Biochemical adaptation of human skeletal muscle to heavy resistance training and immobilization

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MacDOUGALL, J. D., G. R. WARD, D. G. SALE, AND J. R. SUTTON. Biochemical adaptation of human skeletal muscle to heavy resistance training and immobilization. J. Appl. Physiol.: Respirat. Environ. Exercise Physiol. 43(4): 700-703, 1977. - Nine healthy subjects were studied under control conditions and following 5 mo of heavy resistance training and 5 wk of immobilization in elbow casts. Needle biopsies were taken from triceps brachii and analyzed for adenosine triphosphate (ATP), adenosine diphosphate (ADP), creatine (C), creatine phosphate (CP), and glycogen concentrations. Training resulted in an 11% increase in arm circumference and a 28% increase in maximal elbow extension strength. Immobilization resulted in decreases in arm circumference and elbow extension strength of 5% and 35%, respectively. Training also resulted in significant increases in muscle creatine (by 39%), CP (by 22%), ATP (by 18%), and glycogen (by 66%). Conversely, immobilization significantly reduced CP concentration by 25% and glycogen concentration by 40%. It was concluded that training results in increases in muscle energy stores which may be reversed by a period of immobilization-induced disuse.

METHODS

Nine healthy volunteers, aged 19-22 yr, served as subjects with their own informed consent. All were male undergraduate physical education students with no previous formal resistance or weight training experience. Needle biopsies averaging approximately 65 mg were taken from the long head of triceps brachii and analyzed for adenosine triphosphate (ATP), adenosine diphosphate (ADP), creatine (C), creatine phosphate (CP), and glycogen concentrations. Training and immobilization resulted in decreases in arm circumference and elbow extension strength of 5% and 35%, respectively. Training also resulted in significant increases in muscle creatine (by 39%), CP (by 22%), ATP (by 18%), and glycogen (by 66%). Conversely, immobilization significantly reduced CP concentration by 25% and glycogen concentration by 40%. It was concluded that heavy-resistance training results in increases in muscle energy reserves which may be reversed by a period of immobilization-induced disuse.

PreVIOUS STUDIES of the influence of physical training on the biochemical adaptation of skeletal muscle have been confined to endurance training, using low-resistance repeated contractions. Such studies show significant increases in the capacity of muscle to oxidize pyruvate and fatty acids as a result of both increased mitochondrial enzyme activity and an increase in mitochondrial number and size (1, 3, 5, 6, 9-11). Unlike endurance training, however, the brief maximal contractions associated with heavy-resistance strength training require a very high rate of energy production which can be met only by the muscle’s high-energy phosphate reserves and to a lesser extent glycolysis. Consequently, if meaningful biochemical adaptations to strength training were to occur, one would expect them to be associated with these two energy delivery systems. We wanted to determine whether the changes in muscle size and contractile strength which occur with resistance training are reflected by changes in muscle energy stores, and if so, whether they are reversible with immobilization.

The purpose of this study was to determine the effects of a 5-mo heavy-resistance weight training program and a 5-wk period of immobilization on certain biochemical properties of human skeletal muscle. Analyses performed involved resting concentrations of adenosine triphosphate (ATP), adenosine diphosphate (ADP), creatine phosphate (CP), creatine, and glycogen.

The exercises selected to train the elbow extensors included the traditional bench press movement on the Universal Gym (Universal Sales Co., Fresno, Calif.), elbow extension and pull-over on the Nautilus equipment (Nautilus Sports/Medical Industries, De Land, Fla.), and vertical dips between parallel bars with a suspended weight. For each exercise, resistances were chosen to make it impossible for the subject to continue the movement beyond 8-10 repetitions, and 3-5 such sets were performed, with rest periods of approximately 2 min.

Immobilization was achieved by placing the subjects’ arms in fiberglass elbow casts (Lightcast II, Merck and Co., West Point, Pa.) at approximately 120°. The casts extended from shoulder to hand and included the thumb. Other than the casts, no additional restrictions were imposed on movement patterns.

After the training periods, and within 12 h of removing the casts after immobilization, girth and strength were measured. Muscle biopsies were taken within 12 h of cast removal as well, but 4-6 days were allowed to elapse after the last exercise bout before the posttrain-
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ing sample was taken, to avoid any acute effect resulting from the exercise.

Biopsies were immediately frozen in liquid nitrogen for subsequent analysis for ATP, ADP, CP, creatine, and muscle glycogen. In no instance did the elapsed time between sampling and freezing exceed 2 s. The sample was dissected free of blood, adipose tissue, and other nonmuscle material, and weighed in a cold room at -20°C. The biopsy was homogenized for 5 s in a Polytron homogenizer with 20 vol of ice-cold 1.0 M perchloric acid. The acid extract was centrifuged and the supernatant neutralized to pH 6-7 using cold 2.0 N KOH. The concentrations of ATP, ADP, CP, and creatine were determined using enzymatic fluorometric techniques (19). Muscle glucose and muscle glycogen concentrations were determined by means of the hexokinase–glucose-6-phosphate dehydrogenase method, before and after acid hydrolysis of glycogen in 2.0 N H2SO4 at 100°C for 3 h (18).

RESULTS

When the values for all subjects were combined, it was found that training resulted in an increase in upper arm girth by a mean value of 11 ± 4.8 (SD) % over pretraining values. Maximal elbow extension strength as measured on the Cybex, while showing considerable individual variations, also increased significantly in all subjects with training by a mean value of 28 ± 21.8% (Table 1).

Conversely, the immobilization procedure resulted in decreases in upper arm girth and elbow extension strength of 5 ± 3.3% and 35 ± 18.8%, respectively, below preimmobilization values.

Concentrations of both creatine and CP were significantly higher (P < 0.05) following training in both groups (Table 2). CP concentrations decreased significantly in both groups following immobilization. Creatine concentrations were also reduced by immobilization in both groups; however, the changes were significant only in group I, where immobilization was preceded by training.

Concentrations of ATP were significantly higher in both groups as well following training, but, unlike CP, were not significantly affected by the immobilization procedure. ADP concentrations were not significantly affected by either training or immobilization, except for a significant and inexplicable increase in group I following training.

When CP and creatine and ATP and ADP are combined and considered as total creatine and adenosine pools, they show significant increases of 28% and 18%, respectively, following training. After immobilization, the creatine pool decreased significantly by 22%, while the adenosine pool was not significantly affected.

HIGHLY SIGNIFICANT INCREASES AND DECREASES IN MUSCLE GLYCOGEN WERE OBSERVED FOLLOWING TRAINING AND IMMobilIZATION, RESPECTIVELY. THE GREATEST CHANGE WITH TRAINING (112%) OCCURRED IN GROUP II, WHERE TRAINING WAS PRECEDED BY IMMobilIZATION, AND THE GREATEST CHANGE WITH IMMobilIZATION (45%) IN GROUP I, WHERE IMMobilIZATION WAS PRECEDED BY TRAINING.

When individual changes in concentrations of ATP, CP, and glycogen following training were correlated with individual changes in strength, ATP showed the highest correlation, with r = 0.78, while CP and glycogen were considerably lower (r = 0.62 and r = 0.36, respectively).

DISCUSSION

Our data indicate that 5 mo of heavy resistance training result in greater resting concentrations of muscle creatine and adenosine energy pools. We interpret the slight variations in ATP/ADP and CP/creatine evident between conditions as reflecting slight individual variations between sampling and freezing times rather than actual in vivo changes in their ratios. Measurements of CP and ATP alone, because of their high lability, are somewhat difficult to interpret when one uses the needle biopsy technique. In the present study, however, our finding that creatine and ADP concentrations also increased with training suggests that the data are representative of actual in vivo changes in these high energy intermediates. Since training had been terminated 4-6 days prior to sampling in all cases, there is little likelihood that our measurements merely reflect a simple transient overshoot of these metabolites from the last training bout.

The effects of conventional weight training in terms of alterations in the dry-to-wet weight ratios of the biopsied tissue are not known. The findings of Goldberg et al. (4) that the increases in wet weight of rat soleus and plantaris muscle following gastrocnemius tenotomy reflected parallel changes in dry weight and total tissue protein suggest, however, that these changes would be minimal. Cooper (2) too has found that dry-to-wet weight ratios remain constant with prolonged immobilization, and even in tenotomized or denervated tissue.
It is therefore probable that the expression of metabolite concentrations per unit wet weight of muscle is a valid representation of actual concentration values between conditions.

Similar increases in resting ATP concentration in skeletal muscle following endurance training have been demonstrated by previous investigators (3, 15, 16). Evidence of increases in CP concentration following training, however, is confined largely to one study (3). Although Karlsson et al. (16) found increases in CP following 3 mo of endurance training, these changes were not maintained over 6 mo. Moreover, the same author (15) has found lower resting concentrations of CP in a group of endurance-trained students than in a group of untrained military conscripts. The repeated sets of heavy-resistance repetitions to failure employed in the present study involve 15-17 s of intensive activity followed by a 2- to 3-min rest period, during which ATP and CP are presumably being replenished (13). These repeated bouts of CP depletion-repletion may result in a greater degree of muscle uptake of creatine and a form of supercompensation of muscle CP, not unlike the muscle glycogen increments which occur following training (6). Since the rate of phosphagen turnover is directly related to exercise intensity (12, 15), it is probable that this form of training places greater stress on the breakdown and resynthesis of high-energy phosphates than does conventional endurance training. This view is supported by animal studies showing more pronounced increases in CP following short but very intense training (20, 21). Since the process was reversed with immobilization in the present study, it is likely that the phenomenon is indeed a training response.

It has been suggested (16) that the increase in resting ATP following endurance training is a function of the increase in mitochondrial number and size which occurs with this form of training (10, 11). It seems unlikely, however, that the heavy resistance training used in the present study would result in any significant changes in mitochondrial characteristics (8, 21). If the quantity and size of the mitochondria are in fact unaltered, then our data indicate actual increases in the concentrations of either cytoplasmic or mitochondrial ATP, or both, as a result of training.

Although the increases in ATP and CP following training are statistically significant, it is difficult to interpret their functional physiological significance. Since the time to peak force (approx 2 s) in our measurements of maximal elbow extension strength is too brief to suggest that the measurement is limited by depletion of high-energy phosphate stores, we cannot hypothesize that an increase in their concentration contributes to the observed increases in strength following training. Likewise, the decreases in strength following immobilization are no doubt attributable to factors other than a reduction in high-energy phosphate concentrations. Such factors may include changes in cross-sectional fiber areas (14) and motoneuron recruitment patterns (17). Total ATP and CP stores may, however, have a significant effect on the length of time for which a maximal contraction, or a series of repeated contractions, can be sustained. Thus, increases in ATP and CP may be of benefit in such events as sprinting, which call for a maximal power output over a brief duration.

The increases in muscle glycogen concentration with training (approximately 66% in both groups) are considerably smaller than the 2.5-fold increases which have been observed with endurance training over a similar time span (6). This difference may be due to the relatively brief and intermittent nature of heavy-resistance training and hence its less taxing effect on muscle glycogen stores than that produced by endurance training. Although diet was not formally controlled throughout the study, there is little reason to suspect any major alteration in carbohydrate intake over the three conditions, with resultant implications on muscle glycogen. The fact that muscle glycogen concentration did increase suggests that this type of training, for all its brevity, placed considerable demands on glycolytic energy supply in addition to the high-energy phosphate systems. This suggestion is consistent with studies which show significant lactate production within 10-15 s of the onset of heavy exercise (7, 12).

While the casting of a normal healthy limb does not preclude a certain degree of isometric contraction of the triceps, it did in this case undoubtedly result in considerable detraining, as indicated by significant decreases in girth and strength. Our data indicate that the reduction in function brought about by the immobilization procedure resulted in CP and glycogen concentrations lower than those maintained by normal day-to-day use.

The changes in muscle concentrations of glycogen, CP, and ATP observed with training and immobilization suggest even greater changes in absolute muscle content, due to the probable changes in total tissue mass with hypertrophy, as indicated by increased girth measurements. Although an increase in the total content of the high-energy phosphate pool would not be expected to affect the maximal rate of power output from a muscle, it would increase the total energy available from this source, and thus prolong the time that this rate of power output could be sustained.

The potential contribution of resistance training to performance improvement in the power athlete, such as the sprinter, has long been recognized on a purely mechanical basis. The present study indicates that there is a biochemical advantage to be gained from this form of training through an increase in muscle energy reserves.

The authors acknowledge the assistance provided by Dr. G. R. Viviani and the staff at the McMaster Medical Centre Fracture Clinic, in the immobilization procedure. We also express our appreciation to Dr. C. J. Toews, Dept. of Medicine, for his technological assistance and very helpful editorial advice.

This study was funded by the Muscular Dystrophy Association of Canada.

Received for publication 30 December 1976.

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