Low-load resistance muscular training with moderate restriction of blood flow after anterior cruciate ligament reconstruction

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ABSTRACT – We performed a prospective study to determine the effects of introducing low-load muscular training with moderate restriction of blood flow during the first 16 weeks after reconstruction of the anterior cruciate ligament. 44 subjects (average age 29 (18–52) years) were randomized into a group that trained restriction of blood flow (group R, n = 22) and a group that trained without restriction (group N, n = 22). Both groups followed the same training schedule. Evaluations of knee extensor and flexor torques before surgery and 16 weeks after it showed a significant increase in muscular strength in group R as compared to group N. The preoperative/16-week postoperative ratio of the cross-sectional area of the knee extensor muscles showed a statistically significant enlargement in group R as compared to group N. 16 weeks after surgery, the short diameters of type 1 and type 2 fibers of M. vastus lateralis tended to be larger in group R (n = 8) than in group N (n = 8), although the differences were not significant. These findings show that low-load resistance muscular training during moderate restriction of blood flow is an effective exercise for early muscular training after reconstruction of the anterior cruciate ligament.

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Recently, many studies have reported stable postoperative results of ligament reconstruction by autologous tendon grafting of the anterior cruciate ligament (ACL), a procedure which permits early rehabilitation according activities of daily living and sports. However, an important issue is how early the patients can return to athletic activities. Currently, several techniques of ACL reconstruction have been proposed. In all these methods, no aggressive training of the lower limb muscles is performed up to the time when the reconstructed ligament has healed sufficiently to bear a load (Kramer et al. 1993, Muneta 1999, Yagi 1999). Therefore, atrophy of the muscles around the knee, especially the knee extensor muscle, accompanied by reduced muscular strength, is seen during the early postoperative period. Prevention of muscular atrophy and early recovery of muscular strength have been reported to be associated with an early return to athletic activities (Arvidsson et al. 1981, Grimby et al. 1980, Odensten et al. 1983, Murray et al. 1984, Kramer et al. 1993, Muratsu et al. 1996, Osteras et al. 1998). For this reason, research on rehabilitation after ACL reconstruction is very important.

An increase in the strength and size of normal muscles, a load of more than 50–60% of one repetition maximum, has been considered necessary. However, recent reports have indicated that if muscle training of the limb is done during moderate restriction of blood flow produced by an air tourniquet worn on the proximal portion of the limb, then even low-load resistance muscular training may induce the same increase and enlargement of the muscles as high-load muscular training (Takarada et al. 2000a, b).

We hypothesized that the strength and amount of muscle would improve by low-load resistance muscular training with moderate restriction of blood flow after reconstruction of the anterior cruciate ligament.

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Patients and methods

Patients

44 patients (25 males) with a mean age of 29 (18–52) years who underwent ACL reconstruction in our Department from September 1999 to September 2000 were recruited for this study and followed for at least 16 weeks postoperatively (Table 1). ACL reconstruction was done using an autograft of the semitendinosus muscle tendon that was folded into 5 parts. The patients were divided randomly into 2 groups according to whether the last digit of the ID number was an odd or even one. Rehabilitation was done in the usual manner in one group (group N, n = 22), and together with restriction of blood flow in the other (group R, n = 22). The patients participated in light sports activities, and vigorous recreation, according to the classification of Daniel et al. (1990).

The study was approved (Approval No. 45) by the Ethics Committee of our university, and was performed after informed consent was obtained from each patient.

Table 1. Background characteristics of subjects. Values are number or mean (SD)

	N group	R group
Male : female	12 : 10	13 : 9
Age	30 (9.7)	28 (9.7)
Right : left	11 : 11	8 : 14
Weight (kg)	63 (8.8)	65 (14)

Methods

The study took place during 16 weeks after surgery. Blood flow was restricted by the following methods. An air tourniquet was worn on the proximal part of the thigh on the operated side, and a pressure of about 180 mm Hg was applied to induce moderate restriction of blood flow. Each patient in group R borrowed a hand-pumped tourniquet so that he/she was able to practice training individually during restriction of blood flow after discharge from the hospital. The postoperative rehabilitation program was identical in the two groups over the first 16 weeks apart from restriction of blood flow, up to the time of athletic rehabilitation. The intensity of training was low and performed mainly by the closed kinetic chain exercise method.

Postoperative rehabilitation

During the first week, both group R and group N did exercises without restriction of blood flow. From week 2, group R started to exercise during restriction of blood flow.

Straight leg raising exercise and hip joint abduction exercise were maintained for 5 sec and repeated 20 times. These exercises were done in 2 sets daily, 6 times weekly during weeks 1–8 after surgery (day after surgery to week 1 after surgery, no load; weeks 2–4 after surgery, a 1-kg weight was attached to the foot joint; weeks 5–8 after surgery, a 2-kg load).

Hip joint adduction exercise by holding a ball between both knees and quadriceps setting exercise were maintained for 5 sec at maximum effort, repeated 20 times. These exercises were done in 2 sets daily, 6 times weekly during weeks 1–12 after surgery.

Half-squat exercise was done by maintaining half-squatting position for 6 sec, repeated 20 times. Step-up exercise was done by getting up and down a stool 25 cm in height, repeated 20 times. Half-squat exercise was done in 2 sets daily and step-up exercise was done in 3 sets daily, 6 times weekly during weeks 5–16 after surgery (weeks 5–6 after surgery, no load; weeks 7–8 after surgery, a 4- to 6-kg load was held with both hands; weeks 9–12 after surgery, an 8- to 10-kg load; weeks 13–16 after surgery, a 12- to 14-kg load).

Elastic tube exercise was done by bending the knee from 45 to 100 degrees, repeated 20 times. This exercise was done in 1 set daily, 6 times weekly during weeks 9–12 after surgery and in 2 sets daily, 6 times weekly during weeks 13–16 after surgery.

Knee-bending walking exercise was done by walking in a half-squatting position for 60 steps. This exercise was done in 3 sets daily, 6 times weekly during weeks 13–16 after surgery.

A muscular training notebook was given to each patient who recorded what had been achieved every day and the notebook was checked regularly (every 2–4 weeks) in the outpatient clinic.

Evaluation

To evaluate the effect of training, the following

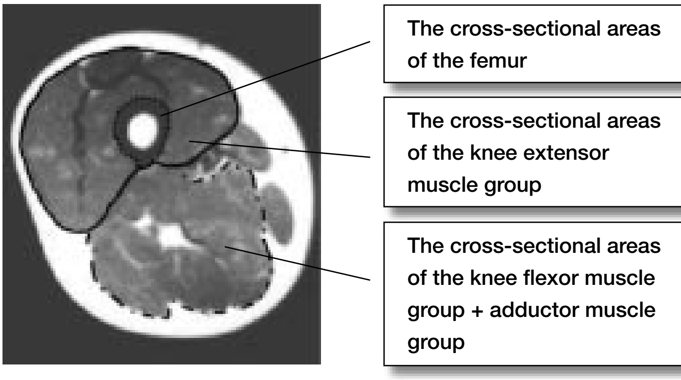

Figure 1. Measurement of cross-sectional area of knee. The cross-sectional area is expressed as a ratio to the cross-sectional area of the femur on the same image.

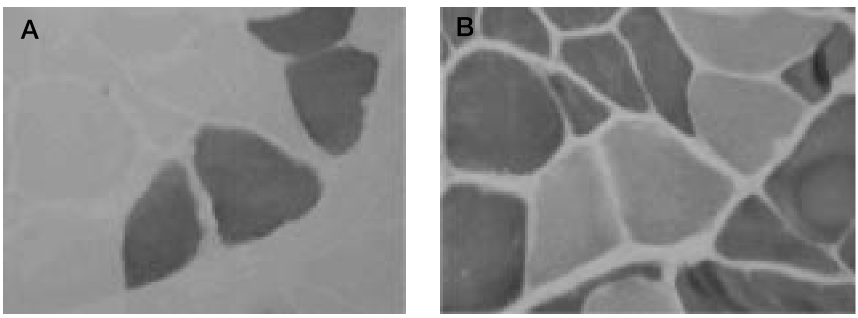

Figure 2. Myosin ATPase staining. A) pH 4.3; type 1 fiber is darkly stained. B) pH 10.6; type 2 fiber is darkly stained.

measurements were made before and 16 weeks after surgery.

Muscular torque of knee extensor and flexor muscles. Using an isokinetic myodynamometer, Biodex System 3 (Biodex Corp.), the concentric contraction strength during isokinetic contraction was measured at angular velocities of 60° (CC60) and 180° per sec (CC180). The isometric contraction strength at 60° knee flexion (IM 60) was also determined. The knee extensor muscle and flexor muscle were assessed separately.

Cross-sectional area of femoral muscle group. A MRI (Visart, Toshiba Corp. Japan) cross-sectional image (T1-weighted coronal images) in a position 15 cm proximal to the upper margin of the patella was used and the data were entered into the NIH Image 1.61 software (National Institutes of Health). The cross-sectional areas of the knee extensor muscle group and knee flexor muscle group + adductor muscle group were measured (Figure 1). The cross-sectional area was expressed as a ratio to the cross-sectional area of the femur on the same image.

Single muscle fiber diameter assessed by fiber type. Samples were collected from the M. vastus lateralis during surgery. 16 weeks after surgery, biopsies were again collected from the same muscle through a small skin incision under local anesthesia in the outpatient clinic.

Samples were frozen in isopentane under liquid nitrogen. 10 μm cryosections were cut with a cryostat at –20 °C. Myosin ATPase staining was done at pH 10.6 and pH 4.3 using adenosine triphosphate (Wako Pure Chemical Industries Ltd. A77) as substrate. Using a Kontron Imaging System KS-400 (Carl Zeiss, Germany), the short diameters of 120–150 single fibers were measured for type 1 and type 2 fibers individually, and averaged to obtain the single muscle fiber diameter for each type of fiber (Figure 2).

Data analysis

Comparison of patient characteristics between 2 groups before surgery was done with the chi-square test. Comparisons of knee extensor and flexor muscle strength, knee femoral muscle group

Table 2. Comparison of range of motion and joint instability between two groups, mean (SD)

	N group	R group
Range of motion (degree)		
Preoperative		
Extension limit	0.7 (2.4)	3.1 (5.8)
Flexion	146 (7.7)	144 (15)
Postoperative		
Extension limit	3.1 (3.6)	1.9 (3.7)
Flexion	143 (8.7)	140 (5.9)
Anterior instability (133N, mm)		
Preoperative KT2000	5.3 (1.6)	5.3 (2.3)
Postoperative KT2000	1.2 (1.2)	1.2 (1.2)

No significant differences were found.

Table 4. Preoperative cross-sectional areas (injured / healthy ratio) and ratios of cross-sectional area before and 16 weeks after surgery, mean percentages (SD)

	Before surgery injured / healthy ratio	Preop. / postop. ratio
Knee extensor muscle group		
N group	92 (11)	92 (12)
R group	91 (7)	101 (11) [a]
Knee flexor muscle + adductor muscle groups		
N group	97 (11)	102 (23)
R group	99 (3)	105 (19)

[a] p=0.04, preoperative / postoperative ratio, N group versus R group at the operated side

cross-sectional area, and single muscle fiber diameter by fiber type were analyzed with the Mann-Whitney U-test. A p-value less than 0.05 was regarded as significant.

Results

Patient characteristics

Age, sex distribution and body weight were similar in group N and group R (Table 1). There was also no difference in preoperative range of motion. The anterior instability of the knee joint was measured using a knee ligament arthrometer KT2000 (MED Metric Corp.) at 133N. No significant difference between the 2 groups was seen before surgery. The postoperative parameters were likewise not significantly different (Table 2).

Table 3. Comparison of preoperative and postoperative knee extensor muscle and flexor muscle strength (operated / healthy ratio) between two groups. Values are mean percentages (SD)

	Before surgery N group	Before surgery R group	16 weeks after surgery N group	16 weeks after surgery R group	p-value
Knee extensor muscle strength					
CC60	86 (14)	84 (13)	55 (17)	76 (16)	<0.001
CC180	90 (9)	84 (14)	65 (13)	77 (13)	0.004
IM60	94 (21)	92 (19)	63 (19)	84 (19)	<0.001
Knee flexor muscle strength					
CC60	90 (16)	96 (21)	72 (15)	81 (14)	0.05
CC180	99 (16)	96 (19)	74 (12)	84 (18)	0.04
IM60	94 (17)	91 (18)	62 (14)	72 (11)	0.02

Muscular torque of knee extensor and flexor muscles

Before surgery, the ratios of the injured side to the healthy side (injured/healthy ratio) of the knee extensor muscle, measured at CC60, CC180 and IM60, were about the same in the 2 groups. At 16 weeks after surgery, the corresponding ratios differed significantly between the 2 groups in all measurements (Table 3).

Before surgery, the injured/healthy ratios of the knee flexor muscle, measured at CC60, CC180 and IM60, were similar in the 2 groups. At 16 weeks after surgery, the corresponding ratios differed significantly between the 2 groups in all measurements (Table 3).

Cross-sectional area of femoral muscle groups

Before surgery, the injured/healthy ratios of the cross-sectional area of the knee extensor muscle groups were similar. At 16 weeks after surgery, the preoperative/postoperative ratios of the cross-sectional area of the knee extensor muscle group on the operated side differed significantly (Table 4).

Before surgery, the injured/healthy ratios of the cross-sectional area of the knee flexor muscle + adductor muscle groups were similar. At 16 weeks after surgery, the preoperative/postoperative ratios of the cross-sectional area of the knee flexor muscle + adductor muscle groups were similar (Table 4).

Single muscle fiber diameter assessed by fiber type

Measurements of preoperative and postoperative short diameters of single muscle fibers could be made in 8 cases in group N and 8 cases in group R. Before surgery, the mean fiber diameter was 64 μm (SD 4.7) in type 1 fibers and 61 μm (SD 5.9) in type 2 fibers. While a tendency to slightly more muscle atrophy was observed in type 2 fibers, the difference was not statistically significant. In group N, the preoperative/postoperative ratios of single fiber diameter were 95% (SD 11) in type 1 and 97% (SD 7) in type 2 fibers, with no significant difference. In group R, the ratios were 103% (SD 10) in type 1 and 102% (SD 8) in type 2 fibers, which was also not a significant difference. The single fiber diameters of both type 1 and 2 fibers tended to be larger in group R than in N, but the difference was not significant.

Discussion

In our subjects with injured ACL, reduced muscular strength and widespread muscular atrophy are known to occur in the knee extensor muscle (Tegner et al. 1984, 1986). Even after reconstruction, about 4–6 months are needed for the reconstructed ligament to mature and able to bear a load. During this convalescent period, elongation or rupture of the reconstructed ligament may occur, therefore a high-load rehabilitation program can not be used (Yasuda et al. 1985, Kurosaka et al. 1997, Muneta et al. 1999). Grimby et al. (1980) and Arvidsson et al. (1981) reported an association between prevention of postoperative loss of muscular strength of M. quadriceps femori and early rehabilitation for sports. Kramer et al. (1993) found that the state of the quadriceps muscle is proportional to the level of activity. Furthermore, Osteras et al. (1998) showed that recovery of the quadriceps promotes improvement in knee joint function after surgery. This evidence clearly indicates that recovery of muscular strength after surgery is most important for an improvement in knee joint function and rehabilitation for performance in athletics.

In recent years, Takarada et al. (2000a, b) reported that low-load resistance muscular training performed in a state of appropriate restriction of blood flow induced the same muscular augmentation and enlargement as high-load muscular training. In the present study, when we compared the postoperative knee extensor muscle torque in groups N and R, significant recovery of muscular strength was observed in group R 4 months after surgery in both isokinetic and isometric contraction strengths. The knee flexor muscle torque also showed significant recovery of muscular strength in group R regardless of the contraction mode. There were no differences between the two groups in age and body weight. The same training programs were used, and there were also no significant differences in the postoperative range of motion or joint stability. Therefore, the effect is due to restriction of blood flow done only in group R.

As regards the cross-sectional areas of the knee extensor muscle group, while a tendency to muscular atrophy was seen after surgery in group N, a trend to muscular enlargement occurred in group R despite the low-load training. On the other hand, the cross-sectional area of the knee flexor muscle + adductor muscle groups showed a milder degree of preoperative atrophy than the extensor muscle group in groups N and R, and an improvement in atrophy was seen after training in both groups. In the present analysis of muscular cross-sectional area, we were unable to assess the knee flexor muscle and adductor muscle groups separately. This is because the morphology of the hamstring muscle changed after the semitendinosus muscle tendon was removed for grafting, so the 2 muscle groups could not be distinguished clearly on MRI. We had no alternative, but to assess the 2 together. Nevertheless, this result supports previous ones of relatively good recovery of the knee flexor muscle after ACL reconstruction using an autologous semitendinosus muscle tendon (Lipscomb et al. 1982, Yasuda et al. 1995, Maeda et al. 1996).

For exercises done in a locally low oxygen state, the type 1 fibers that require large amounts of oxygen for contraction do not function adequately, while type 2 fibers are preferentially or selectively mobilized (Moritani et al. 1992). In that case, we many ask what effect does enlargement of muscle fibers have when training is done during restriction of blood flow? The changes in muscle fibers before and after ACL reconstruction have not been reported so far.

From our preoperative samples, a mild tendency to atrophy was observed in type 2 fibers although there was no significant difference. This would support the finding of Baugher et al (1984). If type 2 fibers were significantly recruited during training with restriction of blood flow, then one would expect type 2 fibers to be enlarged or less atrophied than type 1 fibers after 4 months of training. However, postoperative single fiber diameters showed that although muscular atrophy was suppressed regardless of fiber type in group R compared to group N, there was no difference in the change in single fiber diameter between type 1 and type 2 fibers.

Kraemer et al. (1990) reported an increase in the secretion of growth hormone after high-load training at 80% 1RM. Takarada et al. (2000c) also found an increase in plasma growth hormone to 290 times the normal level immediately after low-load training at 20% 1RM during restriction of blood flow. However, in considering an association of growth hormone with the present results, it is impossible to explain why the effect is seen only on the operated side with restriction of blood flow. On the other hand, Burda et al. (1995) reported that a short duration of ischemia activated the mechanism of protein synthesis. However, the current view is that although several mechanisms of muscular augmentation by local restriction of blood flow have been proposed, as mentioned above, no details are available as to the exact mechanisms. In this study, we had planned to investigate the morphological changes in each muscle fiber type in order to determine the mechanism of muscular augmentation by training during blood restriction. However, we obtained consent for muscle biopsy from only 8 subjects in each group, and a small sample size can not be used as the basis for statistically reliable results. This issue will be examined in future studies.

Muscular training under a pressure of 180 mm Hg exerted by a tourniquet was accompanied by slight discomfort and dull pain in the lower extremities during training. In practice, the training could be done almost without any problems for the first 10 minutes after blood flow restriction was started, but some patients felt discomfort or a dull pain in the lower limb during blood flow restriction after about 12 minutes, although there were individual differences. We instructed the patients to relieve the blood flow restriction after a maximum of 15 minutes, stop for 15–20 minutes and then resume the training. In the present study, 24 patients were initially enrolled in the R group, but 2 patients dropped out because of discomfort or a dull pain in the lower limb. However, apart from such symptoms in the lower extremities, we found no other complications caused by muscular training during blood flow restriction.

Our study suggests that training during moderate restriction of blood flow is effective in rehabilitation after ACL reconstruction. Our findings show the possibilities of this mode of training not only in rehabilitation after ACL reconstruction, but also in training of atrophied muscles in general. However, various problems remained unsolved, such as discomfort or pain during training due to the tourniquet, and the possible effects on the circulation including thrombosis and edema. Further attention to the safety of this training is required.

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No competing interests declared.

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