Anticipatory responses of catecholamines on muscle force production

Duncan N. French,1 William J. Kraemer,1 Jeff S. Volek,1 Barry A. Spiering,1
Daniel A. Judelson,1 Jay R. Hoffman,2 and Carl M. Maresh1

1Human Performance Laboratory, Department of Kinesiology, University of Connecticut, Storrs, Connecticut; and 2Department of Health and Exercise Science, The College of New Jersey, Ewing, New Jersey

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French DN, Kraemer WJ, Volek JS, Spiering BA, Judelson DA, Hoffman JR, Maresh CM. Anticipatory responses of catecholamines on muscle force production. J Appl Physiol 102: 94–102, 2007. First published September 7, 2006; doi:10.1152/japplphysiol.00586.2006.—Few data exist on the temporal relationship between catecholamines and muscle force production in vivo. The purpose of this study was to examine the influence of preexercise arousal on sympathoadrenal neurohormones on muscular force expression during resistance exercise. Ten resistance-trained men completed two experimental conditions separated by 7 days: 1) acute heavy resistance exercise protocol (AHREP; 6 × 10 repetitions parallel squats, 80% 1 repetition maximum) and 2) control (Cont; rest). Peak force (Fpeak) was recorded during a maximal isometric squat preceding each set and mean force (Fmean) was measured during each set. Serial venous blood samples were collected before the AHREP and immediately preceding each set. Blood collection times were matched during Cont. Preexercise epinephrine (Epi), norepinephrine (NE), and dopamine (DA) increased (P < 0.05) above Cont by 270, 255, and 164%, respectively. During exercise, Epi, NE, and DA continued to increase by 512, 271, and 38%, respectively, above preexercise values. Fpeak and Fmean decreased by ~20–25% over the course of the AHREP. Post hoc data analysis revealed that five subjects (Fmaintainers) showed no decline (P > 0.05) in muscular performance (Fpeak, Fmean) during AHREP and that five subjects (Freducers) had significant reductions in Fpeak and Fmean. Integrated area under the curve for Epi, NE, and Fpeak were greater (P < 0.02) for Fmaintainers than Freducers. In conclusion, an anticipatory rise in catecholamines existed, which may be essential for optimal force production at the onset of exercise.

During repetitive muscular stimulation, there is disruption of ionic balance across the sarcolemma, resulting in decreased membrane excitability (1). In vitro studies have shown that this process is attenuated by exposing muscle fibers to catecholamines (25). Acting via β2-adrenergic receptors on the surface of muscle tissue, catecholamines stimulate electrogenic Na+–K+ -transport and assist in membrane excitability and force generation (3, 14). Improved Na+–K+ pump function restores ionic balance across the sarcolemma and promotes actin–myosin interaction in depolarized skeletal muscle cells (3). Therefore, it is clear that catecholamines are important for the expression and/or maintenance of muscle excitability and contractile force generation (25). In humans, the psychophysiological stress associated with heavy resistance exercise has been shown to elicit rapid elevations in plasma concentrations of epinephrine (Epi; [Epi]), norepinephrine (NE; [NE]), and dopamine (DA; [DA]) (16, 19). Induced by a combination of cognitive stress [e.g., anxiety, physical discomfort, arousal (20, 21, 32)] and physical stress [e.g., cardiovascular demand, energy expenditure, H+ accumulation (19, 20)], the release of catecholamines by sympathetic neurons and the adrenal medulla induces a host of hemodynamic, systemic, and metabolic effects (23, 29). In combination, these physiological responses redistribute blood flow, promote energy availability to support the force-requiring demands of high-intensity resistance exercise, and ultimately facilitate the contractile characteristics of skeletal muscle (4, 9, 21, 32, 33).

Although in vitro research clearly defines the temporal kinetics of the influence of catecholamines on muscle force production (25), there are few data to document this relationship in vivo during dynamic exercise. Several studies in humans have reported single measures of preexercise catecholamine concentrations (2, 11, 12, 19); however, to date, no previous studies have used serial blood sampling before and during a bout of high-intensity resistance exercise to investigate the role that catecholamine bioenergetics (i.e., acute changes over time) play in regulating the expression of muscular force. Therefore, the purpose of this study was to examine sympathoadrenal neurohormones and the expression of muscular force before and during high-intensity resistance exercise. By investigating the temporal bioenergetics of plasma catecholamine concentrations, it was hypothesized that the basic expression of muscular force production would pattern its response with the sympathoadrenal changes that occur. It was proposed that after peaking to meet the initial demands of exercise, circulating catecholamine concentrations would decline, which may explain, in part, the decrease in muscular force production with repeated muscular contractions.

A secondary purpose of this study was to determine whether a temporal response pattern existed between circulating concentrations of catecholamines and testosterone during resistance exercise. Recent studies (8, 17) have indicated that catecholamines potentially regulate circulating concentrations of serum testosterone. Independently, the importance of circulating testosterone concentrations for muscular force expression has been highlighted in elite weightlifters (8–10, 18), in whom elevated testosterone levels have been shown to significantly influence muscular performance (8–10, 17, 18); however, the relationship between catecholamines and testosterone has received little attention.
METHODS

Subjects

Ten healthy, recreationally weight-trained men (23 ± 2 yr; 89.1 ± 10.0 kg; 179 ± 7 cm) volunteered to participate in the study. Subjects were collegiate-level athletes or equivalent, and each was engaged in a strength-training program that included the barbell squat exercise for at least 2 yr before the study. The mean (±SD) one-repetition maximum (1 RM) squat recorded during familiarization was 153 ± 22 kg. All subjects were nonsmokers, and each had been weight stable for the previous year. None of the subjects were following specialized dietary interventions, and each was required to refrain from nutritional supplementation for 30 days before and throughout the investigation. After being informed of the benefits and potential risks of the investigation, each subject signed an approved consent form in accordance with the guidelines of the University of Connecticut Institutional Review Board for use of human subjects. Before entering into the study, subjects completed a health-screening questionnaire, and each was cleared of any medical or endocrine disorders that might confound or limit his ability to participate fully.

Experimental Design

A balanced, randomized, within-group, crossover study design was employed. Before data collection, subjects completed an assessment of strength for the 1-RM parallel squat and familiarization trials of all experimental procedures. More than 72 h after 1-RM assessment, subjects returned to the laboratory where they were randomly assigned to an experimental condition initially: 1) acute heavy resistance exercise protocol (AHREP) or 2) resting control (Cont). During the AHREP, subjects completed 6 sets of 10-repetitions maximum (10 RM) parallel barbell squats at 80% 1 RM. Assessments of muscular force were made at regular intervals throughout the exercise intervention. During Cont, subjects were seated at rest in the strength testing laboratory in a quiet and controlled environment for the identical duration as the AHREP. Blood sampling occurred at selected, matched time points during both experimental conditions and was used for the determination of circulating hormonal concentrations. All testing procedures were performed in the morning between 0700 and 1000; to reduce the influence of diurnal hormonal variations the time of day was standardized throughout the study. After subjects had completed their respective experimental trial, they were crossed-over to either side of the bar allowed vertical movement along two steel shafts with minimal friction. The AHREP itself has been used many times in our previous research by our laboratory (26), and it involved 6 sets of 10 repetitions of parallel barbell squat exercise at the subject’s 10 RM (i.e., maximum amount of weight that the subject can complete 10 repetitions). Two-minute rest intervals separated individual sets during the AHREP. The starting weight (80% 1 RM) was determined from preliminary 1-RM strength testing. During testing, if subjects were unable to perform 10 repetitions during a particular set of the AHREP, the weight was adjusted to allow completion of all 10 repetitions. Reliability intraclass Rs for this protocol were ≥0.98.

Muscular Performance

Assessments of muscular performance were carried out at regular intervals throughout the AHREP. Performance was quantified from ground reaction forces using an isometric squat protocol previously discussed elsewhere (26, 27). During this procedure subjects were positioned with their heels in line with the bar, the bar resting across the shoulders, and the bar was set at such a height that there was 130–140° and 120–130° about the knee and hip joints, respectively. This anatomic alignment produced the highest force data during pilot testing and was standardized across all experimental trials. On command, subjects exerted maximal upward force against a fixed bar for ~5 s. During each isometric squat, ground reaction forces were collected at 250 Hz using a Kistler QuatroJump force plate (Kistler Instruments, Winterthur, Switzerland). Subjects received verbal encouragement throughout. Data were stored and interpreted using the PPS software (Norssearch, Lismore, Australia). Repeat trials with this protocol resulted in a test-retest reliability for isometric peak force (N) of ≥0.96. In total, eight isometric squat assessments were made during the AHREP. Pre- and post-AHREP measures were made before and following the 6 sets of 10 RM squat, while further isometric squats were carried out immediately preceding each of the 6 dynamic sets. On completion of each isometric squat (with the exception of pre- and post-AHREP), the bar was adjusted to the appropriate weight (i.e., 80% 1 RM) and subjects immediately commenced 10 dynamic repetitions at a self-selected lifting speed. The experimental time line for the AHREP is presented in Fig. 1.

Further assessments of muscular force were made via ground reaction forces (Kistler Instruments) during each of the six sets of dynamic squats. Data collection began following readjustment of the load and zeroing of the force plate immediately after completion of the isometric squat. During the dynamic phases of the AHREP, subjects lowered to a parallel squat position (thighs parallel to the floor) under the instruction and supervision of the investigators. Data
were collected for each of the 10 repetitions at 500 Hz using the online software and data reduction system (PPS, Norsearch), and mean peak force ($F_{\text{mean}}$) was calculated across all 10 repetitions.

**Blood Collection**

On the day of each experimental intervention (AHREP, Cont), subjects reported to the laboratory following a 12-h overnight fast and abstinence from caffeine or exercise for 48 h. An intravenous catheter (Travenol, 22 gauge, 32 mm) was inserted into an antecubital forearm vein and kept patent using a 10% heparin, 90% saline solution. An indwelling catheter was used to avoid the discomfort of repeat venipuncture, because such procedures may abnormally increase circulating catecholamine and stress hormone concentrations (5). The intravenous catheter was secured using adhesive bandaging and remained localized in the forearm vein throughout both experimental trials. Following a 15-min equilibrium period, serial resting blood samples were collected before AHREP at −60, −30, −15, −10, −5, and 0 min (see Fig. 1). During this time, subjects were seated at rest and were informed of the time remaining before the start of the exercise bout before each resting blood collection for the AHREP. A countdown to the end of the control period was also used. Subjects were uniformly instructed to rest quietly before exercise; however, subjects were not queried on preexercise psychological approaches to exercise performance. Blood samples were also collected at regular intervals during the AHREP intervention immediately preceding each set at 5, 8, 11, 14, 17, and 20 min (i.e., immediately preceding each exercise set). All blood collection times were matched for the Cont trial. In all cases, the first 3 ml of blood withdrawn were discarded to avoid dilution of the sample. Approximately 10 ml of whole blood were subsequently withdrawn, transferred to Vacutainer tubes, and used for processing.

**Biochemical Analysis**

Whole blood samples were collected into 10-ml Vacutainer tubes (plasma was obtained via tubes with liquid K$_3$ EDTA anticoagulant to prevent clotting). Hemoglobin was immediately analyzed in triplicate using cyanmethemoglobin procedures (Sigma Diagnostics, St. Louis, MO), and hematocrit was analyzed in triplicate by microcentrifugation and microcapillary techniques. Intra- and interassay variances were <5% in all cases. Hemoglobin and hematocrit data were used to account for changes in circulating plasma volumes according to the methods of Dill and Costill (4a). Within 15 min of collection, whole blood was centrifuged at 3,000 rpm (4°C) for 15 min. The resultant plasma was removed and stored at −80°C until subsequent analysis. For all biochemical procedures, samples were thawed only once before analysis. Plasma glucose (glucose) and lactate (lactate) concentrations were determined in duplicate using an automated glucose/lactate analyzer (2300 Stat glucose/h-lactate analyzer, YSI, Yellow Springs, OH).

Plasma catecholamine concentrations ([Epi], [NE], [DA]) were determined in duplicate using commercially available $^{125}$I solid-phase TriCat radioimmunoassay (RIA) kits (Immuno-Biological-Laboratories, Hamburg, Germany). Epi, NE, and DA were first extracted using affinity gel-coated macrotiter plates, and then they were eluted using 0.05 N HCl. Following extraction, individual samples were transferred to acylation tubes coated with acylating reagent specific to Epi, NE, and DA. Each sample was combined with enzyme solution containing porcine catechol-O-methyltransferase. $^{125}$I-labeled tracer specific to each of the catecholamines was then added to the respective tubes. Following overnight incubation (~16 h), immunoreactivity values were determined using a gamma counter and online data reduction system (Cobra II, Packard Instruments, Meriden, CT). Absolute concentrations for Epi, NE, and DA were calculated according to manufacturer’s guidelines. The minimum RIA detection limits for [Epi], [NE], and [DA] were $0.44 \times 10^{-4}$ pmol/ml, $1.41 \times 10^{-4}$ nmol/l, and $2.0 \times 10^{-4}$ nmol/l, respectively. Interassay and intraassay variance were 8.93 and 9.95% for Epi, 9.78 and 9.46% for NE, and 8.68% and 8.74% for DA.

Serum total testosterone ($T_{\text{total}}$) concentrations were also determined in duplicate using $^{125}$I competitive solid-phase RIA (Diagnostic Systems Laboratories, Webster, TX). Assay procedures were completed according to the manufacturer’s guidelines. Immunoreactivity values were determined using the same gamma counter and online data reduction system previously described (Cobra II, Packard Instruments). The minimum RIA detection limit for testosterone was 0.28 nmol/l. Intra- and interassay variance were 7.01 and 6.95%, respectively.

**Statistical Analyses**

Means, standard deviations (SD), and standard errors (SE) were calculated using conventional methods. Data presented in the text and tables are means ± SD; data presented in the figures are means ± SE. A two-way ANOVA [treatment (AHREP, Cont) × time] with repeated measures was used to evaluate changes in biochemical indexes for each experimental condition. Where required, for meeting the assumptions for linear statistics, transformations of hormonal data were performed using log$_{10}$ calculations with data then rechecked for the statistical assumptions before using a statistical procedure. One-way repeated-measures ANOVA was used to examine strength and power indexes. In the event of a statistically significant F-ratio, Fisher’s least significant difference post hoc test was employed to determine where pairwise differences lay. Simple dependent t-tests were used where required to evaluate differences in corresponding hormonal and performance measurements between trials. The total area under the integrated hormonal (plasma concentration × time) and force (peak or mean force × time) curves (AUC) was calculated using standardized trapezoidal methods. To examine bivariate relationships between hormone concentrations and indexes of muscular performance, Pearson’s product-moment correlation r values were calculated. Percent change in hormonal and/or performance indexes between time points (i.e., the rate of change) were calculated for the AHREP and Cont respectively and used for “biokinetic” analysis. Using the nQuery Advisor software (Statistical Solutions, Saugus, MA) the statistical power for the n size used ranged from 0.80 to 0.91. Significance was defined as an alpha level of $P \leq 0.05$. All statistical analyses were conducted using Statistica v10.0 statistical software (Statsoft, Tulsa, OK).

**RESULTS**

**Hormonal Analyses**

Plasma [Epi], [NE], and [DA] for both conditions, across all time points, are shown in Fig. 2. At 60 min before AHREP, circulating [Epi], [NE], and [DA] were within normal resting ranges of 0.03–0.55 pmol/ml, 0.47–0.65 nmol/l, and <0.65 nmol/l, respectively. [Epi] and [NE] were not significantly different between AHREP and Cont conditions, however, plasma [DA] was elevated ($P \leq 0.05$) in the AHREP trial. Preexercise [DA] began to increase at −10 min, whereas [Epi] and [NE] began to increase at −5 min. At 0 min, [Epi], [NE], and [DA] were increased ($P \leq 0.05$) compared with Cont by 94.5, 255, and 164%, and 164%, respectively. With the onset of the AHREP, [Epi] was significantly ($P = 0.000$) elevated above preexercise (0 min) levels at 8 min (see Fig. 2). Circulating [Epi] peaked at 20 min (set 6), with the exercise-induced changes in [Epi] reflecting a fivefold increase (512%) from 0 min. [NE] was also significantly elevated in response to exercise ($P = 0.000$) at 8 min (set 2). The exercise-induced change in [NE] reflected a threefold increase (271%) from plasma concentrations reported immediately be-
fore exercise (0 min). Plasma [DA] was significantly higher than preexercise (0 min) concentrations 5 min postexercise (30 min) only. The [DA] response to exercise was equivalent to a 38% increase in circulating levels. Throughout exercise (0 min to 5 min postexercise), [Epi], [NE], and [DA] were all significantly ($P \leq 0.05$) higher than respective Cont measures.

Responses of [T_{total}] to both experimental conditions are shown in Fig. 3. Before exercise, no significant within- or between-trial differences were evident, with all $T_{total}$ measures within the normal range of 9–35 nmol/l. With the onset of the AHREP, serum $T_{total}$ at set 5 was 22% greater than preexercise levels ($P = 0.00$). Circulating concentrations were signif-
Fig. 3. Plasma total testosterone concentration ([testosterone]) responses to AHREP (○) and Cont (●). The exercise trial is represented by dark shading. Values are means ± SE. *P ≤ 0.05 from corresponding Cont time point. †P ≤ 0.05 from corresponding set 0 time point. ‡P ≤ 0.05 from corresponding 0 time point.

Muscular Force Expression

Muscular strength was determined from peak isometric force (F\text{peak}), recorded during the isometric squat carried out before the AHREP, at the start of each set during the AHREP, and post-AHREP (Fig. 4). A significant (P = 0.000) change in F\text{peak} output was observed. Significant reductions in the mean F\text{peak} below preexercise levels (0 min) were evident at set 3 (11 min) into the AHREP. The F\text{peak} continued to decline for all subsequent measures. The largest change in F\text{peak} amounted to a 20% reduction in F\text{peak} output from preexercise standards (0 min).

Changes in within-trial dynamic ground reaction forces (F\text{mean}), recorded during each set of the AHREP, were also significantly different (P = 0.000), and they reflected a reduction in force output of ~20% from initial levels during set 1 (see Table 2). F\text{mean} measures for each set are also presented in Fig. 4. The F\text{mean} recorded during set 1 of the AHREP was significantly different from all subsequent sets (i.e., sets 2–6), with sets 2 and 3 also significantly higher than the force outputs recorded during sets 5 and 6.

Post Hoc Analyses

Additionally, post hoc data analysis was performed to determine the presence of “responders” and “nonresponders” to the exercise intervention. Post hoc analysis indicated that 5 of the 10 subjects showed no significant change (P > 0.05) in both F\text{peak} and F\text{mean} output throughout the AHREP. In comparison, the remaining five subjects had significant reductions (P ≤ 0.05) in F\text{peak} and F\text{mean} below baseline standards. According to these independent exercise-induced responses, subjects were individually classified as 1) force maintainers (F\text{maintain}); subjects who had no significant change (P > 0.05) in muscular performance (n = 5); and 2) force reducers (F\text{reduce}); subjects who had a significant reduction (P ≤ 0.05) in muscular performance (n = 5). Of note, the subject characteristics (age, height, weight, 1-RM squat, and training experience) were not significantly (P > 0.05) different between the two groups identified (F\text{maintain}, F\text{reduce}).

Table 1. Lactate and glucose concentrations response to AHREP and Cont

<table>
<thead>
<tr>
<th>Time, min</th>
<th>Lactate (mmol/L)</th>
<th>Glucose (mmol/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AHREP</td>
<td>Cont</td>
</tr>
<tr>
<td>−60</td>
<td>1.07±0.26</td>
<td>0.97±0.21</td>
</tr>
<tr>
<td>−30</td>
<td>1.02±0.29</td>
<td>0.95±0.25</td>
</tr>
<tr>
<td>−15</td>
<td>1.04±0.25</td>
<td>0.98±0.23</td>
</tr>
<tr>
<td>−10</td>
<td>1.07±0.31</td>
<td>1.00±0.24</td>
</tr>
<tr>
<td>−5</td>
<td>1.42±0.21</td>
<td>0.98±0.21</td>
</tr>
<tr>
<td>0 (Pre)</td>
<td>2.05±1.0</td>
<td>1.01±0.27</td>
</tr>
<tr>
<td>5 (Set 1)</td>
<td>2.72±1.38††</td>
<td>1.03±0.24</td>
</tr>
<tr>
<td>8 (Set 2)</td>
<td>5.56±2.11†††</td>
<td>1.05±0.27</td>
</tr>
<tr>
<td>11 (Set 3)</td>
<td>8.17±2.56†††</td>
<td>1.06±0.29</td>
</tr>
<tr>
<td>14 (Set 4)</td>
<td>9.86±3.56†††</td>
<td>1.17±0.35</td>
</tr>
<tr>
<td>17 (Set 5)</td>
<td>10.97±2.20†††</td>
<td>1.11±0.33</td>
</tr>
<tr>
<td>20 (Set 6)</td>
<td>12.04±2.12†††</td>
<td>1.11±0.33</td>
</tr>
<tr>
<td>25 (Post)</td>
<td>11.89±1.77†††</td>
<td>1.17±0.35</td>
</tr>
<tr>
<td>30 (+5)</td>
<td>11.35±1.86†††</td>
<td>1.10±0.28</td>
</tr>
</tbody>
</table>

Values are as means ± SD given in mmol/L. *P ≤ 0.05 from Cont. †P ≤ 0.05 from −60. ‡P ≤ 0.05 from 0. AHREP, acute heavy resistance exercise protocol; Cont, control; Pre, before exercise; Post, after exercise.
Biokinetic Responses

Preexercise. The AUC for [DA] (n = 10) was significantly correlated (r = 0.81, P < 0.05) with baseline measures of Fpeak at 0 min. Mean preexercise AUC for [Epi] and [NE] were not correlated with any measures of Fmean force or mean power during the AHREP.

During exercise. In response to the exercise challenge, the AUC values (n = 10) for [Epi], [NE], and [DA] were not significantly correlated with Fpeak AUC. Interestingly, following post hoc categorization of subjects as Fmaintain and Freduce, significant between-groups differences were found for the integrated AUC of [Epi] (t = 4.023, P = 0.005), [NE] (t = 3.864, P = 0.026), and Fpeak (t = 5.33, P = 0.001). The respective changes in [Epi] and Fpeak, and in [NE] and Fpeak in response to the AHREP for Fmaintain and Freduce are shown in Fig. 5.

DISCUSSION

This is the first study to detail the temporal relationship between circulating catecholamine concentrations and the expression of muscular force using prolonged biokinetic analysis before and during a bout of high-intensity resistance exercise. The primary findings of this study were the following: 1) before heavy resistance exercise, plasma Epi and NE were greater than resting values at −5 min, whereas DA was elevated at −10 min; 2) during exercise, plasma concentrations of catecholamines continued to rise throughout the protocol, whereas force began to decline at set 3; 3) subjects who were able to maintain force production throughout the exercise protocol had higher catecholamine concentrations than those whose performance decreased; and 4) during exercise, plasma testosterone concentrations were correlated with Epi and NE. The present results support previous research performed in vitro (3, 14) and in vivo (11, 13, 33) and indicate that plasma catecholamines are important contributors to muscular force expression. Among prior investigations in this field, none have adopted a study design that incorporated such regular, serial monitoring of catecholamine concentrations to ascertain their role in force production. These methodological differences could account for some of the novel findings reported here.

Preexercise Catecholamine Responses

The significant increases in resting preexercise plasma catecholamine concentrations (Epi, 131%; NE, 165%; DA, 54%) highlight an “anticipatory” rise (30) in sympathoadrenal activity before challenging resistance-training activity. At 15 min before AHREP, catecholamine concentrations rose exponentially (see Fig. 2), with [DA] significantly higher than Cont 10 min before the start of exercise and with [Epi] and [NE] significantly different 5 min before exercise. These preexercise responses reflect the earlier findings of Kraemer et al., where Epi (20) and Epi, NE, and DA (16) increased before high-intensity bouts of anaerobic exercise in healthy subjects and trained power lifters, respectively. Surprisingly, the magnitude of catecholamine concentrations reported here is lower than indicated by Kraemer and colleagues (Epi, 0.33 vs. 0.80 and 2.5 pmol/ml; NE, 2.74 vs. 3.50 nmol/ml; DA, 0.74 vs. 1.25 nmol/ml) (16, 20); however, the absolute changes from Cont are greater than previously reported (16, 20, 22, 30). Differences between the present results and those of previous studies are likely due to different exercise protocols and subject populations.

The importance of a preexercise rise in catecholamine concentrations to muscular strength has previously been reported (31). From the results of this study, it seems that psychological drive induces catecholamine secretion ≤15 min before the commencement of high-intensity resistance exercise in trained men, with elevations in circulating levels becoming significantly (P < 0.05) higher ≤10 min before exercise. Based on the findings of this study, the preexercise anticipatory rise appears to have a meaningful effect on the magnitude of initial strength measures achieved at the start of exercise.

Table 2. Percent change(s) in load per set during AHREP

<table>
<thead>
<tr>
<th>Group</th>
<th>Group</th>
<th>Initial load, kg</th>
<th>Set 2</th>
<th>%Δ</th>
<th>Set 3</th>
<th>%Δ</th>
<th>Set 4</th>
<th>%Δ</th>
<th>Set 5</th>
<th>%Δ</th>
<th>Set 6</th>
<th>%Δ</th>
</tr>
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<tbody>
<tr>
<td>Mean (n = 10)</td>
<td>122.05±12.32</td>
<td>1.3</td>
<td>6.0</td>
<td>10.8</td>
<td>13.8</td>
<td>16.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fmaintain (n = 5)</td>
<td>122.27±13.91</td>
<td>2.6</td>
<td>7.5</td>
<td>14.9</td>
<td>19.4</td>
<td>22.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Freduce (n = 5)</td>
<td>121.82±9.38</td>
<td>0.0</td>
<td>4.5</td>
<td>6.7</td>
<td>8.2</td>
<td>10.4</td>
<td></td>
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</tbody>
</table>

Values are means ± SD; n, no. of subjects. Fmaintain, force maintainers; Freduce, force reducers %Δ, percent change from the initial load for Set 1 (1 repetition maximum).
An increased concentration of circulating catecholamines by sympathetic neurons and the adrenal medulla would incite physiological responses to support the force-requiring demands of high-intensity resistance exercise, and it would ultimately facilitate the contractile characteristics of skeletal muscle (4, 9, 21, 32, 33). It can be hypothesized that the anticipatory rise in catecholamines before resistance exercise is critical for achieving optimal force production at the onset of exercise. Previous research has indicated the importance of preexercise catecholamine concentrations for force production (31). Additionally, this concept is supported by data revealed in the post hoc analysis, because those subjects secreting the greatest amount of [Epi] and [NE] were able to maintain force production. These findings represent novel and important data when trying to understand preexercise strategies for optimizing force expression (i.e., preexercise arousal).

**Catecholamine Responses During Exercise**

With the onset of the AHREP (80% 1 RM), continued increases in plasma catecholamine concentrations above preexercise levels were also apparent. [Epi], [NE], and [DA] were all elevated (P ≤ 0.05) above preexercise levels by 512, 271, and 38%, respectively. The plasma half-life of Epi, NE, and DA is ~2–3 min (6). Therefore, it was hypothesized that plasma catecholamine concentrations would rise acutely early in the exercise protocol, after which time they may be attenuated, which may partially explain the decrease in performance. However, the present data do not support our initial hypothesis. Instead, in response to the AHREP, [Epi] and [NE] continued to increase at each serial time point throughout the protocol, with circulating concentrations peaking at 20 min (~512%, ~271%). [DA] also continued to increase at the termination of the experimental trial, 5 min following the end of the exercise bout (~38%). Although catecholamine clearance has been shown to increase by ~15% during mild exercise, it has been shown to decrease by 20% during heavy exercise similar to that used here (15, 24). However, such changes in clearance rates do not account for the three- to fivefold increase observed. Instead, the changes in plasma catecholamine concentrations reflect a sustained elevation in sympatho-adrenal-medullary secretion throughout the AHREP challenge, most likely as a means to enhance sympathetic activity and modulate homeostasis to meet the additional force-requiring demands of the exercise bout.

**Fig. 5.** Respective changes in epinephrine (Epi) and peak isometric force (F\text{peak}; A) and norepinephrine (NE) and F\text{peak} (B) in force maintainers (squares) and force reducers (circles). F\text{peak} is represented by solid symbols; hormonal parameters are represented by open symbols. Values are means ± SE. AUC, area under the curve.
The metabolic challenge associated with the AHREP was reflected by peak [La] of 12.04 ± 2.12 mmol/l (see Table 1). Exercise-induced changes in [Epi] ($r = 0.94$) and [NE] ($r = 0.88$) were positively correlated with circulating [La] throughout exercise, a relationship that has been reported elsewhere (28). Epi ($r = 0.57$) and NE ($r = 0.85$) were also positively correlated with circulating [glucose] during exercise. Importantly, from the present findings it can be seen that the metabolic strain associated with high-intensity resistance exercise does not attenuate the capacity of the sympatho-adrenal system to synthesize and secrete catecholamines, as was originally hypothesized. Instead, as the physiological demand of exercise increased (i.e., elevated [La]), [Epi], [NE], and [DA] continued to rise. The exercise-induced increase in plasma [glucose] (~35%) is likely a consequence of enhanced glycogenolysis in the liver, as Epi and NE have both been shown to increase phosphorylase activity in both skeletal muscle and the liver (29), thereby helping to elevate blood glucose for energy utilization.

**Force Maintainers vs. Reducers**

Heavy resistance exercise is a mode of activity that is characterized by high force demands (21). Present data indicate that the exercise intensity (load) decreased by 16% during the AHREP (i.e., final load was ~64% 1 RM). Following post hoc analysis, a number of the subjects from the present study were found to be significantly ($P < 0.05$) affected by fatigue associated with high-intensity resistance exercise (i.e., “force reducers”). In comparison, and perhaps surprisingly, others were able to maintain muscular performance throughout the AHREP similar to preexercise standards ($P > 0.05$) (i.e., “force maintainers”). Such findings were observed for isometric $F_{peak}$ during single efforts and for dynamic $F_{mean}$ across repeated sets and repetitions (see Fig. 4 and Table 2). The maintenance of force is a highly appealing factor in sport and exercise, because it allows for the preservation of near-optimal performance standards for a more prolonged period.

Supporting a regulatory role for catecholamines in muscular force production, Epi and NE AUC were significantly greater for $F_{maintain}$ than $F_{reduce}$ (Fig. 5). Although statistically significant correlations between catecholamine concentrations and force production existed for $F_{maintain}$, the low n size precludes interpretation of the meaningfulness of these relationships. Importantly, though, this is the first study to identify such relationships using serial time points throughout an exercise trial (i.e., biokinetic), rather than by single pre- and postexercise assessments (11). It is therefore proposed that present findings give a more accurate portrayal of the role catecholamines have during high-intensity, intermittent, resistance exercise, similar to that used by most athletes (~4–6 sets at 60–95% 1 RM).

**Relationship Between Catecholamines and Testosterone**

As potent vasodilators and mediators of circulatory redistribution, the catecholamines have been implicated to regulate the secretory activity of other endocrine tissues throughout the body, including the gonads (11, 17). Circulating testosterone has been shown to be important in determining the force-production characteristics of skeletal muscle (8). In the present study, preexercise plasma [T$_{total}$] displayed few within-group changes. Thus the anticipatory changes in mean testosterone secretion reported previously (7) were not apparent here. However, the 22% increase in [T$_{total}$] induced during the AHREP is similar to previously reported findings (7, 13). Of note, from the start of exercise, testosterone was positively correlated with both plasma [Epi] ($r = 0.55$) and [NE] ($r = 0.82$). Although correlation does not indicate causality, and the Epi correlation is only moderate, these findings support the theory of catecholamines acting to promote androgen secretion from the gonads during high-intensity exercise (8, 17). The continuous elevation in plasma testosterone levels (22%) highlights the impact that resistance exercise can have gonadal secretion rates. A continuous rise in plasma testosterone concentrations is proposed to represent a secondary physiological mechanism supporting muscular force production (11, 16). Although it cannot be fully elucidated from present data, catecholamine-induced blood flow elevation to the testis may have enhanced the mechanisms that regulate testosterone secretion (e.g., β-endorphin and nitric oxide) and thus augmented associated physiological responses that lead to its secretion. Such hypotheses emphasize the need for future research, because this question remains to be fully answered here.

In summary, the catecholamine neurohormones, most notably Epi and NE, appeared to have regulatory properties that modulate homeostasis to meet the elevated psychophysiological demands of muscle force development, both before and during exercise. Preexercise values began to increase exponentially ~10 min before high-intensity resistance exercise. During exercise, catecholamines continued to increase, whereas force production began to decrease by set 3. However, results indicate that the relationship between circulating catecholamines and muscular force may be individual in nature. Subjects who were able to maintain force production throughout the exercise protocol were able to elevate plasma [Epi] and [NE] to higher concentrations than those whose performance decreased. Finally, testosterone concentrations during exercise may be affected by catecholamines; however, this relationship requires further study. This study was the first to indicate that the use of biokinetic monitoring may represent a more comprehensive means to assess sympathoadrenal effects on exercise performance. Additionally, the present study gives initial insight into the concept of sympathoadrenal heterogeneity between subjects, a pattern of endocrine function that may compromise the use of catecholamines as potential determinants of muscular performance standards.

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Present address of D. N. French: English Institute of Sport-North East, Gateshead International Stadium, Neilson Rd., Gateshead, Tyne and Wear NE10 9PN, United Kingdom.

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