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ORIGINAL ARTICLE

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The role of metabolites in strength training

I. A comparison of eccentric and concentric contractions

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Abstract This study examined the role of high forces versus metabolic cost in the adaptations following strength training. Ten young, healthy male and female subjects trained one leg using concentric (CL) and the other using eccentric (EL) contractions of the quadriceps muscle for 20 weeks. EL used weights which were 35% higher than those used for CL. Isometric strength, and the length : tension and force : velocity relationship of the muscle were measured before and after training. Muscle cross-sectional area (CSA) was measured near the knee and hip using computed tomography. Increases in isometric strength were greater for CL compared to EL, the difference being significant with the knee at 1.57 rad (90°) [mean (SD), 43.7 (19.6)% vs 22.9 (9.8)%, respectively; $P = 0.01$]. Increases in isokinetic strength tended to be larger for EL, although the differences were not significant. Significant increases in CSA occurred near the hip for both EL and CL. These results suggest that metabolic cost, and not high forces alone, are involved in the stimuli for muscle hypertrophy and strength gains following high-resistance training.

Key words Muscle strength · Hypertrophy · Concentric contractions · Eccentric contractions · Strength training

Introduction

Despite considerable research interest, the stimulus for muscle hypertrophy and strength gains following high-resistance training remains unknown. Evidence suggests that high-force contractions are required for adaptations to occur; this type of contraction will have several consequences for the muscle and the endocrine system. Several hormones are known to be released during and after high-resistance training. These include growth hormone (GH), testosterone, catecholamines and cortisol (Kraemer 1992a). Their release varies depending on several factors including the intensity, length of rest periods and level of training of the subject. The muscle specificity of the training effect requires a mechanism by which systemic hormone release can interact with an individual muscle to result in protein synthesis. This may involve receptor regulation and/or the release of local growth factors in the working muscle in response to hormonal stimulation (Kraemer 1992b). Growth factor release may also occur in the muscle independently of endocrine stimulation and exert autocrine or paracrine actions on the muscle.

Apart from placing high mechanical stresses on the fibres and connective tissue, the high forces used in strength training will also cause metabolic changes within the muscle. Although the majority of strength training regimes utilise low numbers of repetitions, the metabolites may accumulate because the blood supply is occluded during the high-force contractions. These changes may directly, or indirectly via growth factor release, stimulate protein synthesis. In order to differentiate the roles of high mechanical stress versus metabolic cost, use can be made of eccentric and concentric contractions. In the former, high forces can be generated at a relatively low metabolic cost compared to either isometric or concentric contractions (Bigland-Ritchie and Woods 1976). Comparison of the changes resulting from high-force, low-metabolic cost (eccentric) contractions and lower-force, high-metabolic cost (concentric) contractions may provide further insight into the relative importance of stress versus metabolite levels. The purpose of this study was to compare the strength changes and hypertrophy resulting from concentric or eccentric contractions. A preliminary report

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of this work has been presented (Carey Smith and Rutherford 1994).

Methods

Subjects

Ten, young healthy adults (five males) took part in the study. Anthropometric details for the group are given in Table 1. None of the subjects had previously taken part in regular strength training exercise and all maintained their normal level of activity. The study was passed by the Parkside Ethical Committee and all subjects gave their written, informed consent.

Training

Subjects trained the quadriceps muscle three times per week for 20 weeks on the leg extension station of a multigym. The right leg was trained using concentric contractions (CL) and the left with eccentric contractions (EL), both contractions being controlled and lasting approximately 3 s each. Each training session consisted of four sets of ten contractions with a 1-min rest between each set. The weight was assessed as that which could just be lifted (CL) ten times and adjusted as performance improved. The design of the multigym station was such that the load could be varied depending on the position of the foot on the foot plate. The difference in leverage meant that with the foot on the top of the plate, the weight was 35% greater than with the foot on the bottom of the plate. Subjects therefore lifted the weight (CL) with the foot on the bottom of the plate and then lowered (EL) the weight with the other foot on the top of the plate, the latter weight being 35% greater.

Quadriceps strength

Strength was assessed as the maximum voluntary isometric contraction force in a conventional strength testing chair. The percutaneous superimposition technique was used to test for full muscle activation during the contraction (Rutherford et al. 1986). Using an adapted isokinetic dynamometer (Cybex II) the length : tension and force : velocity relationship of the muscle was also measured. The adaptation involved bonding a strain gauge on to the lever arm of the dynamometer from which the undamped force trace was taken and recorded for analysis. For the length : tension relationship the muscle was tested at 0.17 rad (10°) intervals between 0.35 and 1.92 rad (20 and 110°) of knee flexion (from the horizontal). Knee angle was measured using a manual goniometer. The velocities of isokinetic testing were 0.52, 1.05, 1.57, 2.09, 3.14, 4.19 and 5.24 rad $\cdot$ s^{-1} (30, 60, 90, 120, 150, 180, 240 and 300° s^{-1}). Velocities were selected in a random order, with a 3-min rest period between each. The order was the same for each testing occasion.

Quadriceps cross-sectional area

The cross-sectional area (CSA) was measured at two levels on the quadriceps using computed tomography. The levels chosen were one-quarter and three-quarters femur length measured from the knee joint space. For re-scanning the height of these levels were measured from the knee with the subject lying flat. The scanner (Phillips Tomoscan 350) was set to a scan time of 4.8 s and a slice thickness of 9 mm. Images were analysed off-line using an interactive image analysis package (Sun).

Table 1 Anthropometric details of subjects [mean (SD)]

	Age (years)	Mass (kg)	Height (m)
Men (n = 5)	20.6 (0.9)	79.6 (13.8)	1.83 (0.04)
Women (n = 5)	20.2 (1.3)	55.6 (6.2)	1.69 (0.04)

Statistics

Changes with training were analysed using Student's paired t-test. Differences between eccentric and concentric training were compared using Student's unpaired t-test.

Results

All subjects successfully completed all 20 weeks of training. On average, the group improved by 65% in the weights lifted during training.

Isometric strength

The group mean increase for CL was 43.7 (19.6)% [Mean (SD); $P < 0.0001$) and for EL, 22.9 (9.8)%. The increase for CL was significantly greater than for EL ($P = 0.01$). All subjects were able to maximally activate the quadriceps during the testing manoeuvre.

Length : tension

For CL there were significant increases in strength at 0.87, 1.22, 1.40, 1.57 and 1.74 rad of flexion. The increase at 1.57 rad was similar in magnitude (48.4%) to that found in the strength testing chair where the knee was also held at 1.57 rad. For EL there were significant increases in strength at 1.22 and 1.57 rad only. Again the change at 1.57 rad was similar between the chair and dynamometer. Group mean percentage changes and significance values are given in Table 2 and the length : tension relationships illustrated in Fig. 1. There were no significant differences between the changes in strength at any angle between the two legs. The changes, however, were consistently greater over the mid-range for the CL.

Force : velocity

There were significant increases in the forces generated at 0.52 and 1.05 rad $\cdot$ s^{-1} for CL and at 0.52, 1.05, 1.57, 2.09, 2.62 rad $\cdot$ s^{-1} for EL (Table 3). There were no significant differences between the changes for the two legs. The force : velocity relationships for each leg are illustrated in Fig. 2.

Table 2 Length : tension changes (%) following concentric (*CL*) and eccentric (*EL*) training [mean (SE)]

Angle of flexion (rad)	CL	EL
0.35	5.5 (6.3)	16.1 (5.0)
0.52	10.7 (8.2)	19.2 (15.3)
0.70	27.0 (8.1)***	16.8 (7.8)
0.87	48.4 (11.9)***	31.0 (10.7)**
1.05	35.3 (8.9)***	21.5 (14.6)
1.22	30.4 (13.4)*	18.4 (7.4)*
1.40	24.7 (14.2)	24.2 (11.3)
1.57	18.7 (7.6)*	23.6 (11.6)
1.74	4.7 (6.1)	17.0 (8.0)
1.92	– 1.4 (6.2)	12.1 (5.6)

Significance from pre-training: $^{*}P < 0.05$, $^{**}P < 0.02$, $^{***}P < 0.01$

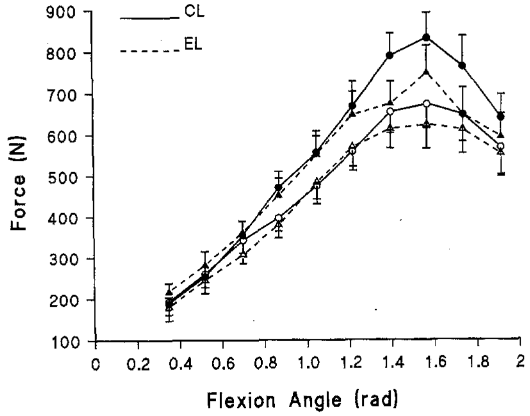

Fig. 1 Length : tension relationship for concentric (*CL*; *circles*) and eccentric (*EL*; *triangles*) leg before (*open symbols*) and after (*closed symbols*) training [mean (SE)]

Table 3 Changes (%) in isokinetic strength following CL and EL training [mean (SE)]

Speed (rad · s^{-1})	CL	EL
0	20.1 (4.9)***	11.0 (5.0)
0.52	13.4 (4.8)*	21.5 (6.4)**
1.05	20.8 (4.5)***	16.6 (13.0)***
1.57	8.9 (16.0)	11.9 (3.5)***
2.09	6.9 (4.2)	13.7 (4.7)**
2.62	3.7 (5.0)	16.7 (3.7)***
3.14	3.3 (6.1)	8.7 (6.1)
4.19	– 2.3 (6.3)	9.8 (5.0)
5.24	– 8.1 (6.7)	10.3 (11.4)

Significance from pre-training: $^{*}P < 0.05$, $^{**}P < 0.02$, $^{***}P < 0.01$

Quadriceps CSA

There were significant increases in muscle CSA at the upper level (three-quarters femur height) only for both CL and EL [4.6 (5.1)%, $P = 0.026$ vs 4.0 (4.3)%, $P = 0.023$, respectively). The changes at one-quarter femur height were not significant [3.6 (18.5)% vs 2.6 (14.7)%]. There were no significant differences between the two legs.

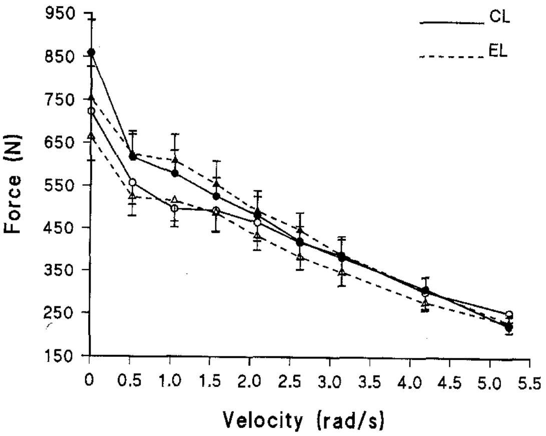

Fig. 2 Force : velocity relationship for *CL* and *EL* before and after training

Discussion

We have found greater increases in quadriceps isometric strength following strength training using concentric contractions compared to eccentric contractions, despite the higher loads used in the eccentric training. To our knowledge this is the first study to demonstrate greater strength improvements following concentric training. There was significant and similar hypertrophy of the quadriceps at three-quarters femur height following both training regimes. The increases in dynamic strength tended to be smaller than for isometric strength and greater following the eccentric training. These results suggest that it is not muscle force per se that is the stimulus for muscle strength increases and hypertrophy.

The difference in loading between the two types of training was about 35%. This is consistent with the 40% difference between eccentric and concentric forces generated by the elbow flexors (Doss and Karpovich 1965). It is possible, however, that even greater loads could have been lowered, but using this training system the weight lowered was a fixed increment above that lifted and could not be altered independently. In a previous study, where the weights to be lowered were lifted by the experimenters, subjects were able to lower about 45% more weight than that lifted by the end of the 3 months of training (Jones and Rutherford 1987). One possibility, which cannot be excluded, is that fewer motor units were recruited during the eccentric contractions in the present study, if the loads were not near maximal. Fewer would then be exposed to a training stimulus. Due to the closeness of the weight differential to the data of Doss and Karpovich (1965), and the difficulty experienced by the subjects in lowering the weights, this possibility seems unlikely. Due to the differences in the position of the foot on the plate during training, there may have been differences in the biomechanics and therefore recruitment pattern between the two regimes. This could lead to subtle differences during isometric testing at the different knee angles. Inspection of the length : tension relationships, however, indicates no difference in the overall shape before and after training.

A number of studies have compared the effects of eccentric and concentric contractions in strength training. A drawback of many of these has been the use of the same weight for both types of training, which fails to utilise the ability of the muscle to generate greater forces during eccentric contractions. Only one study has found greater increases in strength following eccentric training (Komi and Buskirk 1972). In their study the only significant difference was in eccentric strength and not concentric or isometric strength. As the training and testing device was the same, this may simply be due to the eccentric group learning to carry out the eccentric movement. Maximal eccentric movements are unusual to perform and probably subject to a considerable learning process. Several studies have demonstrated no difference between the two types of training (Johnson 1972; Jones and Rutherford 1987; Mannheimer 1970; Pavone and Moffat 1985). Combined concentric and eccentric training has been reported to be more beneficial than just concentric training (Dudley et al. 1991).

Although the forces generated by the CL were lower than EL, the metabolic fluxes would be much greater (Bigland-Ritchie and Woods 1976; Dudley et al. 1991; Menard et al. 1991). Traditionally it has been believed that high-energy work, such as endurance exercise, does not result in large strength gains. However, during endurance exercise the forces generated by the muscle are low and the blood supply would not be substantially interrupted. During strength training, however, the blood supply would be occluded during the contractions and the levels of metabolites in the muscle could therefore vary quite considerably. The stimulus for adaptation may result directly from these metabolites, e.g. lactate, inorganic phosphate, creatinine, or indirectly through the release of local growth factors such as insulin-like growth factor-1 (IGF-1). IGF-1 release following work-induced hypertrophy has been found in rats and can occur independently of GH (De Vol 1990). Alternatively trophic factors could be co-released with acetylcholine at the neuromuscular junction. If recruitment patterns did vary in the two regimes, then the release of these factors might also have differed. That metabolities are involved is, however, further supported in the accompanying paper in which strength improvements were greater following long, fatiguing isometric contractions compared to short contractions (Schott and Rutherford 1995).

As has been demonstrated in many previous studies, the increases in strength were much greater than the increase in muscle size (for review see Jones et al. 1989). There is still no agreement about the apparent increase in force-generating capacity, with opinions divided as to whether it is due to neural or intramuscular changes. The greater increase in size was found in the upper scan site, which is in agreement with the work of Narici et al. (1989). It is not known why hypertrophy should be greater at one level compared to another, but it may reflect the different contribution to the CSA from the constituent muscles of the quadriceps group at the two levels. Scanning was carried out at these levels, rather than mid-femur, because Narici et al. (1989) showed that the greatest hypertrophy occurred at the ends of the muscle. However, one problem with scanning at these sites is that small movements in the re-scanning site could cause large differences in CSA as the muscle size is changing rapidly at these points. At mid-femur the problem is not as great because the quadriceps cross-section remains fairly similar in the centre of the muscle.

Although the isometric changes were greater for the CL, the changes in dynamic force tended to be greater following eccentric training, although the differences were not significant. As both training contractions were carried out at similar speeds, and the testing was concentric, it is difficult to explain this finding.

It has been suggested that one stimulus for muscle hypertrophy is micro- or macro-damage to the fibres resulting from high forces (Goldspink 1971). Eccentric exercise is known to result in greater muscle damage than either isometric or concentric contractions (Asmussen 1956; Newham et al. 1983). Our results do not support the suggestion of Goldspink as eccentric training resulted in smaller strength gains. However, as the number of contractions were small, they may not have caused significant muscle damage. This is supported by the subjects who reported similar low levels of muscle stiffness following both exercise protocols. None reported the severe delayed-onset pain and tenderness felt after repeated eccentric exercise (Newham et al. 1983).

This paper, together with the subsequent paper, indirectly suggests a role for metabolites in the adaptations following strength training. Future work is required to identify those factors responsible and protocols for maximising their release.

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