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Skeletal muscle and hormonal adaptations to circuit weight training in untrained men

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Twelve men either performed 10 weeks of timed circuit weight training 3 days week^{-1} (CWT; $n = 8$; $X \pm SE$; age = 23.6 ± 1.8 years), or were part of a sedentary control group ($n = 4$; age = 20.5 ± 1.0 years). Significance was $P < 0.05$ for all analyses. The CWT program significantly increased 1 repetition maximum (1 RM) strength for nine of 10 exercises (15–42%). Although no body composition measure significantly changed for the CWT group, low-to-moderate effect sizes were evident for body weight, lean body mass, and relative fat. CWT did not alter percent fiber type, but did increase cross-sectional areas for type IIA fibers (μm^2; pre = 5988 ± 323, post = 7259 ± 669). Relative (%) myosin heavy-chain (MHC) expression increased for MHC IIa (pre = 42.5 ± 2.7, post = 50.1 ± 2.6), and decreased for MHC IIb (pre = 21.8 ± 2.8, post = 15.4 ± 2.4) for the CWT group. Serum testosterone, cortisol, and the testosterone/cortisol ratio did not change at any time for the CWT group. None of the measured variables changed for the control group. These data indicate that for untrained subjects, CWT of the type used resulted in improved muscular strength and a tendency toward increased lean mass. Compared with other types of weight training, fewer adaptations of the muscle fibers were evident. This is likely due in part to the relatively low loads used with this type of resistance exercise.

Circuit weight training (CWT) has become popular among the general population and some athletes as a time-effective modality for modestly increasing muscular strength (Wilmore et al., 1978). Furthermore, CWT has been shown to be a safe and effective routine for enhancing muscular strength as well as increasing compliance to exercise regimens in cardiac rehabilitation programs (Kelemen & Stewart, 1985). Various CWT programs have been examined with results dependent on manipulation of work and rest intervals, number of exercises and sets performed, modality used (e.g., isotonic, isokinetic), as well as exercise intensity used. Typically, CWT programs include resistance exercises set up in a specific sequence, and utilizing short inter-set rest intervals (i.e., ≤ 1 min). CWT programs that have used a 1:1 or 2:1 work-to-rest ratio with 40–50% 1 repetition maximum (1 RM) relative intensity have produced strength gains ranging from 7% to 32% in men and women with training programs of varying duration (Wilmore et al., 1978; Gettman et al., 1980, 1982; Haennel et al., 1989). Positive alterations in body composition have also been reported after CWT programs. On average, lean body weight increased significantly (1.0–3.2 kg) and percent fat decreased significantly (0.8–2.9%) (Gettman & Pollock, 1981). CWT programs have also been shown to modestly increase maximal oxygen consumption by approximately 5%, which is considerably less than increases seen in aerobic exercise programs, but greater than or equal to cardiovascular gains from traditional (high-resistance, low-repetition) resistance training (Gettman & Pollock, 1981; Stone & O'Bryant, 1985). No studies to date have examined the muscle fiber or muscle protein adaptations to CWT.

It has been well documented that human skeletal muscle responds to heavy-resistance exercise by altering percentage of fiber types, cross-sectional area of muscle fibers, and myosin heavy-chain (MHC) expression (Costill et al., 1979; Staron et al., 1990, 1991, 1994; Hather et al., 1991; Adams et al., 1993; Kraemer et al., 1995). Presently, human skeletal muscle fiber types can be differentiated using myofibrillar adenosine triphosphatase (mATPase) histochemistry (Staron, 1991; Staron & Hikida, 1992), and three MHC isoforms (I, IIa, IIb) can be electrophoretically separated from human skeletal muscle (Perrie & Bumford, 1986). The MHC content has been found to correlate with the various mATPase-based fiber types, thus supporting the use of histochemical methods for determining human skeletal muscle fiber types (Staron, 1991; Staron &

Hikida, 1992). Further, a correlation exists between relative MHC content and relative fiber-type areas (Fry et al., 1994). Several studies in the past decade have shown that changes in the MHC content after resistance training programs are reflective of the changes in fiber-type distribution as determined by mATPase histochemistry (Hather et al., 1991; Adams et al., 1993; Campos et al., 2002).

Chronic heavy-resistance exercise training has been shown to elicit a muscle fiber transformation from type IIB to IIA in human skeletal muscle (Staron et al., 1990, 1991, 1994; Kraemer et al., 1995). It has also been shown that MHC content undergoes a transformation from MHC IIb to MHC IIa with resistance training (Hather et al., 1991; Adams et al., 1993; Staron et al., 1994; Campos et al., 2002). The studies examining the effects of resistance training on muscle fiber adaptations have typically utilized programs that required intensities of 6–8 RM with 3–6 min rest between sets, or 8–10 RM with 2 min between sets (Staron et al., 1990, 1991, 1994). Recently, Campos et al. (2002) trained men for 8 weeks using either 3–5 RM with 3 min inter-set rest intervals, 9–11 RM with 2 min inter-set rest intervals, or 22–26 RM with 1 min inter-set rest intervals. All groups displayed similar transitions among the fiber types with a decrease in percent IIB fibers and a concomitant increase in percent IIA fibers. It is well known that skeletal muscle is regulated in part by the circulating hormonal environment (Kraemer, 1992), and it has been suggested that muscle adaptations may be related to changes in the anabolic and catabolic hormone profile (Staron et al., 1994). It has also been established that circulating hormonal concentrations are influenced by the cumulative training stresses (Adlercreutz et al., 1986; Häkkinen et al., 1987; Fry et al., 1993).

To date, no studies have examined the effect of CWT on skeletal muscle and hormonal adaptations. Thus, the purpose of this investigation was to examine muscle performance and fiber and protein expression characteristics of human skeletal muscle, and the accompanying hormonal profile before and after 10 weeks of CWT. It was hypothesized that CWT of the type used would result in muscle fiber adaptations similar to what is seen with more traditional resistance exercise programs.

Materials and methods

Subjects

Twelve men between the ages of 18 and 35 years participated in this study. All subjects were sedentary as determined by self-report, and had not been participating in a structured exercise program for at least 12 months prior to the study. Each individual signed an informed statement approved by the Committee for the Use of Human Subjects in Research at The University of Memphis. Subjects were randomly assigned to one of two experimental groups: an exercise group (CWT; $n = 8$; $X \pm$ SE; age = 23.6 ± 1.8 years) and a control group (CON; $n = 4$; age = 20.5 ± 1.0 years).

Training protocol

Subjects in the CWT group participated in a CWT program three times per week for 10 weeks. CWT was operationally defined for the present study as a program characterized by a series of resistance training exercises executed with a set duration (20–30 s) and minimal inter-set rest (10–30 s) at a moderate intensity (40–60% 1 RM) (Fleck & Kraemer, 1997). Subjects completed 10 exercises, seven using Nautilus (N) machines and three utilizing hammer strength (HS) machines. Exercises comprising the circuit, listed in the order performed, were as follows: chest press (HS), chest fly (N), lat pull-down (N), shoulder press (N), seated row (HS), biceps curl (N), triceps extension (N), leg press (HS), leg extension (N), and leg curl (N). To optimize adaptations, the training program was periodized over the 10-week training period by manipulating relative exercise intensity, rest duration, and sets performed (Fleck & Kraemer, 1997). Exercise intensity ranged from 40% to 60% 1 RM. Rest intervals began at 30 s and decreased to 10 s by the last week of the study, while work intervals varied from 20 to 30 s. Sets performed per exercise ranged from 1 to 3. The number of repetitions/set for all exercises ranged from 12 to 20 for the 30 s sets, and from eight to 15 for the 20 s sets. All training sessions were supervised by a Certified Strength and Conditioning Specialist (CSCS). See Table 1 for a detailed training program description. The CON group maintained their sedentary lifestyle during the 10-week training period.

Body composition

Body composition assessments were made before (Test 1) and after (Test 2) the 10-week training period. Body mass was measured using a digital scale accurate to the nearest 0.1 kg. Percent body fat and fat-free mass (FFM) were assessed via hydrostatic techniques. Underwater weight was measured six to 10 times or until three consecutive trials were within 0.1 kg using a Chatillon autopsy scale (Chatillon, NY, USA). The mean of the three heaviest trials was recorded as the underwater weight of the subject. Vital capacity was measured

Table 1. Ten-week periodized circuit weight training program

Week	Work interval (s)	Rest interval (s)	No. of sets
1	30	30	1
2	30	30	2
3	30	20	2
4	30	20	2
5	20	30	1
6	20	30	2
7	20	20	2
8	20	20	2
9	20	10	2
10 (sessions 1 and 2)	20	10	3
10 (session 3)	30	30	1

Note that the first and last training sessions of the 10-week program were identical for the purposes of collecting blood samples.

using a Collins wet spirometer (Warren E. Collins, Inc., Braintree, MA, USA) and residual volume was estimated using the methods of Wilmore (1969). Body density and percent body fat were calculated using the equation of Brozek et al. (1963).

Muscular strength

One RM strength testing was performed for all exercises trained before (Test 1) and after (Test 2) the 10-week training period in order to determine initial and ending strength levels. A strength test protocol as previously described (Kraemer & Fry, 1995) was employed. Briefly, after a warm-up of five to 10 repetitions at 40–60% of perceived maximum, subjects performed three to five repetitions at 60–80% of perceived maximum. An attempt at a conservative estimate of 1 RM was then attempted. If successful, the weight was increased and subjects were given a 1 min rest interval between successive attempts until a failed attempt occurred. One RM test reliability for all exercises performed has been determined to be $r \geq 0.94$ in our laboratory.

Muscle biopsies

Muscle tissue samples were obtained using sterile procedures before (Test 1) and after (Test 2) the 10-week training period. Muscle biopsies (50–100 mg) were extracted from the vastus lateralis m. (Bergström, 1962), oriented in tragacanth gum, frozen in isopentane cooled by liquid nitrogen to -159 °C, and stored at -80 °C. To ensure adequate sample sizes, large pieces were obtained using a double-chop method (Staron, 1991; Staron et al., 1991, 1994) combined with suction (Evans et al., 1982). A mean of 701 ± 43 ($X \pm$ SE) fibers were obtained from these biopsies. The frozen biopsy samples were thawed to -17 °C and serially sectioned (12 μm thick) for fiber-type and protein expression analyses. Although the CWT program involved all the major muscle groups of the body, biopsies were only taken from the vastus lateralis m. It is well documented that this muscle group is highly adaptable in untrained subjects performing resistance exercise (Staron et al., 1990, 1991, 1994; Hather et al., 1991; Adams et al., 1993; Williamson et al., 2000). Although all the major muscle groups were exposed to a similar CWT protocol, it is beyond the scope of the present investigation to determine if similar adaptations would occur in the other involved musculature. For the purposes of the present study, we have chosen to use the fiber-type classification scheme (i.e., I, IIA, IIB) originally developed for human muscle (Brooke & Kaiser, 1970; Staron, 1997), as well as the corresponding MHC classification scheme for humans (i.e., I, IIa, IIb).

Fiber-type analysis

Routine mATPase histochemical analysis was performed using pre-incubation pH values of 4.3, 4.6, and 10.2 (Brooke & Kaiser, 1970) to determine the muscle fiber-type distribution. Resulting fiber types (i.e., I, IIA, IIAB, IIB) were distinguished based on their staining intensities (Staron, 1991; Staron & Hikida, 1992). Computerized images of the histochemical preparations using the 4.6 pH pre-incubation were analyzed using an image-montage ($\times$ 100 magnification). These were used in combination with the other histochemical preparations (pre-incubation pH values of 4.3 and 10.6) to determine fiber-type percentages and total fiber number in each biopsy. Although the hybrid fibers IC, IIC, and IIAC can occasionally constitute a considerable portion of the total fibers in some individuals (Staron & Hikida, 1992), they typically represent a very small proportion of the total fiber population (Staron et al., 1990, 1991, 1994; Staron, 1991), and thus were not quantified in this analysis.

Fiber cross-sectional area

The cross-sectional areas of at least 50 fibers (McCall et al., 1998) per major type (I, IIA, and IIB) per biopsy were determined from computer-generated images ($\times$ 100 magnification) that were scanned and analyzed for area using public-domain NIH Image software. Cross-sectional areas were determined for only the major fiber types (i.e., I, IIA, IIB). Cross-sectional areas were not determined for IIAB fibers since a number of the subjects did not exhibit enough IIAB fibers to permit a valid determination of cross-sectional area.

MHC analysis

Relative (%) content of MHC isoform content of biopsy samples was determined using the sodium dodecyl sulfate polyacrylamide gel electrophoresis (SDS-PAGE) procedures of Perrie and Bumford (1986). Ten to fifteen serial cross-sections (12 μm thick) were placed in 0.5 mL of a lyzing buffer containing 10% (w/v) glycerol, 5% (v/v) β-mercaptoethanol, and 2.3% (w/v) SDS in 62.5 mM Tris(hydroxymethanol)-aminomethane HCl buffer (pH 6.8) and were heated for 10 min at 60 °C. Small amounts (5 μL) were loaded on a 4–8% gradient separating gel with a 4% stacking gel, run overnight (19–21 h) at 120 V, and stained with Coomassie Blue. MHC content analyses using video images of the resulting gels were performed on a Macintosh computer using the public domain NIH Image software program.

Hormonal and lactate concentrations

Whole blood was drawn from a superficial antecubital vein during the first (Test 1) and last (Test 2) training sessions of the 10-week training period. Blood was obtained with a 20 G needle and vacutainer assembly 15 min pre-exercise (Pre-exercise) and 5 min post-exercise (Post-exercise). Both of the training sessions were identical (9.5 min duration, 1 set exercise^{-1}, 30 s:30 s work:rest ratio, 40% of the current 1 RM for each exercise). The CON group followed the same protocol, but remained seated and relaxed during the 9.5 min period. To minimize diurnal variations, all tests were performed between 13:00 and 16:00 hours, with times held constant for each subject for each test. An aliquot of whole blood was immediately analyzed for lactate using a YSI model 1500 Sport Lactate Analyzer (Yellow Springs Instruments, Yellow Springs, OH, USA). The remaining whole blood was allowed to clot at room temperature for 30 min, after which it was centrifuged for 15 min at $1500 \times g$ and 4 °C, with the resulting serum stored at -80 °C until assayed. Enzyme immunoassays (EIAs) were performed in duplicate for total testosterone and cortisol (Diagnostic Systems Laboratories, Webster, TX, USA). Minimum detection limits for the assays were testosterone = 0.14 nmol L^{-1}, and cortisol = 2.76 nmol L^{-1}. Intra-assay variances for both testosterone and cortisol were $<2.0\%$, while inter-assay variances were $<6.0\%$. Regression curves for all assays were $r^2 \geq 0.997$. Serum hormone concentrations were not corrected for plasma volume shifts in this investigation; thus, all statistical analyses were performed on hormonal values based on actual measured circulating concentrations.

Statistical analyses

Physical characteristics and 1 RM strength measures were analyzed using a 2 × 2 (group × test) mixed-model ANOVA. Lactate and hormonal values were analyzed using a 2 × 2 × 2 (group × test × time) mixed-model ANOVA. Fiber cross-sectional area measures were analyzed with a 2 × 2 × 3 (group × test × major fiber-type) mixed-model ANOVA. Percent fiber type (2 × 2 × 5; group × test × type), percent fiber-type area (2 × 2 × 3; group × test × major fiber type), and percent MHC content (2 × 2 × 3; group × test × isoform) were analyzed using mixed-model ANOVAs with the Wilks-Lambda multivariate test of significance used to test for significant differences. Where appropriate, effect sizes were analyzed to account for potentially important results that were not significant due to low statistical power (Cohen, 1977; Vincent, 1995; Wilson et al., 1995). All results are reported as $X \pm$ SE. Significance was $P < 0.05$ for all statistical analyses.

Results

The results for body mass, lean body mass (LBM), fat mass, and percent body fat are presented in Table 2. Although no significant changes were observed for any anthropometric variable due to the CWT program, effect sizes were moderate to low. Table 3 lists the 1 RM strength values for each of the ten CWT exercises performed. Significant increases of 15–42% were observed for all but one of the exercises. Figs 1–4 illustrate the effects of the CWT program on muscle fiber and protein expression characteristics. No significant changes were observed for percent fiber type (see Fig. 2). A significant increase was observed for the cross-sectional area of type IIA fibers (see Fig. 3), while percent MHC IIa increased and percent MHC IIb decreased (see Fig. 4). A significant increase in blood lactate due to exercise for the CWT group was observed during both the first and last CWT sessions, although an attenuated exercise-induced lactate response to an identical training session was evident by the end of the study (see Fig. 5). No significant changes were observed for testosterone, cortisol, or the testosterone/cortisol ratio at any time (see Figs 6–8).

Table 2. Body composition data ($X \pm$ SE)

Variable	Time	CWT ($n = 8$)	CON ($n = 4$)
Body mass (kg)	Test 1	80.9 ± 8.6	74.2 ± 11.8
	Test 2	81.1 ± 5.4	74.6 ± 11.8
	Effect size	0.327	
Lean body mass (kg)	Test 1	65.4 ± 3.4	63.3 ± 10.0
	Test 2	67.3 ± 3.4	63.9 ± 9.7
	Effect size	0.222	
Fat mass (kg)	Test 1	15.5 ± 4.3	11.3 ± 3.0
	Test 2	13.8 ± 3.5	10.7 ± 2.8
	Effect size	0.385	
Percent fat (%)	Test 1	17.6 ± 4.0	14.7 ± 3.6
	Test 2	16.0 ± 3.3	14.2 ± 2.7
	Effect size	0.237	

CWT = circuit weight training group, CON = control group, Test 1 = before study, Test 2 = end of study. Effect sizes (Cohen's d) are shown for the CWT group.

No significant differences were observed for any anthropometric variable ($P > 0.05$). Effect sizes for the CWT group were moderate to small.

Table 3. One repetition maximum strength data (kg; $X \pm$ SE)

Exercise	Time	CWT ($n = 8$)	CON ($n = 4$)
Chest press	Test 1	104.0 ± 8.7	91.5 ± 28.7
	Test 2	119.6 ± 7.4*	88.6 ± 28.4
Chest fly	Test 1	52.3 ± 5.2	44.3 ± 9.7
	Test 2	71.6 ± 4.8*	47.7 ± 9.2
Lat pull-down	Test 1	63.1 ± 4.6	62.5 ± 10.4
	Test 2	79.6 ± 3.6*	62.5 ± 8.8
Shoulder press	Test 1	71.0 ± 6.1	54.6 ± 13.5
	Test 2	83.5 ± 5.7*	56.8 ± 13.2
Seated row	Test 1	108.5 ± 8.6	96.0 ± 28.4
	Test 2	138.6 ± 8.6*	97.7 ± 25.0
Biceps curl	Test 1	47.2 ± 4.0	44.3 ± 9.4
	Test 2	60.8 ± 5.4*	43.2 ± 9.9
Triceps extension	Test 1	38.6 ± 3.9	38.6 ± 9.9
	Test 2	55.1 ± 5.7*	35.2 ± 9.5
Leg press	Test 1	166.5 ± 9.6	118.2 ± 24.9
	Test 2	227.3 ± 7.9*	122.7 ± 20.2
Leg extension	Test 1	84.1 ± 6.3	78.4 ± 10.2
	Test 2	106.8 ± 8.1*	83.0 ± 10.9
Leg curl	Test 1	46.0 ± 3.9	47.7 ± 4.4
	Test 2	61.9 ± 4.1	53.4 ± 8.6

CWT = circuit weight training group, CON = control group, Test 1 = before study, Test 2 = end of study.

*Significantly different from Test 1 value ($P < 0.05$).

Discussion

To the authors' knowledge, this study is the first investigation to report muscle fiber adaptations to a very common type of resistance exercise, CWT. It appears that 10 weeks of CWT elicited a conversion from MHC IIb ➡ MHC IIa without any significant transformations occurring among the relative (%) mATPase fiber types. MHC isoforms have been shown to undergo a transformation between fast isoforms (IIb ➡ IIa), while a change in percent fiber-type distribution occurs (IIB ➡ IIA) after heavy-resistance training programs of eight (Campos et al., 2002) and 19 (Hather et al., 1991; Adams et al., 1993) weeks. Evidence suggests that conversions among MHC isoforms occur before transformation in the percent mATPase fiber types occurs. This faster response of MHC isoform expression to an exercise stimulus compared with mATPase fiber-type adaptations is evident in untrained men after 2 weeks of heavy-resistance exercise (Staron et al., 1994), in untrained men after 6 weeks of sprint cycle training (Allemeier et al., 1994), and with untrained elderly men after 12 weeks of resistance exercise at 80% 1 RM loads (Williamson et al., 2000). In each case,

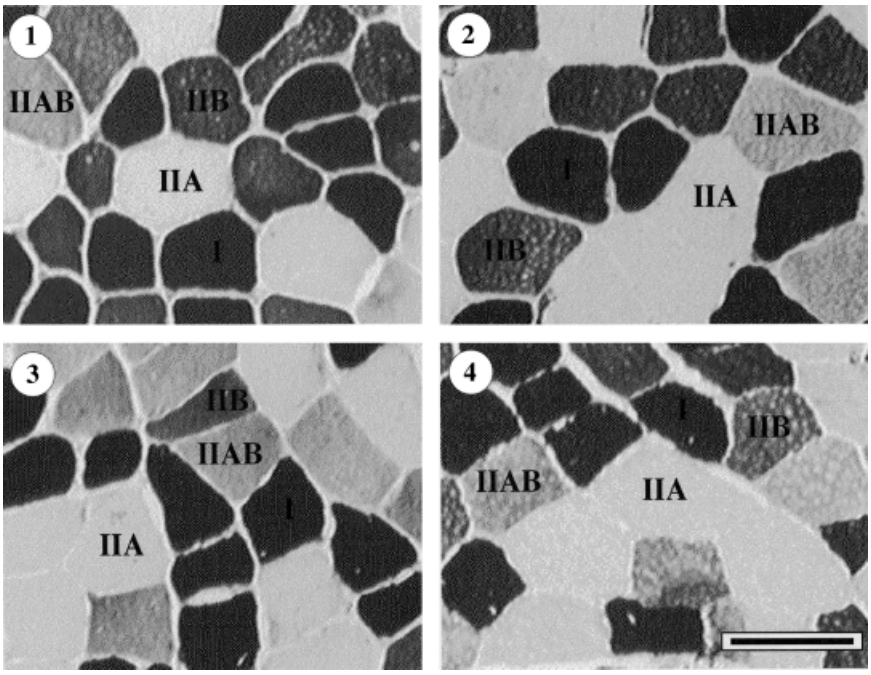

Fig. 1. Photomicrograph of histochemical analysis (pH 4.6 preincubation) of the vastus lateralis m. from a representative subject from both the circuit weight trained (CWT, $n = 8$) and the control (CON; $n = 4$) groups. Panel 1 = CON subject before 10-week training period, panel 2 = CON subject after 10-week training period, panel 3 = CWT subject before 10-week training period, panel 4 = CWT subject after 10-week training period. Labels refer to myofibrillar adenosine triphosphatase (mATPase) fiber type (I, IIA, IIAB, IIB). The sensitivity of the type II fiber sub-types to the mATPase histochemical procedures is readily apparent in each panel. Furthermore, the increased cross-sectional areas for the IIA fibers is visually apparent when comparing panels 3 and 4. Black bar = 100 μm.

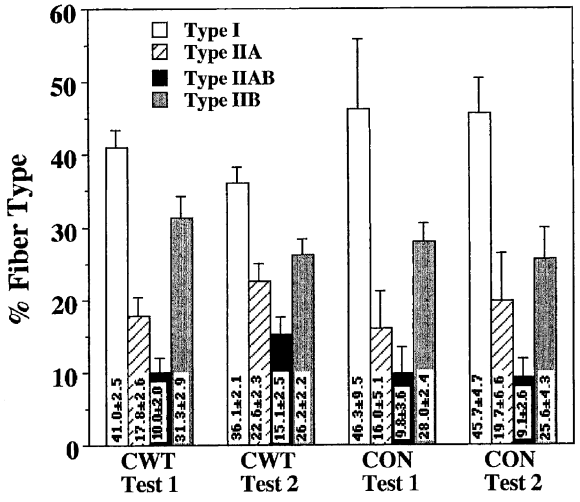

Fig. 2. Percent fiber types ($X \pm$ SE) for the circuit weight trained (CWT, $n = 8$) and the control (CON; $n = 4$) groups. Test 1 = before 10-week training period, Test 2 = after 10-week training period. No significant changes were observed ($P > 0.05$).

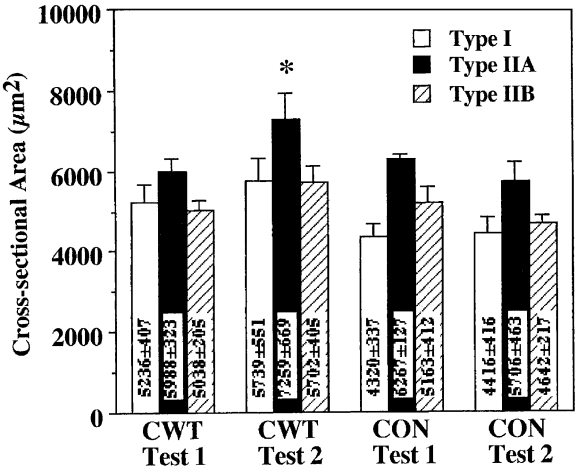

Fig. 3. Muscle fiber cross-sectional areas (μm^2; $X \pm$ SE) for the circuit weight trained (CWT, $n = 8$) and the control (CON; $n = 4$) groups. Test 1 = before 10-week training period, Test 2 = after 10-week training period. *Different from Test 1 value ($P < 0.05$).

significant conversions between the MHC fast isoforms (IIb ➡ IIa) occurred while few or no changes in the percent mATPase fiber-type distribution were observed. As previously observed, the transformation between MHC isoforms that occurs before the conversion between mATPase fiber types suggests that changes in certain contractile proteins (i.e., myosin) may be occurring in response to a lesser stimulus, and may be a more sensitive indicator of muscle fiber adaptations to resistance exercise (Williamson et al., 2000). Furthermore, since MHC expression is highly correlated with percent fiber-type areas (Fry et al., 1994), an additional contributing factor is the fiber-type-specific hypertrophy exhibited in the present study (i.e., increased type IIA areas). It should be noted that intramuscular adaptations can be elicited very early in resistance training programs. A single bout of heavy-resistance exercise has been shown to increase muscle protein synthesis for up to 24 h post-exercise (Chesley et al., 1992). This acute response is further supported by alterations in the myogenic transcription factors Myo-D and myogenin and MHC mRNA after a heavy-resistance exercise training session (Willough-

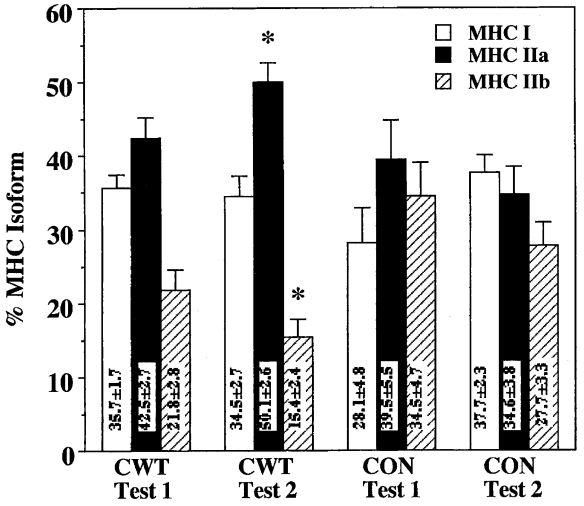

Fig. 4. Percent myosin heavy chain isoform content ($X \pm$ SE) for the circuit weight trained (CWT, $n = 8$) and the control (CON; $n = 4$) groups. Test 1 = before 10-week training period, Test 2 = after 10-week training period. *Different from Test 1 value ($P < 0.05$).

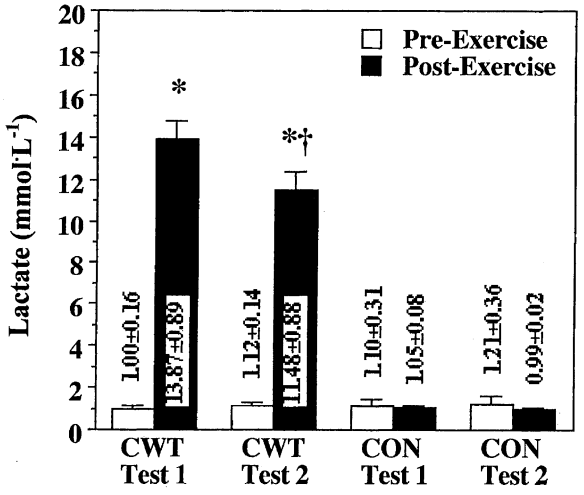

Fig. 5. Blood lactate concentrations (mmol L^{-1}; $X \pm$ SE) for the circuit weight trained (CWT, $n = 8$) and the control (CON, $n = 4$) groups. Test 1 = before 10-week training period, Test 2 = after 10-week training period, Pre-exercise = 15 min before exercise, Post-exercise = 5 min after exercise. *Different from Pre-exercise value ($P < 0.05$), †different from Test 1 value ($P < 0.05$).

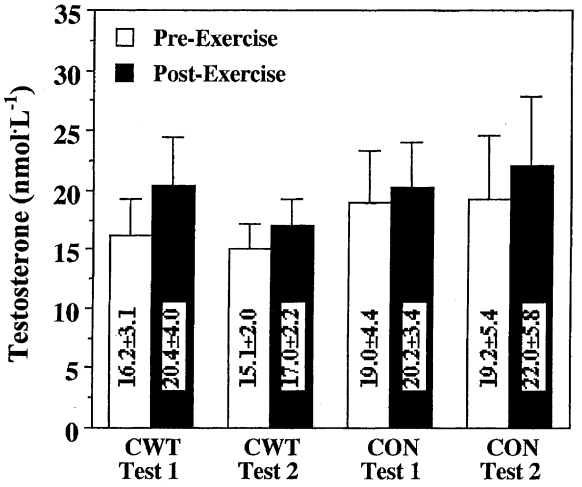

Fig. 6. Serum testsoterone concentrations (nmol L^{-1}; $X \pm$ SE) for the circuit weight trained (CWT, $n = 8$) and the control (CON, $n = 4$) groups. Test 1 = before 10-week training period, Test 2 = after 10-week training period, Pre-exercise = 15 min before exercise, Post-exercise = 5 min after exercise. No significant changes were observed ($P > 0.05$).

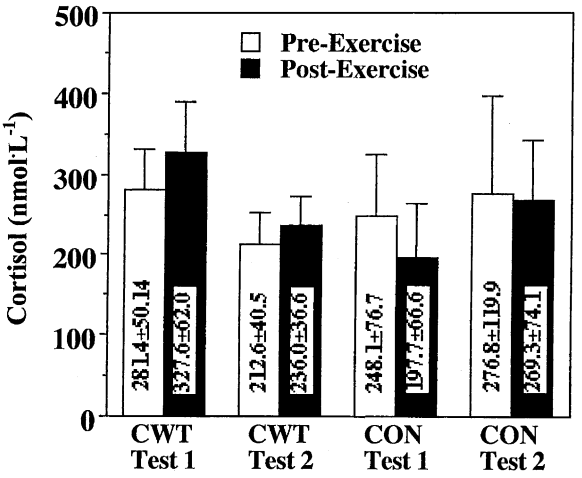

Fig. 7. Serum cortisol concentrations (nmol L^{-1}; $X \pm$ SE) for the circuit weight trained (CWT, $n = 8$) and the control (CON, $n = 4$) groups. Test 1 = before 10-week training period, Test 2 = after 10-week training period, Pre-exercise = 15 min before exercise, Post-exercise = 5 min after exercise. No significant changes were observed ($P > 0.05$).

by & Nelson, 2001). These data suggest that although neural adaptations play a large role in early phases of strength development, adaptations are also occurring at the cellular and molecular levels within the muscle that could ultimately contribute to improved muscular performance.

It should be noted that differences exist when comparing the magnitude of transition between the MHC fast isoforms in the present study with other related investigations. These previous studies using resistance training (Hather et al., 1991; Adams et al., 1993; Campos et al., 2002) reported decreases in MHC IIb content of approximately 12–14% with a concomitant 12–14% increase in MHC IIa content. Comparatively, a 6% decrease in MHC IIb with an 8% increase in MHC IIa was observed in the present study. The results of the present study are similar to the changes observed after sprint cycle training which also created a large glycolytic metabolic stress (Allemeier et al., 1994). Although an increased glycolytic stress has been suggested as a contributing factor to increases in muscle size and performance (Takarada et al., 2000), the metabolic stress as indicated by the large lactate response in the present

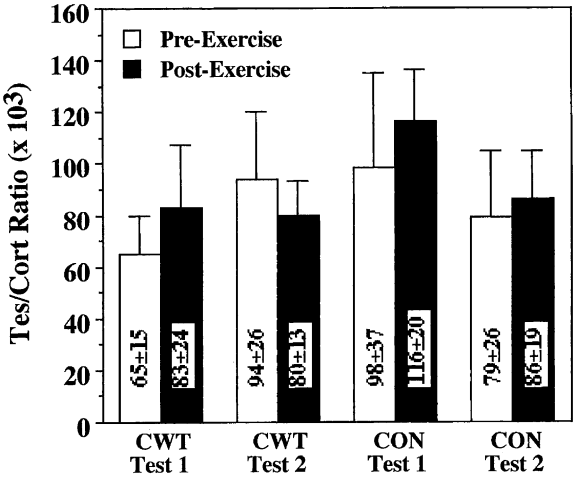

Fig. 8. Serum testosterone/cortisol ratios ($\times 10^3$; nmol L^{-1}; $X \pm$ SE) for the circuit weight trained (CWT, $n = 8$) and the control (CON, $n = 4$) groups. Test 1 = before 10-week training period, Test 2 = after 10-week training period, Pre-exercise = 15 min before exercise, Post-exercise = 5 min after exercise. No significant changes were observed ($P > 0.05$).

study (see Fig. 5) may have not been optimal for muscle fiber-type transitions and hypertrophy within the scope of the present study.

Several possible physiological mechanisms that may have contributed to the muscle fiber adaptations observed exist. First is the lack of both acute and chronic changes in the total testosterone and cortisol concentrations, as well as the testosterone/cortisol ratio. The surrounding endocrine environment can have a profound impact in the adaptation process of skeletal muscle to resistance exercise (Kraemer, 1992). Hormonal variables have also been used as indicators of the magnitude of training stress for resistance exercise and other forms of physical activity (Adlercreutz et al., 1986; Häkkinen et al., 1987; Fry et al., 1993). Although long-term adaptation of the endocrine system has been studied in response to resistance exercise (Häkkinen et al., 1988), not all resistance training protocols appear to elicit an acute endocrine response (Häkkinen & Pakarinen, 1993), which is similar to what was observed in the present study. It has been noted that chronic hormonal adaptations have been correlated to changes in muscular strength and power for competitive Olympic-style weightlifters (Häkkinen et al., 1987; Fry et al., 2000), as well as to fiber-type alterations in previously untrained men (Staron et al., 1994). In the present study, improvements in muscular strength occurred without any accompanying hormonal changes. These data suggest that the muscle performance improvements from the CWT performed for 10 weeks may have been due more to factors such as neural recruitment and metabolic adaptations, rather than changes in the fiber-type profile or the hormonal environment.

Another possible physiological mechanism responsible for the observed responses to the CWT is possibility that a resistance exercise intensity threshold exists for fiber-type adaptations. Previous studies examining the MHC content adaptations to resistance training have used heavy-resistance programs. Staron et al. (1994) trained men and women 2 sessions $week^{-1}$ for 8 weeks using three sets to failure for either six to eight or 10–12 repetitions, while Hather et al. (1991) and Adams et al. (1993) trained men two times per week, with four to five sets designed to induce failure within six to 12 repetitions. Recently, Campos et al. (2002) compared three different resistance training programs to examine differences in muscular adaptations. Subjects participated in an 8-week progressive resistance training program in either a low-repetition group (3–5 RM, 3 min inter-set rest), an intermediate-repetition group (9–11 RM, 2 min inter-set rest), or a high-repetition group (22–28 RM, 1 min inter-set rest). All three training regimens produced transformations in percent fiber-type distribution (IIB ➡ IIA) and percent MHC isoforms (IIb ➡ IIa), while only the low- and intermediate-repetition regimens resulted in fiber hypertrophy (types I, IIA and IIB). To the authors' knowledge, the high-repetition group in Campos' study is the only protocol used with a repetition range (i.e., >20 repetitions set^{-1}) that is somewhat similar to the CWT protocol used in the present study, although the rest intervals were considerably different ($10-30$ s vs. 1 min). It is possible that the difference in rest intervals is responsible for the lesser degree of mATPase fiber-type and MHC protein expression adaptations in the present study. As a result, the role of inter-set rest intervals during resistance exercise may be an extremely important training variable, as previously suggested (Kraemer et al., 1990). Although the subjects significantly increased strength, and the exercise protocol induced a strenuous metabolic demand as demonstrated by the significant lactate response, loads as low as 40% 1 RM may not be enough stimulus to elicit changes in mATPase fiber-type distribution. Given the previously mentioned role of glycolytic stress (Takarada et al., 2000), it is possible that the metabolic stress of CWT contributed to hypertrophy of the IIA fibers and the MHC transitions, while the low relative loads (40% 1 RM) prevented an optimal environment for muscle adaptations. Another possibility is that transformation of fiber types and protein isoform expression in response to the CWT stimulus simply takes longer than 10 weeks. Further study is needed to evaluate this relationship.

Another finding was the significant increase in the cross-sectional area of the IIA fibers only. The lack of hypertrophy in the I and IIB fiber types is in

contrast to hypertrophic responses to other studies using resistance training protocols (Staron et al., 1990, 1991, 1994; Hather et al., 1991; Kraemer et al., 1995; Campos et al., 2002). Again, this may be explained by a resistance exercise intensity threshold for hypertrophy that is greater than 40% 1 RM. A fiber-type-specific difference in hypertrophic response was reported among the various groups in the study by Campos et al. (2002). Only when near maximal loads were used (3–5 RM) was hypertrophy evident in all three major fiber types (I, IIA, IIB). This evidence suggests that increases in cross-sectional area of fiber types is governed in part by relative intensity, at least in programs ranging from 8 to 10 weeks, and that there tends to be a preferential hypertrophy of type II fibers, specifically IIA in this case. These results are not unlike those reported by Kraemer et al. (1995) for training involving a combination of both heavy-resistance exercise and aerobic endurance training. The combination of both anaerobic and aerobic training produced an apparently compromised physiological response at the muscle level. It is likely that the CWT program used in the present study combined a relatively high oxidative (Gettman et al., 1978, 1980; Gettman & Pollock, 1981) and glycolytic (see Fig. 5) stress in combination with moderate loads, resulting in different muscle adaptations when compared with traditional heavy-resistance exercise protocols. Although the authors of the present study intended to determine VO_2max adaptations to the CWT protocol, equipment failure prohibited the collection of these data. It was noted, however, that treadmill times to exhaustion did not significantly change due to the CWT program (unpublished data). It should be pointed out though, that times to exhaustion are not necessarily a very sensitive indicator of VO_2max adaptations, and that further research is needed to determine the contributions of the metabolic requirements of CWT to skeletal muscle adaptations.

In terms of increasing maximal muscular strength, short-term CWT programs have compared favorably with traditional weight training programs when untrained subjects are studied (Gettman et al., 1978, 1980; Gettman & Pollock, 1981). The 37% increase in the chest press and the 15% in the leg press were consistent with past studies of CWT (Gettman et al., 1978, 1980; Gettman & Pollock, 1981). Although heavy-resistance, low-repetition resistance exercise protocols provide a more favorable stimulus for eliciting 1 RM strength gains, substantial strength increases can be expected for untrained individuals participating in CWT. Strength gains without little or no increase in LBM suggests that the increased strength is primarily due to neural factors. Such a response to resistance exercise has been reported before, with increases in muscular strength occurring without any changes in muscle size (Costill et al., 1979; Moritani & deVries, 1979; Tesch et al., 1983). In addition to the strength adaptations, the large lactate response is indicative of the considerable glycolytic stress of the training sessions, with the decreased values by the end of the study due to a metabolic training adaptation.

In the present study, all of the body composition variables exhibited low-to-moderate effect sizes. Considering the short duration of the training program (10 weeks), and the small sample sizes, these effect sizes ($d = 0.222$–0.385) are considerable. Previous CWT research has reported increases in FFM of 1.2–3.2 kg after programs lasting 10–20 weeks (Gettman et al., 1978, 1980, 1982; Wilmore et al., 1978). The 1.9 kg change in FFM was consistent with past studies, as were the changes for fat mass. Decreases of 2–3% in relative body fat have been reported for CWT programs of 10–20 weeks duration (Gettman et al., 1978, 1980, 1982; Wilmore et al., 1978), and the 1.7% change in relative fat in the present study suggests a trend that is consistent with past studies. In general, the CWT protocols utilized in previous studies have all used low relative training intensities (40%–55% 1 RM), somewhat similar to the present study. Pollock (1973) has stated that programs of 8–10 weeks duration generally result in less change in body composition variables than programs of longer duration.

Perspectives

Ten weeks of timed CWT characterized by short inter-set rest periods ($\leq$ 1:1 work:rest ratio), augmented 1 RM strength, elicited hypertrophy of only the type IIA fibers, and resulted in conversions within the MHC fast isoforms. Through manipulation of the acute training variables, resistance training programs can be developed to optimally induce different desired responses (i.e., hypertrophy, strength, power). It appears that the conversion from MHC IIb ➡ MHC IIa is a common response to varied resistance training stimuli, and precedes changes in mATPase fiber-type distribution and hypertrophy. The results from the present study indicate that CWT can be an effective modality of significantly increasing strength for untrained subjects while minimizing some of the muscular adaptations that often accompany resistance exercise (e.g., hypertrophy). It is likely that the major cellular and molecular adaptations to CWT are associated with the considerable glycolytic demand of such exercise.

Key words: body composition, cortisol, fiber type, lactate, muscular strength, myosin heavy chain, resistance exercise, testosterone.

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