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## Effects of resistance exercise combined with vascular occlusion on muscle function in athletes

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**Abstract** The effects of resistance exercise combined with vascular occlusion on muscle function were investigated in highly trained athletes. Elite rugby players ( $n = 17$ ) took part in an 8 week study of exercise training of the knee extensor muscles, in which low-intensity [about 50% of one repetition maximum] exercise combined with an occlusion pressure of about 200 mmHg (LIO,  $n = 6$ ), low-intensity exercise without the occlusion (LI,  $n = 6$ ), and no exercise training (untrained control,  $n = 5$ ) were included. The exercise in the LI group was of the same intensity and amount as in the LIO group. The LIO group showed a significantly larger increase in isokinetic knee extension torque than that in the other two groups ( $P < 0.05$ ) at all the velocities studied. On the other hand, no significant difference was seen between LI and the control group. In the LIO group, the cross-sectional area of knee extensors increased significantly ( $P < 0.01$ ), suggesting that the increase in knee extension strength was mainly caused by muscle hypertrophy. The dynamic endurance of knee extensors estimated from the decreases in mechanical work production and peak force after 50 repeated concentric contractions was also improved after LIO, whereas no significant change was observed in the LI and control groups. The results indicated that low-intensity resistance exercise causes, in almost fully trained athletes, increases in muscle size, strength and endurance, when combined with vascular occlusion.

**Keywords** Athletes · Ischaemia · Muscle hypertrophy · Muscle endurance

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### Introduction

A number of studies have so far shown that endurance exercise training (low resistance/high repetition training) induces in muscle an increase in endurance capacity, comprising increases in the total volume, number and size of mitochondria, the activity of enzymes related to oxidative energy metabolism, capillary density, and glycogen content (Booth and Thomason 1991; Edstrom and Grimby 1986; Holloszy and Booth 1976; Salmons and Henriksson 1981; Saltin and Gollnick 1983). In addition, these adaptations of skeletal muscle to endurance training have been shown to be enhanced by ischaemia (Sundberg 1994).

On the other hand, exercise of relatively high intensity and short duration performed during ischaemia may promote improvements of anaerobic function in skeletal muscle. For example, an increase in the numerical proportion of fast-twitch (type II) fibres has been demonstrated in the leg muscles of patients with heart failure, chronic obstructive lung disease, and peripheral vascular diseases such as intermittent claudication (Hammarsten et al. 1980; Hilderbrand et al. 1991; Mancini et al. 1989). In addition, our recent study has shown that low-intensity [about 20% one repetition maximum (1RM)] resistance exercise combined with vascular occlusion causes a transient, post-exercise increase in concentration of plasma growth hormone as well as an elevated electrical activity of the muscle during exercise (Takarada et al. 2000a). When a study of such low-intensity exercise combined with vascular occlusion was conducted for 16 weeks using the elbow flexors of old women, it caused marked muscle hypertrophy and concomitant increase in strength (Takarada et al. 2000b). However, such a strong effect of low-intensity exercise combined with vascular occlusion may be specific to subjects whose day-to-day physical activities are extremely low.

In the present study, we investigated the long-term effects of low-intensity resistance exercise combined with

vascular occlusion in athletes having much higher levels of physical activity than that in untrained subjects. The results showed large effects of low-intensity resistance exercise combined with vascular occlusion in inducing increases in muscle size and strength as well as improvements of muscle endurance in high-intensity exercise.

## Methods

### Subjects

A group of 17 young male athletes (rugby players) volunteered for the study. The subjects were divided into experimental [mean (SD)] [age 25.9 (0.6) years,  $n=12$ ] and untrained control [age 25.4 (0.8) years,  $n=5$ ] groups, and the former was further divided into groups undertaking training combined with vascular occlusion ( $n=6$ ) and normal training ( $n=6$ ) groups. Their physical characteristics are shown in Table 1. They had previously been engaged in resistance (weight-lifting) training for more than 5 years. All of the subjects had previously been fully informed about the experiment procedures to be used as well as the purpose of the study, and their written informed consents were obtained. The study was approved by the Ethics Committee for Human Experiments, University of Tokyo.

### Regimes for exercise training

The exercises used were low-intensity with vascular occlusion (LIO) and low-intensity without vascular occlusion (LI) for the occlusive training and normal training groups, respectively. The subjects in the experiment groups performed bilateral knee extension exercise in a seated position using an isotonic leg extension machine. Since they had been elite rugby players, we made them train both sides simultaneously and equally, and the non-dominant side was used for measurements. The range of joint motion was from 0° to 90° (0° at full extension). In LIO, both sides of their thighs were trained with the proximal portions being compressed by a specially designed elastic belt (width 33 mm, length 800 mm). The belt contained a small pneumatic bag (width 25 mm, length 100 mm) along its inner surface, which could be connected to an electronic pressure gauge so as to monitor the occlusion pressure (model M.P.S.-700, VINE Medical Instruments Inc., Japan). The mean occlusion pressure throughout the period of training was [mean (SEM)] 196.0 (5.7) mmHg.

The exercise was performed twice a week and lasted for 8 weeks including the period for instruction and orientation (16 sessions in total). In each exercise session, the subjects in the training group performed four sets of exercise with an interset interval of 30 s. The intensity of exercise was approximately 50% of the weight that could just be lifted once throughout the complete range of movement (1RM), which was determined in the initial stage of exercise training and kept unchanged throughout the period of training. In each set of LIO, the subjects repeated the lifting movement until failure, whereas in LI, they were instructed to match the number of repetitions performed by LIO. The mean repetition in each set was

16.3 (0.7). The total amounts of exercise in LIO and LI were calculated as load $\times$ total repetitions of the lifting movement, and were 52,133.5 (6,038.8) kg $\times$ repetitions and 51,892.7 (5,868.6) kg $\times$ repetitions, respectively. The subjects were instructed to lift and lower the load at an approximately constant velocity, taking about 2 s for each concentric and eccentric action. The vascular occlusion was maintained throughout the session of exercise which lasted for approximately 10 min, and was released immediately after the session of exercise. All of the exercise sessions were preceded by a 10 min warm-up on a cycle ergometer at about 50% of the physical exercise capacity and a stretching of the major muscle groups to be trained.

The subjects in the control group were not engaged in the exercise programme. They were instructed to maintain their normal levels of activity with no new exercise activity during the period of the experiment.

### Measurements of muscle strength and endurance

Isokinetic torque-angular velocity relationships of knee extensors were examined by using an isokinetic dynamometer (Myoret, Kawasaki Industry, Co. Ltd., Tokyo, Japan). The subjects were familiarized with the test procedure on several occasions prior to the measurements. They sat on a chair with their backs upright and with their left legs (non-dominant side) firmly attached to the lever of the dynamometer. A pivot point of the lever was accurately aligned with the rotation axis of the knee joint, and the requisite axial alignment of joint and dynamometer axes was maintained during the movement. Isokinetic strength was measured at preset angular velocities of 30, 90, and 180° $\cdot$ s<sup>-1</sup>. The range of angular movement of the knee joint was limited between 0 and 90° of anatomical knee angle. The value of peak torque was measured regardless of where it was developed within the range of movement. Three trials were made at each angular velocity, and the highest value obtained was used for further analyses. Isometric torque was measured at a knee angle of 80°.

Dynamic endurance for knee extension was assessed before and after the 8 week training period from recordings of 50 repeated concentric contractions (0.5 s contraction and 1.0 s rest) at an angular velocity of 180° $\cdot$ s<sup>-1</sup> on the isokinetic dynamometer (Thorstensson and Karlsson 1976). The mechanical work production was calculated by integrating force with respect to knee-joint excursion by using a computer (Macintosh 8100/100AV). The muscle endurance was estimated from the percentage decrease in both the amount of mechanical work and the average value of peak torque during the last ten contractions compared to those during the initial ten contractions.

### Magnetic resonance imaging

To obtain cross-sectional images of the thigh, magnetic resonance imaging (MRI) was performed by using a 0.5 T superconducting system (Gyrosan T5 II, Philips Medical Systems International, Best, The Netherlands) with a wraparound body coil. The coil covered the whole thigh, including markers attached to the skin. Twelve serial sections were acquired with a 6–10 mm sectional thickness and a 0.6–1.0 mm intersection gap. The field of view was 350 mm. Pulse sequences for spin-echo T1-weighted images were

**Table 1** Physical characteristics of subjects. Values are mean (SEM);  $n=6$  for low-intensity exercise combined with vascular occlusion (LIO),  $n=6$  for low-intensity exercise with no occlusion (LI),  $n=5$  for untrained control group

	LIO		LI		Untrained	
	Pre-training	Post-training	Pre-training	Post-training	Initial	Final
Age (years)	25.3 (0.8)		26.5 (0.7)		25.4 (0.8)	
Height (cm)	179.3 (1.8)	179.8 (1.6)	181.0 (3.8)	180.5 (3.7)	180.2 (3.8)	179.8 (3.7)
Body mass (kg)	88.9 (4.1)	89.1 (3.7)	92.4 (6.8)	91.5 (6.5)	91.5 (6.8)	92.8 (6.5)

performed with a repetition time of 500–552 ms and an echo time of 20–25 ms. Two signal acquisitions were used. The scan matrix and reconstruction matrix were 205×256 and 256×256, respectively. The image acquisition was started immediately after the subjects were placed in the supine position to minimize the effect of gravity-induced fluid shift. The time required for the whole sequence was about 4–6 min.

For each subject in the training group, the range of serial sections was deliberately determined on longitudinal images along the femur so as to obtain sections of identical portions before and after the period of exercise training. Among the photographs of the 12 cross-sectional images obtained, those of two portions near the midpoint of the thigh were chosen for the measurements of muscle cross-sectional area (CSA). Photographic negatives were digitized into an 8 bit grey scale at a space resolution of 144 pixels per inch, and stored in a computer using an Epson ART-8500G scanner. Determinations of tissue outlines and measurements of CSA for muscles and other tissues were made by using National Institute of Health Image (version 1.25) software. The measurements were repeated three times for each image and their mean values were used. Deviation in these three sets of measurement was less than 2%. Measurements were made only for the LIO group.

### Electromyogram

Electromyographic (EMG) signals were recorded from vastus lateralis muscle. Bipolar surface electrodes (5 mm in diameter) were placed over the belly of the muscle with a constant interelectrode distance of 30 mm. The EMG signals were amplified, fed into a full-wave rectifier through both low (time constant, 0.03 s) and high (1 kHz) cut filters, and stored in a Macintosh 8100/100AV computer. Integrated EMG with respect to time (iEMG) was used as an indicator of muscle-fibre recruitment during isometric torque exertion (Bigland-Ritchie 1981).

### Statistical analysis

All values are shown as mean (SEM). Because of the small  $n$  values, Wilcoxon signed ranks tests were used to compare differences between pre- and post-training values within the same subjects. To examine differences between groups, one-way analyses of variance (ANOVA) with the Scheffé  $F$ -test post-hoc procedure was used. For all statistical analyses, the 0.05 level of significance was used.

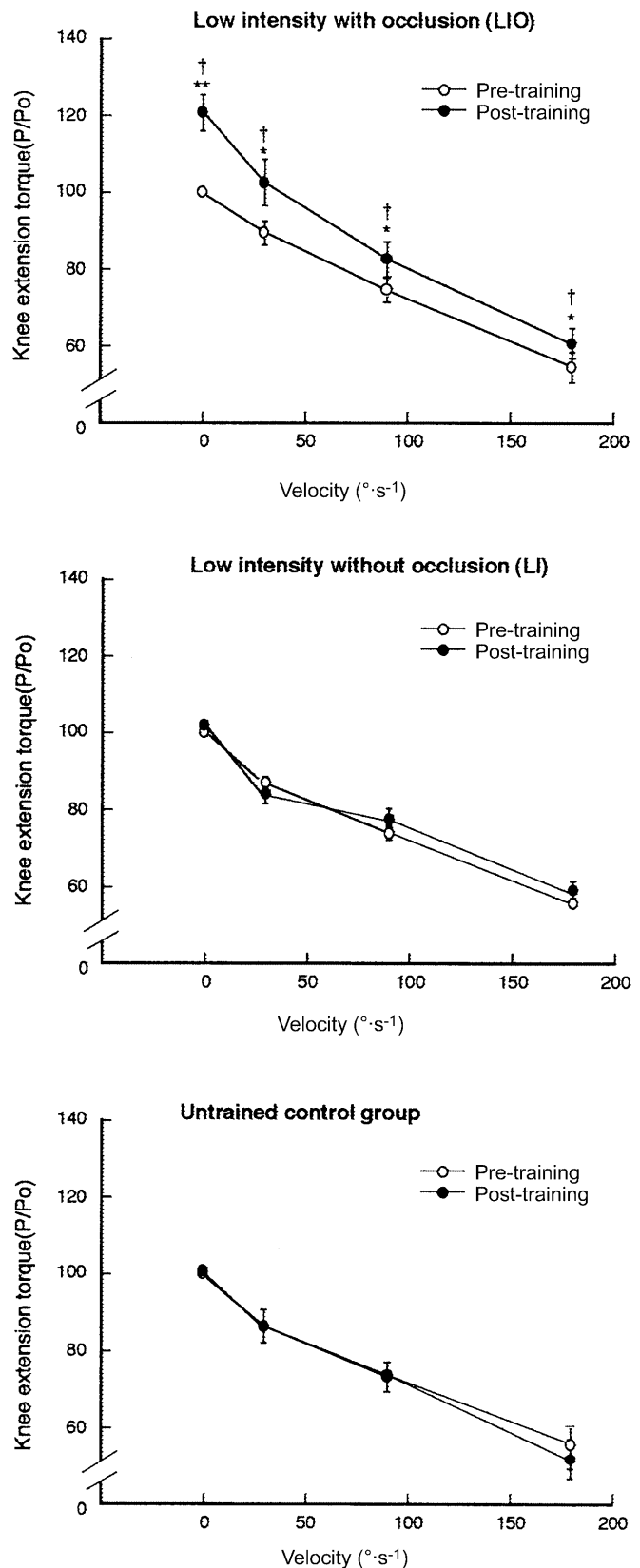
## Results

### Changes in muscle strength following exercise training

Changes in force-velocity relationships after the 8 week training period are shown in Fig. 1. All values of isokinetic torque were normalized to the pre-training values of isometric torque. The LIO showed significant

**Fig. 1** Effects of exercise training on force-velocity relationships. Isokinetic torque-angular velocity relationships of knee extensor muscles were obtained before (*unfilled circle*) and after (*filled circle*) exercise training. All values of knee extension torque ( $P$ ) were normalized to the pre-training values of isometric (velocity=0) torque ( $P_0$ ), and means and SEM were plotted. **A** Exercise at low intensity combined with vascular occlusion (LIO;  $n=6$ ). **B** Exercise at low-intensity with no vascular occlusion (LI;  $n=6$ ). **C** Untrained control group ( $n=5$ ). \*Statistically significant changes from pretraining values within the same subjects ( $P<0.01$ ). †Statistically significant differences between LIO, LI and control groups ( $P<0.05$ )

increases in isometric and isokinetic strengths at all the velocities examined (Fig. 1A), whereas no change in strength was observed in the LI group (Fig. 1B) and



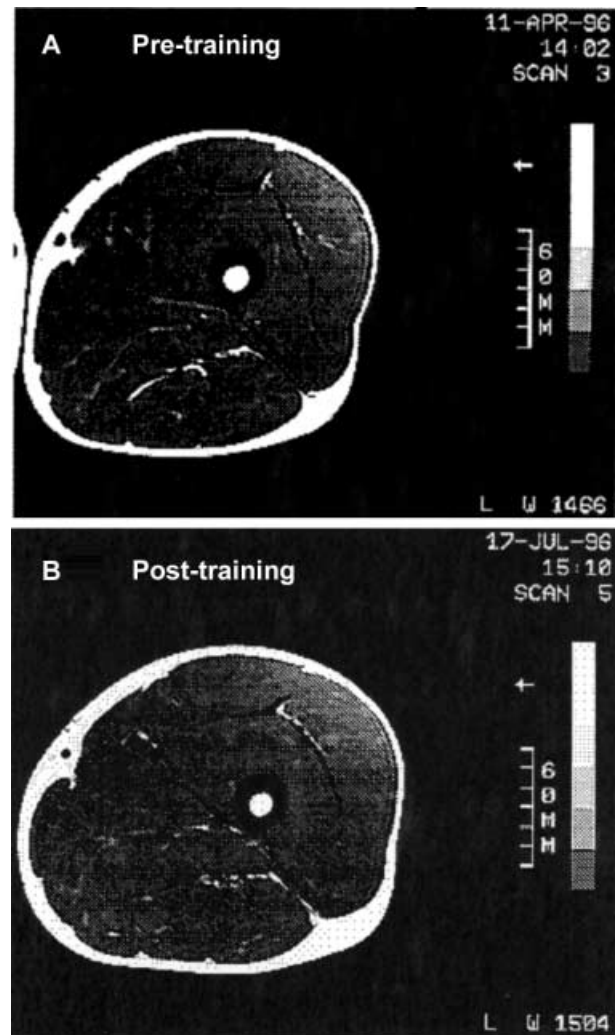
untrained control group (Fig. 1C). When averaged over all velocities, percentage increases in strength after the exercise training were 14.3 (2.0)%, and 3.2 (2.3)% in the LIO and LI groups, respectively. The percentage increases in isometric and isokinetic strengths after LIO were significantly ( $P < 0.05$ ) larger than those in the other two groups at all velocities examined. Also, there was no significant difference between LI and the untrained control group.

#### Changes in muscle CSA following exercise training with vascular occlusion

To see whether the increase in knee extension strength after LIO was mainly caused by muscle hypertrophy or neuromotor adaptation, MRI analysis was made only for the LIO group. Typical examples of the CSA, MRI of identical, mid portions of the thigh are shown in Fig. 2. These images were taken before (A) and after (B) the period of exercise training with vascular occlusion (8 weeks), and exhibit a marked increase (by approximately 15%) in the CSA of knee extensors after the period of training. To reduce errors in measurement associated with a slight mismatch between the sectional portions obtained before and after the period of exercise training and incidental deformations of muscles during the processes of MRI, 2 sections around the mid portion of the femur, each separated by about 20 mm, were selected from 12 serial sections, and mean tissue CSA was obtained from these 2 sections. The LIO showed significant ( $P = 0.002$ ) increases in the CSA of knee extensors compared to those before the exercise training (Fig. 3). The mean percentage increase in CSA of the extensors was 12.3 (0.8)%, whereas no significant changes were observed in those of the knee flexors and femur. The maximal isometric torque per unit CSA was not increased significantly after the training: pre-training 3.8 (0.2), post-training 4.0 (0.2)  $\text{N}\cdot\text{m}^{-1}$ . These results suggest that the increase in muscle strength after LIO (Fig. 1) is due primarily to the muscle hypertrophy.

#### Changes in muscle endurance following exercise training

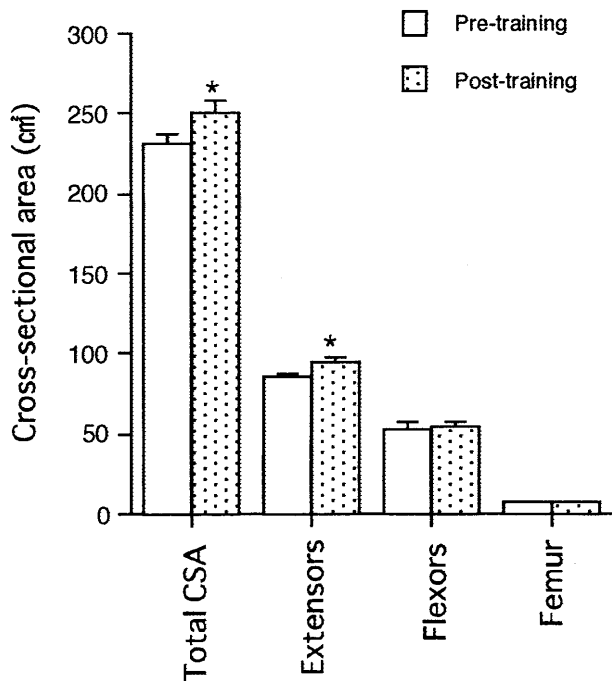
Dynamic endurance for knee extension was assessed before and after the period of exercise training by recording 50 repeated concentric contractions at an angular velocity of  $180^\circ\cdot\text{s}^{-1}$ . The fatigue indices were defined as the declines in the amounts of work and the average values of peak torque, comparing those in the initial 10 contractions and those in the last 10 contractions. Both indices in the LIO group decreased significantly from 63.7 (2.3) to 58.7 (2.3)% ( $P = 0.002$ ) and from 61.3 (2.1) to 53.7 (4.0)% ( $P = 0.002$ ), respectively (Fig. 4A). In contrast, no significant changes were observed in the LI group and untrained control group (Fig. 4B, C). The improvements in muscle endurance were evaluated as percentage reductions in the fatigue



**Fig. 2** Typical magnetic resonance images showing transverse sections of the mid-thigh, taken before (A) and after (B) the exercise training combined with vascular occlusion lasting for 8 weeks. The images show identical sections, mid-way along the femur in the same subject. Bar indicates 60 mm

indices. Those for both the amount of work and the peak torque were significantly ( $P < 0.05$ ) larger in LIO than in the other two groups, whereas no significant difference was observed between the LI and control groups. This indicates that the dynamic endurance of knee extensors was improved only by LIO.

On the other hand, iEMG for the initial and last 10 contractions showed no significant difference between pre- and post-training measurements in either the LIO or control groups (Fig. 5). In the LIO group, no significant difference was observed between the decline of iEMG from the initial 10 to the last 10 contractions in the pre-training measurements [36.2 (4.6)%] and that in the post-training measurement [28.0 (15.8)%]. Although the large deviations in both LIO and control groups may have hindered correct interpretations, these observations suggested that, in the LIO group, the improvement of dynamic endurance was primarily caused by metabolic



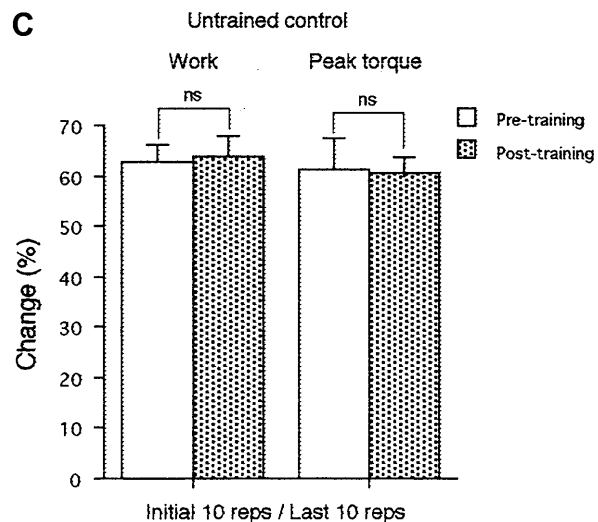
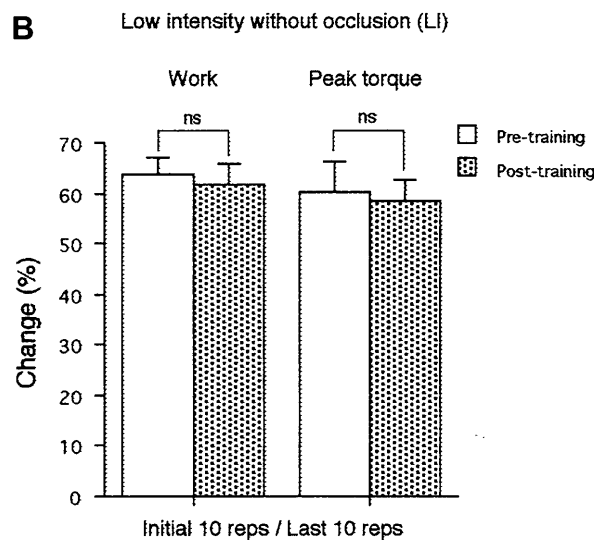
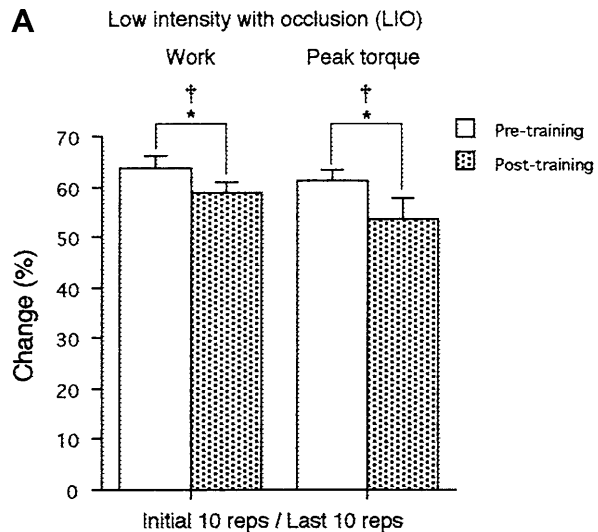
**Fig. 3** Cross-sectional areas (CSA) of knee extensor, flexor and femur measured before (unfilled bars) and after (dotted bars) exercise training combined with vascular occlusion. Values are shown as means and SEM ( $n=6$ ). \*Statistically significant changes within the same subjects ( $P < 0.01$ )

adaptations in the muscle fibres rather than an increased resistance to fatigue in the nervous system.

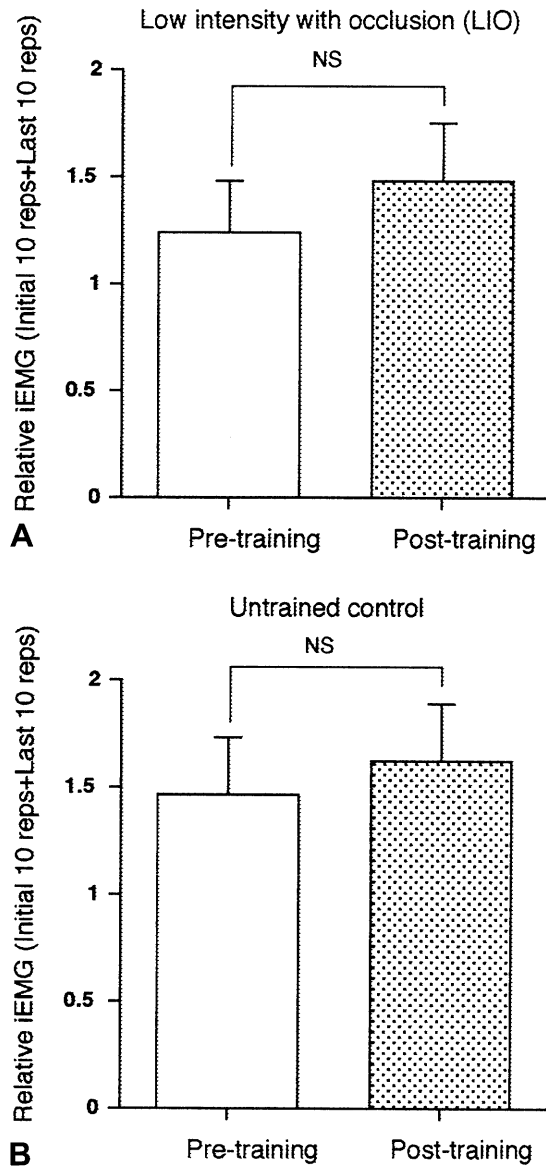
Discussion

The present study showed that low-intensity resistance exercise (approximately 50% 1RM) combined with vascular occlusion caused not only muscle hypertrophy and a concomitant increase in muscle strength, but also an improvement in muscle endurance. The major effect of LIO would have primarily been caused by the occlusion itself, as the LI made at the same intensity and amount showed no significant effect.

The subjects in the present study were highly trained athletes, in which conventional resistance exercise training would not readily cause increases in muscle size and strength (Hakkinen et al. 1987). However, the CSA



**Fig. 4** Percentage decreases in the amount of work and peak torque during 50 repeated contractions. Those during the last 10 contractions were compared with those during the initial 10 contractions. Pre-(unfilled bars) and post- (filled bars) training values are shown as means and SEM. **A** Exercise at low intensity combined with vascular occlusion (LIO;  $n=6$ ). **B** Exercise at low intensity with no occlusion (LI;  $n=6$ ). **C** Untrained control group ( $n=5$ ). \*Statistically significant differences between pre- and post-training values within the same subjects ( $P < 0.01$ ). †Statistically significant changes compared between LIO, LI and control groups ( $P < 0.05$ )



**Fig. 5** Integrated electromyograms (*iEMG*) during the initial 10 and the last 10 contractions during 50 repeated contractions, measured before (*unfilled bars*) and after (*filled bars*) the exercise training. All values of *iEMG* (means and SE) were normalized to pre-training values of *iEMG* in the first 10 contractions. **A** Low intensity exercise combined with vascular occlusion group, **B** untrained control group

of knee extensor muscles and isokinetic knee extension strength increased significantly ( $P < 0.01$ ) after training for a period of only 8 weeks (Fig. 1A, Fig. 3), suggesting that the restriction of blood flow during the exercise provided effectively a new, not previously experienced stimulus.

The externally applied compression restricted the blood circulation during the low-intensity exercise and the resulting hypoxic and acidic intramuscular environment would have induced additional motor-unit recruitment to maintain the given level of force, thereby evoking an increase in the electrical activity of the

muscle (Takarada et al. 2000a), as has also been shown in contractions made in ischaemic (Moritani et al. 1992; Sundberg 1994) and fatiguing conditions (Miller et al. 1996). Such an elevated activity of the muscle during exercise would have been one of the factors involved in the potent effect of the LIO in inducing muscle hypertrophy.

Another factor to consider is hormone action. Kraemer et al. (1990) have demonstrated that a sufficient amount of high-intensity exercise (approximately 6 sets at an intensity of about 80% 1RM for large muscle groups) carried out with an interset interval as short as 1 min transiently provokes more than a 100-fold increase in the plasma concentration of growth hormone (GH). Since such a dramatic increase in plasma GH concentration was not seen after exercise having a longer interset interval (3 min), it has been speculated that local accumulation of metabolites stimulates the hypophyseal secretion of GH. Our recent study with young male subjects also showed that low-intensity (20% 1RM) exercise with vascular occlusion of the lower extremities caused a 290-fold increase in the plasma concentration of GH, whereas no such effect was seen after the exercise without this occlusion (Takarada et al. 2000a). This stimulated secretion of GH may also play a part in the present effects of LIO.

One of the interesting findings in the present study was the increase in the dynamic endurance of knee extensors for 50 repeated concentric contractions (Fig. 4A), in spite of the increase in CSA of knee extensors by 12.3% (Fig. 3). This increase in muscle endurance would have been primarily caused by an adaptation of muscle, e.g. increases in oxidative energy metabolism and acid-buffering capacity, rather than an increase in the resistance to fatigue in the nervous system, because the exercise training did not cause any change in the *iEMG* pattern in either the initial or the last 10 of the 50 repeated contractions (Fig. 5).

High-intensity resistance training tends to cause in the muscle a decrease in the aerobic capacity instead of an increase in strength (Schantz 1982). Mitochondrial density within a muscle fibre in elite powerlifters has been shown to be lower than that in untrained subjects (Tesch et al. 1984). On the other hand, the number of capillaries per unit muscle CSA in body-builders has been shown to be similar to that in untrained subjects, with a substantial increase in the number of capillaries per muscle fibre (Schantz 1982; Tesch et al. 1984).

In the present study, low-intensity exercise training was performed in combination with external compression of the proximal portion of the thighs. Under such conditions, both the venous outflow from and arterial inflow to the exercising muscle would have been considerably suppressed during the exercise, causing both hypoxia and an accumulation of metabolites such as lactate. Both of these factors may have played parts in the angiogenesis within the muscle. Recent studies have shown that hypoxia is strongly related to the growth of

blood vessels at the developmental stage, although it is still unclear whether the same mechanism operates in adults (Risau 1997).

As mentioned previously, type II fibres may be recruited preferentially or additionally during the exercise when the blood flow is suppressed (Moritani et al. 1992; Sundberg 1994), so that more glycogen would be used as an energy source during LIO than during normal exercise at the same intensity and amount. The LIO may therefore have induced an increase in the storage of glycogen and an improvement of glycolytic capacity of type II fibres (MacDougall et al. 1979, 1982). In addition, a previous study using rats has reported that intermittent stimuli of muscles combined with a restriction of blood flow caused increases not only in muscle glycogen content but also in protein content (Elander et al. 1985). Therefore, the present LIO may have been effective in increasing the glycolytic capacity of type II fibres through increases in glycogen content and glycolytic enzyme activity.

In conclusion, low-intensity resistance exercise combined with vascular occlusion caused, in almost fully trained athletes, increases in muscle size, strength and endurance. Neural, hormonal and metabolic factors would have been involved in these combined effects.

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