active individuals.

Vella, Taylor, & Drummer, 2017 (116)

The goal of this study was to compare the adherence, enjoyment, and cardiometabolic outcomes following 8 weeks of HIIT and MICT, matched for energy expenditure, in overweight and obese young adults. Seventeen sedentary, overweight, or obese adults (aged 18–44 years), including seven males and ten females, were randomly assigned to either HIIT or MICT group. The HIIT protocol was performed by 10 bouts of 1-minute high intensity exercise at 75-80% of heart rate reserve, followed by 1-minute recovery intervals after each bout at 35-40% of heart rate reserve. The MICT group completed 30-minute sessions of continuous training, which included 5 minutes warm-up and cool down at 35-40% of heart rate reserve as well as 20-minute of continuous exercise at 55-59% of heart rate reserve. The pre- and post-testing measurements for cardiometabolic outcomes included cardiorespiratory fitness (VO_2peak), lipids, and inflammatory markers. In addition, the exercise enjoyment was measured by the validated Physical Activity Enjoyment Scale. The findings of the study showed that exercise adherence ($93.4 \pm 3.1\%$ vs. $93.1 \pm 3.7\%$, respectively) and mean enjoyment across the intervention (100.1 ± 4.3 vs. 100.3 ± 4.4, respectively) were high, and there were no significant differences between HIIT and MICT ($p > 0.05$). Moreover, the enjoyment levels did not change over time in either group ($p > 0.05$). Following the intervention, the HIIT protocol induced greater reductions in low-density lipoprotein cholesterol than MICT (-0.66 mmol.L^{-1} vs. -0.03 mmol.L^{-1}, respectively) and greater

improvements in VO$_2$peak than MICT (p < .05, +2.6 mL.kg^{-1}.min^{-1} vs. +0.4 mL.kg^{-1}.min^{-1}, respectively). Furthermore, the Interleukin-6 and C-reactive protein levels were enhanced in HIIT (+0.5 pg.mL^{-1} and + 31.4 nmol.L^{-1}, respectively) and were reduced in MICT (-0.6 pg.mL^{-1} and - 6.7 nmol.L^{-1}, respectively, p < .05). The authors concluded that HIIT can be enjoyable and may have high unsupervised adherence rates in sedentary, overweight, and obese adults. They also stated that HIIT may be associated with increased inflammations with short-term exercise in this population.

Rafiei at al., 2019 (97)

The aim of this study was to compare the effects of HIIT versus MICT for improvement of continuous glucose monitoring (CGM)-derived markers of glycemic variability, and biomarkers of endothelial cell damage (CD31+ and CD62+ endothelial microparticles [EMPs]) within a population at elevated risk of developing type 2 diabetes. Fifteen overweight and obese females were randomly assigned to either HIIT (n = 8) or MICT (n = 7) groups to complete the 10-session interventions on a cycle ergometer over 2 weeks. The HIIT group performed four to ten sets of 1-minute sprint cycling at 85-90% maximal power (∼85–90% peak heart rate), followed by 1-minute rest periods after bouts at ∼32.5% maximal power (∼60–65% peak heart rate). The number of intervals was progressed from four in day 1 to ten sets by the last session. The MICT protocol consisted of 20 minutes of continuous cycling at ∼32.5% maximal power (∼60–65% peak heart rate), while it was gradually increased at the same percent increase in estimated total work up to 50 minutes by the last session. Prior to the post-training, fasting blood samples were collected. The results indicated that both HIIT and MICT significantly improved glycemic variability as measured by CGM standard deviation (HIIT: 0.82 ± 0.39 to 0.72 ± 0.33 mmol.L^{-1}; MICT: 0.82 ± 0.19 to 0.62 ± 0.16 mmol.L^{-1}) and mean amplitude of glycemic excursions (HIIT: 1.98 ± 0.81 to 1.41 ± 0.90; MICT: 1.98 ± 0.43 to 1.65 ± 0.48), while there were no significant differences between groups. In addition, the levels of CD62+ EMPs were reduced

following the HIIT (187.7 ± 65 to 174.9 ± 55) and MICT (170 ± 60 to 160.3 ± 59, pre vs. post) groups, despite no significant differences between groups. Furthermore, there was no significant improvement in the 24-hour mean glucose or CD31+ EMPs. In conclusion, the authors stated that two weeks of HIIT or MICT significantly reduced the glycemic variability and CD62+ EMPs to a similar extent in overweight and obese females with elevated risk of type 2 diabetes.

Robinson et al., 2015 (98)

The goal of this investigation was to compare the short-term HIIT with MICT in terms of improvement in cardiorespiratory fitness, markers of inflammation, and glucose control in previously inactive individuals at elevated risk of developing type 2 diabetes. Thirty-nine inactive, overweight, and obese males (n = 7) and females (n = 32) were randomly assigned to either HIIT (n = 20) or MICT (n = 19) to complete the 10-session intervention over 2 weeks. The HIIT protocol was performed by 4-10 sets of one-minute sprint cycling at 85-90% maximal power (~85–90% peak heart rate) with 1-minute active recovery after each sprint at ~32.5% maximal power (~60–65% peak heart rate). The number of intervals was four in day 1, and it was progressed to 10 intervals by the last session. The MICT group performed 20-50 minutes of moderate intensity cycling at ~65% peak heart rate. The duration of the MICT protocol was gradually increased from 20 minutes in day 1 to 50 minutes in the tenth session. The training protocols were modeled after previous studies that indicate improvements in cardiometabolic health in individuals with, and at risk for type 2 diabetes. The pre- and post-testing included performing the peak oxygen uptake test and obtaining the fasting blood samples. The findings of the study demonstrated that both HIIT and MICT significantly ($p < 0.001$) improved peak oxygen uptake (HIIT: 1.8 ± 0.4 to 1.9 ± 0.4 L.min^{-1}; MICT: 1.8 ± 0.5 to 1.9 ± 0.5 L.min^{-1}) and significantly ($p < 0.05$) reduced the levels of plasma fructosamine after the intervention. Moreover, the toll-like receptor (TLR) 4 (TLR4) expression was significantly ($p < 0.05$) decreased in lymphocytes and monocytes following both HIIT and MICT protocols, while there

was a significant reduction on neutrophils only after MICT ($p < 0.01$). In addition, the TLR2 on lymphocytes was significantly ($p < 0.05$) decreased after the HIIT and MICT. Furthermore, the plasma inflammatory cytokines did not alter after training in both groups. However, the MICT protocol elicited a significant ($p < 0.05$) reduction in fasting plasma glucose (5.9 ± 1.0 to 5.6 ± 1.0 mmol.L^{-1}). In summary, the investigators stated that 10 sessions of either HIIT or MICT protocols may induce improvements in cardiorespiratory fitness and glucose control and reductions in TLR2 and TLR4 expression. Nevertheless, the MICT protocol may elicit a greater reduction in fasting glucose due to the exercise duration.

Sawyer et al., 2016 (102)

The goal of this study was to examine whether HIIT would be more effective than MICT at improving endothelial function and maximum oxygen uptake (VO$_2$max) in obese adults. Eighteen males and females (age: 35.1 ± 8.1 years; body mass index = 36.0 ± 5.0 kg.m^{-2}) were randomized to either HIIT or MICT group to complete three supervised training sessions per week for 8 weeks. The HIIT protocol consisted of ten sets of 1-minute sprint cycling at 90-95% maximum heart rate followed by a 1-minute active recovery after each bout at $\sim$25–50 Watts. The MICT group completed 30 minutes of moderate intensity cycling at 70-75% maximal heart rate. The pre- and post-testing sessions included measuring the brachial artery flow-mediated dilation (FMD), resting artery diameter, low flow-mediated constriction (L-FMC), VO$_2$max, biomarkers of cardiovascular risk, and endothelial function. Following the interventions, the findings of the study demonstrated that FMD was significantly increased for the HIIT group ($5.13 \pm 2.80\%$ to $8.98 \pm 2.86\%$, $p = 0.02$), while no significant changes observed for MICT ($5.23 \pm 2.82\%$ to $3.05 \pm 2.76\%$, $p = 0.16$). The resting artery diameter was significantly increased in the MICT group (3.68 ± 0.58 mm to 3.86 ± 0.58 mm, $p = 0.02$). However, there were no significant improvements for the HIIT group (4.04 ± 0.70 mm to 4.09 ± 0.70 mm; $p = 0.63$). Moreover, there was a significant ($p = 0.02$) group × time interaction in L-FMC between HIIT ($-1.04 \pm 4.09\%$ to

$1.74 \pm 3.46\%$; $p = 0.29$) and MICT ($0.63 \pm 2.00\%$ to $-2.79 \pm 3.20\%$; $p = 0.03$). In addition, the

VO_2max values were significantly ($p < 0.01$) improved in both HIIT (2.19 ± 0.65 L.min^{-1} to 2.64

± 0.88 L.min^{-1}) and MICT (2.24 ± 0.48 L.min^{-1} to 2.55 ± 0.61 L.min^{-1}), while biomarkers of

cardiovascular risk and endothelial function did not significantly change. In conclusion, the

authors emphasized that the HIIT and MICT protocols induced different vascular adaptations in

obese adults, despite similar VO_2max adaptations. The HIIT group improved FMD, while the

MICT increased resting artery diameter and L-FMC. The HIIT protocol was completed with

27.5% less total exercise time and ~25% less energy expenditure compared to MICT.

Gibala et al., 2006 (37)

This study was designed to examine changes in exercise capacity and molecular and

cellular adaptations in skeletal muscle after low volume sprint-interval training (SIT) and high-

volume endurance training (ET). Sixteen active males (21 ± 1 years) were randomly assigned to

either SIT ($n = 8$) or ET ($n = 8$) groups. The training intervention included six training sessions

over 2 weeks. The SIT protocol consisted of four to six sets of 30-second all-out cycling at

~250% of VO_2peak with 4 min recovery after each set. The ET group performed 90-120 minutes

of continuous cycling at ~65% of VO_2peak. The total time commitment over 2 weeks was ~2.5

hours for SIT and ~10.5 hours for ET, while the total training volume was ~90% lower for SIT

(~630 kJ) compared to ET (~6500 kJ). The results of the study showed that both training

protocols decreased the time required to complete 50 and 750 kJ cycling time trials, with no

difference between groups (main effects, $p \leq 0.05$). In addition, the muscle biopsy samples

obtained before and after the interventions revealed similar increases in muscle oxidative

capacity, as reflected by the maximal activity of cytochrome c oxidase (COX) and COX subunits

II and IV protein content (main effects, $p \leq 0.05$), but COX II and IV mRNAs were unchanged.

Furthermore, the training interventions resulted in significant increases in muscle buffering

capacity and glycogen content in both SIT and ET groups (main effects, $p \leq 0.05$). In conclusion,

the authors of the investigation stated that SIT was a time-efficient strategy to elicit rapid adaptations in skeletal muscles as well as exercise performance similar to ET in young active males, despite the large difference in training volume.

2.1.3. Exercise Enjoyment

<u>Saglev et al., 2019 (100)</u>

The purpose of this study was to investigate exercise enjoyment following one session of high intensity interval exercise (HIIE) compare to moderate intensity continuous exercise (CE) in iso-caloric conditions using a randomized crossover design. The HIIE protocol consisted of four sets of 4-minute running on the treadmill at >90% of maximal heart rate with 3-minute rest periods at 70% of maximal heart rate. The CE protocol was performed at 70% of maximal heart rate for session of 45 minutes. Seven young healthy participants were recruited to undergo two different exercise sessions in a randomized order. The peak oxygen uptake and maximal heart rate were measure prior to the training sessions. The participants completed the 18-item physical activity enjoyment scale (PACES) questionnaire to report their perceived exercise enjoyment, and also reported their rating of perceived exertion (RPE) using Borg's 6-20 scale. The results of this investigation showed that there was no difference in the PACES score between the high intensity interval exercise session [median: 95.5 (inter-quartile range: 21.8)] and the moderate intensity CE session [91.0 (13.5), $p = 0.36$, r = -0.22]. However, the participants reported a higher RPE in the high intensity interval exercise session [16.5 (2.0)] compared to the CE session [9.0 (2.0), $p = 0.01$, r = -0.88]. The author of the research stated that there was a similar exercise enjoyment following four sets of 4-minute running compared to a moderate intensity CE session in this randomized crossover study with iso-caloric conditions. Furthermore, if enjoyment was a mediating factor for engaging in exercise, one should expect a similar probability of exercise

adherence following high intensity interval and continuous moderate intensity exercise when prescribing aerobic exercise as preventive medicine.

2.1.4. Muscular Strength

<u>*Fyfe et al., 2016 (35)*</u>

The goal of this investigation was to examine the effects of concurrent training incorporating either high-intensity interval training (HIT) or moderate-intensity continuous training (MICT) on maximal strength, counter-movement jump (CMJ) performance, and body composition adaptations, compared with single-mode resistance training (RT). Twenty-three recreationally active males (Age: 29.6 ± 5.5 years; VO$_2$peak: 44 ± 11 mL.kg^{-1}.min^{-1}) were randomly assigned to either combined with RT (HIT+RT group, n = 8), work-matched MICT combined with RT (MICT+RT group, n = 7), or RT performed alone (RT group, n = 8) to complete the 8-week intervention 3 times per week. The testing procedures consisted of the aerobic capacity, maximal (1-RM) strength, CMJ performance, and body composition (DXA) before (PRE), mid-way (MID), and after (POST) the intervention. The protocol was completed by multiple 2-minute intervals at 120-150% of the lactate threshold separated by 1-minute of passive recovery. The MICT protocol was performed by 15-33 minutes of continuous cycling at 80-100% of the lactate threshold. The RT protocol was completed 3 days per week. During sessions 1 and 3, the participants performed the leg press, bench press, seated row, leg extension, and leg curl exercises. The second session of each week consisted of the leg press, flat dumbbell press, lat-pulldown, dumbbell lunges, and leg curl exercises. The RT training was performed at ~65-90% 1-RM with two to three minutes of recovery after each set. The findings of this study demonstrated that the maximal leg press strength (1-RM) was significantly increased for RT (38.5%; $p < 0.001$), HIT+RT (28.7%; $p < 0.001$), and MICT+RT (27.5%; $p < 0.001$), while the magnitude of

the improvement was significantly greater for the RT group compared with both HIT+RT and MICT+RT groups. There were no significant between-group differences in the bench press strength. Moreover, the RT group elicited greater enhancements in peak CMJ force compared to the HIT+RT and MICT+RT groups, whereas there were greater improvements in CMJ rate of force development for RT compared to the HIT+RT group. Furthermore, the lower-body lean mass was significantly increased for both RT (4.1%; $p = 0.023$) and MICT+RT (3.6%; $p = 0.052$) groups to a similar extent, while the improvement was attenuated for the HIT+RT group (1.8%; $p = 0.069$) following the intervention. Finally, the investigators of this study suggested that concurrent training incorporating either or work-matched MICT may attenuate changes in the lower-body strength and CMJ performance to a similar extent compared to the RT group. Therefore, continuous or interval endurance training intensity may not be a significant mediator to develop maximal strength during short-term concurrent training.

2.1.5. Summary of "Comparison of High Intensity Interval Training and Moderate Intensity Continuous Training"

The presented literature primarily focused on comparison the physiological adaptations of high intensity interval training and moderate intensity continuous training. Since prescribing HIIT has gained significant attentions in the scientific community, several studies investigated the effects of HIIT, as an alternative for MICT, on cardiorespiratory adaptations. Previous research, utilized various protocols, has established that both HIIT and MICT programs can be effective tools to significantly improve maximal oxygen consumption (21, 29, 45, 66, 74, 79, 108), stroke volume (45), cardiac output (20, 21), capillary density (21), end-diastolic volume (29), aerobic performance (i.e. 2-km run time trial) (74), lactate threshold (79), and heart rate kinetics (79) to a similar extent.

In addition, several studies examined the effects of HIIT and MICT on cardiometabolic adaptations. The findings of the previous literature demonstrated that there were similar enhancements in insulin resistance (15, 32), blood lipids (32, 116), mitochondrial content (10), endothelial enzyme activity (11, 15), glycemic variability (97), glucose control (98), muscle oxidative capacity (37), and glycogen content (37) following the HIIT and MICT protocols, whereas there were no significant differences between the training protocols. This is while the HIIT protocols were completed with less total exercise time and less energy expenditure compared to the MICT programs.

In general, the HIIT protocols are performed at higher load and intensity but shorter duration compared to the MICT programs. According to the randomized crossover design study, however, there were no significant differences between the HIIT and MICT programs regarding exercise enjoyment after a single session of each protocol (100). Furthermore, the only study comparing the impact of HIIT and MICT on muscular strength (35) reported that there were no significant differences in upper body strength and counter movement jump following the concurrent training incorporating resistance training with either HIIT or MICT. However, the resistance training combined with MICT showed greater improvements in lower body strength compared the resistance training incorporated with HIIT. Finally, the authors stated that neither of HIIT and MICT may be a significant mediator to develop muscular strength compared to single-mode resistance training.

In conclusion, the presented literature serves as evidence that the HIIT programs elicit cardiorespiratory, cardiometabolic, and performance adaptations similar to the traditionally prescribed MICT protocols, despite less exercise volume and duration. Therefore, these investigations advocate the idea that HIIT is a "time-efficient" mode of exercise and can serve as an alternative to longer duration MICT programs due to enabling similar physiological adaptations with a shorter time commitment.

2.2. Physiological Adaptations of High Intensity Interval Training

2.2.1. Cardiorespiratory Adaptations

Hazell et al., 2010 (43)

The aim of this research was to compare the traditional SIT protocol with 30s:4min work-to-rest ratio with modified versions consisting of 10s exercise followed by either 4 or 2 minutes of rest intervals after each bout. Forty-eight recreationally active individuals were randomly assigned to either the 30s:4min, 10s:4min, 10s:2min, or control group. The training protocols were performed on an electronically braked cycle ergometer, 3 times per week, for two weeks. The pre- and post-testing included measuring body fat percentage, anaerobic capacity, peak power, mean power, and maximal oxygen uptake, and aerobic performance determined by a 5-km time trail race. The training protocols consisted of "all-out" sprint cycling, while participants performed active rest between bouts of sprint cycling at 10% of their body weight. The number of bouts was progressed by one bout every two sessions, including four intervals in days 1-2, five in days 3-4, and six in days 5-6. There were recovery periods of 48-72 hours between training sessions. The total work was calculated during each training session. The results of the study demonstrated that all SIT protocols (i.e., 30s:4min, 10s:4min, and 10s:2min) significantly improved the 5-km time trial performance, despite no significant difference between groups. The maximal oxygen uptake was significantly improved for the 30s:4min (9.3%) and 10s:4min (9.2%) groups. However, the 10s:2min (3.8%, $p = 0.06$) and control groups did not significantly improve the maximal oxygen uptake values. Moreover, the peak power and mean power were increased in the 30s:4min (9.5%; 12.1%, respectively), 10s:4min (8.5%; 6.5%, respectively), and 10s:2min (4.2%; 2.9%, respectively) groups, while there was no improvement in the control group. During

32

training sessions, the participants of the 30s:4min, 10s:4min, and 10s:2min groups were able to maintain the power output at 89%, 95%, and 96% of the peak power, respectively. Regarding the mean power output, the 30s:4min, 10s:4min, and 10s:2min groups were able to sustain the mean power output at 58%, 82%, and 84% of the peak power, respectively. However, the mean power values of the 10s:4min and 10s:2min groups were significantly higher than the 30s:4min group, despite greater total work for 30s:4min. Furthermore, there was no significant difference regarding body fat percentage values following the interventions. The authors emphasized that the 10-second "all-out" sprint cycling elicits similar performance and aerobic improvements compared to the traditional 30-second Wingate bout, despite the shorter total work (~50% less) and time commitment (33% shorter). Moreover, the participants of the 10s:4min, and 10s:2min groups were able to maintain the peak power and mean power values significantly higher than the 30s:4min group, which were the important factors in sprint interval training adaptations.

Astorino et al., 2012 (3)

The purpose of this study was to investigate potential gender discrepancies in adaptations to low-volume HIIT. Active young males (n = 11, age = 25.3 ± 5.5 years) and females (n = 9, age = 25.2 ± 3.1 years) matched for age, physical activity, and maximal oxygen uptake participated in six sessions of HIIT training with 48 hours recovery between sessions over a 2-3 weeks. The training protocol included four Wingate tests on days 1 and 2, five on days 3 and 4, and six on sessions 5 and 6. There was a control group of 5 males and 4 females (age = 22.8 ± 2.8 years), who completed the pre- and post-testing, but did not participate in training. The pre- and post-testing measurements included maximal oxygen uptake, oxygen pulse, peak power, mean power, fatigability, substrate oxidation, and voluntary force production of the knee flexors and extensors. The findings of this study demonstrated that maximal oxygen uptake, peak power, and mean power in response to HIIT were significantly improved, while there were significant reductions in respiratory exchange ratio and heart rate during submaximal exercise. The adaptations in

maximal oxygen uptake (males: 5.9%, females: 6.8%), peak power (males: 10.4-14.9%, females: 9.1-10.9%), and substrate oxidation was similar between both genders. In conclusion, it was suggested that the adaptations of low-volume HIIT after 6 sessions were similar in males and females matched for maximal oxygen uptake and physical activity.

Astorino et al., 2017 (4)

The aim of this investigation was to assess changes in maximal oxygen uptake (VO_2max) and cardiac output in response to periodized high-intensity interval training (HIIT) for 20 sessions. Seventy-one recreationally active males and females were randomly assigned to either HIIT (n = 39; age = 22.9 ± 5.4 years; $VO_2max = 39.6 \pm 5.6$ mL·kg^{-1}·min^{-1}) or non-exercising control group (CON; n = 32; age = 25.7 ± 4.5 years; $VO_2max = 40.7 \pm 5.2$ mL·kg^{-1}·min^{-1}). The first 10 sessions of HIIT were completed by eight to ten sets of 60-second bouts of cycling at 90%–110% percent peak power output separated by 75 seconds of recovery. Afterwards, the participants of the HIIT group were randomized to one of three regimes (i.e., sprint interval training [SIT], high-volume interval training [HIITHI], or periodized interval training [PER]) for the subsequent 10 sessions. The testing procedures were completed in 3 different stages (i.e., before, midway, and at end of training) by performing progressive cycling to exhaustion to determine VO_2max and maximal cardiac output. The findings of the study revealed significant improvements in VO_2max following the HIIT + SIT (39.8 ± 7.3 mL.kg^{-1}.min^{-1} to 43.6 ± 6.1 mL.kg^{-1}.min^{-1}), HIIT + HIITHI (41.1 ± 4.9 mL.kg^{-1}.min^{-1} to 44.6 ± 7.0 mL.kg^{-1}.min^{-1}), and HIIT + PER (39.5 ± 5.6 mL.kg^{-1}.min^{-1} to 44.1 ± 5.4 mL.kg^{-1}.min^{-1}) protocols associated with significant increases in maximal cardiac output (20.0 ± 3.1 L.min^{-1} to 21.7 ± 3.2 L.min^{-1}, $p = 0.04$) from pre- to post-HIIT across all three training groups. Although there were no significant improvements in maximal hear rate ($p = 0.88$) or arteriovenous oxygen difference ($p = 0.36$), the maximal stroke volume was significantly increased with HIIT ($p = 0.04$). In summary, the authors of this study emphasized that the 20-session periodized HIIT led to significant improvements in VO_2max that

resulted in significant adaptations of maximal stroke volume and cardiac output. Furthermore, the increased VO$_2$max was the result of HIIT mediated by enhancement in central oxygen delivery rather than peripheral adaptations.

Matsuo et al., 2014 (78)

The purpose of this investigation was to assess the effects of time-efficient, low-volume interval exercises on cardiorespiratory capacity and left ventricular (LV) mass compared to the traditional continuous exercise in sedentary adults. Forty-two sedentary males (age: 26.5 ± 6.2 years) were randomly assigned to one of three exercise protocols, including sprint interval training (SIT, 5 min, 100 kcal a session), high-intensity interval aerobic training (HIAT, 13 min, 180 kcal a session), and continuous aerobic training (CAT, 40 min, 360 kcal a session). The SIT protocol consisted of seven sets of 30-second sprint cycling at 120% of VO$_2$max separated by 15-seconds rest periods. The HIAT protocol was performed by three sets of 3-minute cycling at 80-90% VO$_2$max with a 2-min active rest at 50% VO$_2$max after each bout. The CAT group completed 40 minutes of cycling at 60-65% VO$_2$max on a cycle ergometer. All training protocols were supervised and performed five times per week for 8 weeks. The pre- and post-testing procedures included cardiorespiratory capacity (VO$_2$max) and LV mass measurements. The results of the investigation indicated that there were significant ($p = 0.01$) increases in VO$_2$max values for the SIT ($16.7\% \pm 11.6\%$), HIAT ($22.5\% \pm 12.2\%$), and CAT ($10.0\% \pm 8.9\%$) groups, while HIAT induced the greatest improvements compared to the other protocols. Moreover, the LV mass measurements were significantly improved in the SIT ($6.5\% \pm 8.3\%$) and HIAT ($8.0\% \pm 8.3\%$) groups. In addition, the stroke volume of the SIT and HIAT groups were significantly enhanced by $5.3\% \pm 8.3\%$ and $12.1\% \pm 9.8\%$, respectively. This is while the resting heart rates were significantly decreased in both SIT and HIAT groups by $-7.3\% \pm 11.1\%$ and $-12.7\% \pm 12.2\%$, respectively. However, there were no significant changes for the CAT group in the LV mass ($2.5\% \pm 10.1\%$), stroke volume ($3.6\% \pm 6.6\%$), and resting heart rate ($-2.2\% \pm 13.3\%$). The

investigators of the study concluded that the VO_2max improvements following the HIAT protocol was greater compared to the CAT, despite the fact that the HIAT was performed with lower volume and duration than the CAT. Therefore, the HIAT protocol can serve as a time-efficient strategy to improve VO_2max in sedentary adults.

Cantrell et al., 2014 (12)

The purpose of this investigation was to determine whether concurrent sprint interval and strength training (CT) would result in compromised strength development compared to strength training (ST), and to assess the maximal oxygen consumption (VO_2max) and time to exhaustion (TTE) of sprint interval training (SIT) for developing aerobic performance. Fourteen recreationally active males (Age: 25.6 ± 6.1 years) were randomly assigned to either the CT (n = 7) or ST (n = 7) program. The participants' body composition measurements were obtained before and after the training, while the anaerobic power, one-repetition maximum (1RM) lower- and upper-body strength, VO_2max and TTE were analyzed pre-, mid-, and post-training. The ST protocol consisted of three sets of 4-6 repetitions in upper and lower body exercises at 85 % of 1RM in 2 days per week, including back squat, bench press, leg extension, leg curl, pull-down, and shoulder press. The CT program consisted of concurrent SIT and ST protocols performing 4 days per week (i.e., 2 days SIT and 2 days ST) over 12 weeks. The SIT protocol was completed by four to six sets of 20-second Wingate bouts. The results of this study demonstrated that the participants' upper- and lower-body strength significantly ($p < 0.001$) increased after training, while there were no differences between the groups ($p > 0.05$). Moreover, the VO_2max values were significantly ($p < 0.05$) improved in the CT group (40.9 ± 8.4 to 42.3 ± 7.1 mL.kg^{-1}.min^{-1}), whereas no significant improvements were observed in the ST group. In addition, there was a between-group interaction ($p < 0.05$) in the VO_2max measurements for post-intervention (CT: 42.3 ± 7.1 vs. ST: 36.0 ± 3.0 mL.kg^{-1}.min^{-1}). There was a significant main effect of time and group in TTE ($p < 0.05$), and a significant main effect of time in average power ($p < 0.05$). In

summary, the investigators of the study emphasized that performing concurrent sprint interval and strength training did not attenuate the strength responses compared to the ST program, whereas the CT program also improved aerobic performance measures simultaneously.

Hottenrott, Ludyga, & Schulze, 2012 (51)

The purpose of this study was to examine the effects of high intensity versus moderate intensity exercise on aerobic power and body composition in recreationally active males and females, and to test whether or not participants were able to complete a half marathon race after the intervention period. Thirty-four recreationally endurance runners were randomly assigned to either high intensity or moderate intensity training to complete the 12-week intervention. The moderate intensity group (n = 17) performed 2 hours 30 minutes of continuous running composed of two sessions per week, while the high intensity group (n = 17) consisted of 4 sessions of 30-minute high intensity running with an additional 30 min session of endurance running per week. The results of this study demonstrated that high intensity group significantly improved velocity at lactate threshold and visceral fat similar to moderate intensity group. However, there was a significant between group differences for peak oxygen uptake that the improvements were significantly greater for the high intensity group compared to moderate intensity group. Furthermore, the participants of both groups were able to finish a half marathon race. In conclusion, the authors of the study stated that short-duration, intensive high intensity exercise sessions were more effective to enhance aerobic fitness in recreationally active individuals.

2.2.2. Cardiometabolic Adaptations

Little et al., 2010 (71)

The goal of this investigation was to determine the performance, metabolic and molecular adaptations to a more practical model of low-volume HIIT. Seven males (21 ± 0.4 years,

VO$_2$peak = 46 ± 2 ml.kg^{-1}.min^{-1}) participated in this study to complete six training sessions over 2 weeks. The training protocol consisted of eight to twelve sets of 60-second intervals separated by 75-second recovery periods on a cycle ergometer. The intensity during each bout of exercise was at approximately 100% of peak power output measured during a ramp VO$_2$peak test (355 ± 10 W), while the recovery periods were at 30W. Training increased exercise capacity, as assessed by significant improvements on both 50 kJ and 750 kJ cycling time trials ($p < 0.05$ for both). Muscle biopsy samples were obtained from vastus lateralis before and after training to measure maximal activity of citrate synthase (CS) and cytochrome c oxidase (COX) as well as total protein content of CS, COX subunits II and IV, and the mitochondrial transcription factor A (Tfam). The findings of this study demonstrated significant improvements ($p < 0.05$ for all) in maximal activity of CS and COX, as well as protein content of CS, COX (i.e., II, IV) and Tfam. In addition, the nuclear abundance of peroxisome proliferator-activated receptor gamma co-activator 1alpha (PGC-1alpha) was approximately 25% higher after training ($p < 0.05$), while the total PGC-1alpha protein content remained unchanged. Total SIRT1 content, a proposed activator of PGC-1alpha and mitochondrial biogenesis, was increased by approximately 56% following training ($p < 0.05$). The HIIT protocol also increased resting muscle glycogen and total GLUT4 protein content ($p < 0.05$). The investigators of this research emphasized that a practical model of low-volume HIIT can be a potent stimulus to increase skeletal muscle mitochondrial capacity and improving exercise performance. Furthermore, the increased SIRT1, nuclear PGC-1alpha, and Tfam may be associated with mitochondrial adaptations in response to HIIT in human skeletal muscle.

Dawson et al., 1998 (22)

The purpose of this study was to investigate the effects of short spring training on performance, muscle metabolism, and fiber types. Nine fit males voluntarily participated in this study to perform a mean of 16 outdoor sprint running sessions in 6 weeks. The sprinting distances were between 30 to 80 meters at 90-100% of maximal speed, while about 20 to 40 sprints were

performed during each session. Maximal oxygen uptake, maximal sprint (i.e., 10m and 40m), sustained running speed (i.e., supramaximal treadmill run), and repeated sprint performance (i.e., 6 sets of 40 m sprint) tests were performed before and after the training intervention. Moreover, muscle biopsy samples were taken from vastus lateralis to examine changes in metabolites, enzyme activities, and fiber types. The findings of the study indicated that there was a significant improvement in 40 m sprint time ($p < 0.01$), supramaximal treadmill run time ($p < 0.05$), repeated sprint performance ($p < 0.05$), and maximal oxygen uptake ($p < 0.01$) after 16 sessions of training. However, resting muscle concentrations of adenosine triphosphate (ATP) and phosphocreatine did not significantly change. Moreover, phosphorylase activity increased ($p < 0.025$), citrate synthase activity decreased ($p < 0.01$), but no significant changes were observed in myokinase and phosphofructokinase activities. Furthermore, the proportion of type II muscle fibers ($p < 0.05$) was significantly increased following the intervention. The authors suggested that 6 weeks of short-duration sprint training may enhance endurance, sprint, and repeated sprint abilities in young fit males. Also, they stated that increases in proportions of type II muscle fibers can be possible following this type of training.

Talanian et al., 2007 (110)

The purpose of this study was to investigate the effects of seven sessions of HIIT over 2 weeks on skeletal muscle fuel content, mitochondrial enzyme activities, fatty acid transport proteins, peak oxygen consumption, and whole body metabolic, hormonal, and cardiovascular responses to exercise. Eight females performed a maximal oxygen consumption and a 60-minute cycling trial at approximately 60% of VO$_2$peak before and after the intervention. The HIIT protocol performed by 10 sets of 4-minute bouts at approximately 90% VO$_2$peak with 2-minute rest periods between bouts. The results of the study indicated that the peak oxygen consumption was significantly improved by 13% following the intervention. Moreover, plasma epinephrine and heart rate decreased during the final 30 minutes of the 60-minute cycling trial, which was

performed at approximately 60% of VO$_2$peak. In addition, the whole-body fat oxidation increased by 36%, and net glycogen use was reduced during the post-testing 60-minute cycling trial. The HIIT intervention significantly increased muscle mitochondrial β-hydroxyacyl-CoA dehydrogenase and citrate synthase by 31.8% and 19.88%, respectively. Furthermore, total muscle plasma membrane fatty acid-binding protein content increased significantly by 25%, while the fatty acid translocase/CD36 content did not improve following the HIIT intervention. In summary, the authors suggested that seven sessions of HIIT at 90% VO$_2$peak over 2 weeks was sufficient to elicit significant improvements in maximal oxygen consumption as well as fatty acid oxidation during exercise in moderately active women.

Perry et al., 2008 (92)

The aim of this study was to examine the effects of 6-week HIIT on the capacity for skeletal muscle and whole-body carbohydrate and fat oxidation in recreationally active young males and females. Eight subjects (i.e., 3 females and 5 males) participated to complete a maximal oxygen consumption test, a test to exhaustion at 90% of VO$_2$peak, and a 1-hour cycling test at 60% of VO$_2$peak for pre- and post-testing. The training protocol consisted of 10 sets of 4-minute sprint cycling at 90% of VO$_2$peak with 2-minute rest periods after each set. The training intervention was performed 3 times per week for 6 weeks. During the intervention, the intensity was maintained by monitoring heart rate and increasing power output as subjects progressed. Relative to performance, improvements in VO$_2$peak and training power output were recorded. Moreover, muscle and blood analyses were obtained at pre- and post-testing during the recovery following the test to exhaustion test. The muscle and blood analyses included muscle enzyme activities, muscle metabolites and glycogen content, and blood measurements. The results of the study showed significant improvements in skeletal muscle mitochondrial enzyme activity and content, transport proteins for fatty acids, glucose, and lactate, as well as resting glycogen. The investigators stated that the 18-hour repeated high intensity exercise sessions in 6 weeks can be a

powerful tool to increase whole-body and skeletal muscle capacities to oxidize fat and carbohydrate in untrained recreationally active individuals.

Nybo et al., 2010 (90)

The goal of this investigation was to determine the effectiveness of brief intense exercise conducted as high-intensity interval running compared to the traditional training interventions such as prolonged exercise and strength training in physiological adaptations following the 12-week interventions. The pre- and post-testing included cardiorespiratory fitness, plasma lipid profile, glucose tolerance, fat mass, and blood pressure. Thirty-six untrained males (aged 20-43 years) were randomly assigned to either intense interval running (INT; n = 8), strength training (STR; n = 8), prolonged moderate intense continuous running (MOD; n = 8), and control group (CON; n = 8). The INT protocol consisted of five 2-minute running sprints at 95% of maximal heart rate with 2-minute recovery periods after each bout (total time: ~480 minutes). The STR group performed progressive heavy-resistance strength training (total time: ~1500 minutes). The training consisted of three to four sets of squats, hack squat, incline leg press, isolated knee extension, hamstring curls, and calf raises (weeks 1-4: 12-16 RM; weeks 5-12: 6-10 RM). The MOD protocol was completed by 1 hour of continuous running at 80% of maximal heart rate (total time: ~1800 minutes). The findings of the investigation revealed that the INT protocol (14% ± 2% increase in VO$_2$max) significantly improved cardiorespiratory fitness compared to the MOD (7% ± 2% increase in VO$_2$max) and STR (3% ± 2% increase in VO$_2$max) protocols. Moreover, the blood glucose concentration following 2 hours of ingestion of 75 g of glucose was significantly reduced to a similar extent in both INT (from 6.1 ± 0.6 to 5.1 ± 0.4 mM, $p < 0.05$) and MOD (from 5.6 ± 1.5 to 4.9 ± 1.1 mM, $p < 0.05$) groups. However, the improvements in resting heart rate, fat percentage, and the ratio between total and HDL cholesterol were greater in MOD compared to the INT protocol. Furthermore, the total bone mass and lean body mass did not significantly change in INT and MOD, whereas the STR group significantly improved these

41

variables. The authors of the study concluded that performing 12 weeks of INT can be an effective training stimulus to enhance cardiorespiratory fitness and glucose tolerance. Regarding the treatment of hyperlipidemia and obesity, however, the INT protocol may be less effective than prolonged training such as the MOD protocol. In contrast to strength training, the 12-week INT intervention had no significant impact on muscle mass or bone mass.

Metcalfe et al., 2012 (81)

The goal of this investigation was to examine the effects of a reduced-exertion high-intensity interval training (REHIT) intervention on insulin sensitivity and aerobic capacity in previously sedentary individuals. Twenty-nine sedentary but healthy males and females were randomly assigned to either the RE intervention (males, n = 7; females, n = 8) or a control group (males, n = 6; females, n = 8). The participants of the RE group completed three exercise session per week for 6 weeks (overall 18 sessions), while the participants of the control group were asked to maintain their normal sedentary lifestyle. The RE protocol duration was 10 minutes total in every session, including low intensity cycling at 60 W followed by one (first session) or two (all other sessions) all-out Wingate bouts. The duration of each bout was 10 seconds in week 1, 15 seconds in weeks 2-3, and 20 seconds during the final 3 weeks. The pre- and post-testing procedures involved aerobic capacity (i.e., VO_2peak) as well as the glucose and insulin response to a 75-g glucose load. The results of the study indicated that the insulin sensitivity was significantly increased only in the male RE group by 28% following the intervention ($p < 0.05$). Moreover, the VO_2peak measures were significantly ($p < 0.01$) increased in both males (+15%) and females (+12%), while the ratings of the perceived exertion were relatively low. In summary, the authors of the investigation suggested that RE may be a novel, feasible exercise intervention to enhance metabolic health and aerobic capacity. Furthermore, the RE protocol can offer a genuinely time-efficient alternative strategy to high-intensity interval exercise and traditional

moderate intensity continuous exercise for improving risk factors in individuals with type 2 diabetes.

Metcalfe et al.,2016 (82)

The aim of the study was to assess whether there was a true sex difference in response to reduced-exertion high-intensity interval training (REHIT), or different responses can be explained by the large inter-individual variability to all exercise training. Thirty-five healthy but sedentary males (n = 18; Age: 33 ± 9 years; body mass index: 25.1 ± 2.1 kg.m^{-2}; maximal aerobic capacity: 38.6 ± 8.3 mL.kg^{-1}.min^{-1}) and females (n = 18; Age: 36 ± 9 years; body mass index: 24.1 ± 3.5 kg.m^{-2}; maximal aerobic capacity: 31.6 ± 4.6 mL.kg^{-1}.min^{-1}) were asked to participate in three exercise sessions per week over 6 weeks. The testing procedures included insulin sensitivity (i.e., assessed by oral glucose tolerance test) and VO$_2$max (i.e., measured during an incremental cycle test) measurements before and after the 6-week intervention. The RE exercise protocol consisted of eighteen 10-minute sessions including a 3-minute warm-up, one (first session) or two (all other sessions) of 10-20 seconds of Wingate bout, 3-minute recovery in between sprints, and a 3-min cool-down. The duration of the sprint bouts increased from 10 seconds in the first week, to 15 seconds in second and third weeks, and 20 seconds in the last 3 weeks, while strong verbal encouragements were given during each Wingate bout. The findings of this investigation showed that the RE protocol increased the maximal aerobic capacity (2.54 ± 0.65 to 2.78 ± 0.68 L.min^{-1}; main effect of time: $p < 0.01$) associated with reduction of plasma insulin area-under-the-curve (AUC; 6.7 ± 4.8 to 6.1 ± 4.0 IU.min^{-1}.mL^{-1}; $p = 0.096$). However, there were no significant changes in plasma glucose AUC or the Cederholm index of insulin sensitivity. Moreover, the substantial inter-individual variability in response to RE was observed for all variables, while there were no significant impacts due to gender differences. In summary, the authors of this investigation stated that the RE protocol may enhance the key health marker of aerobic capacity within a minimal total training time-commitment. Nevertheless, a large inter-individual

variability in responses to RE was observed, while there were no gender differences in the responses.

Matsuo et al., 2012 (77)

The goal of this investigation was to examine the total energy expenditure (EE), including excess post-exercise energy expenditure (EPEE), induced by two types of interval cycling protocols with the total EE of a traditional, continuous cycling protocol. Ten healthy recreationally active males (ages 20 to 31 years) were asked to complete 3 distinctive exercise sessions, including sprint interval training (SIT), high-intensity interval aerobic training (HIAT), and continuous aerobic training (CAT) over 3 different visits. The SIT protocol consisted of seven sets of 30-second sprint cycling at 120% of VO_2max separated by 15-seconds rest periods. The HIAT protocol was performed by three sets of 3-minute cycling at 80-90% VO_2max with a 2-min active rest at 50% VO_2max after each bout. The CAT group completed 40 minutes of cycling at 60-65% VO_2max on a cycle ergometer. During each visit, the resting metabolic rate, exercise EE, and post-exercise EE after 180 minutes of exercising were measured. The results of this investigation demonstrated that the EPEE values of the SIT, HIAT, and CAT groups averaged 32 ± 19, 21 ± 16, and 13 ± 13 kcal, respectively. In addition, the total EE of the entire session for each SIT, HIAT, and CAT were 109 ± 20, 182 ± 17, and 363 ± 45 kcal, respectively. The EPEE following the CAT session was significantly lower compared the SIT and HIAT protocols, whereas the total EE after the CAT was the greater than interval training protocols. The authors concluded that the SIT and HIAT exercise protocols may be great strategies to control energy expenditures of astronauts during long space missions.

Gillen et al., 2013 (38)

The aim of this investigation was to examine the effects of low-volume high-intensity interval training (HIT) performed in the fasted (FAST) versus fed (FED) state on body

composition, muscle oxidative capacity, and glycemic control in overweight and obese females. Sixteen females (age: 27 ± 8 years, BMI: 29 ± 6 kg.m^{-2}, VO$_2$peak: 28 ± 3 ml.kg^{-1}.min^{-1}) were randomly assigned to either FAST (n = 8) or FED (n = 8) group to complete the 18-session intervention over 6 weeks. The protocol was performed on a cycle ergometer, which consisted of ten sets of 60-second cycling at ~90% maximal heart rate followed by 60-second recovery after each set. The pre- and post-testing included body composition (i.e., body mass, body fat percentage, and fat-free mass) using dual energy X-ray absorptiometry, muscle oxidative capacity (i.e., mitochondrial capacity measuring activity levels of citrate synthase and β-hydroxyacyl-CoA dehydrogenase), and insulin sensitivity. The findings of the study revealed that body mass did not change following the intervention. However, there were significant reductions in fat percentage in abdominal and leg regions as well as whole body levels in both FAST and FED groups (main effects of time, $p \le 0.05$). Moreover, fat-free mass was significantly increased in the leg and gynoid regions in both groups ($p \le 0.05$). The resting muscle biopsy assessment showed a significant training-induced enhancement in mitochondrial capacity due to the increased activity levels of citrate synthase and β-hydroxyacyl-CoA dehydrogenase in both FAST and FED groups ($p \le 0.05$). Furthermore, there were no changes in insulin sensitivity, while the changes in insulin area under the curve were correlated with changes in abdominal fat percentage (r = 0.54, $p \le 0.05$). In conclusion, the investigator stated that short-term low-volume can be a time-efficient strategy to enhance body composition and muscle oxidative capacity in overweight and obese females. This is while neither of fed- and fasted-state training did not significantly influence this response.

Robinson et al., 2017 (99)

The purpose of this investigation was to examine the impacts of 12 weeks of high-intensity aerobic interval (HIIT), resistance (RT), and combined exercise training on insulin sensitivity, lean mass, aerobic capacity, and skeletal muscle mitochondrial respiration. The

participants were consisted of two distinct age groups, young (n = 45; ages 18–30 years) and older (n = 27; ages 65–80 years) with a goal of an equal number of males and females. The participants were randomly assigned to either HIIT (young = 15; old = 10), RT (young = 18; old = 9) or combined (young = 12; old = 8) group. The HIIT protocol was performed by four sets of 3-4 minutes of cycling at >90% of VO_2peak with 3 minutes of pedaling at no load between sets, 3 times per week, and also treadmill walking for 45 minutes at 70% of VO_2peak 2 days per week. The RT group consisted of upper and lower body exercises, four sets of 8-12 repetitions, performing 2 days per week. The combined exercise group initially underwent a 12-week sedentary period and wore accelerometers to record any type of activity. Afterwards, the participants of the combined exercise group began the training intervention by performing 30 minutes of cycling at 70% of VO_2peak five days per week and weightlifting with fewer repetitions than RT in 4 days per week. The results of the investigation indicated that all three interventions significantly improved insulin sensitivity and lean mass in young and old individuals. However, only HIIT and combined training improved aerobic capacity and skeletal muscle mitochondrial respiration. In addition, the HIIT group elicited a more robust improvement in gene transcripts than other exercise modalities, particularly in older participants, while little overlap with corresponding individual protein abundance was noted. Moreover, HIIT reversed many age-related differences in the proteome, particularly of mitochondrial proteins associated with increased mitochondrial protein synthesis. Both RT and HIIT protocols improved proteins involved in translational machinery irrespective of age, while small changes in methylation of DNA promoter regions were found. The authors claimed that the study provided evidence for predominant exercise regulation at the translational level, enhancing translational capacity, and proteome abundance to explain phenotypic gains in muscle mitochondrial function and hypertrophy in all ages due to the improvements in declined age-related muscle mitochondria following HIIT.

2.2.3. Neuromuscular Function

Schaun et al., 2019 (103)

The aim of this study was to compare the neuromuscular adaptations of ergometer based HIIT, whole-body HIIT, and MICT. Forty-one males were randomly assigned to either ergometer based HIIT (n = 15), whole-body HIIT (n = 12), or MICT (n = 14) to complete 16 weeks of training, 3 times per week. The pre- and post-testing included countermovement vertical jump (CMV), squat jump (SJ), peak power (PP), and rate of force development (RFD). The results of the study showed that ergometer-based HIIT, whole-body HIIT, and MICT similarly improved CMJ ($8.5 \pm 13.3\%$; $6.4 \pm 9.8\%$; $2.2 \pm 9.5\%$, respectively), SJ ($3.1 \pm 9.7\%$; $10.4 \pm 16.1\%$; $4.4 \pm 12.1\%$, respectively), and RFD ($58.1 \pm 50.5\%$; $36.9 \pm 54.2\%$; $38.4 \pm 64.3\%$, respectively). Moreover, only ergometer based HIIT and whole-body HIIT significantly increased PP ($1.7 \pm 3.9\%$; $6.4 \pm 7.9\%$, respectively), while there was no significant difference in MICT ($0.5 \pm 6.5\%$) following the intervention. In addition, number of repetitions was significantly improved in the whole-body HIIT group after 8 weeks of training, while there was no significant improvement after 16 weeks. Furthermore, there was no observed improvement in rectus femoris and vastus lateralis maximal sEMG amplitude for ergometer based HIIT, whole-body HIIT, and MICT following the training interventions. The investigators suggested that 16 weeks of whole-body HIIT may improve neuromuscular function to a similar extent as ergometer based HIIT and MICT.

2.2.4. Muscular Power

Sculthorpe, Herbert, & Grace, 2017 (106)

The goal of this study was to examine the efficacy of a low-frequency HIIT (LfHIIT) intervention on peak muscle power (i.e., peak power output), body composition, and balance in lifelong sedentary but otherwise healthy males. Thirty-three lifelong sedentary males were randomized to either the intervention (n = 22, age 62.3 ± 4.1 years) or control (n = 11, age 61.6 ± 5.0 years) groups. The testing procedure was completed in three distinct measurement points, including phase A (i.e., pre-testing), phase B (i.e., after 6 weeks of conditioning exercise), and phase C (i.e., after 6 weeks of LfHIIT where the control group remained inactive throughout the study). The LfHIIT protocol consisted of 5 minutes of warm-up followed by six sets of 30-second sprint cycling at 50% peak power on a cycle ergometer, with 3-minute active rest intervals between sets. The intervention was completed once every 5 days over 6 weeks. The results of this investigation revealed that there was no significant improvement in static balance. There were no significant differences in both absolute and relative peak power output between the groups at phases A and B. However, the intervention group significantly increased both variables following 6 weeks of LfHIIT ($p < 0.01$). Furthermore, the lean body mass of the intervention group was significantly enhanced after due to an increase between phases B and C ($p < 0.05$). The investigators emphasized that 6 weeks of LfHIIT exercise can be feasible and effective method to elicit clinically relevant improvements in absolute and relative peak power output in sedentary aging males, despite no significant increase in static balance.

Zelt et al., 2014 (119)

The purpose of this investigation was to determine the effects of reducing sprint interval training (SIT) work-interval duration on increases in maximal and submaximal performance. The pre- and post-testing included measurements of maximal oxygen uptake (VO$_2$peak), lactate threshold, critical power test, and Wingate test. Thirty-six healthy males were randomly assigned to either endurance training (ET), or sprint interval training consisting of either repeated 30 (SIT 30) or 15 (SIT 15) second Wingate bouts 3 times per week for 4 weeks. The ET group performed

60-75 minutes of moderate intensity cycling at 65% of VO_2peak (i.e., 60 minutes per session for weeks 1-2, increasing to 75 minutes per session for weeks 3-4). The SIT groups consisted of four to six sets of either 30-second Wingate bouts with 4.5 minutes of active recovery (SIT 30) or 15-second Wingate bout with 4.75 minutes of active recovery (SIT 15), starting with 4 bouts per session for weeks 1-2, increasing to 6 intervals per session for weeks 3-4. The findings of this investigation showed that the VO_2peak values were significantly improved for the ET (~13%), SIT 30 (~4%), and SIT 15 (~8%) groups, while there were no significant differences between three groups. Moreover, the ET, SIT 30, and SIT 15 protocols significantly enhanced the lactate threshold and critical power values to a similar extent following the training interventions ($p <$ 0.05). In addition, all three groups similarly improved Wingate peak power at post-testing. In conclusion, the investigators emphasized that reducing SIT work-interval duration from 30 seconds to 15 seconds had no significant influence on training-induced improvements in aerobic and anaerobic power, or on increases in lactate threshold and critical power.

Moghaddam et al., 2019 (84)

This study was designed to compare the effects of two HIIT configurations, a 10-5 versus a 20-10 second work to rest ratio, on anaerobic and aerobic performance. Thirty-four recreationally active males and females were randomly assigned to either 10-5-HIIT (n = 17) or 20-10-HIIT (n = 17) groups. The intervention was completed 3 time per week for 4 weeks. Both HIIT protocols consisted of 6 sets of 6 different functional fitness exercises. The 10-5-HIIT was performed by 10-second bouts of "all-out" exercises with 5-second rest periods between bouts, and 1-minute recovery between sets. The 20-10-HIIT was completed by 20-second bouts of "all-out" exercises with 10-second rest periods between bouts, and 2-minute recovery between sets. The pre- and post-testing included anaerobic (i.e., peak power, anaerobic capacity, anaerobic power, and total work), and aerobic (i.e., time to exhaustion, absolute VO_2max, and relative VO_2max) assessment. The results of the study demonstrated that the 10-5-HIIT and 20-10-HIIT

significantly improved peak power (by 9.2% and 5.7% respectively), anaerobic capacity (by 14.9% and 8.6% respectively), anaerobic power (by 9.0% and 6.2% respectively), total work (by 15.1% and 8.5% respectively), time to exhaustion (by 4.3% and 5.5% respectively), absolute VO_2max (by 9.4% and 8.9% respectively), and relative VO_2max (by 8.5% and 8.2% respectively). The authors of the study suggested that 10-5-HIIT elicits similar health benefits as 20-10-HIIT, despite exercising for 50% less total time. Furthermore, functional fitness training during HIIT protocols seems to be as beneficial as other types of HIIT (e.g., ergometer based HIIT) to improve anaerobic and aerobic performance. In summary, 10-5-HIIT and 20-10-HIIT can induce performance adaptations to a similar extent. Due to shorter time commitment, however, performing 10-5-HIIT at 10s:5s work-to-rest ratio may offer a shorter and equally efficient interval.

2.2.5. Well-being and Exercise Motivation

Knowles et al., 2015 (64)

The aim of this investigation was to examine the effects of HIIT exercise on health-related quality of life (HRQL), aerobic fitness, and motivation to exercise in ageing males. The participants of the study included males who were either lifelong sedentary (SED; N = 25; aged 63 ± 5 years) or lifelong exercisers (LEX; N = 19; aged 61 ± 5 years). The maximal oxygen uptake (VO_2max) and HRQL measurements were conducted in three phases, which included the baseline (phase A), week seven (phase B), and week thirteen (phase C). In addition, the motivation to exercise was evaluated at the baseline and week 13. The training protocol was completed once every five days for 6 weeks (i.e., 9 sessions), while each exercise session consisted of six sets of 30-second sprint cycling at 40% of peak power output with 3-minute active rest intervals against a low (0–50 W) resistance and self-selected speed. The results of the

study demonstrated that the VO$_2$max values were significantly higher in LEX (39.2 ± 5.6 ml.kg^{-1}.min^{-1}) compared to SED (27.2 ± 5.2 ml.kg^{-1}.min^{-1}) and increased similarly in both groups from Phase A to C by 4.6 ± 3.2 ml.kg^{-1}.min^{-1} in SED and by 4.9 ± 3.4 ml.kg^{-1}.min^{-1} in LEX groups following the intervention. However, the physical functioning (LEX: 97 ± 4; SED: 93 ± 7) and general health (LEX: 70 ± 11; SED: 78 ± 11) were significantly higher in LEX, while they were increased only in the SED group from Phase A to C (physical functioning 17 ± 18, 95 % CI 9-26, general health 14 ± 14, 95 % CI 8-21). Furthermore, the exercise motives related to social recognition (LEX: 2.4 ± 1.2; SED: 1.5 ± 1.0), affiliation (LEX: 2.7 ± 1.0; SED: 1.6 ± 1.2) and competition (LEX: 3.3 ± 1.3; SED: 2.2 ± 1.1) were significantly higher in LEX, but the weight management motives were significantly higher in SED (LEX: 2.9 ± 1.1; SED: 4.3 ± 0.5). The authors emphasized that low-volume HIIT protocol may increase the perceptions of HRQL, exercise motives and aerobic capacity in older adults in both SED and LEX groups.

2.2.6. Summary of "Physiological Adaptations of High Intensity Interval Training"

Numerous studies have investigated the physiological adaptations of various high intensity interval exercise protocols in populations with active or sedentary lifestyles. Previous literature established that the intensity and duration of both exercise and rest portions of each set are the most significant factors for optimizing adaptations of HIIT (8). Various studies compared the effects of the traditional sprint interval training with modified versions of HIIT on cardiorespiratory system. Comparing the traditional and modified SIT protocols (43), the 10-second "all-out" sprint cycling induced performance and cardiorespiratory adaptations similar to the traditional SIT, despite the shorter total work and time commitment. Moreover, it was determined that HIIT elicited significant performance (51) and cardiorespiratory adaptations (3, 51) in both healthy active males and females to a similar extent regardless of potential gender

discrepancies. In sedentary population, however, HIIT induced greater cardiorespiratory adaptations compared to longer duration training programs (78). In addition, periodized HIIT protocols resulted in significant increases in cardiorespiratory fitness due to enhancement in central oxygen delivery rather than peripheral adaptations, which can be explained by improved maximal stroke volume and cardiac output (4). According to the study incorporated HIIT with strength training, performing HIIT combined with resistance exercise did not attenuate the strength responses compared to the strength training program, whereas the combined HIIT and resistance exercise significantly improved cardiorespiratory fitness in comparison with resistance training (12).

The training-induced adaptations of HIIT in cardiometabolic function demonstrated by several investigations. The findings of these studies showed that HIIT significantly enhanced skeletal muscle mitochondrial capacity (71, 92, 99), exercise performance (22, 71, 110), proportion of type II muscle fibers (22), fatty acid oxidation (92, 110), carbohydrate oxidation (92), resting glycogen levels (90, 92), glucose tolerance (90), insulin sensitivity (81, 82), and post-exercise energy expenditure (77). Additionally, the results of the study comparing the effects of HIIT in the fasted versus fed state indicated that short-term low-volume HIIT was a time-efficient strategy to enhance body composition and muscle oxidative capacity in overweight and obese individuals regardless of being in fasted or fed state (38).

Recently, the effects of various exercise modalities (i.e., ergometer based and whole-body) on neuromuscular functions were investigated during HIIT programs (103). The findings of the study demonstrated that both ergometer based HIIT and whole-body HIIT programs improved anaerobic performance (i.e., counter movement jump and peak power), while no significant differences observed between the exercise modalities (103). Furthermore, several studies primarily focused on the effects of HIIT on muscular power (84, 106, 119). The results of these investigations indicated that the HIIT programs were feasible and effective methods to develop

absolute peak power output(106), relative peak power output (84, 106, 119), anaerobic power (84), and anaerobic capacity (84), despite low exercise volume and duration. In regards to well-being, significant improvements in health-related quality of life, aerobic fitness, and motivation to exercise were reported among lifelong sedentary and lifelong exerciser adults (64). The study established that the low-volume HIIT protocol enhanced the perceptions of health-related quality of life, exercise motives, and aerobic capacity in both lifelong sedentary and exerciser adults (64).

These findings suggested that various HIIT protocols with different exercise modalities elicited significant improvements in cardiorespiratory and cardiometabolic systems, neuromuscular function, muscular power, and health related well-being in active and sedentary males and females. Nevertheless, there has been a relative absence of studies on the neuromuscular adaptations, specifically neural drive, of lower duration, higher intensity HIIT protocols.

2.3. *Neuromuscular Adaptations of High Intensity Training*

2.3.1. *Muscular Morphological Adaptations*

<u>*Bruseghini at al., 2019 (7)*</u>

The goal of this study was to compare the effects of aerobic high-intensity interval training (HIT) and isoinertial resistance training (IRT) on the strength, mass, architecture, intermuscular adipose tissue (IMAT) quality, and neuromuscular activation of the quadriceps in elderly subjects. Twelve healthy males (age: 69.3 ± 4.2 years; weight: 77.8 ± 10.4 kg; height: 1.72 ± 0.05 m) were asked to complete 8 weeks of followed by 4 months of detraining, then participated in IRT for 8 weeks. The protocol consisted of seven 2-minute bouts of sprint cycling

at 85–95% of individual VO_2max separated by 2-minute recovery intervals at 40% of VO_2max, 3 times per week for 8 weeks. The IRT protocol was completed on a seated knee extension flywheel ergometer 3 times a week over 8 weeks. Each IRT session was completed by four sets of seven maximal, coupled concentric extensions and eccentric flexions of the knee from about 90° to 160°–170° knee joint angle, separated by 3-minute rest periods. The pre- and post-testing included knee extension isometric (T_{MVC}) and dynamic (T_C) maximal concentric torque, anatomical cross-sectional area (ACSA) at 25, 50, and 75% of femur length, quadriceps volume (Vol), IMAT, pennation angle of the fibers from the vastus lateralis, and voluntary activation (%Act). The results demonstrated that T_{MVC} and T_C values were significantly increased after IRT ($p = 0.008$). The IRT protocol induced greater ACSA than HIT, while both protocols similarly increased quadriceps volume (HIT: $p = 0.003$; IRT: $p = 0.001$). In addition, the IMAT levels at 50% of femur length were decreased following both ($p = 0.001$) and IRT ($p = 0.003$). There were no significant improvements in torque values (i.e., T_{MVC}, T_C) after the interventions. However, the %Act of the quadriceps was significantly increased only after the IRT protocol ($p = 0.011$). In conclusion, the authors stated that both and IRT were able to elicit beneficial modifications of muscular mass, architecture, and quality (i.e., reducing IMAT) in elderly males in connection with an amelioration of strength. Furthermore, the and IRT protocols induced a homogeneous increase of ACSA and of Vol of the quadriceps to a similar extent. The data indicated that IMAT may be a prominent indicator to evaluate metabolic-dependent activity and skeletal muscle quality.

Osawa et al., 2014 (91)

The goal of this study was to examine whether combined leg cycling and arm cranking HIIT (LC-AC-HIIT) improves fitness and morphological characteristics equal to those of leg-based cycling HIIT (LC-HIIT) programs. Twelve healthy male participants (aged 28-48 years) were randomly assigned to either LC-AC-HIIT (n = 6) or LC-HIIT (n = 8) groups. The LC-AC-

HIIT protocol consisted of four to six sets of 60-second sprint cycling at >90% VO_2peak with 60-second rest periods after bouts on a cycle ergometer. Afterwards, the participants of the LC-AC-HIIT protocol performed four to six sets of 60-second arm cycling at >90% peak workload with 60-second rest periods after bouts on an electronically braked arm cranking ergometer. The LC-HIIT group completed eight to twelve sets of 60-second cycling at >90% VO_2peak with 60-second rest periods after bouts on a cycle ergometer. The training protocols were performed twice per week for 12 weeks. The pre- and post-testing included maximal oxygen uptake (i.e., VO_2peak, peak power, and heart rate on a cycle ergometer), the cross-sectional area (CSA) of trunk and thigh muscles, and bone-free lean body mass measured by magnetic resonance imaging and dual-energy X-ray absorptiometry. The findings of the study showed that peak power significantly increased from the baseline in both LC-AC-HIIT ($11\% \pm 9\%$; $p < 0.05$) or LC-HIIT ($23\% \pm 38\%$; $p < 0.05$) groups. Moreover, the CSA of the quadriceps femoris muscles were significantly improved in the LC-AC-HIIT ($5\% \pm 5\%$; $p < 0.05$) and LC-HIIT ($11\% \pm 4\%$; $p < 0.05$) groups. However, significant increases were observed in psoas major ($9\% \pm 11\%$) and musculus anterolateral abdominal ($7\% \pm 4\%$) muscles only in the LC-AC-HIIT group ($p < 0.05$). In summary, the authors stated that a 16-week LC–AC-HIIT protocol can be superior to LC-HIIT to elicit improvements in both upper- and lower-body exercise tolerance capacities, accompanied with muscle hypertrophy of psoas major, anterolateral abdominal, and quadriceps femoris muscles, in healthy males.

2.3.2. Muscle Metabolism

<u>MacDougall et al., 1998 (73)</u>

The goal of this investigation was to determine the effects of sprint interval training (SIT) on muscle glycolytic and oxidative enzyme activity and exercise performance. Twelve healthy

males (age: 22 ± 2 years) were asked to complete the 7-week intense interval training on a cycle ergometer. The SIT protocol consisted of 30-second Wingate bouts separated by 2.5-4 minutes of rest intervals between bouts. The intervention began with four bouts followed by four minutes of rest, and gradually progressed to 10 intervals with 2.5 minutes of recovery per session by week 7. The pre-and post-testing included peak power output and total work as well as maximal oxygen consumption (VO_2max). In addition, muscle biopsy samples were obtained from the vastus lateralis muscle of nine subjects during the pre- and post-testing in order to measure the maximal activity of hexokinase, total glycogen phosphorylase, phosphofructokinase, lactate dehydrogenase, citrate synthase, succinate dehydrogenase, malate dehydrogenase, and 3-hydroxyacyl-CoA dehydrogenase. The results of the study revealed significant improvements in peak power output, total work, and VO_2max ($p < 0.05$). Furthermore, there were significantly higher levels of enzyme activity for hexokinase, phosphofructokinase, citrate synthase, succinate dehydrogenase, and malate dehydrogenase ($p < 0.05$) following the training intervention. In summary, the authors of this research stated that relatively brief but intense SIT may result in improvements in both glycolytic and oxidative enzyme activity, maximum short-term power output, and VO_2max.

Nederveen et al., 2015 (87)

The aim of this study was to examine and compare the acute satellite cell responses in older adults following resistance exercise (RE), high-intensity interval exercise (HIT), and moderate-intensity aerobic exercise (AE). Twenty-two sedentary older males (age: 67 ± 4 years; body mass index: 27 ± 2.6 kg.m^{-2}) were randomly assigned to complete an acute bout of either RE, HIIT, or AE. Muscle biopsy samples were obtained from the mid-portion of the vastus lateralis muscle before, 24, and 48 hours after each bout of exercise. The satellite cell responses were measured using immunofluorescent microscopy of muscle cross sections. The RE protocol was performed by three sets of bilateral leg press and knee extension at approximately 95% of 10-

RM with 2 minutes of rest between each set. The first two sets consisted of 10 repetitions of each, while the last set was performed until failure (leg extension: 13 ± 2; leg press is 19 ± 2 repetitions). The HIIT group completed ten sets of 60-second cycling at 90-95% of maximal heart rate separated by 60-second rest intervals between bouts on a cycle ergometer. The AE protocol was performed by 30 minutes of moderate intensity exercise at 55-60% of maximal heart rate. The results of the study indicated that the satellite cell expansion was associated with type I fibers following 24 and 48 hours of the RE only ($p < 0.05$), while there was no expansion of type II-associated satellite cells in the HIIT and AE groups. Moreover, there was a higher number of activated satellite cells after 24 hours of the RE (pre: 1.3 ± 0.1; 24 hours: 4.8 ± 0.5) and HIIT (pre: 0.7 ± 0.3; 24 hours: 3.1 ± 0.3) sessions ($p < 0.05$). In addition, the percentage of satellite cells associated with type I fibers co-expressing MSTN was decreased only in the RE group after 24 hours of exercise (pre: 87 ± 4; 24 hours: $57 \pm 5\%$) ($p < 0.001$). In summary, the investigators stated that HIIT was more potent to elicit satellite cell activity compared to the AE protocol, although RE was the most potent exercise protocol to induce satellite cell pool expansion.

Jacob et al., 2013 (59)

The purpose of this study was to evaluate the physiological adaptations, such as cardiovascular and skeletal muscle properties, following six sessions of high-intensity interval training (HIT) to examine the mechanisms explaining rapid improvements in exercise performance. Sixteen untrained young males (age: 27 ± 3 years; height: 181 ± 6 cm; VO$_2$peak 43 ± 6 ml.kg^{-1}.min^{-1}) were asked to complete the 6-session intervention over 2 weeks. The protocol consisted of eight to twelve sets of 60-second interval cycling at 100% of peak power output, separated by 75 seconds of recovery at 30 W after each bout. The testing procedures included the potential training-induced changes in skeletal muscle respiratory capacity, mitochondrial content, skeletal muscle oxygenation, cardiac capacity, blood volumes, and peripheral fatigue resistance before and after training. The findings of the investigation revealed that the VO$_2$peak (~8%; $p =$

57

0.026) and time trial cycling performance (∼5%; $p = 0.008$) were significantly improved

following the intervention. Moreover, the skeletal muscle respiratory capacities were enhanced

due to the expansion of skeletal muscle mitochondria (∼20%, $p = 0.026$), which was determined

by the activity of cytochrome c oxidase. In addition, the skeletal muscle deoxygenation was

significantly increased with training, whereas the maximal cardiac output, total hemoglobin,

plasma volume, total blood volume, and relative measures of peripheral fatigue resistance did not

significantly change. In conclusion, the authors suggested that the improved mitochondrial

content elicited the enhancements of respiratory capacity and oxygen extraction, and ultimately

developed the maximal whole-body training capacity and endurance performance in healthy

untrained males.

Bell et al., 2015 (6)

The purpose of this investigation was to determine how resistance exercise (RE), HIIT,

and aerobic exercise influenced the integrated day-to-day response of muscle protein synthesis.

Twenty-two sedentary males (age: 67 ± 4 years; body mass index: 27.0 ± 2.6 kg.m^{-2}) were

randomized to complete either RE, HIIT, or aerobic exercise protocol. The participants were

asked to consume a stable isotope tracer (D2O) for 9 days, and daily saliva samples were

obtained to measure tracer incorporation in body water. Muscle biopsy samples were taken on

days 5-8 of D2O consumption to measure tracer incorporation into muscle at rest, 24 hours, and

48 hours following each exercise session. Following a warm-up of 10 repetitions at 35% 10-RM,

the RE protocol was completed by three sets of leg extension and leg press at loads equal to

~95% of their predetermined 10RM, while the last set of each exercise was performed until

failure. The participants in the HIIT group performed ten sets of 1-minute sprint on a cycle

ergometer at ~95% maximal heart rate (~90% of VO$_2$peak). The AE protocol consisted of 30-

minute continuous cycling at ~70% maximal heart rate (55%–60% VO$_2$peak). The participants'

Heart rates were monitored throughout each session of AE and HIIT. The findings of the study

demonstrated that myofibrillar protein fractional synthetic rate was significantly enhanced relative to the rest, 24, and 48 hours following the RE and HIIT protocols. However, the increased myofibrillar fractional synthetic rate in the RE group was greater compared to the HIIT at both time points. This is while the HIIT protocol was the only mode of exercise to improve the sarcoplasmic protein fractional synthetic rate after 24 hours of exercise ($2.30 \pm 0.34\%$ to $1.83 \pm 0.21\%$). This investigation concluded that the HIIT protocol elicited significant improvements in myofibrillar and sarcoplasmic fractional synthetic rate in older males, although changes in muscle protein synthesis in response to certain exercises can be long lasting.

Scribbans et al., 2014 (105)

The primary goal of this study was to compare the fiber specific and whole muscle responses to acute bouts of either low-volume high-intensity interval training (LV-HIT) or moderate-intensity continuous endurance exercise (END) in a randomized crossover design. The secondary goal of the study was to examine the impact of a six-week training intervention (i.e., END or LV-HIT) on whole-body and skeletal muscle fiber specific markers of aerobic and anaerobic capacity. Six recreationally active males (Age: 20.7 ± 3.8 years; VO$_2$peak: 51.9 ± 5.1 mL.kg^{-1}.min^{-1}) voluntarily visited on two separate occasions to participate in the primary goal of the study. Muscle biopsy samples were obtained in a fasted state, then the participants were asked to complete an acute bout of each exercise protocol (i.e., LV-and END), which was followed by a muscle biopsy to assess glycogen content of type I and IIA fibers and p-ACC levels. The LV-protocol was completed by eight 20-second intervals at ~170% of VO$_2$peak separated by 10 seconds of rest. The END protocol consisted of 30 minutes of continuous exercise at ~65% of VO$_2$peak. The results of the acute adaptations revealed that both LV-and END significantly decreased the glycogen content of type I and IIA fibers ($p < 0.05$), whereas the p-ACC levels were significantly ($p < 0.05$) improved following both protocols. Nineteen recreationally active males (n = 16) and females (n = 3) matched for VO$_2$peak were randomly assigned to either the

LV-(n = 10; Age: 21 ± 2 years) or END (n = 9; Age: 20.7 ± 3.8 years) group to participate in the

secondary goal of the study. The participants of LV-and End completed the 23-session

intervention over 6 weeks. The testing procedures included aerobic capacity, fiber-type specific

oxidative and glycolytic capacity, glycogen and intramuscular triglyceride (IMTG) stores, whole-

muscle capillary density, anaerobic performance, and estimated whole-muscle glycolytic capacity

during the pre-, mid-, and post-intervention. Following 6 weeks, the findings of the study

indicated that both LV-and END protocols elicited significant improvements in aerobic capacity

(END = pre: 48.3 ± 6.0, mid: 51.8 ± 6.0, post: 55.0 ± 6.3 mL.kg^{-1}.min^{-1}; LV-= pre: 47.9 ± 8.1,

mid: 50.4 ± 7.4, post: 54.7 ± 7.6 mL.kg^{-1}.min^{-1}), fiber-type specific oxidative and glycolytic

capacity, glycogen and IMTG stores, and whole-muscle capillary density to a similar extent.

However, only the LV-group showed greater developments in anaerobic performance and

estimated whole-muscle glycolytic capacity. In conclusion, the authors suggested that the LV-

exercise may activate the mechanisms to trigger the induction of exercise-induced adaptations

(e.g., intra-myocellular environment) in a drastically reduced exercise time compared to the

traditional END training.

2.3.3. Muscular Power

Kinnunen, Piitulainen, & Piirainen, 2019 (63)

The purpose of this investigation was to the effects of HIIT on neuromuscular

adaptations, changes in force production, and on-ice performance in female ice-hockey players

during preseason. Fourteen professional ice-hockey players (Age: 22 ± 3 years) participated in

this study to complete the 2½-week HIIT program. The HIIT protocol was performed 2 times per

week, consisted of six 30-second high intensity running on a hill with a gradient of 9.5% and 4-

minute rest period between sprints. The spinal (H-reflex) and supraspinal (V-wave)

neuromuscular responses of the soleus muscle were obtained before and after the intervention. The static jump, countermovement vertical jump, plantarflexion maximum voluntary contraction (MVC), and rate of force development (RFD) were assessed. During MVC and RFD testing, the activations of the soleus and tibialis anterior muscle were recorded. Moreover, skating speed and acceleration tests were completed during on-ice training. The findings of the study demonstrated that the participants significantly improved plantarflexion MVC ($11.6 \pm 11.2\%$, $p < 0.001$), RFD ($15.2 \pm 15.9\%$, $p < 0.01$), and static jump ($4.8 \pm 7.6\%$, $p \leq 0.05$). During plantarflexion, the voluntary motor drive (V-wave) of the soleus muscle was significantly increased by $16.0 \pm 15.4\%$ ($p < 0.01$), whereas the coactivation of the tibialis anterior was significantly decreased by $-18.9 \pm 22.2\%$ ($p \leq 0.05$). Moreover, no significant changes were observed for spinal α-motoneuron excitability (H-reflex) during the plantarflexion MVC or on-ice training. The authors stated that HIIT can be implemented to enhance athletes' capability to perform maximal and explosive contractions through increasing voluntary activations of agonist and reducing coactivation of antagonist muscles. Furthermore, it was recommended that HIIT can be prescribed to improve neuromuscular performance in pre-season training. Nevertheless, a longer duration HIIT protocol was required to enhance on-ice performance in female ice-hockey players.

Hurst, Weston, & Weston, 2019 (52)

The aim of this investigation was to assess the effects of combined upper- and lower-body high-intensity interval training (HIT) on cardiorespiratory and muscular fitness in older adults. Thirty-six older adults (50-81 years; males: n = 21; females: n = 15) were assigned to either (n = 18) or a no-exercise control group (CON, n = 18). The pre- and post-testing included leg extensor muscle power, handgrip strength, cardiorespiratory fitness (predicted VO$_2$max) and health-related quality of life assessment (HRQoL). The protocol consisted of four sets of 4 exercises including a combination of upper- (i.e., bent over row, shoulder press), lower- (i.e., squat, split squat) and full-body (i.e., power clean and press, step and press, pulldown to squat,

high pull) exercises. During the first week, each bout of exercise was performed for 45 seconds followed by 3 minutes rest between bouts. Every 2 weeks, the exercise bout duration was increased by 10 seconds, with duration being 75 seconds by week 10, and maintained until the last week. The training intervention performed using a novel hydraulic resistance ergometer twice per week for 12 weeks. The results of the study showed that the participants of the group completed the intervention with the average ($82 \pm 6\%$ HR_{max}) and maximal ($89 \pm 6\%$ HR_{max}) heart rates confirming a high intensity training stimulus. Compared to CON, the group significantly increased the dominant leg power (10.5%; 90% confidence interval 2.4-19.4%), non-dominant leg power (9.4%; 90% confidence interval 3.3-16.0%), dominant handgrip strength (5.9%; 90% confidence interval 0.5-11.5%), and non-dominant handgrip strength (6.3; 90% confidence interval 1.2-11.5%). Moreover, there were slight improvements in predicted VO_2max (8.4%; 90% confidence interval 1.8-15.4%) and small to moderate enhancements across several domains of HRQoL. In summary, the investigators concluded that combined upper- and lower-body may have clinically relevant beneficial impacts on muscular and cardiorespiratory fitness in older adults.

Buckley et al., 2015 (9)

The goal of this research study was to compare the physiological outcomes of traditional HIIT using rowing (Row-HIIT) with a novel multimodal HIIT (MM-HIIT) circuit incorporating multiple modalities, including strength exercises, within an interval. The pre- and post-testing sessions included maximal aerobic power, anaerobic threshold, respiratory compensation threshold, anaerobic power, and anaerobic capacity, as well as muscular strength (i.e., squat, press, and deadlift), power (i.e., broad jump distance), and endurance (i.e., squat endurance). Thirty-two recreationally active females (age: 24.7 ± 5.4 years) were randomly assigned to either Row-HIIT or MM-HIIT to complete the 6-week intervention. The Row-HIIT protocol was completed by six 60-second all-out intensity rowing followed by 3 minutes of rest after each bout.

The MM-HIIT consisted of six rounds of 60-second intervals with 3 minutes of recovery after each bout. Each bout of MM-HIIT interval was completed in 3 parts, including a strength exercise for 4-6 repetitions, an accessory movement for 8-10 repetitions, and a metabolic component conducted all-out for the remainder of the 60 seconds. Following the intervention, the findings of the study revealed that both MM-HIIT and Row-HIIT protocols similarly improved maximal aerobic power (by 7% and 5%, respectively), anaerobic threshold (by 13% and 12%, respectively), respiratory compensation threshold (7% and 5%, respectively), anaerobic power (15% and 12%, respectively), and anaerobic capacity (18% and 14%, respectively). Moreover, there were significant ($p < 0.01$) improvements following the MM-HIIT protocol in squat (39%), press (27%), deadlift (18%), broad jump distance (6%), and squat endurance (280%). However, there were no significant changes for the Row-HIIT group in any muscle performance variable (p-value range 0.33-0.90). Furthermore, the increases of 1-repetition maximum (1RM) squat (64.2 ± 13.6 vs. 45.8 ± 16.2 kg, $p = 0.02$), 1RM press (33.2 ± 3.8 vs. 26.0 ± 9.6 kg, $p = 0.01$), and squat endurance (23.9 ± 12.3 vs. 10.2 ± 5.6 reps, $p < 0.01$) were significantly higher in the MM-HIIT group than the Row-HIIT group. In conclusion, the investigators stated that the MM-HIIT protocol may result in similar aerobic and anaerobic improvements, but greater muscular performance adaptations compared to the Row-HIIT protocol in recreationally active females.

2.3.4. Muscular Endurance

McRae et al., 2012 (80)

The aim of this investigation was to assess changes in aerobic fitness and muscular endurance following endurance training and very low volume, whole-body, high-intensity, interval-style aerobic-resistance training. The testing procedures included maximal oxygen uptake, muscular endurance (i.e., leg extension, chest presses, sit-ups, push-ups, and back

extensions), and level of enjoyment and implementation intentions. Twenty-two recreationally active females (20.3 ± 1.4 years) were randomly assigned to either control group, endurance treadmill training, or whole-body aerobic resistance training four times per week for 4 weeks. The endurance treadmill training protocol (n = 7) consisted of 30 minutes of continuous training at ~85% maximal heart rate. The whole-body aerobic resistance training group (n = 7) performed one set of 20-second intervals involving burpees, jumping jacks, mountain climbers, or squat thrusts. There was a 10-second rest interval after each bout. The control group was the non-training group (n = 8). Following the interventions, the results of this study demonstrated that maximal oxygen uptake was significantly improved in both the endurance treadmill training (~7%) and whole-body aerobic resistance training (~8%) groups ($p < 0.05$). This is while the muscular endurance was significantly enhanced ($p < 0.05$) in the whole-body aerobic resistance training group for leg extensions (+40%), chest presses (+207%), sit-ups (+64%), push-ups (+135%), and back extensions (+75%) after 4 weeks of intervention. Furthermore, the perceived enjoyment and intentions to engage for the low volume, high-intensity whole-body interval exercise were significantly higher following training ($p < 0.05$). In addition, there were no significant improvements for any variable in the control (i.e., non-training) group. Finally, the investigators of this study stated that both endurance and interval-style training significantly improved cardiovascular fitness to a similar extent. However, the whole-body aerobic-resistance training elicited greater impacts on muscular endurance compared to the endurance treadmill training.

2.3.5. Neural Drive

Creer et al., 2004 (18)

The goal of this study was to investigate the effects of short-term, high-intensity sprint interval training on the root mean squared (RMS) and median frequency (MF) derived from surface electromyography (EMG), as well as peak power, mean power, total work, and plasma lactate levels in trained individuals. Seventeen trained cyclists were randomly assigned to either the sprint training (n = 10, Age: 25 ± 2.0) or control (n = 7, Age: 25 ± 0.5) group to complete the 4-week intervention. The sEMG measurements were obtained before and after training, which consisted of 4 sets of 30-second sprints separated by 4 minutes of active recovery. The plasma lactate, peak power, mean power, and total work values were recorded during each bout of sprinting. The results of the study showed an increase in RMS, and a decrease in MF of the vastus lateralis. The plasma lactate values were increased in the sprint training group during exercise, while they were not different than the control group before and after exercise. The total work output, peak power, mean power, and maximal oxygen uptake were significantly increased in the sprint group. The investigators stated that four weeks of high-intensity sprint training can increase MU activation, exercise plasma lactate levels, and total work output in trained cyclists, despite low volume of sprint exercise compared to endurance training alone.

Martinez-Valdes et al., 2017 (75)

The purpose of this investigation was to examine changes in the properties of vastus medialis and vastus lateralis MU after endurance (END) and high-intensity interval training (HIIT) using a novel technique of high-density surface EMG decomposition and MU tracking. Sixteen healthy recreationally active males (age: 29 ± 3 years; height: 178 ± 6 cm; mass: 79 ± 9 kg) were randomized to either END or HIIT group to complete the 6-session intervention over 2 weeks. The pre- and post-testing procedures involved incremental cycling (i.e., VO_2peak, peak power output), maximal and submaximal voluntary contraction (10%, 30%, 50%, and 70% MVC), and sustained contraction (i.e., until task failure at 30% MVC) during isometric knee extensions, while high-density sEMG signals were obtained from the vastus medialis and vastus

lateralis. The END protocol was completed by 90-120 minutes of moderate intensity continuous exercise at 65% of VO$_2$peak on a cycle ergometer. The duration of exercise increased from 90 minutes in days 1 and 2 to 105 minutes in days 3 and 4, and finally to 120 minutes in the last two sessions. The HIIT protocol consisted of eight to twelve bouts of 60-second high-intensity cycling at 100% peak power output separated by 75 seconds of rest between bouts. The number of intervals was progressed from eight bouts in days 1 and 2 to ten in days 3 and 4, and eventually twelve bouts in the last 2 days of training. The findings of this research demonstrated that both END and HIIT groups significantly improved VO$_2$peak to a similar extent by 5.0% and 6.7%, respectively. The END protocol significantly enhanced the time to task failure (by ~17%) with no change in MU discharge rates ($p > 0.05$). Whereas, the HIIT group showed significant ($p < 0.05$) improvements in maximal knee extension torque by ~7% ($p = 0.02$) accompanied by increases in discharge rate for high-threshold MUs ($\geq 50\%$ knee extension MVC). In summary, the investigators of this study stated that the HIIT and END protocols elicited similar improvements in cardiorespiratory fitness, while there were different adjustments in MU discharge rates following these protocols. The low-volume, high-intensity HIIT induced neuromuscular adaptations that are highly specific for high-threshold MUs due to the differences in exercise load intensity and training volume of HIIT compared to END.

Aagaard et al., 2002 (1)

The goal of this investigation was to examine the effects of resistance training on contractile rate of force development (RFD) and efferent motor outflow (i.e., neural drive) during maximal muscle contraction. Fifteen health males (age: 23.3 ± 3.7 years; body mass: 74.1 ± 5.7 kg; height: 179 ± 3 cm) were asked to complete the 14-week heavy resistance training intervention. The testing procedures consisted of the maximal isometric knee extension at 110° (180° = full extension) to measure the RFD (i.e., during 0-30, 0-50, 0-100, 0-200ms epochs following the onset of torque production). In addition, the neural drive was assessed as peak

amplitude during the entire of each contraction, while mean average voltage (MAV) and rate of EMG rise (RER) were determined in time intervals of 0-30, 0-50, and 0-75ms. The training protocol was completed by progressive heavy resistance training for a total of 38 sessions over 14 weeks. The exercises including hack squats, incline leg press, isolated knee extension, hamstring curls, and seated calf raises were performed by four to five sets of 3-10 repetitions. The findings of this investigation demonstrated that the maximal voluntary knee extension strength ($p < 0.001$) and RFD during the 0-30, 0-50, 0-100, 0-200ms epochs ($p < 0.01\text{-}0.05$) were significantly increased following the intervention. Moreover, there were no significant improvements in peak amplitude ($p > 0.05$), while the MAV was significantly developed for the vastus lateralis during the 0-30, 0-50, 0-100ms epochs ($p < 0.01$), vastus medialis during the 0-100ms epoch ($p < 0.05$), and rectus femoris during the 0-50 ($p < 0.01$) and 0-100ms ($p < 0.05$) epochs. Furthermore, the RER values of the vastus lateralis, vastus medialis, and rectus femoris were significantly ($p < 0.001\text{-}0.01$) increased during the initial 30 and 50ms epochs, while the initial improvements of RER at 0-75ms were observed only for the vastus lateralis muscle ($p < 0.01$). In summary, the authors of the study concluded that the explosive strength increases can be explained by the improvements of efferent neural drive due to the concurrent enhancements of the RFD and EMG amplitude during the initial phases of muscular contraction.

Jenkins et al., 2016 (61)

The goal of this investigation was to compare the effects of high versus low intensity resistance training on the hypertrophic, strength, and neuromuscular adaptations using a randomized, repeated measure design. Fifteen healthy males (Age: 21.7 ± 2.4 years; height: 181.6 ± 7.5 cm; weight = 84.7 ± 23.5 kg) were randomly assigned to either the high-load (80% 1RM; n = 8) or low-load (30% 1RM; n = 7) resistance training program. The training protocols consisted of 3 sets of dynamic constant resistance forearm flexion resistance training until failure with loads corresponding to either 80% 1RM or 30% 1RM, three times per week over 4 weeks.

This is while the loads were adjusted following the mid-testing to reflect accurate load dependent on the new 1RM. The testing procedures were completed at baseline, 2, and 4 weeks of training, including the forearm flexor muscle thickness (MT) and echo intensity, maximal voluntary isometric contraction (MVIC), 1RM strength, electromyography (EMG), mechanomyography (MMG), and percent voluntary activation (%VA) at 10–100% of MVIC. The results of the investigation revealed that the MT measures were significantly ($p < 0.05$) increased from pre- to mid-, pre- to post-, and mid- to post-training in both high-load and low-load groups, whereas the echo intensity values did not significantly change following the intervention. Moreover, there was a significant ($p = 0.03$) interaction effect in MVIC strength because of improvements from week 2 to 4 in the 80% 1RM group, while there were no significant improvements in strength for the 30% 1RM group. In addition, there was a significant ($p < 0.001$) interaction effect in 1RM strength due to increases from pre- to mid-testing, as well as pre- to post-testing in the 80% 1RM group, while there were no significant changes in strength for the 30% 1RM group. Furthermore, there was a significant ($p < 0.01$) interaction effect due to the developments of EMG amplitude during 1RM testing in the 80% 1RM group from pre- to post-testing. However, no significant changes in EMG amplitude were observed in the 30% 1RM group following the intervention. The investigators of this study demonstrated that both high-load and low-load resistance training programs elicited hypertrophic increases. The strength improvements were significantly greater in the 80% 1RM group compared to the 30% 1RM group, while the increased strength could not be explained by neuromuscular adaptations due to the slight and similar improvements of the EMG amplitude in both groups.

Jenkins et al., 2017 (62)

The purpose of this investigation was to assess the neuromuscular adaptations following 3 and 6 weeks of high-load versus low-load resistance training to failure in the leg extensors. Twenty-six recreationally active males (age: 23.1 ± 4.7 years; height: 180.6 ± 6.0 cm;

weight = 80.0 ± 14.1 kg) were randomly assigned to either the high-load (80% 1RM; n = 13) or low-load (30% 1RM; n = 13) resistance training groups. The ultrasonic muscle thickness and echo intensity, 1RM strength, maximal voluntary isometric contraction (MVIC) strength, and contractile properties of the quadriceps femoris were assessed at the baseline, 3, and 6 weeks of intervention. In addition, the voluntary activation percentage (VA) and electromyography (EMG) amplitude were determined during the MVIC, as well as randomly ordered isometric step muscle actions at 10-100% of baseline MVIC. The training protocol consisted of three sets of leg extension training until failure with load corresponding to either 80% or 30% of 1RM, and 2-minute recovery periods after each set. The results of the investigation showed that the muscle thickness measures were significantly increased following both 80% and 30% 1RM groups to a similar extent from baseline to week 3 and 6. Whereas, the MVIC and 1RM strength significantly developed to a greater degree from baseline to week 3 and 6 in the 80% 1RM group compared to the 30% 1RM. Moreover, there were significant improvements in VA during MVIC for the 80% 1RM protocol compared to the 30% 1RM group, while only the 80% 1RM group significantly enhanced the EMG amplitude during MVIC. In addition, the peak twitch torque to MVIC ratio was significantly decreased in the 80% 1RM group, but no significant reduction was observed in the 30% 1RM group. Furthermore, the VA and EMG amplitude measures were decreased during submaximal contractions only after the 80% 1 RM program. The 80% 1RM group solely elicited greater improvements in muscle strength than the 30% 1RM due to the significant increases in the VA and EMG amplitude values, despite similar hypertrophic adaptations in both programs. Moreover, the 80% 1RM protocol significantly decreased neural cost to produce the same amount of force, while no significant improvements observed in the 30% 1RM protocol. In conclusion, the authors of this investigation suggested that the high-load resistance training until failure induced greater neural adaptations than the low-load protocol due to increases in muscle strength, VA, and EMG, despite similar hypertrophic improvements in both training groups.

2.3.6. Summary of "Neuromuscular Adaptations of High Intensity Training"

The comparison of HIIT and isoinertial resistance training demonstrated that both protocols similarly improved muscle mass, architecture, and quality (i.e., reducing intermuscular adipose tissue) in elderly males (7). This is while the reduction of intermuscular adipose tissue following both HIIT and isoinertial resistance training was reported as a prominent indicator to evaluate metabolic-dependent activity and skeletal muscle quality (7). The muscular morphological adaptations of HIIT also established by assessing whether combined leg cycling and arm cranking HIIT can improve fitness and morphological characteristics equal to those of leg-based cycling HIIT protocols (91). The findings of the intervention indicated that the combined leg cycling and arm cranking HIIT was a great strategy to improve upper- and lower-body exercise tolerance capacities and to induce muscle hypertrophy in upper- and lower-body (91).

Regarding muscle metabolism, the muscle glycolytic and oxidative enzyme activity as well as exercise performance were assessed following a sprint interval training protocol (73). The findings of the study indicated that relatively brief but intense HIIT caused improvements in both glycolytic and oxidative enzyme activity, accompanied with significant increases in power output and maximal oxygen uptake (73). Moreover, previous studies demonstrated that performing HIIT resulted in significant improvements of satellite cell activity (87), mitochondrial content (59), skeletal muscle oxygenation (59, 105), myofibrillar fractional synthetic rate (6), sarcoplasmic protein fractional synthetic rate (6), and intramuscular glycogen and triglyceride stores (105).

Several studies demonstrated the effects of short-duration high intensity HIIT on muscular power (9, 52, 63). The findings of these investigations showed that HIIT developed muscular strength (9, 52, 63), rate of force development (63), muscular power (52, 63), and

anaerobic capacity (9) in young and adult males and females. The muscular endurance adaptations of HIIT versus long duration continuous training were previously studied by implementing whole-body exercises during HIIT (80). The findings of the investigation indicated that the short-duration whole-body HIIT program elicited greater improvements in muscular endurance compared to longer-duration low- to moderate-intensity training (80).

High intensity exercise programs such as sprint interval training and heavy resistance exercise are performed at either high-velocity or high-loads, which activate higher-threshold motor units that are composed primarily of fast-twitch muscle fibers (104). Previous literature provided insights into neuromuscular adaptations of high intensity exercise utilizing HIIT or resistance training programs. In general, only a few studies primarily focused on the effects of HIIT on neural drive (18). Creer and colleagues (18) demonstrated the effects of short-term, high-intensity sprint interval training on neural drive and exercise performance. The results of the study showed that high-intensity sprint training can increase motor unit activation, exercise plasma lactate levels, and total work output, despite low exercise volume and duration (18, 75). Moreover, Martinez-Valdes and colleagues used a novel technique (i.e., high-density surface EMG decomposition and MU tracking) to investigate the cardiorespiratory as well as motor unit properties of vastus medialis and vastus lateralis following HIIT and endurance exercise (75). The results of investigation showed that both HIIT and endurance training protocols similarly improved cardiorespiratory fitness, whereas the low-volume, high-intensity HIIT elicited neuromuscular adaptations that are highly specific for high-threshold motor units (75), which can be explained by the differences in exercise load intensity and training volume of HIIT compared to moderate intensity endurance exercise. According to the study conducted on neural adaptations of resistance exercise (1), performing high intensity resistance training induced significant improvements in muscle strength, rate of force development, and efferent neural drive. Furthermore, Jenkins and colleagues compared the effects of high- versus low-intensity upper-

71

(61) and lower-body (62) resistance training on the hypertrophic, strength, and neuromuscular adaptations. The findings established that muscle thickness was increased following both high- and low-intensity resistance training, while the echo intensity, muscle strength, EMG amplitude were improved only after the high-intensity resistance exercise protocol (61, 62).

These findings have demonstrated that performing high-intensity exercise programs activate higher-threshold motor units that are composed primarily of fast-twitch muscle fibers. Since each bout of HIIT is performed at high-velocity and high-intensity, the higher-threshold motor units are likely recruited during exercise. However, the lower-intensity continuous training likely results in the recruitment of low- to moderate-threshold motor units. Therefore, the presented literature supports the idea that shorter-duration higher-intensity HIIT programs, similar to heavy resistance exercise, elicit greater neuromuscular adaptations than low- to moderate-intensity training.

CHAPTER III

METHODOLOGY

3.1. Participants

Fifty males and females, between the ages of 18 – 39 years old, were recruited to voluntarily participate in this study. However, 1 male and 1 female dropped out after enrollment and prior to familiarization, and 1 female dropped out during the second week due to a schedule conflict. Therefore, 47 recreationally active individuals (mean ± SD, males: n = 17, age = 21.6 ± 2.1 years, height = 176.0 ± 5.1 cm, mass = 85.3 ± 13.6 kg; females: n = 30, age = 20.9 ± 3.0 years, height = 165.6 ± 7.6 cm, mass = 67.7 ± 11.4 kg) completed this study. Due to the inclusion criteria, the participants needed to be recreationally active by participating in a minimum of 30 minutes of physical activity, at least 3 times per week, during the previous 3 months. The participants were apparently healthy and free from any sign or symptom of disease, and also without any musculoskeletal injury (i.e., broken bone, sprained ligament, or strained muscle) within the previous 6 months. This study was approved by and carried out in accordance with the recommendations of the Institutional Review Board (IRB) for the protection of human participants (IRB Application #: ED-18-175). Prior to the start of the investigation, the participants completed the IRB approved informed consent form as well as an Exercise Pre-Participation Health Screening Process and the Physical Activity Readiness Questionnaire (PAR-Q & You).

3.2. Experimental Design

A randomized, repeated measures design was used to compare the effects of the ultrashort-HIIT, Tabata-HIIT, and MICT on neuromuscular adaptations. The participants were divided into two groups based on gender (i.e., males = 17, females = 30). Each group was then entered in a random drawing to be assigned to either the ultrashort-HIIT (6 males and 10 females), Tabata-HIIT (6 males and 10 females), or MICT (5 males and 10 females) group. During the first visit, following the completion of the informed consent and required paperwork (i.e., PAR-Q form), the participants were asked to step barefoot on the weighing platform and stadiometer to measure body weight and height, respectively. Afterwards, each participant completed a short familiarization trial consisting of all tasks required during the testing session. During the second visit, the participants were asked to lay supine and the ultrasound scans were obtained from the rectus femoris (RF) and vastus lateralis (VL) muscles. While the participants were still in the supine position, the sEMG sensors were placed on the RF and VL muscles. Then, the participants were asked to complete a low-intensity warm-up on a cycle ergometer, at 55-65 rpm, for 5 minutes. Then, the participants performed two series of maximal and submaximal voluntary isometric contractions of the knee extensors from which sEMG and torque signals were recorded simultaneously. Upon completion of the pre-testing, training protocols were performed on a stationary air-resistant fan bike (ROGUE®, Echo Bike, Columbus, OH, USA) 3 times a week (48-72 hours apart) for a duration of four weeks. The post-testing sessions took place 48-72 hours following the last training session and were identical to the pre-testing (without the paperwork).

3.3. Instrumentation and Procedures

3.3.1. Ultrasonography

During the first visit, participants' muscle cross-sectional area (mCSA) and echo intensity (EI) of the RF and VL muscles were assessed using a brightness mode (B-mode) of the ultrasound imaging system (General Electric LOGIQ S8, Wauwatosa, WI, USA) and a multi-frequency linear-array probe (Model ML6-15-D 4-15 MHz, 50-mm field of view). For the assessment of the RF, the participants were asked to lay supine on a padded plinth. Ultrasonic images were taken on the right leg with the transverse plane at 50% of the distance from the anterior superior iliac spine (ASIS) to the superior edge of the patella. To scan the VL muscle, participants were positioned on their left side at a knee angle of 10°. The VL measurements were obtained from the right leg at 50% of the distance between the greater trochanter of femur and lateral edge of patella. Locations of measurements were marked with indelible ink to ensure scans were taken at the same area for both muscles.

A high-density padding foam was placed on the skin to facilitate moving the probe perpendicular to the limb and along the transverse plane. During every scan, water-soluble gel was applied on the skin and ultrasound probe to maximize acoustic coupling and to reduce near-field artifacts. To limit compression of the muscle, the probe was carefully placed on the skin surface and consistent minimal pressure was applied. The system setting for image gain was set at 50 decibels (dB), the dynamic range was set at 72 dB, and the image depth was set at 6 cm. One investigator took and analyzed all ultrasound scans, using image analysis software (ImageJ, version 1.50i) provided by the National Institutes of Health (NIH, Bethesda, Maryland). The ImageJ software displayed every scan with the greatest visual contrast to define borders for analysis. To determine mCSA, every image was assessed by selecting the borders of muscle tissue without including any surrounding fascia by the polygon function of the ImageJ software (Figure 2). However, the EI measurement of each scan was computed by analyzing the grayscale of the selected area of mCSA through the standard histogram function of ImageJ. The average EI was calculated as an arbitrary unit (AU) value between 0 and 255 (0 = black; 255 = white).
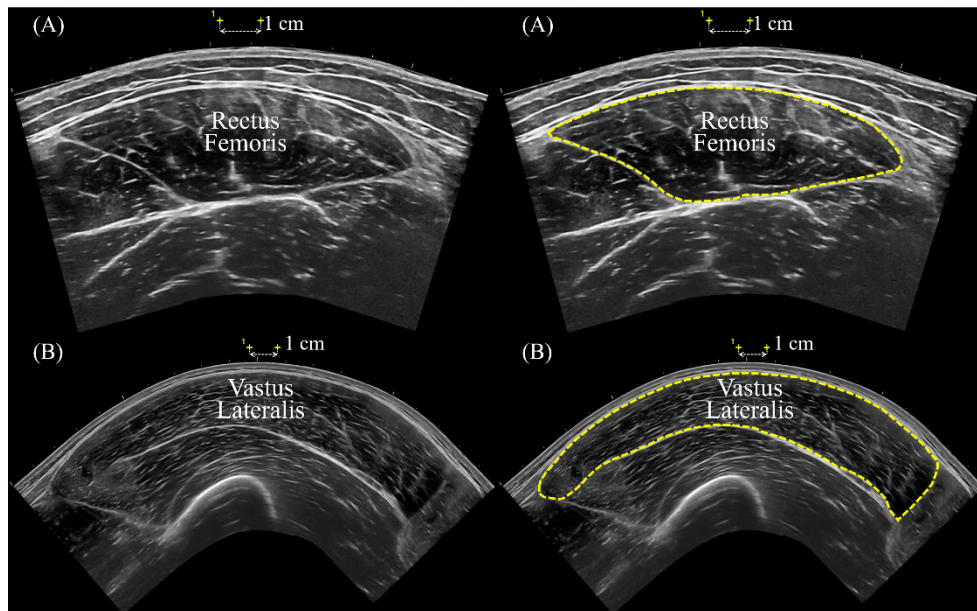
Figure 2 – Ultrasound Imaging: The borders of muscle tissue without including any surrounding fascia were selected by the polygon function of the ImageJ software to determine mCSA and EI. **A)** Rectus Femoris, **B)** Vastus Lateralis.

3.3.2. Isometric Strength Testing

For all maximal and submaximal knee extension contractions, the participants were seated with straps securing their trunk, pelvis, and contralateral thigh on a calibrated isokinetic dynamometer (BIODEX System 4; BIODEX Medical Systems, Inc. Shirley, NY, USA). The seat was adjusted to align the axis of the rotation of the dynamometer head with the lateral epicondyle of the right femur. The right knee was flexed to 120° (180° = full knee extension) between the tibia and the horizontal plane. This position was used for the submaximal and maximal contractions. The dynamometer head was locked at 120° (180° = full knee extension) during all maximal voluntary isometric contractions (MVIC). All torque signals were displayed on a computer screen for real-time visual feedback.

Prior to measuring the maximal voluntary contractions strength, the participants performed 4-second warm-up isometric knee extensions at 25%, 50%, and 75% of their perceived

effort with 30 seconds of rest after each contraction. Following the warm-up and 2 minutes rest, the participants performed 3, 4-5s MVICs of the knee extensors with 2 minutes of rest after each muscle contraction. During these contractions, participants were instructed to kick out as fast and hard as possible to determine the maximal strength and rate of torque development (RTD). Loud verbal encouragement was given during each maximal contraction.

After another 5 minutes of recovery, the participants completed maximal and submaximal ramp isometric contractions, including gradual increase of force, a 6s-10s hold at a constant force level, and a gradual decrease of force. During these contractions, a force template (trapezoidal shaped) and real-time force output were displayed for the participants in order to trace the template (Figure 3-A). These contractions were necessary for recording sEMG signals to assess muscle activation (Figure 3-B). During the ramp contractions, the force trajectory inclined in the beginning and declined at the end at a rate of 10% of $MVIC.s^{-1}$ and held at 40%, 70%, and 100% peak torque for 10s, 10s, and 6s, respectively. The participants completed 4 submaximal (2 at 40% MVIC, and 2 at 70% MVIC at the constant force level section) and 2 maximal (i.e., 100% of MVIC at the constant hold section) tracing contractions, with a 2-minute rest after each.

Figure 3 – Submaximal Isometric Ramp Contraction: Example of 70% submaximal ramp isometric contraction. **(A):** A trapezoidal shaped force template (red) and real-time force output (black) were displayed for the participants in order to trace the template. **(B):** sEMG signals were recorded to assess muscle activation.
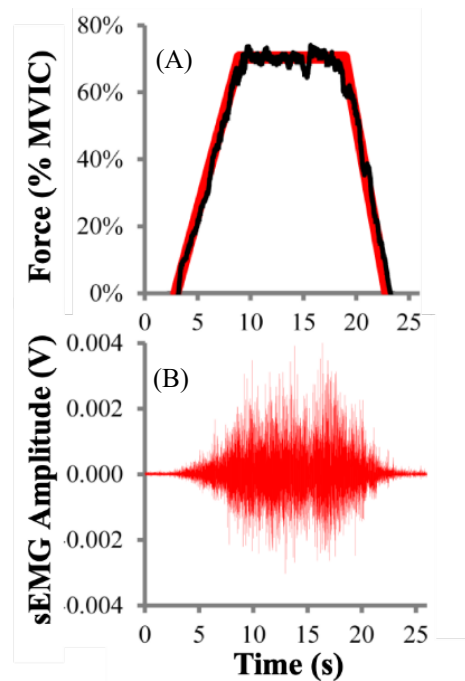
For post-testing, however, participants completed the submaximal (i.e., 40% MVIC, 70% MVIC) and maximal (i.e., 100% MVIC) tracing contractions associated with their pre-treatment and post-treatment strength. After the performing the post-treatment targeted forces, there was a 10-minute rest period for adequate recovery before completing the tracing contractions associated with the pre-treatment MVIC.

3.3.3. Electromyography

Prior to the maximal and submaximal contractions, the sEMG (Delsys DE-2.1, Delsys, Inc., Natick, MA, USA) electrodes were placed on the VL and RF portions of the right quadriceps to record the sEMG signals at the surface of the skin. Prior to the placement of the electrodes, the areas of the skin underwent the standard skin preparation procedures started by shaving the skin to remove any hair. Then, the shaved areas were abraded utilizing abrasion pads to remove dead skin. Next, the abraded areas of skin were cleansed with isopropyl alcohol wipes to ensure that the skin is free of hair, dead skin, and/or dirt. Afterwards, the sEMG sensors were placed on the skin after the alcohol was dry, utilizing a double-sided sensor adhesive (Delsys, Inc., Boston, MA, USA) and further secured with hypoallergenic tape to limit unwanted movement. The sEMG sensors were placed in accordance with SENIAM recommendations (48) on the RF muscle at 50% of distance from the ASIS to the superior border of the patella, and on the VL muscle at 66% of distance between the ASIS to the lateral edge of the patella. The sEMG signals were obtained using parallel-bar, bipolar sEMG sensor with a 10-mm inter-electrode distance (Delsys DE-2.1, Delsys, Inc., Natick, MA, USA) during the maximal and submaximal voluntary isometric contractions. A single pre-gelled surface electrode (Dermatrode, American Imex, Irvine, CA, USA) was placed on the spinous process of the C7 vertebrae to serve as the reference electrode to reduce inter-electrode impedance and increase the signal-to-noise ratio (23).

3.3.4. Signal Processing

The sEMG and torque signals, recorded during the maximal and submaximal contractions, were sampled simultaneously at 20k Hz via a 16-channel Bagnoli acquisition system (Delsys Inc., Boston, MA, USA) and, recorded on a computer, and processed using the custom-built software (LabVIEW v. 17.0, National Instruments, Austin, TX, USA). The sEMG signals were zero-meaned and digitally Bandpass filtered (zero-phase shift 4th-order Butterworth filter) with a 10 Hz low cutoff and a high cutoff at 499 Hz, rectified and analyzed. The maximal sEMG amplitude values were analyzed from the highest 500-millisecond epoch corresponding to the highest average torque value that occurred during the MVIC plateau (Figure 4) (113). The sEMG amplitude was expressed as the root-mean-square (RMS) value. The muscle activation values were determined as the RMS value associated with the peak torque (PT-RMS) as well as the peak RMS value from the entire sEMG signal (pRMS). The early phase muscle activation values were determined as RMS during the first 30 ($sEMG_{30}$), 50 ($sEMG_{50}$), and 100 ($sEMG_{100}$) ms epochs following the sEMG onset. In addition, the RMS values during the maximal and submaximal contractions relative to the pre-treatment strength were calculated as relative PT-RMS (r-PT-RMS) and relative pRMS (r-pRMS) during 40%, 70%, and 100% of pre-treatment MVIC.

The torque signals were low-pass filtered (zero-phase shift 4th-order Butterworth filter) with a 15 Hz cutoff to be analyzed subsequently. The peak torque (PT) value was determined as the average of highest 500ms epoch calculated during the plateau of each MVIC (Figure 4), while the highest value was used for further analysis and signal processing. The rate of torque development (RTD) was calculated as the slope of the torque-time relationship ($Nm.s^{-1}$) during the first 30 (RTD_{30}), 50 (RTD_{50}), 75 (RTD_{75}), 100 (RTD_{100}), 200 (RTD_{200}), and 100-200 ($RTD_{100-200}$) ms epochs of each MVIC following the torque onset (Figure 4). The peak RTD (pRTD) was determined as the torque-time relationship ($Nm.s^{-1}$) between the onset of the torque and PT.

The onset of sEMG was determined at the point, which the sEMG signal deviates from the baseline by ±3 standard deviations. However, the onset of torque was recorded as the first positive deflection of the torque signal where it crossed the baseline and began to rise. Nevertheless, the electromechanical delay (EMD) was calculated as the time difference (ms) between the onset of sEMG and the onset of torque for knee extensors. All sEMG and torque onsets were analyzed and detected through visual inspection by the same investigator and proceed via custom-built software (LabVIEW v. 17.0, National Instruments, Austin, TX, USA).

Figure 4 – Maximal Voluntary Isometric Contraction: **(A):** The peak torque value was determined as the average of highest 500ms epoch calculated during the plateau of each MVIC. **(B):** The maximal sEMG amplitude value was analyzed from the highest 500-millisecond epoch corresponding to the highest average torque value. **(C):** The rate of torque development was calculated as the slope of the torque-time relationship.
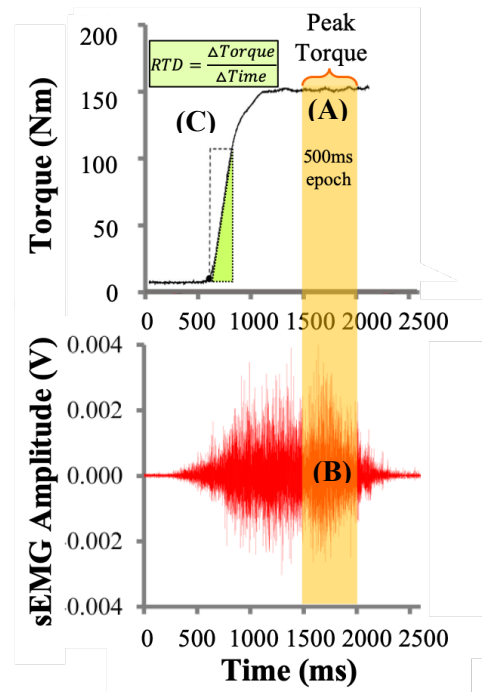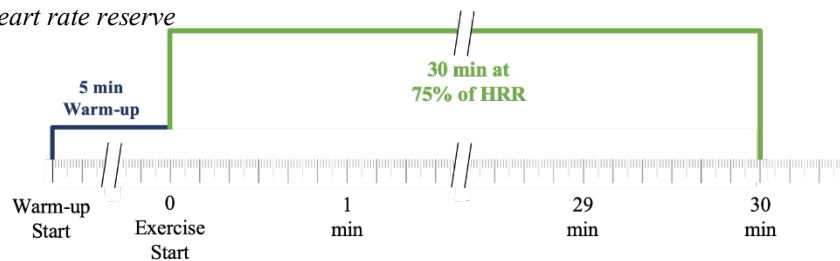
3.3.5. Training Intervention

The training protocols began approximately 48-72 hours after the pre-testing and consisted of 3 days of training per week for 4 weeks. Each protocol was performed on non-consecutive days (i.e., Monday, Wednesday, and Friday). All training protocols (i.e., ultrashort-HIIT, Tabata-HIIT, and MICT) were performed on a stationary air-resistance fan bike (ROGUE®, Echo Bike, Columbus, OH, USA). Since air-resistance fan bikes have handles moving synchronously with the pedaling action, the participants engaged their upper- and lower-bodies during exercise simultaneously. Each training session included a 5-minute warm-up on the bike at 55-65 rpm, a training protocol (i.e., ultrashort-HIIT, Tabata-HIIT, and MICT), and a 5-minute self-paced cool-down. The MICT protocol consisted of 30 minutes of continuous cycling at 75% of heart rate reserve, using Karvonen method (Figure 5-A). While, the ultrashort-HIIT and Tabata-HIIT protocols included 3 sets of interval cycling. During each set, the participants performed 8 bouts of sprint cycling at self-perceived maximal-effort intensity against the air-resistance applied by a large fan. The ultrashort-HIIT intervals were accomplished by performing 10s sprint cycling followed by 5s inactive rest, and a 2.5-min recovery period between sets (Figure 5-B). Whereas, the Tabata-HIIT intervals consisted of 20s sprint cycling followed by 10s inactive rest, and a 5-min recovery period between sets (Figure 5-C). During exercise sessions, the participants' heart rates were monitored continuously, utilizing heart rate sensors (Polar H10, Polar™ Electro, Inc., Port Washington, NY, USA). Every training session was supervised by one investigator.
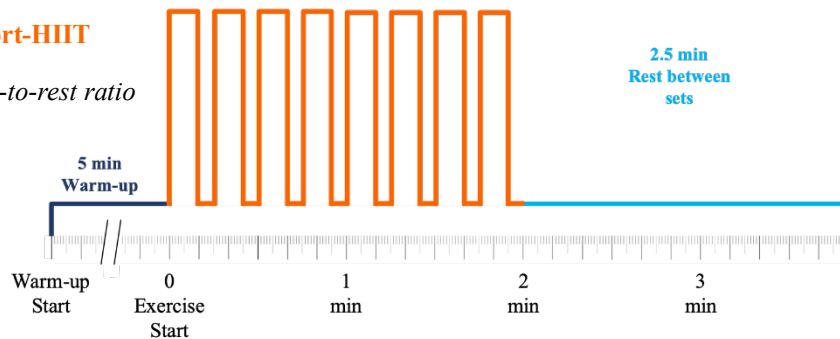
A) MICT

At 75% of heart rate reserve

5 min
Warm-up

30 min at
75% of HRR

Warm-up
Start

0
Exercise
Start

1
min

29
min

30
min

B) Ultrashort-HIIT

10s:5s work-to-rest ratio

2.5 min
Rest between
sets

5 min
Warm-up

Warm-up
Start

0
Exercise
Start

1
min

2
min

3
min

C) Tabata-HIIT

20s:10s work-to-rest ratio

5 min
Rest between
sets

5 min
Warm-up

Warm-up
Start

0
Exercise
Start

1 min

2 min

3 min

4 min
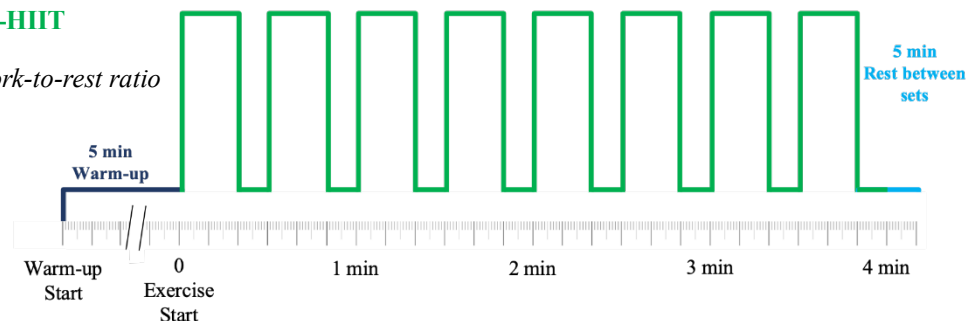
Figure 5 – Training Protocols: **A)** MICT: 30 minutes of continuous cycling at 75% of heart rate reserve. **B)** Ultrashort-HIIT: 3 sets of 8 intervals with 10s sprint cycling at maximal effort intensity followed by 5s rest, and a 2.5-min recovery period between sets. **C)** Tabata-HIIT: 3 sets of 8 intervals with 20s sprint cycling at maximal effort intensity followed by 10s rest, and a 5-min recovery period between sets.

3.3.6. Statistical Analysis

Prior to analyzing data, the assumptions of normality and homogeneity of variance were assessed. Shapiro-Wilk's Test was used to evaluate the normality of the data distribution, while the box and whisker plots were used to determine and eliminate outliers from analysis. The Levene's test was performed for equality of variances to evaluate the homogeneity of variances. If the homogeneity of variances assumption was violated, the error term and degrees of freedom

were adjusted using the Welch's test. The Mauchly's test was applied to evaluate the assumption of sphericity for repeated measures analysis of variance (ANOVA). Two-way mixed factorial repeated measures ANOVAs were utilized to examine mean differences between groups for pre- and post-testing measurements. For all significant ANOVA models, follow-up analyses included one-way repeated measures ANOVAs and dependent samples t-tests with Bonferroni corrections. The main effects were analyzed for the variables that showed no significant interaction effects. The partial eta squared effect sizes (η_p^2) were calculated for each ANOVA and interpreted as small (0.01), medium (0.06), and large (0.14). Pearson correlation coefficients were performed to assess the strength of relationships between muscle activation, muscular strength, and muscular morphological variables. All ANOVAs, Bonferroni-corrected t-tests, partial eta squared effect sizes, and regression analyses were administered using IBM SPSS Statistics software (Version 25.0, IBM Corp., Chicago, Illinois). The alpha (α) level was set at $p \leq 0.05$, and all results were expressed as mean ± standard deviation (SD).

Thirty-two separate two-way mixed-factorial ANOVAs (Time [Pre- vs. Post-testing] × Group [ultrashort-HIIT vs. Tabata-HIIT vs. MICT]) were utilized to analyze the mean differences in muscle activation of rectus femoris and vastus lateralis during MVIC (i.e. PT-RMS, pRMS, early muscle activation [$sEMG_{30}$, $sEMG_{50}$, $sEMG_{100}$], EMD), as well as the maximal (i.e., 100% MVIC [pRMS and r-pRMS]), and submaximal (i.e., 40% MVIC [pRMS, PT-RMS, r-pRMS, r-PT-RMS] and 70% MVIC [pRMS, PT-RMS, r-pRMS, r-PT-RMS]) ramp contractions. In addition, eight separate two-way mixed-factorial ANOVAs (Time [Pre- vs. Post-testing] × Group [ultrashort-HIIT vs. Tabata-HIIT vs. MICT]) were applied to assess the mean differences between pre- and post-training measures of muscular strength (i.e. PT, RTD_{30}, RTD_{50}, RTD_{75}, RTD_{100}, RTD_{200}, $RTD_{100-200}$, and pRTD). Moreover, four separate two-way mixed-factorial ANOVAs (Time [Pre- vs. Post-testing] × Group [ultrashort-HIIT vs. Tabata-HIIT vs. MICT]) were used to evaluate the mean differences between pre- and post-training measures of muscular

83

morphological adaptations of rectus femoris (i.e., mCSA and EI) and vastus lateralis (i.e., mCSA and EI).

Furthermore, Pearson correlation coefficients were computed to compare the magnitude of the relationships between the changes (Δ) in muscular strength and muscle activation, as well as muscular strength and muscular morphological adaptations following the training interventions.

CHAPTER IV

FINDINGS

4.1. Descriptive Statistics

Forty-seven recreationally active males and females completed the ultrashort-HIIT (males: n = 6, age = 22.8 ± 3.1 years, height = 176.5 ± 6.7 cm, body mass = 85.2 ± 7.1 kg; females: n = 10, age = 21.9 ± 4.8 years, height = 167.3 ± 9.4 cm, body mass = 67.9 ± 9.8 kg), Tabata-HIIT (males: n = 6, age = 21.3 ± 1.2 years, height = 174.7 ± 4.5 cm, body mass = 77.9 ± 7.2 kg; females: n = 10, age = 20.6 ± 1.8 years, height = 167.1 ± 7.5 cm, body mass = 67.9 ± 13.9 kg), and MICT (males: n = 5, age = 20.6 ± 0.9 years, height = 177 ± 4.2 cm, body mass = 94.4 ± 20.7 kg; females: n = 10, age = 20.1 ± 1.0 years, height = 162.5 ± 4.8 cm, body mass = 67.4 ± 11.3 kg) protocols. The results of one-way ANOVAs showed no significant differences ($p < 0.05$) between the groups in age, height, and body mass (Table 1).

Table 1 – Demographic data.

	Ultrashort-HIIT	Tabata-HIIT	MICT	p-value
Age (years)	22.3 ± 4.1	20.9 ± 1.6	20.3 ± 1.0	0.111
Height (cm)	170.8 ± 9.4	169.9 ± 7.4	167.3 ± 8.4	0.509
Body Mass (kg)	74.4 ± 12.2	71.6 ± 12.6	76.4 ± 19.4	0.675

Mean ± SD; cm: centimeter; kg: kilogram

4.2. Muscular Strength and Power Adaptations

4.2.1. Peak Torque during Maximal Voluntary Isometric Contraction

The PT results demonstrated no significant Time × Group interaction effect ($p > 0.05$), as well as no significant main effect of Time ($p > 0.05$) following the intervention (Table 2).

4.2.2. Rate of Torque Development

There were no significant Time × Group interaction effects ($p > 0.05$) for pRTD, RTD_{30}, RTD_{50}, RTD_{75}, RTD_{100}, RTD_{200}, and $RTD_{100-200}$. However, there were significant main effects of Time ($p < 0.05$), and all groups similarly improved the RTD_{50} ($F(1,44) = 7.270$, $p = 0.01$; $\eta_p^2 = 0.142$) [Figure 6], RTD_{75} ($F(1,44) = 4.302$, $p = 0.044$; $\eta_p^2 = 0.089$) [Figure 7], RTD_{100} ($F(1,44) = 4.480$, $p = 0.04$; $\eta_p^2 = 0.092$) [Figure 8], and $RTD_{100-200}$ ($F(1,44) = 5.266$, $p = 0.027$; $\eta_p^2 = 0.107$) [Figure 9] following the 4-week intervention (Table 2).

Table 2 – Muscular Strength and Power Adaptations

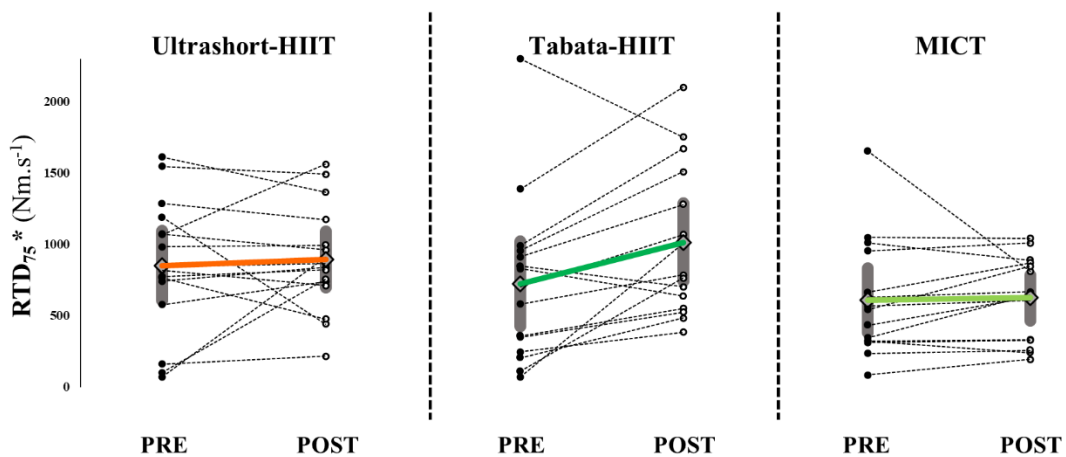|		Ultrashort-HIIT	Tabata-HIIT	MICT	p-value
PT (Nm)	Pre	227.5 ± 85.5	248.4 ± 90.9	214.1 ± 73.9	0.262
	Post	234.5 ± 85.7	247.9 ± 92.9	219.2 ± 62.0	
pRTD ($Nm.s^{-1}$)	Pre	1579.0 ± 612.9	1533.6 ± 637.7	1314.7 ± 736.9	0.765
	Post	1456.3 ± 432.6	1599.9 ± 525.8	1327.7 ± 589.8	
RTD_{30} ($Nm.s^{-1}$)	Pre	296.2 ± 173.7	321.3 ± 281.0	201.8 ± 179.2	0.887
	Post	269.4 ± 192.4	312.4 ± 239.1	221.8 ± 137.1	
RTD_{50} * ($Nm.s^{-1}$)	Pre	564.9 ± 346.6	480.9 ± 458.8	340.8 ± 318.0	0.010
	Post	625.0 ± 318.1	744.6 ± 468.2	406.0 ± 257.4	
RTD_{75} * ($Nm.s^{-1}$)	Pre	851.1 ± 463.7	723.2 ± 560.0	628.5 ± 467.2	0.044
	Post	894.9 ± 369.0	1014.8 ± 513.9	624.9 ± 290.7	
RTD_{100} * ($Nm.s^{-1}$)	Pre	972.7 ± 477.7	912.9 ± 615.5	791.3 ± 473.1	0.040
	Post	1006.4 ± 351.6	1155.1 ± 482.8	841.6 ± 411.1	
RTD_{200} ($Nm.s^{-1}$)	Pre	988.5 ± 367.7	952.1 ± 450.2	859.0 ± 400.1	0.058
	Post	976.8 ± 305.1	1103.2 ± 376.9	918.4 ± 355.1	
$RTD_{100-200}$ * ($Nm.s^{-1}$)	Pre	729.2 ± 208.5	808.1 ± 332.6	750.6 ± 332.0	0.027
	Post	888.7 ± 376.0	889.7 ± 354.9	724.4 ± 220.7	

*Mean ± SD; * significant main effect of Time; PT: Peak torque; pRTD: Peak rate of torque development; RTD_{30}: Rate of torque development during first 30 millisecond epoch; RTD_{50}: Rate of torque development during first 50 millisecond epoch; RTD_{75}: Rate of torque development during first 75 millisecond epoch; RTD_{100}: Rate of torque development during first 100 millisecond epoch; $RTD_{100-200}$: Rate of torque development between first 100 and 200 millisecond epochs; Nm: Newton-meter; $Nm.s^{-1}$: Newton-meter per second; MICT: Moderate intensity continuous training*
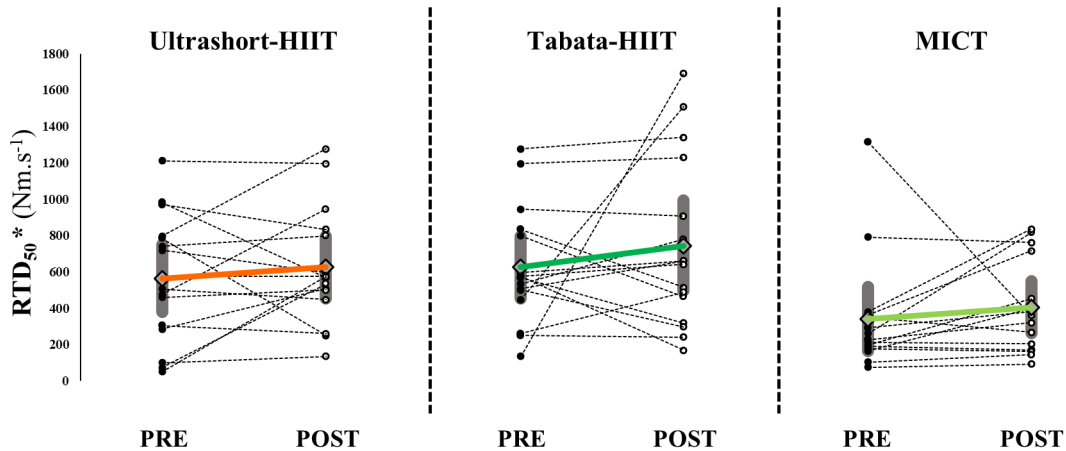
Figure 6 – Comparison of the rate of torque development during the first 50 millisecond epoch for participants completing ultrashort-HIIT, Tabata-HIIT or MICT training. *Significant main effect of Time (collapsed across group); Nm.s^{-1}: Newton-meter per second; MICT: Moderate intensity continuous training

Figure 7 – Comparison of the rate of torque development during the first 75 millisecond epoch for participants completing ultrashort-HIIT, Tabata-HIIT or MICT training. *Significant main effect of Time (collapsed across group); Nm.s^{-1}: Newton-meter per second; MICT: Moderate intensity continuous training
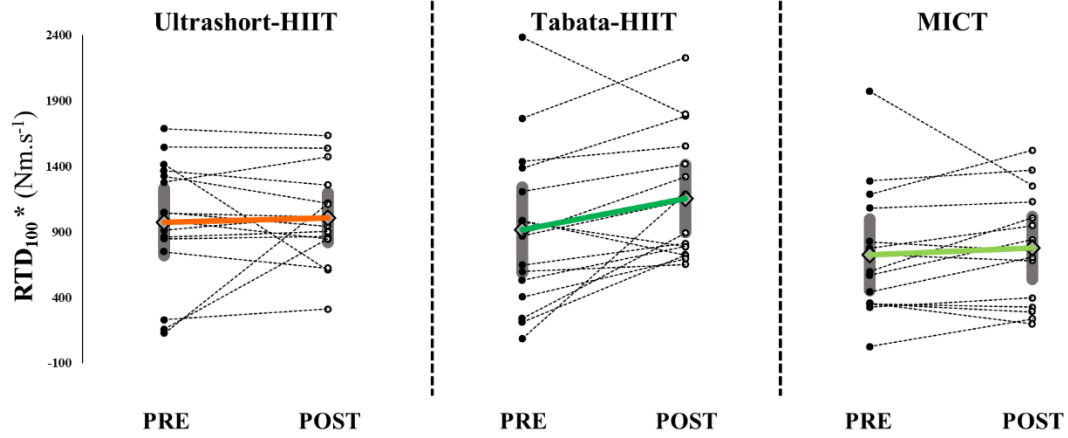
Figure 8 – Comparison of the rate of torque development during the first 100 millisecond epoch for participants completing ultrashort-HIIT, Tabata-HIIT or MICT training. *Significant main effect of Time (collapsed across group); Nm.s^{-1}: Newton-meter per second; MICT: Moderate intensity continuous training
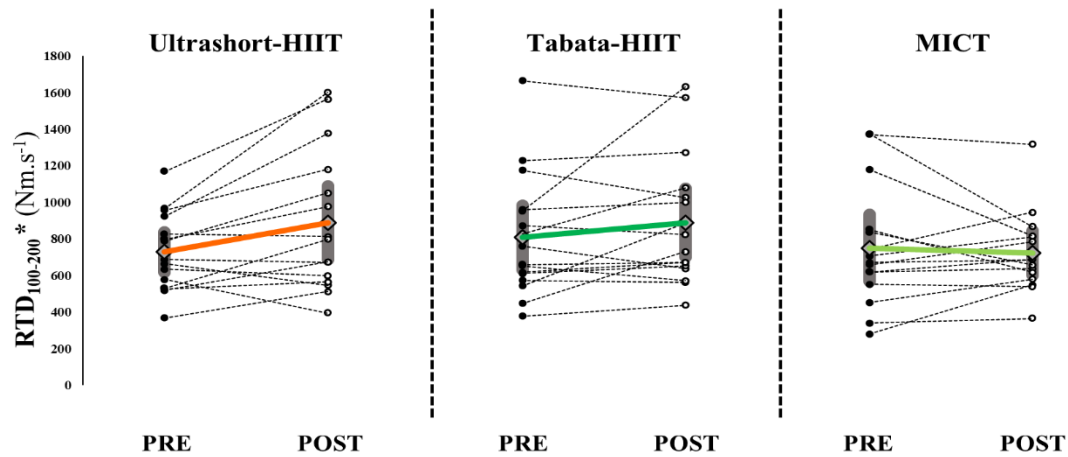

Figure 9 – Comparison of the rate of torque development between the first 100 and 200 millisecond epochs for participants completing ultrashort-HIIT, Tabata-HIIT or MICT training. *Significant main effect of Time (collapsed across group); Nm.s^{-1}: Newton-meter per second; MICT: Moderate intensity continuous training

4.3. Neuromuscular Adaptations

4.3.1. Rectus Femoris Surface Electromyography Signal Amplitude

The statistical analyses indicated significant Time × Group interaction effects ($p < 0.05$) in rectus femoris PT-RMS during the 70% MVIC ramp contraction (Table 4, Figure 15). The post-hoc analyses revealed that only Tabata-HIIT significantly improved the rectus femoris PT-RMS during the 70% MVIC ramp contraction ($F(1,15) = 7.626$, $p = 0.015$; $\eta_p^2 = 0.337$) following the intervention (Table 4, Figure 15). Moreover, there were significant main effects of Time ($p < 0.05$), and the 10-5-HIIT, 20-10-HIIT, and MICT groups similarly improved the pRMS ($F(1,44) = 6.811$, $p = 0.012$; $\eta_p^2 = 0.134$) [Figure 12] and PT-RMS ($F(1,44) = 6.153$, $p = 0.017$; $\eta_p^2 = 0.123$) [Figure 13] during 40% MVIC ramp contraction, pRMS ($F(1,44) = 7.484$, $p = 0.009$; $\eta_p^2 = 0.145$) [Figure 14] during 70% MVIC ramp contraction, pRMS ($F(1,44) = 11.869$, $p = 0.001$; $\eta_p^2 = 0.212$) [Figure 16] during 100% MVIC ramp contraction, r-pRMS ($F(1,44) = 4.169$, $p = 0.047$; $\eta_p^2 = 0.087$) [Figure 17] during 100% MVIC ramp contraction relative to pre-treatment strength, as well as pRMS ($F(1,44) = 12.362$, $p = 0.001$; $\eta_p^2 = 0.219$) [Figure 10] and PT-RMS ($F(1,44) = 10.106$, $p = 0.003$; $\eta_p^2 = 0.187$) [Figure 11] during MVIC for rectus femoris muscle (Tables 3 and 4).

4.3.2. Vastus Lateralis Surface Electromyography Signal Amplitude

There was no significant Time × Group interaction effect ($p > 0.05$), nor significant main effect of Time ($p > 0.05$) in vastus lateralis muscle activation during the MIVC (i.e., pRMS and PT-RMS) as well as 40%, 70%, and 100% MVIC (i.e., pRMS, PT-RMS, r-pRMS, and r-PT-RMS) ramp contractions (Tables 5 and 6).

4.3.3. Rectus Femoris Early Muscle Activation

There was no significant Time × Group interaction effect ($p > 0.05$), nor significant main effect of Time ($p > 0.05$) in the early activation (i.e., $sEMG_{30}$, $sEMG_{50}$, and $sEMG_{100}$) of the rectus femoris muscle during the first 30, 50, and 100 ms epochs (Table 3).

4.3.4. Vastus Lateralis Early Muscle Activation

There was no significant Time × Group interaction effect ($p > 0.05$), nor significant main effect of Time ($p > 0.05$) in the vastus lateralis early activation (i.e., $sEMG_{30}$, $sEMG_{50}$, and $sEMG_{100}$) during the first 30, 50, and 100 ms epochs (Table 5).

4.3.5. Rectus Femoris Electromechanical Delay

There was no significant Time × Group interaction effect ($p > 0.05$), nor significant main effect of Time ($p > 0.05$) in the EMD of the rectus femoris muscle following the intervention (Table 3).

*4.3.6. Vastus Lateralis Electromechanical Delay*

The results of the vastus lateralis EMD demonstrated no significant Time × Group interaction effect ($p > 0.05$), nor significant main effect of Time ($p > 0.05$) following the intervention (Table 5).

Table 3. Rectus Femoris Neuromuscular Adaptations During Maximal Voluntary Isometric Contractions

		Ultrashort-HIIT	Tabata-HIIT	MICT	p-value
pRMS* MVIC (μV)	Pre	129.9 ± 120.4	165.3 ± 102.6	117. 9 ± 46.0	0.001
	Post	160.5 ± 168.5	201.8 ± 142.4	129.3 ± 65.2	
PT-RMS* MVIC (μV)	Pre	118.5 ± 111.2	146.4 ± 96.6	102.2 ± 43.7	0.003
	Post	149.5 ± 163.8	171.5 ± 114.4	112.6 ± 55.3	
$sEMG_{30}$ MVIC (μV)	Pre	51.5 ± 65.6	51.3 ± 48.6	24.9 ± 11.3	0.058
	Post	55.5 ± 58.3	70.9 ± 69.8	35.7 ± 25.1	
$sEMG_{50}$ MVIC (μV)	Pre	68.9 ± 76.0	78.3 ± 68.7	42.0 ± 28.0	0.272
	Post	68.6 ± 61.6	90.8 ± 80.1	49.8 ± 26.6	
$sEMG_{100}$ MVIC (μV)	Pre	94.4 ± 103.0	113.9 ± 76.5	65.2 ± 34.4	0.418
	Post	86.6 ± 75.7	138.4 ± 99.6	67.7 ± 31.8	
EMD (ms)	Pre	32.2 ± 19.5	33.8 ± 14.6	25.5 ± 15.6	0.355
	Post	27.4 ± 13.8	28.6 ± 15.9	29.6 ± 14.0	

*Mean ± SD; * significant main effect of Time, MVIC: Maximal voluntary isometric contraction; pRMS: Maximal sEMG amplitude size during the entire MVIC; PT-RMS: Maximal sEMG amplitude size during the peak torque of MVIC; $sEMG_{30}$: Early phase muscle activation during the first 30 millisecond epoch; $sEMG_{50}$: Early phase muscle activation during the first 50 millisecond epoch; $sEMG_{100}$: Early phase muscle activation during the first 100 millisecond epoch; EMD: Electromechanical delay; MICT: Moderate intensity continuous training; μV: microvolt; ms: millisecond*
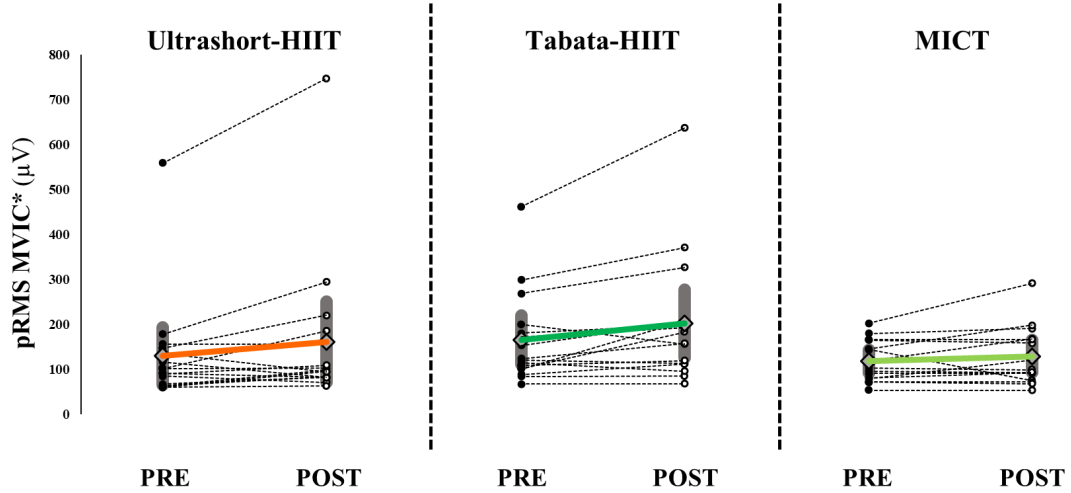
Figure 10 – Comparison of the rectus femoris sEMG amplitude during the entire MVIC for participants completing ultrashort-HIIT, Tabata-HIIT or MICT training. *Significant main effect of Time (collapsed across group); MVIC: Maximal voluntary isometric contraction; pRMS: Maximal sEMG amplitude size during the entire MVIC; MICT: Moderate intensity continuous training; μV: microvolt
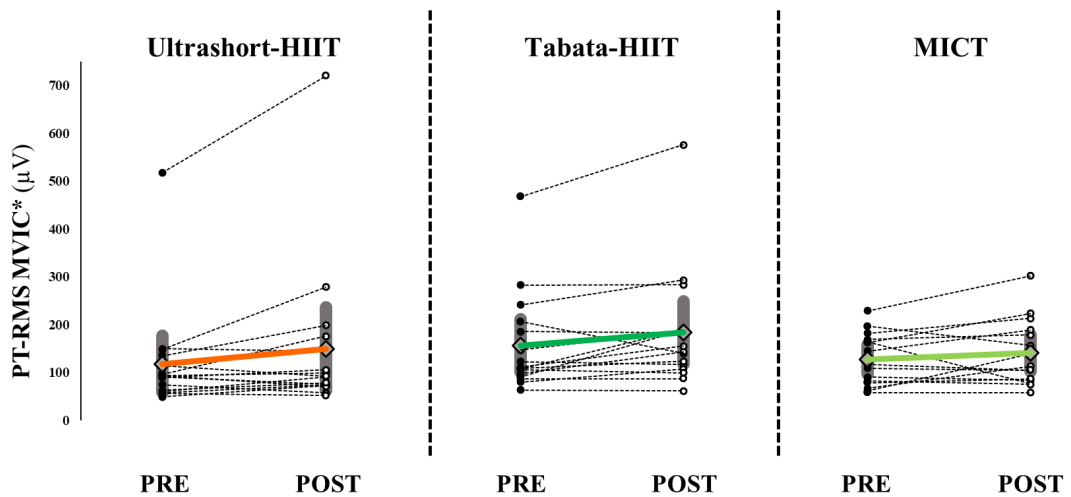
Figure 11 – Comparison of the rectus femoris sEMG amplitude during the peak torque of MVIC for participants completing ultrashort-HIIT, Tabata-HIIT or MICT training. *Significant main effect of Time (collapsed across group); MVIC: Maximal voluntary isometric contraction; PT-RMS: Maximal EMG amplitude size during the peak torque of MVIC; MICT: Moderate intensity continuous training μV: microvolt

Table 4. Rectus Femoris Neuromuscular Adaptations During Submaximal and Maximal Ramp Contractions

		Ultrashort-HIIT	Tabata-HIIT	MICT	p-value
pRMS* 40% MVIC (µV)	Pre Post	48.7 ± 44.9 63.6 ± 83.0	78.2 ± 67.7 98.8 ± 94.0	45.5 ± 24.0 50.4 ± 40.0	0.012
PT-RMS* 40% MVIC (µV)	Pre Post	41.0 ± 44.1 44.8 ± 52.2	54.8 ± 40.4 80.4 ± 77.0	37.7 ± 20.6 42.6 ± 38.9	0.017
pRMS* 70% MVIC (µV)	Pre Post	118.7 ± 111.9 131.5 ± 123.4	154.3 ± 102.3 206.7 ± 165.6	106.0 ± 55.4 113.4 ± 62.1	0.009
PT-RMS** 70% MVIC (µV)	Pre Post	97.8 ± 86.2 108.4 ± 98.2	123.2 ± 83.8** 173.4 ± 146.0	89.9 ± 51.7 91.4 ± 53.7	0.015
pRMS* 100% MVIC (µV)	Pre Post	128.7 ± 100.0 163.2 ± 128.9	171.2 ± 102.5 220.1 ± 156.1	124.0 ± 57.4 133.8 ± 68.7	0.001
r-pRMS 40% MVIC (µV)	Pre Post	48.7 ± 44.9 53.6 ± 52.6	78.2 ± 67.7 89.9 ± 72.1	45.5 ± 24.0 52.4 ± 45.1	0.092
r-PT-RMS 40% MVIC (µV)	Pre Post	41.0 ± 44.1 42.4 ± 42.2	54.8 ± 40.4 64.2 ± 41.1	37.7 ± 20.6 41.7 ± 28.9	0.190
r-pRMS 70% MVIC (µV)	Pre Post	118.7 ± 111.9 120.3 ± 100.3	154.3 ± 102.3 188.4 ± 129.6	106.0 ± 55.4 108.7 ± 72.8	0.127
r-PT-RMS 70% MVIC (µV)	Pre Post	97.8 ± 86.2 95.2 ± 72.0	123.2 ± 83.8 155.3 ± 117.5	89.9 ± 51.7 91.5 ± 65.1	0.187
r-pRMS* 100% MVIC (µV)	Pre Post	128.7 ± 100.0 147.1 ± 115.7	171.2 ± 102.5 199.5 ± 124.5	124.0 ± 57.4 126.5 ± 70.3	0.047

*Mean ± SD; * significant main effect of Time; ** significant Time × Group interaction; MVIC: Maximal voluntary isometric contraction; pRMS: Maximal sEMG amplitude size during the entire MVIC; PT-RMS: Maximal sEMG amplitude size during the peak torque of MVIC; r-pRMS: Maximal sEMG amplitude size during the entire MVIC relative to pre-treatment strength; r-PT-RMS: Maximal sEMG amplitude size during the peak torque of MVIC relative to pre-treatment strength; µV: microvolt*
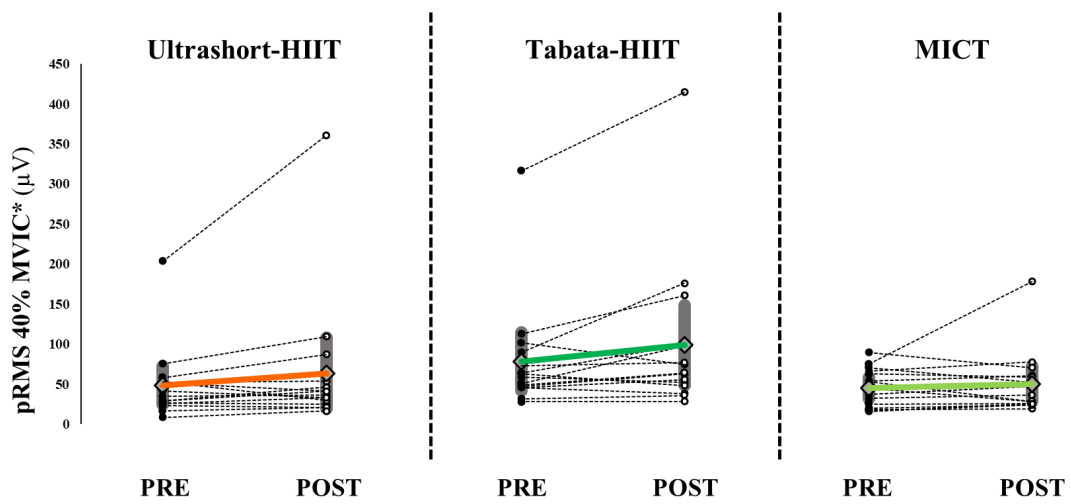
Figure 12 – Comparison of the rectus femoris sEMG amplitude size during the entire 40% MVIC for participants completing ultrashort-HIIT, Tabata-HIIT or MICT training. *Significant main effect of Time (collapsed across group); MVIC: Maximal voluntary isometric contraction; pRMS: Maximal sEMG amplitude size during the entire MVIC; MICT: Moderate intensity continuous training; µV: microvolt
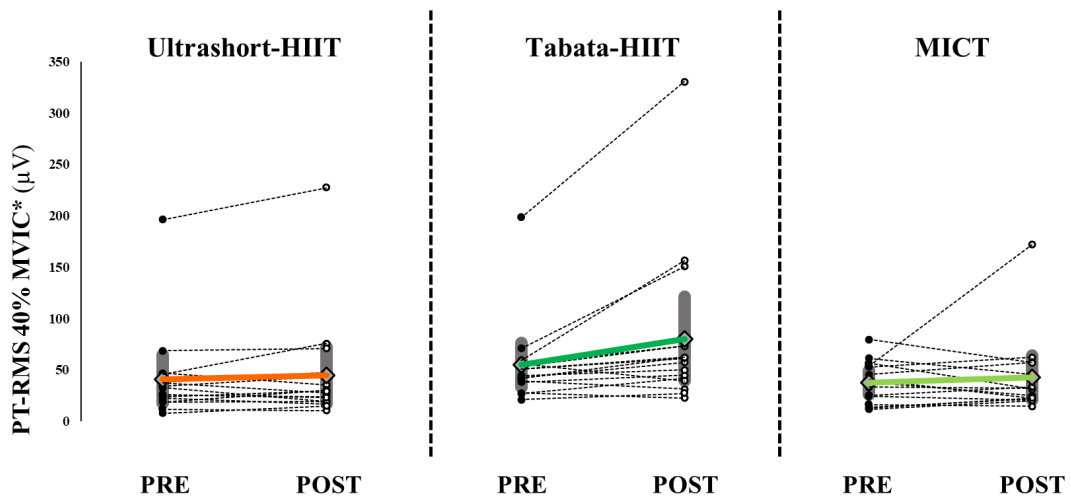
Figure 13 – Comparison of the rectus femoris sEMG amplitude size during the peak torque of 40% MVIC for participants completing ultrashort-HIIT, Tabata-HIIT or MICT training. *Significant main effect of Time (collapsed across group); MVIC: Maximal voluntary isometric contraction; pRMS: Maximal sEMG amplitude size during the entire MVIC; MICT: Moderate intensity continuous training; µV: microvolt

Figure 14 – Comparison of the rectus femoris sEMG amplitude size during the entire 70% MVIC for participants completing ultrashort-HIIT, Tabata-HIIT or MICT training. *Significant main effect of Time (collapsed across group); MVIC: Maximal voluntary isometric contraction; pRMS: Maximal sEMG amplitude size during the entire MVIC; MICT: Moderate intensity continuous training; μV: microvolt
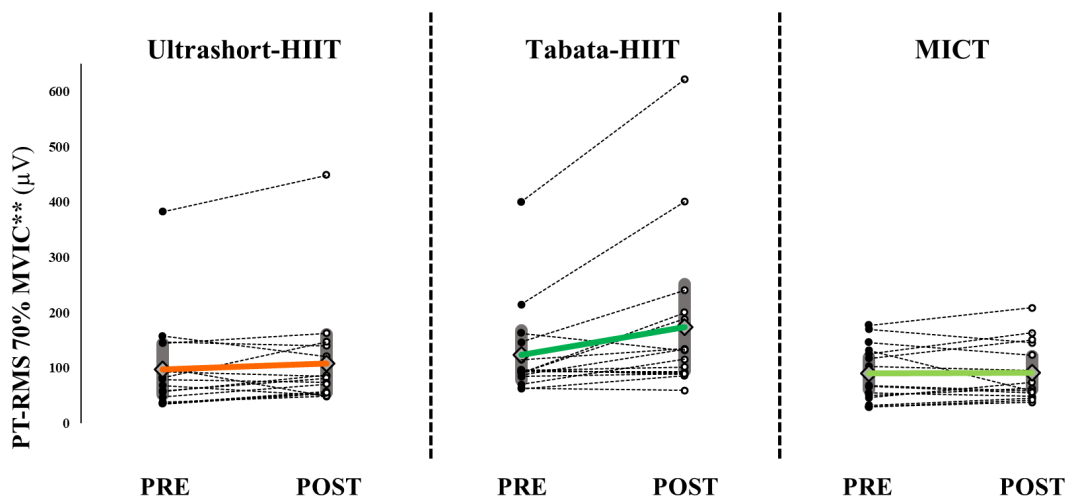
Figure 15 – Comparison of the rectus femoris sEMG amplitude size during the peak torque of 70% MVIC for participants completing ultrashort-HIIT, Tabata-HIIT or MICT training. *Significant main effect of Time (collapsed across group); MVIC: Maximal voluntary isometric contraction; pRMS: Maximal sEMG amplitude size during the entire MVIC; MICT: Moderate intensity continuous training; μV: microvolt
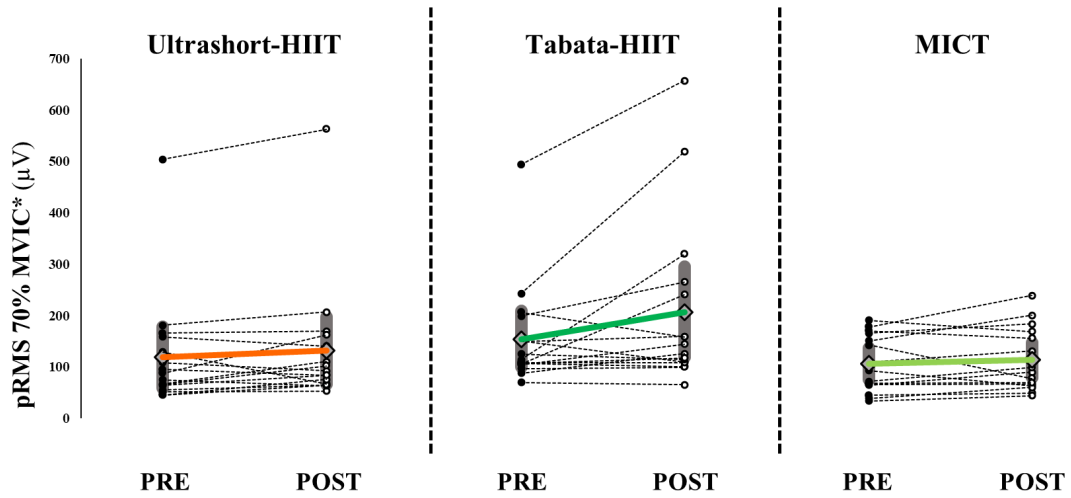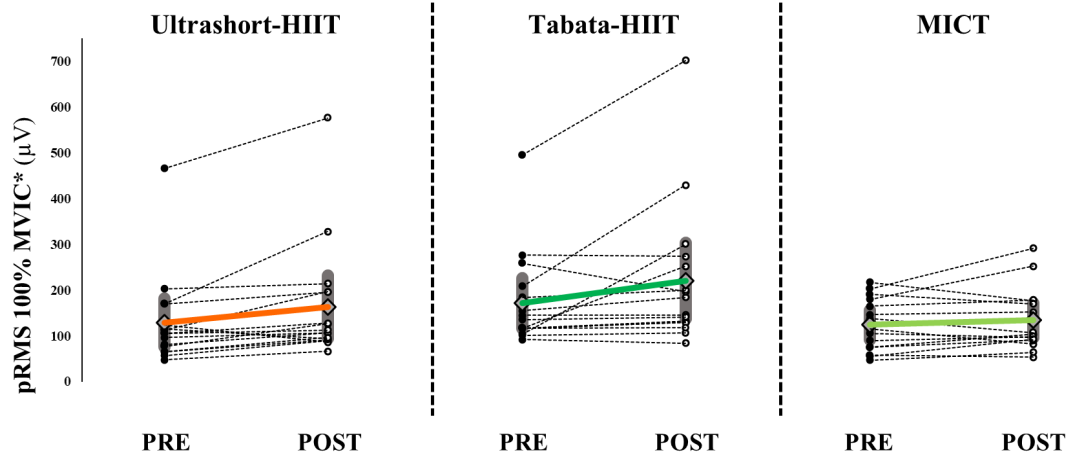
Figure 16 – Comparison of the rectus femoris sEMG amplitude size during the entire 100% MVIC for participants completing ultrashort-HIIT, Tabata-HIIT or MICT training. *Significant main effect of Time (collapsed across group); MVIC: Maximal voluntary isometric contraction; pRMS: Maximal sEMG amplitude size during the entire MVIC; MICT: Moderate intensity continuous training; µV: microvolt
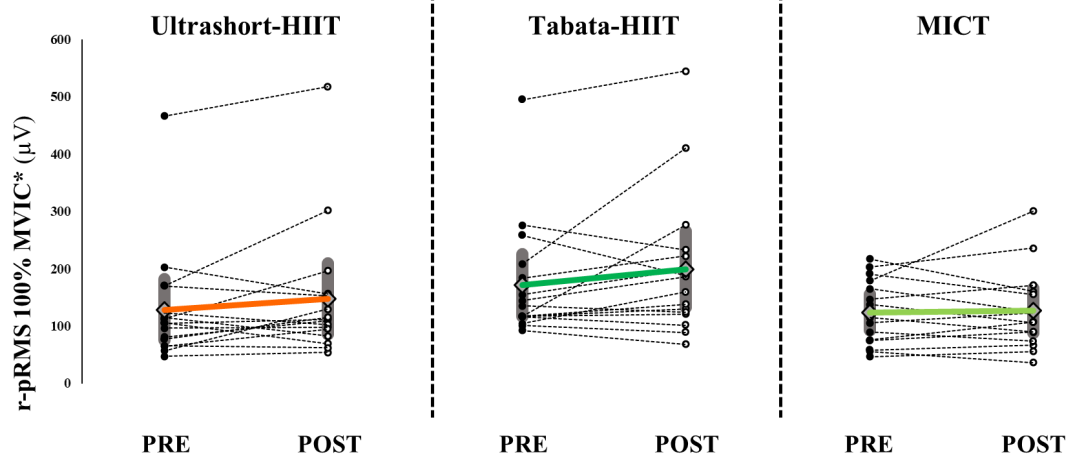
Figure 17 – Comparison of the rectus femoris sEMG amplitude size during the entire 40% MVIC relative to pre-treatment strength for participants completing ultrashort-HIIT, Tabata-HIIT or MICT training. *Significant main effect of Time (collapsed across group); MVIC: Maximal voluntary isometric contraction; r-pRMS: Maximal sEMG amplitude size during the entire MVIC relative to pre-treatment strength; MICT: Moderate intensity continuous training; µV: microvolt

Table 5. Vastus Lateralis Neuromuscular Adaptations During Maximal Voluntary Isometric Contractions

		Ultrashort-HIIT	Tabata-HIIT	MICT	p-value
pRMS MVIC (μV)	Pre	130.6 ± 59.4	149.3 ± 95.5	120.8 ± 68.3	0.323
	Post	140.4 ± 102.5	161.1 ± 96.9	118.7 ± 63.0	
PT-RMS MVIC (μV)	Pre	113.1 ± 46.2	128.3 ± 85.1	101.0 ± 61.6	0.094
	Post	125.7 ± 92.4	144.8 ± 85.2	103.1 ± 55.1	
$sEMG_{30}$ MVIC (μV)	Pre	45.9 ± 50.7	52.9 ± 70.7	25.7 ± 17.8	0.611
	Post	41.5 ± 34.5	61.8 ± 62.1	33.8 ± 35.61	
$sEMG_{50}$ MVIC (μV)	Pre	66.0 ± 62.6	80.0 ± 89.2	43.5 ± 39.4	0.729
	Post	68.4 ± 74.4	80.8 ± 72.5	50.9 ± 39.0	
$sEMG_{100}$ MVIC (μV)	Pre	99.6 ± 101.5	115.5 ± 125.4	67.5 ± 36.5	0.562
	Post	88.9 ± 70.0	102.6 ± 72.6	69.8 ± 38.9	
EMD (ms)	Pre	38.5 ± 27.8	34.6 ± 13.3	32.9 ± 11.6	0.286
	Post	35.1 ± 28.1	32.0 ± 14.2	31.5 ± 15.6	

Mean ± SD; MVIC: Maximal voluntary isometric contraction; pRMS: Maximal sEMG amplitude size during the entire MVIC; PT-RMS: Maximal sEMG amplitude size during the peak torque of MVIC; $sEMG_{30}$: Early phase muscle activation during the first 30 millisecond epoch; $sEMG_{50}$: Early phase muscle activation during the first 50 millisecond epoch; $sEMG_{100}$: Early phase muscle activation during the first 100 millisecond epoch; EMD: Electromechanical delay; MICT: Moderate intensity continuous training; μV: microvolt; ms: millisecond

Table 6. Vastus Lateralis Neuromuscular Adaptations During Submaximal and Maximal Ramp Contractions

		Ultrashort-HIIT	Tabata-HIIT	MICT	p-value
pRMS 40% MVIC (µV)	Pre Post	57.3 ± 28.3 66.9 ± 61.6	80.1 ± 46.0 77.3 ± 48.6	54.6 ± 30.8 48.0 ± 24.7	0.993
PT-RMS 40% MVIC (µV)	Pre Post	46.0 ± 18.0 58.9 ± 59.4	61.7 ± 34.2 66.5 ± 43.9	45.4 ± 27.7 41.2 ± 23.0	0.311
pRMS 70% MVIC (µV)	Pre Post	111.9 ± 43.1 124.0 ± 86.7	138.1 ± 72.4 143.3 ± 77.0	105.9 ± 60.2 100.0 ± 50.2	0.522
PT-RMS 70% MVIC (µV)	Pre Post	97.4 ± 34.6 107.4 ± 72.9	110.1 ± 53.1 125.5 ± 67.5	89.7 ± 51.7 83.6 ± 41.8	0.207
pRMS 100% MVIC (µV)	Pre Post	145.0 ± 60.7 163.0 ± 122.5	160.1 ± 83.0 168.1 ± 87.2	132.3 ± 73.6 122.0 ± 57.2	0.482
r-pRMS 40% MVIC (µV)	Pre Post	57.3 ± 28.3 60.8 ± 45.3	80.1 ± 46.0 74.3 ± 45.6	54.6 ± 30.8 46.2 ± 23.9	0.324
r-PT-RMS 40% MVIC (µV)	Pre Post	46.0 ± 18.0 51.1 ± 31.8	61.7 ± 34.2 64.3 ± 40.0	45.4 ± 27.7 39.6 ± 19.8	0.812
r-pRMS 70% MVIC (µV)	Pre Post	111.9 ± 43.1 110.5 ± 64.5	138.1 ± 72.4 137.4 ± 76.1	105.9 ± 60.2 94.0 ± 45.7	0.288
r-PT-RMS 70% MVIC (µV)	Pre Post	97.4 ± 34.6 98.1 ± 58.3	110.1 ± 53.1 115.9 ± 59.2	89.7 ± 51.7 82.9 ± 40.9	0.980
r-pRMS 100% MVIC (µV)	Pre Post	145.0 ± 60.7 136.5 ± 90.5	160.1 ± 83.0 165.3 ± 87.2	132.3 ± 73.6 132.7 ± 78.3	0.876

Mean ± SD; MVIC: Maximal voluntary isometric contraction; pRMS: Maximal sEMG amplitude size during the entire MVIC; PT-RMS: Maximal sEMG amplitude size during the peak torque of MVIC; r-pRMS: Maximal sEMG amplitude size during the entire MVIC relative to pre-treatment strength; r-PT-RMS: Maximal sEMG amplitude size during the peak torque of MVIC relative to pre-treatment strength; µV: microvolt

4.4. Muscular Morphological Adaptations

4.4.1. Rectus Femoris Muscle Cross-sectional Area Adaptations

The statistical analyses revealed no significant Time × Group interaction effect ($p > 0.05$) in mCSA of the rectus femoris. However, there was a significant main effect of Time ($p < 0.05$) following the training intervention. The results demonstrated that all groups significantly ($F(1,44)$ = 51.656, $p < 0.001$; $\eta_p^2 = 0.540$) increased mCSA of the rectus femoris to a similar extent (Table 7; Figure 18).

4.4.2. Vastus Lateralis Muscle Cross-sectional Area Adaptations

The results showed that there was no significant Time × Group interaction effect ($p > 0.05$) in mCSA of the vastus lateralis. However, there was a significant main effect of Time ($p < 0.05$) following the training intervention and the ultrashort-HIIT, Tabata-HIIT, and MICT groups significantly ($F(1,44) = 66.122$, $p < 0.001$; $\eta_p^2 = 0.600$) improved the mCSA of the vastus lateralis (Table 7; Figure 19).

4.4.3. Rectus Femoris Echo Intensity Adaptations

There was no significant Time × Group interaction effect ($p > 0.05$) in EI of the rectus femoris. While, the statistical analyses indicated a significant main effect of Time ($p < 0.05$) following the training intervention that all groups significantly ($F(1,44) = 4.709$, $p = 0.035$; $\eta_p^2 = 0.097$) enhanced the EI of the rectus femoris (Table 7; Figure 20).

4.4.4. Vastus Lateralis Echo Intensity Adaptations

The results of ultrasound imaging displayed a significant Time × Group interaction effect ($p < 0.05$) in EI of the vastus lateralis. The post-hoc analyses revealed that the ultrashort-HIIT

group significantly decreased ($F_{(1,15)} = 6.452$, $p = 0.023$; $\eta_p^2 = 0.301$) the EI of the vastus

lateralis compared to the Tabata-HIIT and MICT following the intervention (Table 7; Figure 21).

Table 7. Muscle Cross-sectional Area and Echo Intensity Adaptations

		Ultrashort-HIIT	Tabata-HIIT	MICT	p-value
Rectus Femoris mCSA* (cm^2)	Pre	10.7 ± 3.1	10.0 ± 2.2	11.2 ± 3.4	<0.001
	Post	11.3 ± 3.1	10.9 ± 2.2	11.6 ± 3.5	
Vastus Lateralis mCSA* (cm^2)	Pre	24.3 ± 7.2	22.5 ± 5.0	24.2 ± 7.1	<0.001
	Post	25.8 ± 7.2	24.5 ± 5.7	25.2 ± 7.7	
Rectus Femoris EI* (AU)	Pre	61.6 ± 8.6	60.7 ± 7.7	59.6 ± 8.9	0.035
	Post	60.0 ± 7.7	57.5 ± 6.1	59.3 ± 7.4	
Vastus Lateralis EI** (AU)	Pre	69.3 ± 8.8**	66.4 ± 6.0	67.1 ± 9.7	0.023
	Post	67.1 ± 8.5	65.8 ± 6.1	68.5 ± 9.0	

*Mean ± SD; * significant main effect of Time; ** significant Time × Group interaction; mCSA: Muscle cross-sectional area; EI: Echo intensity; cm^2: centimeter-squared; AU: arbitrary units*
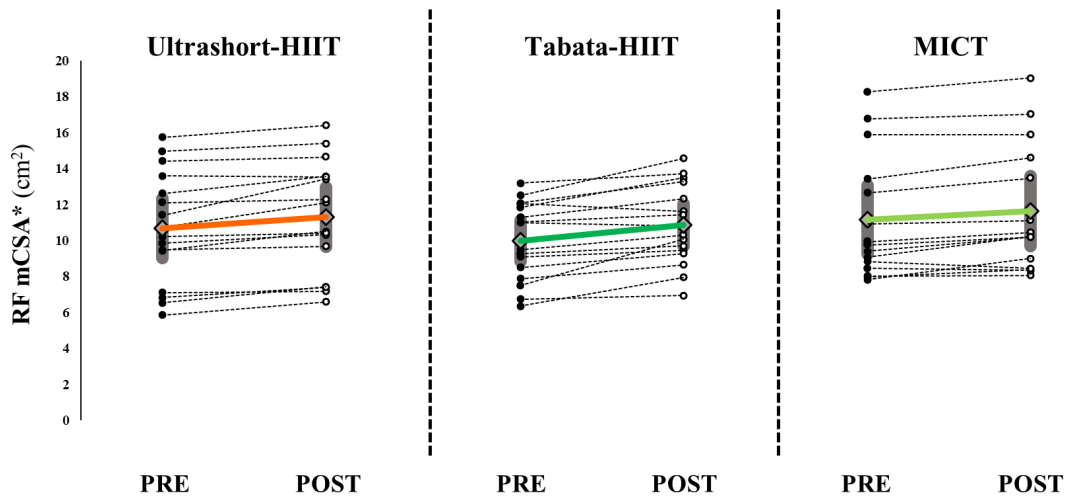
Figure 18 – Comparison of the rectus femoris muscle cross-sectional area for participants completing ultrashort-HIIT, Tabata-HIIT or MICT training. *Significant main effect of Time (collapsed across group); MICT: Moderate intensity continuous training, cm^2: centimeter-squared
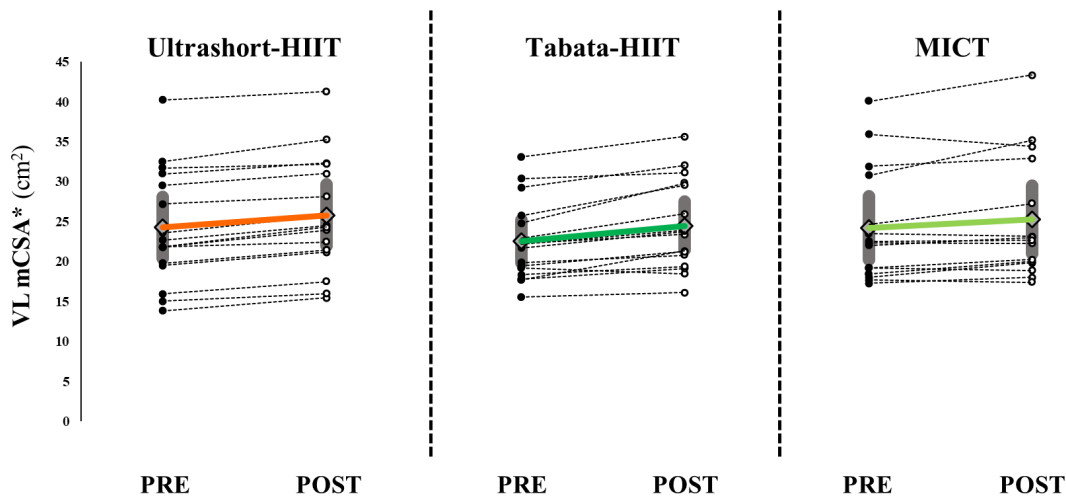
Figure 19 – Comparison of the vastus lateralis muscle cross-sectional area for participants completing ultrashort-HIIT, Tabata-HIIT or MICT training. *Significant main effect of Time (collapsed across group); MICT: Moderate intensity continuous training, cm^2: centimeter-squared
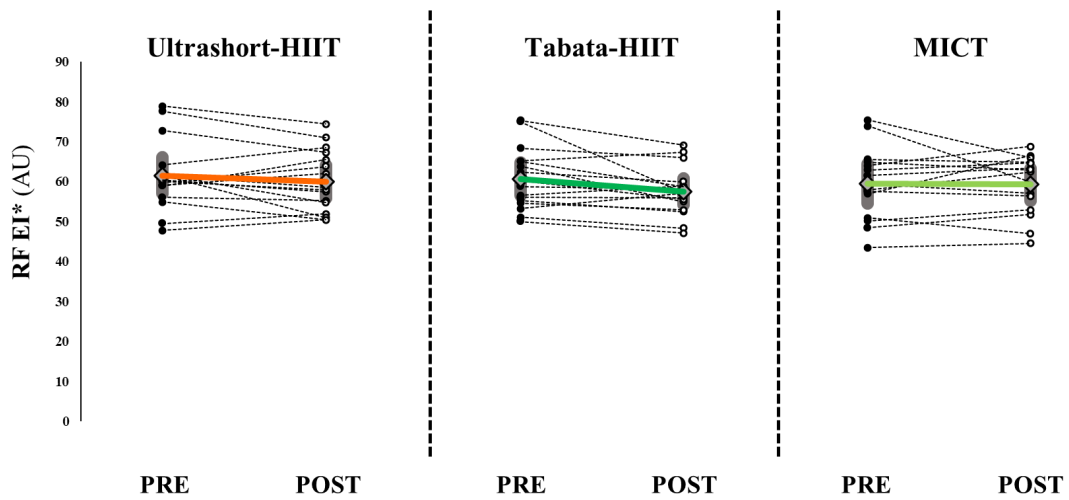
Figure 20 – Comparison of the rectus femoris echo intensity for participants completing ultrashort-HIIT, Tabata-HIIT or MICT training. *Significant main effect of Time (collapsed across group); MICT: Moderate intensity continuous training, AU: arbitrary units
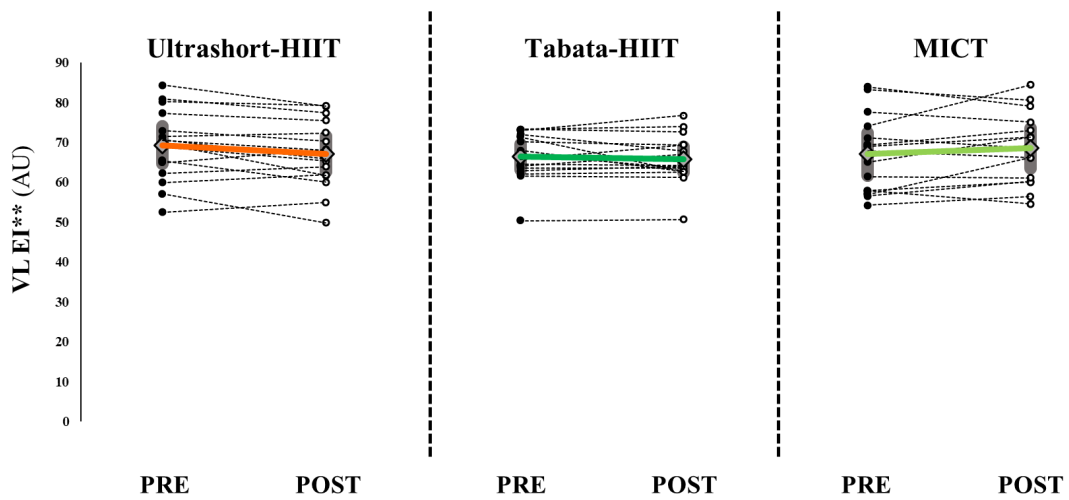
Figure 21 – Comparison of the vastus lateralis echo intensity for participants completing ultrashort-HIIT, Tabata-HIIT or MICT training.: **Significant Time × Group interaction effect; Ultrashort-HIIT significantly decreased EI of vastus lateralis compared to other groups; MICT: Moderate intensity continuous training, AU: arbitrary units

4.5. Relationships between Changes in Muscular Strength, Muscle Activation, and Muscular

Morphological Adaptations

Pearson correlation coefficients were utilized to determine the magnitude of the

relationships between the changes (Δ) in muscular strength and muscle activation, as well as

muscular strength and muscular morphological adaptations. The PT and VL PT-RMS showed a

moderate significant relationship (r(47) = 0.329, p = 0.024), while the RF PT-RMS displayed a

weak insignificant relationship (r(47) = 0.210, p = 0.156) with the PT. Moreover, there was a

positive weak relationship between PT and PT-RMS (i.e., collapsed between RF and VL muscles)

indicating a significant (r(47) = 0.329, p = 0.024) linear relationship between the two variables.

Furthermore, there was a weak insignificant relationship between the PT and VL mCSA (r(47) =

-0.021, p = 0.889), while positive weak insignificant relationships were observed between PT and

RF mCSA (r(47) = 0.108, p = 0.471), and PT and mCSA collapsed between RF and VL muscles

(r(47) = 0.027, p = 0.858).

CHAPTER V

DISCUSSION

To the best of our knowledge, this was the first investigation to examine the neuromuscular adaptations following 4 weeks of the low-volume HIIT designs compared to the high-volume MICT on an air-resistance fan bike. The primary findings of the study demonstrated similar improvements between groups in muscular power (i.e., RTD_{50}, RTD_{75}, RTD_{100}, and $RTD_{100-200}$) and rectus femoris neural drive (i.e., pRMS [during MVIC, 40%, 70%, and 100% MVIC ramp contractions], PT-RMS [during MVIC and 40% MVIC ramp contraction], and r-pRMS [i.e., 100% MVIC ramp contraction]). However, the Tabata-HIIT protocol elicited greater neural drive (i.e., PT-RMS) during the peak torque of 70% MVIC ramp contraction compared to the ultrashort-HIIT and MICT groups (Tables 2-4; Figures 6-17). Moreover, despite similar adaptations in mCSA of rectus femoris and vastus lateralis as well as rectus femoris EI for all groups, the ultrashort-HIIT group displayed greater muscular morphological adaptation by decreasing the EI of vastus lateralis compared to the Tabata-HIIT and MICT groups (Table 7; Figures 18-21). Furthermore, there was a moderate significant relationship between changes in muscular strength and muscle activation, whereas there was a weak insignificant relationship between muscular strength and muscular morphological adaptations. Consequently, these data suggested that the low-volume HIIT protocols may induce greater neural adaptations than the high-volume MICT, despite similar muscle hypertrophy adaptations.

5.1. Muscular Strength and Power Adaptations

The maximal isometric strength, as indicated by PT during MVIC, did not significantly change following the training protocols on an air-resistance fan bike. These findings are in accordance with the previous investigation that showed no significant improvements in muscular strength for healthy males and females after high intensity exercise intervention on a cycle ergometer (3). Similarly, there were no significant improvements in muscular power, as measured by RTD during the ballistic MVIC. However, the analyses of early phase RTD epochs revealed that RTD_{50}, RTD_{75}, RTD_{100}, and $RTD_{100-200}$ were improved when collapsed across group. The notable findings among these analyses were greater improvements in early phase RTD during the first 50, 75, 100, and between 100-200 ms epochs for the ultrashort-HIIT and Tabata-HIIT groups compared to MICT. Although there were no significant differences between groups.

5.2. Neuromuscular Adaptations

Several studies have previously established that concurrent improvements in muscular strength and sEMG amplitude size (i.e., RMS) may indicate enhanced neural drive as a result of training intervention (41, 49, 53, 54, 56, 85, 86). The neuromuscular changes of rectus femoris and vastus laterlis were investigated through assessing the sEMG amplitude size (i.e., pRMS and PT-RMS) during MVIC and ramp contractions, early muscle activation (i.e., $sEMG_{30}$, $sEMG_{50}$, and $sEMG_{100}$), and EMD. The findings showed that there were no significant differences between groups in pRMS and PT-RMS of rectus femoris during MVIC, whereas there were significant differences in both variables when collapsed across. Despite no difference between groups, the ultrashort-HIIT and Tabata-HIIT protocols showed greater improvements in rectus femoris pRMS (by 21.2% and 21.6%, respectively) and PT-RMS (by 21.0% and 21.4%, respectively) than MICT group (pRMS: by 8.8%; PT-RMS: by 15.0%).

107

There were significant increases in rectus femoris sEMG amplitude size measures during 40% MVIC ramp contraction when collapsed across group. The rectus femoris pRMS and PT-RMS during 40% MVIC ramp contraction were enhanced following the ultrashort-HIIT (by 22.0% and 10.7%, respectively), Tabata-HIIT (by 23.3% and 36.6%, respectively), and MICT (by 13.2% and 20.0%, respectively) protocols, while Tabata-HIIT displayed greater increases than other groups. In addition, the pRMS of rectus femoris during 70% MVIC ramp contraction was increased in ultrashort-HIIT (by 18.3%), Tabata-HIIT (by 32.5%), and MICT (by 11.8%), while no significant differences observed between groups. In contrast, there were significant differences between groups in PT-RMS of rectus femoris during 70% MVIC ramp contraction, and Tabata-HIIT showed greater increases (36.0%) compared to ultrashort-HIIT (19.9%) and MICT (9.3%). Furthermore, ultrashort-HIIT, Tabata-HIIT, and MICT increased rectus femoris pRMS measures during 100% MVIC ramp contraction by 30.0%, 30.6%, and 11.3%, respectively, as well as rectus femoris r-pRMS during 100% MVIC ramp contraction relative to pre-treatment strength by 20.4%, 19.0% and 3.2%, respectively.

Nevertheless, one unanticipated finding was that no significant improvements observed for vastus lateralis muscle in pRMS and PT-RMS during the MVIC as well as maximal and submaximal ramp contractions (i.e., 40%, 70%, and 100% MVIC) following the intervention. These results may be explained by the fact that the rectus femoris is the only biarticular muscle among quadriceps femoris group crossing both hip and knee joints. Being bifunctional muscle, the rectus femoris not only flexes the hip joint but also extends the knee joint. In contrast, the vastus lateralis muscle is monoarticular and it only serves to extend the knee joint. The kinematic analysis of cycling indicated that biarticular and monoarticular quadriceps muscles have distinctly various functions (58, 115). Specifically, the biarticular rectus femoris is responsible for controlling net torque as well as transferring power between the hip and knee joints, whereas the monoarticular vastus lateralis muscle only generates force and power at the knee joint (40, 57,

114). During 360° pedaling cycle, the rectus femoris muscle functions as hip flexor and knee extensor contracting between 200° and 110°, while the vastus lateralis muscle is knee extensor and is active between 300° and 130° (33). Consequently, the rectus femoris was activated to a greater extent, and elicited greater neuromuscular adaptations than vastus lateralis due to the biomechanical differences between the biarticular and monoarticular quadriceps muscles (94). Furthermore, previous literature has established that greater motoneuron excitation is required to induce small increases in muscle activation during high intensity muscle contractions greater than 90% MVIC (47, 67). Nevertheless, it can be speculated that the increased muscle activations during maximal and submaximal contractions were due to the greater motor unit excitation in all groups following the 4-week intervention.

Generally, electromechanical delay is defined as the time difference between the onset of electrical and mechanical activities of muscle (13). The results showed that there were no significant differences in EMD between groups following the intervention. Similarly, no significant changes found in EMD from pre- to post-intervention when collapsed across group. These findings were consistent with the previous investigation conducted by Jenkins and colleagues (60), who found no significant improvements in EMD following a 4-week resistance training intervention. Previously, it was stated that EMD is less likely to be influenced by an intervention, even up to 24 weeks of training (55). A similar pattern emerged in the study investigating EMD, which concluded that no significant enhancements exist in EMD throughout lifespan (70). On the other hand, it was suggested that younger individuals showed lower values in EMD measures compared to older adults (16). Since the participants consisted of young recreationally active males and females, it can be speculated that the potential improvements of EMD were limited due to the age and physical fitness status of the individuals.

As previously mentioned, the results of early phase muscle activation indicated that there were no significant improvements in $sEMG_{30}$, $sEMG_{50}$, and $sEMG_{100}$ for both rectus femoris and

vastus lateralis muscles during the ballistic MVIC. The most interesting finding among these analyses was the early phase muscle activation of rectus femoris during the first 30 ms epoch ($sEMG_{30}$), which was slightly increased in all three groups and showed a trend towards significance ($p = 0.058$) after analyses. Previous study established significant enhancements in early phase muscle activation during the first 30, 50, and 75 ms epochs of onset of ballistic MVIC following 14 weeks of training intervention (1). It can, therefore, be assumed that the increased sample size and longer training intervention could have provided a significant outcome in early phase muscle activation, especially in $sEMG_{30}$ after the training protocols.

5.3. Muscular Morphological Adaptations

The results of this investigation showed that there were no significant differences between groups in rectus femoris muscle size (i.e., mCSA). Further analyses revealed that the rectus femoris mCSA was significantly increased when collapsed across group. Despite no difference between groups, the ultrashort-HIIT, Tabata-HIIT, and MICT groups improved it by 6.5%, 9.5%, and 4.6%, respectively. Similarly, no significant differences were observed in vastus lateralis mCSA between the groups. Whereas the vastus lateralis mCSA significantly increased from pre- to post-testing when collapsed across group. The ultrashort-HIIT, Tabata-HIIT, and MICT groups increased vastus lateralis mCSA by 6.9%, 8.6%, and 4.1%, respectively. These results confirmed previous findings and contributed additional evidence demonstrating hypertrophic adaptations following low-volume HIIT and high-volume MICT (7, 30, 42, 91). Although there were no significant differences between groups, the low-volume HIIT designs (i.e., ultrashort-HIIT and Tabata-HIIT) showed greater improvements in mCSA of rectus femoris and vastus lateralis compared to the high-volume MICT (Table 7; Figures 18-21).

Since the increased muscle size after 3-4 weeks of exercise intervention can be the result of muscular damage or edema, measuring muscle quality, as indicated by ultrasound EI, was recommended to evaluate the potential influence of muscular edema or damage (19). The results of the present study revealed that no significant differences observed in rectus femoris EI between groups. However, it was significantly decreased from pre- to post-intervention when collapsed across group. Despite no significant difference between groups, the magnitude of changes in rectus femoris EI was greater for ultrashort-HIIT (-2.0%) and Tabata-HIIT (-4.8%) than MICT (0.2%). In contrast, the results demonstrated that there were significant differences in vastus lateralis EI between groups. The ultrashort-HIIT (-3.0%) significantly decreased vastus lateralis EI compared to Tabata-HIIT (-0.9%) and MICT (2.5). Although the influence of muscular edema and damage cannot be neglected, these findings, as previously suggested (19), indicated that the impact of muscular edema and damage was minimal following the intervention.

It has been previously established that ultrasound EI values can be also used to evaluate muscle quality (2, 34, 93, 96) and to indicate intramuscular water and glycogen content (50, 89). In fact, lower ultrasound EI values are associated with higher intramuscular water and glycogen content, which result is hypoechoic ultrasonic images (72, 111). Recent studies, investigating the sensitivity of EI, suggested that increased intramuscular water and glycogen concentrations are strongly related to decreasing ultrasound EI values following training intervention (50, 89). In the present study, therefore, there is a possibility that the increased muscle size could be influenced by intramuscular water and glycogen levels. However, there was the lack of sufficient data for further analyses to test this hypothesis. Therefore, future studies are needed to compare the effects of low-volume HIIT designs and high-volume MICT on muscle size and quality using ultrasound measures as well as intramuscular water and glycogen concentrations.

5.4. Relationships between Changes in Muscular Strength, Muscle Activation, and Muscular Morphological Adaptations

The results of this investigation showed that the differences observed in muscular isometric strength, as indicated by PT during MVIC, were more strongly associated with changes in neural adaptations, as indicated by PT-RMS during MVIC. In contrast, there were insignificant ($p > 0.05$) weak relationships between changes in PT and muscle hypertrophy values (i.e., mCSA). These results were consistent with those of previous studies (24, 26, 36, 85) and suggested that the neural adaptations were the primary contributor to muscular strength following 4 weeks of training, despite the significant improvements in muscular hypertrophy.

5.5. Conclusions

The purpose of the present study was to investigate the neuromuscular adaptations following 4 weeks of the low-volume HIIT designs compared to the high-volume MICT on an air-resistance stationary fan bike. To the best of our knowledge, the current study was the first investigation to examine the neuromuscular adaptations of HIIT (i.e., ultrashort-HIIT, Tabata-HIIT) and MICT following 4 weeks of training. Despite significant differences in exercise duration, all training protocols elicited similar muscle hypertrophy adaptations in rectus femoris and vastus lateralis as indicated by ultrasound imaging. Another important finding was that the muscle activation of rectus femoris was significantly improved following the intervention, while no significant improvements observed in muscle activation of the vastus lateralis. A possible explanation for this might be that the rectus femoris is the only biarticular muscle of the quadriceps, functioning as hip flexor and knee extensor, while the vastus lateralis muscle is monoarticular acting as knee extensor (33). Hence, the biomechanical differences between

biarticular and monoarticular muscles of quadriceps group can explain the greater activation of rectus femoris than vastus lateralis (94).

Although the neural adaptations during maximal and submaximal contractions seemed to be equivalent among the groups, the ultrashort-HIIT and Tabata-HIIT protocols tended to induce greater improvements in neural adaptations (i.e., sEMG amplitude size) compared to the MICT protocol. For instance, the maximal muscle activation of rectus femoris during MVIC was improved by the ultrashort-HIIT (21.2%) and Tabata-HIIT (21.6%) to a greater extent compared to MICT (8.8%), despite no significant difference between groups. In addition, the results demonstrated that there were significant differences between groups in the rectus femoris muscle activation during 70% MVIC submaximal contraction. The Tabata-HIIT showed greater improvements by 36% compared to the ultrashort-HIIT and MICT protocols that showed enhancements by 19.9% and 9.3%, respectively. Nevertheless, the ultrashort-HIIT protocol also elicited greater increases than MICT in the rectus femoris muscle activation during 70% MVIC ramp contraction. These results can be explained by the fact that the HIIT protocols are performed at high-velocity and high-loads, which activate higher-threshold MUs being composed primarily of fast-twitch muscle fibers (104). Therefore, it can be concluded that the HIIT protocols elicited greater neuromuscular improvements than MICT. Furthermore, the Tabata-HIIT protocol showed greater improvements than ultrashort-HIIT following the intervention, which might possibly be due to the significant differences in exercise volume between the HIIT protocols. Although both HIIT protocols were performed at maximal effort intensity, the ultrashort-HIIT duration was 50% shorter than the Tabata-HIIT. Despite similar training intensity, the duration of ultrashort-HIIT protocol seemed to be inadequate to stimulate neuromuscular adaptations to a similar extent as Tabata-HIIT.

The results of the present study were consistent with previous literature, which suggested that HIIT is a more "time-efficient" exercise alternative to traditionally prescribed MICT (8). In

the current study, the ultrashort-HIIT, Tabata-HIIT, and MICT protocols elicited similar muscular morphological and neuromuscular adaptations, while the HIIT designs were performed with significantly shorter time-commitment compared to MICT. Although there were no significant differences between groups, it can be speculated that increasing sample size or duration of the intervention would have elicited significant differences between low-volume HIIT programs and high-volume MICT. Taken together, our findings concluded that the low-volume HIIT designs are "time-efficient" exercise mode to induce neuromuscular and muscular morphological adaptations compared to high-volume MICT. Furthermore, the HIIT protocols have the potentials to elicit greater neuromuscular adaptations in comparison to traditionally prescribed MICT.

There were numbers of important limitations that need to be considered in the present study. The primary limitation of the current investigation was the lack of a control group. The second limitation was lack of sufficient data to determine the potential impacts of intramuscular water and glycogen concentrations on ultrasound echo intensity values. Another limitation was the duration of the intervention that seemed insufficient for strength and muscular morphological adaptations, despite adequate duration regarding neural adaptations. Furthermore, the sample size as well as unequal number of male and female participants were other limitations of this study. However, future research will need to investigate the effects of various HIIT and MICT protocols as well as longer interventions on neuromuscular adaptations in different age groups with larger sample sizes. Additionally, using the recent EMG technologies should be considered to decompose the sEMG signals into individual MU action potential trains, which can be used to track adaptations of large numbers of motor units across a wide spectrum of force production and recruitment thresholds (27, 76, 88).

REFERENCES

1.	**Aagaard P, Simonsen EB, Andersen JL, Magnusson P, and Dyhre-Poulsen P.** Increased rate of force development and neural drive of human skeletal muscle following resistance training. *Journal of applied physiology* 93: 1318-1326, 2002.

2.	**Arts IM, Schelhaas HJ, Verrijp KC, Zwarts MJ, Overeem S, van der Laak JA, Lammens MM, and Pillen S.** Intramuscular fibrous tissue determines muscle echo intensity in amyotrophic lateral sclerosis. *Muscle & nerve* 45: 449-450, 2012.

3.	**Astorino TA, Allen RP, Roberson DW, and Jurancich M.** Effect of high-intensity interval training on cardiovascular function, VO2max, and muscular force. *The Journal of Strength & Conditioning Research* 26: 138-145, 2012.

4.	**Astorino TA, Edmunds RM, Clark A, King L, Gallant RA, Namm S, Fischer A, and Wood KM.** High-intensity interval training increases cardiac output and V˙ O2max. *Medicine & Science in Sports & Exercise* 49: 265-273, 2017.

5.	**Ayers K, Pazmino-Cevallos M, and Dobose CJVJ.** The 20-hour rule: Student-athletes time commitment to athletics and academics. 33: 22-27, 2012.

6.	**Bell KE, Séguin C, Parise G, Baker SK, and Phillips SM.** Day-to-day changes in muscle protein synthesis in recovery from resistance, aerobic, and high-intensity interval exercise in older men. *The Journals of Gerontology: Series A* 70: 1024-1029, 2015.

7.	**Bruseghini P, Capelli C, Calabria E, Rossi AP, and Tam E.** Effects of high intensity interval training and isoinertial training on leg extensors muscle function, structure and intermuscular adipose tissue in older adults. *Frontiers in physiology* 10: 1260, 2019.

8.	**Buchheit M and Laursen PBJSm.** High-intensity interval training, solutions to the programming puzzle. 43: 927-954, 2013.

9.	**Buckley S, Knapp K, Lackie A, Lewry C, Horvey K, Benko C, Trinh J, and Butcher S.** Multimodal high-intensity interval training increases muscle function and metabolic performance in females. *Applied Physiology, Nutrition, and Metabolism* 40: 1157-1162, 2015.

10.	**Burgomaster KA, Howarth KR, Phillips SM, Rakobowchuk M, MacDonald MJ, McGee SL, and Gibala MJ.** Similar metabolic adaptations during exercise after low volume sprint interval and traditional endurance training in humans. *The Journal of physiology* 586: 151-160, 2008.

11.	**Burgomaster KA, Hughes SC, Heigenhauser GJ, Bradwell SN, and Gibala MJ.** Six sessions of sprint interval training increases muscle oxidative potential and cycle endurance capacity in humans. *Journal of applied physiology* 98: 1985-1990, 2005.

12.	**Cantrell GS, Schilling BK, Paquette MR, and Murlasits Z.** Maximal strength, power, and aerobic endurance adaptations to concurrent strength and sprint interval training. *European journal of applied physiology* 114: 763-771, 2014.

13.	**Cavanagh PR and Komi PV.** Electromechanical delay in human skeletal muscle under concentric and eccentric contractions. *European journal of applied physiology and occupational physiology* 42: 159-163, 1979.

14.	**Clark A, Annie B, DeRevere JL, and Astorino TA.** Effects of various interval training regimes on changes in maximal oxygen uptake, body composition, and muscular strength in sedentary women with obesity. *European Journal of Applied Physiology*: 1-10, 2019.

15.	**Cocks M, Shaw CS, Shepherd SO, Fisher JP, Ranasinghe AM, Barker TA, Tipton KD, and Wagenmakers AJ.** Sprint interval and endurance training are equally effective in increasing muscle microvascular density and eNOS content in sedentary males. *The Journal of physiology* 591: 641-656, 2013.

16.   **Conchola E, Thompson BJ, and Smith D.** Effects of neuromuscular fatigue on the electromechanical delay of the leg extensors and flexors in young and old men. *European journal of applied physiology* 113: 2391-2399, 2013.

17.   **Control CfD and Newsroom PJCO.** Falls are leading cause of injury and death in older Americans. 2016.

18.   **Creer AR, Ricard M, Conlee R, Hoyt G, and Parcell A.** Neural, metabolic, and performance adaptations to four weeks of high intensity sprint-interval training in trained cyclists. *International journal of sports medicine* 25: 92-98, 2004.

19.   **Damas F, Phillips SM, Lixandrão ME, Vechin FC, Libardi CA, Roschel H, Tricoli V, and Ugrinowitsch C.** Early resistance training-induced increases in muscle cross-sectional area are concomitant with edema-induced muscle swelling. *European journal of applied physiology* 116: 49-56, 2016.

20.   **Daussin F, Ponsot E, Dufour S, Lonsdorfer-Wolf E, Doutreleau S, Geny B, Piquard F, and Richard R.** Improvement of $\varvec{\dot{V}\hbox{O}_{2\max}},$ by cardiac output and oxygen extraction adaptation during intermittent versus continuous endurance training. *European Journal of Applied Physiology* 101, 2007.

21.   **Daussin FN, Zoll J, Dufour SP, Ponsot E, Lonsdorfer-Wolf E, Doutreleau S, Mettauer B, Piquard F, Geny B, and Richard R.** Effect of interval versus continuous training on cardiorespiratory and mitochondrial functions: relationship to aerobic performance improvements in sedentary subjects. *American Journal of Physiology-Regulatory, Integrative and Comparative Physiology*, 2008.

22.   **Dawson B, Fitzsimons M, Green S, Goodman C, Carey M, and Cole K.** Changes in performance, muscle metabolites, enzymes and fibre types after short sprint training. *European journal of applied physiology and occupational physiology* 78: 163-169, 1998.

23.   **De Caterina R and El-Sohemy AJLG.** Moving towards specific nutrigenetic recommendation algorithms: caffeine, genetic variation and cardiovascular risk. 9: 106-115, 2016.

24.   **De Lorme TL and Watkins AL.** *Progressive resistance exercise: technic and medical application*: Appleton-Century-Crofts, 1951.

25.   **De Luca CJ.** The use of surface electromyography in biomechanics. *Journal of applied biomechanics* 13: 135-163, 1997.

26.   **Del Balso C and Cafarelli E.** Adaptations in the activation of human skeletal muscle induced by short-term isometric resistance training. *Journal of Applied Physiology* 103: 402-411, 2007.

27.   **Duchateau J, Semmler JG, and Enoka RM.** Training adaptations in the behavior of human motor units. *Journal of Applied Physiology* 101: 1766-1775, 2006.

28.   **Ebersole KT, Housh TJ, Johnson GO, Perry SR, Bull AJ, and Cramer JT.** Mechanomyographic and electromyographic responses to unilateral isometric training. *Journal of strength and conditioning research* 16: 192-201, 2002.

29.   **Esfandiari S, Sasson Z, and Goodman JM.** Short-term high-intensity interval and continuous moderate-intensity training improve maximal aerobic power and diastolic filling during exercise. *European journal of applied physiology* 114: 331-343, 2014.

30.   **ESTES RR, MALINOWSKI A, PIACENTINI M, THRUSH D, Salley E, Losey C, and Hayes E.** The effect of high intensity interval run training on cross-sectional area of the vastus lateralis in untrained college students. *International journal of exercise science* 10: 137, 2017.

31.   **Farina D, Merletti R, and Enoka RM.** The extraction of neural strategies from the surface EMG. *Journal of applied physiology* 96: 1486-1495, 2004.

32.   **Fisher G, Brown AW, Brown MMB, Alcorn A, Noles C, Winwood L, Resuehr H, George B, Jeansonne MM, and Allison DB.** High intensity interval-vs moderate intensity-training for improving cardiometabolic health in overweight or obese males: a randomized controlled trial. *PloS one* 10, 2015.

33.   **Fonda B and Sarabon N.** Biomechanics of cycling. *Sport Science Review* 19: 187-210, 2010.

34.   **Fukumoto Y, Ikezoe T, Yamada Y, Tsukagoshi R, Nakamura M, Mori N, Kimura M, and Ichihashi N.** Skeletal muscle quality assessed from echo intensity is associated with muscle strength of middle-aged and elderly persons. *European journal of applied physiology* 112: 1519-1525, 2012.

35.   **Fyfe JJ, Bartlett JD, Hanson ED, Stepto NK, and Bishop DJ.** Endurance training intensity does not mediate interference to maximal lower-body strength gain during short-term concurrent training. *Frontiers in physiology* 7: 487, 2016.

36.   **Gabriel DA, Kamen G, and Frost G.** Neural adaptations to resistive exercise. *Sports Medicine* 36: 133-149, 2006.

37.   **Gibala MJ, Little JP, Van Essen M, Wilkin GP, Burgomaster KA, Safdar A, Raha S, and Tarnopolsky MA.** Short‐term sprint interval versus traditional endurance training: similar initial adaptations in human skeletal muscle and exercise performance. *The Journal of physiology* 575: 901-911, 2006.

38.   **Gillen JB, Percival ME, Ludzki A, Tarnopolsky MA, and Gibala MJ.** Interval training in the fed or fasted state improves body composition and muscle oxidative capacity in overweight women. *Obesity* 21: 2249-2255, 2013.

39.   **Goldberg LJ and Derfler B.** Relationship among recruitment order, spike amplitude, and twitch tension of single motor units in human masseter muscle. *Journal of neurophysiology* 40: 879-890, 1977.

40.   **Gregoire L, Veeger H, Huijing P, and van Ingen Schenau G.** Role of mono-and biarticular muscles in explosive movements. *International journal of sports medicine* 5: 301-305, 1984.

41.   **Hakkinen K, Komi P, and Alen M.** Effect of explosive type strength training on isometric force-and relaxation-time, elelectromyographic and muscle fibre characteristics of leg extensor muscles. *Acta Physiologica Scandinavica* 125: 587-600, 1985.

42.   **Harber MP, Konopka AR, Undem MK, Hinkley JM, Minchev K, Kaminsky LA, Trappe TA, and Trappe S.** Aerobic exercise training induces skeletal muscle hypertrophy and age-dependent adaptations in myofiber function in young and older men. *Journal of Applied Physiology* 113: 1495-1504, 2012.

43.   **Hazell TJ, MacPherson RE, Gravelle BM, and Lemon PW.** 10 or 30-s sprint interval training bouts enhance both aerobic and anaerobic performance. *European journal of applied physiology* 110: 153-160, 2010.

44.   **Heckman C and Enoka RM.** Motor unit. *Comprehensive physiology* 2: 2629-2682, 2012.

45.   **Helgerud J, Høydal K, Wang E, Karlsen T, Berg P, Bjerkaas M, Simonsen T, Helgesen C, Hjorth N, and Bach R.** Aerobic high-intensity intervals improve V˙ O2max more than moderate training. *Medicine & Science in Sports & Exercise* 39: 665-671, 2007.

46.   **Henneman E.** Relation between size of neurons and their susceptibility to discharge. *Science* 126: 1345-1347, 1957.

47.   **Herbert R and Gandevia S.** Twitch interpolation in human muscles: mechanisms and implications for measurement of voluntary activation. *Journal of Neurophysiology* 82: 2271-2283, 1999.

48.   **Hermens HJ, Freriks B, Merletti R, Stegeman D, Blok J, Rau G, Disselhorst-Klug C, Hägg GJRr, and development.** European recommendations for surface electromyography. 8: 13-54, 1999.

49.   **Higbie EJ, Cureton KJ, Warren III GL, and Prior BM.** Effects of concentric and eccentric training on muscle strength, cross-sectional area, and neural activation. *Journal of applied physiology* 81: 2173-2181, 1996.

50.   **Hill JC and Millan IS.** Validation of musculoskeletal ultrasound to assess and quantify muscle glycogen content. A novel approach. *The Physician and sportsmedicine* 42: 45-52, 2014.

51.   **Hottenrott K, Ludyga S, and Schulze S.** Effects of high intensity training and continuous endurance training on aerobic capacity and body composition in recreationally active runners. *Journal of sports science & medicine* 11: 483, 2012.

52.   **Hurst C, Weston KL, and Weston M.** The effect of 12 weeks of combined upper-and lower-body high-intensity interval training on muscular and cardiorespiratory fitness in older adults. *Aging clinical and experimental research* 31: 661-671, 2019.

53.   **Häkkinen K, Alen M, and Komi P.** Changes in isometric force‐and relaxation‐time, electromyographic and muscle fibre characteristics of human skeletal muscle during strength training and detraining. *Acta physiologica scandinavica* 125: 573-585, 1985.

54.   **Häkkinen K and Komi P.** Electromyographic changes during strength training and detraining. *Medicine and science in sports and exercise* 15: 455-460, 1983.

55.   **HÄkkinen K and Komi PV.** Training-induced changes in neuromuscular performance under voluntary and reflex conditions. *European journal of applied physiology and occupational physiology* 55: 147-155, 1986.

56.   **Häkkinen K, Newton RU, Gordon SE, McCormick M, Volek JS, Nindl BC, Gotshalk LA, Campbell WW, Evans WJ, and Häkkinen A.** Changes in muscle morphology, electromyographic activity, and force production characteristics during progressive strength training in young and older men. *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences* 53: B415-B423, 1998.

57.   **Jacobs R and Bobbert MF.** Function of mono-and biarticular muscles in running. *Medicine and science in sports and exercise* 25: 1163-1173, 1993.

58.   **Jacobs R and van Ingen Schenau G.** Control of an external force in leg extensions in humans. *The Journal of physiology* 457: 611-626, 1992.

59.   **Jacobs RA, Flück D, Bonne TC, Bürgi S, Christensen PM, Toigo M, and Lundby C.** Improvements in exercise performance with high-intensity interval training coincide with an increase in skeletal muscle mitochondrial content and function. *Journal of applied physiology* 115: 785-793, 2013.

60.   **Jenkins N, Housh TJ, Buckner S, Bergstrom H, Smith C, Cochrane KC, Hill E, Miramonti AA, Schmidt RJ, and Johnson G.** Four weeks of high-versus low-load resistance training to failure on the rate of torque development, electromechanical delay, and contractile twitch properties. *Journal of musculoskeletal & neuronal interactions* 16: 135, 2016.

61.   **Jenkins ND, Housh TJ, Buckner SL, Bergstrom HC, Cochrane KC, Hill EC, Smith CM, Schmidt RJ, Johnson GO, and Cramer JT.** Neuromuscular adaptations after 2 and 4 weeks of 80% versus 30% 1 repetition maximum resistance training to failure. *Journal of strength and conditioning research* 30: 2174-2185, 2016.

62.   **Jenkins ND, Miramonti AA, Hill EC, Smith CM, Cochrane-Snyman KC, Housh TJ, and Cramer JT.** Greater neural adaptations following high-vs. low-load resistance training. *Frontiers in physiology* 8: 331, 2017.

63.   **Kinnunen J-V, Piitulainen H, and Piirainen JM.** Neuromuscular Adaptations to Short-Term High-Intensity Interval Training in Female Ice-Hockey Players. *The Journal of Strength & Conditioning Research* 33: 479-485, 2019.

64.   **Knowles A-M, Herbert P, Easton C, Sculthorpe N, and Grace FM.** Impact of low-volume, high-intensity interval training on maximal aerobic capacity, health-related quality of life and motivation to exercise in ageing men. *Age* 37: 25, 2015.

65.   **Komi P, Viitasalo J, Rauramaa R, and Vihko V.** Effect of isometric strength training on mechanical, electrical, and metabolic aspects of muscle function. *European journal of applied physiology and occupational physiology* 40: 45-55, 1978.

66.   **Kong Z, Fan X, Sun S, Song L, Shi Q, and Nie J.** Comparison of high-intensity interval training and moderate-to-vigorous continuous training for cardiometabolic health and exercise enjoyment in obese young women: a randomized controlled trial. *PloS one* 11, 2016.

67.   **Kooistra R, De Ruiter C, and De Haan A.** Conventionally assessed voluntary activation does not represent relative voluntary torque production. *European journal of applied physiology* 100: 309-320, 2007.

68.   **Larsson L, Sjödin B, and Karlsson JJAPS.** Histochemical and biochemical changes in human skeletal muscle with age in sedentary males, age 22–65 years. 103: 31-39, 1978.

69.   **Laursen PB and Jenkins DGJSm.** The scientific basis for high-intensity interval training. 32: 53-73, 2002.

70.   **Libardi CA, Souza TM, Conceição MS, Bonganha V, Chacon‐Mikahil MPT, Cavaglieri CR, de Moraes AC, and Ugrinowitsch C.** Electromechanical delay of the knee extensor muscles: comparison among young, middle‐age and older individuals. *Clinical physiology and functional imaging* 35: 245-249, 2015.

71.   **Little JP, Safdar A, Wilkin GP, Tarnopolsky MA, and Gibala MJ.** A practical model of low‐volume high‐intensity interval training induces mitochondrial biogenesis in human skeletal muscle: potential mechanisms. *The Journal of physiology* 588: 1011-1022, 2010.

72.   **MacDougall J, Ward G, Sale D, and Sutton J.** Biochemical adaptation of human skeletal muscle to heavy resistance training and immobilization. *Journal of Applied Physiology* 43: 700-703, 1977.

73.   **MacDougall JD, Hicks AL, MacDonald JR, McKelvie RS, Green HJ, and Smith KM.** Muscle performance and enzymatic adaptations to sprint interval training. *Journal of applied physiology* 84: 2138-2142, 1998.

74.   **Macpherson RE, Hazell TJ, Olver TD, Paterson DH, and Lemon PW.** Run sprint interval training improves aerobic performance but not maximal cardiac output. *Medicine & Science in Sports & Exercise* 43: 115-122, 2011.

75.   **Martinez-Valdes E, Falla D, Negro F, Mayer F, and Farina D.** Differential motor unit changes after endurance or high-intensity interval training. *Medicine & Science in Sports & Exercise* 49: 1126-1136, 2017.

76.   **Martinez-Valdes E, Laine C, Falla D, Mayer F, and Farina D.** High-density surface electromyography provides reliable estimates of motor unit behavior. *Clinical Neurophysiology* 127: 2534-2541, 2016.

77.   **Matsuo T, Ohkawara K, Seino S, Shimojo N, Yamada S, Ohshima H, Tanaka K, and Mukai C.** An exercise protocol designed to control energy expenditure for long-term space missions. *Aviation, space, and environmental medicine* 83: 783-789, 2012.

78.   **Matsuo T, Saotome K, Seino S, Shimojo N, Matsushita A, Iemitsu M, Ohshima H, Tanaka K, and Mukai C.** Effects of a low-volume aerobic-type interval exercise on v o2max and cardiac mass. *Medicine & Science in Sports & Exercise* 46: 42-50, 2014.

79.   **McKay BR, Paterson DH, and Kowalchuk JM.** Effect of short-term high-intensity interval training vs. continuous training on O2 uptake kinetics, muscle deoxygenation, and exercise performance. *Journal of applied physiology* 107: 128-138, 2009.

80.   **McRae G, Payne A, Zelt JG, Scribbans TD, Jung ME, Little JP, and Gurd BJ.** Extremely low volume, whole-body aerobic–resistance training improves aerobic fitness and muscular endurance in females. *Applied Physiology, Nutrition, and Metabolism* 37: 1124-1131, 2012.

81.   **Metcalfe RS, Babraj JA, Fawkner SG, and Vollaard NB.** Towards the minimal amount of exercise for improving metabolic health: beneficial effects of reduced-exertion high-intensity interval training. *European journal of applied physiology* 112: 2767-2775, 2012.

82.   **Metcalfe RS, Tardif N, Thompson D, and Vollaard NB.** Changes in aerobic capacity and glycaemic control in response to reduced-exertion high-intensity interval training (REHIT) are not different between sedentary men and women. *Applied Physiology, Nutrition, and Metabolism* 41: 1117-1123, 2016.

83.   **Milner‑Brown H, Stein R, and Yemm R.** The orderly recruitment of human motor units during voluntary isometric contractions. *The Journal of physiology* 230: 359-370, 1973.

84.   **Moghaddam M, Estrada CA, Muddle TW, Magrini MA, Jenkins ND, and Jacobson BH.** Similar Anaerobic and Aerobic Adaptations After 2 High-Intensity Interval Training Configurations: 10 s: 5 s vs. 20 s: 10 s Work-to-Rest Ratio. *Journal of strength and conditioning research*, 2019.

85.   **Moritani T and deVries HA.** Neural factors versus hypertrophy in the time course of muscle strength gain. *American journal of physical medicine* 58: 115-130, 1979.

86.   **Narici MV, Roi G, Landoni L, Minetti A, and Cerretelli P.** Changes in force, cross-sectional area and neural activation during strength training and detraining of the human quadriceps. *European journal of applied physiology and occupational physiology* 59: 310-319, 1989.

87.   **Nederveen J, Joanisse S, Séguin C, Bell K, Baker S, Phillips S, and Parise G.** The effect of exercise mode on the acute response of satellite cells in old men. *Acta Physiologica* 215: 177-190, 2015.

88.   **Negro F, Muceli S, Castronovo AM, Holobar A, and Farina D.** Multi-channel intramuscular and surface EMG decomposition by convolutive blind source separation. *Journal of neural engineering* 13: 026027, 2016.

89.   **Nieman DC, Shanely RA, Zwetsloot KA, Meaney MP, and Farris GE.** Ultrasonic assessment of exercise-induced change in skeletal muscle glycogen content. *BMC sports science, medicine and rehabilitation* 7: 9, 2015.

90.   **Nybo L, Sundstrup E, Jakobsen MD, Mohr M, Hornstrup T, Simonsen L, Bülow J, Randers MB, Nielsen JJ, and Aagaard P.** High-intensity training versus traditional exercise interventions for promoting health. *Medicine & Science in Sports & Exercise* 42: 1951-1958, 2010.

91.   **Osawa Y, Azuma K, Tabata S, Katsukawa F, Ishida H, Oguma Y, Kawai T, Itoh H, Okuda S, and Matsumoto H.** Effects of 16-week high-intensity interval training using upper and lower body ergometers on aerobic fitness and morphological changes in healthy men: a preliminary study. *Open access journal of sports medicine* 5: 257, 2014.

92.   **Perry CG, Heigenhauser GJ, Bonen A, and Spriet LL.** High-intensity aerobic interval training increases fat and carbohydrate metabolic capacities in human skeletal muscle. *Applied Physiology, Nutrition, and Metabolism* 33: 1112-1123, 2008.

93.   **Pillen S, Tak RO, Zwarts MJ, Lammens MM, Verrijp KN, Arts IM, van der Laak JA, Hoogerbrugge PM, van Engelen BG, and Verrips A.** Skeletal muscle ultrasound: correlation between fibrous tissue and echo intensity. *Ultrasound in medicine & biology* 35: 443-446, 2009.

94.   **Prior BM, Jayaraman RC, Reid RW, Cooper TG, Foley JM, Dudley GA, and Meyer RA.** Biarticular and monoarticular muscle activation and injury in human quadriceps muscle. *European journal of applied physiology* 85: 185-190, 2001.

95.   **Purves D, Augustine G, Fitzpatrick D, Katz L, LaMantia A, McNamara J, and Williams S.** Neuroscience 2nd edition. sunderland (ma) sinauer associates: Inc, 2001.

96.   **Radaelli R, Botton CE, Wilhelm EN, Bottaro M, Lacerda F, Gaya A, Moraes K, Peruzzolo A, Brown LE, and Pinto RS.** Low-and high-volume strength training induces similar neuromuscular improvements in muscle quality in elderly women. *Experimental gerontology* 48: 710-716, 2013.

97.   **Rafiei H, Robinson E, Barry J, Jung ME, and Little JP.** Short-term exercise training reduces glycaemic variability and lowers circulating endothelial microparticles in overweight and obese women at elevated risk of type 2 diabetes. *European journal of sport science* 19: 1140-1149, 2019.

98.   **Robinson E, Durrer C, Simtchouk S, Jung ME, Bourne JE, Voth E, and Little JP.** Short-term high-intensity interval and moderate-intensity continuous training reduce leukocyte TLR4 in inactive adults at elevated risk of type 2 diabetes. *Journal of applied physiology* 119: 508-516, 2015.

99.   **Robinson MM, Dasari S, Konopka AR, Johnson ML, Manjunatha S, Esponda RR, Carter RE, Lanza IR, and Nair KS.** Enhanced protein translation underlies improved metabolic and physical adaptations to different exercise training modes in young and old humans. *Cell metabolism* 25: 581-592, 2017.

100.   **Sagelv EH, Hammer T, Hamsund T, Rognmo K, Pettersen SA, and Pedersen S.** High intensity long interval sets provides similar enjoyment as continuous moderate intensity exercise. The Tromsø Exercise Enjoyment Study. *Frontiers in psychology* 10: 1788, 2019.

101.   **Saltin B and Gollnick PD.** Skeletal muscle adaptability: significance for metabolism and performance. *Handbook of Physiology Skeletal Muscle* 10: 555-631, 1983.

102.   **Sawyer BJ, Tucker WJ, Bhammar DM, Ryder JR, Sweazea KL, and Gaesser GA.** Effects of high-intensity interval training and moderate-intensity continuous training on endothelial function and cardiometabolic risk markers in obese adults. *Journal of Applied Physiology* 121: 279-288, 2016.

103.   **Schaun GZ, Pinto SS, Brasil B, Nunes GN, and Alberton CL.** Neuromuscular adaptations to sixteen weeks of whole-body high-intensity interval training compared to ergometer-based interval and continuous training. *Journal of sports sciences* 37: 1561-1569, 2019.

104.   **Schiaffino S and Reggiani CJPr.** Fiber types in mammalian skeletal muscles. 91: 1447-1531, 2011.

105.   **Scribbans TD, Edgett BA, Vorobej K, Mitchell AS, Joanisse SD, Matusiak JB, Parise G, Quadrilatero J, and Gurd BJ.** Fibre-specific responses to endurance and low volume high intensity interval training: striking similarities in acute and chronic adaptation. *PloS one* 9, 2014.

106.   **Sculthorpe NF, Herbert P, and Grace F.** One session of high-intensity interval training (HIIT) every 5 days, improves muscle power but not static balance in lifelong sedentary ageing men: a randomized controlled trial. *Medicine* 96, 2017.

107.   **Suetta C, Aagaard P, Rosted A, Jakobsen AK, Duus B, Kjaer M, and Magnusson SPJJoAP.** Training-induced changes in muscle CSA, muscle strength, EMG, and rate of force development in elderly subjects after long-term unilateral disuse. 97: 1954-1961, 2004.

108.   **Tabata I, Nishimura K, Kouzaki M, Hirai Y, Ogita F, Miyachi M, and Yamamoto K.** Effects of moderate-intensity endurance and high-intensity intermittent training on anaerobic capacity and VO2max. *Medicine & Science in Sports & Exercise* 28: 1327-1330, 1996.

109.   **Tabata I, Nishimura K, Kouzaki M, Hirai Y, Ogita F, Miyachi M, Yamamoto KJM, sports si, and exercise.** Effects of moderate-intensity endurance and high-intensity intermittent training on anaerobic capacity and VO~ 2~ m~ a~ x. 28: 1327-1330, 1996.

110.   **Talanian JL, Galloway SD, Heigenhauser GJ, Bonen A, and Spriet LL.** Two weeks of high-intensity aerobic interval training increases the capacity for fat oxidation during exercise in women. *Journal of applied physiology* 102: 1439-1447, 2007.

111.   **Tesch P.** Skeletal muscle adaptations consequent to long-term heavy resistance exercise. *Medicine and Science in Sports and Exercise* 20: S132-134, 1988.

112.   **Thompson WRJAsH and Journal F.** Worldwide survey of fitness trends for 2019. 22: 10-17, 2018.

113.   **Tomko PM, Colquhoun RJ, Magrini MA, Muddle TW, and Jenkins ND.** Global electromyographic signal characteristics depend on maximal isometric contraction method in the knee extensors. *Journal of Electromyography and Kinesiology* 42: 111-116, 2018.

114.   **Van Ingen Schenau G.** Boots PJ, de Groot G, Snackers RJ, and van Woensel WW. *The constrained control of force and position in multi-joint movements Neuroscience* 46: 197-207, 1992.

115.   **van Ingen Schenau G, Dorssers W, Welter T, Beelen A, De Groot G, and Jacobs R.** The control of mono‐articular muscles in multijoint leg extensions in man. *The Journal of physiology* 484: 247-254, 1995.

116.   **Vella CA, Taylor K, and Drummer D.** High-intensity interval and moderate-intensity continuous training elicit similar enjoyment and adherence levels in overweight and obese adults. *European journal of sport science* 17: 1203-1211, 2017.

117.   **Vila-Chã C, Falla D, and Farina DJJoAoP.** Motor unit behavior during submaximal contractions following six weeks of either endurance or strength training. 1455-1466, 2010.

118.   **Ward BW, Clarke TC, Freeman G, and Schiller JS.** Early release of selected estimates based on data from the January–September 2014 National Health Interview Survey. 2013.

119.   **Zelt JG, Hankinson PB, Foster WS, Williams CB, Reynolds J, Garneys E, Tschakovsky ME, and Gurd BJ.** Reducing the volume of sprint interval training does not diminish maximal and submaximal performance gains in healthy men. *European journal of applied physiology* 114: 2427-2436, 2014.

APPENDICES

APPENDIX A

IRB Approved Informed Consent for Participation in the Study

INFORMED CONSENT
OKLAHOMA STATE UNIVERSITY

Project Title: High Intensity Interval Training versus Moderate Intensity Continuous Training to Maximize Physiological Adaptations

Investigators: Masoud Moghaddam, M.S.
Bert H. Jacobson, Ed.D.
Carlos A. Estrada, M.S.
Applied Neuromuscular Physiology Laboratory
Oklahoma State University

Purpose: The purpose of this study is to investigate the effects of high intensity interval training (HIIT) and moderate intensity continuous training (MICT) on physiological adaptations.

Procedures: Your part in this study will be to complete the body composition, voluntary contractions, and aerobic fitness tests before, halfway, and after participating in the training program; you will have a chance of being in one of the exercise groups (ultrashort-HIIT, Tabata-HIIT, and MICT). All three groups will complete the pre-, mid-, and post-testing procedures.

Medical history and health assessment
You will be asked to complete the Exercise Pre-Participation Health Screening Process and physical activity readiness (PAR-Q & You) questionnaires to determine your health status and possible risks of exercising.

Body composition tests
Your body composition will be assessed via a Bioimpedance Spectroscopy equipment (BIS), and your quadriceps muscle size and quality will be scanned by ultrasound system.

Maximal and Submaximal Voluntary Contractions
For all maximal and submaximal contractions, you will be seated with straps securing your trunk, pelvis, and contralateral thigh on a calibrated isokinetic dynamometer. The right knee will be flexed to 90° between the tibia and the horizontal plane. This position will be used for the submaximal and maximal contractions. Following the warm-up and 2 minutes of rest, you will perform 3, 4-5s maximal voluntary contractions of the knee extensors with 2 minutes of rest after each muscle contraction. During these contractions, you will be instructed to kick out as hard as possible. After 5 minutes of recovery, you will perform 3 isometric muscle actions during which you will be instructed to kick out as fast as possible in order to determine the rate of torque development. Loud verbal encouragement will be given during each maximal contraction.

Aerobic fitness test
You will perform three Maximal Oxygen Uptake (VO_{2max}) Tests, Bruce Protocol. Bruce VO_{2max} Test is exercise increasing in intensity or difficulty and in this case is achieved by increasing the

Approved: 01/04/2019
Expires: 01/03/2020
Protocol #: ED-18-175

130

resistance and speed of the cycle ergometer. The exercise intensity will begin at a level you can easily accomplish and will be advanced in stages until you reach your maximal volitional ability. The goal of the test is for you to exercise as long as possible. You will breathe through a mask to measure your inhaled/exhaled gas exchanges. You will also wear a heart rate monitor chest strap. Your breathing pattern and heart rate will be monitored during the test. <u>At any time during the pre-, mid-, post-testing, you can stop the test if you feel uncomfortable because of breathing through the mask.</u>

Training Protocols

You will be randomly assigned to participate in one of three exercise groups. You will wear a heart rate monitor chest strap to monitor your heart rate during the exercise sessions. The training protocols will begin approximately 72 hours after the aerobic test, and will consist of 3 days of training per week for 8 weeks. Each protocol will be performed on Mondays, Wednesdays, and Fridays. All training protocols (i.e., ultrashort-HIIT, Tabata-HIIT, MICT) will be performed on a cycle ergometer. Each training session includes a 5-minute self-paced warm-up session at 20 W, a training protocol (i.e., ultrashort-HIIT, Tabata-HIIT, or MICT), and a 5-minute cool-down at 20 W. The MICT protocol will consist of 30 minutes of continuous cycling at 65% of VO2max. Both HIIT protocols will include 3 sets. Each set includes 8 bouts of "all-out" sprint cycling at your maximal effort. The ultrashort-HIIT protocol will be accomplished at 10s:5s work-to-rest ratio followed by a 1-minute recovery after each set (4 minutes of total exercise time), while the Tabata-HIIT will be completed at 20s:10s work-to-rest ratio, and a 2-minute recovery after each set (8 minutes of total exercise time).

Risks and Discomforts: There are certain discomforts that you might expect if you take part in this research. During the voluntary contractions and aerobic tests, you may experience discomforts similar to those associated with any type of heavy exercise.
During the exercise programs, risks or discomforts include muscle fatigue, muscle soreness (similar to what might be expected of high intensity exercises). Every effort and instruction will be made to minimize the risk of injuries by careful observation during the exercise sessions. Emergency equipment and trained personnel are available for unusual situations.
Your responsibilities during the current study are the following:
- Ask questions about anything you do not understand.
- Follow the instructions of the investigator.
- Let the investigator know about any unusual symptom.

In case of injury or illness resulting from this study, emergency medical treatment will be available from OSU Health Services or Stillwater Medical Center. Compensation for an injury resulting from your participation in this study is not available.

Termination of Participation: The investigator may stop your participation in the current study without your consent due to any one of the following conditions:
- Injury during the exercise testing or training program.
- Voluntary withdrawal of the participant.
- The investigator believes that participation in the research is not safe for your health.

- Missing the appointments
- Not following the instructions of the investigator.

During your participation, if you feel any discomfort or unusual symptoms, it is your responsibility to ask the investigator to terminate your participation for your safety and benefit. In addition, you should inform the investigator or advisor if you are pregnant, have a heart condition, experience chest pain or lose consciousness during exercise, or take medication for blood pressure or a heart condition. According to the exercise pre-participation health screening process, your participation will be terminated, if medical clearance is required prior to exercise. Also, if you are sedentary or an elite athlete you will be excluded from the study.

Benefits of Participation: You will receive information regarding your strength and aerobic fitness level as well as body composition. You will be randomly selected to be in one of the exercise training groups, and you will participate in a supervised exercise training program, free of charge. Participation in the current study may or may not develop your physical fitness. However, you will learn how to perform conditioning exercises, and use fitness equipment. Also, you may enhance your exercise capacity and fitness level, if you follow the instructions. Other people could benefit from the results of this research in the future. The results of this study could lead to develop new methods of conditioning programs to improve fitness levels.

Confidentiality: The information that is obtained during exercise testing will be remained confidential, and will not be released or revealed to any person without your written consent. The collected information, however, may be used for statistical analysis or scientific purposes with maintaining your confidentiality. We will do everything we can to protect your privacy and confidentiality. We will not tell anybody outside of the research team that you were in this study or what information we collected about you in particular. Confidentiality could be broken if materials from this study were subpoenaed by a court of law.
The data will be stored in locked file cabinets and/or encrypted electronically within a locked room in investigator's office, Colvin 198. Only the investigators have access to the data. For maintaining confidentiality, certain ID codes will be used instead of names when analyzing the data. The data will be maintained for three years after the study is concluded, then the collected data will be destroyed.

Compensation: To encourage participation, course/extra credit may be offered for research participation by faculty members. If extra credit is offered, the amount and type of extra credit will be determined by each individual professor. The same extra credit will be available for a non-research activity that involves the same effort and time investment, which will also be determined by the professor. There is no monetary compensation for the current study.

Participant Rights: I understand that my participation is voluntary, that there is no penalty for refusal to participate, and that I am free to withdraw my consent and participation in this project at any time, without penalty.

Contacts: This study has been reviewed and approved by OSU Institutional Review Board (IRB). If you have any question or concern about this study, you may contact Masoud Moghaddam

masoud.moghaddam@okstate.edu or Dr. Bert H. Jacobson bert.jacobson@okstate.edu. If you have questions about your rights as a research volunteer, you may contact the IRB Office at 223 Scott Hall, Stillwater, OK 74078, 405-744-3377 or irb@okstate.edu .

CONSENT DOCUMENTATION:

I have been fully informed about the procedures listed here. I am aware of what I will be asked to do and of the benefits of my participation. I also understand the following statements:

I affirm that I am 18 years of age or older.

I have read and fully understand this consent form. I sign it freely and voluntarily. A copy of this form will be given to me. I hereby give permission for my participation in this study.

_____   _____
Signature of Participant   Date

I certify that I have personally explained this document before requesting that the participant sign it.

_____   _____
Signature of Researcher   Date

VITA

Masoud Moghaddam

Candidate for the Degree of

Doctor of Philosophy

Dissertation: HIGH INTENSITY INTERVAL TRAINING VERSUS MODERATE
INTENSITY CONTINUOUS TRAINING TO MAXIMIZE
NEUROMUSCULAR ADAPTATIONS

Major Field: Health, Leisure, and Human Performance

Biographical:

Education:

Completed the requirements for the Doctor of Philosophy in Health, Leisure,
and Human Performance at Oklahoma State University, Stillwater, Oklahoma in
May, 2020.

Completed the requirements for the Master of Science in Exercise Science at
Texas A&M University-Commerce, Commerce, Texas in 2016.

Completed the requirements for the Bachelor of Science in Physical Education
at Imam Reza International University, Mashhad, Iran in 2014.

Experience:

Graduate Teaching Associate, August 2016 – Present
School of Kinesiology, Applied Health, and Recreation
Oklahoma State University

Professional Memberships:

American College of Sports Medicine
National Strength and Conditioning Association
National Association for Kinesiology in Higher Education
Honor Society of Phi Kappa Phi, Oklahoma State University Chapter