Skeletal muscle fiber area alterations in two opposing modes of resistance-exercise training in the same individual

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Summary. The purpose of this study was to observe fiber area changes that might occur in the same subject from two opposing resistance-exercise training regimes isolating the quadriceps muscle group. Twelve college-age men divided into two groups participated in each of two 7.5-week regimens; one performed a muscular strength program (high-resistance, low-repetition) 4 days a week on a resistance-exercise apparatus, while the other performed a muscular endurance (low-resistance, high-repetition) program. After a 5.5-week hiatus, the groups changed regimens for the second 7.5 weeks. Closed-needle biopsies of the dominant vastus lateralis and isokinetic dynamometer evaluations were made before and at the end of each training period. The muscle samples were analyzed for area changes. In both groups the initial exercise stimulus, whether for strength or endurance, increased the area of fibers of all three major types (I, IIA, and IIB). Subjects doing strength exercises as their second treatment showed a further increase in the area of type I and IIB fibers, whereas those doing endurance exercises showed a decrease in all fiber types. From the first to the last biopsy all fiber areas were decreased ($P<0.05$) in the control-strength-endurance group and increased ($P<0.05$) in the control-endurance-strength group. These results suggested that endurance exercise preceding strength exercise in an isolated muscle group maximized fiber area adaptations to exercise stress. Consideration should thus be given in exercise and rehabilitation programs to the muscle cellular adaptations evidenced in different orders of training, particularly if muscular strength is considered important.

Key words: Muscle fiber area – Resistance exercise – Adaptations to training – Opposing modes of training – Human skeletal muscle

Introduction

It is well known that skeletal muscle will adapt specifically to distinctly divergent stresses and external work-

performance measures have exhibited certain trends. Strength training typically involves high-resistance, low-repetition exercises using large muscle masses, with the express purpose of increasing the force output of the muscle group (Atha 1981). Participants in such programs usually show measurable increases in strength and skeletal muscle hypertrophy (Gollnick et al. 1972), whereas the aerobic power of the entire body is not affected (Wilmore et al. 1978). In contrast, endurance training involves low-resistance, high-repetition exercises aimed at increasing the body’s aerobic capacity (Pollock 1973). It is possible to increase maximum oxygen uptake ($VO_2$ max) without muscle hypertrophy. Adaptations to training, therefore, appear to be specific to the kind of stress applied; adaptations at the cellular level are not as clear.

Much has been published regarding physiological adaptations to endurance training; much less is currently known concerning strength training (Hickson 1980; Jackson 1988; Jackson et al. 1983; Dudley and Djamil 1985; Saltin and Gollnick 1983). Information regarding their compatibility is sparse, although combinations of training are currently very popular. Two groups of investigators using similar forms of whole body training concluded that concomitant strength and endurance training may adversely affect strength adaptation without greatly compromising endurance adaptation (Hickson 1980; Dudley and Djamil 1985). Among the explanations offered in further analysis was the suggestion that cellular changes might play a role, but to date no study of the muscle tissue at the cellular level has been published (Dudley and Fleck 1987). The present study aimed to help explain the whole body observations by looking at cellular responses; specifically, to observe the cellular cross-sectional area and external work-performance adaptations, in the same individual, to muscular strength and endurance training separated as single stresses.

Methods

Twelve men consented to take part in this experiment after being
Table 1. Subject data by experimental group

<table>
<thead>
<tr>
<th></th>
<th>Height (cm)</th>
<th>Mass (kg)</th>
<th>VO2max (ml/kg/min)</th>
<th>Peak torque/body weight (N m/kg)</th>
<th>Total work to 50% peak torque/body weight (N m/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C-E-S (n=6)</td>
<td>180.3</td>
<td>73.7</td>
<td>48.6</td>
<td>3.23</td>
<td>35.80</td>
</tr>
<tr>
<td>C-S-E (n=6)</td>
<td>178.4</td>
<td>67.3</td>
<td>49.3</td>
<td>2.89</td>
<td>30.62</td>
</tr>
</tbody>
</table>

Values given are mean values. C-S-E, Control-strength-endurance group; C-E-S, control-endurance-strength group; VO2max, maximum oxygen uptake.

informed of risk in accordance with the policies and approval of the Human Subjects Committee of the University of Colorado.

The 12 subjects were untrained, of college-age and had not participated in any form of fitness training for 1 year before the study. They were randomly assigned to two groups. The groups were not significantly different in height, mass, VO2max, and the ratio of peak torque and total work in the quadriceps muscle group. One group had higher strength initially (Table 1). Since they were randomly assigned to groups the effect of differing initial external work-performance measures could not be evaluated.

The protocol for the study is shown in Fig. 1. Both groups were initially evaluated, and biopsy samples were taken, using the closed-needle technique, from the midportion of the vastus lateralis of the leg ipsilateral to the dominant hand (Bergstrom 1982). The first sample was the control; subsequently they were taken at the end of each treatment.

The muscles to be stressed during the experiment were the quadriceps extensors of the leg. The muscular endurance program consisted of a 4 day per week regimen on a resistance apparatus (N-K Exercise Unit, Model 300, N-K Products Co., Santa Cruz, Calif., USA). The training consisted of high-repetition/low-resistance exercise, performed initially for 20 min and gradually increased to 30 min each session. The resistance level at the beginning was set at 15% of the highest mass (1 RM) that the individual could move. When this was well tolerated it was increased to 20% and then 25% of the 1 RM. The training load was then increased by lengthening the work bout from 20 to 25 min and finally to 30 min duration. Exercise was done to a cadence of 20 leg movements min⁻¹.

The muscular strength program consisted of a 4 day per week regimen on a resistance exercise apparatus (Orthotron, Lumex Corp., Ronkonkoma, NY, USA). It consisted of high-repetition/low-repetition exercise performed as five sets of four maximum contractions with 2 min rest between sets. The first resistance setting was as low in resistance velocity as the subject could tolerate and still perform four maximum contractions with a 2-min rest between sets. Periodically the resistance setting was decreased in movement velocity, resulting in an increase in the maximum force production by the knee extensors.

The biopsy specimens were frozen in isopentane, cooled in liquid nitrogen, and stored at −80°C until analyzed. Serial cross-sections 10 μm thick were cut in a cryostat at −20°C and stained histochemically for nicotinamide adenine dinucleotide (NADH-TR) and myofibrillar myosin adenosine triphospate (ATPase) after preincubations at pH of 9.4, 4.6, and 4.2 (Dubowitz and Brooke 1973). We classified the fibers as either I, IIA, IIB, or IHC according to previously reported procedures (Brooke and Kaiser 1970).

We photographed randomly selected fiber fields of myofibrilar ATPases pH 4.6 and 4.2 and made 8×10 in. prints resulting in an overall magnification of ×430. From the photographs, we selected for measurement 30 fibers of each of the major fiber types from each biopsy. Additionally, a random group of typed fibers was matched individually by fiber in NADH-TR in order to assess shrinkage in the myofibrillar ATPases. Fiber cross-sectional areas (FCSA) are often reported from the NADH-TR stain, on the assumption that this stain produces less shrinkage of tissue in processing (Tesch and Karlsson 1985). However, we encountered difficulty in detecting clear cell boundaries in NADH-TR stained sections. Since the difference in area (and thus shrinkage in processing) between tissues processed in NADH-TR and those processed in ATPases was less than 3%, we chose the latter for measurement.

Since we observed both torque fibers and loss of orientation in the fields, we extrapolated FCSA from measured least-diameters using the formula published by Clarkson et al. (1980). To measure least-diameters (Dubowitz and Brooke 1973), we used a micro-tablet digitizer whose stylus was modified for accurate measurement (GTCO Version 4.2).

We measured performance with an isokinetic dynamometer (Cybex, Lumex Corp., Ronkonkoma, NY, USA), using a 1.05 rad s⁻¹ velocity to evaluate muscular strength (peak torque) and 3.14 rad s⁻¹ velocity to evaluate muscular endurance (total work). For muscular strength the highest value from five trials was recorded and for muscular endurance the value chosen was one trial to 50% of peak torque. Results were analysed using a two-way ANOVA applied to a two-factor experiment with repeated measurements on one. The main experimental factors were the order of either strength or endurance training and time. The interaction effect measured the training differences (Ferguson 1976). Results were further analyzed with a post hoc test.

![Fig. 2. Skeletal muscle fiber (I, IIA, IIB) area adaptations to strength followed by endurance training in the same individual. * Significance from previous treatment (P<0.05). Control to endurance (C-E) loss in area is significant for type I and IIB fibers (P<0.005).](image-url)
The peak torque and total work indicated that after endurance training, muscular endurance improved while strength either decreased or remained unchanged. After strength training muscular strength improved (Fig. 4). Results of two-way ANOVA were significant for treatment between subjects and the interaction within subjects for type I (*P<0.01, *P<0.05) and IIb (*P<0.01, *P<0.01) fiber areas and for treatment by order within subjects for the type IIa (*P<0.05) fiber areas. The results of the post hoc test are shown in Figs. 2 and 3. Results of two-way ANOVA analysis were significant for treatment between subjects (*P<0.05), treatment by order within subjects (*P<0.01), and interaction within subjects for the measured total work and for treatment by order within subjects (*P<0.01) for the measured peak torque.

Discussion

There is considerable interest among athletes and trainers in whether it is practical to train for both strength and endurance, either sequentially or concurrently. However, very little research has been done to assess the effects of one type of training upon the other. It has not been shown clearly whether or not combinations of opposing training modes enhance, compromise, or do not affect adaptive responses within the muscle (Dudley and Djamil 1985), although measures of external work performance have suggested that there is a difference in adaptation when opposing training regimens are combined. Combinations of training are, nevertheless, frequently used in physical therapy and athletics (Pauletto 1985), and to enhance endurance in high-intensity, short-term activities (Hydrik 1986), despite the lack of any rationale based on research findings at the cellular level.

Most training studies in humans encompass short time periods of 6 weeks or less (Saltin and Gollnick 1983), during which both type I and type II fibers have been shown to hypertrophy with conditioning (MacDougall et al. 1980; Tesch and Karlsson 1985). These results, however, often conflict with those found in studies of elite athletes. The present study indicates that all major fiber types (I, IIa, and IIb) may respond to a short training period such as 7.5 weeks by increasing FCSA, no matter whether the exercise aims at strength or endurance. We propose that short-term training studies may reflect the muscles initial propensity to adapt quickly in selected variables such as area, a change that may serve as a general preparation for further, more training-specific changes over longer time courses. It is difficult to interpret this general increase in fiber size, as it may not last through a longer exercise regimen when more specific adaptation takes place. Additionally, changes in fiber size at the cellular level may not be reflected in measurable external work performance measures. However, neither the initial increase in size nor the 5.5-week hiatus between the exercise stresses appeared to diminish the muscle's readi-
ness to adapt specifically to demand; it adapted differently to the second stimulus than it had to the first.

Strength training that followed endurance training resulted in a continued increase in fiber size, particularly in the IIB fibers. While the IIA fibers decreased minimally in size, all fiber-type FCSAs were greater in the last measurement than in the control measurement. The fact that the greatest change seen was in the IIB fiber supports the contention that the IIB fiber is greatly, but not exclusively, stressed in strength-training activities. Within the time period used in this study, then, short-term endurance exercise followed by strength exercise may result in hypertrophy of all fiber types. The implications for physical therapy or for endurance athletes who wish to vary their training for the off-season are clear. The tendency of muscle fibers to increase in size with training may not be diminished and may be enhanced by periodic strength training after endurance training as endurance exercise preceding strength exercise in an isolated muscle group maximized fiber area adaptations to exercise stress.

In contrast, endurance training that followed strength training produced an overall decrease in the FCSAs of all fiber types from the control measurements, with the greatest decrease seen in the IIB fiber. It has been shown that after a certain threshold is reached, concurrent endurance training compromises the adaptive response to strength training (Dudley and Djamil 1985), and that vertical jump ability is less than average in endurance athletes (Ono et al. 1976) but returns with cessation of training (Costill 1967). Since strength increase is related to cross-sectional size, which in turn is positively correlated to type II content of muscle (Dons et al. 1979), attention has focused on the percentage of II fibers in the population (Tesch and Karlsson 1985). Dudley and Fleck (1987) have proposed that the transformation of fiber type that has been shown to accompany intense endurance training (Green et al. 1984) may explain strength loss with concurrent endurance training. However, the present study indicates that endurance training per se, without any consideration of the percentage of II fibers in the muscle, will decrease FCSA and thus may decrease the strength of previously strength-trained muscle. We propose a mechanism in addition to fiber composition to explain this observation.

Oxygen transport studies have shown that existing capillarity can maintain only a limited range of fiber area. A decrease in FCSA may thus be physiologically necessary when there is a sudden increase in oxygen demand, an effect that has been shown in stimulation studies (Pette 1985). MacDougall and coworkers (1979) have suggested that strength training decreases aerobic capacity, as after heavy resistance training there appears to be a reduction in mitochondrial volume density. Tesch et al. (1984) have also reported that resistance training may reduce capillary density. Since the IIB fiber has the least average number of capillaries around the fiber (Jackson et al. 1987) and the lowest mitochondrial volume density, it thus has the least capacity for aerobic metabolism, and the factors affecting oxygen delivery may be most salient in this fiber type. The present study did indeed indicate that, under a regime in which endurance training followed strength training, the IIB fiber had a greater loss in FCSA than other fiber types.

We suggest that the oxygen needs of the fiber may impose constraints on the adaptability of systems. The fact that our reversal in training retinems did not produce mirror-image effects suggests that systems other than size of fiber had adapted to the initial training. The fact that all fiber types did initially adapt in size, however, indicates that the time-frame of a training study needs to be long enough to pass what appears to be a readiness stage of the muscle.

Our immediate results contraindicate concurrent aerobic training if power is to be maintained; if the individual wishes to develop optimal strength, this may preclude off-season aerobic training. This recommendation, however, does not consider either the cumulative effect of both types of training over very long time periods or the potential health benefits of conditioning the cardiovascular system. Still, it would seem that great caution should be used in requiring the muscle to adapt to activities that are physiologically in direct opposition to those desired in performance, particularly where that performance requires strength, since the specificity of adaptation to training is most acute in strength-trained muscle.

References

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