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Acute Effects of Enhanced Eccentric and Concentric Resistance Exercise on Metabolism and Inflammation

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Abstract

This study compared the metabolic, cardiopulmonary and inflammatory responses of novel acute machine based concentrically-focused resistance exercise (CON RX) and eccentrically-focused resistance exercise (ECC RX). Twenty healthy adults (26.8 ± 5.9 yrs; 25.4 ± 4.0 kg/m^2) performed two work-matched RX exercise sessions. Cardiopulmonary responses, rating of perceived exertion (RPE), soreness, oxygen consumption; (VO2) were collected during each session. Blood lactate and levels of inflammatory cytokines interleukin-1 alpha (IL1α), interleukin-6 (IL6) and tumor necrosis factor-alpha (TNFα) were analyzed pre, post ad 24 hours post-exercise. HR were higher (5-15bpm) during ECC RX (p<.05). Soreness ratings were consistently higher post-ECC RX compared to CON RX. VO2 area under the curve was higher during ECC than CON (31,905 ml/kg/min vs 25,864 ml/kg/min; p<.0001). Post-ECC RX, TNFα levels increased compared to CON RX 23.2 ± 23.9% versus 6.3 ± 16.2% (p=.021). ECC RX induced greater metabolic, cardiopulmonary and soreness responses compared to matched CON RX. This may be due to recruitment of additional stabilizer muscles and metabolic stress during the ECC RX. These factors should be considered when designing ECC RX programs particularly for untrained persons, older adults or those with history of cardiovascular disease.

Keywords

Eccentric; Resistance exercise; Cytokine; Lactate; Soreness; Oxygen uptake

Introduction

Resistance Exercise (RX) promotes muscle strength and physical performance and healthy living [1]. During RX, there are two phases of muscle contraction, concentric and eccentric.

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Skeletal generates higher forces during the eccentric phase of muscle contractions. Eccentric muscle actions are essential in performing normal daily activities and physical activities such as stair climb and descent, body transfers and balance tasks [2]. Eccentric actions occur during sport activities such as running and walking. Also, eccentric strength is important for retaining functional independence with aging [1].

At present, there is a gap in the translation of the eccentric resistance exercise (ECC RX) model into a practical, accessible exercise machine type. This limits the populations who might obtain benefit from this type of resistance exercise. Eccentric exercise has been previously studied using isokinetic dynamometers or cycle ergometers that rotate backwards (thereby producing eccentric contractions) [2-8]. Metabolic studies of resistance exercise have been conducted in isolated muscle groups, [9], but not in a whole body program. Also, isokinetic dynamometers allow one muscle group to be trained and do not combine both concentric and eccentric contractions as would be performed in daily functional activities. To address this gap in the literature, we developed an eccentrically focused resistance exercise machine system that could safely control eccentric and concentric phases of multiple resistance exercises for all main muscle groups. These machines could be operated by a single user who controlled resistance loads for concentric and eccentric phases of movement. Unlike other eccentric RX programs, our enhanced ECC RX system provides an electronically controlled, reproducible eccentric phase for long term training. This system also allows for the study of the direct comparison of muscle work generated during eccentric and concentric RX sessions.

Acute resistance exercise responses may trigger different metabolic, cardiopulmonary and inflammatory responses depending on the nature of the exercise protocol. RX transiently increases circulating Creatine Kinase (CK) and inflammatory cytokines over 24-48 hours [10,11] (indicative of muscle damage, repair and remodeling). It is not clear how our machine based ECC RX affects these responses compared to CON RX. What is known is that short-term training (using enhanced eccentric squats and bench press) compared to traditional CON RX in young men induced similar lactate levels and anabolic hormones such as growth hormone and testosterone [12]. The magnitude of the metabolic demand and fatigue may directly affect the cytokine responses to acute RX. Differences in these parameters are important to understand before prescriptions of enhanced ECC RX can be applied to various populations.

The purposes of this study were to: 1) comparing the acute metabolic and cardiopulmonary responses of enhanced eccentric and concentric resistance exercise, and 2) comparing biochemical indices of muscle remodeling and inflammation with eccentric and concentric RX out to 24 hours after each exercise session.

Materials and Methods

Participants

Twenty healthy adults (aged 18-45 years) were recruited locally through flyers and online web departmental study opportunity listings. Each participant had resistance trained for a minimum of one year, for at least one time per week. All participants read and signed an informed consent document approved by the Institutional Review Board. This study was approved by the University Institutional Review Board. All procedures were in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki.

Design

This was a randomized, cross-over study design in which all participants completed two exercise sessions. The two sessions were separated by one week. One session involved the use of traditional, concentrically focused resistance exercise machines (CON RX; MedX®) and the second session involved exercise with modified MedX® machine that enhances the eccentric phase of contraction (Figures 1a and 1b). This was the eccentrically focused resistance exercise (ECC RX). The testing order was balanced and randomized. Participants received sealed envelopes with the assigned testing order.

Enhanced eccentric exercise machines

Figures 1a and 1b illustrates the assistive lifting apparatus and the eccentric overload in the modified machines compared to the traditional MedX® machines. To create the enhanced eccentric resistance, a main weight stack was lightened by a secondary, counter balance weight stack (Figure 1b). The counterbalance stack permitted participants to raise the main weight stack. This constituted the concentric resistance.

The counter balance weight for enhanced eccentric exercise used a conventional weight stack of 9.1 kg plates. With the entire weight stack suspended above ground, the stack slid vertically along guide rods. The bottom of the weight stack was supported by a carriage plate, which likewise slides on the same guide rods as the weight plates. The carriage plate moved up the guide rods pulled by a cable that was connected to an electric motor. When the electric motor was activated, the motor pulled a cable attached to the carriage plate. The carriage plate was pulled vertically until it reached the top of its excursion (which was the bottom of the suspended weight stack). The resistance load that was supported by the carriage plate directed its pull to the main weight stack. This way the carriage plate “lightened” the resistance load of the main weight stack. The weight was pinned to the center post so that the participant could choose the amount of counter balance help that is desired. When the motor was placed into reverse, the carriage plate received the plates that moved downward along the guide rods. This offset force on the main weight stack. The motor wound up the cable and reset the counter weight in the raised, unengaged position.

Exercise schedule and protocol

All participants visited the Laboratory for a total of three occasions during the hours of 8:30am-1:00pm. Height and weight and were measured by standard methods. In order to minimize the effect of diurnal variation, each test was arranged at a similar time of day (± 1 hour) with stable environmental conditions (~22° C, ~60% humidity). On the first visit, participants were familiarized to the exercise equipment. A one repetition maximum (1RM) was obtained for each of the exercise machines using a procedure described previously [13]. In brief, a rating of perceived exertion (6-20 points, Borg scale; where 6=no muscle exertion and 20=greatest muscle exertion possible) was used by the participants to rate the muscular effort for each trial until the 1RM was obtained. Based on the 1RM value, the resistance loads on the machines were set for the following two sessions.

The second and thirds visits consisted of acute exercise sessions with either the traditional concentrically focused machines or the enhanced eccentric exercise machines. Visits were separated by one week. Each session was preceded by a five-minute warm up on a treadmill (Quinton) at 5.3 km/hr. The two exercise sessions were matched with exercises on six equivalent machines. Two sets were performed of each of the following exercises: leg extension, leg curl, chest press, seated row, shoulder press and pull-down. The exercise protocols were matched for work volume completed during each session. The following concentric intensity and repetition structure was chosen because this is well tolerated even by older adults, and provides a moderate training stimulus that is within the exercise recommendations of the American College of Sports Medicine (ACSM). The ECC RX repetition structure was chosen to match work volume across conditions, and was well tolerated by subjects during pilot testing. During the CON RX session, participants completed 12 repetitions for each exercise set at 60% of 1RM. The enhanced ECC RX consisted of performing 10 repetitions for each set at 100% 1RM for the eccentric phase and 50% 1RM for the concentric phase. The time to lift and lower the weight was kept consistent using a timer and verbal counting for each participant (two seconds up, two seconds down). A one minute rest period separated each exercise set. After the last set, participants rested for a five-minute cool down period.

Muscle soreness ratings

Muscle soreness ratings were collected pre, post and 24 hours post-exercise for each session. A visual analogue scale (0-10 cm; VAS, with 0=no soreness, 10=worst soreness imaginable) was used to rate soreness. Standardized instructions were provided to each participant on rating soreness in the quadriceps muscle group, hamstrings muscles, shoulder muscles and pectorals muscles. Soreness was measured while sitting at rest and during activity (leg extension, leg curl, and chest press and shoulder press actions with no weight).

Metabolic and cardiopulmonary assessments

To determine whether or not there was a difference in oxygen cost between the two exercise protocols, comprehensive metabolic assessments were captured during each exercise session using a portable oxygen consumption (VO_2) device (COSMED, $K4b^2$). The $K4b^2$ unit acquired a breath-by-breath measurement of gas exchange via a rubberized facemask and a turbine for gas collection. The appropriately sized facemask was selected to ensure a proper fit. Prior to testing, the $K4b^2$ analyzer was warmed-up for a minimum of 30 minutes. After the warm-up period, the O_2 and CO_2 analyzers were calibrated using reference gases of known concentrations. Participants wore the $K4b^2$ continuously during a five minute pre-exercise baseline period, during the five minute treadmill warm-up, during the exercise sessions and during the five minute cool down. The overall oxygen use was calculated as the area under the curve for this time period. In addition to the VO_2 values, (collected in oxygen uptake in milliliters per minute [$mL \cdot min^{-1}$], milliliters per kilogram of body weight per minute [$mL \cdot kg^{-1} \cdot min^{-1}$]), kilocalories per minute ($kcal \cdot min^{-1}$), minute ventilation and respiratory quotient values were collected.

Heart Rates (HR) were obtained in parallel with the K4b^2 assessments. HRs was captured using an integrated telemetric heart rate monitor (Polar, Inc.). Blood Pressure (BP) measures were manually collected after each exercise. RPE values were collected after each exercise set for a total of 12 measures per session. These measures were also used to monitor exercise safety.

Blood sampling and analysis

Blood lactate concentrations were collected using a portable lactate meter (Lactate Plus, Nova Biomedical Corporation, Waltham, MA). Samples were obtained from a finger at baseline and after finishing the leg curl, seated row, and pull down. Samples were obtained in duplicate. A second blood sample was collected from an antecubital forearm vein at baseline, immediately following the recovery period and at 24 hours post-exercise. Creatine Kinase (CK) concentrations were measured to estimate muscle damage using an enzyme linked immunosorbent assay (ELISA). Inflammatory cytokine levels were measured using a Milliplex MAP kit of Human Cytokines/ Chemokine (Millipore Corp; Billerica, MA) for the simultaneous quantification of several cytokines including IL-1α, IL-6 and TNFα. These cytokines were chosen for their potential roles in modulating skeletal muscle mass [14] and post- exercise inflammation. [15] Samples were run in duplicate; if one sample was markedly different than the other, a third sample was analyzed.

Additional subjective safety assessments

To track safety issues related with either exercise protocol, we collected information from participants regarding any abnormal musculoskeletal pain, injuries, gastrointestinal discomfort, headaches, lightheadedness, cardiac issues and weakness. Data were collected during, immediately post-exercise and at 24 hours post-exercise.

Statistics

Data analysis was performed using the Statistical Package for the Social Sciences (SPSS, v 20). Descriptive measures and frequencies were compared at baseline. Repeated measures analysis of variance (ANOVA) were performed on the physiological and biochemical variables, where exercise condition was the within group factor was exercise condition (concentric, eccentric) with Greenhouse-Geisser correction. Change scores in the cytokine levels and CK were determined (change from pre-exercise condition to 24 hours post-exercise) and compared between exercise conditions using a univariate ANOVA. A significance level of $p<.05$ was established á priori.

Results

The study group was comprised of 70% men. The work completed during the concentric and eccentric sessions was 73,623 ± 29286 Nm and 72,281 ± 17,108 Nm, respectively. This indicated that the sessions were well matched for work load (Table 1).

Muscle soreness

All participants indicated no muscle soreness for any muscle group at baseline. Immediately post-exercise, muscle soreness ratings were significantly higher post-ECC RX in the chest and shoulders (Table 2). At 24 hours, muscle soreness ratings were higher post-ECC exercise in all muscle groups compared with the CON RX condition (all p<.05).

Cardiopulmonary responses and rating of perceived exertion

The area under the curve for VO_2 values attained during the CON RX were lower than those during the ECC RX (45,539 ± 24,988 ml/kg*min versus 57,798 ± 32,439 ml/kg*min; p<0.05 respectively). The peak VO_2 values, however, were not different between sessions (31.9 ± 13.9 ml/kg*min with CON RX versus 35.4 ± 10.8 ml/kg*min with ECC RX). Peak minute ventilation values were lower during CON RX than during ECC RX (81.3 ± 27.8 L/min versus 97.3 ± 22.4 L/min; p<0.05).

Systolic and diastolic blood pressures were not significantly different between sessions, with the exception of a higher diastolic blood pressure after ECC RX leg extension compared to CON RX leg extension (69 ± 8 mmHg versus 64 ± 9 mmHg; p=0.05). Peak blood pressure values were not different between exercise sessions. Heart rate values were generally higher after ECC exercise sets compared to CON exercise sets (Figure 2). The RPE ratings were also generally higher during the ECC RX session compared with those in CON RX session (Figure 3).

Blood analyses

Figure 4 presents the blood lactate levels before and during each exercise bout. Lactate levels were higher with ECC RX after leg extension-curl and chest-seated row sets (p<.05). The CK and cytokine levels are presented in Table 3. The raw data and the changes in these levels over time are shown. Among all blood measures, the change in TNF-α increased significantly post-ECC RX exercise compared to the change post-CON RX (p<.05).

Additional safety measures

During all the exercise testing sessions, there was one minor adverse event of nausea after the ECC exercise. This event resolved with rest. There were no major safety concerns with either exercise protocol. All measured cardiovascular responses were normal.

Discussion

This study compared the metabolic, cardiopulmonary and inflammatory responses of a novel ECC RX protocol and work-matched CON RX. The cardiopulmonary responses, metabolic responses and perceptions of difficulty were generally higher after ECC RX compared to CON RX. Overall, the ECC RX was well tolerated and safe, with no significant change in CK values. There were no adverse events to report other than transient nausea in one participant. Among the inflammatory cytokines measured, TNFα levels increased after ECC RX compared to CON RX.

Concentric actions are believed to be a large contributor to the oxygen and energy cost of resistance exercise [9,16]. In our study, we found that oxygen cost was higher with ECC RX than CON RX. This unanticipated finding could indicate other factors that are contributing to increase VO_2. For example, supporting musculature such as the abdominals, lumbar muscles and upper extremity muscles may have been activated during our ECC RX protocol. The additional muscle recruitment may be necessary to stabilize our participants and control the movement during the weight-lowering at 100% of 1RM. Greater muscle activity would directly increase the rate of oxygen consumption. This is an important consideration when developing enhanced eccentric exercise prescriptions. The stabilization activity around the exercising muscle group may drive the cost of metabolic work, cardiopulmonary responses and perceptions of effort. We attempted to address this issue using electromyographic (EMG) measures in a subset of participants. However, the wires were compressed underneath the hamstrings and low back while on the machines and this caused significant signal noise. We did find in two participants that EMG activity patterns and amplitude differed during leg curl and leg extension and shoulder press, with increased recruitment of lumbar extensors and abdominal muscles in the ECC condition. Additional EMG studies would be important in determining the contribution of co-activated muscles in each exercise.

From the clinical point of view, eccentric resistance exercise has strong potential for rehabilitation protocols and performance improvement. However, using the model in the present study, ECC RX can dramatically change metabolic and cardiopulmonary responses compared to CON exercise. Our findings suggest that a slow transition from moderate eccentric loads (e.g., 50-75% of maximal concentric strength) to the maximal loads should be done over a period of weeks. This transition would to permit the cardiopulmonary systems to adapt in untrained or older individuals. This finding is in contrast to earlier work which showed that ECC ergometry induced lesser cardiopulmonary responses despite higher muscle force generation [17].

Soreness ratings were higher in the pectoral and trapezius muscles immediately after the eccentric exercise compared to the concentric exercise. Soreness levels achieved in this study are similar to other studies that used heavy leg resistance exercise (5 sets of 10 RM bilateral leg presses and squats) where a few days rest was required for full functional recovery [18]. Comparative post-exercise soreness data are limited for shoulder or chest musculature. Multiple sets of isokinetic eccentric depressions of the shoulder girdle increased trapezius muscle soreness by 88% [19]. Isolated shoulder exercise increased soreness levels as much as 80% by 24 hours [20]. We are unaware of any study examining enhanced eccentric exercise and soreness in the pectoralis muscles. Because two exercise sets induced soreness levels similar to that attained with multiple sets, we suggest that enhanced ECC RX should be administered conservatively in untrained or older adults to avoid unintended severe muscle soreness and difficulty performing upper body activities.

The lactate and TNF-α responses with ECC RX was greater compared with the CON RX. The serum CK levels were not significantly elevated after either exercise bout. Some studies of eccentric exercise have not found elevations in IL-1, IL-6 or TNF-α post-exercise [21]. Contrasting data show that elevations of IL-6 occur with acute, prolonged bilateral leg extension [22], or after multiple sets of squatting activity [23]. Differences in cytokine production may be due to the combined differences in the size of the muscle groups exercised (one small group versus a few large muscle groups), exercise mode, the resistance load and the number of sets or duration of the exercise. Other evidence shows that circulating levels of TNF-α, IL-1 or IL-6 do not increase after acute leg resistance exercise [15], but the mRNA content of these cytokines was increased in skeletal muscle. Training status may influence cytokine production. Long term resistance training can reduce circulating levels of proinflammatory cytokines such as TNFα IL-6 and IL-1 in clinical populations [24,25] and older adults [26]. In the present study, the total body exercise regimen in these trained participants may not have generated sufficient mechanical stress any one or all muscle groups to cause cytokine release.

Additional considerations for rare adverse events

Appropriately prescribed resistance exercise is recommended to all adults, even among persons in cardiac rehabilitation [27]. However, very strenuous resistance exercise can dramatically increase systolic and diastolic blood pressures. Persons with preexisting conditions such as aortic enlargement [28] or vascular blockage can develop aortic or celiac dissection with strenuous resistance exercise compared to people who do not have these conditions [29,30]. Persons with a smoking history or with a propensity for excessive sport drink usage may also be more likely to experience cardiovascular events. Sport drinks, when used with strenuous resistance exercise, may trigger tachycardia [31] and exacerbate existing conditions. Preexisting cardiovascular conditions are commonly inflammatory in nature. Interventional studies are warranted to determine whether the ECC RX induced inflammation is transient as the exerciser adapts over time, or whether the inflammation causes vascular damage and triggers cardiovascular events.

Study limitations and strengths

This study was a comparison of acute exercise responses, and we did not determine the training adaptations to this enhanced ECC RX. The relatively small sample size and large variability in the inflammatory cytokine responses may have prevented statistical significance, and larger participant pools are needed to offset this variability. Electromyographic measures would have provided evidence of whether there was increased recruitment of stabilizing muscle groups in the ECC RX condition, but we were unable to get reliable signals. Our study group was fairly homogenous. We might have observed inflammatory cytokine differences within other age groups or levels of training experience. The strengths of the study include a comprehensive assessment of subjective and objective variables before, during and after each exercise bout. These data provide direction for future studies of this resistance exercise model and have yielded considerations regarding physiological responses that are necessary for safe prescription of this exercise mode in varying populations.

Conclusion

ECC RX induced moderate changes in metabolic and cardiopulmonary measures, muscle soreness and TNFα compared to CON RX. This ECC RX model was well tolerated. Because of the greater metabolic response with ECC RX, participants should transition slowly with progressive loading. This would be most important for untrained persons, older adults or individuals with recent musculoskeletal injury.

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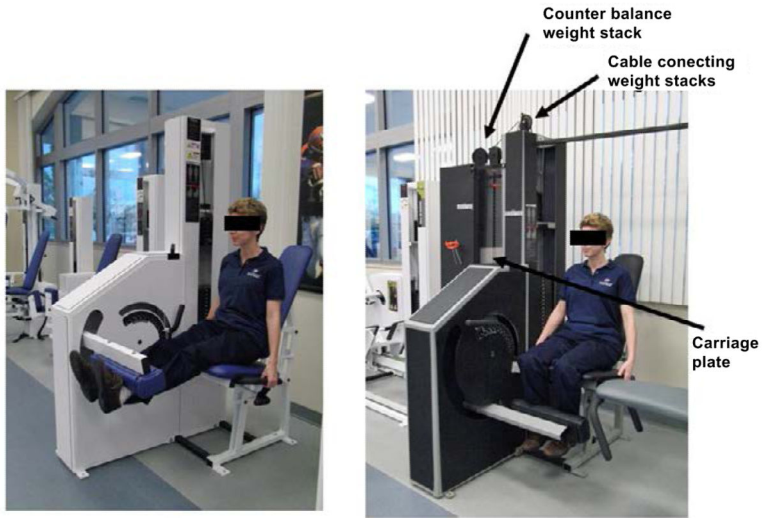

Figure 1.

(a): The traditional concentrically based resistance exercise machine with a resistive weight stack that applies the same resistance during both phases of muscle contraction.

(b): The enhanced eccentric resistance exercise machine with an assistive weight stack coupled with the resistive weight stack. The assistive stack can be modified to control the amount of weight supported during the concentric phase.

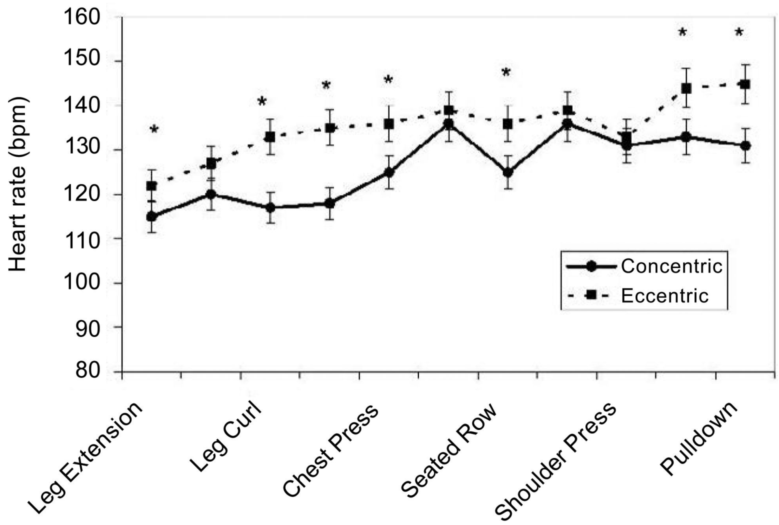

Figure 2.

Heart rate pattern comparison during a session of concentric and enhanced eccentric exercise. Values are means ± SD. * denotes different from the concentric exercise group at the same time point at $p<0.05$.

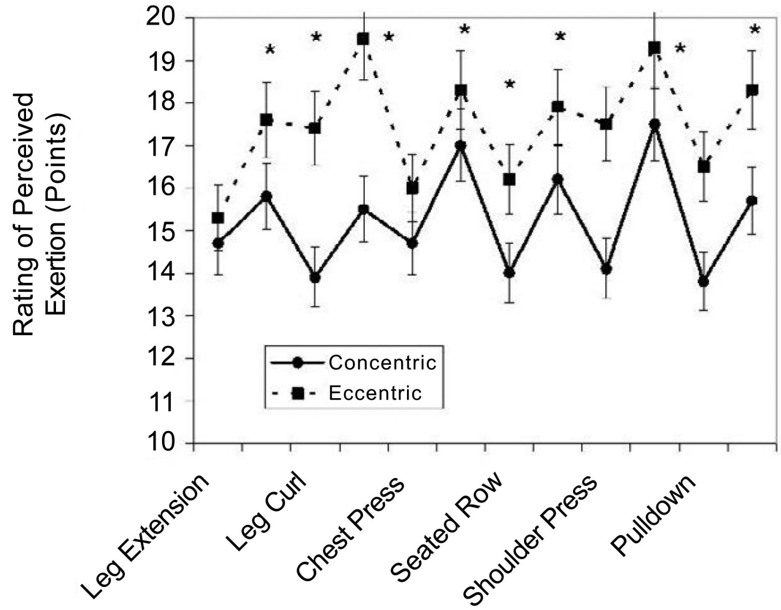

Figure 3.

RPE values obtained during a session of concentric and enhanced eccentric exercise. Values are means ± SD. * denotes different from the concentric exercise group at the same time point at $p<0.05$.

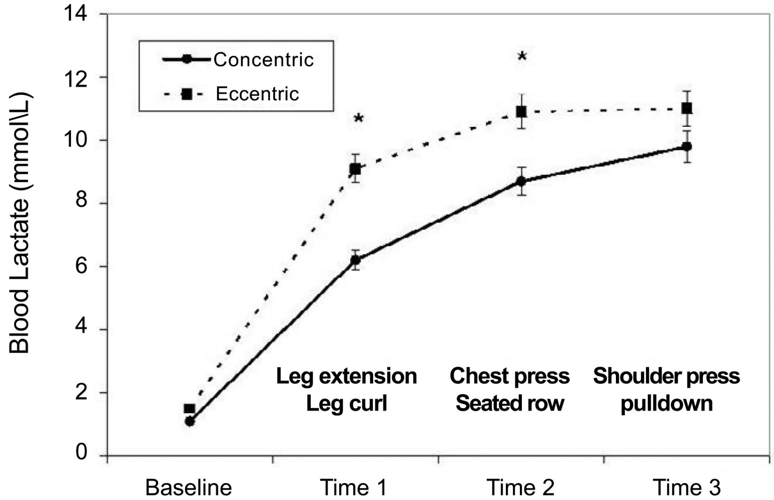

Figure 4.
Blood lactate levels during acute concentric and eccentric resistance exercise sessions. Values are means ± SD. * denotes different from the concentric exercise group at the same time point at $p<0.05$.

Table 1

Participant characteristics.

Variable	
Age (years)	26.8 ± 5.9
Height (cm)	172 ± 8
Weight (kg)	76.3 ± 14.1
Body mass index (kg/m^2)	25.4 ± 4.0
Resting VO_2 (ml/kg*min)	3.8 ± 1.1
Resting HR (bpm)	69 ± 9
Resting systolic BP (mmHg)	120 ± 10
Resting diastolic BP (mmHg)	67 ± 7

VO_2 = Rate of Oxygen Consumption; HR = Heart Rate; BP = Blood Pressure

Values are means ± SD.

Table 2

Muscle soreness values immediately after exercise and 24 hours post-exercise with specific activities.

	CON RX	ECC RX
Quadriceps with flexion/ extension		
Post-exercise	1.8 ± 2.1	2.2 ± 2.1
24 hours post	1.4 ± 1.5	2.9 ± 2.5 *
Hamstrings with flexion/ extension		
Post-exercise	1.7 ± 1.9	2.2 ± 2.3
24 hours post	1.4 ± 1.5	4.0 ± 2.0 *
Simulated chest press motion		
Post-exercise	2.3 ± 1.9	3.0 ± 2.4 *
24 hours post	2.4 ± 2.5	3.7 ± 2.4 *
Simulated shoulder press motion		
Post-exercise	1.4 ± 1.9	2.2 ± 2.0 *
24 hours post	1.5 ± 1.9	3.6 ± 2.2 *

All participants reported no soreness at baseline.

*different from CON RX, $p<.05$

Table 3

Plasma creatine kinase (CK) and inflammatory biomarker levels before and after CON RX and ECC RX.

Concentric RX					
	pre-exercise	**immediately post-exercise**	**Change from pre-exercise (%)**	**24 hours post-exercise**	**Change from pre-exercise (%)**
CK	60.3 ± 84.6	70.3 ± 97.9	(15.1 ± 57.9)	72.2 ± 88.2	(63.7 ± 138.1)
IL-1α	20.2 ± 47.5	16.8 ± 30.4	(55 ± 119)	20.7 ± 49.9	(14.2 ± 87.2)
IL-6	2.6 ± 3.7	2.8 ± 2.6	(79.1 ± 125.1)	2.8 ± 4.6	(−1.5 ± 57.8)
TNF-α	4.7 ± 2.1	4.8 ± 1.5	(6.3 ± 16.2)	4.5 ± 2.6	(−6.6 ± 26.8)

Enhanced Eccentric RX					
	pre-exercise	**immediately post-exercise**	**Change from pre-exercise (%)**	**24 hours post-exercise**	**Change from pre-exercise (%)**
CK	54.7 ± 81.7	66.3 ± 85.4	(47.0 ± 68.8)	88.4 ± 85.4	(168.2 ± 247.2)
IL-1α	14.3 ± 27.1	21.6 ± 43.9	(66.8 ± 103.7)	19.8 ± 40.6	(60.6 ± 91.0)
IL-6	2.6 ± 3.2	3.5 ± 4.4	(75.7 ± 129.3)	2.8 ± 3.4	(24.1 ± 88.7)
TNF-α	4.0 ± 1.5	5.0 ± 2.5	(23.2 ± 23.9) *	4.5 ± 2.2	(10.8 ± 32.8)

CK = creatine kinase; IL= interleukin; TNF = tumor necrosis factor

Values are means ± SD and percent change relative to the pre-exercise time point.

*different from the concentric group at the same time point, p<0.05.