Determining the neuroendocrine, metabolic, and performance responses to various resistance training protocols may enable clinicians to prescribe safer and more effective training programs for healthy and at-risk individuals. Traditional resistance exercise (TRAD) involves coupled concentric and eccentric muscle actions performed with equal loading. However, eccentric strength is reportedly 40–50% greater than concentric strength (7); thus, eccentric muscle action is relatively underloaded in TRAD. Eccentric-enhanced resistance exercise (ECC+), which involves a concentric contraction coupled with an overloaded eccentric action, has been shown to result in similar (12) or greater improvements in muscular strength (10,16,17,19) and accentuated skeletal muscle mass adaptations (10) compared with equivalent-volume TRAD protocols. The mechanism(s) underlying the heightened muscular responses have not been determined, but they may be associated with the altered anabolic and metabolic environment accompanying resistance exercise.

Recent evidence indicates that TRAD stimulates local muscle-growth factors (2) and systemic neuroendocrine responses that affect protein synthesis and/or degradation (23). It has been suggested that the postexercise elevations in anabolic hormone concentrations enhance the skeletal muscle hypertrophic response, possibly by stimulating protein synthesis (23). TRAD reportedly increases postexercise serum total testosterone (TT) and growth hormone (GH) in a load- (22) and volume-dependent (14) manner. Additionally, eccentric-only muscle actions have been shown to increase postexercise TT, GH, and lactate concentrations (8,20,21), indicating that overloaded eccentric actions may be sufficient stimuli to alter the in vivo anabolic and/or metabolic environment.

Excessive lactate accumulation during resistance exercise may limit muscular performance; conversely, lower lactate accumulation may allow greater total work performance. Eccentric-only muscle actions result in lower lactate accumulation than concentric-only actions matched for either absolute (8) or relative (20) workload. Hortobagyi...
et al. (16) have reported that heart rate response, mean arterial pressure, rate-pressure product, and rating of perceived exertion (RPE) are lower during ECC+ compared with TRAD, suggesting that ECC+ may result in a lower lactate accumulation than TRAD. However, to date, this hypothesis has not been confirmed.

Determining the anabolic and metabolic responses to an acute bout of ECC+ may provide a basic mechanistic understanding of the accentuated skeletal muscle adaptations associated with ECC+. Previous research suggests that ECC+ may result in increased anabolic hormone concentrations and relatively low metabolic responses, but this has not been investigated. Therefore, the purpose of this study was to compare anabolic responses after acute bouts of ECC+ and TRAD.

METHODS

Subjects. Twenty-two college-age (21.09 ± 0.8 yr) males volunteered for this study. To be included, subjects had to be 18–34 yr old, untrained (no resistance exercise during the previous 6 months) males. Subjects were excluded if they 1) had competed in powerlifting, bodybuilding, Olympic weightlifting, or other competitive athletics during the previous year, 2) had an orthopedic injury that would limit participation, 3) had a metabolic disease, 4) had a dietary intake low in calories, fat, carbohydrates, or protein that could affect hormonal levels (32), or 5) had used any nutritional supplement or pharmacological agent within the past month that could affect hormonal levels. All study participants signed a written informed consent approved by the university institutional review board.

Study design. For this randomized matched-group study, participants reported to the laboratory on four occasions, separated by a minimum of 48 h, with no more than two bouts per week. Baseline information was collected during bouts 1–2, and subjects completed standardized exercise trials during bouts 3–4 (Fig. 1). Subjects were instructed to continue their normal activities and to abstain from resistance training not associated with this study. Participants were given standard dietary instructions based on American Heart Association guidelines for nutrient intake (26) for the day before each exercise bout, and dietary logs were maintained throughout the study period to evaluate dietary adherence. Analysis of total dietary kilocalories and macronutrient consumption was performed using the DietOrganizer 2.2 (MulberrySoft) dietary program. Additionally, subjects recorded the total number of hours slept each night throughout the study. Training volume was recorded by the researcher during each exercise bout, using the following equation:

\[
\text{Training volume} = [\text{number of CON actions} \times \text{CON mass}] + [\text{number of ECC actions} \times \text{ECC mass}]
\]

Baseline testing. Baseline anthropometric measures including body mass, height, and % fat were obtained during the first laboratory visit. Additionally, subjects were familiarized with all strength-testing procedures, including a TRAD one-repetition maximum (1RM), which was performed using a bench press and a squat exercise, according to standard protocol (5). Body mass and height were measured on a calibrated medical scale. Body composition was determined using the three-site skinfold method (18). A single investigator collected all body composition data, and a separate analysis confirmed the tester reliability (ICC = 0.99). During baseline bout 2, a true 1RM was performed on both exercises, and this value was used to establish exercise training loads.

Exercise intervention. Participants completed two exercise bouts composed of volume-matched resistance training protocols. During exercise bout 1, subjects performed a traditional resistance exercise (TRAD) protocol consisting of four sets of six repetitions on both the bench press and squat exercise at 52.5% 1RM. After the initial TRAD bout, subjects were matched for age, height, weight, % body fat, and strength and were randomly assigned to either TRAD (N = 10) or eccentric-enhanced resistance exercise (ECC+; N = 12) groups. The TRAD group repeated the bout 1 exercise protocol, and the ECC+ group performed a protocol consisting of three sets of six repetitions on both the bench press and squat exercise at 40% 1RM concentric and 100% 1RM eccentric. All exercises were performed on MaxOut (Myonics Corporation, Metairie, LA) exercise equipment, which can provide either isotonic resistance without mechanical motor assistance, or eccentric overloaded resistance by using a counterbalanced mechanical motor to assist with the concentric phase of the exercise (19). Because of the constraints of the MaxOut mechanical motor, each repetition was performed for 6 s, to the cadence of a metronome; additionally, this standardized the time under tension between protocols. Further, each exercise set was separated by 1 min of rest, to equate rest periods between exercise protocols, because previous research has indicated that differing rest periods can affect postexercise hormonal responses (22). Additionally, a 15-category Borg scale of RPE was recorded after each exercise bout (11,31). The training intensities selected for this study were the maximal intensities completed by all

![Figure 1—Study design for the traditional (TRAD) and eccentric-enhanced (ECC+) protocols.](http://www.acsm-msse.org)
subjects in a pilot study (N = 5; mean intensity, 54.9% 1RM; range, 52.5–60% 1RM) using the specified exercise cadence and were established to equate training volumes between groups.

**Blood acquisition.** Blood was acquired from an antecubital forearm vein at rest and after exercise during both exercise bouts. Subjects reported for each exercise bout after a 10-h overnight fast and rested for 10 min in a semirecumbent position before blood sample acquisition. Blood was obtained at five additional time points (t = 1, 15, 30, 45, and 60 min) after exercise. Blood was stored at 4°C until centrifugation at 3000g for 12 min, after which serum was separated and stored at −80°C until analyzed. Day-to-day variability in blood parameters was minimized by collecting all samples during morning hours (7:00–10:30 A.M.) for each subject.

**Biochemical analyses.** Hematocrit was determined by the microcapillary tube method (6). Hemoglobin concentration was determined with the Hgb Pro hemoglobin analyzer (ITC, Edison, NJ). Whole-blood lactate was measured by the Accusport Lactate Analyzer (Roche Molecular Biochemicals, Mannheim, Germany) (4). Serum aliquots were corrected for plasma volume change, estimated by hemoconcentration (6), and analyzed for GH, TT, and BT. Serum GH was determined by an enzyme-linked immunosorbent assay (ELISA) (Diagnostic Systems Laboratories, Inc., Webster, TX). Serum TT was determined by enzyme immunoassay (EIA) (Diagnostic Systems Laboratories, Inc., Webster, TX). Serum BT was determined by an ammonia sulfate precipitation method (27). Briefly, a saturated ammonia sulfate/DI water solution was combined with serum (1:1) to induce precipitation of sex hormone–binding globulin. The combined samples were immediately vortexed and stored at room temperature for 10 min before centrifugation. The supernatant was then analyzed by EIA (Diagnostic Systems Laboratories, Inc., Webster, TX). All samples were performed in duplicate and in a single run. The intraassay variances were 5.1% GH, 2.6% TT, and 1.9% BT.

**Data analysis.** The SPSS 12.0.1 statistical package was used for the statistical analysis. All values are reported as the mean ± SE. Separate 2 (group) × 6 (time) repeated-measures ANOVA were run to determine differences in the outcome measures (TT, BT, GH, and plasma volume) between groups in this investigation. Additionally, the lactate change from rest, RPE values, training volumes, and subject characteristics were evaluated using Student’s t-test. When necessary, a Tukey’s post hoc analyses was implemented. An alpha level of ≤ 0.05 was selected as the criterion for statistical significance.

**RESULTS**

**Subject characteristics.** Characteristic data from all subjects are presented in Table 1. No differences were noted between groups for any dietary measure or for average time slept per night (~7–8 h). On average, subjects consumed 2238 kcal on the day before each bout, consuming approximately 50% carbohydrates, 33% fat, and 17% protein (1.1 g kg−1 body mass). Additionally, each subject completed a 10-h fast before blood acquisition, as indicated by dietary records and follow-up questions concerning food, drink, alcohol, and caffeine consumption before blood acquisition.

**Plasma volume.** Under all conditions, plasma volume decreased (~5–8%) immediately after exercise and gradually returned to baseline values within 30 min. No differences were observed between groups at any time point.

**Total and bioavailable testosterone.** No differences in resting total (6.2 ± 0.9 vs 7.1 ± 0.5 ng·mL−1) or bioavailable (4.1 ± 0.4 vs 4.1 ± 0.4 ng·mL−1) testosterone concentrations were observed between the TRAD and ECC+ groups, respectively, indicating that subjects were apparently eugonadal (30). During TRAD, the TT concentrations (immediately to 30 min after) were not different from baseline (Fig. 2); however, 45–60 min after training, the TT concentrations decreased below baseline (P < 0.05). Similarly, the postexercise BT (immediately to 15 min after) were not different from baseline (Fig. 2); however, 30–60 min after training, the BT concentrations decreased below baseline in both groups (P < 0.05). During exercise bout 2, the TT concentrations after the TRAD and ECC+ (Fig. 3A) were not different than at baseline.

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**TABLE 1. Subject characteristics and maximal strength.**

<table>
<thead>
<tr>
<th></th>
<th>Mass (kg)</th>
<th>BMI</th>
<th>% body fat</th>
<th>1RM chest (kg)</th>
<th>1RM squat (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traditional</td>
<td>80.1 ± 3.3</td>
<td>25.9 ± 1.2</td>
<td>20.7 ± 2.0</td>
<td>77.7 ± 1.3</td>
<td>98.2 ± 1.8</td>
</tr>
<tr>
<td>Eccentric</td>
<td>81.1 ± 2.7</td>
<td>25.8 ± 1.3</td>
<td>20.1 ± 2.2</td>
<td>75.2 ± 1.4</td>
<td>103.6 ± 1.3</td>
</tr>
</tbody>
</table>

**FIGURE 2—Total and bioavailable testosterone responses to traditional resistance exercise protocol (TRAD) during exercise bout 1.** * Different from corresponding preexercise value; † different from corresponding postexercise value; ‡ different from corresponding 15-min postexercise value (P < 0.05). Data are means ± SE.
(immediate to 45 min after); however, TT was lower from both baseline and immediately postexercise concentrations by 60 min into recovery (P < 0.05). In both groups, the BT concentrations (Fig. 3B) increased 15–16% immediately after exercise and decreased to below baseline concentrations within 60 min of exercise completion (P < 0.05). No differences between groups were observed for postexercise TT or BT concentrations after either exercise protocol.

**Growth hormone.** After bout 1, GH concentrations increased approximately 4800% (P < 0.05) above baseline and subsequently returned to resting value within 45 min of exercise cessation (Fig. 4A). During bout 2, GH concentrations increased approximately 250% in the TRAD and 3700% in the ECC+ groups before returning to baseline (Fig. 4B). No differences in GH concentrations were observed between groups at any time point.

**Lactate.** Figure 5 represents the blood lactate change from before to immediately after exercise. The ECC+ lactate values were approximately 130–180% greater than exercise bout 1 and 2 TRAD protocols (P < 0.01).

**RPE and training volume.** The RPE value after the ECC+ (16.3 ± 0.6) was greater than the TRAD protocol value after exercise bouts 1 (14.3 ± 0.3) and 2 (13.3 ± 0.5).

No other differences were observed for RPE. No differences in total training volume were observed between the bout 1 TRAD protocol (4652 ± 146 kg) and the bout 2 (4561 ± 234 vs 4299 ± 197 kg) TRAD and ECC+ protocols, respectively.
DISCUSSION

Others have reported that ECC+ results in similar (12) or greater (10,16,17,19) muscular strength and mass adaptations compared with traditional resistance training (TRAD). However, the mechanism(s) underlying the accentuated muscular responses to ECC+ require clarification. We evaluated several neuroendocrine markers that reportedly affect skeletal muscle protein synthesis (33) in an attempt to identify possible mechanisms explaining the heightened muscular adaptations associated with ECC+. To our knowledge, no published study has reported hormone responses after ECC+. The primary finding of this study was that in previously untrained ECC+ naive males, ECC+ and TRAD result in apparently similar postexercise anabolic hormone (GH, TT, and BT) responses within 60 min of exercise cessation. Our results suggest that acute alterations in postexercise serum anabolic hormone concentrations may not explain the heightened muscular adaptations associated with ECC+.

Furthermore, our results indicate that TT concentrations are not elevated after resistance exercise in previously untrained subjects, which is consistent with findings by Kraemer et al. (24) but inconsistent with others (34). Additionally, we observed a decrease in TT and BT concentrations 45–60 min after exercise under all conditions, which is similar to findings by Tremblay et al. (34). The observed reductions in postexercise TT and BT observed in our study may indicate that testosterone 1) followed normal metabolic pathway biotransformation and/or 2) became bound to androgen receptors and stimulated protein synthesis (3). Future research designed to determine the metabolic fate of testosterone and its subfractions after resistance exercise may elucidate the effect of endogenous testosterone on localized skeletal muscle hypertrophy.

Previous research on resistance-trained subjects suggests that eccentric-only muscle actions result in a blunted GH response (8,21) and a similar (21) or reduced (8) testosterone response compared with concentric-only resistance exercise matched for absolute intensity. Additionally, similar pre- and postexercise GH (20) and testosterone (2,20) responses have been reported after eccentric-only and concentric-only muscle actions matched for relative exercise intensity. Our study provides novel data indicating that coupled concentric and overloaded eccentric muscle actions seem to have little effect on the postexercise GH and testosterone response. These results suggest that the concentric muscle action is primarily responsible for the neuroendocrine responses after resistance exercise, because the addition of overloaded eccentric muscle actions altered neither the GH nor testosterone responses compared with TRAD. Future research evaluating longitudinal anabolic hormone responses and/or local muscle growth factor responses to ECC+ may contribute to an understanding of the mechanism(s) responsible for the heightened muscular adaptations associated with ECC+.

We observed that BT concentrations are greater after resistance exercise, despite constant TT concentrations. Bioavailable testosterone is composed of approximately 4% free and approximately 96% albumin-bound testosterone fractions and reportedly reflects the total concentration of testosterone that is capable of traversing cell membranes, binding with androgen receptors, and stimulating protein translation (27). Our results indicate that an alteration in the free:albumin-bound:sex hormone–binding globulin (SHBG)-bound testosterone ratio occurred, suggesting an acute increase in bioactive androgen availability after both ECC+ and TRAD. Previous reports from others indicate that free testosterone increases acutely after resistance training (1,34). Although we did not directly measure free testosterone concentrations, it is plausible that changes in the free testosterone fraction influenced our TT and BT results. Given the influence of binding proteins on both the biological effects and measurement of testosterone, studies designed to carefully measure the postexercise free, albumin-bound, and SHBG-bound fractions of testosterone are indicated.

In our study, lactate accumulation was greater after ECC+ compared with TRAD. Previous research suggests that ECC+ muscle actions result in lower lactate accumulation than concentric only, matched for either absolute (8) or relative (20) intensity. The inconsistency of our findings with previous reports may be attributable to the differences in exercise modes between studies (ECC+ vs concentric/ eccentric-only resistance exercise). Regardless, our study indicates that the overloaded eccentric muscle actions result in significant lactate accumulation. It is possible that the heightened lactate values we observed in the ECC+ were the result of greater eccentric-specific recruitment of fast glycolytic and/or fast oxidative glycolytic muscle fibers, which reportedly accompany eccentric muscle actions (28). To our knowledge, motor unit recruitment patterns during ECC+ have not been evaluated. However, Friedmann et al. (10) report upregulation of myosin heavy-chain (MHC) type IIA and IIX mRNA after 4 wk of ECC+, but not TRAD, possibly indicating increased fast motor unit recruitment and concomitant lactate production during ECC+. Research evaluating motor unit recruitment patterns during ECC+ may provide insight into the mechanism(s) underlying lactate accumulation.

Growth hormone concentrations have been found to be positively associated with both blood lactate (15) and H+ accumulation (9). Additionally, Luger et al. (29) have suggested that lactate accumulation partially regulates the exercise-induced GH response. In our study, we have reported similar GH responses between the ECC+ and TRAD protocols, despite significantly greater lactate accumulation after the ECC+. Therefore, our data do not support the conjecture that lactate accumulation positively affects GH secretion. Further, we observed no relationship between lactate concentrations and postexercise GH concentrations or GH area under the curve. Our data suggest that additional
factors beyond lactate/H+ accumulation may regulate the postexercise GH responses to eccentric exercise in untrained subjects, such as blood flow characteristics, nitric oxide release, and/or musculoskeletal afferent input (13).

We report that the RPE after the ECC+ was greater than that after the TRAD. These results corroborate previous reports indicating that RPE is associated with both exercise intensity and lactate accumulation (25). However, our findings contrast those of Hortobagyi et al. (16), who report that RPE responses were significantly lower after ECC+ compared with TRAD. Studies designed to evaluate the RPE responses would enhance current understandings of fatigue and exertion as they relate to resistance exercise.

The neuroendocrine, metabolic, and performance responses to resistance exercise are of concern when prescribing resistance training protocols. The results from our study indicate that ECC+ results in similar neuroendocrine responses to TRAD, suggesting that ECC+ is a suitable alternative to TRAD when muscular hypertrophy and strength are desired outcomes. However, the heightened lactate concentrations and RPE associated with ECC+ indicate that ECC+ may not be as appropriate for clinical populations that experience muscular fatigue, pain, and/or weakness associated with their condition. Future research designed to evaluate the neuroendocrine, metabolic, and performance responses to ECC+ training, in both healthy and at-risk populations, may provide additional insight into the appropriateness of exercise prescriptions using ECC+.

In summary, neither ECC+ nor TRAD resulted in increased postexercise TT concentrations, whereas postexercise BT increased similarly between groups. Both resistance exercise protocols resulted in similar acute increases in GH after exercise. Additionally, ECC+ resulted in a greater lactate accumulation and RPE than TRAD. In conclusion, our results suggest that acute alterations in postexercise anabolic hormone responses may not be the primary mechanism explaining the heightened muscular adaptations associated with ECC+.

This material is the result of work supported with resources and the use of facilities at the Malcolm Randall VA Medical Center, Gainesville, FL. The results of this study do not constitute endorsement of the product by the authors or ACSM.

REFERENCES


