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Triple-bundle ACL grafts evaluated by second-look arthroscopy

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Abstract
Purpose The purpose of this study was to evaluate the morphology of transplanted triple-bundle anterior cruciate ligament (ACL) grafts by second-look arthroscopy.
Methods The subjects were 41 patients with a mean age of 25.5 ± 8.5 years who underwent second-look arthroscopy at between 6 and 22 months after the anatomical triple-bundle ACL reconstruction using semitendinosus tendon autograft. Lachman test was negative in 38 knees and mildly positive with a firm endpoint in 3 knees. Arthroscopic evaluation of grafts was performed for the anteromedial graft (AM), the intermediate graft (IM), and the posterolateral graft (PL), focusing on tension and graft damage.
Results All grafts showed "fan-out" shape approaching the tibial attachment, which looked closer to the natural ACL compared to the double-bundle grafts. As to graft tension, 93% of AM, 90% of IM, and 88% of PL grafts were evaluated as taut, respectively. As to graft damage, there was no apparent rupture in the AM and IM grafts, while complete or substantial rupture was observed in 10% of PL grafts around the femoral tunnel aperture. The incidence of graft rupture in PL grafts was significantly greater than those in the AM and IM grafts. As to synovial coverage, 76% of AM, 78% of IM, and 59% of PL grafts were evaluated as "Good," while 41% of PL grafts were not fully covered with synovium. All of the synovial defects were observed around the femoral tunnel aperture.
Conclusion The morphology of the triple-bundle grafts resembled that of the natural ACL, while complete or substantial rupture was observed in 10% of the PL grafts.
Level of evidence Study of case series with no comparison group, Level IV.

Keywords Triple-bundle ACL reconstruction · Semitendinosus tendon autograft · Second-look arthroscopy · Graft morphology

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Introduction

Anterior cruciate ligament (ACL) reconstruction using hamstring tendon has become popular because of less donor site morbidity [4, 6, 14]. In addition, recent improvement in operative technique has made it possible to perform anatomical double-bundle ACL reconstruction, superior in biomechanical performances [13, 26] to the traditional Rosenberg's 1 or 2 femoral sockets ("bi-socket") procedure. This could have resulted in more

favorable clinical results [15] while the results remain controversial [19, 20].

According to the previous reports on the functional anatomy of the ACL, it could be divided into three bundles: the anteromedial (AM), the intermediate (IM), and the posterolateral (PL) [1, 17]. Additionally, it is well known that the natural ACL forms a crescent-shaped footprint on the femur and a triangular one on the tibia. Furthermore, in the double-bundle ACL reconstruction, the authors have found no graft implanted into the anterolateral portion of the tibial footprint (Fig. 1a). To closely mimic this normal structure and restore normal knee function, we have developed the triple-bundle ACL reconstruction [23]. As previously described, we have divided the "anteromedial graft" in the anatomical double-bundle ACL reconstruction into further two bundles (the AM and the IM grafts) to form a triangular shape in the tibial attachment (Fig. 1b) [23]. The aim of this study was to evaluate the morphology of the transplanted triple-bundle grafts by second-look arthroscopy.

Materials and methods

Between 2004 and 2006, the anatomical triple-bundle ACL reconstruction using semitendinosus tendon autograft was performed on 172 knees. Of those, second-look arthroscopy was performed on 42 knees in 42 patients who gave their informed consent. It has been our policy to recommend patients to undergo second-look arthroscopy as well as hardware removal. As the clinical record of one patient was incomplete, the other 41 patients were included in this study. Patients included 16 men and 25 women, with a mean age of 25.5 ± 8.5 years. The mean duration of follow-up was 11.4 ± 3.9 months. At the time of second-look arthroscopy, none of the patients complained of subjective instability. Lachman test was negative in 38 knees and mildly positive with a firm endpoint in 3 knees. Positive pivot shift test of +1 was found in one patient. The mean side-to-side difference with the KT-1000 arthrometer at maximum manual force was 0.7 ± 1.2 mm (Fig. 2).

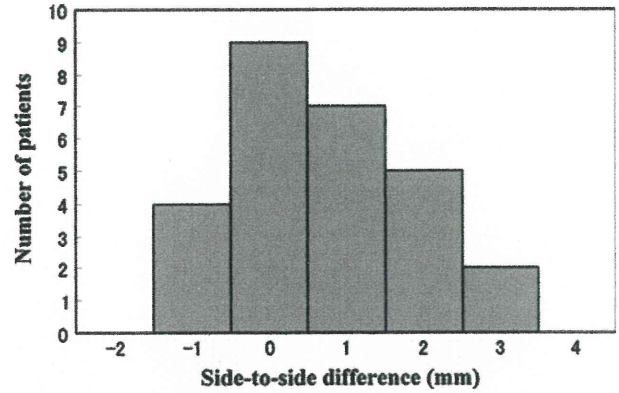

Fig. 2 The distribution of side-to-side differences in anterior laxity measured with the KT-1000 in 27 patients and the average value was 0.7 ± 1.2 mm

Surgical procedure

The procedure of triple-bundle ACL reconstruction was previously described in 2005 [23]. Briefly, two 2.4-mm guide pins were inserted to the points between the Resident's ridge and the posterior margin of the notch at 2, 3 o'clock for the left or at 9, 10 o'clock for the right knee using the anterolateral entry femoral aimer (Smith & Nephew Endoscopy, MA). For the tibia, three parallel guide pins were inserted using the offset parallel pin guide (Smith & Nephew Endoscopy, MA). Then, each wire was overdrilled with a drill bit of appropriate diameter (5–6 mm in diameter) (Fig. 3). After introducing the anteromedial and posterolateral grafts into each femoral tunnel, both the grafts were fixed with Endo-button CLs (Smith and Nephew Endoscopy, MA). For the tibial fixation, two double-spike plates (DSP; MEIRA Corp., Nagoya, JAPAN; US Patent No. 6117,139,21) and the tensioning boot were used as described [22, 23]. After the posterolateral graft and the two anterior graft sutures (the AM and IM) were tied to the DSPs, the tensioning sutures, which were applied to the bottom of the DSPs, were connected to the tensioners. The tensioners were mounted on the tensioning boot, which was affixed to the

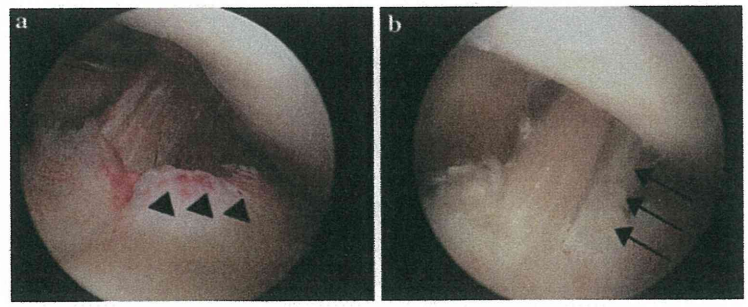

Fig. 1 Arthroscopic appearance of transplanted grafts in the left knee at the primary reconstruction. **a** Double-bundle reconstruction. Note the graft defect in the anterolateral portion of the tibial footprint (*arrowheads*). **b** Triple-bundle reconstruction. The intermediate graft occupies the anterolateral space (*arrows*)

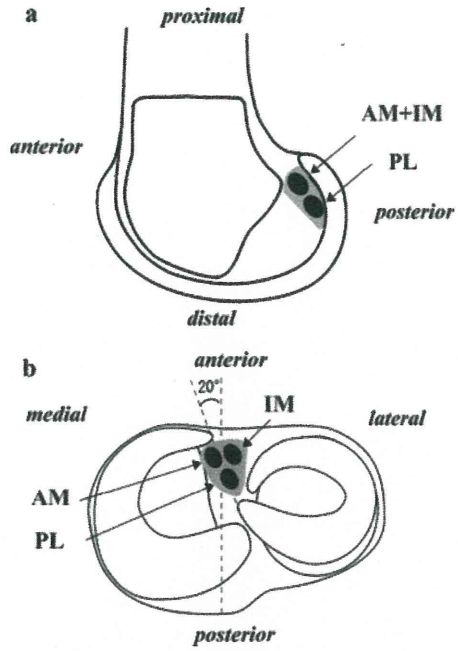

Fig. 3 Tunnel locations in the original ACL footprints (**a** femoral; **b** tibial): *AM* anteromedial, *IM* intermediate, *PL* posterolateral tunnel

tibia with a bandage. The 0.5 MPa of stress (approximately 10–15 N for each graft) was applied as the initial tension, and the knee was moved through a passive flexion and extension movement several times. After retighten tensioning suture by repetitive manual pulling to remove stress relaxation, each graft was fixed at 15–20° of knee flexion with DSPs and cancellous screws.

Postoperative rehabilitation

Postoperatively, the knee was immobilized with a brace for a week. Partial weight bearing was allowed at 3 weeks, followed by full weight bearing at 5 weeks. Jogging was allowed at 3 months and running was permitted at 4 months, followed by return to previous sports activity at 6–9 months.

Arthroscopic evaluation of the transplanted grafts

Arthroscopic evaluation of the grafts was performed by meticulous probing as described, focusing on tension and graft damage [10, 18, 25]. Tension of the graft was classified as taut or lax by probing at 20–90° of knee flexion. The grafts as tense as normal ACL throughout the range of motion were evaluated as taut, while those with grafts looser than the normal were evaluated as lax (Fig. 4). Graft damage was evaluated in each bundle and classified according to whether there was a substantial tear (Fig. 5). In addition, synovial coverage of the grafts was classified into the following 3 categories: "good," when the whole length of the graft was covered with the synovium; "fair," when more than 50% of the entire surface of the graft was

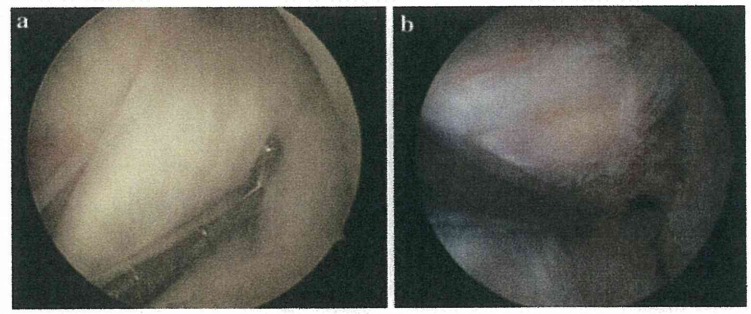

Fig. 4 Arthroscopic classification of transplanted grafts based on graft tension. **a** Taut AM, IM, and PL grafts. **b** Lax AM, IM, and PL grafts

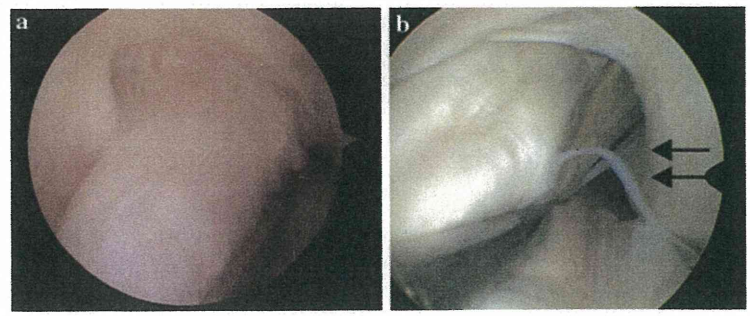

Fig. 5 Arthroscopic classification of transplanted grafts based on graft damage. **a** No rupture in all the grafts. **b** Complete rupture in the PL graft (*arrows*)

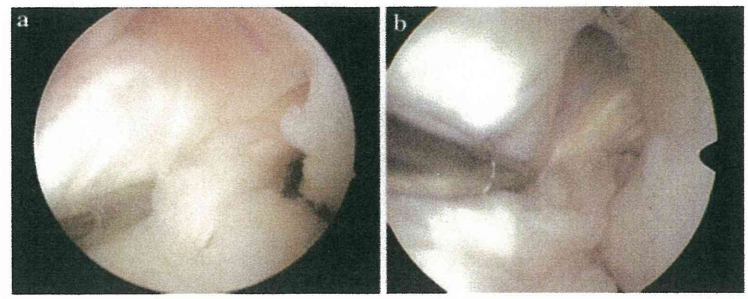

Fig. 6 Arthroscopic classification of transplanted grafts based on synovial coverage over the grafts. **a** "Good" synovial coverage in the AM and "Fair" in the IM. **b** "Poor" synovial coverage in the PL around the femoral tunnel aperture

covered with synovium; and "poor," when less than 50% of the graft showed synovial coverage (Fig. 6).

Correlation between morphological defects and clinical results

We examined whether these morphological defects in the PL grafts, including graft damage and incomplete synovial coverage, have an effect on clinical results at 2 years postoperatively.

Statistical analysis

The chi-square test and the Mann–Whitney U test were used for statistical analysis; a difference of $P < 0.05$ was considered significant.

Results

Graft morphology

All of the grafts showed more broad or "fan-out" shape approaching the tibial attachment (Fig. 7a). As to graft tension, 93% of the AM, 90% of the IM, and 88% of PL grafts were evaluated as taut, respectively. Significant differences in graft tension were not found among the three bundles (Table 1).

In terms of graft damage, there was no apparent rupture in the AM and IM grafts, while complete or substantial rupture was observed in 10% of the PL grafts around the femoral tunnel aperture (Fig. 5b). There was a significant difference in the incidence of graft damage among the three bundles ($P < 0.05$) (Table 1).

As to synovial coverage in the AM, thirty one grafts (76%) were evaluated as "Good," while five other grafts (12%) were evaluated as "Fair" and five (12%) as "Poor". In the IM grafts, 32 grafts (78%) were evaluated as "Good," five (12%) as "Fair," and four (10%) as "Poor". As to the PL, twenty-four grafts (59%) were evaluated as "Good," ten (24%) as "Fair," and seven (17%) as "Poor," respectively (Table 1). As a result, 41% of the PL grafts were not fully covered with synovium, while significant differences in the condition of synovial coverage were not found among the three bundles. In these cases, all of the synovial defects were observed around the femoral tunnel aperture, showing poor graft-tunnel integration (Fig. 6b).

Correlation between morphology of the PL graft and clinical results

After the arthroscopic evaluation, 22 of the patients could be followed up for 2 years after the reconstruction post-operatively and directly examined the correlation between

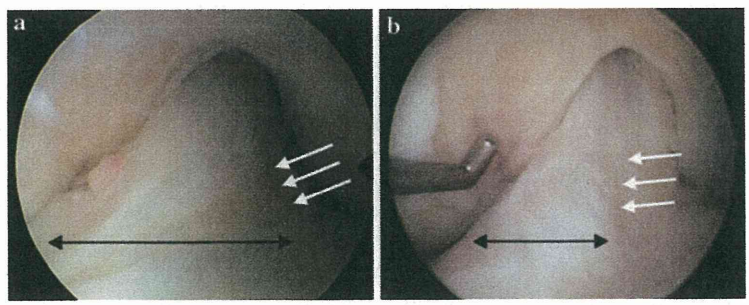

Fig. 7 Arthroscopic views of the multi-bundle ACL grafts. **a** A triple-bundle graft. Note the "fan-out" morphology approaching to the tibial attachment (*double-headed arrows*). **b** A double-bundle graft. Its anterior portion around the tibial attachment looks narrower (*double-headed arrows*). The *white arrows* show boundary between the anterior portion and the posterolateral of the graft

Table 1 Arthroscopic morphology of each graft

	Tension		Graft damage		Synovial coverage		
	Taut	Lax	−	+	Good	Fair	Poor
AM graft	38	3	41	0	31	5	5
	(93%)	(7%)	(100%)	(0%)	(76%)	(12%)	(12%)
IM graft	37	4	41	0	32	5	4
	(90%)	(10%)	(100%)	(0%)	(78%)	(12%)	(10%)
PL graft	36	5	37	4	24	10	7
	(88%)	(12%)	(90%)	(10%)	(59%)	(24%)	(17%)
P value	NS		0.016		NS		

morphology of the PL graft and clinical results among them.

According to IKDC subjective evaluation, 14 patients (64%) were graded as "normal" and the other eight patients (36%) as "nearly normal". There was no obvious deterioration throughout the follow-up period in the grade of Lachman test and pivot shift test in all of them. While three had showed apparent damage in the PL at the second-look arthroscopy, it did not make significant differences in the results of a subjective evaluation, Lachman test, pivot shift test, or KT measurement (Table 2). In terms of the synovial coverage of the PL, although those with incomplete synovial coverage at second-look arthroscopy revealed less favorable results in the subjective evaluation than those with complete coverage, no significant difference was found (Table 3). Similarly, the incomplete synovial coverage has not yet led to inferior results in Lachman and pivot shift tests at least 2 years postoperatively (Table 3).

Table 2 Correlation between graft damage of the PL graft and clinical results

	PL graft damage		*P* value
	− ($n = 19$)	+ ($n = 3$)	
IKDC subjective evaluation			NS
A (normal)	12	2	
B (nearly normal)	7	1	
C (abnormal)	0	0	
D (severely abnormal)	0	0	
Lachman test			NS
Normal	18	3	
1+	1	0	
2+	0	0	
Pivot shift test			NS
Negative	18	3	
Gliding	1	0	
Positive	0	0	
KT side-to-side difference (mm)	1.0 ± 1.3	0.0 ± 0.0	NS

Table 3 Correlation between synovial coverage of the PL graft and clinical results

	Synovial coverage		*P* value
	Good ($n = 13$)	Fair/poor ($n = 9$)	
IKDC subjective evaluation			NS
A (normal)	9	5	
B (nearly normal)	4	4	
C (abnormal)	0	0	
D (severely abnormal)	0	0	
Lachman test			NS
Normal	12	9	
1+	1	0	
2+	0	0	
Pivot shift test			NS
Negative	12	9	
Gliding	1	0	
Positive	0	0	
KT side-to-side difference (mm)	1.0 ± 1.5	0.7 ± 1.0	NS

Discussion

The most important finding of the present study was that the morphology of the triple-bundle grafts resembled that of the natural ACL. The natural ACL is composed of multiple fascicles, the basic unit of which is collagen. Each fascicle is composed of 3–20 subfasciculi that consist of groups of subfascicular unit [24]. It has been also described to be a complex anatomical structure where straight collagen bundles are formed by a complex network of interlacing fibrils [3]. To reproduce or mimic this multi-fascicular complex structure, current ACL reconstruction procedures are performed using multiple-bundle grafts.

Some authors have increasingly reported on an anatomical double-bundle ACL reconstruction, for it has several advantages to restore normal knee functions and to achieve successful results [13, 26]. Biomechanical study by Yagi et al. [26] revealed the importance of the anatomical reconstruction of both the anteromedial and the posterolateral bundle. Mae et al. [13] reported the study focusing on the laxity match pretension in which comparison was made in it between the anatomical double-bundle technique and the isometric bi-socket procedure and concluded that the former might restore the anterior stability more effectively than the latter.

In addition, it has been reported that the natural ACL consists of multiple bundles that share tensile force during knee motion [1, 2, 17]. Amis and Dawkins divided the ACL into three functional bundles (AM, IM, and PL bundles) and showed force distribution among these bundles [1]. The IM bundle shared approximately 30% of the

total force at 0° and 90°. On the other hand, Norwood and Cross reported their different functions in tibial rotation [17]. The IM bundle contributed to straight anterior and anteromedial stability. These results indicate the IM is a discrete functional bundle and the triple-bundle ACL reconstruction should be one of the reasonable approaches to restore the normal knee function.

Residual anterior instability measured with the KT-1000 of 0.7 ± 1.2 mm in the triple-bundle reconstruction was almost equal to that of 0.8 ± 1.0 mm in the double-bundle ACL reconstruction [18]. As mentioned above, however, the IM bundle could be assumed to have distinct biomechanical roles different from those of the AM or the PL. Further biomechanical study or development in clinical analysis of the ACL reconstruction will clarify advantages of the triple-bundle reconstruction over the double-bundle procedure.

As gross appearance of the anatomical triple-bundle ACL graft at the second-look arthroscopy resembled that of the native one, this technique could reproduce the ACL morphologically. Although a comparison study was lacking, the anterolateral portion of the tibial attachment was appeared to filled with the more robust structure in the triple-bundle reconstruction compared with the morphology of the double-bundle graft (Fig. 7a, b). In terms of graft damages, Toritsuka et al. [25] have reported on the results of second-look arthroscopy of Rosenberg's ACL reconstruction that 34% of the grafts showed partial tear in their anterior portion, suggesting graft impingement against the intercondylar notch or the PCL. On the contrary, the anatomically placed grafts in the double-bundle reconstruction showed no damage in the anterior portion [18]. Theoretically, the IM graft in the triple-bundle technique has greater risk of impingement against the medial aspect of the lateral femoral condyle than the AM graft in the double-bundle procedure because of its alignment. In our cases, however, this type of graft damage was not seen. This suggests that the anatomically placed grafts could avoid the risk of the impingement, even if the notchplasty was not combined.

On the other hand, there were substantial damages in 10% of the PL grafts as seen in cases of the anatomical double-bundle ACL reconstruction [18]. In addition, poor synovial coverage was observed in 41% of the PL grafts around the femoral tunnel aperture. These poor results in the PL grafts might be due to greater length change of the graft during extension–flexion movement. Iwahashi et al. have compared differences in the length change among three bundles of the natural ACL using MRI-based three-dimensional virtual models. Therefore, length change of the PL graft in the current triple-bundle procedure could be assumed the largest among these three bundles [9]. Furthermore, shorter PL graft results in the shorter distance between the femoral and tibial fixations for the PL graft. These might lead to increase in force change to the graft during flexion–extension movement, to more pronounced "bungee cord" effect, and to poorer graft-to-bone tunnel healing around the femoral tunnel aperture [7, 12, 21]. Improvement in graft fixation to shorten the distance between femoral and tibial fixations might reduce this unfavorable effect to achieve better graft-tunnel healing. Another potential factor to affect the healing process could be the rehabilitation program at an early phase after surgery. In our study, patients wore a knee brace for 1 week, and further study will be required to examine whether postoperative bracing for more than 1 week has a positive effect on the healing. Although these poor results in second-look arthroscopy have not yet resulted in clinical failures at 2 years postoperatively, the cases with better synovial coverage on second-look arthroscopy have been reported to present better clinical results [11] and this attenuated area may be subject to further graft rupture in the future and to symptomatic instability.

One limitation of this study could be lacking in the other evaluation modalities such as MRI or relatively short duration of follow-up. While arthroscopic evaluation can address the grafts' surface only, MRI is the other useful way to evaluate the core portion of the grafts [16]. In addition, longitudinal assessment of the grafts can be carried out using MRI [5, 8].

The other limitations of the study included the short-term follow-up and the time delay between the arthroscopic evaluation of the graft and the clinical findings, as there was one patient who underwent the graft examination at 4.4 months. This suggests that the arthroscopic observation was performed on the grafts on the way to maturation. However, this study did bring us some information of the morphological defects in the PL grafts on clinical results at 2 years. Further follow-up with additional imaging analysis may more clearly elucidate the correlation between the current arthroscopic findings and the clinical results.

Conclusion

The morphology of the triple-bundle grafts resembled that of the natural ACL, while complete or substantial rupture was observed in 10% of the PL grafts.

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SYMPOSIUM: COMPLEX KNEE LIGAMENT SURGERY

Single- versus Double-bundle ACL Reconstruction: Is There Any Difference in Stability and Function at 3-year Followup?

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Abstract

Background Despite a number of studies comparing postoperative stability and function after anatomic double-bundle and single-bundle anterior cruciate ligament reconstruction (ACLR), it remains unclear whether double-bundle reconstruction improves stability or function.

Questions/purposes We therefore asked whether patients having single- and double-bundle ACLR using semitendinosus (ST) alone differed with regard to (1) postoperative stability; (2) ROM; and (3) five functional scores.

Methods We prospectively followed 60 patients with an isolated anterior cruciate ligament (ACL) injury. Thirty patients underwent single-bundle and 30 patients underwent double-bundle ACL reconstruction. Clinically we assessed stability and range of motion (ROM); anteroposterior stability was assessed by Rolimeter and rotational stability by a pivot shift test. Function was assessed by IKDC, Noyes, Lysholm, Marx, and Tegner activity scales. The minimum followup was 36 months (mean, 46.2 months; range, 36–60 months).

Results Residual anteroposterior laxity at 3 years postoperatively was similar in both groups: 1.4 ± 0.3 mm versus 1.4 ± 0.2 mm, respectively. We observed no difference in the pivot shift test. ROM was similar in both groups, although double-bundle patients required more physical therapy sessions to gain full ROM. IKDC, Noyes, Lysholm, Marx, and Tegner scores were similar at final followup.

Conclusion Double-bundle reconstruction of the ACL did not improve function or stability compared with single-bundle reconstruction.

Level of Evidence Level II, therapeutic study. See Guidelines for Authors for a complete description of levels of evidence.

Introduction

Disruption of the ACL is among the most frequent musculoskeletal injuries affecting physically active men and women. According to an ongoing study in the United States, an estimated 200,000 ACL reconstructions (ACLR) are performed annually, and the incidence of ACL injury is roughly one in 3000 per year [32]. Anatomic studies have demonstrated the anterior cruciate ligament consists of two functional bundles: the anteromedial (AM) and the posterolateral (PL) bundle whose nomenclature is related to their insertion in the tibial plateau [2, 11, 36]. In cadaveric studies, the AM bundle tightens during knee flexion, whereas the PL bundle slackens; in contrast, the PL bundle tightens during knee extension, whereas the AM bundle slackens [2, 27, 36].

Some authors consider single-bundle ACLR the standard option to treat ACL lesions [5, 7, 17, 42]. However, recent

Each author certifies that he or she has no commercial associations (eg, consultancies, stock ownership, equity interest, patent/licensing arrangements, etc) that might pose a conflict of interest in connection with the submitted article.
Each author certifies that his or her institution approved the human protocol for this investigation, that all investigations were conducted in conformity with ethical principles of research, and that informed consent for participation in the study was obtained.

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studies suggesting the need for better rotational control have stimulated interest in a more anatomic reconstruction with double-bundle [6, 9, 21, 26, 38, 41, 49, 51]. Several studies suggest the anatomic double-bundle ACLR should improve pivot shift resistance and increase rotational knee control [8, 38, 46, 47, 49, 51] and should help preserve menisci and limit progression toward arthritis [8, 38, 46, 47, 49, 51]. A number of studies, however, reported no difference in terms of anteroposterior laxity, rotational stability, and/or any other clinical aspects at final followup between the two techniques [1, 4, 20, 23, 24, 30, 34, 43].

A recent systematic review [47] suggested that in most published studies on double-bundle ACLR have inadequate descriptions of the specific operative technique data. The authors found a low percentage of Level 1 and 2 studies (2.7% and 14.9%, respectively), whereas most of studies classified as Level 3 (23%) and Level 5 (mainly consisted of technical notes and expert opinions [60%]). Foremost among the concerns associated with this particularly complex procedure is the expertise required to perform the double-bundle technique properly; therefore, some theoretical advantages could be negated by the complexity of this procedure and steep learning curve. One recent study demonstrated a higher number of patients with tibial and femoral bone tunnel enlargement and double-tunnel communication in patients treated with the double-bundle technique [40]. Performing an anatomic double-bundle reconstruction entails the use of both the semitendinosus (ST) and the gracilis autografts, requiring the use of independent femoral and tibial fixations. Further, hamstring strength deficits in deep flexion and internal rotation resulting from the use of both tendons could represent a possible complication documented in various studies [12, 14, 31]. Therefore, we have used ST in this study to reduce the risk of this complication and none of the published studies compare single-bundle versus double-bundle techniques with the use only of ST. Furthermore, despite one review [47], it remains unclear whether there is any difference in stability or function after double-bundle or single-bundle reconstructions.

We therefore asked whether patients having single- and double-bundle ACLR using ST alone differed with regard to (1) postoperative stability; (2) ROM; and (3) five functional scores.

Patients and Methods

We prospectively followed 60 athletes who underwent ACLR from February 2004 until January 2007. During that same time, we treated 138 patients with either single- or double-bundle ACLR; from these patients, only 60 met the inclusion-exclusion criteria as mentioned. The patients were randomly assigned to two treatment groups: ST single-bundle (SB group; n = 30) and ST double-bundle (DB group; n = 30) ACLR group. The 60 patients were blinded to the specific type of reconstruction they would undergo. Each patient was allocated to the one treatment or the other depending on the order of arrival; researchers did not have the total sample of patients from the beginning and did not know in advance the specific characteristics of each patient.

The inclusion criteria for the study were: (1) primary ACLR with no associated Grade III ligament injury, PL rotatory instability, or fracture around knee, no previous knee ligament surgery (except diagnostic arthroscopy or partial meniscectomy), no arthritic changes or Grade III–IV chondral damage, no subtotal or total meniscectomy, no malalignment, and a normal contralateral knee; (2) ACL injury reported within 5 months; (3) consent for participation in this study; (4) willingness to followup at 3, 6, 12, 24, and 36 months or when asked for; and (5) compliance to a specific rehabilitation program. Patients were excluded from the study when the examination under anesthesia or intraoperative findings did not meet the previously mentioned inclusion criteria. Patients with a partially torn ACL were also excluded from the study.

In the SB group, the mean age of patients at surgery was 31.9 ± 1.9 years; 50% of patients were males and 50% females. In the DB group, the mean age of our patients at surgery was 28.9 ± 1.9 years; 60% of patients were males and 40% females (Table 1). We determined confidence intervals to compare the demographic factors (Table 2).

The injuries were all sports-related. Pivoting, while playing a sport (eg, skiing, soccer, karate), was the main mechanism of injury (82%), whereas a fall during sports participation (eg, motocross) accounted for only 18%. In our series, injuries while playing soccer made up 38%, skiing 33%, motocross 16%, tennis 10%, and karate 3%. All of the patients clinically presented with an ACL-deficient knee with a positive Lachman test [45] and pivot shift [22], both of which were confirmed with a complete ACL rupture on MRI. Associated knee injuries included first- and second-degree medial collateral ligament sprain in 11%, meniscal lesions in 30%, Grade I or II chondropathy in 7%, and a combined meniscal and chondropathy lesion in 15%. Concomitant injuries for both groups and confidence intervals are reported in Table 3. Pearson

Table 1. Patients' demographic data

Variable	Group SB	Group DB
Age	31.9 ± 1.92	28.9 ± 1.89
Gender	15 male/15 female	18 male/12 female
Side involved	18 left/12 right	12 left/18 right
Psychovitality	11 ± 0.45	12.10 ± 0.68

Table 2. Confidence intervals for mean ages

Group	Number of patients	Mean age	SD	SE	95% Confidence interval for mean	
					Lower bound	Upper bound
Group SB	30	31–87	7–427	1–356	29–09	34–64
Group DB	30	28–93	7–306	1–334	26–21	31–66
Total	60	30–4	7–452	0–962	28–47	32–33

Table 3. Concomitant injuries and confidence intervals

Concomitant injuries		Group SB	Group DB	Total
1°–2° MCL sprain	Count	3	4	7
	Percent within group	15–80%	21–10%	18,40%
Meniscal lesions	Count	10	8	18
	Percent within group	52–60%	42–10%	47,40%
1°–2° chondropathy	Count	2	2	4
	Percent within group	10–50%	10–50%	10,50%
Meniscal lesion + chondropathy	Count	4	5	9
	Percent within group	21–10%	26–30%	23,70%
Total	Count	19	19	38
	Percent within group	100–00%	100–00%	100–00%

MCL = medial collateral ligament.

chi-square test was performed and showed that the two groups were homogeneous regarding concomitant injuries ($p > 0.0476$). The minimum followup was 36 months (mean, 46.2 months; range, 36–60 months). No patients were lost to followup.

The sample size of each group was determined beforehand by using statistical power analysis. Anteroposterior laxity (ΔLaxity), which was evaluated at 3 years postoperatively, was defined as the primary parameter. To detect a difference of 1.7 mm with a SD of 2.2 mm, 25 patients were required per group (power = 0.8 and $p < 0.05$). Therefore, we included 30 patients per group [50].

After the administration of either a spinal or general anesthesia, the patient was positioned supine on the operating table. A tourniquet was placed at the proximal aspect of the thigh with sufficient distance from the expected exit point of the Kirschner wire suture passer in the thigh's lateral aspect. A lateral post for thigh support and a foot bar were then placed to enable the knee to be positioned at 90° flexion on the table during surgery. This setup also allowed intraoperative testing of full ROM. The preparation of the graft was similar irrespective of the surgeon performing a single- or double-bundle technique. Once standard prepping and draping were completed, the tourniquet was inflated to 300 mmHg only for graft harvesting and then deflated. A 3-cm vertical incision was then made centered approximately 5 cm below the medial joint line midway between the tibial tubercle (Gerdy's tubercle) and the posteromedial aspect of the tibia. The sartorial fascia was incised and the ST tendon was dissected. The tendon was completely detached from its proximal attachment with an open tendon stripper. On its tibial end, the tendon's length was maximized preserving as much length as possible by detaching the ST close to the bone. Ideally, a length of 28 cm or greater was desired. While the surgeon prepared the tunnels, the surgical assistant at the back table proceeded with the preparation of the graft. Once the graft was cleaned and devoid of excess tissues, measurement of the tendon followed. The minimum length needed was 28 cm to allow the possibility of cutting the graft in half with sufficient length to fold each half of the graft to a length of 7 cm. In such way, we had a 2-cm graft length for the femoral and tibial tunnels and 3 cm intra-articularly. The ends of the grafts were then whipstitched using Orthocord™ sutures (Orthocord; DePuy, Mitek, Raynham, MA) (Fig. 1A–B).

For the SB technique, using standard anterolateral and anteromedial portals, the knee was visualized and prepared for tunnel placements. The anatomic footprints of the native ACL on both the femoral and tibial sides were identified and not removed. We used remnants of torn ACL on femoral and tibial sides as landmarks for positioning of tunnels. Notchplasty was never performed in any patient in either group. We used the center of the ACL footprint on femoral and tibial sides as a landmark for placing tunnels for SB ACL reconstruction. The femoral tunnel position was first identified and drilled using a Kirschner wire in an

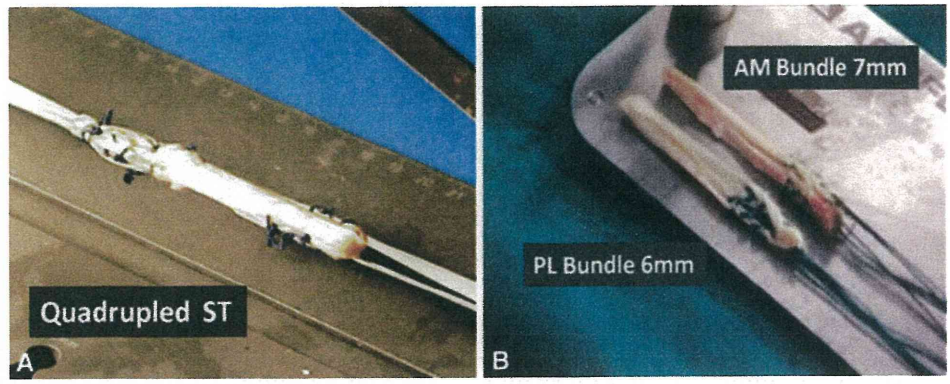

Fig. 1A–B Graft preparation for single-bundle (**A**) and double-bundle (**B**) ACL reconstruction using semitendinosus (ST) tendon. AM = anteromedial; PL = posterolateral.

anatomic position through the anteromedial portal with the knee flexed at 110° of flexion. After checking the proper positioning at 10 o'clock for the right knee, a 4.5-mm cannulated drill was used to create the femoral tunnel and with the specific instrument and the length of the tunnel was measured (Smith & Nephew Endoscopy, Andover, MA) [9, 20, 39]. Once the required graft size was assessed, the half tunnel was prepared using a drill and dilators to obtain a tunnel 0.5 mm in diameter smaller than the graft to have a good press-fit and avoid possible movement of the graft. Average diameter of femoral tunnel in the SB group was 9 mm and the length of the tunnel was 40 mm. The tibial tunnel was then prepared in an anatomic position at the ligament's footprint using an endoscopic aimer adjusted to a 45° position in the coronal plane (Smith and Nephew tibial guide) [9, 20, 39]. The alignment on the sagittal plane should be at 70° with respect to the medial plateau [9, 20, 39]. Average diameter of tibial tunnel in the SB group was 9.5 mm and the length was 45 mm. After selecting the appropriate size of the EndoButton® CL (Smith & Nephew Endoscopy), the quadrupled ST tendon was inserted and fixed at the femoral end with an EndoButton. At this point, we suggest appropriate preconditioning of the graft with cyclic flexion and extension of the knee and finally the two strands were fixed at the tibial side under maximum manual tension (30 Newtons) using a new-generation biocomposite screw (average size, 9 × 30 mm).

For the DB technique, the PL femoral tunnel was initially prepared using an "outside-in" technique. To properly achieve this step, a customized PL tunnel guide was used (Smith &. Nephew Inc Endoscopy). This customized guide has a component arm designed to reach either the 9 o'clock or the 3 o'clock position. The arm of the PL guide was inserted in the anterolateral portal and positioned at either 9 o'clock or 3 o'clock on the medial wall of the lateral condyle while the handle was maneuvered at the area of the junction of the distal femur and lateral condyle to fix the entry point for the tunnel. We used the lateral intercondylar ridge and lateral bifurcate ridge, indicating the superior border of the femoral ACL insertion site and the border between the AM and PL bundle, respectively, as bony landmarks for placement of tunnels [8]. A guidewire was inserted from outside in, which was followed by a 4.5-mm cannulated drill to prepare the pilot hole. Once the length of this hole was measured, a 6-mm PL tunnel with its appropriate depth is drilled. Preparation of the 7-mm AM tunnel followed using standard techniques with the tunnel placed at the either the 11 o'clock or 1 o'clock position. At the end of this step, we have two divergent tunnels positioned anatomically. The tibial tunnels were prepared at an angle of 50° to 60° with the entry point separated by a distance of 1 to 1.5 cm. These tunnels converge on the ACL ligament's footprint intraarticularly [6, 8, 9, 20, 47]. The appropriate size of the EndoButton® CL (Smith & Nephew Endoscopy) as determined by the AM and PL tunnel lengths was then attached at the end of each graft. The diameter of each bundle was then measured using 0.5-mm increment sizers to match the size of the femoral and tibial tunnels. With the tunnels ready, the PL bundle was positioned first followed by the AM bundle. Once in place, the femoral fixation was double-checked to determine if the EndoButton was securely anchored against the cortex. On the other hand, after pretensioning and preconditioning with cyclic flexion and extension, the tibial end of the graft was fixed using a single screw-post construct connected to the graft with a new-generation high-strength suture (Orthocord; DePuy; and Fiberwire; Arthrex, Naples, FL). The AM bundle was secured at 20° of flexion and the PL bundle fixed at full extension; the graft was then checked for impingement and the knee examined for ROM and stability with the Lachman test. The graft's position was confirmed with the postoperative radiograms (Fig. 2A–B).

The postoperative rehabilitation protocol was identical for both groups. For the first 3 weeks, walking with crutches with partial weightbearing was allowed without any brace or splint. Patients were encouraged to restore full extension of the knee and strengthen the quadriceps muscle power. Four weeks after surgery, patients returned to

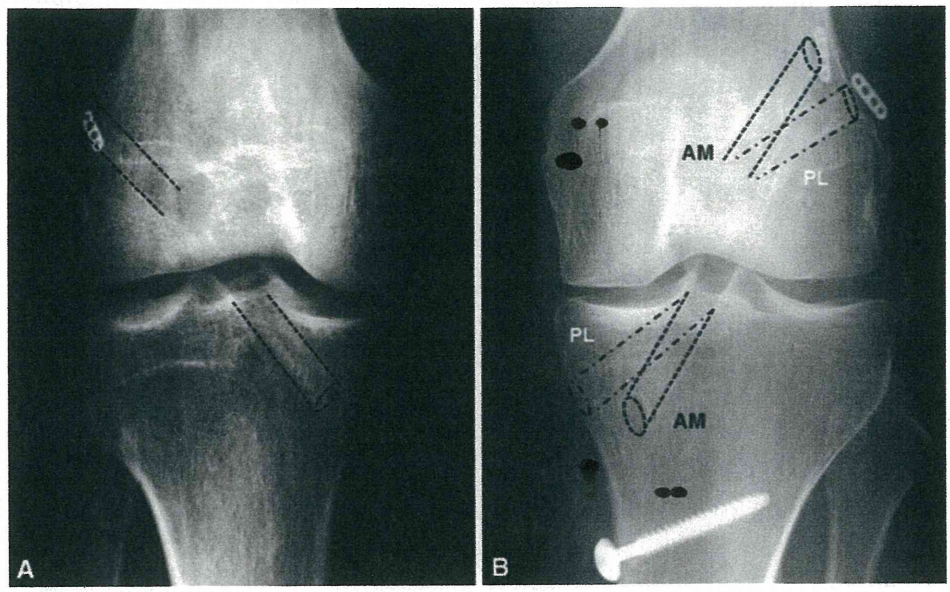

Fig. 2A–B Postoperative anteroposterior radiographs after the ACL reconstruction demonstrating tunnels location in (**A**) the single-bundle technique and (**B**) double-bundle technique. AM = anteromedial tunnel; PL = posterolateral tunnel.

performing activities of daily living. Noncontact sports were permitted after 3 months, and contact sports were permitted 1 year after surgery (Table 4).

Patients were followed at 3, 6, 12, 24, and 36 months postoperatively. A single orthopaedic surgeon (CS), not associated with the surgery and blinded to the surgical procedure evaluated all patients pre- and postoperatively. The type and level of sport participation were documented at preoperative and postoperative intervals. The major complications were defined as postoperative intra-articular infection, rerupture of graft, vascular complications, or fractures after ACL reconstruction. Minor complications were defined as donor site morbidity, stiffness, and hardware complications [35]. Anterior laxity was documented using the Rolimeter (Aircast, Boca Raton, FL) [3, 10] preoperatively and at the same intervals postoperatively. The integrity of the hamstring function of both knees was determined using the modified technique of Nakamura for range of movement [31]. We obtained standard IKDC [19, 48], Noyes [33], Lysholm [25], Marx [29], and Tegner [44] knee scores. To determine the patients' psychologic profile, a specific questionnaire (Psychovitality) was administered preoperatively (Socrates™ Orthopaedic Outcomes Software, Ortholink, Australia). This test is a six-item questionnaire including psychologic factors such as patients' expectations related to treatment outcome and motivation to resume preinjury activity levels. Scores can range from 3 to 18 points; a higher score would indicate better motivation on the part of the patient [15].

Continuous data were described as average means ± standard error of the mean. Nonparametric analysis was performed with Friedman's test to compare the anteroposterior stability as measured with Rolimeter from preoperative to postoperative 6-, 12-, and 36-month evaluation. Nonparametric Friedman's test was also performed to evaluate postoperative improvement in clinical evaluation scores for each group (IKDC, Noyes, Lysholm, Tegner, and Marx). We used the nonparametric Mann-Whitney U test for intergroup comparison with respect to anteroposterior stability as well as in clinical evaluation scores at preoperative to postoperative 6-, 12-, and 36-month followup. Spearman's rho test was performed to analyze the correlation between preoperative psychovitality and Tegner score at last followup for both groups. Z-score and p values are provided for all the parameters evaluated. For statistical analysis, SPSS software was used (SPSS 17.0; SPSS, Chicago, IL).

Results

Patients in both groups improved ($p < 0.001$) in terms of anteroposterior laxity from preoperatively and at 6-, 12-, and 36-month followup (Table 5). We observed no difference in improvement between the two groups at final followup; both SB and DB group patients maintained postoperative stability at 3-year followup (Table 5). The lateral pivot shift test at 3-year followup was negative in 83.3% and Grade 1 in 16.7% in the SB group patients and was negative in 87% and Grade 1 in 13% in the DB group patients (Table 6).

At final followup, the ROM was similar in both groups: a mean of 135.5° ± 5.5° in the SB group and 134.5° ± 1.0° in the DB group (Table 6). The rehabilitation time involved 10% more physical therapy sessions in the DB group than the SB group to regain the same ROM.

All clinical scores (IKDC, Noyes, Lysholm, Tegner, and Marx) improved from preoperative evaluation to final

Table 4. Rehabilitation protocol after ACLR

Time period	Rehabilitation protocol
First month	
First week	• Apply ice on the knee for 15 minutes/2 hours
	• CPM 10°–60°, for 8 hours/day adding 5° per day until 90°
	• At night, set the CPM to slow speed
	• Walk with crutches with partial weight bearing
	• Isometric quadriceps exercises
	• Active movement of the ankle
Second week	• Apply ice on knee for 15 minutes/2 hours
	• CPM 0°–90°
	• Walk with crutches with partial weight bearing
	• Start PT-assisted exercises
	• Patellar mobilization
	• Electrostimulation (low-intensity)
	• Isometric cocontraction on CPM
	• No showers (keep surgical wounds dry)
Third week	• Stop CPM (should have achieved 110° of flexion)
	• Walk with one crutch outdoor; full weightbearing
	• Supervised PT as before, add the following:
	Exercises in water-impermeable wound dressing
	Resisted flexion-extension exercises with
	Thera band against manual resistance by the therapist at 10°–90°
	Proprioceptive exercises without loads Exercise other joints (no adduction)
Fourth week	• Full weightbearing; abandon crutches completely
	• Achieve 120° of flexion
	• Isometric contraction
	• Careful leg presses, mini squat (closed-chain exercises)
	• Cycling and manually resisted flexion exercises
Second month	• Free ambulation with full weight bearing
	• Proprioceptive exercises with bipedal load
	• Isotonic exercises with leg presses (closed-chain exercises)
	• Exercise other joints (include adduction)
Third month	• Free active extension
	• Isokinetic work/controlled running exercises
	• Swimming/road cycling
	• First knee laxity and isokinetic strength tests
Fourth month	• Start running on soft terrain/swimming
	• Sport-specific drills
Fifth month	• Return to individual low-risk sports
	• Sport-specific drills
Sixth month	• Return to team sports and higher-risk sports
	• Second knee laxity and isokinetic strength tests
Twelfth month	• Strengthening and proprioceptive exercises
	• Third knee laxity and isokinetic strength tests

ACLR = anterior cruciate ligament reconstruction; CPM = continuous passive machine; PT = physical therapy.

followup for each group of patients; however, there was no difference between the two groups at final followup (Table 5). All patients returned to their previous sports activities. In the SB group, patients went back to competitive sports at an average of 7.4 months and in the DB group at an average of 8.2 months; we observed no difference in Tegner scores between preinjury and last followup for both groups (Fig. 3A–B). We observed

Table 5. Examination findings and functional scores at 3-year followup

Variable	Technique	Preoperative (mean ± SEM)	3-Year followup (mean ± SEM)	Improvement chi-square test (p value/Z score)	Cross-comparison *U test (p value/Z score)
IKDC Subjective	SB	41.5 ± 4.21	89.4 ± 1.47	< 0.001/72.380	0.823/−0.224
	DB	43.0 ± 3.98	88.0 ± 2.20	< 0.001/70.969	
IKDC Objective	SB	22C/8D	20A/10B	< 0.001/78.760	0.783/−0.275
	DB	20C/10D	21A/9B	< 0.001/79.682	
Tegner	SB	2.0 ± 0.37	6.73 ± 0.38	< 0.001/94.633	0.572/−0.565
	DB	2.3 ± 0.32	7.10 ± 0.32	< 0.001/104.639	
Marx	SB	6.4 ± 0.50	11.3 ± 0.47	< 0.001/70.409	0.001/−3.404
	DB	7.1 ± 0.61	13.3 ± 0.56	< 0.001/72.498	
Noyes	SB	29.5 ± 4.93	88.5 ± 2.01	< 0.001/70.036	0.795/−0.260
	DB	30.0 ± 4.57	87.8 ± 2.37	< 0.001/77.968	
Lysholm	SB	42.4 ± 3.30	93.3 ± 1.69	< 0.001/72.948	0.734/−0.340
	DB	40.4 ± 3.11	92.8 ± 1.96	< 0.001/71.129	
ΔLaxity (mm) Rolimeter	SB	7.7 ± 0.67	1.41 ± 0.26	< 0.001/78,650	0.885/−0.145
	DB	8.6 ± 0.58	1.38 ± 0.21	< 0.001/89.004	

* Intergroup comparison between single- and double-bundle groups at 3-year followup; IKDC = International Knee Documentation Committee; SB = single bundle; DB = double bundle.

Table 6. Anteroposterior laxity, pivot shift test evaluation, and ROM at 3-year followup

Variable	Group SB	Group DB
ΔLaxity (mean)	1.41 ± 0.26	1.38 ± 0.21
Pivot shift (normal/glide +)	25/5	26/4
ROM	0–135.5° ± 5.5°	0–134.5° ± 1.0°

SB = single bundle; DB = double bundle.

a correlation between preoperative psychovitality score and Tegner score at last followup for both groups (Fig. 4A–B).

We observed no major postoperative complications and no reruptures. One year after surgery one of the patients in the SB group was involved in a motocross crash and sustained a tibial plateau fracture (Schatzker Type I). Diagnostic arthroscopy was performed and the ACL was intact. The patient was treated nonoperatively and returned to motocross after 3 months. Another patient in the DB group after 4.5 years sustained a tibial plateau fracture (Schatzker Type IV) after a trivial trauma while playing soccer and was managed operatively with open reduction and fixation with an LCP plate and screws.

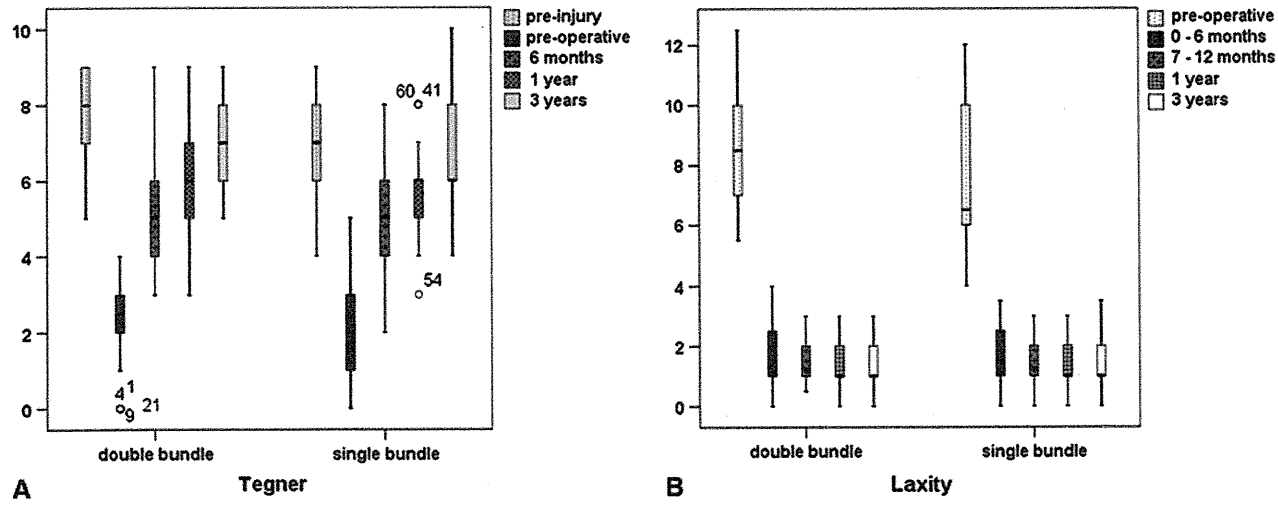

Fig. 3A–B Box plots showing improvement in Tegner score (A) and laxity (B) from preoperative evaluation to 6-, 12-, and 36-month followup. We observed no difference in improvement between the two groups at the prospective followup; the Tegner score at last followup approached that of the preinjury value in the single-bundle group.

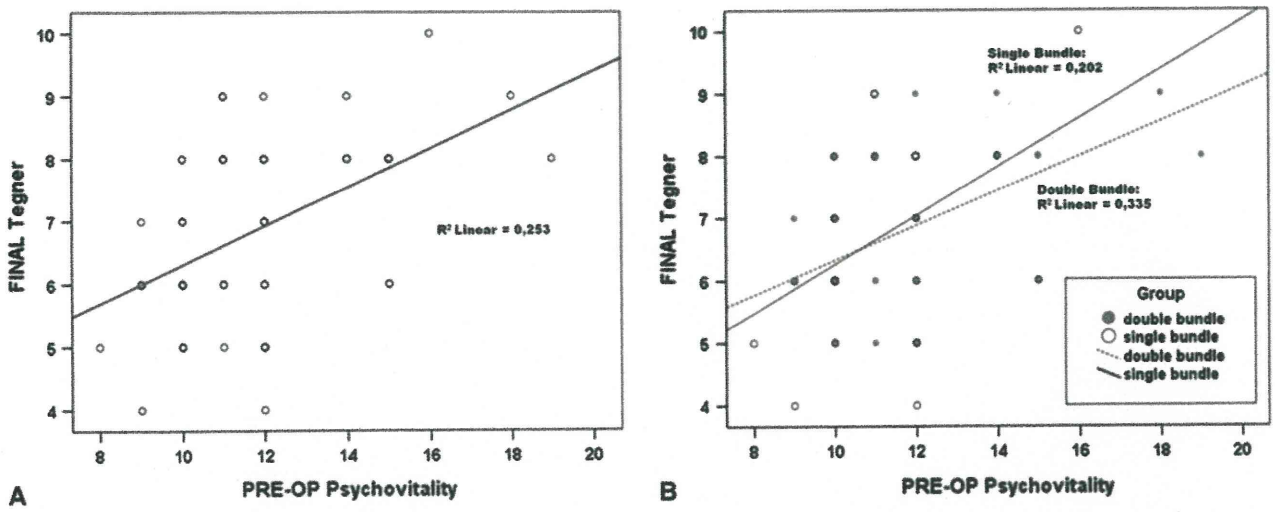

Fig. 4A–B Scatterplot showing a correlation between preoperative psychovitality and Tegner score at last followup for all the patients (**A**) as well as for each group separately (**B**).

Discussion

The ACL is composed of AM and PL bundles, each with its own characteristics. Many surgeons try to reconstruct each bundle of the ACL separately. For more successful reconstruction of the ACL, the ideal outcome would be restoration of the anatomy of the ACL, which means functional restoration of the ACL to its native dimensions, collagen orientation, and insertion sites to achieve better stability [8]. Many different techniques have been suggested for anatomic ACLR using different tunnels positions, fixation systems, and types of graft [16, 28, 37, 39]. A number of studies have been conducted to compare postoperative stability and function after anatomic DB and SB ACLR. Some authors consider SB ACLR as the standard option to treat ACL lesions [5, 7, 17, 42], whereas others suggest the anatomic DB ACLR should improve pivot shift resistance and increase rotational knee control and should help preserve menisci and limit progression toward arthritis [8, 38, 46, 47, 49, 51]. Many studies, however, found no difference in terms of anteroposterior laxity, rotational stability, and/or any other clinical aspects at final followup between the two techniques [1, 4, 20, 23, 24, 30, 34, 43]. Furthermore, it remains unclear if one has clear long-term advantages over the other. We therefore asked whether patients having single- and double-bundle ACLR using ST alone differed with regard to (1) postoperative stability; (2) ROM; and (3) five functional scores.

Our study has some limitations. First, it was not possible to objectively evaluate the pivot shift test in our patients with specific instruments because these instruments are not freely available and accessible. We used the pivot shift test, which is a subjective test commonly used during clinical examination. We believe it would be important to compare patients with Grade 3 pivot shift treated with SB and DB reconstruction using specific instruments. Second, we did not include patients with complex instability because we believed it would introduce confounding variables such as medial-lateral collateral instability and posterior ligament insufficiency. Further studies are required to compare patients with complex instability treated with SB and DB reconstruction.

Our findings confirm those of several previous studies [1, 34, 43] reporting no difference between ACL-deficient patients treated either with single- or double-bundle ACLR regarding postoperative stability, pivot shift grade, varus-valgus limb morphology, and type of sport (Table 7). Recent meta-analyses also found no difference in the chance of having a normal pivot shift between single- and double-bundle ACL reconstruction [23, 24, 30]. Our data also showed no difference between the two groups regarding postoperative stability as assessed with the Rolimeter and pivot shift test (Table 6). Although double-bundle ACLR reportedly produces better intraoperative stability than SB ACLR [43], the two modalities are similar in terms of clinical aspects evaluated such as Lysholm and Tegner scores as well as postoperative stability after a minimum of 2 years of followup [43]. The AP laxity as measured with the Rolimeter was also similar in the two groups at 3 years; furthermore, for each group, we found no difference in laxity from 1 to 3 years of followup. Our observations confirm recent studies suggesting stability was achieved and remained for both groups [34, 43].

Even with theoretical advantages of DB ACLR, there will still be room for the anatomic SB technique with its

Table 7. Side-to-side difference in anteroposterior laxity

Study	Number of patients	Group SB	Group DB	p Value
Adachi et al. [1]	108	1.2 ± 2.5	1.3 ± 2.5	*No significance
Park et al. [34]	147	1.2 ± 1.3	1.4 ± 1.2	0.393
Song et al. [43]	40	2.8 ± 2.0	2.7 ± 1.9	0.872
Our study	60	1.41 ± 0.26	1.38 ± 0.21	0.885

* No significant difference; no p value provided.

less complex preparation of tunnels. An increasing arsenal in the sports surgeon's hands must now lead us to create an improved algorithm in treating ACL complete tears: what technique, graft type, and fixation for a specific patient should be used? This should be answered by an algorithm [46]. We must always plan our surgery according to the type of patient we are presented with; for instance, a double-bundle ACLR may be more appropriate for an athlete of high-contact or impact sport but certainly not for a skeletally immature patient or a patient with important lateral femoral condyle bone bruise [8, 38, 46, 47, 49, 51]. Furthermore, we must also consider the anthropometric anatomy; thus, a thin light female would not be a good candidate for DB ACLR [13]. There is a considerable learning curve associated with DB ACLR. A recent study [18] demonstrated most European and American surgeons performing ACLR do less than 10 cases per year; should these surgeons be addressed about the DB technique? The failure rate is approximately 10% to 20% of all ACLRs; this rate might increase if all surgeons were to perform this new technique.

We found no differences in ACLR using SB or DB. Based on our findings and those in the literature, we suggest that at present, the surgeon should use the most anatomic technique for ACLR with less complexity, easier fixation, a least invasive revision technique, and minor graft harvesting morbidity. Surgeons should be aware of the reported incidence of hamstring weakness when using both the ST and the gracilis tendons for this type of reconstruction; therefore, we emphasize harvesting only the ST tendon for ACLR [12, 14, 31]. Today ACLR cannot be a fixed menu in the clinics of sports surgeons; rather, we advise a "menu a la carte" with many options to choose from, including regenerative therapy (stem cells); different graft sources, autografts, and allografts; and different fixations and a variety of techniques, which would not limit the surgeon in doing what is best for the patient. Further studies in the future might demonstrate if the DB technique could offer better stability and clinical outcome than SB, especially in patients with complex instability and greater transverse plane rotational knee stress demands.

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SYMPOSIUM: COMPLEX KNEE LIGAMENT SURGERY

Surgical Technique

Revision ACL Reconstruction With a Rectangular Tunnel Technique

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Abstract

Background We developed the rectangular tunnel ACL reconstruction (RT ACLR) using a 10-mm wide bone-patellar tendon-bone (BTB) graft through rectangular tunnels with a rectangular aperture to reduce tunnel size: the cross-sectional area of the tunnels of 50 mm^2 (5 × 10 mm) in RT ACLR is less than that of 79 mm^2 in a conventional 10-mm round tunnel technique presuming the technique would be more suitable in revision ACLR with previous improperly placed tunnels.

Description of Technique Two contiguous 5-mm tunnels inside the anatomic ACL femoral and tibial attachment areas along their long axes, and they are expanded with a 5 × 10-mm dilator into parallelepiped ones.

Patients and Methods We indicated and intended to perform the RT ACLR procedure in 31 patients requiring revision between 2004 and 2008. Eighteen of the 31 patients treated with the procedure were followed a minimum of 24 months (mean, 38 months; range, 24 to 73 months). We evaluated ROM, obtained IKDC scores, and determined stability with KT-1000.

Results The procedure could be applied in 30 of the 31 cases. One of the 18 reruptured the graft at 28 months. Of the remaining 17 patients with followup of 24 months or longer, 15 had full ROM, while the remaining two lost 5° of flexion; 11 were classified as normal and six were nearly normal according to the IKDC evaluation. Stability measured with KT-1000 was 1.0 ± 1.5 mm.

Conclusion The RT ACLR technique provided acceptable results after one-stage revision ACLR.

Level of Evidence Level IV, therapeutic study. See Guidelines for Authors for a complete description of levels of evidence.

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Introduction

The incidence of ACL injury is reportedly between 36.9 and 60.9 per 100,000 persons per year [17, 30]. Because of the poor healing potential of a ruptured ACL [2, 19, 23, 24, 28], ACL reconstruction (ACLR) has been one of the most common surgical procedures in orthopaedic practice [16, 27]. Because primary ACLR has been performed with restoration of stability in 75% to 97% of patients [4–8, 28, 35, 40], many patients require revision. Revision ACLR accounted for approximately 5% of the ACLRs in our practice between 2008 and 2009.

Revision ACLR is indicated for patients with instability resulting from a malpositioned graft, from improperly placed tunnels, poor graft healing/remodeling, and/or traumatic graft rupture. However, the most frequent cause for the failure may be femoral tunnel malposition [41, 42]. Revision ACLR is technically difficult. If possible, it is ideal to create new tunnels away from the previous tunnel aperture. Therefore, the smaller the aperture areas of new tunnels, the more likely one can avoid overlapping tunnels.

We developed the rectangular tunnel ACL reconstruction (RT ACLR) with a 10-mm wide bone-patellar

tendon-bone (BTB) graft to mimic the natural fiber arrangement inside the native ACL and to minimize tunnel size [36, 38, 39]. Because the cross-sectional area of the tunnels of 50 mm^2 (5 × 10 mm) in RT ACLR is less than that in a conventional 10-mm round tunnel technique (79 mm^2), the former is advantageous to more consistently avoid overlapping tunnels and/or to more easily avoid improperly placed tunnels from the previous surgery.

Because tunnel encroachment would hypothetically be less of a problem, we presumed the RT ACLR technique could be applied as a one-stage revision procedure to those after failed primary ACLR. The purposes of our report were to (1) describe the procedure; (2) determine how frequently we could obtain properly placed tunnels; (3) determine whether function and stability were restored; and (4) describe complications.

Description of Technique

The principles were to (1) create parallel tunnels with rectangular apertures inside the anatomic attachment areas (Fig. 1) [1, 12, 14]; (2) avoid overlapping tunnels or staged operations (Fig. 2); and (3) accept the pre-existing tunnel apertures if they were in the anatomic attachment areas (Fig. 3).

The patient is positioned supine with the thigh horizontally kept using a leg holder. The anteromedial portal is used for viewing and the far anteromedial portal for instrumentation [33, 36]. For the femoral tunnel, instruments are used through the far anteromedial portal with the knee fully flexed, whereas the tibial tunnel is created through the anteromedial cortex to the anatomic intra-articular insertion. Two contiguous 5-mm tunnels along the long axis of the attachments are created and then expanded with a 5 × 10-mm dilator into a single tunnel.

With previous properly placed tunnels after BTB reconstruction, the revision can be performed as the primary RT ACLR using any type of graft: two double-looped semitendinosus tendon (SMT) grafts, quadriceps tendon-bone (QTB), or the contralateral BTB graft (Fig. 4; Cases 11, 12). However, for those with a widened femoral tunnel after use of a SMT graft, the extra space might be filled with an interference screw of greater than 6 mm (Fig. 5; Case 16).

With improperly placed previous tunnels on the femoral side, the distance between the aperture rim of the previous tunnel and that of the new tunnel is 5 mm or greater; the new femoral tunnel is created as the primary ACLR (Fig. 6). If the distance is less than 5 mm, however, the divergent tunnel can be used either by changing the approach to inside-out through the far anteromedial portal [3, 33] or outside-in through a lateral femoral incision

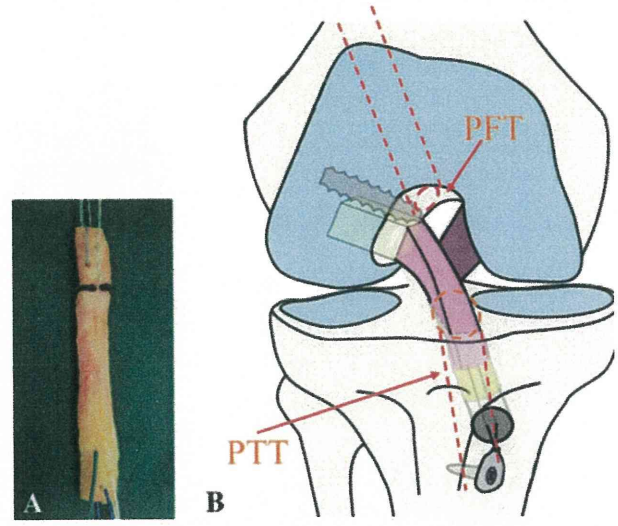

Fig. 2A–B (**A**) A prepared bone-patellar tendon-bone (BTB) graft of 10-mm width. (**B**) Schema of revision rectangular tunnel ACL reconstruction (RT ACLR) with BTB graft. The bone plug is fixed to the femur with a 6-mm interference screw, whereas tibial fixation is achieved with a modified pullout suture technique using the DSP (Double Spike Plate) and a screw. With this procedure, the new properly placed femoral tunnel can be created in most cases without overlapping tunnels despite the previous high and anterior femoral tunnel (PFT) leading to a vertical graft. In most cases, a new tibial tunnel is created with the same aperture as the previous tibial tunnel (PTT), whereas the direction is changed.

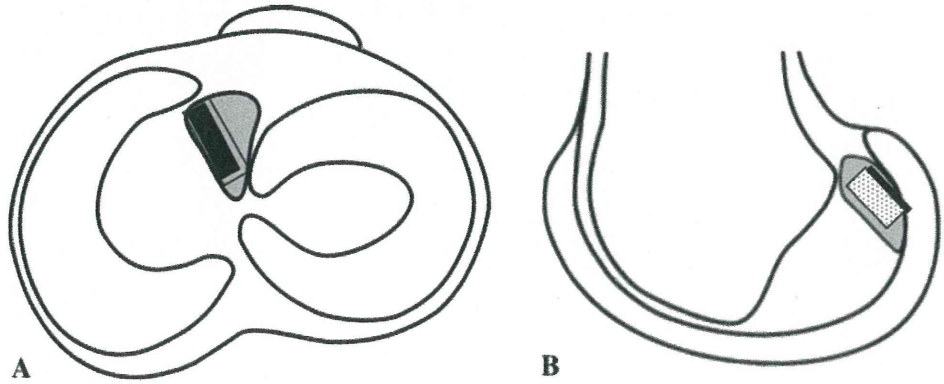

Fig. 1A–B Intra-articular tunnel apertures of the tibia (**A**) and the femur (**B**) in rectangular tunnel ACL reconstruction (RT ACLR). (**A**) The tibial tunnel aperture is almost filled with the tendon (black-painted area); (**B**) note the tendinous side of the bone plug (black-painted area) located posteriorly superiorly on the femoral tunnel aperture.