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ORIGINAL ARTICLE

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The role of metabolites in strength training

II. Short versus long isometric contractions

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Abstract The role of intramuscular metabolite changes in the adaptations following isometric strength training was examined by comparing the effect of short, intermittent contractions (IC) and longer, continuous (CC) contractions. In a parallel study, the changes in phosphate metabolites and pH were examined during the two protocols using whole-body nuclear magnetic resonance spectroscopy (NMRS). Seven subjects trained three time per week for 14 weeks. The right leg was trained using four sets of ten contractions, each lasting 3 s with a 2-s rest period between each contraction and 2 min between each set. The left leg was trained using four 30-s contractions with a 1-min rest period between each. Both protocols involved isometric contractions at 70% of a maximum voluntary isometric contraction (MVC). The MVC, length:tension and force:velocity relationships and cross-sectional area (CSA) of each leg were measured before and after training. The increase in isometric strength was significantly greater ($P = 0.041$) for the CC leg (median 54.7%; $P = 0.022$) than for IC (31.5%; $P = 0.022$). There were no significant differences between the two protocols for changes in the length:tension or force:velocity relationships. There were significant increases in muscle CSA for the CC leg only. NMRS demonstrated that the changes in phosphate metabolites and pH were greater for the CC protocol. These findings suggest that factors related to the greater metabolite changes during CC training results in greater increases in isometric strength and muscle CSA.

Key words Strength training · Muscle hypertrophy · NMR spectroscopy · Skeletal muscle

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Introduction

As discussed in the preceding paper (Carey Smith and Rutherford 1995) there is still controversy over the stimulus for muscle hypertrophy and strength gains following high-resistance training. The high mechanical stress placed on the muscle as a result of this type of exercise may act as a stimulus for hypertrophy. In addition, there will be metabolite changes in the muscle and the stimulus for adaptation may arise as a result of these changes or indirectly through hormonal or growth factor release. In the preceding paper, we found greater strength increases following concentric compared to eccentric training, suggesting a role for metabolites in the process of adaptation. In this paper we examine the role of metabolites further by comparing the changes in quadriceps strength and cross-sectional area (CSA) resulting from short, intermittent isometric contractions compared to longer, fatiguing contractions. Both training protocols were carried out at 70% of the maximum isometric force; it is known that blood flow to the quadriceps is occluded above 20% of a maximum voluntary contraction (MVC; Barcroft and Millen 1939; Edwards et al. 1972). We proposed that the changes in metabolites would be greater following the longer contractions, as the blood supply would be occluded for longer. In order to test this we have also measured the changes in phosphate metabolites and pH during the two protocols using nuclear magnetic resonance spectroscopy (NMRS).

Methods

Subjects

Seven young healthy adults (six female) were recruited and all gave their written informed consent. The study was approved by the Parkside Ethical Committee. The mean (range) characteristics of the subjects were: age, 22.7 (19–31) years; height, 1.66 (1.63–1.69) m and

mass 62.3 (53–68.5) kg. None of the subjects were engaged any other form of regular training.

Protocol

Subjects trained three times per week for 14 weeks. The right leg was trained using the short, intermittent contractions (IC) and the left using the longer, continuous contractions (CC). The IC protocol involved four sets of ten contractions, each contraction lasting 3 s with a 2-s rest between each and a 2-min rest between each set. Hence there was a total of 40 contractions, lasting a total of 120 s. The CC protocol involved four contractions of 30 s duration with a 1-min rest between each. Again the total duration of contraction was 120 s. The shorter rest period for CC was to minimise the clearing of metabolites within the muscle without compromising the ability to generate the required level of force during each set. Both protocols were carried out in a quadriceps strength testing chair to a force target set to 70% of the MVC force, the latter being tested before each training session. Training and testing was carried out with the hip and knee at right angles. Every 2 weeks the activation of the muscle was tested using the twitch superimposition technique (Rutherford et al. 1986).

Quadriceps strength and size

Details of the testing procedures have been given in detail in the preceding paper (Carey Smith and Rutherford 1995). Briefly, the MVC was measured as described above and the length:tension and force:velocity relationships of each quadriceps were measured before and at the end of training using an isokinetic dynamometer (Cybex II). Muscle size was measured from computer tomographic scans taken at one quarter (distal) and three-quarters (proximal) femur length measured from the knee joint space.

NMR spectroscopy

In a second series of experiments, on a group similar in age and state of training to the subjects in this study, the metabolite changes accompanying each protocol were examined using NMRS. Phosphorus metabolites were measured with a 780-mm clear bore, 2.0-T magnet with a home-built spectrometer system (for details see McCully et al. 1994). Six subjects (three male) aged between 20 and 30 years were tested. Subjects lay supine within the magnet and were aligned with a 9-cm surface coil over the quadriceps muscle. Straps were applied just above the knee, and at the top of the thigh, so as to prevent the thigh from being raised during the exercise and a strain gauge was placed at the ankle. As feedback information on force level was difficult to provide to the subjects, they were asked to push as hard as possible, rather than to 70% of maximum. Resting spectra were collected for 2 min before exercise began. During the two exercise protocols spectra were collected every 10 s. Recovery spectra were collected every 10 s, for 3 min, at the end. Spectra were Fourier-transformed with 5 Hz line broadening and were integrated in the frequency domain.

Muscle pH was calculated from the frequency difference between inorganic phosphate (P_i) and phosphocreatine (PCr) (Strear et al. 1989). PCr concentrations were calculated based on resting adenosine triphosphate (ATP) levels being 5.5 $mM \cdot kg^{-1}$ wet weight and correcting the area of the PCr peak based on the ratio of PCr to ATP at rest.

Statistics

Data was analysed using non-parametric statistics as the changes were not normally distributed. The significance of changes after each protocol were tested using one-sign Wilcoxon, and the difference between the two protocols using Mann-Whitney. In the NMR experiments differences in changes in metabolite levels were also compared using Mann-Whitney.

Results

All subjects completed the 14 weeks of training; during the first 2 weeks the training caused considerable stiffness in the left leg carrying out the CC protocol.

Quadriceps strength

All subjects were able to maximally activate their quadriceps muscle on each testing occasion. There were large and significant increases in isometric strength at 1.57 rad (90°) for both legs, with the change following CC being significantly greater than after IC ($P = 0.041$). The median (range) change for IC was 31.5 (12–106)% ($P = 0.022$) and for CC 54.7 (35–142)% ($P = 0.022$). All subjects had greater strength increases following CC and these increases were significantly greater than baseline from week 2 of training, whereas for the IC protocol the changes only became significant after 8 weeks (Fig. 1).

Length:tension

Significant increases in isometric strength were only seen at 1.57 and 1.74 rad (90 and 100°) of flexion. The median increase was similar for both legs and of the order of 30–40% (Fig. 2).

Force:velocity

The isokinetic strength increases were much smaller than the isometric, and the only significant changes

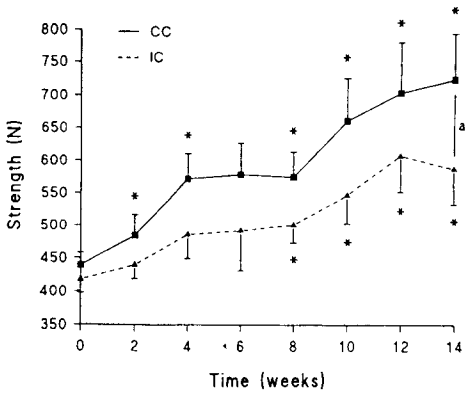

Fig. 1 Group mean (SE) maximum isometric force every 2 weeks during training with the long contractions (*CC*) and intermittent contractions (*IC*). *Significance from baseline, $P < 0.05$; [a]significant difference between CC and IC, $P < 0.05$

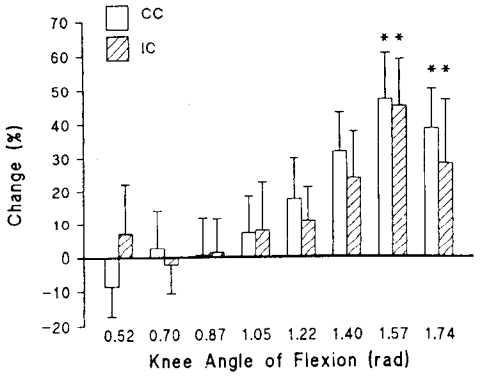

Fig. 2 Group mean (SE) percentage changes in isometric force at a range of different knee angles. *Significantly different from baseline, $P = 0.022$

Table 1 Median (range) percentage changes in quadrices cross-sectional area at two scan levels

Protocol	Upper level (3/4 femur)	Lower level (1/4 femur)
IC	6.5 (− 5.5 to 29.6)	4.3 (− 1.3 to 23.9)
CC	10.1* (0.8 to 24.4)	11.1* (1.0 to 32.0)

* Significantly diferent from pre-training, $P = 0.022$

were for the IC protocol at 2.09 rad·s^{-1} (120°·s^{-1}; median 11.3% $P = 0.022$) and 3.14 rad·s^{-1} (180°·s^{-1}; median 11.6%; $P = 0.035$). There were no significant differences between the two legs.

Cross-sectional area

There were no significant changes in CSA following the IC protocol at either scan level. There were significant increases in CSA at both scan sites following CC. The changes and significance values are given in Table 1.

Metabolite changes

The P_i:PCr ratio and P_i concentrations were greater following the CC compared to IC protocol, this difference being particularly evident, and significant, by the fourth set (P_i, $P = 0.0453$; P_i:PCr, $P = 0.036$). Similarly, pH was lower following the CC protocol; however, the difference between the protocols was not significant. Figure 3 illustrates the group mean values for the last 10 s of each rest and exercise period for the two protocols.

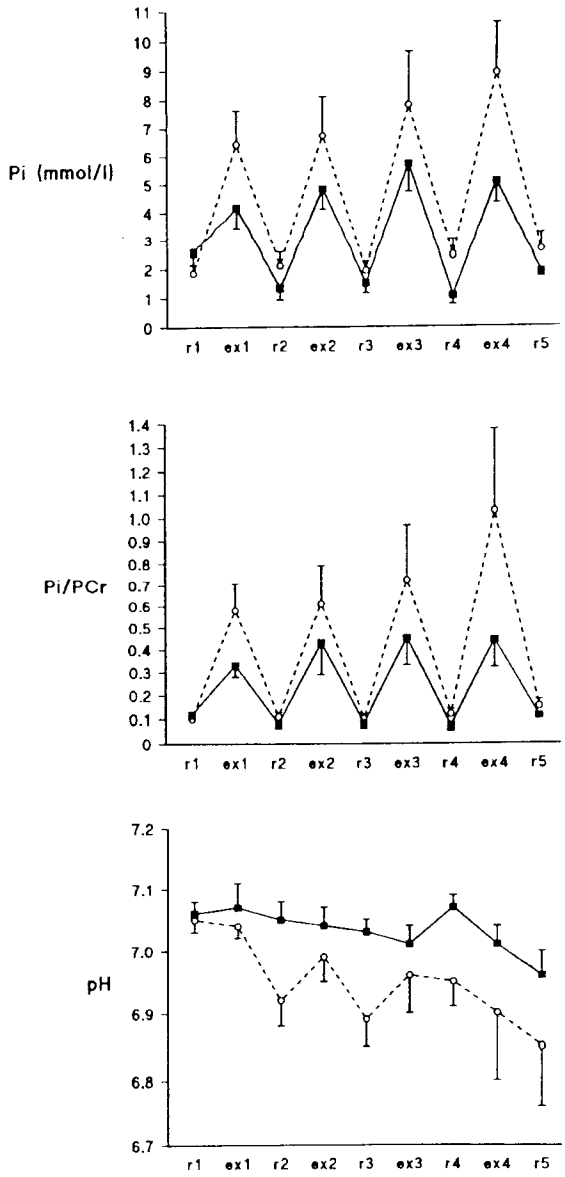

Fig. 3 Group mean values for Pi/PCr, Pi and pH measured by NMRS during rest (*r*) and exercise (*ex*) periods for the CC (*dashed line*) and IC (*full line*) protocols. Data are mean (SE) for the last 10 s of each rest and exercise period

Discussion

This study has demonstrated greater isometric strength gains and muscle hypertrophy following isometric strength training using long, fatiguing contractions compared to short, intermittent contractions. The metabolite changes within the muscle were also different for the two protocols, with the longer contractions resulting in a greater drop in pH and PCr and a greater rise in P_i and P_i:PCr ratio. This would suggest that metabolite changes are involved in the adaptational response to strength training, rather than the high forces alone. The results of this study and the preceding

study comparing concentric and eccentric contractions are therefore in agreement.

The increase in strength observed for the IC protocol in the current study was of a similar magnitude to previous studies using isometric training in which the contractions were of short duration (Jones and Rutherford 1987; Lindh 1979). Although not significant, the changes in muscle CSA following the IC protocol were also of similar magnitude to previous studies (Davies et al. 1988; Jones and Rutherford 1987; Young et al. 1983). The increases in CSA following the CC protocol were rather larger than many reported in the literature. Previous studies have usually measured quadriceps CSA at mid-femur rather than the proximal and distal ends measured in the current study. Following isokinetic training, Narici et al. (1989) found the greatest increases in CSA at the proximal end of the quadriceps and the smallest changes at the distal end; the mechanism for these variations along the muscle length is unknown. We found equal changes at both ends of the muscle. This difference between the two studies may simply reflect the different types of training.

Although the changes in isometric strength and CSA were greater after CC, there were no differences in the changes in isokinetic strength between the two protocols. If anything, the increases were greater following IC. In the previous study (Carey Smith and Rutherford 1995), similar discrepancies occurred between the two protocols, with eccentric training resulting in smaller isometric strength gains but larger changes in dynamic strength. In the study presented here the small changes in dynamic strength may simply reflect the known specificity of training with larger increases in strength being evident in contractions similar to those used in training (Rutherford and Jones 1986). Specificity cannot explain the greater isometric strength gains in the CC leg as both protocols were isometric. The greater hypertrophy following CC also indicates differential changes following the two protocols.

Using NMRS we have demonstrated that there were differences in muscle levels of phosphate metabolites and pH following the two protocols. This is most likely due to the longer interruption of the circulation during CC resulting in lower clearance of lactate and carbon dioxide, accompanied by a slower provision of oxygen. Whether these metabolite changes directly stimulate protein synthesis, or cause the release of local growth factors, is unknown. In work- and stretch-induced muscle hypertrophy in rats (DeVol et al. 1990) and chickens (Czerwinski et al. 1994), there is increased expression of insulin-like growth factor-1 (IGF-1) mRNA which, in the work-induced model, is independent of growth hormone release. IGF-1 is known to stimulate protein synthesis in muscle (Florini 1987); it also has metabolic actions, including increasing glucose uptake, and therefore may be released in response to metabolic stress.

The recruitment patterns during the two protocols may also have been different despite both exercises being set to 70% of maximum. During the longer contractions some motor units will fatigue and others will be recruited to maintain force. This may result in a greater number of motor units being active and exposed to a training stimulus in the CC protocol, either through greater activity or via release of trophic factors at the neuromuscular junction. We have, however, no information on recruitment patterns and cannot rule out this possibility.

In conclusion, we have demonstrated greater increases in strength and muscle hypertrophy following long, fatiguing contractions compared to short, intermittent contractions in the quadriceps muscle. One mechanism responsible for this differential effect may be the greater change in metabolite levels and pH during the former. Future work should aim to identify the metabolites involved and methods for maximising their change.

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