

Assisted Reproduction of the Anterior Cruciate Ligament

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ABSTRACT: This article describes a technique for anterior cruciate ligament (ACL) repair using a synthetic braided ligament made of 75% degradable polyglycolic acid filaments and 25% nondegradable, 6.5-mm Dacron thread, wrapped in a free synovial graft. In a prospective study of 70 consecutive patients, this technique (experimental group) was compared to a standard bone-patellar tendon-bone autograft technique (autograft group). All of the patients improved after surgery. There were no surgical complications, and all of the patients returned to full activity without pain or instability. After mean follow-up of 12 years (range, 8-19 years), patients in the experimental group functioned well and statistically better than patients in the autograft group using International Knee Documentation Committee, Knee Injury Osteoarthritis Outcome Score, and Lysholm evaluation measurement tools. These results suggest a partially biodegradable replacement ligament prosthesis protected by a synovial wrap can result in a functionally stable knee.

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INTRODUCTION

It is generally believed that a complete tear of the anterior cruciate ligament (ACL) will not heal, even if repaired. Poor healing may result, in part, from the damage to the blood supply of the ligament.³⁰ Poor healing also may result from the effect of synovial fluid on the damaged tissue. Although the ACL is intracapsular, it is normally protected from synovial fluid because it lies outside

the synovial sleeve. The intact synovium protects the ACL from high molecular weight molecules such as hyaluronic acid that inhibit migration and proliferation of fibroblasts, while allowing passage of smaller molecular weight components that are necessary for a healthy ligament. However, tearing the ligament usually disrupts the synovial sleeve, exposing the ACL directly to the washing effect of the fluid, which inhibits clot formation and initial healing. Compared to cells from the medial collateral ligament, cells cultured from the ACL have a reduced potential for proliferation *in vitro*.^{2,20}

Conventional treatment of an unstable knee with an ACL tear is rehabilitation, along with activity modification and bracing, or reconstruction using an autograft or allograft. The disadvantages of tendon graft reconstruction of the ACL include a potential for donor-site complications such as patellar fracture, anterior knee pain, hamstring weakness, or rupture of the remaining tendon(s). Risks associated with allograft techniques include reduced healing potential, rejection, and disease transmission.^{1,8,10,11}

This study sought to determine whether a satisfactory patient outcome could be achieved with the use of allograft or autograft techniques. A surgical technique using a partially biodegradable ligament prosthesis protected by a free synovial graft was developed in an attempt to create an environment in which a torn ACL could regain function or possibly even heal in a way comparable to a torn collateral ligament. This article describes treatment of the ruptured ACL using this technique to achieve a stable knee and compares the results of this treatment to a bone-patellar tendon-bone autograft.

MATERIALS AND METHODS

Study Population

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TABLE 1

PREOPERATIVE DEMOGRAPHICS AND INJURY HISTORY

Variable	Experimental Group	Autograft Group
No. patients	35	35
Mean (range) age (y)	26 (19-43)	25 (18-42)
Mean (range) follow-up (y)	12 (8-19)	11 (7-18)
Male/female ratio	23/12	24/11
IKDC sports category		
I (highly competitive)	17 (49%)	16 (46%)
II (frequent sporting)	7 (20%)	8 (23%)
III (sometimes sporting)	7 (20%)	7 (20%)
IV (nonsporting)	4 (11%)	4 (11%)
Trauma contact/noncontact		
Sport	12/18	11/18
Traffic	3/0	4/0
Work	2/1	2/1
Mean (range) time from injury to surgery (months)	14 (2-72)	11 (4-61)

Abbreviations: IKDC, International Knee Documentation Committee.

[Query #2: In the rows related to "Trauma contact/noncontact," the numbers in the second and third columns do not sum 35. Please explain in a footnote or correct within the table text.]

Seventy patients with an isolated unilateral ACL tear were enrolled prospectively in this study. All of the patients had been treated with extensive rehabilitation before they were offered surgery. Surgeries were performed between 1985 and 1998. Patients were eligible for the procedure if they had a symptomatic ACL tear confirmed by both physical examination and magnetic resonance imaging (MRI).¹³ Inclusion criteria were age between 18 and 45 years, no prior knee surgery, and no significant degenerative changes on arthroscopy or MRI. Exclusion criteria included osteochondral defects >3 mm, additional ligament injuries to the knee, open growth plates, and meniscal tears requiring repair or resection of more than one fourth of a meniscus. Eligible patients were offered the option of undergoing ACL repair using the experimental technique (experimental group) or reconstruction using a bone-patellar tendon-bone autograft (autograft group). The study received institutional review board approval, and all patients provided informed written consent.

A KT-1000 arthrometer (MedMetric, San Diego, Calif) was used to examine the knees and assess side-to-side differences with the knee in 30° of flexion. A physical therapist performed the testing at 30 lb (134 N) and maximum manual stress.⁷ The study population should allow

determination of a 1-mm difference with 80% statistical power if a deviation of 1.5 mm is observed, as expected from previous studies.⁷ Patient demographics, history of trauma, and preoperative sports participation were comparable between the 2 groups (Table 1).

Peak extension torque was measured using a Cybex isokinetic testing device (Cybex, Ronkonkoma, NY) at 60° and 180° per second. Side-to-side ratio at peak torque was presumed to represent thigh strength. In addition, prior to ACL reconstruction, articular and meniscal damage was assessed arthroscopically.

Surgical Technique

In the experimental group, a braided synthetic ligament of 75% degradable polyglycolic acid (PGA) filaments and 25% nondegradable Dacron threads measuring 6.35 mm was used as a scaffold to help fibrous regrowth of the damaged ACL. The multiple strands of the braid were congealed at the ends of the device by heat sealing to prevent unraveling. The synthetic ligament was made by Surgitex (Southfield, Mich) and came in a sterile package.

The ACL remnant was preserved (Figure 1) and kept in continuity with the ligament prosthesis and synovial wrap to serve as a source of healing fibroblasts. As many remaining remnant ACL fibers as possible were preserved. Sometimes only a small number of fibers were present, but in other instances, the ACL was largely intact with detachment at its femoral origin.

The prosthetic ligament was passed through bony tunnels drilled in the femur and tibia (Figure 2), and the ligament was fixed with screws used as posts or staples. The tunnels were made using guides on both the tibia and femur. For the tibia, the guide pin was directed into the anterior and medial part of the tibial ACL footprint. The remnants of the ACL were not removed. A cannulated drip was passed over the guide pin to prepare a 6.35-mm tunnel. The margins of the tibial tunnel were chamfered. A guide was used to locate the position for the femoral tunnel on the posterior aspect of the femoral condyle just anterior to the over-the-top position, with the desired position located at the posterior part of the insertion of the ACL on the femur.

A full-thickness synovial graft was harvested from the suprapatellar area using a 7.5-cm to 8-cm mini-open medial arthrotomy without dislocating the patellofemoral joint. The graft was peeled from the underlying capsule by blunt dissection. The intra-articular side of the graft was placed outward (away from the ligament prosthesis) and sutured around the prosthesis with absorbable suture. The prosthesis-graft composite was advanced into the tunnels and fixed in position under the correct tension.

In the autograft group, the central or medial one third



Figure 1. AP view of a knee showing a complete tear of the anterior cruciate ligament. The torn fibers are preserved during the reconstruction.

of the patellar tendon was harvested with bone plugs from the tibial tubercle and patella. Using guides, tunnels were drilled in the tibia and femur, and the graft was advanced and fixed in place with screws.

Postoperative Protocol

The preoperative and postoperative rehabilitation was identical for both groups and remained the same throughout the study period. Immediate motion was encouraged following surgery. Bracing was not used, and patients were allowed weight bearing as tolerated. Patients performed isometric quadriceps and closed kinetic chain exercises for 3 months. Bicycling was allowed at 2 weeks, and running was allowed at 12 weeks. Patients were allowed to return to sports-specific training at 4 months. Competitive athletics was allowed at 8 months.

All patients were evaluated before surgery and at their final follow-up visit by an independent and blinded observer (K.M.). No patients were lost to follow-up, and minimum follow-up was 7 years (Table 1). Patients completed standardized questionnaires, and standing radiographs were obtained. Outcomes were assessed using the

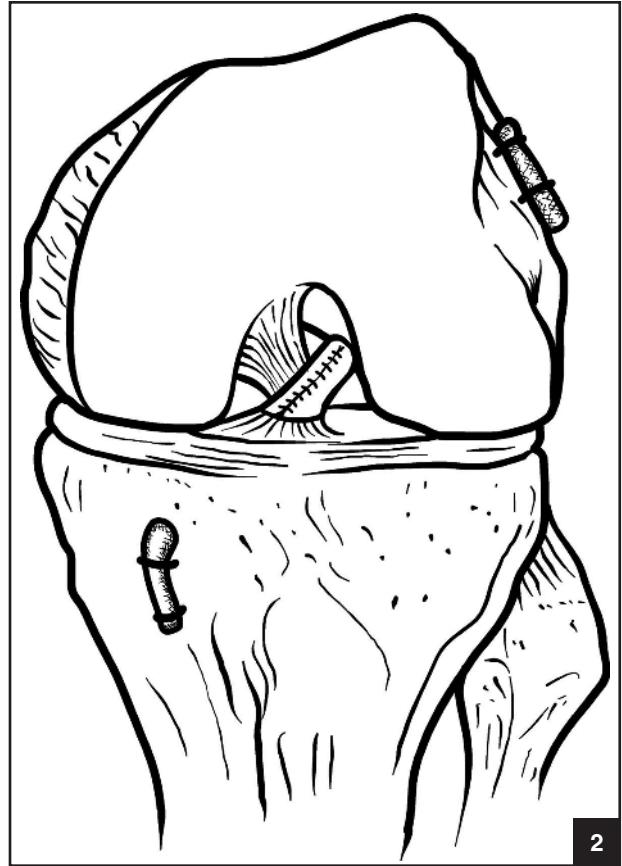


Figure 2. AP view of a knee showing the ligament prosthesis in position. The synovial wrap covers the intra-articular portion, and the remnant anterior cruciate ligament serves as a source of fibroblasts.

International Knee Documentation Committee (IKDC) subjective knee form¹⁶ and the Knee Injury and Osteoarthritis Outcome Score (KOOS).²⁵ The questionnaire-based modified Lysholm scale was included to allow comparison to other studies on ACL instability.²⁸ The IKDC 2000 examination form also was used to record an objective result.

Statistical Analysis

Statistical analyses were performed using Stat Win II software (Stat-Soft, Tulsa, Okla). Nonparametric Wilcoxon, chi-square, and Fisher tests were used to make comparisons. An alpha level of .05 was considered significant.

RESULTS

All patients demonstrated a significant improvement in their knee scores after surgery ($P = .002$) (Table 2). Preoperatively, IKDC evaluation scores¹⁶ were severely abnormal in 34 patients in the experimental group and 33

TABLE 2

MEAN PREOPERATIVE AND POSTOPERATIVE SCORES FOR OUTCOME QUESTIONNAIRES

Questionnaire	Experimental Group		Autograft Group	
	Preoperative	Postoperative	Preoperative	Postoperative
KOOS	46±7	90±5 ^a	48±6	86±5
IKDC subjective knee score	59±5	84±6 ^a	60±5	79±5
Lysholm score	34±7	88±9	36±6	86±7

Abbreviations: IKDC, International Knee Documentation Committee; KOOS, Knee Injury and Osteoarthritis Outcome Score.

^a Statistically significant compared to autograft group ($P \leq .05$).**TABLE 3**

PREOPERATIVE AND POSTOPERATIVE KT-1000 ARTHROMETER MAXIMUM SIDE-TO-SIDE DIFFERENCES

KT-1000 Difference	Experimental Group		Autograft Group	
	Preoperative	Postoperative	Preoperative	Postoperative
0-2 mm	0	25 (71%) ^a	0	19 (54%)
3-5 mm	3 (9%)	8 (23%) ^a	5 (14%)	13 (37%)
>6 mm	32 (91%)	2 (6%)	30 (86%)	3 (9%)

[Query #3: Please note the percentages in the Autograft Postoperative column were changed.]

^a Statistically significant compared to autograft group ($P \leq .05$).

patients in the autograft group. Postoperatively, results in the experimental group were significantly better than in the autograft group. Mean IKDC subjective knee score improved by 19 to 25 points (Table 2). All patients had full range of motion within 2 months after surgery, and all patients returned to activity within 8 months after surgery.

Modified Lysholm score showed 21 (60%) knees with an excellent result, 12 (34%) with a good result, 1 (3%) with a fair result, and 1 (3%) with a poor result in the experimental group. There were 20 (57%) excellent, 13 (37%) good, 1 (3%) fair, and 1 poor (3%) result in the autograft group. The KOOS evaluation with subgroups of pain, symptoms, activities of daily living, function in sports, and recreation improved by a mean of 31, 34, 29, 66, and 61 points, respectively, in the experimental group, and 28, 31, 26, 65, and 59 points, respectively, in the autograft group. Overall KOOS scores were statistically better in the experimental group compared with the autograft group.

The KT-1000 maximum side-to-side differences showed the experimental group to be significantly more stable than the autograft group (Table 3). Both groups were more stable postoperatively, and 84% of experimental patients and 71% of autograft patients had a negative pivot shift postoperatively.

Preoperatively, side-to-side ratios of peak torque at 60° and 180° per second were similar in the 2 groups. Cor-

responding quadriceps strength at 2 years postoperatively recovered to 85%±15% at 60° per second and 87%±11% at 180° per second in the experimental group. In the autograft group, postoperative measurements at 2 years were 84%±15% at 60° per second and 86%±17% at 180° per second. These differences between the 2 groups were not significant.

For patients in the experimental group, IKDC score at their last examination was normal or nearly normal in 51%, abnormal in 34%, and severely abnormal in 14%. For patients in the autograft group, IKDC score at their last examination was normal or nearly normal in 43%, abnormal in 40%, and severely abnormal in 17% (Table 4).

No surgical complications occurred in either group. There were no infections or recurrent effusions in the experimental group, and only 1 patient in the autograft group had recurrent effusions. There was no suggestion of synovitis from the grafts used in the experimental group. There were 2 failures in the experimental group and 3 failures in the autograft group from reinjury. One patient in each group was treated with repeat surgery, with an allograft used in each instance. Two patients in the experimental group and 3 patients in the autograft group were treated later for meniscus tears.

Standing radiographs of both knees were obtained for all patients. Degenerative changes were present in 8 knees reconstructed with an autograft and 7 knees reconstructed with a PGA-Dacron graft. These degenerative changes

TABLE 4

KNEE EXAMINATION USING THE IKDC ASSESSMENT TOOL

IKDC Classification	Experimental Group		Autograft Group	
	Preoperative	Postoperative	Preoperative	Postoperative
A (normal)	0	4	0	3
B (nearly normal)	0	14	0	12
C (abnormal)	1	12	2	14
D (severely abnormal)	34	5	33	6

Abbreviations: IKDC, International Knee Documentation Committee.

consisted of joint space narrowing of at least 3 mm from preoperative films and degenerative osteophyte formation. There were no cysts or radiographically lucent pockets around the tibial or femoral bone tunnels.

DISCUSSION

The main finding of this study is that satisfactory stability and functional results after covering an ACL ligament prosthesis with a synovial graft are possible. The results were statistically better than those for autograft, and complications were infrequent. The results have continued to remain satisfactory for several years.

The major limitation of this study was the small number of patients treated. In addition, although the study was prospective, it was not randomized, which creates the potential for selection bias. During the time patients underwent surgery, clear information was not available for the surgeon to make an evidence-based decision on graft choice. Therefore, the potential for selection bias was mitigated by uncertainty about the indications for each graft choice. In addition, accepting the patient's preference for a particular graft type added less potential for surgeon-selection bias.

Another limitation was that the quality of the reconstruction was unknown, as no ligaments were removed for histologic studies. Nonetheless, patients functioned well for a long interval, and both the subjective and objective scores of patients treated in this study compared favorably to those in other published works. Therefore, these findings seem to indicate that it is possible to achieve a functional ACL after reconstruction. In addition, the incidence of degenerative changes noted on radiographs in this study was the same as or lower than that reported in other studies.^{8,9,24}

Outcome measures have gained importance and have become increasingly dependent on patient satisfaction.⁸⁻¹⁰ The KOOS, IKDC, and modified Lysholm scales have been validated as useful measures and were used in this study to assess outcome.^{15-17,25,28}

The technique described in this series was semi-open and demanding to perform. The synovial graft must be carefully harvested, sutured, and positioned. The procedure for positioning the graft and prosthetic ligament was similar to that used with other methods. It appears that a limited open procedure does not delay recovery nor compromise outcome after ACL reconstruction.^{6,23} It is possible that performing an arthrotomy increases capsular fibrosis enough to result in additional stability.

Numerous synthetic materials have been used to reconstruct the ACL with varying degrees of short-term success but mostly disappointing long-term results.^{3-5,14,18,26,27} In short, prosthetic reconstruction of the ACL to date has been unsuccessful. Synthetic ligaments can be divided into 3 types: true prostheses such as polytetrafluoroethylene (Gore-Tex) or Dacron,^{14,16} scaffolds that provide a latticework for collagen ingrowth such as the Leed's-Keio device (**manufacturer name?, city?, state?**) [Query #4: **Please provide the manufacturer information.**],²⁷ and augmentation devices such as the Kennedy ligament augmentation device (**manufacturer name?, city?, state?**) [Query #5: **Please provide the manufacturer information.**].¹⁸ It initially was hoped these augmentation devices would protect autogenous tissue during healing; however, none of these prosthetic devices have worked well or remain in common use.

For ligament and tendon repairs and reconstruction, PGA has been useful as a scaffold, a carrier of cells and extracellular matrix, and as a means to deliver growth factors to stimulate the repair process.^{3,5,24} The ACL cells with the best ability to form matrix are at the bony rather than fibrous attachment zone.²⁰

A PGA-Dacron device was shown to have excellent strength and handling properties for tendon and ligament repairs in rabbits and dogs.^{5,29} Although a completely biodegradable intra-articular ligament made of PGA was well-tolerated in dogs, the PGA was completely reabsorbed by 5 weeks, which is too short a time to produce a satisfactory ACL. At 8 weeks, the fibrous tissue that had grown into the Dacron scaffold was insufficient and not in

a load-bearing orientation. Of note, in these studies, the ligament stent was not protected from synovial fluid.⁵

In another study, the ACL was excised in both knees in 3 dogs. The ligament was replaced with a composite prosthesis of Dacron and PGA. The ligament was wrapped with a free synovial graft in 1 knee and left uncovered in the opposite knee. When the animals were sacrificed a year later, on gross examination, the synovial-wrapped prosthetic ligaments had a 2-fold increase in the size of fibrous tissue compared with the corresponding ligaments on the unwrapped side. Microscopic sections demonstrated abundant collagen ingrowth along the supporting Dacron scaffold.²⁹ It is possible that the synovial graft provides cells for the synthesis of fibrous tissue and that this, as well as the protective effect of the synovial sheath, assists in producing a functionally stable ACL.

Spontaneous healing of the ACL can occur but is uncommon, probably limited to very proximal or distal injuries in a child or young adult.¹⁹ In most cases, significant disability and late degenerative changes occur in the ACL-deficient knee.^{8-10,21,22} Graft techniques all have some potential for donor-site morbidity and are not a full substitute for healing of the ACL. Although ACL reconstruction may not decrease the chance of developing posttraumatic osteoarthritis, reconstruction may be helpful in reducing the chance of a meniscus tear.^{8-10,21} However, ACL reconstructions usually are performed to improve symptoms of instability.

Cell-based therapies, growth factors, and gene therapy may be possible future techniques used to induce ligament or tendon healing. Until then, the findings of this study indicate functional improvement with possible healing of the ACL may occur with the use of a partially biodegradable ligament replacement that is protected with a free synovial graft. The technique is meticulous, but the results are satisfactory without the need for autograft or allograft ligaments.

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