2021, Volume 4 (Issue 1): 2 OPEN ACCESS

The Cardiometabolic Responses to Eccentric Resistance Exercise are Attenuated Compared to Load Matched Concentric and Traditional Resistance Exercise

Original Research

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Abstract

Introduction. It is well documented that eccentric contractions have a lower metabolic cost than concentric contractions. However, the net impact of this difference across an entire resistance training session is less clear. This study compared the cardiometabolic responses between full body resistance training sessions comprised of either eccentric only (ECC), concentric only (CONC), or traditional (TRAD) muscular actions. **Methods.** Twelve subjects (6 males) completed 3 work-matched exercise bouts of either ECC, CONC, or TRAD exercises (6 exercises performed at 65% one repetition maximum). Oxygen consumption (VO_2), respiratory exchange ratio (RER), heart rate (HR) and mean arterial pressure (MAP) were recorded continuously throughout the entire session, while blood glucose and lactate were measured during exercise and recovery. **Results.** Cumulative VO_2 was greater during CONC compared to ECC and TRAD (423.4 ± 35 mLO_2/kg, 249.6 ± 46.0 mLO_2/kg, and 287.7 ± 53.9 mLO_2/kg, respectively; all $P<0.001$). HR and MAP were also 46% and 4.3% greater during CON compared to ECC. Lastly, post exercise lactate accumulation was significantly greater in TRAD and CON compared to ECC (both $P<0.001$). **Conclusions.** These results indicate that an exercise session comprised of eccentric work evokes an attenuated cardiometabolic response compared to concentric or traditional exercises.

Key Words: Positive Work, Metabolism, Cardiovascular

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Published January 28, 2021

Introduction

Resistance training typically incorporates both the eccentric and concentric muscle contractions. Concentric, or shortening contractions, are considered positive work. In this instance, the force produced by the muscle is greater than the force acting against it. In contrast, eccentric muscle actions are considered negative work, as the force acting against the muscle exceeds the force produced by the muscle [1,2]. Eccentric muscle actions, also known as active lengthening, have been found to have a much lower metabolic requirement compared to concentric actions, which is attributed to a combination of mechanical decoupling of the actin-myosin binding site and the role of Titin in increasing passive stiffness during muscle lengthening [3,4].

Research identifying the lower metabolic cost of eccentric muscle actions of equal force dates to the early 1950s, when a classic study by Abbott, Bigland and Ritchie [5] compared the oxygen cost of two subjects cycling in opposition of one another while attached by the same bicycle chain. The authors reported the oxygen cost of the subject performing negative work (eccentric cycling) was significantly lower than the subject performing positive work (concentric cycling). Since then, these findings have been replicated across various exercise modalities, including leg cycling [6-8], arm ergometry [9,10] and isolated muscular contractions [11,12]. Moreover, this increased metabolic demand results in an augmented cardiovascular response (HR and MAP) to concentric work compared to eccentric work [13,14].

Despite these numerous reports, the differences in the metabolic and cardiovascular demand across a full body resistance exercise training session consisting of only eccentric or concentric exercise has yet to be investigated. This information can be particularly important for exercise prescription in a variety of populations, including individuals with cardiovascular, pulmonary, or metabolic diseases, as well as individuals participating in resistance training as part of a weight loss program. Accordingly, the purpose of this study was to compare oxygen cost (VO_2), respiratory exchange ratio (RER), hemodynamic responses (mean arterial pressure [MAP] and heart rate [HR]), rate pressure product (RPP), blood lactate accumulation, and blood glucose levels in between full body resistance training sessions consisting of eccentric only (ECC) concentric only (CONC), or traditional (eccentric and concentric phases; TRAD) exercises. We hypothesized that VO_2, HR, RER, RPP, and blood lactate accumulation would be attenuated during the ECC trials compared to traditional and CONC resistance exercise. Likewise, we expected to observe augmented responses during the CONC trials compared to traditional and ECC exercise. In contrast, we expected blood glucose to be not different or mildly attenuated during the CONC condition compared to the ECC condition (secondary to an augmented metabolic demand).

Methods

Participants

Twelve healthy individuals (6 male, 6 female, 21 ± 2 years of age, 23.1 ± 3.6 kg/m^2) agreed to participate in this investigation. The subjects were asked to report for a total of 4 visits to the vascular function laboratory. The first visit began with the signing of informed consent, followed by completion of a health history questionnaire. Next, each subject's one repetition maximum (1RM) was assessed for each of the six exercises performed (described in the *Protocol* section), and subjects were familiarized with the study protocol. All subjects were required to be free from upper and lower extremity injuries, cardiovascular or metabolic disease, nicotine use, and to have been participating in resistance training for at least one month prior to participation in this study. The protocol for this project was approved by the Institutional Review Board at Kent State University.

Table 1. *Exercise Data*

Exercise	1RM (lb)	Repetitions Performed		
		CONC	ECC	TRAD
CP	126 ± 55	15 ± 5	15 ± 5	8 ± 2
LE	205 ± 59	18 ± 3	18 ± 3	9 ± 1
LP	206 ± 65	17 ± 3	17 ± 3	9 ± 1
LC	137 ± 37	17 ± 4	17 ± 4	8 ± 2
BC	78 ± 38	15 ± 5	15 ± 5	7 ± 2
TE	87 ± 28	17 ± 4	17 ± 4	8 ± 2

Data presented as Mean ± Standard Deviation; CP= Chest Press; LE= Leg Extension; LP= Wide-Grip Lateral Pull-Down; LC= Leg Curl; BC= Biceps Curl; TE= Triceps Extension.

Visit 1. After the pre-screening process, each subject's 1RM was assessed for each of the six different exercises. Exercises included (in order) the chest press (CP), leg extension (LE), wide-grip lateral pull-down (LP), leg curl (LC), biceps curl (BC), and triceps extension (TE). All exercises were performed on guided weight-stack machines (Cybex, Franklin Park, Illinois), which was preceded by a five-minute warmup on a cycle ergometer. Subjects then performed one repetition at 90% of their self-predicted maximum for each exercise. Subjects rested for 90 seconds between each attempt. After each rest interval, the weight was increased approximately 10% before the attempt was repeated. This cycle continued for five total repetitions.

Visits 2-4. Following determination of each 1RM, subjects returned to the laboratory for three experimental exercise sessions. Subjects reported to each visit at least 3 hours postprandial, and having abstained from caffeine for 8 hours, and alcohol and intense physical activity for 24 hours prior to each visit. Also, in order to control for diurnal variation within subjects, each experimental visit was scheduled during the same time of day for each individual subject. Visit 2 was a CONC only exercise session consisting of three sets of 20 repetitions of each of the six previously mentioned exercises. Load was set at 65% of each subject's 1RM, and 90 seconds of recovery was provided between each set and between each exercise. Visits 3 and 4 were counterbalanced and consisted of ECC-only exercise or TRAD exercise that incorporated both the concentric and eccentric phase of every exercise. Similar to the CONC trial, the ECC trial consisted of three sets of 20 repetitions at 65% 1 RM for the six exercises. However, during the TRAD workout, since the subject was required to actively perform both the concentric and eccentric phase of the exercise, they were asked to perform three sets of 10 repetitions at 65% 1 RM. This was intended for matching of mechanical work. Pilot testing indicated that the CONC condition was the most difficult, therefore it was performed first. Thus, if subjects did not complete all CONC trial repetitions successfully, the subsequent ECC and TRAD trials were matched for the number of repetitions performed in the CONC trial. The average 1RM and total repetitions performed for each exercise and each condition are presented in Table 1. Of note, for subjects who completed an odd number of repetitions in the CONC and ECC trials, the number of repetitions in the TRAD trial was rounded to the nearest whole number. To allow the subjects to perform exclusively CONC or ECC muscle actions, a 3:1 pulley system was placed above the weight stack of each machine. The pulley system was utilized so that the investigators could lower or raise the weight stack depending on the trial that was being completed. For example, when each subject performed the ECC trial, the investigators would raise the weight stack with the pulley system and have the subjects

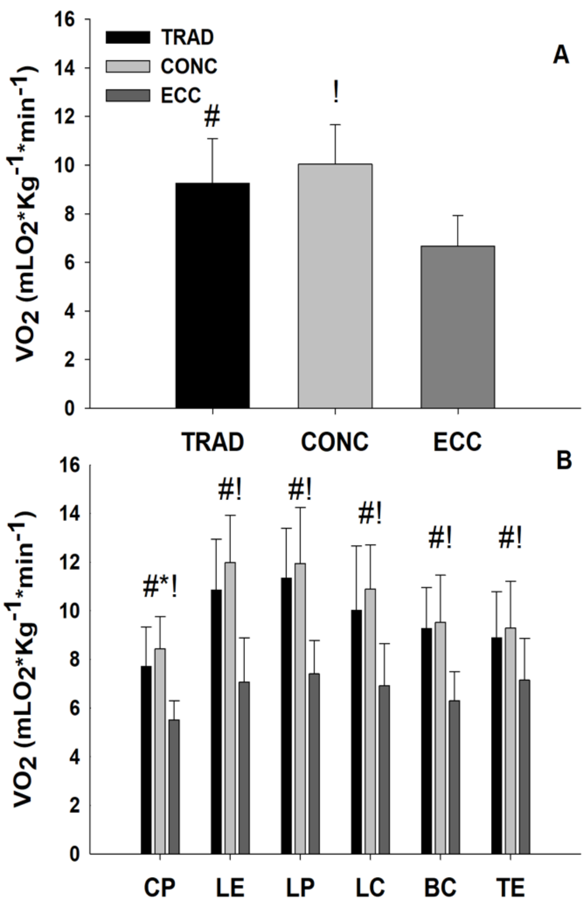

Figure 1. VO_2 compared between sessions (a) and across each exercise (b). (#) indicates a significant difference between TRAD and ECC conditions. (!) Indicates a significant difference between CONC and ECC conditions. (*) Indicates a significant difference between CONC and TRAD conditions. All data presented as (mean ± SD), and significant is set at ($P \leq 0.05$).

lower the weight stack. A metronome was used to maintain a constant rate of 3.5 seconds per full repetition (combined concentric and eccentric phases). Specifically, each subject performed half of each 3.5 second repetition for 20 total repetitions in the CONC and ECC conditions, and performed the entire 3.5 second repetition for only 10 repetitions in the TRAD condition. This approach assured that time under tension was consistent between conditions.

Dependent Variables. During visits 2-4, metabolic and cardiovascular variables were collected during and following the exercise bouts. VO_2, RER, and HR were monitored via a metabolic cart (Parvo Medics, True One 2400 Metabolic Measurement System, Provo, UT) continuously throughout the entire exercise session. Heart rate (Polar, RS800 CX, Polar Polar Electro Oy, Kempele, Finland) and blood pressure (collected manually via aneroid sphygmomanometry) were recorded immediately after the third set of each exercise. Rate Pressure Product (RPP; the measured systolic blood pressure multiplied by the heart rate) was calculated for the entire session. Blood glucose (mg/dL) (ACCUCHEK Glucometer, Roche Diabetes Care Inc, Indianapolis, IN) and blood lactate (mmol/L) (Lactate Plus Monitor, Nova Biomedical, Waltham, MA) were recorded at five specific time points during each exercise session. These time points were pre-exercise (baseline), immediately following the fourth exercise (Leg Curl), immediately following the last exercise (Triceps Extension), and at 30 and 60 minutes post exercise.

Statistical Analysis
The average VO_2, carbon dioxide production (VCO_2) and RER values from the start of the first set of an exercise to the start of the next exercise (including the 90 seconds recovery periods) were used for analysis. Initially the effect of biological sex on changes in oxygen consumption (VO_2) was examined using a mixed-design analysis of variance (ANOVA) (sex x condition). Results indicated no significant effect of sex, and therefore, all subjects were combined into one group. Subsequently, one-way repeated measures ANOVAs were used to determine the effect of condition (CON, ECC, TRAD) on VO_2, RER, HR, RPP and MAP. These ANOVA's were performed for each exercise as well as the average values across the entire exercise session. Significant differences were examined further with post-hoc analyses. Two-way ANOVA with repeated measures (condition x time point) were used to analyze blood glucose and lactate as these variables were measured at 5 specific time points during and after exercise. An alpha level of 0.05 was used for significance in all comparisons and all data are presented as mean ± SD.

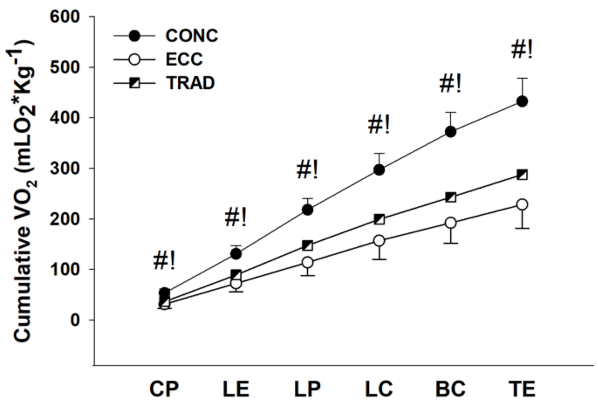

Figure 2. Cumulative VO_2 compared between conditions at each exercise (a). (#) indicates a significant difference between TRAD and ECC conditions. (!) Indicates a significant difference between CONC and ECC conditions. These data are presented as (mean ± SD), and significant is set at ($P \leq 0.05$). Panel (b) shows the individual data distribution for CONC and ECC.

Results
VO_2. Analysis of variance performed on average VO_2 (mL/kg/min) across the entire exercise bout indicated a main effect of condition ($P \leq 0.001$). Both the CONC (10.0 ± 1.6 ml/kg/min) and TRAD (9.3 ± 1.8 ml/kg/min) conditions evoked significantly greater responses than ECC (6.7 ± 1.3 ml/kg/min) ($P \leq 0.001$) (*Figure 1a*). VO_2 was also significantly greater during each individual exercise during CONC compared to ECC (all $P \leq 0.001$). VO_2 was also significantly greater during the CONC chest press compared to TRAD ($P = 0.010$). Moreover, VO_2 was also significantly greater during TRAD compared to the ECC for every individual exercise (all $P \leq 0.006$) (*Figure 1b*). Cumulative VO_2, defined as the volume (mL) of O_2 consumed per Kg body mass throughout the entire session, was also significantly greater in

CON compared to TE and ECC (432.4 ± 143.6 mLO_2/Kg, 287.7 ± 53.9 mLO_2/Kg, and 249.6 ± 46.0 mLO_2/Kg, respectively; all $P \leq 0.007$; *Figure 2*).

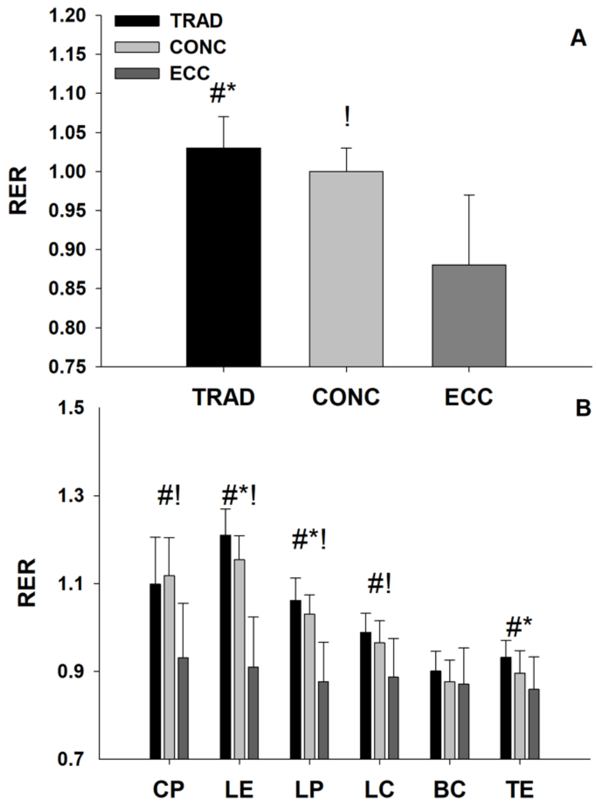

Figure 3*.* RER compared between sessions (a), and across each exercise (b). (#) Indicates a significant difference between TRAD and ECC conditions. (!) Indicates a significant difference between CONC and ECC conditions. (*) Indicates a significant difference between CONC and TRAD conditions. All data presented as (mean ± SD), and significant is set at ($P \leq 0.05$).

RER. Analysis of Variance revealed a main effect of condition ($P \leq 0.001$) for RER. Specifically, RER during the TRAD (1.03 ± 0.04) condition was significantly greater than during both the CONC (1.00 ± 0.03) and ECC (0.88 ± 0.09) conditions when averaged across the entire session ($P = 0.045$ and $P \leq 0.001$, respectively; *Figure 3a*). RER during the CONC condition was also significantly greater when compared to ECC ($P \leq 0.001$), and the RER during each individual exercise, except for biceps curl, was greater during the CONC and TRAD conditions compared to ECC (all $P \leq 0.015$; *Figure 3b*).

Heart Rate. The average heart rate across the entire CONC condition (149 ± 7 bpm) was significantly greater compared to TRAD (133 ± 11 bpm) and ECC (102 ± 9 bpm, all $P \leq 0.001$; *Figure 4a*). HR during the TRAD condition was also significantly greater compared to ECC ($P \leq 0.001$). In addition, HR during CONC and TRAD was significantly greater than ECC through all individual exercises (all $P \leq 0.001$). Additionally, with regards to each specific exercise, HR during the CONC condition was significantly greater than TRAD for the Chest Press, Leg Extension, Lateral Pulldown, Leg Curl, and Triceps Extension (all $P \leq 0.019$; *Figure 4b*).

MAP. There was no significant difference between baseline measurements of MAP. MAP during CONC (98 ± 5 mmHg) was significantly greater than both TRAD (96 ± 6 mmHg) and ECC (94 ± 7 mmHg; $P = 0.009$ and $P = 0.002$, respectively; *Figure 5a*). The MAP response during CONC was also significantly greater compared to ECC through the first four exercises (all $P \leq 0.008$), and was also significantly greater than TRAD through chest press, lateral pulldown and leg curl (all $P \leq 0.05$). The leg extension was the only exercise with a significant difference when comparing TRAD (100 ± 7) to ECC (96 ± 8), where the TRAD was significantly greater ($P = 0.009$; *Figure 5b*).

RPP. RPP during the CONC condition (20,864 ± 1218 mmHg x bpm) was significantly greater than both TRAD (18,274 ± 2035 mmHg x bpm) and ECC (13,321 ± 1801 mmHg x bpm; both $P \leq 0.001$, respectively). RPP during TRAD was also significantly greater than ECC ($P \leq 0.001$).

Glucose and Lactate. There were no significant differences in blood glucose levels between conditions (*Figure 6),* however, results indicated a main effect of condition on blood lactate ($P \leq 0.001$). Specifically, blood lactate taken following leg curl and triceps extension during CONC (8.9 ± 1.7 mmol/L and 7.6 ± 2.9

mmol/L) and TRAD (9.0 ± 3.0 mmol/L and 8.4 ± 2.8 mmol/L) were significantly greater than that of the ECC condition (2.5 ± 1.0 mmol/L and 2.9 ± 1.3 mmol/L; all $P \leq 0.001$; *Figure 6*). There were no significant differences between the TRAD and CONC conditions at any of the designated time points.

Discussion

The purpose of this study was to compare cardiovascular and metabolic demands during full body workouts consisting of eccentric only, concentric only or traditional resistance exercise. Our findings indicate a much greater cardiovascular and metabolic demand from concentric resistance exercise compared to eccentric exercise when the load and mechanical work is matched. Prior to this investigation, metabolic factors such as heart rate, VO_2, and RER had not been examined across a combined upper and lower body resistance exercise session composed of only eccentric or concentric exercise. These results have implications for exercise prescription related to weight control, as well as those afflicted with cardiovascular or metabolic diseases.

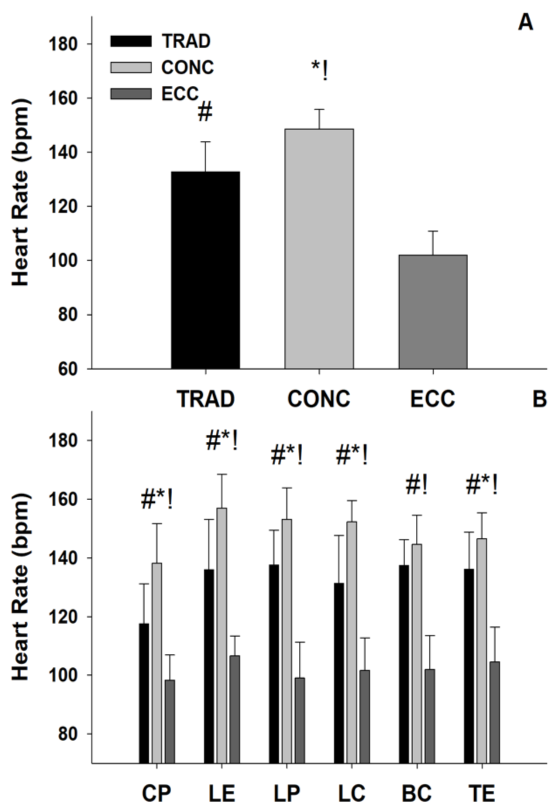

Figure 4. Heart rate compared between sessions (a), and across each exercise (b). (#) Indicates a significant difference between TRAD and ECC conditions. (!) Indicates a significant difference between CONC and ECC conditions. (*) Indicates a significant difference between CONC and TRAD conditions. All data presented as (mean ± SD), and significant is set at ($P \leq 0.05$).

Metabolic Differences. Previous investigators have reported that concentric exercise has a greater metabolic demand compared to eccentric exercise [5-10]. For example, Beaven et al. (2014)[10] reported significantly greater oxygen uptake (L/min), RER and ventilation (V_E) during concentric arm ergometry compared to eccentric arm ergometry. The current data also indicates greater metabolic demand from the concentric condition. Specifically, VO_2 averaged 50% greater across the whole concentric session compared to the eccentric bout and ranged from 30% (Triceps Ext.) to 70% (Leg Ext.) greater for each individual exercise. VO_2 was also greater during TRAD compared to ECC (*Figure 1a and b*). Perhaps more importantly, the total volume of oxygen consumed (and therefore total caloric expenditure) was substantially higher in the concentric exercise bout. These results agree with the mechanisms underlying eccentric contractions. Historically it was believed that the requirement of ATP is reduced during eccentric muscle actions because the myosin head is mechanically pulled off actin rather than dissociated via ATP hydrolysis. More recently the active role of titin during eccentric actions has been elucidated. Specifically, it's believed that during active lengthening contractions, calcium flux into the myoplasm initiates the binding of N2A to the thin filament, essentially eliminating the more compliant Ig segment and increasing the passive force that has no metabolic requirements (for review see the 2011 review by Nishikawa and colleagues[3].)

RER was lowest during ECC, however, contrary to our initial hypothesis RER was significantly greater during TRAD compared to CONC. This could be explained by the combination in the different rates of ATP utilization and the interaction between muscle blood contractions and blood flow. Specifically, unlike the CONC and ECC exercise, during the TRAD bouts of exercise the muscle is active for both phases of the exercise. Thus, increases in intramuscular pressure and ischemia related to contracting muscle are present during the entire set. This likely limited the O_2 supply to the muscle, resulting in a greater energy derived from carbohydrates (a shift to a predominantly anaerobic energy pathway). However, during the concentric and eccentric sessions, muscle actions are separate by periods of passive movement, which transiently reperfuses the muscle and spares metabolite accumulation.

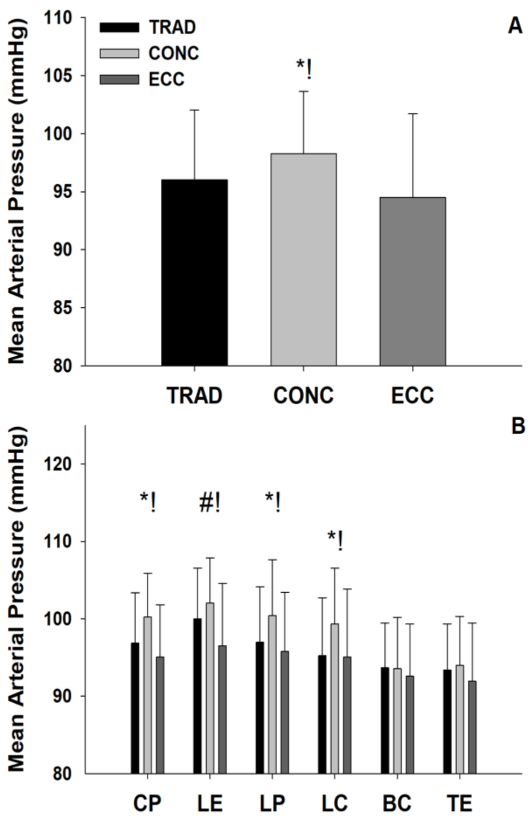

Figure 5. Mean Arterial Pressure (MAP) compared between sessions (a), and across each exercise (b). (#) Indicates a significant ($p \leq 0.05$) difference between TRAD and ECC conditions. (!) Indicates a significant difference between CONC and ECC conditions. (*) Indicates a significant difference between CONC and TRAD conditions. All data presented as (mean ± SD), and significant is set at ($P \leq 0.05$).

Blood lactate was 256% and 162% greater during the midpoint and at the end of the CONC trial, respectively, compared to the ECC trial; and was 260% and 189% greater at the midpoint and end of the TRAD trial, respectively, compared to the ECC trial. This again suggests a much greater metabolic demand from concentric muscle contractions in a resistance exercise bout. These findings agree with work by Durand et al. (2003)[15] and Kraemer et al. (2004)[16] who, under similar conditions, found much greater blood lactate levels after concentric exercise compared to eccentric exercise.

Cardiovascular Differences. In general the cardiovascular demand was much greater during the CONC compared to ECC conditions. Heart rate following each exercise and across the session was greater during CONC compared to TRAD and ECC. This difference tended to be larger during the exercise utilizing greater muscle mass. MAP was also greater during the concentric condition compared to both the eccentric and traditional conditions. These results reflect comparisons in heart rate and mean arterial pressure reported by Okamoto et al.[13] and Overend et al.[14] who observed a greater cardiovascular demand through concentric contractions compared to eccentric contractions using isokinetic resistance exercise. Interestingly, the greater metabolic demand during concentric exercise would presumably lead to greater vasodilation within the skeletal muscle and a smaller increase in MAP. However, the concentric condition demonstrated a significantly greater MAP response, which would indicate that the metabolically induced vasodilation was overcome by greater cardiac output and sympathetically mediated vasoconstriction in the non-active tissue. Interestingly, Stavres et al. (2019)[17] also reported an augmentation of post-exercise hypotension following concentric only resistance exercise compared to eccentric only resistance exercise, which may be explained by a sympathetically mediated neural adjustment to post exercise blood pressure regulation[18]. The eccentric condition had the lowest MAP, likely due to lower metabolic demand which, in turn, led to reduced sympathetic drive. Furthermore, HR and SBP are both represented by the RPP, which was significantly lower in the ECC condition compared to both the TRAD and CONC conditions.

Implications. This is the first investigation to compare the cardiovascular and metabolic responses between sessions of upper and lower body resistance exercise comprised of either traditional, concentric only, or eccentric only contractions. Our findings indicate that the cardiovascular strain associated with eccentric exercise is significantly lower compared to work-matched concentric or traditional exercise. This is the first step in understanding the differences between whole body eccentric and concentric exercise training, and this information is particularly important for exercise prescription in subjects with a challenged cardiovascular system. Specifically, concentric and eccentric muscle contractions have been suggested to elicit similar gains in muscular size and strength [19,20]. Therefore, eccentric exercise might serve as a safer alternative for those who are at risk of a cardiovascular event due to cardiovascular disease. The next logical step in this line of research is to examine the influence of prescribing exercise intensity based on the individual eccentric and concentric 1RM. Further exploration would also be needed with regards to the muscle soreness evoked by eccentric exercise [21], though the repeated bout effect seems to attenuate this [22]. Also, as indicated by VO_2 and RER, metabolic demand was attenuated during the ECC condition compared to CONC and TRAD. In contrast to the implications concerning eccentric exercise, concentric resistance exercise would have possible implications for weight loss and those with metabolic diseases (i.e. diabetes). Although blood glucose levels did not vary across conditions in this investigation, this may be influenced by the balance between glucose utilization during the exercise and glucose release from the liver related to circulating catecholamines. In future studies, measuring epinephrine and norepinephrine or utilizing glucose tracers would better describe how these different contractions affect blood glucose regulation.

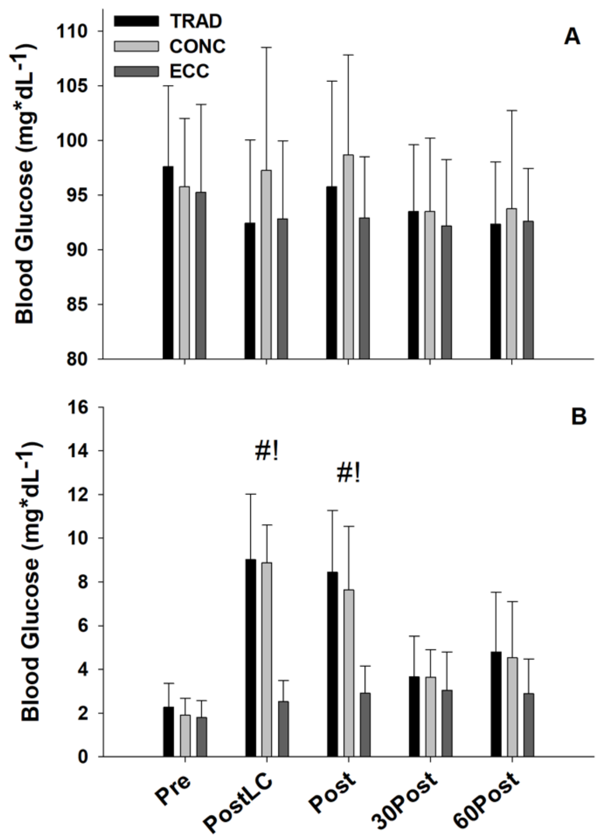

Figure 6. Blood glucose (a) and blood lactate accumulation (b) compared across time and between conditions. (#) Indicates a significant difference between TRAD and ECC conditions. (!) Indicates a significant difference between CON and ECC conditions. All data presented as (mean ± SD), and significant is set at ($p \leq 0.05$).

Limitations. As in any human investigation, this study was subject to certain limitations. First, since the concentric and eccentric conditions required twice as many contractions (3x20) to match for the mechanical work performed during the traditional condition (3x10), the exercise sessions took a longer period of time to complete. However, equalizing the exercise durations between each condition would have required either extended rest periods in the TRAD condition or slower rate of repetition. As those options also have their own inherent limitations, we chose to keep the rest periods and repetition rates consistent between all three conditions. Second, although exercises were matched for mechanical work, we were unable to match for relative effort. Future investigations may consider expanding these findings to include comparisons of the cardiometabolic responses between eccentric and concentric exercise bouts of the same relative (or perceived) effort.

In conclusion, these results support the hypothesis that a full body resistance training session comprised of eccentric only exercises evokes attenuated cardiovascular and metabolic responses compared to work matched resistance training sessions comprised of concentric only and traditional exercises. This has significant implications for exercise prescription in a variety of populations, especially considering the beneficial muscular adaptations reported with eccentric muscle training [19,20].

Media-Friendly Summary

During a typical strength training session, contractions are performed in two phases. When the weight is lifted (and the muscle is shortened), this is called a concentric contraction. When the weight is lowered (and the muscle lengthens), this is called an eccentric muscle action. Eccentric exercise has emerged as an area of interest in strength training programs, and therefore, it is important to understand how this form of exercise effects the cardiovascular and metabolic systems. This investigation examined the cardiovascular and metabolic responses to three different resistance training sessions comprised of either concentric only exercise, eccentric only exercise, or traditional (combined) exercise. Our data suggest that, when matched for total work (weight moved over time), a full bout of eccentric exercise has a much lower cardiovascular and metabolic strain compared to traditional or concentric resistance exercise sessions. This information is important for designing exercise programs for a variety of populations.

Conflicts of Interest

The authors do not have any conflicts of interest to report.

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