Acute Resistance Exercise Performance Is Negatively Impacted by Prior Aerobic Endurance Exercise

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Abstract

Ratamess, NA, Kang, J, Porfido, TM, Ismaili, CP, Selamie, SN, Williams, BD, Kuper, JD, Bush, JA, and Faigenbaum, AD. Acute resistance exercise performance is negatively impacted by prior aerobic endurance exercise. *J Strength Cond Res* 30(10): 2667–2681, 2016—The purpose of the present study was to examine acute resistance exercise (RE) performance after 4 different aerobic endurance (AE) protocols. Eleven healthy, resistance-trained men (21.0 ± 1.2 years) performed a control RE protocol and 4 RE protocols 10 minutes after different AE protocols in random sequence. The RE protocol consisted of 5 exercises (high pull, squat, bench press, deadlift, and push press) performed for 3 sets of 6–10 repetitions with 70–80% of one repetition-maximum (1RM) with 3-minute rest intervals in between sets. The AE protocols consisted of treadmill running at velocities corresponding to: (a) 60% of their $\dot{V}O_2$ reserve ($\dot{V}O_2R$) for 45 minutes (P1); (b) 75% of their $\dot{V}O_2R$ for 20 minutes (P2); (c) 90–100% of $\dot{V}O_2R$ in 3-minute intervals (1:1 ratio) for 5 sets (P3); and (d) 75% of $\dot{V}O_2R$ (4.5 mph) uphill (6–9% grade) for 20 minutes (P4). Completed repetitions, average power and velocity, heart rate (HR), and ratings of perceived exertion (RPE) were assessed each set. Protocols P1–P4 resulted in 9.1–18.6% fewer total repetitions performed compared with the control RE protocol with the squat experiencing the greatest reduction. Average power and velocity were significantly reduced for the high pull, squat, and bench press after most AE protocols. Ratings of perceived exertion values for the high pull and squat were significantly higher in P1–P4 compared with control. Heart rate was significantly higher during RE after P1–P4 compared with control by 4.3–5.5%. These results indicate acute RE performance is significantly compromised in healthy men after AE exercise of different type, intensity, and duration with largest reductions observed after high-intensity interval exercise.

Key Words incompatibility, concurrent training, strength training, power, velocity

Introduction

The inclusion of concurrent aerobic endurance (AE) and resistance training (RT) may be necessary for endurance athletes and hybrid athletes who require high levels of local muscular endurance, strength, and power. A primary challenge for strength and conditioning professionals is to design programs that maximize each modality's benefits while minimizing potential incompatibility effects. Since 1980, a number of studies have addressed the impact of concurrent high-intensity AE and RT (5,14,20,22,25,32). Several studies have shown an "interference effect" where RT-induced gains in lower-body muscle strength (5,14,20–22,25), power (18,21,22,25), and hypertrophy (5,25) were attenuated when RT was performed concurrent with high-intensity AE training. However, other studies have shown that both modalities can be trained concurrently with no observed interference in strength increases (3,12,17,18,30,32,44). In a meta-analysis, Wilson et al. (48) reported a significant interference effect of simultaneous AE and RT. Large effect sizes were observed for lower-body muscle strength and power reductions with power more susceptible to attenuation than strength (48). They reported that AE mode (i.e., running more than cycling), frequency, and duration were significantly related to the incompatibility (48). The magnitude of incompatibility depends on the individual's training status, training modes, performance tests used, sequencing of AE and RT, and the volume, frequency, and intensity of AE and RT (16).

Several explanations have been proposed to explain the incompatibility. A competing adaptation hypothesis has been proposed whereby altered neuromuscular recruitment patterns between AE and RT impedes optimal neural drive necessary for maximal strength and power expression (25). Fiber-type transitions, e.g., type II to I (32), elevated

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concentrations of cortisol (5,25), and attenuated muscle hypertrophy (5,25,36) have been shown during concurrent training and suggested to limit muscle strength and power gains. Other studies have shown that concurrent AE and RT may attenuate satellite cell density (2), alter molecular signaling in protein synthesis (Akt-TSC2-mTOR-p70S6k) and mitochondrial biogenesis (AMPK-PGC-1α) pathways (9,10), and attenuate IGF-1Ea mRNA, mechano-growth factor and MyoD mRNA abundance when AE precedes resistance exercise (RE) (10). The chronic interference hypothesis suggests that potential overreaching or overtraining may occur from the culminating effects (related to training frequency, volume, and intensity) of both modalities (21,32). These proposed explanations entail chronic adaptations of competing mechanisms.

Another plausible explanation focuses on the sequence of AE and RE when both are performed within the same day or workout. The acute fatigue hypothesis entails AE performed before RE prematurely fatigues active musculature involved in RE thereby leading to reduced effort and intensity (11). It has been suggested that central (reduced neural activation) and peripheral (accumulation of metabolites such as inorganic phosphate, H^+, and ammonia), depletion of ATP, creatine phosphate and muscle glycogen, and muscle damage may account for the force decrement observed after AE (28). The reduced force output is thought to limit potential strength and power development over time (11). Performing AE exercise before RE has been shown to limit various measures of strength gains compared with performing RE before AE exercise in some (4,6,33,34) but not all (17,47) studies. Sale et al. (43) reported that concurrent AE and RT produced greater strength decrements when performed during the same day versus different days. The authors suggested that RE performance may have been compromised because half of the workouts consisted of performing AE before RE (43). The acute fatigue hypothesis is one that has been studied on a limited basis but demonstrates merit when examining potential incompatibility (1,11,26,27,42,46).

A few studies have shown impaired isokinetic peak torque and maximal lower-body squat and leg press strength and endurance immediately and up to 8 hours after RE (1,46). However, no changes in upper-body (bench press) RE performance were noted (42,46). These data indicate that AE exercise may have the most substantial adverse effects on lower-body rather than upper-body RE performance. However, only few studies have addressed this concept and only 4 investigations compared different types of AE exercise performed before RE (1,16,26,46). It is poorly understood whether the type of AE exercise (long slow distance, continuous moderate-to-high intensity, high-intensity intervals, or continuous incline running) may affect subsequent RE performance. Each AE protocol induces a unique physiological response (i.e., motor unit recruitment pattern, substrate usage and depletion, metabolite formation, etc.) that may culminate in varied levels of fatigue. The extent to which the fatigue manifests during subsequent RE is critical to sequencing strategies during concurrent training program design. Thus, the purpose of the present study was to examine the effects of 4 different AE protocols (performed 10 minutes after RE) on acute RE performance. Unique to the present study, multiple AE running protocols were examined before a RE protocol consisting of 5 multiple-joint exercises that stress all major muscle groups (as opposed to a strength or endurance test characteristic of most studies). We hypothesized that completed repetitions, power, and velocity would be reduced during RE after AE exercise.

Methods

Experimental Approach to the Problem

To examine the primary hypothesis of the present investigation, subjects were tested for $\dot{V}O_2$max, running performance, and maximal strength on 5 free-weight exercises and subsequently performed (in a randomized sequence) a control RE protocol (5 exercises, 70–80% of 1RM, 6–10 repetitions, 3-minute rest intervals) and 4 additional RE protocols initiated 10 minutes after 4 different AE protocols: (a) continuous running at moderate intensity for 45 minutes (P1); (b) continuous running at moderately high intensity for 20 minutes (P2); (c) running at high-intensity intervals for 15 minutes (with 15 minutes of low-intensity running in between [P3]); and (d) continuous running at moderately high intensity uphill for 20 minutes (P4). Blood lactate, heart rate (HR), ratings of perceived exertion (RPE), and RE performance data were collected during each protocol and subsequently analyzed. This study design enabled us to examine if the intensity, duration, and type of AE exercise affected acute RE performance.

Subjects

Eleven healthy, resistance-trained men (age range = 19 to 23) agreed to participate in the present study (Table 1). Each subject initiated the study in a trained state (i.e., were resistance training 2–4 days per week) and none were taking any medications such as anabolic steroids known to affect RE performance. Seven of the 11 subjects were currently participating in aerobic training (swimming, running 1–5 days per week). Two of the subjects stated preferences for aerobic training, one subject prioritized both aerobic and resistance training, and eight subjects cited resistance training as their prioritized modality. Subjects underwent 1 week of familiarization (2–3 sessions) with study procedures before testing. Familiarization focused on subjects' ability to perform all of the exercises with good technique. During this time, height was measured using a wall-mounted stadiometer and body mass was measured using an electronic scale. Percent body fat was estimated via a 3-site skinfold test. The sites measured were the pectoral, anterior thigh, and abdominal skinfolds using methodology previously described (23). Body density was calculated using the equation of Jackson and

Table 1. Descriptive characteristics.

	Subjects ($N = 11$)
Age (y)	21.0 ± 1.2
Height (cm)	178.5 ± 8.7
Body mass (kg)	79.9 ± 13.9
Body fat (%)	13.1 ± 3.9
Resistance training experience (y)	5.1 ± 2.8
1RM high pull (kg)	81.4 ± 19.9
1RM squat (kg)	132.0 ± 41.0
1RM bench press (kg)	100.4 ± 27.4
1RM deadlift (kg)	164.0 ± 39.0
1RM push press (kg)	74.0 ± 14.5
$\dot{V}O_2max$ ($ml\cdot kg^{-1}\cdot min^{-1}$)	48.7 ± 4.9

Pollock (23) and percent body fat was calculated using the equation of Siri (45). The same research assistant performed all skinfold assessments. This study was approved by the College's Institutional Review Board and each subject subsequently signed an informed consent document before participation. No subject had any physiological or orthopedic limitations that could have affected exercise performance as determined by completion of a health history questionnaire.

Maximal Aerobic Capacity ($\dot{V}O_2max$) Testing

All subjects reported to the laboratory for maximal aerobic capacity testing. Subjects refrained from exercise for at least 24 hours before each testing session. $\dot{V}O_2max$ was assessed using a progressive, multistage ramp protocol on a treadmill using a metabolic data collection system (MedGraphics ULTIMA Metabolic System; MedGraphics Corp., St. Paul, MN, USA). It consisted of 2-minute stages at a speed of 6.0 mph with increments in percent grade of 2.5% per stage. All subjects were verbally encouraged to continue exercise until volitional exhaustion. Breath-by-breath $\dot{V}O_2$ data were obtained and $\dot{V}O_2max$ was determined by recording the highest measure. Gas analyzers were calibrated before each trial using gases provided by MedGraphics Corporation: (a) calibration gas: 5% CO_2, 12% O_2, balance N_2; and (b) reference gas: 21% O_2, balance N_2.

Running Test

Approximately 48 hours after the $\dot{V}O_2max$ test, subjects performed a flat treadmill running test (0% grade) to establish running velocities for 3 of the 4 endurance protocols. It consisted of 2-minute stages (starting at 5.0 mph) with increments in velocity of 0.5 mph each stage (following a general warm-up of walking at 3.5 mph) and was terminated when subjects could no longer volitionally continue or at least 90–95% of their $\dot{V}O_2max$ was reached. All subjects were verbally encouraged to continue until volitional exhaustion. $\dot{V}O_2$ was obtained for each breath. Gas analyzers were calibrated using gases provided by MedGraphics Corporation: (a) calibration gas: 5% CO_2, 12% O_2, balance N_2; and (b) reference gas: 21% O_2, balance N_2 before each trial.

Incline Running Test

Approximately 48 hours after the running test, subjects performed an incline treadmill running test (at 4.5 mph) to establish percent incline for the uphill AE protocol. It consisted of 2-minute stages (starting at 0%) with increments in percent grade of 1.0% each stage (following a general warm-up of walking at 3.5 mph) and was terminated when subjects could no longer volitionally continue (which occurred between 2 and 11% grade for all subjects depending on their aerobic capacity). $\dot{V}O_2$ was obtained for each breath. Gas analyzers were calibrated using gases provided by MedGraphics Corporation: (a) calibration gas: 5% CO_2, 12% O_2, balance N_2; and (b) reference gas: 21% O_2, balance N_2 before each trial.

Strength Testing

One-repetition maximum (1RM) strength was assessed for 5 free-weight resistance exercises using a standard protocol (24,38). For each exercise, a warm-up set of 5–10 repetitions was performed using 40–60% of the perceived 1RM. After a 1-minute RI, a set of 2–3 repetitions was performed at 60–80% of the perceived 1RM. Subsequently, 2–4 maximal trials were performed to determine the 1RM with 2–3 minutes RI between trials. Maximal strength was determined for 2–3 exercises per session separated by 24–48 hours. A complete range of motion and proper technique was required for each successful 1RM trial. For the bench press (BP), the bar was lowered until it touched the lower-to-mid sternum (with no "bouncing") and was lifted to full elbow extension (with no excessive arching of the back). For the back squat (SQ), subjects descended with the bar on the rear shoulders until their upper thighs were parallel to the ground. At that point, a "lift" signal was given by a research assistant (to ensure proper depth) and the subject ascended to the starting position. For the push press (PP), subjects initiated the exercise from the racked bar position across the shoulders, performed a small counter-movement, and rapidly lifted the bar to the overhead (elbows fully extended) position. For the high pull (HP), subjects began the exercise from the "hang" position above the knees and rapidly lifted the barbell as fast as possible until it reached the level of the inferior sternum. A research assistant visually confirmed proper range of motion for the exercise. For the conventional-style deadlift (i.e., arms were positioned lateral to the legs with a grip width wider than stance width) (DL), subjects lifted the bar from the ground until full hip extension was achieved. Assessment of 1RM strength enabled calculation of the protocol loads.

Resistance Exercise Protocols

The RE protocol consisted of 5 exercises performed in the following sequence: high pull, back squat, bench press, deadlift, and push press. The high pull was performed for 3 sets of up to 6 repetitions with 80% of 1RM. The squat and

Table 2. Repetition performance.

	Control	P1	P2	P3	P4
High pull					
Set 1	6.0 ± 0.0	5.8 ± 0.4	5.9 ± 0.3	5.8 ± 0.4	5.9 ± 0.3
Set 2	6.0 ± 0.0	6.0 ± 0.0	5.9 ± 0.3	5.7 ± 0.6	5.8 ± 0.6
Set 3	6.0 ± 0.0	5.9 ± 0.3	6.0 ± 0.0	5.9 ± 0.3	5.9 ± 0.3
Total	18.0 ± 0.0	17.7 ± 0.5	17.8 ± 0.4	17.5 ± 1.3	17.6 ± 1.2
Squat					
Set 1	10.0 ± 0.0	7.3 ± 2.6*†‡	8.5 ± 2.7*§‖	6.6 ± 2.8*†‡	9.3 ± 1.2§‖
Set 2	9.8 ± 0.6	6.8 ± 2.9*	7.7 ± 2.8*§	6.3 ± 2.8*†	7.1 ± 2.6*‖¶
Set 3	8.8 ± 2.6¶	6.0 ± 2.7*‡¶	6.8 ± 3.0*¶	6.2 ± 3.3*‡	7.2 ± 2.4*§‖¶
Total	28.6 ± 3.0	20.1 ± 7.6*†‡	23.0 ± 7.5*§‖	19.0 ± 8.6*†‡	23.5 ± 5.6*§‖
Bench press					
Set 1	9.8 ± 0.6	9.2 ± 1.5	9.9 ± 0.3	9.3 ± 1.6	9.9 ± 0.3
Set 2	8.8 ± 1.5¶	7.4 ± 1.7*¶	8.2 ± 1.7‖¶	7.3 ± 1.6*†‡¶	8.4 ± 1.6¶
Set 3	7.5 ± 2.8¶#	5.5 ± 2.5*¶#	5.6 ± 2.4*¶#	5.0 ± 2.4*¶#	5.4 ± 2.7¶#
Total	26.1 ± 4.5	22.1 ± 4.1*	23.7 ± 3.8*‖	21.5 ± 3.6*†‡	23.6 ± 3.8*‖
Deadlift					
Set 1	9.1 ± 2.1	8.0 ± 2.9	8.1 ± 3.1	7.5 ± 2.7	8.8 ± 2.1
Set 2	8.2 ± 2.7	8.2 ± 2.2	7.7 ± 3.3	6.9 ± 3.0	7.8 ± 2.6
Set 3	7.9 ± 2.7¶	7.7 ± 2.8	7.3 ± 2.7	6.7 ± 3.3	7.5 ± 3.0¶
Total	25.2 ± 7.2	23.9 ± 7.1	23.1 ± 8.6	21.2 ± 8.6	24.1 ± 7.2
Push press					
Set 1	9.5 ± 1.2	9.1 ± 1.4	9.6 ± 0.8	9.1 ± 1.6	9.2 ± 1.5
Set 2	9.5 ± 0.9	8.3 ± 2.0*	8.2 ± 2.1*¶	7.5 ± 2.0*¶	8.6 ± 1.7
Set 3	9.1 ± 1.5	7.5 ± 2.6*¶	7.0 ± 2.7*¶#	6.9 ± 2.5*¶	7.8 ± 1.8**¶
Total	28.1 ± 2.1	24.8 ± 4.9*	24.8 ± 5.0*	23.5 ± 5.4*	25.6 ± 4.4**

*$p \leq 0.05$ compared with control.
†$p \leq 0.05$ compared with P2.
‡$p \leq 0.05$ compared with P4.
§$p \leq 0.05$ compared with P1.
‖$p \leq 0.05$ compared with P3.
¶$p \leq 0.05$ from set 1.
#$p \leq 0.05$ from set 2.
**$p = 0.08$ compared with control.

bench press were performed for 3 sets of up to 10 repetitions with 75% of 1RM. The deadlift and push press were performed for 3 sets of up to 10 repetitions with 70% of 1RM. Loads/repetitions and rest intervals were selected based on RE recommendations and pilot testing. Loads for the deadlift and push press were reduced to 70% because pilot testing revealed great difficulty with some subjects' ability to complete the protocols after performing AE. In addition, pilot testing revealed that 3 minutes of rest was more tolerable for our subjects than 2 minutes. Rest intervals between all sets were 3 minutes and RE protocol durations ranged from 52 to 60 minutes. Standard exercise technique (similar to criteria used for strength testing) was used and only those repetitions that met the criteria were counted. Resistance remained constant, whereas total numbers of repetitions were recorded. Subjects used a self-selected cadence (with no rest in between repetitions) to maximize RE performance. Following each set, ratings of perceived exertion (RPE) were obtained using a category ratio (CR) 10-point (0–10) scale. Subjects remained standing or paced within a small designated area in between sets of RE. Data presented are the mean RPEs averaged over 3 sets for each exercise. Bar peak and average velocity and power for each repetition were measured with a Tendo Power Output Unit (Tendo Sports Machines, Trencin, Slovak Republic). Power and velocity were averaged for each set (for all completed repetitions) and for each protocol. Test–retest reliability for the Tendo unit in our laboratory has consistently shown $R > 0.90$ (15). Subjects were also fitted with a Polar HR monitor (Polar Electro, Inc., Woodbury, NY, USA), which was used to measure HR pre-exercise, during each set of RE and during the rest intervals. Mean HR for each AE and RE protocol are reported.

Subjects performed a control (CT) RE protocol on 2 occasions. The first occurred 48 hours after the last preliminary testing session. This session was designed to allow the subjects to experience the physiological demands of the protocol and familiarize them to the procedures. It also enabled subjects to experience mild delayed onset muscle soreness, so subsequent sessions would be less stressful. A second CT protocol was

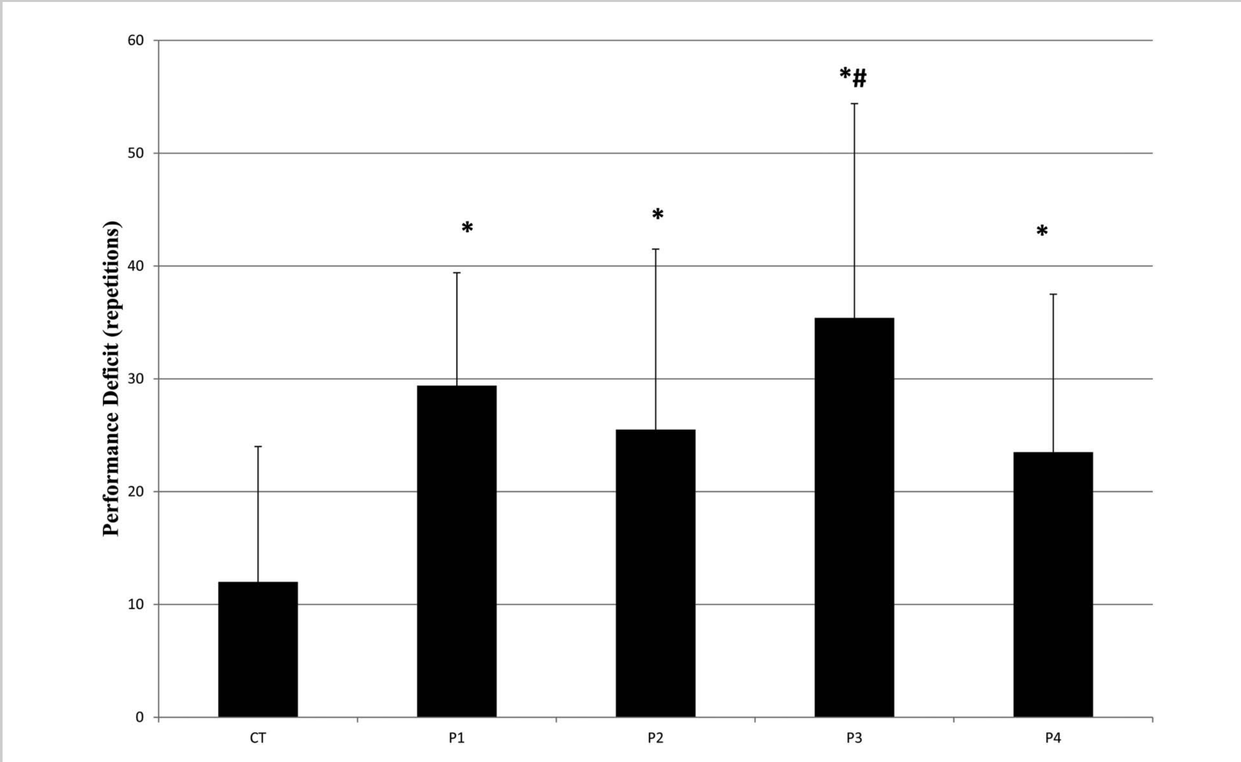

Figure 1. Performance deficits observed during the resistance exercise (RE) protocols. Data were calculated by subtracting completed repetitions from the theoretical maximum of 138. CT = control RE protocol; P1-4 = RE protocols following 4 aerobic endurance protocols; *$p \leq 0.05$ from CT; #$p \leq 0.05$ compared with P2 and P4.

performed in random sequence with the other experimental protocols and data were used for analysis. This design was used to minimize any potential training effect that could have taken place if the CT protocol was always performed first in sequence. For the CT protocol, subjects arrived at the laboratory at a standard time of day, performed a warm-up consisting of 3–5 minutes of treadmill walking, light stretching, and 1–2 light sets of the exercises. Water was provided ad libitum during this time. When RE followed an AE protocol (P1–P4), subjects were given a 10-minute rest interval. Although previous studies have shown muscle performance may be compromised 2 minutes to 8 hours following AE (1,26,27,46), a 10-minute rest period was selected because it more realistically represents the amount of time taken between modalities in practical settings and has been studied previously (13). During this time, subjects spent 2 minutes on the treadmill cooling down from the AE protocol and performed 3 light sets of RE (1 set each of the high pull, squat, and bench press with 30–50% of 1RM for 5–10 repetitions per set) in preparation for the protocol which promptly began 10 minutes after completion of the AE protocol.

Aerobic Endurance Protocols

On 4 occasions (separated by at least 72 hours), subjects performed an AE protocol before performing the RE protocol. Upon arrival, each subject was encouraged to drink water ad libitum to prehydrate and consumed water during the protocol. The AE protocols consisted of treadmill running at a velocity corresponding to: (a) 60% of their $\dot{V}O_2$ reserve ($\dot{V}O_2R$) for 45 minutes (P1); (b) 75% of their $\dot{V}O_2R$ for 20 minutes (P2); (c) 90–100% of $\dot{V}O_2R$ in 3-minute intervals (1:1 ratio) for 5 sets separated by 3-minute bouts of jogging at 40% of $\dot{V}O_2R$ (P3); and (d) 75% of $\dot{V}O_2R$ (4.5 mph) uphill (6–9%) for 20 minutes (P4). All treadmill velocities/percent grades were determined from the baseline treadmill running tests. Before each protocol, subjects performed a standard 5-minute warm-up consisting of 5 minutes of walking at 4.0 mph. Subjects were also fitted with a Polar HR monitor used to measure HR pre-exercise and after each minute of exercise. Mean HR per session was reported. Following each minute, RPEs were obtained using a Borg 15-point (6–20) scale.

Blood Lactate

Whole blood lactate was assessed in duplicate via a portable lactate analyzer (Lactate Plus Meter; Nova Biomedical, Waltham, MA, USA) taken at the fingertip using a sterile lancet. Blood lactate samples were taken at rest, immediately following each AE protocol, and following each RE protocol. Reliability of this analyzer has been shown to be high (19).

TABLE 3. Average power (W).

	Control	P1	P2	P3	P4
High pull					
Set 1	772.5 ± 189.5	733.5 ± 193.3*†	741.0 ± 174.2*	736.1 ± 178.6*†	757.6 ± 172.5*‡§
Set 2	782.0 ± 193.4	726.8 ± 194.6*†	743.6 ± 173.1*	722.3 ± 187.8*†	748.2 ± 203.8*‡§
Set 3	774.8 ± 191.1	732.2 ± 174.0*†	723.8 ± 171.3*	714.8 ± 169.4*†	758.5 ± 185.5*‡§
Mean	776.4 ± 191.3	730.8 ± 187.3*†	736.1 ± 172.9*	724.4 ± 178.6*†	754.8 ± 187.3*‡§
Squat					
Set 1	521.6 ± 229.1	427.9 ± 166.6*‖†	466.7 ± 188.0*‡	407.2 ± 198.0*‖	459.6 ± 188.2*‡
Set 2	496.3 ± 188.4¶	426.2 ± 187.6*†	442.0 ± 179.1*¶	402.5 ± 173.7*	444.2 ± 163.6*
Set 3	450.0 ± 168.6#**	396.4 ± 188.7*†‖#**	443.2 ± 196.8‡#	392.1 ± 180.1*#	427.1 ± 159.9*‡#
Mean	489.3 ± 195.4	416.8 ± 181.0*‖†	450.6 ± 188.0*‡	400.6 ± 183.9*	443.6 ± 170.6*‡
Bench press					
Set 1	297.3 ± 89.2	255.1 ± 85.8*	276.6 ± 90.1	248.6 ± 74.2*	275.3 ± 80.8
Set 2	266.9 ± 76.0#	240.3 ± 73.2*	255.0 ± 86.2#	234.8 ± 70.7*	252.3 ± 74.0#
Set 3	233.2 ± 59.3#**	219.7 ± 67.4#**	220.6 ± 75.9#**	223.6 ± 73.0#	215.6 ± 70.8#**
Mean	265.8 ± 74.8	238.4 ± 75.5*	250.7 ± 84.1	235.7 ± 72.6*	247.7 ± 75.2
Deadlift					
Set 1	582.6 ± 115.7	555.4 ± 139.0	546.1 ± 116.8	537.1 ± 136.3	569.5 ± 130.8
Set 2	560.3 ± 124.0	544.3 ± 154.4	492.5 ± 168.7	530.7 ± 132.0	554.3 ± 125.8
Set 3	554.4 ± 131.9	529.6 ± 155.1	523.4 ± 158.0	505.1 ± 117.2	553.5 ± 108.0
Mean	565.8 ± 123.9	543.1 ± 149.5	520.7 ± 147.8	524.3 ± 128.5	559.1 ± 121.5
Push press					
Set 1	499.1 ± 140.6	487.3 ± 165.2	470.1 ± 145.2	457.2 ± 145.8	482.1 ± 116.9
Set 2	511.1 ± 167.1	480.6 ± 156.8	496.0 ± 148.4	464.2 ± 158.5	500.3 ± 153.3
Set 3	526.8 ± 143.8¶	498.4 ± 155.4	488.1 ± 131.7	481.1 ± 150.2¶	500.9 ± 154.7
Mean	512.4 ± 150.5	488.8 ± 159.1	484.7 ± 141.8	467.5 ± 151.5	494.5 ± 141.6

*$p \leq 0.05$ compared with control.
†$p \leq 0.05$ compared with P4.
‡$p \leq 0.05$ compared with P1.
§$p \leq 0.05$ compared with P3.
‖$p \leq 0.05$ compared with P2.
¶$p = 0.08$ from set 1.
#$p \leq 0.05$ from set 1.
**$p \leq 0.05$ from set 2.

Statistical Analyses

Descriptive statistics (means ± *SD*) were calculated for all dependent variables. A 1 (group) × 5 (protocols) analysis of variance (ANOVA) with repeated measures was used to analyze within-subject performance, RPE, HR, and lactate data. Subsequent Tukey's post hoc tests were used to determine differences when significant main effects were obtained. Partial eta-square (η^2) effect sizes were determined for treatment effects and interpreted using the following criteria: 0.01 = small; 0.06 = medium; and 0.13 = large. Pearson product-moment correlations were calculated between $\dot{V}O_2max$, maximal strength, blood lactate, and selected performance variables. For all statistical tests, a probability level of $p \leq 0.05$ denoted statistical significance.

RESULTS

Repetition Performance

Repetition performance data are presented in Table 2. No significant differences were observed for the high pull in any protocol compared with the control RE protocol ($p = 0.61$, $\eta^2 = 0.06$). Significant differences were found between protocols for the squat ($p < 0.001$, $\eta^2 = 0.48$), bench press ($p < 0.001$, $\eta^2 = 0.42$), and push press ($p = 0.03$, $\eta^2 = 0.23$) but not the deadlift ($p = 0.17$, $\eta^2 = 0.15$). For the squat, all AE protocols led to significant reductions in repetitions performed with P1 and P3 resulting in the fewest. For the bench press, all AE protocols led to significant reductions in repetitions performed with P3 resulting in the fewest. For the push press, P1, P2, and P3 (plus a trend in P4) led to significant reductions in repetitions performed. Set-specific differences for all exercises are shown in Table 2. When total repetitions performed for all 5 exercises were analyzed, a significant difference was observed ($p < 0.001$, $\eta^2 = 0.62$) where the CT protocol yielded the highest (126.0 ± 12.0) repetition total and P1 (108.6 ± 10.1), P2 (112.5 ± 15.8), P3 (102.6 ± 19.0), and P4 (114.5 ± 14.3) was all significantly lower by 9.1–18.6%. P1 and P3 resulted in the fewest repetitions performed. Figure 1 depicts the repetition deficits (calculated by

Table 4. Peak power (W).

	Control	P1	P2	P3	P4
High pull					
Set 1	1,147.2 ± 271.4	1,100.0 ± 265.3*	1,108.3 ± 251.9*	1,108.5 ± 262.4*	1,111.0 ± 261.0†
Set 2	1,144.3 ± 265.4	1,093.6 ± 259.6*	1,098.9 ± 257.9*	1,080.2 ± 278.9*	1,111.6 ± 282.9†
Set 3	1,141.1 ± 270.2	1,098.4 ± 257.0*	1,088.1 ± 248.9*	1,070.3 ± 259.1*	1,117.1 ± 271.5
Mean	1,144.2 ± 269.0	1,097.3 ± 260.6*	1,098.4 ± 252.9*	1,086.3 ± 266.8*	1,113.2 ± 271.8†
Squat					
Set 1	859.8 ± 315.3	762.6 ± 275.3*‡	840.8 ± 315.3§‖	656.2 ± 306.8*‡	793.2 ± 265.9¶
Set 2	828.0 ± 279.7	756.4 ± 306.6*	780.6 ± 267.3‖	705.6 ± 290.9*‡	774.8 ± 216.5¶
Set 3	776.6 ± 251.8#**	695.1 ± 283.3*‡#**	786.1 ± 310.5§‖	676.2 ± 272.7*‡	752.3 ± 234.5#
Mean	821.5 ± 282.3	738.0 ± 288.4*‡	802.5 ± 297.7§‖	679.3 ± 290.0*‡	773.4 ± 239.0¶
Bench press					
Set 1	404.3 ± 134.0	355.9 ± 126.4*	373.8 ± 126.3‖¶	348.6 ± 110.2*‡††	393.1 ± 131.0‖
Set 2	386.3 ± 135.0	346.6 ± 126.1*	385.6 ± 142.8‖	335.2 ± 100.1*‡††	366.2 ± 113.7‖
Set 3	358.8 ± 96.6#**	343.4 ± 125.7	344.3 ± 120.4#**	330.4 ± 103.9*#	326.7 ± 99.0#**
Mean	383.1 ± 121.9	348.6 ± 126.1*	367.9 ± 129.8‖¶	338.1 ± 104.7*‡††	362.0 ± 114.6‖
Deadlift					
Set 1	885.2 ± 203.4	811.3 ± 189.4	807.1 ± 154.2	804.0 ± 197.7	833.5 ± 202.4
Set 2	856.0 ± 191.5	815.7 ± 234.9	757.1 ± 209.9	798.4 ± 199.0	815.7 ± 176.2
Set 3	846.2 ± 208.7	806.8 ± 230.2	811.2 ± 223.8	754.4 ± 155.3	806.9 ± 158.9
Mean	862.5 ± 201.2	811.3 ± 218.2	791.8 ± 196.0	785.6 ± 184.0	818.7 ± 179.2
Push press					
Set 1	850.9 ± 159.8	859.8 ± 193.3	838.2 ± 178.7	831.4 ± 185.9	850.3 ± 142.4
Set 2	885.2 ± 186.2#	879.9 ± 170.7	886.4 ± 177.1#	853.8 ± 196.5#	895.7 ± 181.2#
Set 3	904.4 ± 177.5#**	893.7 ± 179.0#	889.5 ± 173.5#	886.5 ± 192.3#**	907.8 ± 175.4#
Mean	880.1 ± 174.5	877.8 ± 181.0	871.4 ± 176.4	857.2 ± 191.6	884.6 ± 166.3

*$p \leq 0.05$ compared with control.
†$p = 0.07$ compared with control.
‡$p \leq 0.05$ compared with P2.
§$p \leq 0.05$ compared with P1.
‖$p \leq 0.05$ compared with P3.
¶$p = 0.10$ compared with control.
#$p \leq 0.05$ from set 1.
**$p \leq 0.05$ from set 2.
††$p \leq 0.05$ compared with P4.

Table 5. Average velocity ($m \cdot s^{-1}$).

	Control	P1	P2	P3	P4
High pull					
Set 1	1.22 ± 0.06	1.17 ± 0.10*†	1.17 ± 0.07*	1.17 ± 0.11*†	1.20 ± 0.10‡§
Set 2	1.23 ± 0.06	1.14 ± 0.10*†‖	1.18 ± 0.11*	1.15 ± 0.09*	1.17 ± 0.10‡¶
Set 3	1.22 ± 0.09	1.16 ± 0.10*†§‖	1.14 ± 0.08*	1.13 ± 0.06*†	1.20 ± 0.10‡§
Mean	1.22 ± 0.07	1.16 ± 0.10*†§‖	1.17 ± 0.09*	1.15 ± 0.09*†	1.19 ± 0.10‡§¶
Squat					
Set 1	0.52 ± 0.08	0.43 ± 0.07*†‖	0.47 ± 0.07*‡	0.42 ± 0.11*	0.48 ± 0.11*‡
Set 2	0.50 ± 0.06	0.43 ± 0.08*†‖	0.45 ± 0.09*‡	0.42 ± 0.12*	0.46 ± 0.08*‡
Set 3	0.46 ± 0.06#**	0.40 ± 0.10*†‖#**	0.45 ± 0.09‡#	0.41 ± 0.11*	0.44 ± 0.09‡#
Mean	0.49 ± 0.07	0.42 ± 0.08*†‖	0.46 ± 0.08*‡	0.42 ± 0.11*	0.46 ± 0.09*‡
Bench press					
Set 1	0.40 ± 0.07	0.34 ± 0.07*‖††	0.37 ± 0.06*‡	0.35 ± 0.08*	0.38 ± 0.07
Set 2	0.37 ± 0.09#	0.32 ± 0.06*‖#††	0.35 ± 0.07‡#	0.33 ± 0.08*#	0.35 ± 0.09#
Set 3	0.33 ± 0.09#**	0.29 ± 0.07*#**	0.30 ± 0.08*#**	0.30 ± 0.08*#**	0.30 ± 0.10*#**
Mean	0.37 ± 0.08	0.32 ± 0.07*‖††	0.34 ± 0.07*‡	0.33 ± 0.08*	0.34 ± 0.09*
Deadlift					
Set 1	0.51 ± 0.07	0.50 ± 0.12	0.49 ± 0.11	0.48 ± 0.10	0.50 ± 0.09
Set 2	0.50 ± 0.08	0.48 ± 0.11	0.44 ± 0.15‡‡	0.47 ± 0.09	0.49 ± 0.09
Set 3	0.49 ± 0.11	0.47 ± 0.12‡‡	0.47 ± 0.13	0.44 ± 0.09‡‡	0.50 ± 0.11
Mean	0.50 ± 0.09	0.48 ± 0.12	0.47 ± 0.13	0.46 ± 0.09	0.50 ± 0.09
Push press					
Set 1	0.97 ± 0.17	0.96 ± 0.22	0.93 ± 0.21	0.90 ± 0.19	0.96 ± 0.19
Set 2	0.99 ± 0.21	0.94 ± 0.20	0.98 ± 0.20	0.90 ± 0.20	0.98 ± 0.20
Set 3	1.05 ± 0.17	0.97 ± 0.18	0.96 ± 0.17	0.95 ± 0.19	0.98 ± 0.18
Mean	1.00 ± 0.18	0.96 ± 0.20	0.96 ± 0.19	0.92 ± 0.19	0.98 ± 0.19

*$p \leq 0.05$ compared with control.
†$p \leq 0.05$ compared with P4.
‡$p \leq 0.05$ compared with P1.
§$p \leq 0.05$ compared with P3.
‖$p \leq 0.05$ compared with P2.
¶$p = 0.06$ compared with control.
#$p \leq 0.05$ from set 1.
**$p \leq 0.05$ from set 2.
††$p = 0.10$ compared with P4.
‡‡$p = 0.08$ from set 1.

subtracting the number of repetitions completed from the theoretical maximum number of 138). All repetition deficits were significantly higher in P1–P4 compared to CT with the highest reduction seen in P3.

Power

Average power data are presented in Table 3. For the high pull ($p = 0.001$, $\eta^2 = 0.37$) and squat ($p = 0.003$, $\eta^2 = 0.33$), significant differences were shown where average power was significantly lower for P1–P4 compared with control. For the bench press, a significant difference ($p = 0.05$, $\eta^2 = 0.20$) was found where average power was significantly lower in P1 and P3 compared with control. No significant differences were observed for the deadlift ($p = 0.32$, $\eta^2 = 0.11$) and push press ($p = 0.20$, $\eta^2 = 0.14$) between protocols. No differences were observed between sets 1 through 3 within each protocol for the high pull ($p = 0.35$) and deadlift ($p = 0.12$; $\eta^2 = 0.19$). However, significant differences were found for the squat ($p < 0.001$, $\eta^2 = 0.55$) and bench press ($p < 0.001$, $\eta^2 = 0.68$) where average power declined between sets 1 and 3. For the push press, a trend was observed ($p = 0.07$, $\eta^2 = 0.23$) where average power was higher in set 3 than set 1 for control and P3.

Peak power data are presented in Table 4. For the high pull ($p = 0.014$, $\eta^2 = 0.26$) and squat ($p = 0.017$, $\eta^2 = 0.26$), significant differences were shown where peak power was significantly lower for P1–P4 compared with control (with the exception of P2 and P4 for the squat). For the bench press, a significant difference ($p = 0.015$, $\eta^2 = 0.26$) was found where peak power was significantly lower in P1 and P3 compared with control. No significant differences were observed for the deadlift ($p = 0.21$, $\eta^2 = 0.13$) and push press ($p = 0.37$, $\eta^2 = 0.10$) between protocols. No differences were observed between sets 1 through 3 within each protocol for the high pull ($p = 0.18$, $\eta^2 = 0.16$) and deadlift ($p = 0.25$; $\eta^2 = 0.13$). However, significant differences were found for the squat ($p = 0.04$, $\eta^2 = 0.27$) and bench press ($p = 0.001$, $\eta^2 = 0.51$) where peak power declined between sets 1 and 3. For the push press,

Table 6. Peak velocity ($m \cdot s^{-1}$).

	Control	P1	P2	P3	P4
High pull					
Set 1	1.81 ± 0.09	1.74 ± 0.11*†	1.76 ± 0.10*	1.76 ± 0.14*	1.79 ± 0.13‡
Set 2	1.81 ± 0.09	1.73 ± 0.10*	1.73 ± 0.14*§	1.69 ± 0.10*‡§	1.75 ± 0.12‖§
Set 3	1.80 ± 0.14	1.74 ± 0.12*	1.72 ± 0.11*§	1.69 ± 0.11*†§	1.77 ± 0.13‡‖
Mean	1.81 ± 0.11	1.74 ± 0.11*†	1.74 ± 0.12*	1.71 ± 0.12*†	1.77 ± 0.13‡‖
Squat					
Set 1	0.87 ± 0.12	0.78 ± 0.11*¶	0.82 ± 0.14*‖	0.68 ± 0.19*†¶	0.81 ± 0.14‖
Set 2	0.85 ± 0.09	0.77 ± 0.13*†	0.80 ± 0.11*	0.74 ± 0.20*†¶	0.82 ± 0.13‡‖
Set 3	0.80 ± 0.10§	0.68 ± 0.12*†¶§#	0.80 ± 0.13‡	0.71 ± 0.18*¶	0.78 ± 0.12‡‖
Mean	0.84 ± 0.10	0.74 ± 0.12*†¶	0.81 ± 0.13*‡‖	0.71 ± 0.19*†¶	0.80 ± 0.13‡‖
Bench press					
Set 1	0.55 ± 0.08	0.47 ± 0.08*†	0.50 ± 0.06*‖	0.48 ± 0.08*†	0.53 ± 0.09‡‖
Set 2	0.53 ± 0.09	0.45 ± 0.07*†¶	0.51 ± 0.07‡	0.46 ± 0.08*†¶	0.50 ± 0.07‡‖
Set 3	0.49 ± 0.08§#	0.45 ± 0.09*	0.46 ± 0.08§#	0.45 ± 0.08*§	0.45 ± 0.08*§
Mean	0.52 ± 0.08	0.46 ± 0.08*†¶	0.49 ± 0.07*‡‖	0.46 ± 0.08*†¶	0.49 ± 0.08*‡‖
Deadlift					
Set 1	0.78 ± 0.11	0.72 ± 0.13	0.72 ± 0.13	0.71 ± 0.12	0.74 ± 0.12
Set 2	0.76 ± 0.10	0.72 ± 0.12	0.68 ± 0.18	0.70 ± 0.11	0.72 ± 0.12
Set 3	0.75 ± 0.15	0.71 ± 0.16	0.71 ± 0.14	0.67 ± 0.11	0.72 ± 0.13
Mean	0.76 ± 0.12	0.72 ± 0.14	0.70 ± 0.15	0.69 ± 0.11	0.73 ± 0.12
Push press					
Set 1	1.67 ± 0.15	1.70 ± 0.16	1.66 ± 0.15	1.64 ± 0.14	1.70 ± 0.19
Set 2	1.75 ± 0.12§	1.74 ± 0.11	1.75 ± 0.12§	1.68 ± 0.12§	1.77 ± 0.15§
Set 3	1.79 ± 0.08§#	1.77 ± 0.14§	1.75 ± 0.10§	1.75 ± 0.11§#	1.80 ± 0.12§
Mean	1.73 ± 0.12	1.74 ± 0.14	1.72 ± 0.12	1.69 ± 0.12	1.76 ± 0.15

*$p \leq 0.05$ compared with control.
†$p \leq 0.05$ compared with P4.
‡$p \leq 0.05$ compared with P1.
§$p \leq 0.05$ from set 1.
‖$p \leq 0.05$ compared with P3.
¶$p \leq 0.05$ compared with P2.
#$p \leq 0.05$ from set 2.

a significant difference was observed ($p < 0.001$, $\eta^2 = 0.62$) where peak power increased from set 1 to 3.

Velocity

Average velocity data are presented in Table 5. For the high pull ($p < 0.001$, $\eta^2 = 0.40$), squat ($p = 0.001$, $\eta^2 = 0.36$), and bench press ($p = 0.004$, $\eta^2 = 0.31$), significant differences were shown where average velocity was significantly lower for P1–P4 compared with CT. No significant differences were observed for the deadlift ($p = 0.25$, $\eta^2 = 0.12$) and push press ($p = 0.25$, $\eta^2 = 0.12$) between protocols. No differences were observed between sets 1 through 3 within

Table 7. Resistance exercise mean RPE.

	Control	P1	P2	P3	P4
High pull	4.23 ± 1.83	5.55 ± 1.55*†	5.09 ± 1.56*†	6.21 ± 1.28*‡§‖	5.30 ± 0.94*†
Squat	6.83 ± 1.62	8.18 ± 0.81*	7.79 ± 1.20*	8.12 ± 0.87*	7.92 ± 1.51*
Bench press	7.03 ± 1.73	7.86 ± 1.36	7.27 ± 1.71	7.67 ± 1.53	7.55 ± 1.68
Deadlift	7.76 ± 1.41	7.92 ± 1.22	8.00 ± 1.37	8.15 ± 1.17	7.82 ± 1.32
Push press	7.55 ± 1.49	8.03 ± 1.04	8.00 ± 1.35	8.27 ± 1.09	7.91 ± 1.10

*$p \leq 0.05$ compared with control.
†$p \leq 0.05$ compared with P3.
‡$p \leq 0.05$ compared with P1.
§$p \leq 0.05$ compared with P2.
‖$P \leq$ P4.

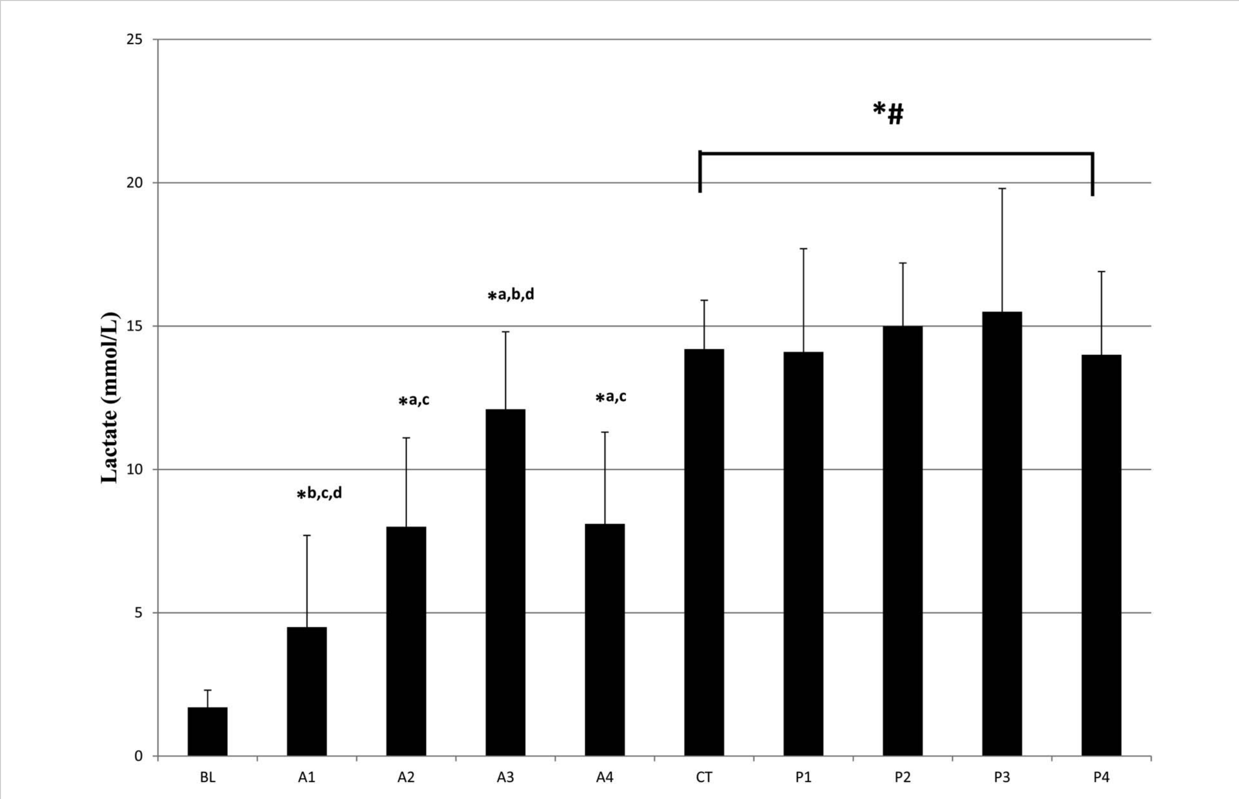

Figure 2. Lactate responses to the aerobic endurance and RE protocols. BL = baseline; A1-4 = aerobic endurance protocol; CT = control RE protocol; P1-4 = RE protocols following 4 aerobic endurance protocols; $*p \leq 0.05$ from BL; $\#p \leq 0.05$ compared with all aerobic endurance protocols; $^{a}p \leq 0.05$ compared with A1; $^{b}p \leq 0.05$ compared with A2; $^{c}p \leq 0.05$ compared with A3; $^{d}p \leq 0.05$ compared with A4.

each protocol for the high pull ($p = 0.25$; $\eta^2 = 0.13$) and push press ($p = 0.14$; $\eta^2 = 0.18$). However, significant differences were found for the squat ($p < 0.001$, $\eta^2 = 0.56$) and bench press ($p < 0.001$, $\eta^2 = 0.79$) where average velocity declined between sets 1 and 3. For the deadlift, a trend was observed ($p = 0.08$; $\eta^2 = 0.23$) where average velocity tended to be lower during set 3 in P1 and P3 compared with CT.

Peak velocity data are presented in Table 6. For the high pull ($p = 0.003$, $\eta^2 = 0.33$), squat ($p = 0.007$, $\eta^2 = 0.29$), and bench press ($p < 0.001$, $\eta^2 = 0.42$), significant differences were shown where peak velocity was significantly lower for P1–P4 compared with CT (with the exception of P4 for the high pull and squat). No significant differences were observed for the deadlift ($p = 0.14$, $\eta^2 = 0.16$) and push press ($p = 0.22$, $\eta^2 = 0.13$) between protocols. Significant differences were found for the high pull ($p = 0.014$, $\eta^2 = 0.35$), squat ($p = 0.007$, $\eta^2 = 0.39$), and bench press ($p < 0.001$, $\eta^2 = 0.58$) where peak velocity declined between sets 1 and 3. For the push press, a significant difference was observed ($p < 0.001$, $\eta^2 = 0.65$) where peak velocity increased from set 1 to 3. No differences were observed between sets 1 through 3 within each protocol for the deadlift ($p = 0.17$; $\eta^2 = 0.16$).

Ratings of Perceived Exertion (RPE)

A significant difference ($p = 0.018$, $\eta^2 = 0.28$) was observed between AE protocols (A1 to A4) for mean session RPE where A3 (15.8 ± 2.3) was significantly higher than A1 (12.9 ± 3.3), A2 (13.7 ± 2.6) and A4 (14.3 ± 2.1). No significant differences were observed between A1, A2, and A4. Table 7 depicts mean RPE values for each exercise per RE protocol. For the high pull ($p < 0.001$, $\eta^2 = 0.42$) and squat ($p = 0.018$, $\eta^2 = 0.25$), significant differences were shown where RPE was significantly higher for P1–P4 compared with control. RPE was significantly higher in P3 than P1, P2, and P4 for the high pull. No significant differences in RPE were observed for the bench press ($p = 0.34$, $\eta^2 = 0.11$), deadlift ($p = 0.93$, $\eta^2 = 0.02$), and push press ($p = 0.54$, $\eta^2 = 0.07$) between protocols.

Blood Lactate

Blood lactate responses to the aerobic endurance and RE protocols are presented in Figure 2. Blood lactate was significantly different between protocols ($p < 0.001$, $\eta^2 =$

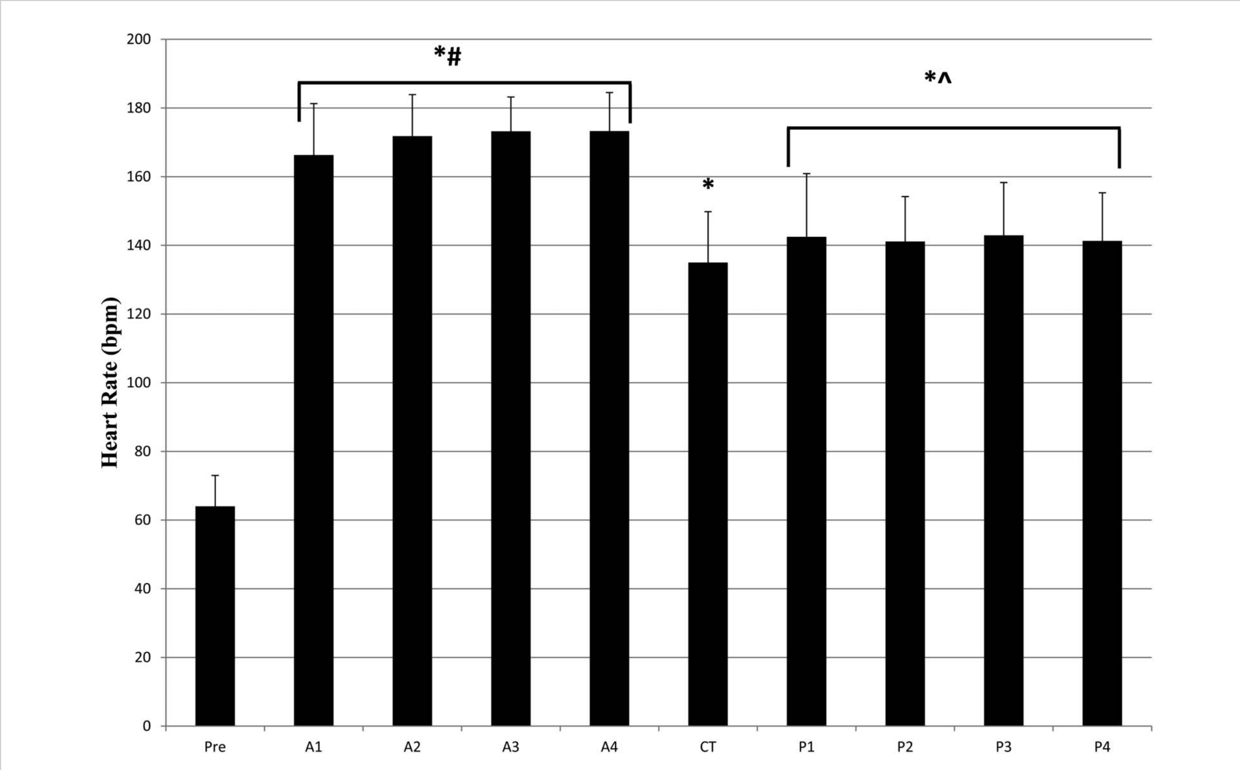

Figure 3. Heart rate responses to the aerobic endurance and RE protocols. Pre = pre-exercise; A1-4 = aerobic endurance protocol; CT = control RE protocol; P1-4 = RE protocols following 4 aerobic endurance protocols; *$p \leq 0.05$ from Pre; #$p \leq 0.05$ compared with all resistance exercise protocols; ^$p \leq 0.05$ compared with CT.

0.81). All exercise protocols resulted in higher blood lactates compared with BL. In comparing the AE protocols, A3 (interval) resulted in the highest lactate response whereas A1 (45-minute) yielded the lowest lactate response. Both 20-minute protocols (A2, A4) produced similar blood lactate responses. All blood lactates were significantly higher following the RE protocols than the AE protocols. No significant differences were observed between CT, P1, P2, P3, and P4.

Heart Rate

Heart rate responses to the AE and RE protocols are presented in Figure 3. All HR values were significantly higher than pre-exercise (Pre). During the AE protocols, mean HR did not significantly differ between protocols ($p = 0.13$, $\eta^2 = 0.17$). The range of HR values (from the mean values of the first to the last minute of each protocol) was: A1 = 145.7 ± 19.9 to 174.4 ± 17.7 $b \cdot min^{-1}$; A2 = 152.3 ± 19.4 to 177.4 ± 15.5 $b \cdot min^{-1}$; A3 = 140.9 ± 14.8 to 193.6 ± 8.5 $b \cdot min^{-1}$; and A4 = 147.9 ± 183.5 ± 13.5 $b \cdot min^{-1}$. All mean HRs for the AE protocols were significantly higher than those seen during RE. During RE, P1, P2, P3, and P4, mean HRs were all significantly higher than CT ($p = 0.03$, $\eta^2 = 0.23$) by 4.3–5.5%. No significant differences were observed between P1, P2, P3, and P4.

Correlations

$\dot{V}O_2max$ was significantly correlated with 1RM squat ($r = -0.60$; $p = 0.05$), 1RM deadlift ($r = -0.56$; $p = 0.05$), and total repetitions performed during CT ($r = 0.61$; $p = 0.047$). Maximal strength (the sum of all 1RMs) was significantly correlated with total repetitions performed during the CT ($r = -0.68$; $p = 0.02$), P1 ($r = -0.73$; $p = 0.01$), P2 ($r = -0.81$; $p = 0.003$), P3 ($r = -0.70$; $p = 0.016$), and P4 ($r = -0.58$; $p = 0.05$) protocols. No significant correlations were observed between post-AE or RE blood lactates and repetition performance.

Discussion

The salient finding from the present study was that AE exercise performed 10 minutes before RE led to significant reductions in performance. All AE protocols resulted in 9.1–18.6% fewer repetitions performed compared to the CT protocol with the squat experiencing the greatest reduction. Average power and velocity per set were significantly reduced for the high pull, squat, and bench press following most AE protocols. The first 3 resistance exercises in sequence were most negatively affected in repetition, power, and velocity decrements. The interval (P3) protocol led to the greatest acute RE performance reductions followed by the 45-minute run (P1).

Repetition performance was significantly compromised in 3 of the 5 resistance exercises performed following AE exercise compared with the CT protocol. Squat (by 5–9 repetitions), bench press (by 2.5–4.5 repetitions), and push press (by 2.5–4.5 repetitions) performances were significantly reduced in P1–P4. Although not statistically significant, deadlift performance was reduced by 1–4 repetitions. These results indicated that prior AE exercise induced a significant level of fatigue that remained during subsequent RE protocols. These results support previous research showing attenuated lower-body RE performance following AE exercise. Leveritt and Abernethy (27) reported squat performance (3 sets to failure at 80% of 1RM) was significantly reduced by 26.7% 30 minutes following an interval cycling protocol. Sporer and Wenger (46) reported leg press (but not bench press) performance was reduced by 25% (after 4 hours) and 9% (after 8 hours) following either interval or long slow distance cycling protocols. Reed et al. (42) reported significant reductions in squat repetitions (6 sets to failure with 80% of 1RM), but not bench press repetitions, following 45 minutes of cycling. De Souza et al. (13) reported significant reductions in leg press repetitions (no effect on bench press) and a trend for decreased 1RM leg press following an interval run protocol but not a continuous 5-km run. Similar results were reported by Lemos et al. (26) in elderly women. Thus, our data support previous studies showing compromised lower-body RE performance following AE exercise but extend current knowledge by demonstrating that multiple exercises (including upper body) are negatively affected by prior performance of multiple types of AE exercise.

A novel finding was that bench press performance was compromised in the present study. Previous studies have shown no reductions in bench press performance following cycling (42,46) and running (13) protocols. Although specific mechanisms were not investigated, running has been shown to elicit passive and active arm swing actions (31,35), thereby demonstrating an upper-body contribution to locomotion. Swinging the arms is a proposed mechanism for increasing postural stability by counteracting torques about the longitudinal axis generated via motion of the legs (35) and increasing metabolic efficiency and neural performance (31). Passive components of arm swings are thought to be driven by motion of the pelvis and legs with force transferred to the shoulders and arms via spring-like elements in spine and shoulder ligaments and muscles (35). Active components of arm swings are thought to be driven by scapular and glenohumeral muscular contractions (35). For example, the deltoid muscles have been shown to act primarily to stabilize the shoulder primarily through eccentric muscle actions (35). The magnitude may depend on the individual's running technique and velocity. In addition, as the bench press was performed third in sequence, it is possible that greater fatigue from the previous 2 RE exercises could have reduced bench press performance. High pull velocity and power and squat repetition performance, power, and velocity were all significantly reduced and these exercises preceded the bench press in sequence. It is possible that additional fatigue from these exercises carried over to bench press performance. Thus, a combination of factors could have compromised bench press performance.

Prior AE exercise did not affect high pull repetition performance in the present study. The high pull was performed for 3 sets of up to 6 repetitions with 80% of 1RM with 3-minute rest intervals in between sets. This intensity prescription is below RM loading and may elicit more repetitions when performed in a nonfatigued state. However, the high pull is an Olympic lift variation that is performed with maximal velocity and power where repetition quality supersedes repetition number (37). It is commonly performed for 6 repetitions or less during strength and power training. Although subjects were able to maintain repetition performance following AE exercise in the present study, the quality of repetitions (as determined by peak and average power and velocity) was significantly compromised. Peak and average power and velocity per set were 2.8–5.4% lower following all AE protocols compared with CT. Average power was 20–40 W lower and peak power was 31–58 W lower compared with CT. These data indicate that power and velocity are compromised during performance of a high-velocity/power exercise such as the high pull following AE exercise despite the fact that repetition performance was maintained.

Unique to the present study was the measurement of power and velocity during each set of RE following AE exercise. Average and peak power and velocity were significantly reduced for the squat and bench press although the deadlift and push press were not significantly affected. These data, in addition to the high pull, showed that the first 3 exercises in sequence were most negatively affected. Average power for squat and bench press were significantly reduced by 7.9–18.1% and 5.7–11.3%, respectively, whereas the 1.2–9.0% reductions in average power of the deadlift and push press did not reach statistical significance. It was not surprising that the squat was most negatively affected by prior AE exercise considering the muscular involvement in running and squatting. Nevertheless, these results show that RE power and velocity is attenuated despite the AE protocol used. Further research is needed to examine if chronic RE performance with reduced repetition power and velocity leads to attenuation of maximum power development when AE precedes RE in sequence.

The results of the present study showed that the type of AE protocol affected subsequent RE performance. Although all (P1–P4) AE protocols led to various levels of performance reductions, the interval program (P3) led to largest reductions (followed by the 45-minute long duration protocol). Previous studies have shown running protocols produced greater attenuation of lower-body muscle strength and hypertrophy compared with cycling (48). Wilson and colleagues (48) suggested that the high eccentric component observed in running (compared with cycling) could have produced greater muscle damage and subsequent fatigue. In comparison, only a few studies examining the acute fatigue hypothesis have directly compared different AE protocols. Similar reductions in isokinetic peak torque (1) and leg press performance (46) have been reported following long slow distance (36–150 minutes) and interval cycle ergometry. In elderly women, larger reductions in repetition number were seen following a high-intensity (80% of HRmax) versus a moderate-intensity (60% of HRmax) treadmill protocol (26). During 9 weeks of concurrent training, similar lower-body strength attenuation has been reported between walking uphill and cycling (20–40 minutes) before RE (16). Few studies have compared different running protocols before RE. De Souza et al. (13) compared a continuous 5-km run to interval running (1:1 ratio, 1-minute bouts at $\dot{V}O_2$max speed) and reported no negative effects on 1RM strength or endurance following the continuous run but significant reductions in leg press repetitions and a trend for a reduced 1RM following the interval protocol. Our results confirm the findings of De Souza et al. (13) regarding the prefatiguing effects of the interval running protocol. However, in contrast to De Souza et al. (13), we reported all AE protocols resulted in significant RE performance decrements. Interestingly, smaller-scale reductions in performance were seen following the two 20-minute AE protocols (continuous flat and incline) although the largest reductions were seen following the interval protocol. These results and the findings of other researchers (13,26) indicate that high-intensity AE interval exercise performed before RE may lead to the most significant reductions in acute RE performance.

A critical component to the acute fatigue hypothesis is the timing of initiation of RE following AE exercise. A 10-minute period was used in the present study because it is a practical representation of a time period used in various training settings and has been studied previously (13). Other studies have used rest intervals as little as 2 minutes with subsequent RE performance reductions (26). Interestingly, lower-body RE performance reductions have been noted 30 minutes (27), 4 (1,46) and 8 (46) hours after AE exercise, whereas other authors have reported RE performance restored within 8 (29) and 24 hours (46) after AE exercise. These data indicate that a long recovery period may be needed if AE exercise precedes RE during the same day and the goal is to maximize RE performance (i.e., quality of repetitions, completed repetitions with a specific load, and loading per set). Performing AE exercise before RE has been shown to limit various measures of strength gains compared with performing RE before AE exercise in some (4,6,33,34) but not all (8,17,47) studies. Likewise, placing RE before AE exercise can attenuate the development of $\dot{V}O_2$max. Chtara et al. (7) reported greater improvements in aerobic fitness when AE exercise preceded RE in sequence versus the opposite sequence. Thus, it appears the goals of the training phase may assist in determining an appropriate sequence during same-day concurrent training.

Ratings of perceived exertion differed among AE protocols where mean session RPE in A3 was significantly higher than A1, A2, and A4. In addition, blood lactate values were significantly higher in A3 compared with A1, A2, and A4. These data indicate that the high-intensity interval AE protocol elicited the largest metabolic demand and perceived exertion among the subjects. During RE, RPE values for the high pull and squat were significantly higher in P1–P4 compared with CT. RPE values observed in P3 were significantly higher than P1, P2, and P4 for the high pull. This was expected because the high pull was performed first in sequence following the high-intensity interval AE protocol. These data support Lemos et al. (26) who reported higher RPE values during RE following the higher intensity (80 versus 60% of HRmax) of 2 AE protocols. No significant differences in RPE were observed for the bench press, deadlift, and push press. These data indicate that subjects' greater perceived difficulty during RE as a result of prior AE exercise persisted in duration only for the first 2 exercises in sequence.

Mean HR for each AE protocol did not significantly differ despite differences in intensity, duration, and type (i.e., long slow distance, continuous incline and flat, and intervals) and all mean AE protocol HRs were significantly higher than those observed during RE. The mean HR for all AE protocols combined was $171.2 \pm 12.0\ b\cdot min^{-1}$, which equated to ~86% of subjects' HRmax. These data, in addition to RPE and blood lactates, confirm the intense and challenging nature of all of the AE protocols employed in the present study.

During RE, all mean protocol (P1–P4) HR values were significantly higher than CT by 4.3–5.5% with no significant differences observed between protocols. These data indicate that mean HR values observed during RE are significantly higher when preceded by AE exercise. It is possible that the higher initial HR values seen at the beginning of RE contributed to the higher observed HR values during RE. In addition, it is likely the greater difficulty observed during RE (as evidenced by reduced repetitions, power, and velocity, and higher RPE values) potentiated the acute HR response. The HR response to RE is dependent on the exercise performed and the volume, intensity, and rest interval length (40). The responses observed (i.e., highest value seen during the set while decreasing with each minute of rest) were similar to previous reports (data not shown) (40). The HR data for P1–P4 seen in the present study were slightly higher than previous values we reported when 2–3 minutes rest intervals were used (40,41) but not when 1–2 minutes intervals were used (40). Regardless of the mechanism(s) involved, prior AE exercise appears to potentiate the cardiovascular response to subsequent RE.

Significant negative correlations were observed between $\dot{V}O_2$max and 1RM squat, 1RM deadlift, and total repetitions performed during the CT protocol. These data confirm previous results from our laboratory showing strong negative relationships between $\dot{V}O_2max$ and lower-body maximal strength (40). In addition, maximal strength was significantly negatively correlated with total repetitions performed in all protocols. We previously reported similar results when comparing bench press repetition performance during RE protocols of different rest interval lengths (39). These data indicate a relationship between maximal strength and fatigability during RE primarily when rest intervals are short. Taken together, these results suggest that stronger individuals may be more susceptible to fatigue-induced reductions in RE performance when it is performed by itself using short rest intervals or following AE exercise.

In summary, all AE protocols (long slow distance, intervals, and continuous flat and incline) resulted in performance decrements although in some instances greater reductions were observed following the high-intensity interval AE protocol. Total repetitions, peak and average power, and velocity of each exercise were attenuated to some extent compared with a control RE protocol that was not preceded by AE exercise. Mean HR and RPE values (for the first 2 exercises) were significantly higher during RE when it was preceded by AE exercise. These data indicate acute RE performance is significantly compromised when performed 10 minutes following AE exercise. It is important to note that all AE protocols were physiologically demanding and the acute fatigue incurred during AE persisted through the RE protocol. The total-body RE protocol consisted of multiple-joint exercises performed for moderately high intensities. Thus, our data indicate a program of this magnitude may be better performed on its own rather than following a challenging AE protocol. These results suggest that priority may need to be given to the modality most associated with training goals when sequencing AE and RE during the same session. Alternative strategies including rotating the sequence or using a periodized approach to target specific goals may be used. The type of RE program used is critical because moderate-to-high intensity multiple-joint exercises stressing large muscle groups that require high force and power output may be more susceptible to the prefatiguing nature of AE. Future research studies are warranted to address potential varying levels of performance decrements with RE programs of different design.

Practical Applications

The potential "interference" effects of concurrent high-intensity/volume AE and resistance training have been extensively studied (5,14,20,22,25,32). Although several mechanisms are likely contributing to this phenomenon, the acute fatigue hypothesis is one potential explanation where fatigue from AE exercise may limit maximal RE performance. Although some studies (4,6,33,34) but not all (17,47) have shown attenuated lower-body strength gains when AE exercise is performed before RE in sequence, every acute study to date has shown reduced lower-body dynamic, isometric, and isokinetic strength and endurance when AE exercise precedes RE (1,26,27,42,46). The negative effects have been noted as few as 2 minutes after AE exercise (26) and up to 8 hours after AE exercise (46). The results of the present study support previous studies showing RE performance decrements following AE exercise.

Unique to the present study was that performance reductions were quantified within the context of a total-body RE protocol consisting of 5 multiple joint exercises (as opposed to a single-exercise strength or endurance assessment). Total repetitions, peak and average power, and velocity of each RE were attenuated to some extent compared with a control RE protocol that was not preceded by AE exercise. In addition, all AE protocols (long slow distance, intervals, and continuous flat and incline) resulted in performance decrements; although in some instances, greater reductions were seen following the high-intensity interval AE protocol. These results indicate that performing intense AE exercise before RE is not desirable if increases in muscle strength and power are training goals. Specific training phases may be incorporated to train each fitness component if both cardiovascular endurance and muscle strength and power are needed in athletes and fitness enthusiasts.

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