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The Effects Of Exercise Mode And Intensity On Energy Expenditure During And After Exercise In Resistance Trained Males

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THE EFFECTS OF EXERCISE MODE AND INTENSITY ON ENERGY EXPENDITURE
DURING AND AFTER EXERCISE IN RESISTANCE TRAINED MALES

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DEDICATION

To my family, who have continually made generations of sacrifices for each other and afforded me to have this opportunity.

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To my dissertation committee, Dr. Clemens Drenowatz, team EEVET, and the many great mentors and colleagues from whom I have received tutelage and support, I am honored and humbled to have been able to work with each of you in the completion of this dissertation.

ABSTRACT

Purpose: The purpose of this study was to examine the effects of exercise mode and intensity on energy expenditure (EE) during and after five time-matched aerobic and resistance exercise protocols in resistance trained males.

Methods: 14 resistance trained males (mean \pm SD; age = 24.2 ± 4.0 yr; body mass = 84.7 ± 13.3 kg; height = 181.2 ± 8.8 cm; and body fat = $15.9 \pm 4.6\%$) completed five separate protocols: continuous aerobic (continuous), high intensity interval aerobic (HIIT), strength endurance (2x20), traditional resistance (3x10), and high intensity resistance (4x6). EE was measured before, during, immediately post (0-30 minutes), and delayed post exercise (60-90 minutes).

Results: No significant differences in exercise EE were seen between aerobic protocols, both of which were significantly greater ($p < 0.0001$) than all three resistance protocols. When comparing exercise EE across resistance protocols, the 4x6 protocol was significantly greater than the 3x10 and 2x20 protocols by 38 ± 10 kcal ($p = 0.04$) and 67 ± 8 kcal ($p < 0.001$), respectively. In the 30 minutes following exercise, a 6.2% mean increase in EE was seen following the 2x20 protocol ($p < 0.05$) compared to baseline. In the 60-90 minutes post-exercise, the 3x10, 4x6, and HIIT protocols showed significant average reductions in EE of 10.7%, 8.7%, and 7.1% ($p < 0.05$) compared to baseline, respectively. The

combined EE from during and after exercise resulted in the same rank order as during exercise (least to greatest: 2x20, 3x10, 4x6, continuous, and HIIT).

Conclusion: Continuous and HIIT aerobic protocols were responsible for the greatest EE during exercise when compared to the resistance protocols. Within resistance protocols, intensity was associated with an increase in exercise EE. Despite the reductions in EE 60-90 minutes post exercise observed in the 3x10, 4x6, and HIIT protocols, exercise EE was the greatest contributor to total EE measured during and after exercise. These results can potentially be used when designing exercise training programs in order to monitor EE and avoid negative effects of potential energy deficits.

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LIST OF ABBREVIATIONS

EB	Energy Balance
EE	Energy Expenditure
EI	Energy Intake
EPOC	Excess Post-Exercise Oxygen Consumption
GXT	Graded Exercise Test
HIIT	High Intensity Interval Training
NEAT	Non-Exercise Activity Thermogenesis
PA	Physical Activity
RED-S	Relative Energy Deficiency in Sport
RM	Repetition Maximum
RMR	Resting Metabolic Rate
TDEE	Total Daily Energy Expenditure
TEF	Thermic Effect of Food

CHAPTER ONE

OVERALL INTRODUCTION

Energy Balance Model

Chronic energy imbalance is the primary causal factor related to the development of obesity and relative energy deficiency in sport (RED-S) [1, 2]. The development of obesity and RED-S are most simply shown by the Energy Balance (EB) model. Developed from the First Law of Thermodynamics, the EB model shows that energy storage (ES) is the difference of energy intake (EI) and energy expenditure (EE). Shown as $ES = EI - EE$, the model indicates that body mass can be gained when the rate of energy intake chronically exceeds EE. Alternatively, the EB model also shows that body mass can be lost when the rate of energy intake is chronically exceeded by the rate of EE [3]. Energy expenditure is a consequence of both behavioral and physiological components, whereas EI is a consequence of behavior and environment [4].

Both EI and EE have several components, as shown in **Figure 1.1**. The primary component of EE is total daily energy expenditure (TDEE), which is the sum of energy expended via resting metabolic rate (RMR, ~70% TDEE), physical activity (PA, ~15-50%) from non-exercise activity thermogenesis (NEAT) and exercise, and the thermic effect of food (TEF, ~10%) [1, 5-8]. RMR is defined as the energy cost of basic vital functions and is the largest component of TDEE in the general population [6]. NEAT and exercise are forms of PA in that both require

skeletal muscle contractions, expend energy above a resting level, and are positively associated with physical fitness. Exercise differs from NEAT in that it is structured, repetitive, and is performed to improve or maintain physical fitness [9]. The thermic effect of food is the energy cost of feeding, resulting from the digestion and storage of food [10]. RMR and TEF are primarily regulated by physiological mechanisms [6, 11, 12], while NEAT, exercise, and EI are regulated by behavioral and environmental means [4].

Excess post-exercise oxygen consumption (EPOC) is defined as the elevation of oxygen consumption and metabolic rate following exercise and PA and is comprised of a fast component and a slow component [13]. The fast component lasts approximately five minutes and is largely determined on the elevation in blood lactate concentration and muscle phosphocreatine phosphorylation, while the slow component has been shown to last up to 72 hours [14, 15]. EPOC is influenced by the mode, intensity, and duration of exercise and PA [13, 16-18]. EPOC is influenced by the replenishment of adenosine triphosphate-phosphocreatine, protein synthesis and tissue repair, and lactate metabolism [8, 17, 18] In addition to the exercise and PA characteristics that influence EPOC, physical characteristics can also influence EPOC which include sex, body mass, body composition, and training status [17, 19, 20]. Because EPOC is a temporary elevation in metabolic rate following exercise and PA, resting EE during this post-exercise period is subsequently elevated for up to 72 hours and accounts for an additional 10-15% of the energy that was expended during

exercise [14, 18]. This elevation in resting EE can subsequently increase TDEE and therefore alter energy balance.

Increases in physical inactivity paired with decreases in habitual PA have led to the increase in obesity due to a decrease in TDEE and subsequent positive EB [21-23]. Sustained positive energy balance leads to weight gain and is the primary etiological factor for obesity, which is associated with numerous negative health outcomes and health care costs [24-27]. Additionally, obesity is a threat to national security [28, 29]. Sustained negative energy balance may lead to excessive weight loss, injuries, immunosuppression, hormonal imbalance, and/or poor performance [2, 30-37]. Exercise affects energy balance by raising TDEE through exercise EE and RMR, which is affected after exercise. Therefore, better understanding the ways in which exercise influences total daily EE and subsequently energy balance can provide knowledge to be used in exercise training program design.

Since exercise EE and RMR are major components of energy balance in active individuals, exercise mode must be considered when developing training regimens. If the additional EE from the EPOC is not addressed, negative energy balance and subsequently decreased performance and injury are possible. Therefore, better understanding the EE related causes of obesity and chronic negative energy balance and subsequently developing effective exercise training interventions is a national public health and safety priority.

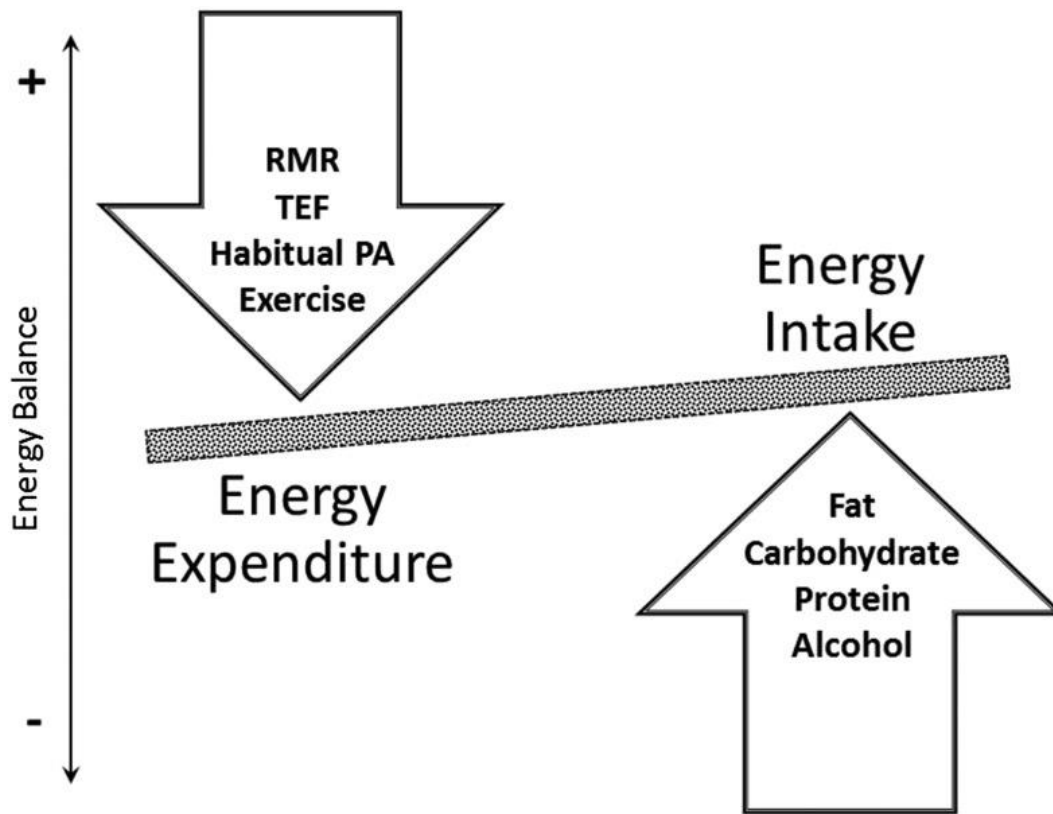


Figure 1.1. The relationship between energy expenditure and intake, and their individual components. Used with permission from Drenowatz 2015 [4].

CHAPTER TWO

LITERATURE REVIEW

Methods for measuring EE

Given the importance of EE in weight loss, weight maintenance, and weight gain [2, 22, 38], the measurement of EE is vitally important in exercise and PA prescription. EE is commonly measured using direct calorimetry, doubly labeled water (DLW), and indirect calorimetry. Though each of these measures are valid measures of EE, each have their own strengths and limitations which are described in more detail in the following sections.

Direct Calorimetry

Direct calorimetry is the most accurate method for quantifying metabolic rate and involves the measurement of metabolic heat generation of living organisms [39]. Rooted in the First Law of Thermodynamics, direct calorimetry assumes that all metabolic processes generate heat and the rate of these metabolic processes can be measured based on the rate of heat produced [40]. Direct calorimeters are comprised of a whole room or chamber with devices in place to measure the heat loss of the subject, which is comprised of four components: radiation, convection, conduction, and evaporation of heat. The components of heat loss are all measured using four versions of direct calorimeters which include isothermal, heat sink, direct differential, and direct convection calorimeters. All versions of direct calorimeters measure the difference between

environmental heat and heat loss of the subject, though with slightly different means ranging from the measurement of liquid temperature differences in the walls of the chamber to the measurement of air temperature differences of the chamber between incoming and outgoing air. The details for the calculations of EE with direct calorimetry have been described elsewhere [39, 40]. In addition to the high level of accuracy of measuring heat loss, direct calorimetry carries the advantage of operation in a tightly-controlled environment, free from environmental confounders on EE. However, all versions of direct calorimeters carry the disadvantages of the high initial and maintenance costs of the equipment and technical expertise for operation. Additionally, direct calorimeters are unable to detect acute changes in heat loss and therefore are inappropriate for measuring EE for periods less than a few hours [1]. Furthermore, due to the design of direct calorimeters necessitating a small room or chamber, the types of activities that can be performed within the calorimeter are limited by the available space.

Doubly Labeled Water

Doubly labeled water was first discovered for EE measurement in animals in 1949 and has since progressed to become the gold standard for long-term EE measurement of daily living in humans [1, 41-44]. DLW consists of non-radioactive isotopes of hydrogen (^2H) and oxygen (^{18}O) and is typically consumed orally. Following ingestion, the ^2H and the ^{18}O isotopes reach a state of equilibrium with body water through the actions of carbonic anhydrase. Subsequently, both ^2H and ^{18}O are expelled from the body, with ^2H expelled only through water loss and ^{18}O expelled through both exhalation of CO_2 and water loss. Based on the measured

rates of isotope elimination through blood, saliva, or most commonly urine, CO₂ production can be estimated and subsequently TDEE can be calculated. The details for calculating EE with DLW have been described elsewhere [43-46]. DLW is effective for measuring EE over periods of 4 to 21 days [1, 47]. The most striking advantage of DLW over other EE measurement methods is that participants can consume the DLW at baseline and have EE calculated by simply providing saliva, blood, or urine samples at specified time points throughout the measurement period. Participants are not limited to a chamber as with direct calorimetry and no measurement equipment needs to be worn as with indirect calorimetry. However, one disadvantage is that the DLW itself is very expensive in addition to the isotope-ratio mass spectrometry equipment that is needed for analysis. Furthermore, DLW is not an accurate measure of EE for periods of less than 4 days and can only be used to measure TDEE and not the EE cost of individual activities [1].

Indirect Calorimetry

Indirect calorimetry involves the measurement of expired O₂ and CO₂, subsequently allowing the estimation of metabolic rate from the energy released from substrate oxidation and therefore allows EE to be calculated [1, 48]. The calculation of EE using indirect calorimetry have been described in detail elsewhere [49-51]. Indirect calorimeters are valid and accurate in the measurement of resting EE, RMR, and exercise EE [1, 50, 52-54]. A metabolic cart is the most common version of indirect calorimeter and consists of a platform-mounted gas analysis system with a breathing apparatus attached by a hose. The breathing apparatus consists of a ventilatory hood, mask, or mouthpiece [50] and

is worn by the participants in close proximity to the cart. Expired gasses are passed through the hose into the gas analyzer, where the percentage of expired O₂ and CO₂ are measured. Metabolic carts are limited in the types of activities that can be measured, as the length of the hose dictates one's proximity to the cart. However, portable indirect calorimeters are an alternative to metabolic carts that allow more freedom of movement. In contrast to the metabolic cart, which has a platform-mounted gas analyzer, portable indirect calorimeters have a backpack-mounted gas analyzer with an attached battery pack. While portable indirect calorimeters offer more freedom of movement than metabolic carts, portable indirect calorimeters can be cumbersome and limited in power supply by the battery pack [1, 50].

Measuring exercise EE with indirect calorimetry

Even though direct calorimetry and DLW are accurate and valid methods of measuring EE and have their own unique advantages, direct calorimetry and DLW present limitations for exercise study protocols. In addition to the high initial and maintenance costs, direct calorimetry confines the activities and protocols performed to the available space within the calorimeter. DLW can only be used to accurately measure EE over several days to weeks and therefore is inappropriate for the measurement of EE during single exercise sessions. Indirect calorimetry therefore serves as the most appropriate method for measuring the EE of single exercise sessions due to the greater freedom of movement compared to direct calorimetry and the ability to measure EE for shorter periods than DLW. Additionally, indirect calorimetry has lower costs than direct calorimetry [1].

Measuring RMR/Resting EE with indirect calorimetry

Indirect calorimetry is an effective and practical method of measuring RMR and resting EE [53] but has specific actions that must be taken in order to get a true measurement of resting EE. Food consumption, drug intake, PA, and environmental setting have all been shown to influence RMR. Moderate-intensity aerobic PA and alcohol consumption can have a positive influence on RMR for up to 2 hours, meal consumption up to 5 hours, and vigorous-intensity resistance exercise can have a significant for up to 14 hours [55]. Additionally, caffeine and nicotine can positively influence RMR for up to 4 hours. Furthermore, a noisy, humid, and bright room may also influence RMR. Due to the potential confounding nature of PA, food consumption, drug intake, and environmental setting on RMR, the appropriate length of abstinence in a quiet and environmentally controlled setting should be applied for each potential confounder.

In addition to diet, drugs, PA, and environment, RMR is determined by body size, body composition, training mode, training status, and cardiorespiratory fitness (CRF) [56, 57]. RMR is a function of lean body mass [56] and is greater in individuals with larger body mass due to the increased metabolic demands. Additionally, CRF is positively associated with RMR independent of body composition [57]. Many studies examining resting EE and RMR have examined the group means instead of examining individual changes [58-61]. Individual variability is an important factor in the measurement of EE and should be considered when examining EE.

Measuring exercise EE and EPOC with indirect calorimetry

When using indirect calorimetry, EPOC is measured in the same manner as RMR, with the obvious exception being that the EPOC measurements are performed following exercise compared to a resting state as with RMR. Most studies have examined EPOC during the immediate time frame of ≤ 120 minutes following exercise, though some studies have performed follow up EPOC measurements up to 72 hours after the exercise session [14, 17, 62, 63].

EE and Exercise

EE during exercise is a function of the duration, rate, and intensity of the work performed, in addition to the amount of muscle mass recruited [17, 18, 58, 64, 65]. When discussing aerobic exercise, continuous aerobic exercise is typically responsible for a greater EE than low volume interval training, mostly because of the differences in duration [66-68]. When matched for duration, high intensity interval training (HIIT) exercise is responsible for greater EE due to the greater intensity. However, most studies comparing continuous and HIIT aerobic exercise have not been matched for total duration or work. A 2017 meta-analysis [69] showed that of 13 training studies that examined the effects of HIIT and continuous aerobic exercise on weight loss, the continuous aerobic exercise protocols were responsible for 102% greater EE than the HIIT exercise protocols due to a longer duration. Because of the greater duration and amount of work performed during the continuous aerobic exercise protocols than the HIIT exercise protocols, if any differences in weight loss were due to the difference in mode, work performed, or duration is uncertain. Therefore, a more uniform matching of duration and work

performed in aerobic exercise protocols is needed for a better understanding of aerobic exercise EE when comparing continuous and HIIT aerobic exercise.

Like aerobic exercise, EE during resistance exercise is a function of the duration and intensity of the work performed [70]. When matched for relative intensity, aerobic exercise has been shown to be responsible for a greater total exercise EE than resistance exercise, likely due to the constant movement throughout the entire session in contrast to resistance exercise protocols, which are typically of an intermittent nature [71, 72]. However, when examining work per minute of the time in which actual exercise was performed instead of per minute of the entire session, resistance exercise is responsible for a greater work than aerobic exercise when matched for relative intensity [71]. Bloomer et al. examined the effect of relative intensity-matched aerobic and resistance exercise on exercise EE in 10 aerobic and resistance trained young males. The aerobic exercise protocol consisted of 30 minutes of cycling at 70% of maximal oxygen consumption $\dot{V}O_{2max}$ and the resistance exercise protocol consisted of 30 minutes of intermittent squatting at 70% 1RM. They showed that the total exercise EE of the 30 minutes of aerobic exercise was significantly ($p < 0.001$) greater (Mean \pm SE = 441.92 \pm 16.98 kcal) than the total exercise EE of the 30 minutes of resistance exercise (Mean \pm SE = 269.21 \pm 13.09 kcal). However, when examining the work (kJ) of the time in which the exercises were performed, the aerobic protocol was responsible for significantly ($p < 0.001$) less work (Mean \pm SE = 11.16 \pm 1.13 kJ) than the resistance protocol (Mean \pm SE = 20.93 \pm 1.14 kJ). While the design of the study called for both 70% $\dot{V}O_{2max}$ and 70% 1RM for the exercise protocols, the authors

state that the resistance protocol was performed at approximately 10% less than the designed intensity (Mean \pm SE = 61.81 \pm 1.58%). Despite the lower than intended intensity that was performed during the resistance exercise protocols, the authors state that if the resistance exercise was performed at the originally intended 70% one repetition maximum (1RM), the difference in exercise EE between protocols would have been less. However, even if a smaller difference in exercise EE did occur, the aerobic exercise would have resulted in a greater exercise EE than the resistance exercise.

Reis et al. [73] examined the energy cost of individual resistance exercises of low and high intensities in 58 resistance trained males and found that exercises performed at 80% of 1RM was responsible for significantly greater EE than the same exercises performed at 20% 1RM. Further, the authors showed that large muscle exercises were responsible for significantly greater EE than small muscle exercises performed at the same intensity. Additionally, Farinatti et al. [58] examined the effect of muscle mass on oxygen uptake during resistance exercise in 10 resistance trained males and showed that resistance exercises for smaller muscle groups expended less energy than exercises for larger muscle groups at the same relative workload. Similar results have been shown in other studies [73-75].

Falcone et al. [76] examined the effects of steady state treadmill aerobic exercise, cycling aerobic exercise, concentric-only hydraulic resistance system (HRS) exercise circuit, and traditional resistance exercise protocols of similar duration on exercise EE in nine physically active young males. The steady state

treadmill aerobic protocol consisted of 30 minutes of aerobic exercise on a treadmill performed at 70% of age predicted maximum heart rate (APMHR), and the steady state cycle aerobic protocol consisted of 30 minutes of aerobic exercise on a cycle ergometer also performed at 70% of APMHR. The HRS protocol was a full body resistance exercise circuit that was provided by the HRS equipment manufacturer (Surge Performance Training, Austin, TX, USA). The protocol consisted of four sets per exercise with eight exercises total, 20 seconds of exercise, 40 second rest periods with an unspecified relative intensity and lasted a total of 32 minutes. The traditional resistance exercise protocol was a full body protocol that consisted of three sets of ten repetitions with six separate resistance exercises at 75% 1RM, with 60 seconds between sets, and lasted a total of approximately 30 minutes. They found that with a similar duration among all four exercise protocols, the HRS protocol resulted in a significantly greater exercise EE (Mean \pm SD = 12.62 \pm 2.36 kcal/min, $p < 0.05$) than the treadmill (Mean \pm SD = 9.48 \pm 1.30 kcal/min), cycling (Mean \pm SD = 9.23 \pm 1.25 kcal/min), and traditional resistance exercise protocols (Mean \pm SD = 8.83 \pm 1.55 kcal/min). Though slightly less than the treadmill and cycling protocols, interestingly no significant differences in exercise EE of the resistance exercise protocol compared to the treadmill and cycling protocol were found. These differences in EE may have been due to a mismatch of intensities, as the aerobic exercises performed at the relatively low-moderate intensity of 70% APMHR (approximately 50% $\dot{V}O_{2max}$) did not equate to the moderate-high intensity of the traditional resistance exercise protocol performed at 75% 1RM [76]. While this study quantified the exercise EE of steady

state treadmill aerobic exercise, cycling aerobic exercise, a concentric-only HRS exercise circuit, and traditional resistance exercise protocols, the effects of these protocols on EPOC are unknown.

Bloomer et al. [71] nicely showed the differences in exercise EE between time-matched continuous aerobic exercise and resistance exercise when performed at similar relative intensities (Mean \pm SE = 73.06 \pm 0.50% $\dot{V}O_{2max}$ vs. 61.81 \pm 1.58% 1RM) in the same exercise trained individuals. Additionally, Falcone et al. [76] presented a well performed comparison of exercise EE in continuous aerobic exercise and resistance exercise of similar duration in the same individuals. Furthermore, in a review of 13 studies examining the exercise EE of resistance exercise, Meirelles and Gomes [15] called for individual characteristics “such as nutritional status, age gender, body composition and fitness level” must be considered when examining the EE of resistance exercise. To date, no studies exist that compare the exercise EE of both continuous and HIIT exercise with the exercise EE of resistance exercise of varying intensities in the same exercise trained individuals. Therefore, more work is warranted in this area to understand the relationship between training status on exercise EE.

Studies that measured EPOC of aerobic and resistance exercise

Aerobic Exercise

During aerobic exercise, intensity and duration are the primary factors that influence EPOC [17, 77-79]. Børsheim and Bahr [17] reviewed 58 studies from 1960 to 2000 and found that short-duration, low- to moderate- intensity aerobic exercise (<30min at <80% $\dot{V}O_{2max}$) results in a short-lasting elevation of metabolic

rate following exercise (<40 minutes). Additional subsequent studies have also shown that short duration and low-to moderate-intensity aerobic exercise results in a short duration elevation of metabolic rate following exercise [18, 65]. Furthermore, the intensity has been shown to explain up to five times the variance of elevation in metabolic rate following exercise than total work completed or exercise duration [80].

HIIT performed at maximal effort has been shown to elicit a similar elevation of metabolic rate following exercise to continuous aerobic exercise, despite the shorter duration of exercise [67]. In a randomized trial, Skelly et al. [67] examined the effects of HIIT, continuous aerobic exercise cycling protocols, and a control resting protocol on metabolic rate following exercise in 9 young men. The HIIT protocol was performed at 90% maximum heart rate for a total of 20 minutes (10 sets of 60 second work intervals followed by 10 sets of 60 second active recovery intervals performed at 50 watts), the continuous aerobic exercise protocol was performed at 70% maximum heart rate for 50 minutes, and the control resting protocol involved performing no activity. The continuous aerobic protocol was found to have had a significantly higher exercise EE than the HIIT and control protocols (HIIT: 352 ± 34 , continuous: 547 ± 65 , control: 125 ± 15 kcal, $p < 0.01$). Additionally, despite the HIIT protocol being 30 minutes shorter in duration and having a lower exercise EE than the continuous aerobic protocol, the 24-hour post-exercise EE was similar for the HIIT ($3,368 \pm 443$ kcal) and the continuous ($3,464 \pm 469$ kcal) protocols, and that both resulted in a higher post-exercise EE than the control ($3,005 \pm 335$ kcal, $p < 0.01$) [67]. The authors conclude that despite the

lower exercise EE during HIIT compared to the continuous aerobic protocols, no significant differences in 24-hour EE between the two modes existed. Therefore, HIIT was proposed as being a time efficient form of exercise for increasing TDEE.

In addition to duration and intensity of the aerobic exercise performed, training status is also associated with EPOC magnitude (i.e. level of elevation in post-exercise metabolic rate). Well aerobic trained participants have a lower magnitude of elevation in metabolic rate following exercise than moderately aerobic trained participants, and in untrained individuals, the magnitude of elevation in metabolic rate following exercise has been shown to be greater than in trained participants after performing exercise of similar intensity. Additionally, the elevated metabolic rate following exercise has been shown to last longer in untrained individuals compared to trained individuals [17, 78, 81]. Hagberg, Mullin, and Nagle [82] examined the effects of cycling at 50, 65, and 80% of $\dot{V}O_{2max}$ for 5 and 20 minutes on the fast component of EPOC in 18 young men with moderate aerobic fitness ($\dot{V}O_{2max}$ 51.9 ± 1.4 ml/kg/min) and found that at a greater intensity of 80% $\dot{V}O_{2max}$ with a duration of 20 minutes led to a greater magnitude of elevation in metabolic rate following exercise than the lower intensity sessions at 50% and 65% $\dot{V}O_{2max}$ at both 5 and 20 minutes, respectively.

In a counterbalanced design, Gore and Withers [80, 83] examined the metabolic rate following exercise of 9 well-trained young men ($\dot{V}O_{2max}$ Mean \pm SD = 63.0 ± 5.7 ml/kg/min) who performed 20, 50 and 80 minutes of treadmill exercise at 30, 50 and 70% $\dot{V}O_{2max}$. Metabolic rate following exercise was measured for 80 minutes. The study results were that exercise intensity was the major determinant

for the magnitude of elevation in metabolic rate following exercise following exercise with the 70% $\dot{V}O_{2max}$ exercise session of performed for 20, 50, and 80 minutes eliciting a significantly greater EPOC than the exercise sessions performed at 50% $\dot{V}O_{2max}$ for 20, 50, and 80 minutes. Also, exercise intensity was responsible for five times the EPOC variance than exercise duration [80].

Additionally, the metabolic rate of aerobically trained individuals following exercise returns to resting values at a faster rate than untrained individuals [17]. Short and Sedlock [84] examined the effects of two cycling protocols (relative intensity performed at 70% $\dot{V}O_{2peak}$ and absolute intensity performed at 1.5L/min) for 30 minutes on 22 aerobically trained and untrained individuals (11 females, 11 males) on metabolic rate following exercise measured for 60 minutes and found that following exercise, the trained individuals had a shorter elevation of metabolic rate and a faster return to baseline metabolic rate following both protocols (70% $\dot{V}O_{2peak}$ Mean \pm SD = 40 \pm 15 min, 1.5L/min = 21 \pm 9 min) 1.5L/min (70% $\dot{V}O_{2peak}$ Mean \pm SD = 50 \pm 14 min, 1.5L/min = 39 \pm 14 min, $p < 0.01$). However, both groups returned to baseline metabolic rate within one hour. No difference in magnitude of EPOC between the trained and untrained individuals after performing both protocols was observed. Moreover, Frey et al. [85] examined the effects of cycling at 65% and 80% $\dot{V}O_{2max}$ until 300 kcal were expended in 13 trained and untrained females (7 untrained, 6 trained) on metabolic rate following exercise measured for 60 minutes. Similar to Short and Sedlock [84], they also found that the elevation in metabolic rate following exercise was shorter in the trained versus untrained individuals. Following the 65% and 80% $\dot{V}O_{2max}$ aerobic exercise sessions, the

trained individuals had an elevation in metabolic rate for 40 and 50 minutes, respectively, while the untrained individuals still had an elevation in metabolic rate present at the end of the 60 minutes measurement period [85].

Matsuo et al. [86] examined the effects of three cycling protocols of varying intensities on metabolic rate following exercise in 10 healthy males. The protocols consisted of a sprint interval training protocol consisting of seven sets of 30 second sprints performed at 120% $\dot{V}O_{2max}$ with 15 seconds of rest between exercise sets, a HIIT protocol consisting of three sets of three minutes performed at 80-90% $\dot{V}O_{2max}$ with two minutes of active rest at 50% $\dot{V}O_{2max}$ between sets, and a continuous aerobic protocol consisting of 40 minutes performed at 60-65% $\dot{V}O_{2max}$. Metabolic rate was measured for 180 minutes post-exercise. The authors reported that the sprint interval training protocol had the highest magnitude of elevation in metabolic rate following exercise (6.8 ± 4.0 L), the HIIT protocol had the second highest magnitude of elevation in metabolic rate following exercise (4.5 ± 3.3 L), and the continuous protocol had the lowest magnitude of elevation in metabolic rate following exercise (2.9 ± 2.8 L). The authors also reported a significant inverse association between CRF and magnitude of elevation in metabolic rate following exercise in the HIIT protocol ($r = -0.79$, $p < 0.01$), a trend between CRF and sprint interval training ($r = -0.61$, $p = 0.06$), but no significant association between CRF and the continuous protocol ($r = -0.42$, $p = 0.23$) [86]. The inverse association between CRF and magnitude of elevation in metabolic rate following exercise was reportedly due to the physiological adaptations that occur with aerobic training and that are associated with having higher CRF. The adaptations mentioned by the

authors were a better thermoregulatory capacities and better lactate clearance than individuals with lower CRF.

In addition to these cross-sectional studies, training studies have also shown that following training, elevation in metabolic rate following exercise lasts for a shorter duration than before training. In other words, the speed at which the elevation in metabolic rate following exercise returned to pre-exercise resting values was quicker after training than the speed at which the elevation in metabolic rate following exercise returned to pre-exercise resting values before training [87, 88]. The results of the above cross-sectional studies and training studies indicate that training status and CRF are important factors in the length of the elevation in metabolic rate following exercise.

Resistance Exercise

As with aerobic training, the elevation in metabolic rate following resistance exercise is influenced by duration and intensity, as well as volume [17, 19, 63]. Additionally, the elevation in metabolic rate following resistance exercise is influenced by the size of the muscle mass that is worked during the exercise, speed of the movements performed, and the length of the rest intervals between sets[63]. Vianna et al. [89] examined the EPOC of 14 resistance trained young men following individual exercise sessions consisting of the bench press, half-squat, triceps pushdown, and pull-down exercises. Each exercise was performed at 80% 1RM until exhaustion, the fast component of EPOC was measured for five minutes, and each remaining exercise was performed 60 minutes after the last. The intensity of the exercises performed was a factor in the magnitude of elevation in

metabolic rate following exercise in addition to the type of exercise. Vianna et al. [74, 89] showed that the half-squat exercise was responsible for a significantly greater magnitude of elevation in metabolic rate following exercise than the bench press and triceps pushdown, with the exercise utilizing the most muscle mass responsible for the greatest magnitude of elevation in metabolic rate following exercise [89]. Also reported was that the elevation in metabolic rate following resistance exercise returned to pre-exercise levels within five minutes, regardless of the exercise performed.

Their results are not the only results showing that muscle mass is positively associated with the elevation in metabolic rate following resistance exercise. Farinatti et al. [58] also showed that larger muscle mass exercises were responsible for a greater magnitude of elevation in metabolic rate following exercise than smaller muscle mass exercises. Using a counterbalanced design, they examined the effect of five sets of 10 repetitions at 100% 15RM of leg press and chest fly on exercise and post-exercise EE and EPOC in 10 resistance trained males, and showed that both the leg press and chest fly sessions resulted in an elevation in metabolic rate following exercise lasting approximately 40 minutes, and that the leg press exercise session was responsible for a significantly greater elevation in metabolic rate following exercise than the chest fly session (Mean \pm SD = $7.36 \pm 1.10L$ vs. $4.73 \pm 0.99L$; $p < 0.001$) [58]. The rest intervals between exercises have also been shown to be a factor to influence magnitude of elevation in metabolic rate following exercise following resistance exercise. Farinatti et al. [60] showed that when performing resistance exercise of the same intensity and

muscle mass, one minute long rest periods between sets resulted in a greater magnitude of elevation in metabolic rate following exercise than three minute long rest periods. They examined the effect rest period length on magnitude of elevation in metabolic rate following exercise in 10 resistance trained males. The protocol consisted of five sets of 10 repetitions with 15RM in the leg press or chest fly with rest periods of one or three minutes followed by a 90-minute post-exercise metabolic rate measurement period. The leg press performed with one and three-minute rest periods and the chest fly performed with one minute rest periods had a significantly longer elevation in metabolic rate following exercise (approximately 40 minutes) than the chest fly performed with three minute rest periods (20 minutes, $p < 0.05$) [60].

In addition to duration, intensity, and muscle mass of the resistance exercise performed, training status is also associated with the magnitude of elevation in metabolic rate following exercise. Benton et al. [20] examined the effects of resistance exercise on metabolic rate following exercise in 22 women (11 trained, 11 untrained). The participants performed a full body resistance exercise session consisting of eight exercises and three sets of eight repetitions at 80% 1RM. Following exercise, metabolic rate was measured for 120 minutes. Both the trained and untrained women had an metabolic rate following exercise that was significantly greater than baseline for 60 minutes ($p = 0.01$), and that the resistance trained women had a trend for greater metabolic rate following exercise (31.3L) than the non-resistance trained women (27.4L, $p = 0.07$), independent of volume load completed [20]. The authors suggested the mechanism for the

increased post-exercise metabolic rate was an increase in protein synthesis, and that the trained individuals had less muscle damage, a lower rate of protein synthesis, and therefore lower post-exercise metabolic rate.

Abboud et al. [90] examined the effects of resistance exercise load volume on metabolic rate following exercise in eight highly resistance trained males. The protocols consisted of two full body resistance exercise sessions performed at 85% 1RM, with one consisting of a total of 10,000kg load volume and the other consisting of 20,000kg load volume. The 10,000kg protocol (Mean \pm SD = 43.6 \pm 7.9 minutes) was significantly ($p < 0.01$) shorter than the 20,000kg protocol (Mean \pm SD = 90.3 \pm 16.1 minutes). The 10,000kg protocol also had significantly ($p < 0.01$) less exercise EE (Mean \pm SD = 247.0 \pm 18.0 kcal) than the 20,000kg protocol (Mean \pm SD = 484.0 \pm 29.0 kcal). Resting metabolic rate was measured at 12, 24, 36, and 48 hours post-exercise, and there were no significant differences in RMR at any of the post-exercise measurement time points. The authors concluded that in highly resistance trained males, RMR was not affected at 12, 24, 36, and 48 hours post-exercise due to the lack of a large enough stimulus to instigate a significant increase in metabolic rate [90].

Aerobic and Resistance Exercise

While there are many studies examining the effects of aerobic and resistance exercise on metabolic rate following exercise, there are few studies directly comparing the two modes with the same participants. Burleson et al. [91] examined the effects of 27 minutes of a full body, moderate-intensity resistance exercise circuit and 27 minutes of low-intensity aerobic treadmill exercise on

metabolic rate following exercise at 30, 60, and 90 minutes post-exercise. The resistance exercise circuit consisted of five different exercises performed at 60% 1RM, and the aerobic treadmill exercise was performed one week after the resistance bout and matched for the same $\dot{V}O_2$ performed during the resistance bout (1.55 L/min). The authors found that the resistance exercise circuit was responsible for a significantly greater metabolic rate following exercise at 30 minutes post-exercise than the aerobic exercise (19.0L vs 12.7L, $p < 0.05$). They also found that the resistance exercise circuit metabolic rate following exercise was significantly greater than baseline at 30, 60, and 90 minutes post-exercise, while the aerobic exercise session did not result in a metabolic rate following exercise that was significantly greater than baseline at 30, 60, or 90 minutes post-exercise. As shown in the previous literature [17, 18, 65], the lack of an elevated metabolic rate following exercise that was significantly greater than baseline following the aerobic exercise protocol may have been due to a combination of the relatively low intensity of the aerobic exercise (approximately 45% $\dot{V}O_{2max}$) as well as the short duration (27 minutes).

In a similar study, Greer et al. [16] examined the effects of isocaloric exercise sessions of a full-body resistance exercise circuit, steady-state aerobic exercise, and HIIT aerobic exercise on metabolic rate following exercise measured for 30 minute intervals at 12 and 21.5 hours post-exercise in 10 young men. These participants were not specifically resistance or aerobically trained, and were classified as “low to moderately physically active men [16].” The resistance exercise circuit was performed for 45 minutes at a moderate intensity (60% 1RM)

and consisted of five total circuits of full body exercises. One week after the resistance session, the steady state aerobic exercise was performed on a cycle ergometer at a low intensity ($39\% \dot{V}O_{2\text{peak}}$) and was ended when the total EE matched the EE from the resistance exercise circuit. One week after the steady state session, the HIIT aerobic exercise was performed on a cycle ergometer at high intensity ($90\% \dot{V}O_{2\text{peak}}$) for 30 seconds followed by low intensity (no resistance on cycle ergometer) for 120-180 seconds. The HIIT aerobic exercise was ended when total EE matched the total EE from both the resistance and steady state sessions.

As designed, exercise EE did not differ between trials, but the metabolic rate following the resistance and HIIT exercise sessions were significantly greater than the metabolic rate following steady state aerobic exercise session at both 12 and 21.5 hours post exercise. At 12 hours post exercise, both the resistance (Mean \pm SD = 58.0 ± 4.5 vs 50.0 ± 5.2 kcal, $p < 0.008$) and HIIT (Mean \pm SD = 62.0 ± 7.2 vs 50.0 ± 5.2 kcal, $p < 0.008$) protocols were responsible for a significantly greater EE than baseline, while the steady state protocol had no significant difference from baseline (Mean \pm SD = 50.0 ± 5.3 vs 50.0 ± 5.2 kcal, $p > 0.05$). Additionally, at 12 hours post-exercise the resistance and HIIT protocols had a significantly greater EE when compared to the steady state protocol. At 21.5 hours post exercise, only the resistance protocol had a significantly greater EE as compared to baseline (Mean \pm SD = 45.0 ± 4.4 vs 38.0 ± 3.4 kcal) and the steady state protocol (Mean \pm SD = 45.0 ± 4.4 vs 39.0 ± 5.8 kcal) [16]. Supplementary Table S1 has additional

studies that show the effects of resistance exercise and combined aerobic and resistance exercise on metabolic rate following exercise [14, 62, 90-96].

Additional Influences on Energy Expenditure

In addition to exercise mode, intensity, duration, and training status, other factors that influence EE following exercise exist. Hypothalamic regulation, glycogen saturation, and protein synthesis all have an influence on metabolic rate [97-106]. Following exercise, protein synthesis has been shown to increase to a greater extent than protein degradation, leading to an increased protein turnover and metabolic rate [101-103, 107, 108]. Additionally, glyconeogenesis from lactate following exercise is also responsible for an increase in EE [98]. Lastly, hypothalamic regulation regulates EE and energy homeostasis [97, 109, 110]. An in-depth review of these factors is beyond the scope of this literature review.

Conclusion

In conclusion, the consensus from the literature is that exercise EE of aerobic exercise is greater than the exercise EE of resistance exercise when matched for time and relative intensity. Regardless, resistance training is an important component of exercise program design, as many health benefits are associated with resistance training [111, 112]. Sedentary, obese individuals beginning an exercise regimen may have difficulty adhering to aerobic exercise programs due to low initial CRF, discomfort during the exercise, and low exercise tolerance [4, 18]. Because of these difficulties that may be encountered with aerobic exercise, resistance exercise may be a viable alternative for increasing physical activity, functional capacity, CRF, and EE [4, 71, 113] due to the protocols

that are generally shorter in the duration of activity performed than aerobic exercise protocols [71].

As shown in the literature, exercise EE is not the only component responsible for increasing TDEE via exercise. EPOC is also an important component to TDEE that can be responsible for 10-15% of total exercise EE, and is most influenced by exercise mode, duration, intensity, and training status. Resistance exercise is generally responsible for a longer elevation in metabolic rate following exercise than aerobic exercise, and high intensity and long duration of exercise results in a greater magnitude of increased metabolic rate following exercise. Additionally, training status has a large influence on metabolic rate following exercise, as resistance trained individuals have a shorter duration of elevated metabolic rate following resistance exercise than untrained individuals following resistance exercise, and aerobically-trained individuals have a shorter duration of elevated metabolic rate following aerobic exercise than untrained individuals following aerobic exercise.

In contrast to the majority of exercise-based weight loss programs that have relied solely on aerobic exercise due to greater exercise EE than resistance exercise [4], overall efficiency of increasing TDEE resulting from exercise needs to be considered when designing exercise regimens instead of only the exercise EE itself. A key component that should be considered when designing a training regimen for increasing TDEE is the training status of the individuals performing the regimen. For example, if a resistance trained individual needs to lose weight for athletic or health reasons, then performing aerobic exercise could possibly lead to

a greater duration and magnitude of elevated metabolic rate following exercise than if that individual continued to rely on resistance training for increasing TDEE, as his/her resistance training-induced adaptations could limit the amount of post-exercise EE [90]. Furthermore, performing both aerobic and resistance exercise may yield health benefits from both modes of exercise, in addition to increasing TDEE via exercise EE and elevated metabolic rate following exercise more than only performing one mode. In contrast, an aerobically-trained individual needing to lose weight for athletic or health reasons could benefit from performing resistance exercise or a combination of resistance and aerobic exercise for the same reasons mentioned above. Of course, if a sedentary individual is beginning an exercise-based weight loss regimen, then training status is an irrelevant consideration. However, because resistance training is a viable option for sedentary, obese individuals beginning exercise training, training status of said individual would be a relevant consideration for program design and modification after a few months of resistance training adherence.

Consider an 85kg recreationally active male who is looking to lose weight following his physician's recommendation. To be most efficient at increasing TDEE as well as receiving the health benefits of both aerobic and resistance training, he would benefit the most from adhering to a combined moderate-vigorous intensity aerobic ($\geq 70\% \dot{V}O_{2max}$) and resistance ($\geq 70\% 1RM$) training program. In doing so, as a result of exercise he would likely expend the largest amount of energy during aerobic exercise [72], second largest amount of energy during resistance exercise [15], third largest amount of energy during the hours/days following resistance

exercise (up to 72 hours) [14], and fourth largest amount of energy during the hours/days following aerobic exercise (up to 48 hours) [94]. In addition to a potentially extended elevated metabolic rate following exercise resulting from resistance exercise, another potential benefit would be an extended increase in fat oxidation following exercise [94, 96]. Therefore, by performing moderate-vigorous intensity aerobic exercise three days per week and moderate-vigorous intensity resistance exercise two days per week, this male would potentially have a substantial increase in TDEE via exercise EE from aerobic exercise in addition to the elevated metabolic rate following exercise from resistance exercise for all days of the week.

These findings are not only relevant to weight loss, but also optimal athletic performance. Energy balance is an important item to consider with training programs in athletes and military personnel, [2, 33-35] as a prolonged negative energy balance can lead to decreases in muscle mass, bone density, metabolic rate, and ultimately lead to injuries [36, 37]. Because exercise EE and RMR are major components of energy balance in active individuals, exercise mode must be considered when developing training regimens. Resistance training has both health and performance benefits in athletes and has an appropriate place in training program design [114, 115]. However, if the additional EE from the potentially increased metabolic rate following exercise is not addressed, negative energy balance and subsequently decreased performance and injury are possible.

Literature limitations

While the literature on EPOC resulting from continuous aerobic exercise is extensive, studies on EPOC resulting from HIIT and resistance exercise are lacking. Additionally, the literature is lacking on the effects of time-matched aerobic and resistance exercise of varying intensities on metabolic rate following exercise in resistance trained individuals. Furthermore, there is a lack of cross comparison of exercise and post-exercise EE between aerobic and resistance exercise sessions of different intensities between the same individuals, notably resistance trained individuals.

There are also a limited number of studies examining the effects of intense resistance exercise on metabolic rate following exercise. In their 2003 review, Børsheim and Bahr [17] call for more studies that examine the effect of intense exercise on metabolic rate following exercise since most existing studies were of low intensity. Lastly, the current literature on EPOC examines changes in group means and fails to address individual variability in analyses.

To date, no studies have examined the effect of both intense aerobic exercise and intense resistance exercise that are matched for time on exercise and post-exercise EE in resistance trained individuals. Also, no studies have examined the metabolic rate following exercise resulting from both intense aerobic exercise and intense resistance exercise that are matched for time in resistance trained individuals. Furthermore, no studies have examined the effect of aerobic and resistance exercise on different levels of combined exercise and post-exercise EE

Therefore, this study aimed to 1) examine differences in EE during five different exercise protocols of matched duration with different modes and intensities in resistance trained males, 2) examine differences in post-exercise EE during five different exercise protocols of matched duration with different modes and intensities in resistance trained males, and 3) examine which of the five different exercise protocols of matched duration contributes the most to TDEE when combining EE from exercise and post-exercise in resistance trained males. By examining the effects of exercise mode and intensity on EE during and after exercise, we may have a better understanding of how exercise can affect health and performance.

CHAPTER THREE

GENERAL METHODOLOGY

The study was a within-subjects, randomized trial consisting of a baseline laboratory visit and five supervised exercise trial visits.

Participants

Participants were eligible for participation if they were male, between the ages of 18 to 35 years, and resistance trained. Exclusion criteria included currently taking metabolism-altering medications and/or the presence of acute or chronic health conditions. Females were ineligible for participation in order to control for EE variations due to the hormonal fluctuations of the menstrual cycle [116]. Resistance trained was defined as participating in structured resistance exercise for ≥ 2 x/week for at least the consecutive six months prior to recruitment. All participants provided informed consent to participate in the study and all components of the study were approved by the University of South Carolina Institutional Review Board. A total of 14 participants enrolled in the study and 10 completed the baseline visit and all five exercise visits.

Baseline visit

At the baseline visit, height was measured with a wall-mounted stadiometer (Model S100, Ayerton Corp., Prior Lake, MN) according to ACSM standards [117]. Body mass was measured twice in a row with an electronic scale (Healthometer model 500 KL, McCook, IL) with the participants wearing only exercise clothes with

empty pockets and bare feet. Participants' blood pressure was taken manually with a mercury column sphygmomanometer (American Diagnostic Corporation, Hauppauge, NY) and stethoscope (3M Littmann classic, St. Paul, MN) at the antecubital fossa of the right arm after resting for five minutes in the seated position. A total body composition scan was performed with a Lunar fan-beam dual energy X-ray absorptiometry (DXA) scanner (GE Healthcare model 8743, Waukesha, WI). Immediately following anthropometric measurements, participants completed full-body 12-repetition maximum (12RM) testing on six resistance exercise machines. The exercises performed in order were leg press, leg curl, leg extension, chest press, lat pulldown, and shoulder press. Participants were asked for their approximate 12RM prior to performing each exercise and based on the self-perceived 12RM of the participant, a load equating to approximately 50% of their 12RM was loaded on the resistance exercise machine and performed for 12 repetitions. Upon completion of 50% 12RM, the load was increased to 80% self-perceived 12RM and was performed for 12 repetitions. The load was then gradually increased until the participant could maximally perform 12 repetitions to momentary muscular failure. A two-minute rest period was provided between each 12RM attempt. Further, two minutes rest was provided between completion of the previous 12RM test and beginning the next, and the same process was performed for all six resistance exercise machines. The 12RMs achieved were used to determine the load for each participant's resistance exercise sessions. The 12RM equates to approximately 70% one-repetition maximum (1RM) [118].

Upon completion of the 12RM testing, participants rested for 20 minutes before completing a maximal graded exercise test (GXT) to determine cardiorespiratory fitness (CRF), as measured by $\dot{V}O_{2max}$. The GXT was performed on a motorized treadmill (h/p/cosmos, Nußdorf, Germany) using a COSMED K4b² (COSMED USA Inc., Chicago, IL) metabolic analyzer for the measurement of $\dot{V}O_2$ and associated respiratory data. The COSMED K4b² has been validated and shown to be a reliable measure of $\dot{V}O_2$ and EE elsewhere [52, 54, 119-122]. The COSMED K4b² was calibrated prior to each measurement using the manufacturer's protocol. The GXT protocol can be seen in **Table 3.1** and consisted of a three-minute warmup walking stage at 3.5 mph and 0% grade, followed by a two-minute running stage where the speed increased to 7.0 mph and remained there for the remainder of the test. Each subsequent stage was one-minute in length and increased in two percent grade from each previous stage. Participants performed the GXT until volitional exhaustion. Criteria for $\dot{V}O_{2max}$ included a plateau in $\dot{V}O_2$ which was defined as any two 30-second $\dot{V}O_2$ values in which the second was not higher than the first, provided increase in ventilation at maximal effort [123], a respiratory exchange ratio ≥ 1.15 , and maximum heart rate ± 10 beats per minute of age predicted value ($208 - (0.67 * \text{age})$). Of the 14 participants, 12 met $\dot{V}O_{2max}$ using all three criteria while the other two participants met two. The $\dot{V}O_{2max}$ achieved on the GXT was used to determine the intensity for each participant's aerobic exercise sessions using the ACSM metabolic equations [124]. Baseline testing order followed the testing battery specifications of the National Strength and Conditioning Association [115].

Exercise sessions

Participants were assigned to complete five separate, time-matched, varying intensity exercise sessions in random order. The five exercise protocols consisted of two aerobic exercises and three resistance exercise and are described in **Table 3.2**. The aerobic exercise visits consisted of a continuous aerobic exercise protocol performed at 70-80% $\dot{V}O_{2max}$ and a 4x4 HIIT exercise protocol with the 4-minute high intensity bouts performed at 85-95% $\dot{V}O_{2max}$ and the 4-minute active rest bouts performed at 60-70% $\dot{V}O_{2max}$. The resistance exercise visits consisted of a strength-endurance protocol (2x20), a traditional hypertrophy protocol (3x10), and a high-intensity strength protocol (4x6). Each of the resistance exercise visits included the exercises of leg press, leg curl, leg extension, chest press, lat pulldown, and shoulder press performed at varying intensities. The 2x20 protocol was performed at 75% of 12RM (~55% 1RM) for two sets of 20 repetitions for each exercise, the 3x10 protocol was performed at 100% of 12RM (~70% 1RM) for three sets of 10 repetitions each exercise, and the 4x6 protocol was performed at 125% 12RM (~85% 1RM) for four sets of six repetitions each exercise. In addition to being matched for total time, all resistance exercise protocols were matched for total volume of weight moved. To represent total body muscular strength, the 12RMs from all six exercises were averaged together into the total body average 12RM. All 12RM values hereafter refer to total body average 12RM.

Participants were asked to refrain from vigorous exercise for 24 hours, as well as to fast for two hours prior to each laboratory visit. Additionally, participants

were asked to replicate their usual diets for the 24 hours preceding each laboratory visit. Upon arrival to the laboratory, baseline EE was measured for 30 minutes while participants laid undisturbed in a quiet room in the supine position. Following the baseline measurement, participants began the 60-minute exercise session with a 10-minute treadmill warmup at 3.5 mph and 0% grade. Participants then performed 40 minutes of aerobic or resistance exercise and completed the session with a 10-minute treadmill cool-down at 3.5 mph and 0% grade. During each exercise session, participants were monitored and proper form was ensured. For the 30 minutes immediately post-exercise, EE was measured in the same manner as the baseline EE measurement. For the 30 minutes following the immediately post-exercise EE measurement (minutes 30-60 post-exercise), participants removed the COSMED K4b² metabolic analyzer and completed a 24-hour diet recall (ASA24™, National Cancer Institute) while seated and in the same room as the resting EE measurements. For the 30 minutes after the diet recall (minutes 60-90 post-exercise), delayed post-exercise EE was measured in the same manner as the baseline and immediately post-exercise EE measurements. An overview of each laboratory visit is displayed in **Table 3.2** and all EE measurements were taken with the COSMED K4b².

Statistical Analyses

Preliminary data processing. All EE data were collected in a breath-by-breath manner. Due to the variations in breathing frequencies among participants, all respiratory data were averaged into 15-second epochs to standardize the number of data points. The first seven minutes of the immediately post-exercise

EE measurement were eliminated from analyses, as participants were then permitted to hydrate and use the restroom. The baseline and delayed post-exercise measurements were also truncated to 20 minutes (minutes seven to 27) for analysis to time-match the immediately post-exercise measurement.

Repeated measures ANOVA was used to examine the differences in exercise EE (outcome variable) between the HIIT, Continuous, 2x20, 3x10, and 4x6 exercise sessions (independent variables/conditions) using SPSS v24 (IBM Corp., Armonk, NY). The model consisted of five conditions (one for each exercise session) with 50 total observations ($n=10$). Pearson correlations between all independent variables and the outcome were examined. Mass was the only descriptive variable to have a significant ($p<0.05$) correlation with exercise EE for each exercise protocol and was subsequently included in the model as a covariate. Model diagnostics were applied to assess the normality assumptions and Mauchly's test of sphericity was used to test the assumption of sphericity of variances. The Bonferroni correction was used for post-hoc pairwise comparisons.

The following analyses were conducted using R version 3.2.4 [125]. Statistical significance was set at the 0.05 level in all analyses. To compare post-exercise EE to baseline EE, a one-way functional ANOVA for repeated measurements was used [126]. Functional ANOVA is used when the responses are continuous functions (i.e. curves) and can be used to test for differences in temporal activity in two or more groups. Functional ANOVA has many advantages, including an absence of restrictive assumptions since all tests are permutation-based and effectiveness in analysis of studies with small sample size [127-129].

In our study, the outcomes (EE in kcal/min) were functions of time during the baseline, immediately post-exercise, and delayed post-exercise time periods. The immediately post-exercise and delayed post-exercise EE were compared to baseline EE as the reference. The R package `fdaMixed` was used for the functional ANOVA analysis.

To compare total measured EE across the five exercise sessions, quantile regression was used. Quantile regression is a statistical regression method that allows examination at multiple points in the conditional distribution of the outcome rather than solely at the mean as with linear regression. Quantile regression is robust to outliers and requires no assumption on the distribution of the errors. Therefore, it can be applied when the errors are skewed or heavy tailed, resulting in greater statistical efficiency than mean regression [130]. Lastly, the estimator of quantile regression coefficients is consistent in the presence of cluster dependency [131], hence standard errors can be calculated by means of block bootstrap. Alternatively, clustering can be accounted for by random effects [132].

We examined the 25th and 75th centiles of total measured EE with body mass (kg), total body average 12RM (kg), $\dot{V}O_{2\max}$ (L/min), and baseline EE (kcal) as covariates. Since we aimed to examine group-level and not individual-level estimates, we fitted models using the `quantreg` package for standard quantile regression and estimated standard errors via block bootstrap. However, in a separate analysis (results not shown), we also fitted linear quantile mixed models using the R package `lqmm` [133]. Standard errors were in general smaller than those obtained using block bootstrap, therefore our conclusions are conservative.

Table 3.1. Treadmill Graded Exercise Test Protocol.

Time (minutes)	Stage	Speed (mph)	Grade (%)
0	1	3.5	0
1		3.5	0
2		3.5	0
3	2	7.0	0
4		7.0	0
5	3	7.0	2
6	4	7.0	4
7	5	7.0	6
8	6	7.0	8
9	7	7.0	10
10	8	7.0	12
11	9	7.0	14
12	10	7.0	16
13	11	7.0	18
14	12	7.0	20

Table 3.2. Overview of exercise protocols completed in random order.

Time	Moderate-intensity continuous aerobic exercise	High-intensity interval aerobic exercise	Strength endurance exercise †	Traditional resistance exercise †	High-intensity resistance exercise †
0-30 min *	Baseline resting measurement				
30-40 min *	Warm-up: Walking at 3.5 mph and 0% incline				
40-80 min *	Walking or Jogging at 70-80% of $\dot{V}O_{2max}$	5 sets of: 4 min at 60-70% $\dot{V}O_{2max}$ followed by 4 min at 85-95% $\dot{V}O_{2max}$	2 sets of 20 repetitions at 75% of 12 RM: <i>Leg Press; Leg Curl; Leg Extension; Lat Pulldown; Chest Press; Shoulder Press</i>	3 sets of 10 repetitions at 100% of 12 RM: <i>Leg Press; Leg Curl; Leg Extension; Lat Pulldown; Chest Press; Shoulder Press</i>	4 sets of 6 repetitions at 125% of 12 RM: <i>Leg Press; Leg Curl; Leg Extension; Lat Pulldown; Chest Press; Shoulder Press</i>
80-90 min *	Cool-down: Walking at 3.5 mph and 0% incline				
90-120 min *	Immediately post-exercise resting measurement				
120-150 min	Completion of online diet recall (ASA24™)				
150-180 min *	Delayed post-exercise resting measurement				

* energy expenditure measured via indirect calorimetry (COSMED K4b²)

† participants had 6 minutes to complete the required sets for each exercise and 48 seconds to transition from one resistance machine to the next; protocols are matched for total weight moved during each exercise

CHAPTER FOUR

THE EFFECTS OF EXERCISE MODE AND INTENSITY ON
ENERGY EXPENDITURE DURING AND AFTER EXERCISE IN
RESISTANCE TRAINED MALES¹

¹ Grieve GL, Davis JM, Durstine JL, Geraci M, Wang X, Ritchey JS, Drenowatz C, Sarzynski MA. To be submitted.

Introduction

Energy balance is modeled as the balance between energy intake and energy expenditure (EE). Total daily energy intake consists of energy that is consumed in a 24-hour period, while total daily EE consists of energy expended from resting metabolic rate, thermic effect of food, exercise, and habitual physical activity [4]. Energy balance is an important factor of health and performance in active and training populations such as athletes and military because in these populations, negative energy balance can lead to excessive weight loss, injuries, immunosuppression, hormonal imbalance, and/or poor performance [2, 30-33, 134-138]. Given the importance of energy balance in athletes and military populations, both energy intake and expenditure need to be accurately monitored and regulated to ensure optimal health and performance [2].

The 2008 United States Physical Activity Guidelines recommend a combination of both regular aerobic and resistance exercise for health benefits [139]. The effects of aerobic exercise on EE are well established, while the effects of resistance exercise on EE are not fully understood. Aerobic exercise is generally responsible for a higher EE than resistance exercise of similar duration [140]. Recently, much attention is given to high-intensity interval training (HIIT) aerobic exercise as a supplement/replacement for moderate-intensity continuous training (continuous) in order to achieve a greater EE in a shorter period of time. However, most aerobic exercise and training studies have not matched the time of HIIT and continuous bouts when comparing the two protocols, leaving unknown how the EE of the two protocols compare when matched for time [69].

Following exercise, oxygen consumption and metabolic rate are typically elevated above a basal level, which is known as excess post-exercise oxygen consumption (EPOC) [13]. The magnitude of EPOC can be positively affected by exercise intensity, volume, duration, as well as mode with resistance exercise generally resulting in a greater EPOC than aerobic exercise [17, 18, 63, 80, 141]. Additionally, training status has been shown to influence EPOC, with untrained individuals having a higher EPOC than trained individuals [14, 17]. The majority of studies that have examined EPOC have done so in recreationally-active males following either aerobic or resistance exercise. If the EPOC is not considered in calculating total daily EE, then an energy deficit may occur, subsequently leading to negative health outcomes. Because of many factors that influence EPOC and total daily EE, a better understanding of EPOC must be gained in order to ensure that an energy deficit does not occur.

To date, no study has examined the differences in exercise EE and post-exercise EE among various aerobic and resistance exercise protocols of similar duration. Given the elevations of EE during and after exercise and the effect on energy balance, such information would be valuable for developing future exercise training, recovery, and dietary programs. Therefore, the aims of this study were to compare 1) EE during exercise, 2) EE after exercise (i.e., EPOC), and 3) total EE during and after exercise across 5 different exercise sessions in resistance trained individuals. These aims were evaluated within individuals across the five following protocols: strength endurance resistance (2x20), traditional resistance (3x10), high-intensity resistance (4x6), HIIT aerobic, and continuous aerobic exercise

protocols. We hypothesized that 1) when matched for time, aerobic exercise would result in greater EE during exercise than resistance exercise, 2) the post-exercise EE from resistance exercise would be greater than aerobic exercise, and 3) the total measured EE during and after aerobic exercise would be greater than the total measured EE during and after resistance exercise.

Methods

The study was a within-subjects, randomized trial consisting of a baseline laboratory visit and five supervised exercise trial visits.

Participants

Participants were eligible for participation if they were male, between the ages of 18 to 35 years, and resistance trained. Exclusion criteria included currently taking metabolism-altering medications and/or the presence of acute or chronic health conditions. Females were ineligible for participation in order to eliminate EE variations due to menstrual cycle hormonal fluctuations [116]. Resistance trained was defined as participating in structured resistance exercise for ≥ 2 x/week for at least the consecutive 6 months prior to recruitment. All participants provided informed consent to participate in the study and all components of the study were approved by the University of South Carolina Institutional Review Board. A total of 14 participants enrolled in the study, and ten subjects completed the baseline visit and all five exercise visits.

Baseline visit

At the baseline visit, a total body composition scan was performed with a Lunar fan-beam dual energy X-ray absorptiometry (DXA) scanner (GE Healthcare model 8743, Waukesha, WI). Immediately following anthropometric measurements, participants completed full-body 12-repetition maximum (12RM) testing on six resistance exercise machines. The exercises performed in order were leg press, leg curl, leg extension, chest press, lat pulldown, and shoulder press. Participants were asked for their approximate 12RM prior to performing each exercise and based on the self-perceived 12RM of the participant, a weight equating to approximately 50% of their 12RM was loaded on the resistance exercise machine, and subjects completed 12 repetitions. Upon completion of 50% 12RM, the weight was increased to 80% self-perceived 12RM, and again the subject completed 12 repetitions. The weight was gradually increased until the participant could maximally perform 12 repetitions to muscular failure. A two-minute rest period was provided between each 12RM attempt. Further, two minutes of rest was provided between completion of the previous 12RM test and beginning the next 12RM set, and the same process was performed for all six resistance exercise machines. The weight achieved for each 12RMs were used to determine the load for each participant's resistance exercise sessions. The 12RM equates to approximately 70% one-repetition maximum (1RM) [118].

Upon completion of the 12RM testing, participants rested for 20 minutes before completing a maximal graded exercise test (GXT) to determine cardiorespiratory fitness (CRF) and maximal oxygen consumption ($\dot{V}O_{2max}$). The

GXT was performed on a motorized treadmill (h/p/cosmos, Nußdorf, Germany) using a COSMED K4b² (COSMED USA Inc., Chicago, IL) metabolic analyzer for the measurement of $\dot{V}O_2$ and associated respiratory data. The COSMED K4b² has been validated and shown to be a reliable measure of $\dot{V}O_2$ and EE elsewhere [52, 54, 119-122]. The COSMED K4b² was calibrated prior to each measurement using the manufacturer's protocol. Participants performed the GXT until volitional exhaustion. Criteria for $\dot{V}O_{2max}$ included a plateau in $\dot{V}O_2$ which was defined as any two 30-second $\dot{V}O_2$ values in which the second was not higher than the first, provided increase in ventilation at maximal effort [123], a respiratory exchange ratio ≥ 1.15 , and maximum heart rate ± 10 beats per minute of age predicted value ($208 - (0.67 * \text{age})$). Of the 14 participants, 12 met $\dot{V}O_{2max}$ using all three criteria while the other two participants met two. The $\dot{V}O_{2max}$ achieved on the GXT was used to determine the intensity for each participant's aerobic exercise sessions using the ACSM metabolic equations [124]. Baseline testing order followed the testing battery specifications of the National Strength and Conditioning Association [115].

Exercise sessions

Participants were assigned to complete five separate, time-matched, varying intensity exercise sessions in random order. The five exercise protocols consisted of two aerobic exercise protocols and three resistance exercise protocols and are described in **Table 4.1**. The aerobic exercise visits consisted of a continuous aerobic exercise protocol performed at 70-80% $\dot{V}O_{2max}$ and a 4x4 HIIT exercise protocol with the 4-minute high intensity periods performed at 85-

95% $\dot{V}O_{2max}$ and the 4-minute active rest periods performed at 60-70% $\dot{V}O_{2max}$. The resistance exercise visits consisted of a strength-endurance resistance protocol (2x20), a traditional hypertrophy resistance protocol (3x10), and a high-intensity strength resistance protocol (4x6). Each of the resistance exercise visits included the exercises of leg press, leg curl, leg extension, chest press, lat pulldown, and shoulder press performed at varying intensities. The 2x20 resistance protocol was performed at 75% of 12RM (~55% 1RM) for two sets of 20 repetitions for each exercise, the 3x10 resistance protocol was performed at 100% of 12RM (~70% 1RM) for three sets of 10 repetitions each exercise, and the 4x6 resistance protocol was performed at 125% 12RM (~85% 1RM) for four sets of six repetitions each exercise. In addition to being matched for total time, all resistance exercise protocols were matched for total volume of weight moved. To represent total body muscular strength, the 12RMs from all six exercises were averaged together into the total body average 12RM. All 12RM values hereafter refer to total body average 12RM.

Participants were asked to refrain from vigorous exercise for the prior 24-hour period as well as to refrain from food intake for two hours prior to each laboratory visit. Additionally, participants were asked to replicate their usual diets for the 24 hours preceding each laboratory visit. Upon arrival to the laboratory, baseline EE was measured for 30 minutes while participants laid undisturbed in a quiet room in the supine position. Following the baseline measurement, participants began the 60-minute exercise session with a 10-minute treadmill warmup at 3.5 mph and 0% grade. Participants then performed 40 minutes of

aerobic or resistance exercise and completed the session with a 10-minute treadmill cool-down at 3.5 mph and 0% grade. For the 30 minutes immediately post-exercise, EE was measured in the same manner as the baseline EE measurement. For the 30 minutes following the immediately post-exercise EE measurement (minutes 30-60 post-exercise), participants removed the COSMED K4b² metabolic analyzer and completed a 24-hour diet recall (ASA24™, National Cancer Institute) while seated and in the same room as the resting EE measurements. For the 30 minutes after the diet recall (minutes 60-90 post-exercise), delayed post-exercise EE was measured in the same manner as the baseline and immediately post-exercise EE measurements. An overview of each laboratory visit is displayed in **Table 4.1** and all EE measurements were taken with the COSMED K4b².

Statistical Analyses

Preliminary data processing. All EE data were collected in a breath-by-breath manner. Due to the variations in breathing frequencies among participants, all respiratory data were averaged into 15-second epochs to standardize the number of data points. The first seven minutes of the immediately post-exercise EE measurement were eliminated from analyses, as participants were then permitted to hydrate and use the restroom. The baseline and delayed post-exercise measurements were also truncated to 20 minutes (minutes seven to 27) for analysis to time-match the immediately post-exercise measurement.

Repeated measures ANOVA was used to examine the differences in exercise EE (outcome variable) between the HIIT, Continuous, 2x20, 3x10, and

4x6 exercise sessions (independent variables/conditions) using SPSS v24 (IBM Corp., Armonk, NY). The model consisted of five conditions (one for each exercise session) with 50 total observations ($n=10$). Pearson correlations between all independent variables and the outcome were examined. Mass was the only descriptive variable to have a significant ($p<0.05$) correlation with exercise EE for each exercise protocol and was subsequently included in the model as a covariate. Model diagnostics were applied to assess the normality assumptions and Mauchly's test of sphericity was used to test the assumption of sphericity of variances. The Bonferroni correction was used for post-hoc pairwise comparisons.

The following analyses were conducted using R version 3.2.4 [125]. Statistical significance was set at the 0.05 level in all analyses. To compare post-exercise EE to baseline EE, a one-way functional ANOVA for repeated measurements was used [126]. Functional ANOVA is used when the responses are continuous functions (i.e. curves) and can be used to test for differences in temporal activity in two or more groups. Functional ANOVA has many advantages, including an absence of restrictive assumptions since all tests are permutation-based and effectiveness in analysis of studies with small sample size [127-129]. In our study, the outcomes (EE in kcal/min) were functions of time during the baseline, immediately post-exercise, and delayed post-exercise time periods. The immediately post-exercise and delayed post-exercise EE were compared to baseline EE as the reference. The R package `fdaMixed` was used for the functional ANOVA analysis.

To compare total measured EE during and after exercise (i.e., sum of EE measured during exercise, immediately post-exercise, and delayed post-exercise) across the five exercise sessions, quantile regression was used. Quantile regression is a statistical regression method that allows examination at multiple points in the conditional distribution of the outcome rather than solely at the mean as with linear regression. Quantile regression is robust to outliers and requires no assumption on the distribution of the errors. Therefore, it can be applied when the errors are skewed or heavy tailed, resulting in greater statistical efficiency than mean regression [130]. Lastly, the estimator of quantile regression coefficients is consistent in the presence of cluster dependency [131], hence standard errors can be calculated by means of block bootstrap. Alternatively, clustering can be accounted for by random effects [132].

We examined the 25th and 75th centiles of total measured EE with body mass (kg), total body average 12RM (kg), $\dot{V}O_{2max}$ (L/min), and baseline EE (kcal) as covariates. Since we aimed to examine group-level and not individual-level estimates, we fitted models using the `quantreg` package for standard quantile regression and estimated standard errors via block bootstrap. However, in a separate analysis (results not shown), we also fitted linear quantile mixed models using the R package `lqmm` [133]. Standard errors were in general smaller than those obtained using block bootstrap, therefore our conclusions are conservative.

Results

Participant characteristics are found in **Table 4.2** while the mean percentage of each exercise protocol completed is found in **Table 4.3**. On average, participants expended 67 ± 8 kcal less during the 2x20 resistance exercise protocol compared to the 4x6 resistance exercise protocol ($p < 0.001$), while there was no difference in exercise EE between the 2x20 and 3x10 resistance exercise protocols ($p = 0.17$) (**Figure 4.1**). The average exercise EE during the 3x10 resistance exercise protocol was 38 ± 10 kcal less than the 4x6 resistance exercise protocol ($p = 0.04$). No difference in exercise EE between the continuous and HIIT aerobic exercise protocols ($p = 1.0$) was found. The exercise EE during both the HIIT and continuous aerobic protocols were significantly greater than all three resistance exercise protocols ($p < 0.0001$) (**Figure 4.1**).

Differences in post-exercise EE between protocols are shown in **Figure 4.2**. In the 2x20 resistance protocol, the group mean EE immediately post-exercise was 6.19% greater than the baseline ($p < 0.05$). No significant differences in EE between baseline and immediately post-exercise in the other four protocols were found. When comparing the EE at baseline to delayed post-exercise, the group mean EE at delayed post-exercise was 10.65% less in the 3x10 resistance protocol, 8.70% less in the 4x6 resistance protocol, and 7.14% less in the HIIT protocol with all values $p < 0.05$ compared to baseline.

Differences between centiles of total measured EE during and after exercise can be seen in **Figure 4.3**. When examining differences in total measured EE during and after exercise between centiles in an unadjusted model at the 25th

centile of total measured EE during and after exercise, no significant differences were found between the three resistance exercise protocols or between the two aerobic exercise protocols. Both aerobic exercise protocols had significantly greater ($p < 0.0001$) total measured EE during and after exercise than all three resistance exercise protocols at the 25th centile. Similarly, at the 75th centile, no significant differences were found between the two aerobic exercise protocols, but the total measured EE during and after exercise of the 4x6 resistance protocol was 76 ± 30 kcal ($p = 0.009$) greater than the 2x20 resistance protocol. No significant effects of body mass, baseline EE, and $\dot{V}O_{2max}$, were found at the 25th centile of total measured EE during and after exercise, whereas at the 75th centile, 12RM had a significant effect on total measured EE during and after exercise ($\beta = 0.89$, $p = 0.02$). Reductions in EE were observed in the post-exercise measurement periods as compared to baseline following the 3x10 and 4x6 resistance protocol and HIIT protocols, but total measured EE during and after exercise resulted in the same rank order as exercise EE across the five exercise protocols (from least to greatest: resistance 2x20, resistance 3x10, resistance 4x6, HIIT, and continuous). However, the total measured EE during and after exercise from the 3x10 resistance protocol was not significantly different ($p = 0.10$) from the 2x20 resistance protocol.

Discussion

Main findings

When examining differences in exercise EE across varying aerobic and resistance exercises, our hypothesis was supported that the aerobic exercise protocols would result in a greater EE than resistance exercise protocols. No differences were seen in exercise EE between the HIIT and continuous aerobic protocols. Additionally, the 4x6 resistance exercise protocol resulted in a greater exercise EE than the 3x10 and 2x20 resistance exercise protocols. Thus, the intensity of resistance exercise was positively associated with exercise EE, despite only an average of $97.21 \pm 4.54\%$ completion in the 3x10 protocol and $89.87 \pm 10.50\%$ completion in the 4x6 protocol.

In the examination of total measured EE during and after exercise, our hypothesis was supported that aerobic exercise would contribute the most to total measured EE during and after exercise. In unadjusted quantile regression analysis, at the 25th centile of total measured EE during and after exercise, both HIIT and continuous were significantly greater than the resistance exercise protocols and no significant differences were seen between resistance exercise protocols. At the 75th centile of total measured EE during and after exercise, both HIIT and continuous were again significantly greater than the resistance exercise protocols, and no significant differences were seen between 2x20 and 3x10, but 4x6 was significantly greater than 2x20. Interestingly, independent of mass, baseline EE, and $\dot{V}O_{2max}$, 12RM had a significant positive effect on total measured EE during and after exercise at the 75th centile but not at the 25th centile. We found

three protocols (3x10, 4x6, and HIIT) that had reductions in post-exercise EE, yet this did not change the rank order of EE that was seen during exercise. Therefore, exercise EE was the greatest contributor to total measured EE during and after exercise.

When examining differences in post-exercise EE across the five protocols, our hypothesis was not fully supported. A significant increase in EE was seen in the immediately post-exercise measurement period in the 2x20 protocol, but EE returned to baseline in the delayed post-exercise measurement period. No significant increase in EE was seen following the continuous aerobic protocol. Interestingly, when compared to baseline, average decreases in EE of 10.65%, 8.70%, and 7.14% were seen in the delayed post-exercise measurement period (60-90 min after exercise) for the 3x10, 4x6, and HIIT protocols, respectively.

Previous studies have shown an increase in post-exercise EE following resistance exercise [16-18, 63, 91]. Hackney et al. [14] examined the effects of full body resistance exercise with 2,000 kg and 2,500 kg load volumes performed for 8 sets of 6 repetitions with emphasized eccentric contractions on post-exercise metabolic rate in resistance trained and untrained males. It was found that at 24, 48, and 72 hours post-exercise, metabolic rate was significantly greater than baseline in both trained and untrained groups. Hackney et al. [14] stated that the elevations in metabolic rate may have been due to the muscle repair process resulting from muscle damage instigated by the protocol, specifically the volume and emphasis on eccentric contractions. The authors did note that feeding was not controlled before and immediately after the resistance protocols and that may have

affected metabolic rate. Abboud et al. [90] examined the effects of 10,000 kg and 20,000 kg resistance exercise load volumes at 85% 1RM on exercise EE and post-exercise metabolic rate in resistance trained males and did not see an increase in metabolic rate from 12 to 48 hours post-exercise. They attributed this to the training status of the participants, where the load volume was not enough of a stimulus to instigate a significant level of protein synthesis and tissue repair. The participants in our study were of a similar training status and strength of the participants examined by Hackney et al. [14] and Abboud et al. [90]. Therefore, the difference in our results is unlikely due to training status, as well as load volume, as our average load volume of approximately 17,000 kg was similar to the load volume used by Abboud et al. [90]. Differences in post-exercise EE may be due to differences in feeding among protocols, as in previous studies, the participants were free living between post-exercise measurement periods and could feed freely. Additionally, it is unknown whether the content of participants' diets influenced the metabolic rate up to 72 hours post-exercise.

No change in post-exercise metabolic rate was seen following the continuous aerobic protocol, which was similar in both intensity and duration to previously used moderate intensity continuous exercise protocols [17, 18, 80, 83]. Reviews on EPOC by Børsheim and Bahr [17], as well as Laforgia et al. [18] found that short-duration, low- to moderate- intensity aerobic exercise (<30 min at <80% $\dot{V}O_{2max}$) results in a short-lasting EPOC (<40 minutes). Additionally, longer duration aerobic exercise performed at moderate- to high- intensity (≥ 50 min at $\geq 70\%$ $\dot{V}O_{2max}$) results in a long-lasting EPOC (3 - 24 hours). In our study, we saw no

elevation in post-exercise metabolic rate following the continuous aerobic protocol (0-30 min or 60-90 min), despite the duration of 40 minutes and moderate intensity (70-80% $\dot{V}O_{2max}$). Bahr and Sejersted [142] examined the effects of exercise and feeding on EPOC in untrained males following 80 minutes of cycling at 75% $\dot{V}O_{2max}$. EPOC was measured incrementally up to 7 hours post exercise, and they concluded that the slow component of EPOC was present in the fasted state. Bahr and Sejersted [142] acknowledged that energy-sparing mechanisms in highly-trained participants may affect post-exercise metabolic rate, which is why they chose to examine untrained subjects. Our study examined the effects of 40 minutes of aerobic exercise at 70-80% $\dot{V}O_{2max}$, but with resistance trained males. It appears that the training status of our participants may have influenced the post-exercise EE, despite being in a semi-fasted state. Our protocol was different from the protocols used by Bahr and Sejersted [142] in that our duration was shorter (40 min vs 80 min), we examined specifically resistance trained males in contrast to untrained males, in addition to an extended period of refraining from food (~4 hours) prior to exercise. Previous studies examining post-exercise metabolic rate largely have not controlled for diet, but among those where diet was controlled, results have been equivocal. Resistance exercise has been shown to result in a greater post-exercise fat oxidation than aerobic exercise [96]. Thus, of the protocols in our study that resulted in a reduced post-exercise metabolic rate, the intensity and volume in the 3x10 and 4x6 resistance protocols combined with a prolonged lack of feeding may explain why a lower post-exercise metabolic rate was observed compared to the other protocols. Furthermore, glycogen depleting

exercise has been shown to increase fat oxidation post-exercise and that glycogen resynthesis is a metabolic priority following exercise [143]. In our study, it is possible that the extended lack of feeding in addition to the training status of our participants were reasons for a lack of elevated metabolic rate following exercise.

The reduced EE as compared to baseline following the 3x10, 4x6, and HIIT protocols may be partially explained by the constrained total EE model described by Pontzer et al. [144, 145], where total daily EE is maintained within a specific range or at a set point. As shown in both human and animal studies, when PA metabolic activity increases, decreases in non-physical activity metabolic activity can occur as a means of maintaining total EE under a maximal daily amount (**Figure 4.4B**). This is in contrast to the additive total EE model, where non-physical activity metabolic activity is not altered by an increase in total daily EE resulting from an increase in physical activity (**Figure 4.4A**) [144, 145]. Following the logic of the constrained total EE model, a possible explanation for the reduced EE following the 3x10, 4x6, and HIIT exercise protocols is that the combination of the intensity, volume, and exercise EE of the exercise protocols exceeded the total EE set point of the participants, and therefore resulted in a reduced EE following exercise. Additionally, considering that the participants had already fasted for at least four hours prior to arrival as verified with verbal questioning and dietary recall at each visit, once delayed-post exercise EE was measured, a total of approximately eight hours had passed since the participants last fed. Thus, in combination with the energy expended as well as potential muscle damage and glycogen depletion induced during each exercise protocol, it is possible that the

non-physical activity metabolic activity decreased to compensate for the prolonged absence of feeding, high level of EE, and metabolic demand of tissue repair and glycogen resynthesis. This reduction in EE may have been due to the greater difficulty of the 3x10, 4x6, and HIIT protocols as compared to the 2x20 and continuous. Of the resistance protocols, the 3x10 and 4x6 protocols had lower average percentage of completion as compared to the 2x20 protocol, and of the aerobic protocols, the HIIT protocol had a lower percentage of completion than the continuous protocol, indicating a greater difficulty. Additionally, a greater load volume was performed in the 3x10 resistance protocol ($97.21 \pm 4.54\%$ of total) compared to the 4x6 resistance protocol ($89.87 \pm 10.50\%$ of total), which could partially explain the greater reduction of EE following the 3x10 protocol than the 4x6 protocol, despite the lower intensity.

Strengths

Strengths of our study include the randomized within-subjects design and each of the trials conducted in a controlled clinical setting. To our knowledge, this was the first study to examine differences in EE in time-matched aerobic and resistance protocols in resistance trained males in addition to matching the duration of the HIIT and continuous aerobic protocols, a design component that has been inconsistent in the literature [69]. Additionally, our study was the first to quantify the EE of full body resistance protocols of varying intensities that were matched for both duration and total volume using indirect calorimetry. Lastly, this study was the first to implement consistent time-matched post-exercise EE

measurement periods across both aerobic and resistance exercise protocols of varying intensity in the same individuals.

Limitations

This study is not without limitations. First, the small sample size and lack of generalizability are limitations, as the present study only included resistance trained males. Secondly, within the resistance exercise protocols, the rest periods between sets were inconsistent between protocols. This was due to the allotment of 6 minutes for all sets of each exercise to be performed within the total 40 minutes of exercise. The length of time varied to complete sets of different repetitions and subsequently rest periods were extended on the 2x20 protocol and decreased on the 3x10 and 4x6 protocols. Farinatti [60] showed that shorter between-set rest intervals can positively influence the first few minutes of post-exercise metabolic rate compared to longer rest intervals. Due to the time-matched design of our study, we were unable to match the between-set rest intervals. Additionally, in our study, the fast component of post-exercise metabolic rate (minutes 0 – 7 immediately post-exercise) (minutes 90-97) was not captured, as participants could remove the COSMED K4b² for the seven minutes immediately after exercise to hydrate and use the restroom. Therefore, the magnitude and rate of decline of post-exercise metabolic rate during this period is unknown. Time differences in rest intervals between protocols may have affected the fast component of post-exercise metabolic rate, but Farinatti [60] showed that differences in rest intervals did not influence total EE. Although we were unable to match the between-set rest intervals, it is unlikely that our presented results were confounded.

Third, although matched for total time, the aerobic and resistance exercise protocols were not equally matched for total work. The resistance exercise protocols required approximately 85% of the total work of the aerobic exercise protocols. However, due to the difficulty level and load volume of the resistance exercise protocols and inability for all participants to complete the prescribed volume, it is very unlikely that participants would have been able to complete the sessions if the work was greater and subsequently matched with the aerobic sessions. Conversely, decreasing the work of the aerobic sessions via a reduction in time and/or intensity would have resulted in aerobic exercise sessions that were shorter and/or less than the public health guidelines and commonly used aerobic protocols [69, 139, 146].

Ultimately, the major limitation of this study is that all variables that influence EE such as time, intensity, duration, and total work are very difficult to match when examining the effects of exercise on EE during and after exercise. Therefore, we decided to match the aerobic and resistance exercise protocols for time rather than for total work. This has practical implications, as 40-60 minutes is a common duration for aerobic and resistance exercise and meets the physical activity guidelines when performed three to four days per week [14, 16, 139].

Conclusions

In conclusion, in resistance trained males, aerobic exercise required a greater EE than resistance exercise and EE during resistance exercise was positively associated with intensity. Additionally, the two most difficult resistance protocols and the most difficult aerobic protocol, as indicated by percentage of

completion, resulted in a decreased post-exercise EE as compared to baseline. Further, when measuring EE during exercise and up to 90 minutes post-exercise, exercise EE was the greatest contributor to total measured EE during and after exercise.

Our novel methods of using Quantile Regression and Functional Data Analysis to examine EE during and after exercise demonstrate the potential of these methods to be used in the analysis of future exercise and training studies. Future work should examine the effects of aerobic and resistance exercise of similar load volumes and intensities on EE in hourly increments up to 48 hours post-exercise, as well as examine the effects of post-exercise feeding in similar conditions in resistance trained males. Given the importance of energy balance in athletes and military, a greater understanding of the effects of exercise mode, duration, and intensity is needed. The knowledge gained from this study and future work will aid in the design and implementation of diet and exercise training programs for athletes and military personnel and will help these individuals to avoid the negative effects of energy deficit.

Table 4.1. Overview of exercise protocols completed in random order.

Time	Moderate-intensity continuous aerobic exercise	High-intensity interval aerobic exercise	Strength endurance exercise †	Traditional resistance exercise †	High-intensity resistance exercise †
0-30 min *	Baseline resting measurement				
30-40 min *	Warm-up: Walking at 3.5 mph and 0% incline				
40-80 min *	Walking or Jogging at 70-80% of $\dot{V}O_{2max}$	5 sets of: 4 min at 60-70% $\dot{V}O_{2max}$ followed by 4 min at 85-95% $\dot{V}O_{2max}$	2 sets of 20 repetitions at 75% of 12 RM: <i>Leg Press; Leg Curl; Leg Extension; Lat Pulldown; Chest Press; Shoulder Press</i>	3 sets of 10 repetitions at 100% of 12 RM: <i>Leg Press; Leg Curl; Leg Extension; Lat Pulldown; Chest Press; Shoulder Press</i>	4 sets of 6 repetitions at 125% of 12 RM: <i>Leg Press; Leg Curl; Leg Extension; Lat Pulldown; Chest Press; Shoulder Press</i>
80-90 min *	Cool-down: Walking at 3.5 mph and 0% incline				
90-120 min *	Immediately post-exercise resting measurement				
120-150 min	Completion of online diet recall (ASA24™)				
150-180 min *	Delayed post-exercise resting measurement				

* energy expenditure measured via indirect calorimetry (COSMED K4b²)

† participants had 6 minutes to complete the required sets for each exercise and 48 seconds to transition from one resistance machine to the next; protocols are matched for total weight moved during each exercise

Table 4.2. Baseline characteristics of participants.

	Age (yrs)	Height (cm)	Mass (kg)	BMI (kg/m²)	Percent fat (%)	Spine BMD (g/cm³)	$\dot{V}O_{2max}$ (ml/kg/min)	Total Body 12RM (kg)
Mean \pm SD	24.21 \pm 4.04	181.20 \pm 8.81	84.69 \pm 13.34	25.32 \pm 2.78	15.87 \pm 4 .61	1.35 \pm 0. 11	41.55 \pm 5.78	90.15 \pm 24.2 7
Range	20.00 ,34.0 0	168.20, 201.30	66.00, 114.0	20.37, 2 9.48	9.20, 25.30	1.18, 1.53	28.96, 51.47	53.69, 150.79

Values are presented as mean \pm standard deviation (SD), and range for age (yrs), height (cm), body mass (kg), body mass index (BMI) (kg/m²), percent body fat, spine bone mineral density (BMD) (g/cm³), cardiorespiratory fitness ($\dot{V}O_{2max}$) (ml/kg/min), and total body average 12 repetition maximum (12RM) (kg).

Table 4.3. Percentage completion of exercise protocols.

Exercise Protocol	Prescribed Volume (Mean \pm SD) (kg)	Percentage Completed (Mean \pm SD)
2x20 (n=12)	17,492 \pm 4,468	99.12 \pm 1.85
3x10 (n=13)	17,054 \pm 4,309	97.21 \pm 4.54
4x6 (n=11)	16,745 \pm 4,226	89.87 \pm 10.50
HIIT (n=12)	NA	99.58 \pm 1.44
Continuous (n=13)	NA	100.00

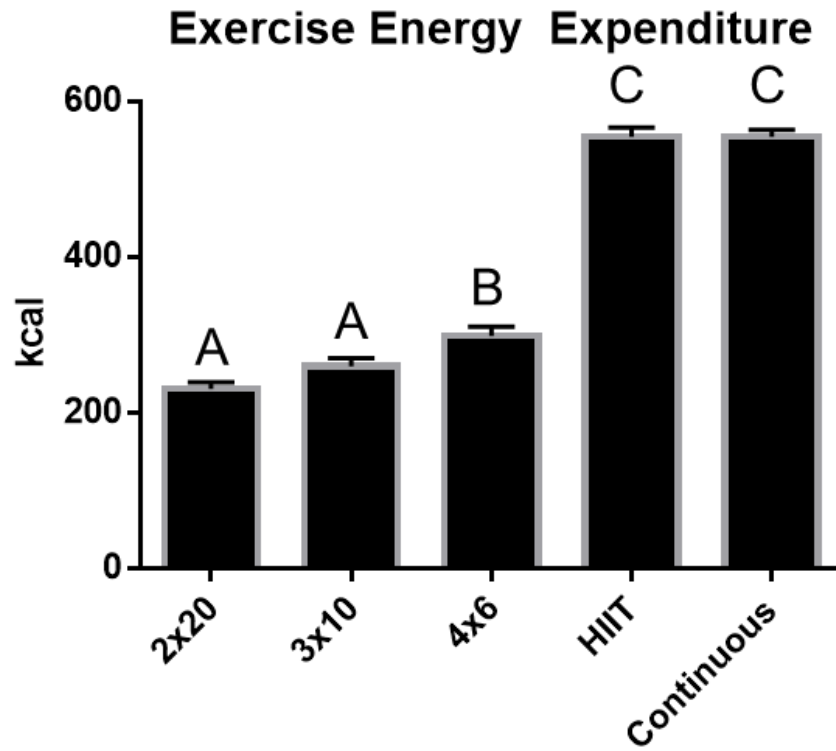
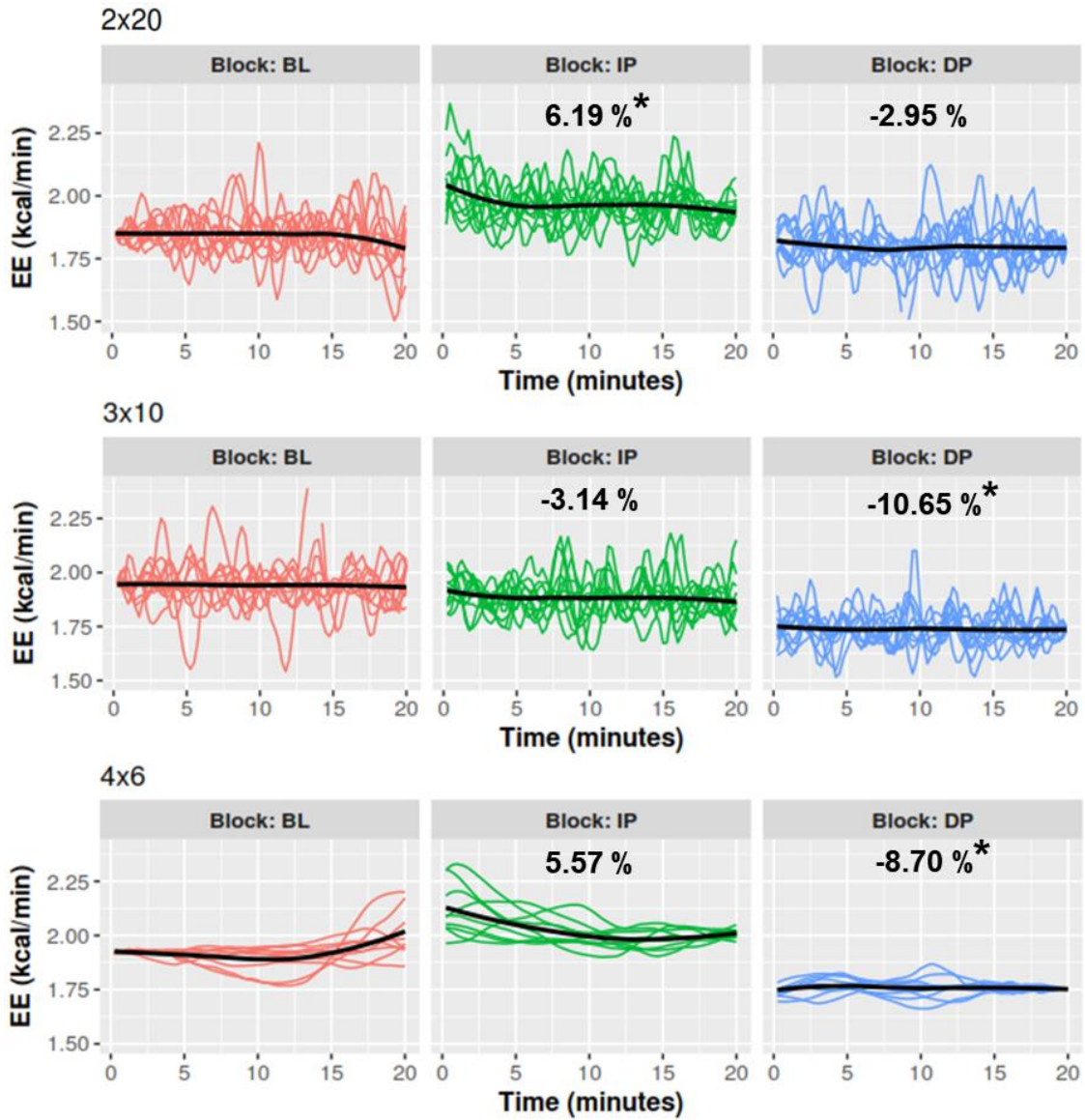


Figure 4.1. Total exercise energy expenditure of each exercise protocol, adjusted for body mass (n=10). Matching letters represent $p > 0.05$.



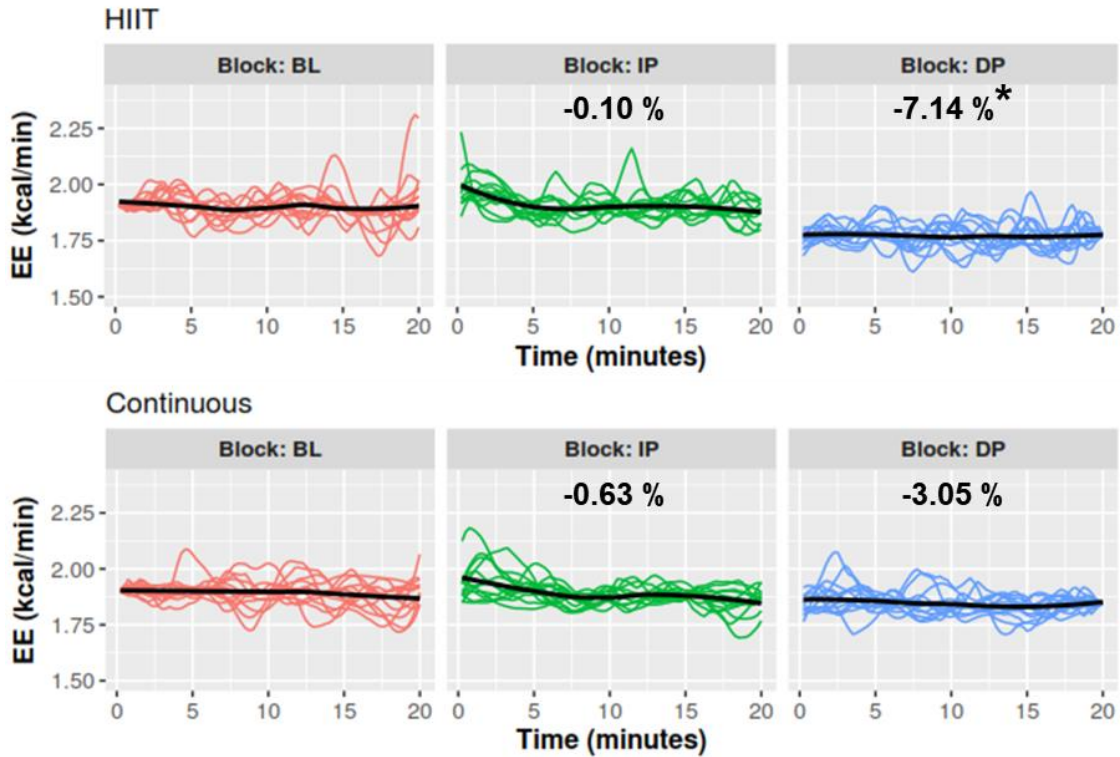


Figure 4.2. Resting energy expenditure (kcal/minute) over time at each resting measurement with group mean percent change from baseline displayed. BL = baseline, IP= immediate post-exercise, DP = delayed post-exercise. Asterisk represents significantly different from baseline ($p < 0.05$).

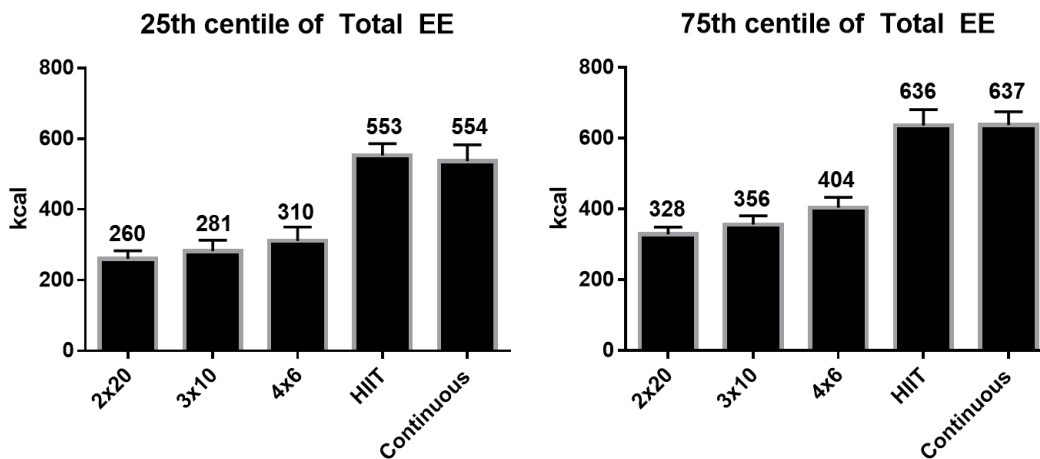


Figure 4.3. Unadjusted estimates from Quantile Regression at the 25th and 75th centiles of total EE.

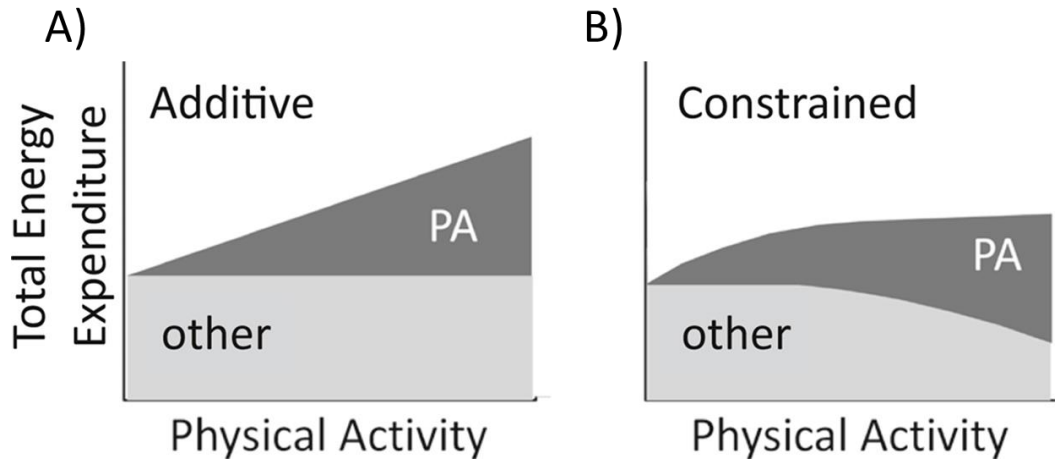


Figure 4.4. Additive total energy expenditure model (A) and constrained total energy expenditure model (B). In Additive total energy expenditure models, total energy expenditure is a simple linear function of physical activity, and variation in physical activity energy expenditure (PA) determines variation in total energy expenditure. In Constrained total energy expenditure models, the body adapts to increased physical activity by reducing energy spent on other physiological activity, maintaining total energy expenditure within a narrow range. Used with permission from Pontzer, et al. 2016 [145].

CHAPTER FIVE

OVERALL DISCUSSION

Main findings

When examining differences in exercise EE across varying aerobic and resistance exercises, our hypothesis was supported that the aerobic exercise protocols would result in a greater EE than resistance exercise protocols. No differences were seen in exercise EE between the HIIT and continuous aerobic protocols. Additionally, the 4x6 resistance exercise protocol resulted in a greater exercise EE than the 3x10 and 2x20 resistance exercise protocols. Thus, the intensity of resistance exercise was positively associated with exercise EE, despite only an average of $97.21 \pm 4.54\%$ completion in the 3x10 protocol and $89.87 \pm 10.50\%$ completion in the 4x6 resistance exercise protocol.

In the examination of total measured EE during and after exercise, our hypothesis was supported that aerobic exercise would contribute the most to total measured EE during and after exercise. In unadjusted quantile regression analysis, at the 25th centile of total measured EE during and after exercise, both HIIT and continuous were significantly greater than the resistance exercise protocols and no significant differences were seen between resistance exercise protocols. At the 75th centile of total measured EE during and after exercise, both HIIT and continuous were again significantly greater than the resistance exercise protocols, and no significant differences were seen between 2x20 and 3x10, but

4x6 was significantly greater than 2x20. Interestingly, independent of mass, baseline EE, and $\dot{V}O_{2max}$, 12RM had a significant positive effect on total measured EE during and after exercise at the 75th centile but not at the 25th centile. We found three protocols (3x10, 4x6, and HIIT) that had reductions in post-exercise EE, yet this did not change the rank order of EE that was seen during exercise. Therefore, exercise EE was the greatest contributor to total measured EE during and after exercise.

When examining differences in post-exercise EE across the five protocols, our hypothesis was not fully supported. A significant increase in EE was seen in the immediately post-exercise measurement period in the 2x20 protocol, but EE returned to baseline in the delayed post-exercise measurement period. No significant increase in EE was seen following the continuous aerobic protocol. Interestingly, when compared to baseline, average decreases in EE of 10.65%, 8.70%, and 7.14% were seen in the delayed post-exercise measurement period (60-90 min after exercise) for the 3x10, 4x6, and HIIT protocols, respectively.

Previous studies have shown an increase in post-exercise EE following resistance exercise [16-18, 63, 91]. Hackney et al. [14] examined the effects of full body resistance exercise with 2,000 kg and 2,500 kg load volumes performed for 8 sets of 6 repetitions with emphasized eccentric contractions on post-exercise metabolic rate in resistance trained and untrained males. It was found that at 24, 48, and 72 hours post-exercise, metabolic rate was significantly greater than baseline in both trained and untrained groups. Hackney et al. [14] stated that the elevations in metabolic rate may have been due to the muscle repair process

resulting from muscle damage instigated by the protocol, specifically the volume and emphasis on eccentric contractions. The authors did note that feeding was not controlled before and immediately after the resistance protocols and that may have affected metabolic rate. Abboud et al. [90] examined the effects of 10,000 kg and 20,000 kg resistance exercise load volumes at 85% 1RM on exercise EE and post-exercise metabolic rate in resistance trained males and did not see an increase in metabolic rate from 12 to 48 hours post-exercise. They attributed this to the training status of the participants, where the load volume was not enough of a stimulus to instigate a significant level of protein synthesis and tissue repair. The participants in our study were of a similar training status and strength of the participants examined by Hackney et al. [14] and Abboud et al. [90]. Therefore, the difference in our results is unlikely due to training status, as well as load volume, as our average load volume of approximately 17,000 kg was similar to the load volume used by Abboud et al. [90]. Differences in post-exercise EE may be due to differences in feeding among protocols, as in previous studies, the participants were free living between post-exercise measurement periods and could feed freely. Additionally, it is unknown whether the content of participants' diets influenced the metabolic rate up to 72 hours post-exercise.

No change in post-exercise metabolic rate was seen following the continuous aerobic protocol, which was similar in both intensity and duration to previously used moderate intensity continuous exercise protocols [17, 18, 80, 83]. Reviews on EPOC by Børsheim and Bahr [17], as well as Laforgia et al. [18] found that short-duration, low- to moderate- intensity aerobic exercise (<30 min at <80%

$\dot{V}O_{2max}$) results in a short-lasting EPOC (<40 minutes). Additionally, longer duration aerobic exercise performed at moderate- to high- intensity (≥ 50 min at $\geq 70\%$ $\dot{V}O_{2max}$) results in a long-lasting EPOC (3 - 24 hours). In our study, we saw no elevation in post-exercise metabolic rate following the continuous aerobic protocol, despite the duration of 40 minutes and moderate intensity (70-80% $\dot{V}O_{2max}$). Bahr and Sejersted [142] examined the effects of exercise and feeding on EPOC in untrained males following 80 minutes of cycling at 75% $\dot{V}O_{2max}$. EPOC was measured up to 7 hours post exercise, and they concluded that the slow component of EPOC was present in the fasted state. Bahr and Sejersted [142] acknowledged that energy-sparing mechanisms in highly-trained participants may affect post-exercise metabolic rate, which is why they chose to examine untrained subjects. Our study examined the effects of 40 minutes of aerobic exercise at 70-80% $\dot{V}O_{2max}$, but with resistance trained males. It appears that the training status of our participants may have influenced the post-exercise EE, despite being in a semi-fasted state. Our protocol was different from the protocols used by Bahr and Sejersted [142] in that our duration was shorter (40 min vs 80 min), we examined specifically resistance trained males in contrast to untrained males, in addition to an extended period of refraining from food (~4 hours) prior to exercise. Previous studies examining post-exercise metabolic rate largely have not controlled for diet, but among those where diet was controlled, results have been equivocal. Resistance exercise has been shown to result in a greater post-exercise fat oxidation than aerobic exercise [96]. Thus, of the protocols in our study that resulted in a reduced post-exercise metabolic rate, the intensity and volume in the

3x10 and 4x6 resistance protocols combined with a prolonged lack of feeding may explain why a lower post-exercise metabolic rate was observed compared to the other protocols. Furthermore, glycogen depleting exercise has been shown to increase fat oxidation post-exercise and that glycogen resynthesis is a metabolic priority following exercise [143]. In our study, it is possible that the extended lack of feeding in addition to the training status of our participants were reasons for a lack of elevated metabolic rate following exercise.

The reduced EE as compared to baseline following the 3x10, 4x6, and HIIT protocols may be partially explained by the constrained total EE model described by Pontzer et al. [144, 145], where total daily EE is maintained within a specific range or at a set point. As shown in both human and animal studies, when PA metabolic activity increases, decreases in non-physical activity metabolic activity can occur as a means of maintaining total EE under a maximal daily amount (**Figure 4.4B**). This is in contrast to the additive total EE model, where non-physical activity metabolic activity is not altered by an increase in total daily EE resulting from an increase in physical activity (**Figure 4.4A**) [144, 145]. Following the logic of the constrained total EE model, a possible explanation for the reduced EE following the 3x10, 4x6, and HIIT exercise protocols is that the combination of the intensity, volume, and exercise EE of the exercise protocols exceeded the total EE set point of the participants, and therefore resulted in a reduced EE following exercise. Additionally, considering that the participants had already fasted for at least four hours prior to arrival as verified with verbal questioning and dietary recall at each visit, once delayed-post exercise EE was measured, a total of

approximately eight hours had passed since the participants last fed. Thus, in combination with the energy expended as well as potential muscle damage and glycogen depletion induced during each exercise protocol, it is possible that the non-physical activity metabolic activity decreased to compensate for the prolonged absence of feeding, high level of EE, and metabolic demand of tissue repair and glycogen resynthesis. This reduction in EE may have been due to the greater difficulty of the 3x10, 4x6, and HIIT protocols as compared to the 2x20 and continuous. Of the resistance protocols, the 3x10 and 4x6 protocols had lower average percentage of completion as compared to the 2x20 protocol, and of the aerobic protocols, the HIIT protocol had a lower percentage of completion than the continuous protocol, indicating a greater difficulty. Additionally, a greater load volume was performed in the 3x10 resistance protocol ($97.21 \pm 4.54\%$ of total) compared to the 4x6 resistance protocol ($89.87 \pm 10.50\%$ of total), which could partially explain the greater reduction of EE following the 3x10 protocol than the 4x6 protocol, despite the lower intensity.

Strengths

Strengths of our study include the randomized within-subjects design and each of the trials conducted in a controlled clinical setting. To our knowledge, this was the first study to examine differences in EE in time-matched aerobic and resistance protocols in resistance trained males in addition to matching the duration of the HIIT and continuous aerobic protocols, a design component that has been inconsistent in the literature [69]. Additionally, our study was the first to quantify the EE of full body resistance protocols of varying intensities that were

matched for both duration and total volume using indirect calorimetry. Lastly, this study was the first to implement consistent time-matched post-exercise EE measurement periods across both aerobic and resistance exercise protocols of varying intensity in the same individuals.

Limitations

This study is not without limitations. First, the small sample size and lack of generalizability are limitations, as the present study only included resistance trained males. Secondly, within the resistance exercise protocols, the rest periods between sets were inconsistent between protocols. This was due to the allotment of 6 minutes for all sets of each exercise to be performed within the total 40 minutes of exercise. The length of time varied to complete sets of different repetitions and subsequently rest periods were extended on the 2x20 protocol and decreased on the 3x10 and 4x6 protocols. Farinatti [60] showed that shorter between-set rest intervals can positively influence the first few minutes of post-exercise metabolic rate compared to longer rest intervals. Due to the time-matched design of our study, we were unable to match the between-set rest intervals. Additionally, in our study, the fast component of post-exercise metabolic rate (minutes 0 – 7 immediately post-exercise) (minutes 90-97) was not captured, as participants could remove the COSMED K4b² for the seven minutes immediately after exercise to hydrate and use the restroom. Therefore, the magnitude and rate of decline of post-exercise metabolic rate during this period is unknown. Time differences in rest intervals between protocols may have affected the fast component of post-exercise metabolic rate, but Farinatti [60] showed that differences in rest intervals did not

influence total EE. Although we were unable to match the between-set rest intervals, it is unlikely that our presented results were confounded.

Third, although matched for total time, the aerobic and resistance exercise protocols were not equally matched for total work. The resistance exercise protocols required approximately 85% of the total work of the aerobic exercise protocols. However, due to the difficulty level and load volume of the resistance exercise protocols and inability for all participants to complete the prescribed volume, it is very unlikely that participants would have been able to complete the sessions if the work was greater and subsequently matched with the aerobic sessions. Conversely, decreasing the work of the aerobic sessions via a reduction in time and/or intensity would have resulted in aerobic exercise sessions that were shorter and/or less than the public health guidelines and commonly used aerobic protocols [69, 139, 146].

Ultimately, the major limitation of this study is that all variables that influence EE such as time, intensity, duration, and total work are very difficult to match when examining the effects of exercise on EE during and after exercise. Therefore, we decided to match the aerobic and resistance exercise protocols for time rather than for total work. This has practical implications, as 40-60 minutes is a common duration for aerobic and resistance exercise and meets the physical activity guidelines when performed three to four days per week [14, 16, 139].

Conclusions

In conclusion, in resistance trained males, aerobic exercise required a greater EE than resistance exercise and EE during resistance exercise was

positively associated with intensity. Additionally, the two most difficult resistance protocols and the most difficult aerobic protocol, as indicated by percentage of completion, resulted in a decreased post-exercise EE as compared to baseline. Further, when measuring EE during exercise and up to 90 minutes post-exercise, exercise EE was the greatest contributor to total measured EE during and after exercise.

Our novel methods of using Quantile Regression and Functional Data Analysis to examine EE during and after exercise demonstrate the potential of these methods to be used in the analysis of future exercise and training studies. Future work should examine the effects of aerobic and resistance exercise of similar load volumes and intensities on EE in hourly increments up to 48 hours post-exercise, as well as examine the effects of post-exercise feeding in similar conditions in resistance trained males. Given the importance of energy balance in athletes and military, a greater understanding of the effects of exercise mode, duration, and intensity is needed. The knowledge gained from this study and future work will aid in the design and implementation of diet and exercise training programs for athletes and military personnel and will help these individuals to avoid the negative effects of energy deficit.

Future Directions

Future work should first cross-compare the EE during and after aerobic and resistance exercise sessions that are matched for total work and not time to help tease out the effects of both time and work on post-exercise EE. Secondly, individual differences should be further examined to determine which factors

influence post-exercise EE. Moreover, since feeding can influence EE at rest and following exercise [7, 10], the effect of feeding on post-exercise EE should be examined following aerobic and resistance protocols with load volumes and intensities similar to this study. Lastly, the association of aerobic and resistance exercise of different intensities on habitual physical activity levels should be investigated. Aerobic exercise has been associated with reductions in habitual physical activity, while resistance training has been associated with increases in habitual physical activity in sedentary individuals beginning exercise training [113, 147]. However, it is unknown if aerobic or resistance exercise is associated with habitual physical activity changes in resistance trained males, and if so, at what dose. Therefore, steps should be taken to investigate these gaps to provide knowledge for exercise training program design in athletes and the general population.

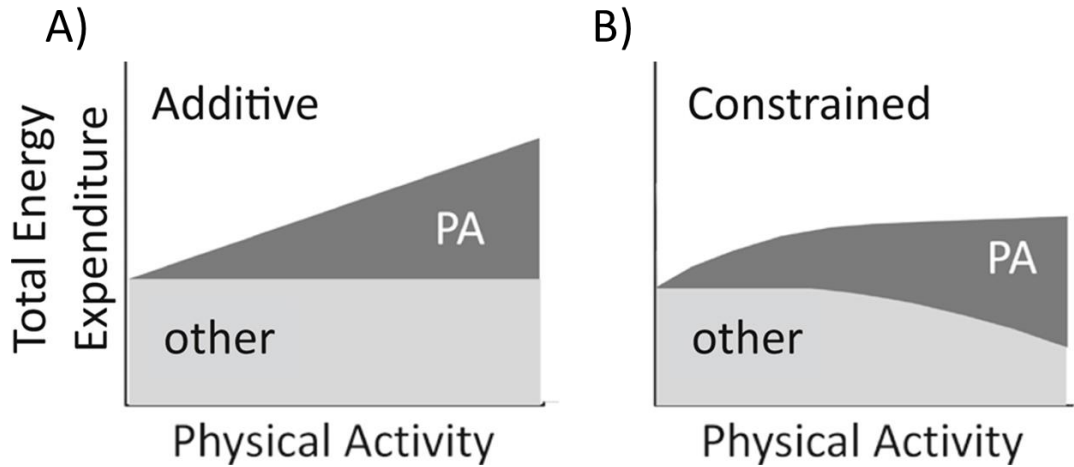


Figure 5.1. Additive total energy expenditure model (A) and constrained total energy expenditure model (B). In Additive total energy expenditure models, total energy expenditure is a simple linear function of physical activity, and variation in physical activity energy expenditure (PA) determines variation in total energy expenditure. In Constrained total energy expenditure models, the body adapts to increased physical activity by reducing energy spent on other physiological activity, maintaining total energy expenditure within a narrow range. Used with permission from Pontzer, et al. 2016 [145].

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