METABOLIC DIFFERENCES BETWEEN
A BOUT OF ECCENTRIC, CONCENTRIC AND TRADITIONAL
RESISTANCE EXERCISE

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METABOLIC DIFFERENCES BETWEEN A BOUT OF ECCENTRIC, CONCENTRIC
AND TRADITIONAL RESISTANCE EXERCISE (pp. 46)

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PURPOSE: To determine the extent to which metabolic variables such as VO_2 (ml/kg/min), percentage of energy derived from carbohydrates (%CHO) and heart rate (HR) as well as blood glucose and lactate vary between resistance workouts comprised of solely eccentric, concentric or traditional muscle contractions.

METHODS: N=12 men and women completed a traditional (TRAD), concentric (CONC), and eccentric (ECC) full-body resistance workout at 65% of a measured 1 repetition max with each condition matched for work. During each condition, the subject was fitted to a metabolic cart and metabolic variables were recorded through indirect calorimetry and heart rate monitor. Blood glucose and blood lactate were taken at five different stages. **RESULTS:** Both the TRAD and CONC conditions resulted in significantly ($p < 0.001$, and $p < 0.001$ respectively) greater VO_2 values when compared to the ECC condition. Accumulation of lactate Post Ex. was also significantly (both $p <$

0.001) greater in the TRAD and CONC compared to the ECC. **CONCLUSION:** Results indicate a much greater metabolic demand from concentric and traditional contractions compared to eccentric muscle contractions on a whole body level.

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CHAPTER I

INTRODUCTION AND BACKGROUND

The primary function of skeletal muscle is to exert force through the joint. There are three types of muscle contraction, concentric (actively shortening), eccentric (actively lengthening), and isometric (actively holding length). All of these types of contractions serve their primary function, but in different ways. Resistance training in itself is a widely practiced form of physical activity. A survey conducted by the CDC in 2004 estimated that 19.6% of American citizens participated in some form of resistance training (CDC 2004). Resistance training is prescribed to a multitude of diverse athletic populations as a means to improve fitness and performance. It has been shown to improve muscle mass and function, as well as bone density. It is often prescribed to the aging and diseased populations as a means to fight the natural process of sarcopenia, improve mobility and lessen instances of falling by improving balance.

Resistance training is typically performed using both eccentric and concentric muscle contractions. Researchers investigating the lower metabolic cost of eccentric contractions compared to concentric contractions of equal force dates as far back as the 1950s. Abbott, Bigland, and Ritchie (1952) conducted a study in which they used mechanically linked back-to-back stationary bicycles where one subject was pedaling forward, while the other subject was resisting. The consequences of each individual mode of contraction have different energy costs which suggests that each contraction may

serve a specific rehabilitative health goal or purpose. This initial comparison of metabolic and cardiovascular demand between eccentric and concentric exercise was followed by additional investigations using aerobic cycling (Asmussen, 1953; Bigland-Ritchie & Woods, 1976; Henriksson, Knuttgen, & Bonde-Petersen, 1972; Penailillo, Blazeovich, Numazawa, & Nosaka, 2013), as well as aerobic arm ergometry (Beaven, Willis, Cook, & Holmberg, 2014) and isokinetic resistance bouts (Okamoto, Masuhara, & Ikuta, 2006; Overend, Versteegh, Thompson, Birmingham, & Vandervoort, 2000). However, in most previous studies the exercise was limited to single muscle groups, or they failed to collect a complete array of metabolic and cardiovascular variables.

Determining how greatly these resistance exercise sessions vary in metabolic cost is important because of its potential relevance to both recreational and clinical rehabilitative settings. Considering the previous evidence that eccentric contractions elicit similar gains in size and strength of the muscle (Kim, Ko, Farthing, & Butcher, 2015), if an entirely eccentric resistance workout were found to have reduced cardiovascular and metabolic demand, those afflicted with cardiovascular or pulmonary diseases could make the same gains in size and strength of the muscle while not putting themselves at risk. However, an entirely concentric workout might benefit those looking to lose weight because a greater metabolic cost would require greater kcal expenditure.

The purpose of this investigation is to determine the extent to which metabolic and cardiovascular variables such as oxygen consumption (VO_2 , mL/kg/min), percentage of energy derived from carbohydrates (%CHO), blood lactate (BLa, mM), heart rate (HR,

bpm), mean arterial pressure (MAP, mmHg) (and blood glucose (mg/dL) vary between isolated concentric, isolated eccentric, and traditional bouts of resistance exercise. We hypothesized that all metabolic variables will be significantly greater during the concentric condition when compared to the traditional and eccentric condition. Succinctly we expect to see all metabolic variables to be significantly lower during the eccentric condition when compared to the traditional and concentric condition. Concerning blood glucose, we expect the concentric condition to cause an initial spike in blood glucose followed by a significant drop. We expect blood glucose levels to remain relatively the same during the eccentric condition.

CHAPTER II

REVIEW OF THE LITERATURE

Most resistance exercise sessions involve both eccentric and concentric muscular contractions. Consider a bicep curl, there are two components to the full lift, the lifting and the lowering of the weight. The lifting of the weight results from the active muscles producing force while shortening (concentric) and the lowering of the weight results from the active muscles producing force while lengthening. Shortening contractions are considered positive work because work is being performed on the environment (ie: external work). The force produced by the muscle is greater than the force acting upon it. However, during eccentric contractions the force applied to the muscle exceeds the force produced by the muscle resulting in muscle lengthening or work being performed on the muscle also known as negative work (Lindstedt, LaStayo, & Reich, 2001; Vogt & Hoppeler, 2014). The purpose of this review is to look at the existing literature on the processes, metabolic cost, and substrate requirements for eccentric versus concentric muscle contractions. And additionally, to explore the rehabilitative or training implications of their results and how those may lead to future research.

Mechanisms of Muscle Contraction

The physiology underlying concentric muscle contractions has been investigated more extensively than eccentric contractions. The widely accepted *Cross-bridge theory*

(adapted from *Sliding Filament Theory*) is the known process of shortening contractions (A. F. Huxley & Niedergerke, 1954; H. E. Huxley, 1969). To briefly summarize, motor nerves stimulate an action potential to pass to the neuromuscular junction. The action potential then stimulates the sarcoplasmic reticulum to release Ca^{2+} into the muscle cell. The Ca^{2+} ions then bind with the protein troponin. The force is then produced by the interaction of two protein filaments found in the sarcomeres of each muscle fiber, the actin (thin) and myosin (thick). The myosin head attaches to the actin filament, creating a sort of bridge between the two filaments called an actomyosin bond resulting in a ‘powerstroke’ or sliding of the two filaments across each other. Once this occurs, adenosine triphosphate (ATP), a nucleoside triphosphate that is our primary molecular source of energy, is converted to free energy by way of ATP hydrolysis via myosin ATPase. This causes detachment of the actomyosin bonds and allows the myosin head to reset for another attachment cycle ATP hydrolysis via myosin ATPase accounts for about 60 – 70% of the ATP cost during muscle contraction. The remaining 30 – 40% is a result of muscle activation and relaxation and required by the calcium pumps to pump Ca^{2+} back into the sarcoplasmic reticulum (Hogan, Ingham, & Kurdak, 1998; Homsher & Kean, 1978). These are the widely accepted mechanisms behind shortening muscle contractions, though recently, the *Winding Filament Hypothesis* proposed by Nishikawa et al. (2012) has been gaining traction. This hypothesis suggests the protein *titin* has a much more pivotal role in the mechanisms of muscle contraction than originally thought. To briefly summarize, the hypothesis states that an influx of Ca^{2+} causes actomyosin

cross-bridges to not only shorten, but to act as rotors that wind titin around the thin filaments which creates and stores elastic potential energy to be used during the shortening phase.

Eccentric, or active lengthening, contractions are performed by way of a much different process. During active lengthening of the muscle, the actomyosin bond is broken due to mechanical stress (in essence, the sarcomeres are overloaded and the myosin heads are torn from their actin binding sites) instead of active detachment based on the hydrolysis of ATP. This high stress and overall process is likely what contributes to the often noted muscle damage that occurs after exercise involving high force eccentric muscle contractions.

Muscle Damage

An additional consequence of eccentric contractions is commonly known as delayed-onset muscle soreness (DOMS). This effect occurs generally after a new or unfamiliar exercise, but is known to occur after eccentric exercise because of both the mechanisms behind it and its general unfamiliarity (Newham, 1988; Schwane, Johnson, Vandenakker, & Armstrong, 1983). Although this augmented soreness often deters individuals from eccentric exercise as a means for both strength training and rehabilitative purposes, this negative effect can be attenuated fairly quickly due to adaptation (Penailillo et al., 2013). For example, Penailillo and colleagues had ($n=10$) male subjects perform 3 separate cycling trials, one concentric (CONC) and then two

consecutive eccentric (ECC1 and ECC2) bouts for 30 minutes at 60% of the maximal concentric power output at 60rpm. HR, oxygen consumption VO_2 , BLa, RPE (Borg's Scale) as well as plasma creatine kinase (CK) were recorded before, immediately after, and 1-4 days after the exercise bout. To assess muscle soreness, the investigators used a 100-mm visual analog scale (VAS) where 0 indicates no pain at all and 100 indicates the worst pain imaginable. The subjects were allotted 2 weeks between bouts for recovery and to avoid sessions affecting each other. CK levels were significantly higher than baseline (147.4 ± 21.1 IU/L) 1 day after both the CONC (219.5 ± 40.3 IU/L) and the ECC1 (246.5 ± 33.0 IU/L), however, CK levels were not significantly higher after the ECC2 bout (173.1 ± 16.0 IU/L). Concerning muscle soreness, significant bout and interaction effects were found between CONC and ECC1 (in that muscle soreness was significantly greater in the ECC1 compared to the CONC condition) and between ECC1 and ECC2 (in that muscle soreness was significantly lower in the ECC2 compared to the ECC1 condition.) This study indicates an adaptive factor to multiple bouts of solely eccentric work, which should negate the fear of excessive muscle soreness following the first or second bout of familiarization. Many other investigations have also reported attenuation of muscle damage during chronic eccentric exercise training (Chen, Chen, Lin, Wu, & Nosaka, 2010; Howatson, Van Someren, & Hortobagyi, 2007; Margaritelis et al., 2015).

Metabolic Requirement of Eccentric and Concentric Contractions

The differences in energy requirement between lengthening and shortening contractions have been noted as early as 1952 by Abbot, Bigland and Ritchie. In their study, they developed an apparatus using two back to back bicycle ergometers as to allow one subject to pedal forward (concentric) while the other subject resisted (eccentric). The subjects pedaled for 10 minutes, then an additional 3 minutes (during this time, the expired air was collected in Douglas bags). There were 3 separate trials with 3 corresponding pedaling rates at 25, 35.4 and 52 revolutions per minute respectively. The results showed a larger oxygen requirement for the subject performing positive work in all 3 trials. For example, at the 35 rev/min Subject A (doing positive work) consumed 0.70 L O₂/min greater than their resting rate where Subject B (doing negative work) consumed only 0.19 L O₂/min greater than resting. When the subjects reversed roles, Subject B (now performing positive work) consumed 0.69 L O₂/min greater than resting and Subject A (now doing negative work) consumed 0.19 L O₂/min greater than resting. These findings were later validated by the findings of (Asmussen, 1953; Bigland-Ritchie & Woods, 1976; Bonde-Petersen, Knuttgen, & Henriksson, 1972).

More recently, a study was conducted in 2014 by Beaven et al. to compare the physiological responses of concentric versus eccentric arm cycling on an arm ergometer. The study called for ($n = 14$) physically active participants, 7 men and 7 women. Each participant completed three 4-minute trials of either eccentric or concentric arm cycling at 40, 60, and 80% of their previously measured Work Peak at 60 rev/min. There was a 3.5-minute recovery period between each 4-minute trial. The relevant variables were HR,

ventilation (V_E), RE, and Bla concentration, all of which were found to be significantly higher in the concentric condition in all three trials.

As mentioned previously, the investigation by Panilillo and colleagues (2013) collected metabolic variables in addition to the variables involving muscle soreness. Their findings further solidify the findings of other reports. The results indicated average HR (156.1 ± 5.9 vs 126.7 ± 8.5 bpm), Bla (7.6 ± 0.8 vs 2.7 ± 0.5 mmol/L), RPE (13.6 ± 2.4 vs 10.6 ± 2.9), and Vo_2 (2.3 ± 0.1 vs 1.2 ± 0.1 L/min) were all significantly higher in the CONC bout versus the ECC1. When comparing the ECC1 and ECC2 bouts, they saw a 12% lower HR (126.7 ± 8.5 vs 111.4 ± 8.5 bpm, $p = 0.003$), and 35% lower Bla (2.7 ± 0.5 vs 1.7 ± 0.4 mmol/L) respectively.

In addition to the studies mentioned that have utilized aerobic exercise modalities, some investigators have also employed resistance exercise to compare the metabolic requirements between these two types of contractions. Goto et al. (2009) conducted a study to examine the metabolic effects of 4 separate resistance exercise trials on a bilateral knee extension machine concerning eccentric versus concentric muscle contractions. The duty cycle of each trial was manipulated to put greater or lesser emphasis on the eccentric or concentric phase of the lift. The trials were as follows, a 5 – 1 (concentric: 5 seconds, eccentric: 1 second), 1 – 5 (concentric: 1 sec, eccentric: 5 sec), 3 – 3 (concentric: 3 seconds, eccentric: 3 seconds) and a 1 – 1 (concentric: 1 second, eccentric: 1 second). The slow movement trials (5 – 1, 1 – 5, 3 – 3) were done at 50% of their measured 1 repetition max, and 80% for the 1 – 1 trial. The trials called for 4 sets to

exhaustion with 1-minute rest in between each trial. Concerning blood lactate concentration, the 1 – 5 trial, which emphasized the eccentric phase, showed the lowest levels and also had the lowest fatigue index, implying a lower energy requirement of eccentric contraction.

In 2004, Kraemer et al. conducted a study looking at hormonal and metabolic responses to eccentric versus concentric resistance exercise. After measuring 10-RM loads for bench press, leg extension, military press and leg curl, the subjects completed two trials of either concentric or eccentric contractions with 4 sets of 12 repetitions at 80% of their measured 10-RM with 90s rest in between sets. The investigators used a pulley system or steel levers positioned above each machine to raise or lower the weight to allow the subject to perform only eccentric (ECC), or only concentric (CON) contractions. They took blood samples pre-exercise, post-exercise, and 15 minutes post-exercise. The results showed a significantly greater Bla concentration for the CON trials immediately post-exercise ($7.47\text{mM} \pm 1.10$ vs $1.86\text{mM} \pm 0.33$) as well as 15 minutes post-exercise ($4.87 \pm 0.69\text{mM}$ vs $1.27\text{mM} \pm 0.19$) despite having similar baseline values (0.89mM (CON) and 1.02mM (ECC).) These findings concerning blood lactate are consistent with what was found, under similar conditions, by Durand et al. in 2003. Blood glucose was affected more consistent between the two trials as both experienced a similar increase immediately post exercise. However, it is worth noting that the CON trial showed lower levels 15 post-exercise than the ECC. This would suggest that taking

a further look into how these different contractions affect blood glucose would not be without value (Durand et al., 2003; Kraemer et al., 2004).

The literature concerning differences in substrate utilization between the two types of contractions is very thin. One example is a classic one done by Seliger, Dolejs, Karas, and Pachlopnikova (1968). This study used 15 trained rugby athletes that were split into two groups where the athletes were either lifting the weight (Group A: concentric) or lowering the weight (Group B: eccentric) on a squat rack. The complete lifting or lowering was timed to last 3 seconds. The corresponding weight was 90-95% of their previously measured 1RM for Group A and 145-150% of their 1RM for Group B due to the findings of a previous study by Bethe in 1929 that stated that the force at an eccentric contraction was 28 to 56% greater than a concentric contraction. After initial 1RM measurements, the athletes trained for 13 weeks performing strictly these lifts (along with their regular training regimens). The relevant results though, were their examination of caloric expenditure during lifting versus lowering. The net kcals burned during the lifting for Group A was measured at 6.0 ± 1.6 kcals pre-training, and 5.3 ± 2.7 kcals post-training period, while despite lifting at a higher % of their measured 1RM, Group B burned 4.7 ± 2.4 kcals performing the lift pre-training, and 4.0 ± 2.1 kcals post-training period. This denotes a large disparity between energy requirements of these two types of contractions, during a single lift. There also seemed to be an equal adaptation in efficiency of both types of lifts as each caloric expenditure dropped 0.7 kcals by the end of the training period. Extrapolated over an entire full-body resistance bout, the

differences in energy cost would be vast (concentric being much greater, eccentric much lower).

Summary and Application For Isolated Eccentric and Concentric Exercise Training

A review of the literature implies a much lower metabolic requirement for eccentric resistance training and a much greater effect on blood glucose for concentric resistance training. These phenomena seem obvious but have not been examined yet, likely due to the difficulty in isolating the muscle contractions. The lower metabolic demand seen in eccentric training would suggest that populations with contraindications to vigorous exercise like the aging population, or those with COPD could partake in a more rigorous exercise regimen without the increases in HR and overall metabolic effort due to the high-force, low-energy cost nature of eccentric exercise. One example of this in action was an investigation performed by LaStayo, Ewy, Pierotti, Johns, and Lindstedt (2003) using a training intervention involving high force eccentric contractions compared with traditional resistance exercise on an elderly population. Their results indicated a significantly greater increase in strength, balance, and stair decent abilities comparing the eccentric group to the traditional group. Though both groups saw an increase in all three tests. Researchers (Gerber et al., 2007; Kim et al., 2015) have also found isolated eccentric resistance training to elicit similar muscular adaptations to traditional resistance exercise. This would mean improvement of overall quality of life and delaying of sarcopenia (age-related muscle loss) with a much lower risk of a cardiac event.

The implications of isolating eccentric and concentric muscular work could have major rehabilitative offers for specific higher-risk populations in need of exercise. As noted earlier, the aging population, COPD population and Type I Diabetics (along with other diseases with a consequence of chronic hypoglycemia) could benefit from a strictly eccentric resistance regimen to improve overall muscular strength with a lower metabolic cost. While a strictly concentric resistance regimen could benefit the Type II Diabetic population by exhibiting a possible lowering effect post-exercise on blood glucose levels, as well as the temporary rise in insulin sensitivity that is commonly associated with exercise.

Purpose and Hypothesis

Despite all of the findings in the literature, HR, RER, VO₂ and substrate utilization during a full body training session containing isolated eccentric versus concentric resistance exercise have not been examined. Thus the purpose of this investigation was to isolate eccentric and concentric contractions for a full-body resistance workout and determine the metabolic differences associated with this isolation. With our research, we hope to use healthy subjects to provide a base for further research into the clinical and recreational rehabilitative benefits to isolating these contractions for a full-body resistance regimen. Our measured variables will be HR, oxygen uptake (VO₂), Percentage of energy derived from Carbohydrates (%CHO), MAP, blood glucose (mg/dL), and blood lactate concentration (mmol). We hypothesize that we will see a greater VO₂, HR, %CHO, MAP, blood lactate concentration, and blood glucose

concentration in the concentric sessions compared to the traditional sessions. Succinctly, we hypothesize that we will see a lower VO_2 , HR, %CHO, MAP, blood lactate concentration and blood glucose concentration in the eccentric sessions compared to the traditional sessions.

CHAPTER III
MANUSCRIPT
Introduction

Resistance training typically requires individuals to perform both the eccentric and concentric phase of the lift. Concentric, or shortening contractions, are considered positive work because the force produced by the muscle is greater than the force acting upon it. Eccentric contractions are considered negative work because the force being applied to the muscle exceeds the force produced by the muscle (Lindstedt et al., 2001; Vogt & Hoppeler, 2014). Eccentric contractions, also known as active lengthening, have been found to have a much lower metabolic requirement. Research identifying the lower metabolic cost of eccentric contractions compared to concentric contractions of equal force dates as far back as the 1950s when Abbott et al. (1952) reported that oxygen consumption was significantly lower during eccentric cycling compared to traditional concentric cycling. These findings have been supported by multiple investigators that have utilized leg cycling (Asmussen, 1953; Bigland-Ritchie & Woods, 1976; Bonde-Petersen et al., 1972; Henriksson et al., 1972; Penailillo et al., 2013) or arm ergometry (Beaven et al., 2014). To our knowledge, the only studies comparing metabolic data during concentric versus eccentric resistance work are (Seliger et al., 1968; Vallejo, Schroeder, Zheng, Jensky, & Sattler, 2006).

Considering the metabolic demand is greater, there would likely be a greater cardiovascular response. This has been shown proven to be the case according to

investigations (Okamoto et al., 2006; Overend et al., 2000) who reported a greater increase in heart rate (HR) and mean arterial pressure (MAP) during bouts of isokinetic concentric resistance exercise compared to eccentric exercise. In addition, cardiovascular and metabolic differences would likely result in greater blood glucose, blood lactate production and caloric expenditure/substrate utilization during concentric compared to eccentric exercises. Studies by Kraemer et al. (2004) and Durand et al. (2003) delved into the differences in blood lactate caused by isolated eccentric and concentric contractions noting much greater blood lactate levels in the concentric group post exercise.

An investigation in 1968 by Seliger et al., found a significantly higher caloric expenditure during concentric work, compared to eccentric work, during a 13-week training intervention. Greater utilization of substrates would logically imply a greater effect on blood glucose during and post-exercise. The only investigation into this was again Kraemer et al. (2004) who found no significant results, but further inquiry would likely be not without value upon noting that the concentric (CON) trial showed lower blood glucose levels post-exercise when compared to the eccentric (ECC) trials. Despite these numerous reports, the differences in metabolic and cardiovascular demand across an entire workout session consisting of upper and lower body eccentric or concentric only exercise has yet to be investigated. The results would have implications for a variety of populations including those with cardiovascular, pulmonary or metabolic diseases or those who are utilizing resistance training to lose weight.

Thus, the purpose of this study is to compare cardiovascular and metabolic demand, substrate utilization, and blood glucose during full body resistance workouts consisting of eccentric only, concentric only or both eccentric and concentric exercise. The measured variables will be blood lactate and blood glucose, VO_2 , HR, %CHO and MAP. We hypothesized that we will see a greater rise in blood glucose (and subsequent lowering concerning blood glucose) and blood lactate, VO_2 , HR, RER, and substrate utilization during the CON trials compared to traditional resistance exercise. Succinctly, we expect to see lower levels of all these variables in the ECC trials compared to traditional exercise.

Methods

Subjects

Twelve healthy individuals 6 male, 6 female (a) 21 ± 2 years of age (b) $1.72 \pm 0.08m$ tall (c) weighing $68.83 \pm 10.83kg$, agreed to participate in this investigation. After signing an Informed Consent, as well as answering a Health History Questionnaire, the subjects were asked to visit the lab on 4 separate occasions. Subjects were required to be free of upper or lower extremity injuries, cardiovascular or metabolic disease and have been performing resistance training for at least one month prior to their participation. This resistance training experience is required to minimize the risk of injury and excessive muscle soreness that that would affect any of the subsequent visits.

Visit 1

The first visit required the recording of the subjects' 1 repetition concentric max (1RM) for 6 different lifts. The lifts (in order) were the Chest Press, Leg Extension, Lat Pulldown, Leg Curl, Bicep Curl and Triceps Extension. To summarize, the subject performed a quick 5-10 minute warmup, then performed 1 repetition at 90% of their predicted max for each lift. Following 90 seconds rest, a small percentage of weight was added until they could not fully perform the lift.

Visits 2-4

Following determination of the subject's 1 RM the subject came to the laboratory for 3 separate workout trials. Visit 2 was a concentric (CONC) resistance workout consisting of 3 sets of 20 repetitions on each of the six previously mentioned weight machines set at 65% 1RM. Ninety seconds of recovery were provided between each set as well as between each exercise. Visits 3 and 4 were counterbalanced and consisted of a fully eccentric (ECC) workout, and a traditional (TRAD) workout, respectively. Similar to the CONC trial, the ECC trial consisted of 3 sets of 20 repetitions at 65% 1 RM for each of the 6 exercises. However, during the TRAD workout, since the subject was required to actively perform both the concentric and eccentric phase of the lift, they were asked to perform 3 sets of 10 repetitions at 65% 1 RM. The CONC visit was chosen to be first because pilot subjects indicated it was the most difficult and they were most likely to fail prior to completing all repetitions in the CONC trial. If subjects did not complete all CONC trials successfully, the subsequent ECC and TRAD trials were matched for the number of repetitions performed in the CONC trial. For example, if they

only completed 18 repetitions on the 3rd set of the Chest Press on the CONC trial the next two visits were adjusted accordingly to reflect the same amount of work (9 repetitions in the TRAD and 18 repetitions in the ECC trial.) To allow the subjects to perform exclusively CONC or ECC contractions, 3:1 or 4:1 pulley systems were placed above each individual weight set. The pulley system was designed so that the investigators could lower or raise the weight stack depending on the trial that was being completed (e.g. when performing the eccentric trial, the investigators would use the pulley system to raise the weight stack.) A metronome was set to 70 beats per minute (two beats equaling one contraction) to assist with the timing of both the subjects and investigators for their respective movements.

Dependent Variables

During visits 2-4, metabolic and cardiovascular variables were collected during and following the exercise bouts. Prior to each exercise session, the subject was fitted to a metabolic cart (Parvo Medics, Provo Utah) via a facemask. VO₂, VCO₂ and RER and HR were recorded at baseline and continuously throughout the entire exercise session. Thus the average VO₂, VCO₂ and RER value from the start of the first set of a lift to the start of the first set of the next lift (including the 90 seconds recovery periods) were used for analysis. The measured RER was used to determine %CHO. Heart rate (Polar heart rate monitor) and blood pressure were recorded immediately after the third set of each lift. Additionally, blood glucose (mg/dL) (ACCUCHEK Glucometer) and blood lactate (mM) (Lactate Plus Monitor) were recorded at 5 specific time points during each exercise

session. These time points were pre exercise (baseline), immediately following the 4th exercise (Leg Curl), immediately post exercise, and 30 and 60 minutes post exercise.

Data Analysis

Initially we performed a mixed-design analysis of variance (ANOVA) (gender x condition) on average VO₂ across the entire workout sessions to determine if gender influenced the results. In that analysis, gender was not significant therefore all subjects were combined into one group. Subsequently, seven 1-way Repeated measures ANOVA were used to determine if there were differences in VO₂, %CHO, HR and MAP. The first was performed for each variable across the entire workout session. The subsequent six were performed to compare averages across each lift. Post-Hoc T-tests were then used to determine where the differences were located. Concerning glucose and lactate, a mixed-design ANOVA (gender x condition) was run to determine if there were differences between gender. The analysis determined gender was not significant, therefore all subjects were combined into one group. Two-way Repeated measures ANOVA (condition x time point) were used to determine differences in blood glucose and blood lactate for each time point. Post-Hoc T-tests were used to determine where the differences were located.

Results

Of the 12 subjects, only 1 was able to complete the entire 3 sets of 20 concentric repetitions at each of the six exercises. The mean repetitions across all 3 sets in the

CONC condition for each exercise were as follows; Chest Press: 16 ± 5 , Leg Extension: 18 ± 4 , Lat Pulldown: 18 ± 4 , Leg Curl: 17 ± 4 , Bicep Curl: 16 ± 5 , and Triceps Extension: 17 ± 5 . As the next two conditions were matched for mechanical work, the ECC condition had the same number of reps as concentric while the traditional required half of the repetitions (rounded up to the nearest whole contraction).

Metabolic Variables

VO₂. Analysis of Variance performed on relative VO₂ (mL/kg/min) during the entire exercise bout indicated a main effect of condition ($p \leq 0.001$). Both the CONC (10.03 ± 1.63 mL/kg/min) and TRAD (9.26 ± 1.83 mL/kg/min) conditions were found to be significantly greater than the ECC condition (6.67 ± 1.25 mL/kg/min) ($p \leq 0.001$ for both comparisons) (*Figure 1*). The CONC condition was also found to be significantly greater than the ECC condition for every lift (all $p \leq 0.001$) as well as significantly greater than the TRAD condition during Chest Press ($p = 0.010$). The TRAD condition was also significantly greater than the ECC condition through all lifts (all $p \leq 0.006$) (*Figure 2*).

%CHO. Analysis of Variance revealed a main effect of condition ($p \leq 0.001$) on %CHO. Both CONC ($85.60 \pm 7.66\%$) and TRAD ($88.67 \pm 5.44\%$) conditions were significantly greater than the ECC ($54.77 \pm 17.24\%$) condition when averaged across the entire workout ($p \leq 0.001$ and $p \leq 0.001$, respectively) (*Figure 3*). The %CHO of the subjects for the TRAD condition and the CONC condition were not significantly different

from one another. Upon breaking it down per lift, the %CHO in the CONC condition was significantly greater than the ECC condition during the Chest Press, Leg Extension, Lat Pull, Leg Curl and Triceps Extension (all $p \leq 0.015$) (*Figure 4*). The TRAD condition was found to be significantly greater than the ECC condition during all lifts (all $p \leq 0.003$). There were no significant differences between the CONC and TRAD conditions during any lift.

Cardiovascular Variables

Heart Rate. Analysis of Variance of HR showed a main effect of condition ($p \leq 0.001$). The average heart rate immediately taken after each lift during the CONC (149 ± 7 bpm) condition proved to be significantly greater than both the TRAD (133 ± 11 bpm) and ECC (102 ± 9 bpm) conditions (both $p \leq 0.001$) (*Figure 5*). The average HR post lift of the TRAD condition was also found to be significantly greater than the ECC condition ($p \leq 0.001$). When dividing the workout into individual lifts, the CONC was significantly greater than the ECC through all lifts (all $p \leq 0.001$). The TRAD condition was also significantly greater than the ECC condition through all lifts (all $p \leq 0.001$). Additionally, the CONC condition showed to be significantly greater through the Chest Press, Leg Extension, Lat Pull, Leg Curl, and Triceps Extension (all $p \leq 0.019$) (*Figure 6*).

MAP. With regards to MAP, analysis of Variance revealed a main effect of condition through the first four lifts (Chest Press, Leg Extension, Lat Pull, and Leg

Curl)(all $p \leq 0.008$). Concerning the mean of each measurement of MAP the CONC ($98.2 \pm 5.4\text{mmHg}$) condition proved to be significantly greater than both the TRAD ($96.0 \pm 6.0\text{mmHg}$) and ECC ($94.5 \pm 7.2\text{mmHg}$) conditions ($p = 0.009$ and $p = 0.002$, respectively) (*Figure 7*). The CONC condition proved to have a significantly greater blood pressure response than the ECC condition through the first four lifts (all $p \leq 0.008$). The CONC condition also proved to have a significantly greater BP response than the TRAD condition through Chest Press, Lat Pull and Leg Curl (all $p \leq 0.05$). The Leg Extension was the only lift with a significant difference when comparing the TRAD (99.97 ± 6.54) condition to the ECC (96.50 ± 8.04) where the TRAD condition was significantly greater ($p = 0.009$) (*Figure 8*). There was no significant difference between baseline measurements of MAP.

Glucose and Lactate

Glucose. There were no significant results regarding blood glucose levels. (*Figure 9*)

Lactate. Analysis of Variance of blood lactate also revealed a main effect of condition ($p \leq 0.001$). The measurements at the Post Leg Curl and Post Exercise measurements for the CONC (8.9 ± 1.7 mmol and 7.6 ± 2.9 mmol) and TRAD (9.0 ± 3.0 mmol and 8.4 ± 2.8 mmol) conditions were found to be significantly greater than that of the ECC (2.5 ± 1.0 mmol and 2.9 ± 1.3 mmol) condition (all $p \leq 0.001$)(*Figure 10*).

There were no significant differences between the TRAD and CONC conditions at any of the designated time points.

Discussion

The purpose of this study is to compare cardiovascular and metabolic demand, substrate utilization, and blood glucose during full body resistance workouts consisting of eccentric only, concentric only or both eccentric and concentric exercise. The findings of this study indicate a much greater cardiovascular and metabolic demand from concentric resistance exercise when compared to eccentric exercise. Prior to this investigation, metabolic factors such as heart rate, VO_2 , and RER had not been examined during isolated bouts of eccentric and concentric resistance exercise on a whole body level. The results of this investigation help us understand the differences in metabolic and cardiovascular demand during an entire bout of eccentric or concentric exercise and have applications to those who use exercise for weight control, as well as those afflicted with cardiovascular or metabolic diseases.

Metabolic Differences

Previous investigators have reported that concentric exercise has a greater metabolic demand compared to eccentric exercise (Abbott et al., 1952; Asmussen, 1953; Beaven et al., 2014; Bigland-Ritchie & Woods, 1976; Henriksson et al., 1972; Penailillo et al., 2013). For example, Beaven et al. (2014) reported significantly greater oxygen uptake (L/min), RER and V_E in the concentric group when comparing concentric and

eccentric exercise on an arm ergometer at 3 ascending workloads (40%, 60%, and 80% peak concentric work). Our results are similar to these previous investigations as our data also indicated greater metabolic demand from the concentric condition. Specifically, VO_2 was significantly greater during the concentric bout compared to the eccentric bout. VO_2 was also found to be greater during the entirety of the traditional bout as well as during each exercise (*Figure 1*) (*Figure 2*). These results agree with the mechanisms underlying eccentric contractions. During concentric muscle contractions, ATP is required to release the myosin head from the actin filament. ATP is required to a far lesser degree during eccentric muscle contractions because the myosin head is essentially being ripped from the actin due to mechanical stress. Eccentric work, compared to concentric work, has also been found to require less muscle activation which would point to a lesser metabolic demand (Lindstedt et al., 2001).

Our data indicated %CHO to be greater in the traditional condition than both the concentric and eccentric conditions. Though this is contrary to our initial hypothesis, the physiology behind it has a likely explanation. During the traditional bouts of exercise, the muscle is active for both phases of the lift. This means that each contraction/repetition takes twice as long to complete. Thus the elevated intramuscular pressures, that likely limit muscle perfusion, are present during the entire set. This causes the muscles to utilize more anaerobic energy sources thus resulting in a greater percentage of the energy utilized being from carbohydrates. However, during the concentric and eccentric sessions, the muscle goes through phases in which they are

completely relaxed, likely resulting in greater muscle perfusion which in turn allows for greater oxygen delivery to the muscles and reliance on aerobic energy sources. This results in a greater %CHO during the traditional session, but overall, the concentric sessions resulted in the greatest caloric expenditure because they took longer to complete.

The work by Kraemer et al. (2004) and Durand et al. (2003) under similar conditions (isolating the contractions in a resistance bout) found much greater blood lactate levels after concentric exercise compared to eccentric exercise. Our results indicated a similar trend. We saw significantly greater blood lactate responses during exercise in the concentric and traditional conditions compared to the eccentric conditions. This again indicates a much greater metabolic demand from concentric muscle contractions in a resistance exercise bout.

Cardiovascular Differences

Heart rate was found to be significantly greater when averaged through each measurement than both traditional and eccentric bouts, as well as significantly greater when averaged through each exercise. The isolation of contraction also showed a significant increase in mean arterial pressure during the concentric condition compared to both the eccentric and traditional conditions. These results reflect that of comparisons in heart rate and mean arterial pressure indicated in investigations by Overend et al. (2000) and Okamoto et al. (2006) who saw a greater cardiovascular demand through concentric contractions compared to eccentric contractions using isokinetic resistance exercise. The

results concerning mean arterial pressure are interesting because, as has been noted, concentric contractions have a greater metabolic demand which would lead to greater vasodilation within the skeletal muscle and a smaller increase in mean arterial pressure. Our results indicated that the concentric condition has a significantly greater mean MAP which would indicate that the metabolically induced vasodilation was overcome by the greater sympathetic stimulation during exercise. The eccentric condition was found to have the lowest MAP likely due to lower metabolic demand which in turn led to lesser vasodilation and reduced sympathetic drive.

Implications

Cardiovascular Disease

Previous research indicates that concentric and eccentric muscle contractions elicit similar gains in muscular size and strength (Kim et al., 2015). The current data indicates that the cardiovascular and metabolic demand across an entire exercise session of eccentric and concentric exercise is markedly different. Though these results only apply to healthy college-age individuals, the data has implications toward future research with various populations both healthy and aging/diseased. As indicated by HR and MAP, the cardiovascular demand was significantly greater during concentric exercise. The mean heart rate taken immediately post-lift during the eccentric condition was 103 ± 9 bpm. Looking at the concentric (149 ± 7 bpm) and traditional (133 ± 11 bpm) condition averages, we see a very large disparity which is not just statistically significant, but

clinically significant. This is also true with MAP. Specifically, MAP following eccentric condition was 97 ± 8 mmHg compared to 100 ± 7 mmHg and 96 ± 6 mmHg for the concentric and traditional condition, respectively. Consider cardiovascular disease as it does not allow those afflicted to perform rigorous exercise due to the risks associated. Eccentric resistance exercise would be a mode in which this population could experience the same gains in strength without the cardiovascular stress.

Metabolic Benefits

Also, as indicated by VO_2 and % of energy derived of CHO, the metabolic demand was different between eccentric and the traditional/concentric workouts. Converse to the implications concerning eccentric exercise, concentric resistance exercise would have possible implications for weight loss, the diabetic population, metabolic syndrome. Specifically, it might be beneficial to emphasize concentric exercise when employing resistance training as a weight loss intervention or to improve glucose regulation. Although blood glucose levels did not vary across conditions in this investigation, it was likely due to the balance between glucose utilization during the exercise and glucose release from the liver due to circulating catecholamines. In future studies, measuring epinephrine and norepinephrine or utilizing glucose tracers would give a better look at how these different contractions affect blood glucose regulation

Future Directions

Referring back to measuring epinephrine and norepinephrine, in future studies, it would give us a better understanding of what is occurring on a molecular level during the isolation of these muscle contractions. We would be able to see if perhaps the concentric condition caused a surge in epinephrine and norepinephrine due to sympathetic activation caused by metabolic and cardiovascular stress. Overall, there were no significant findings referring to blood glucose levels, so recording catecholamines would likely not result in any monumental findings. That does not mean that the undertaking would not be without value.

Another interesting undertaking would be examining post exercise hypotension (PEH). PEH is a well-documented phenomenon in which blood pressure following exercise transiently drops below pre-exercise values (MacDonald, 2002). Though the mechanisms behind this phenomenon are not completely understood, manipulating the metabolic requirements to perform a given amount of work could shed light on the mechanisms underlying PEH. The rehabilitative effects we could hope to see from this isolation could affect both ends of the proverbial spectrum. As shown by Kim et al. (2015), both types (eccentric and concentric) of contractions elicit similar, if not equal, muscular adaptation. By isolating a workout regimen to include only shortening contractions, we would hope to see a greater post-exercise hypotension response which would be beneficial for the hypertensive population. Inversely, by isolating the lengthening contractions we could avoid the post-exercise dip in blood pressure caused by much lower metabolic demand so that individuals with hypotension, or who

experience excessive post-exercise hypotension (e.g. individuals with Parkinson's Disease), or individuals with orthostatic intolerance can complete a workout with less risk of injury or discomfort.

Limitations

There are some limitations to this investigation to be considered. When matching for mechanical work, we cannot match for time. Specifically, since the concentric and eccentric conditions required twice as many contractions to match for mechanical work, the exercise sessions took a longer period of time to complete. Another limitation was our inability to accurately calculate carbohydrate and fat oxidation due to the RER being greater than 1.0 for the majority of the exercise session in each of the conditions. Another limitation was that we did not record VO₂ for an extended period of time after the cessation of the exercise protocol and therefore do not have data to determine how long it took the subjects to fully recover following each condition.

Conclusions

Overall, the results support our hypothesis in that concentric muscle contractions, when applied to a full body resistance bout of exercise, seem to have a greater metabolic demand than both eccentric and traditional bouts. The implications of a full body eccentric resistance workout resulting in significantly lower levels in every metabolic variable is very important when considering the contractions illicit similar growths in muscular size and strength (Kim et al., 2015).

Figures and Data

Figure 1. VO2 Full Bout. Bars represent VO2 (oxygen uptake) comparisons throughout the entire exercise session of each of the three conditions. Error bars are equal to 1 standard deviation. (#) indicates a significant ($p \leq 0.05$) difference between TRAD and ECC conditions. (!) Indicates a significant difference between CON and ECC conditions.

Figure 2. VO2 During Each Lift. Bars are grouped according to corresponding lift. Error bars are equal to 1 standard deviation. VO2 value for each lift corresponds to data recorded from the start of the 1st set to the beginning of the 1st set of the next lift. (#) Indicates a significant ($p \leq 0.05$) difference between TRAD and ECC conditions. (!) Indicates a significant difference between CON and ECC conditions. (*) Indicates a significant difference between CON and TRAD conditions.

Figure 3. %CHO Full Bout. Bars represent %CHO comparisons throughout the exercise session of each of the three conditions. Error bars are equal to 1 standard deviation. (#) Indicates a significant ($p \leq 0.05$) difference between TRAD and ECC conditions. (!) Indicates a significant difference between CON and ECC conditions.

Figure 4. %CHO During Each Lift. Bars are grouped according to corresponding lift. Error bars are equal to 1 standard deviation. %CHO value for each lift corresponds to data recorded from the start of the 1st set to the beginning of the 1st set of the next lift. (#) Indicates a significant ($p \leq 0.05$) difference between TRAD and ECC conditions. (!) Indicates a significant difference between CON and ECC conditions.

Figure 5. Heart Rate Full Bout. Bars correspond to mean of six heart rate measurements taken immediately after each lift. Error bars are equal to 1 standard deviation. (#) Indicates a significant ($p \leq 0.05$) difference between TRAD and ECC conditions. (!) Indicates a significant difference between CON and ECC conditions. (*) Indicates a significant difference between CON and TRAD conditions.

Figure 6. Heart Rate During Each Lift. Bars are grouped according to corresponding lift. Error bars are equal to 1 standard deviation. HR value for each lift corresponds to mean measurement at each of the six exercises. (#) Indicates a significant ($p \leq 0.05$) difference between TRAD and ECC conditions. (!) Indicates a significant difference between CON and ECC conditions. (*) Indicates a significant difference between CON and TRAD conditions.

Figure 7. Mean Arterial Pressure Full Bout. Bars correspond to mean MAP derived from blood pressure measurements immediately after each lift. Error bars are equal to 1 standard deviation. (#) Indicates a significant ($p \leq 0.05$) difference between TRAD and ECC conditions. (!) Indicates a significant difference between CON and ECC conditions. (*) Indicates a significant difference between CON and TRAD conditions.

Figure 8. Mean Arterial Pressure During Each Lift. Bars correspond to mean MAP derived from blood pressure measurements immediately post lift. Error bars are equal to 1 standard deviation. (#) Indicates a significant ($p \leq 0.05$) difference between TRAD and ECC conditions. (!) Indicates a significant difference between CON and ECC conditions. (*) Indicates a significant difference between CON and TRAD conditions.

Figure 9. Blood Glucose Findings. Bars correspond to blood glucose measurement at each time point. Error bars are equal to 1 standard deviation.

Figure 10. Blood Lactate Findings. Bars correspond to blood lactate (mM) measurements taken at each time point. Error bars are equal to 1 standard deviation. (#) Indicates a significant ($p \leq 0.05$) difference between TRAD and ECC conditions. (!) Indicates a significant difference between CON and ECC conditions.

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