ORIGINAL ARTICLE

J. Schott · K. McCully · O.M. Rutherford

The role of metabolites in strength training

II. Short versus long isometric contractions

Accepted: 12 April 1995

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

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 Mil- len 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 in 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) and phosphocreatine (PCr) (Strair et al. 1989). PCr concentrations were calculated based on resting adenosine triphosphate (ATP) levels being 5.5 mM·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

![Graph](image_url)
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 quadriceps cross-sectional area at two scan levels

<table>
<thead>
<tr>
<th>Protocol</th>
<th>Upper level (3/4 femur)</th>
<th>Lower level (1/4 femur)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IC</td>
<td>6.5 (–5.5 to 29.6)</td>
<td>4.3 (–1.3 to 23.9)</td>
</tr>
<tr>
<td>CC</td>
<td>10.1* (0.8 to 24.4)</td>
<td>11.1* (1.0 to 32.0)</td>
</tr>
</tbody>
</table>

*Significantly different from pre-training, \( P = 0.022 \)

were for the IC protocol at 2.09 rad \( \cdot \) s\(^{-1}\) (120° \( \cdot \) s\(^{-1}\); median 11.3\% \( P = 0.022 \)) and 3.14 rad \( \cdot \) s\(^{-1}\) (180° \( \cdot \) 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 \( P_i/\text{PCr} \) 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 (\( P_i, P = 0.0453; \ P_i/\text{PCr}, P = 0.036 \)). Similarly, \( \text{pH} \) 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 \( P_i/\text{PCr} \), \( P_i \) and \( \text{pH} \) 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 \( \text{pH} \) and \( \text{PCr} \) and a greater rise in \( P_i \) and \( P_i/\text{PCr} \) 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
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 metabolic levels and pH during the former. Future work should aim to identify the metabolites involved and methods for maximising their change.

Acknowledgements We would like to thank Smith Kline Beecham and the Edgar Lawley Travel Scholarship for support and the NIH (grant RR02305) for partial support. In addition, we would like to thank Keith Kendrick and Glenn Walter for technical help with the NMRS.

References

Barcroft H, Millen JLE (1939) Blood flow through muscle during sustained contraction. J Physiol (Lond) 97:17–31


