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.

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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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 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

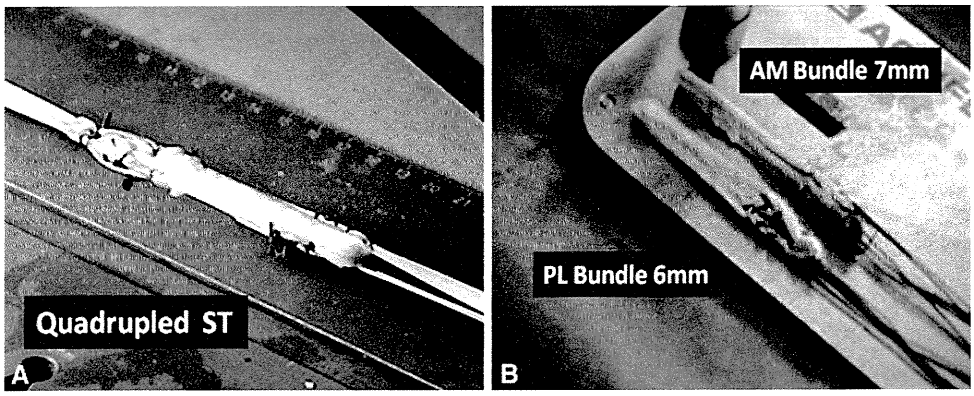

Fig. 1A–B Graft preparation for single-bundle (**A**) and double-bundle (**B**) ACL reconstruction using semitendinosus (ST) tendon. AM = anteromedial; PL = posterolateral.

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

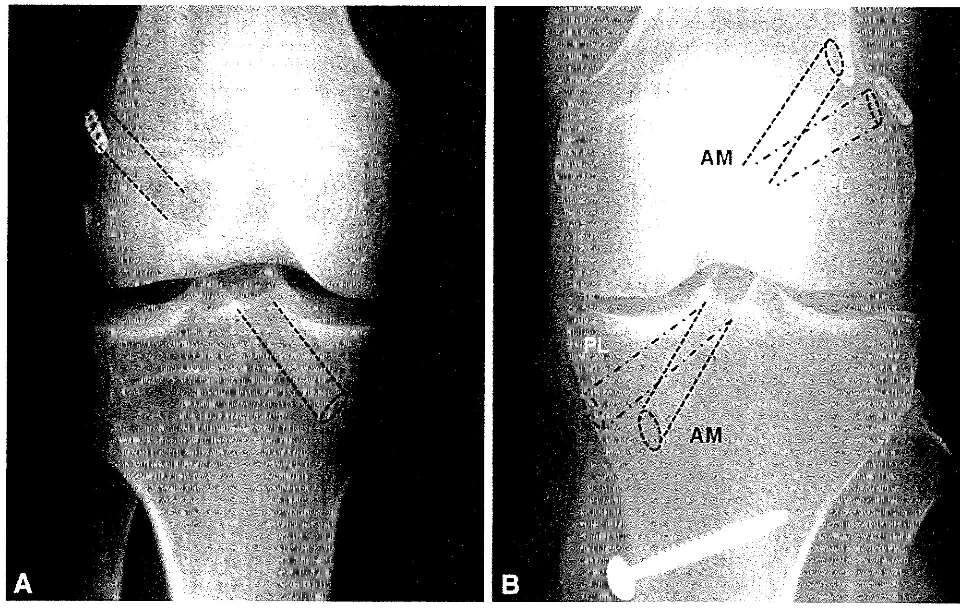

Fig. 2A–B Postoperative anteroposterior radiographs after the ACL reconstruction demonstrating tunnels location in (**A**) the single-bundle technique and (**B**) double-bundle technique. AM = anteromedial tunnel; PL = posterolateral tunnel.

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.

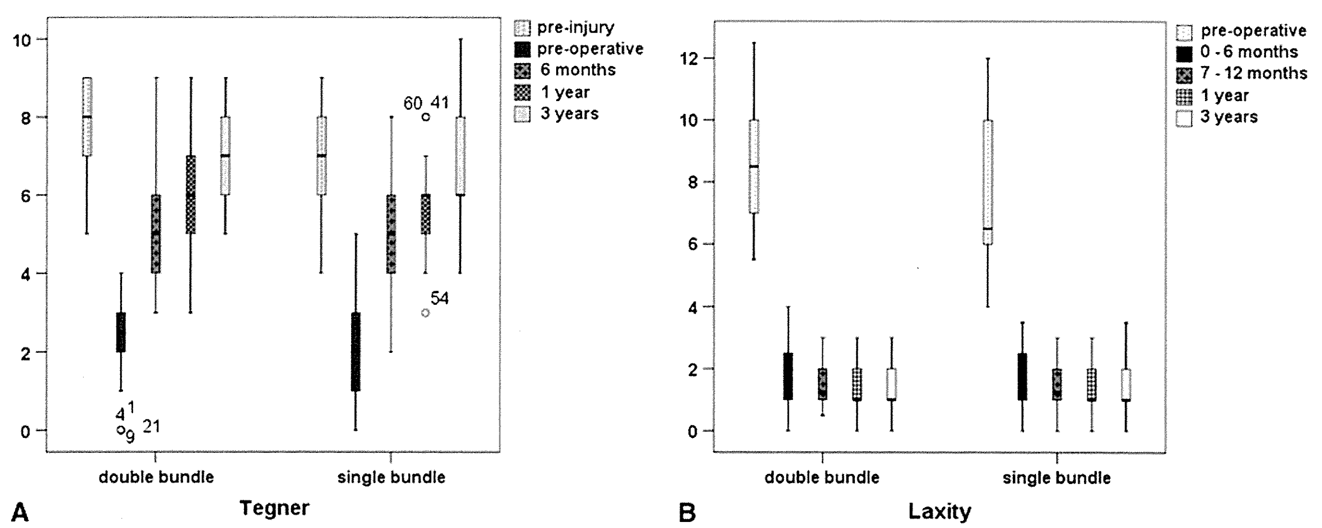

Fig. 3A–B Box plots showing improvement in Tegner score (**A**) and laxity (**B**) from preoperative evaluation to 6-, 12-, and 36-month followup. We observed no difference in improvement between the two groups at the prospective followup; the Tegner score at last followup approached that of the preinjury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

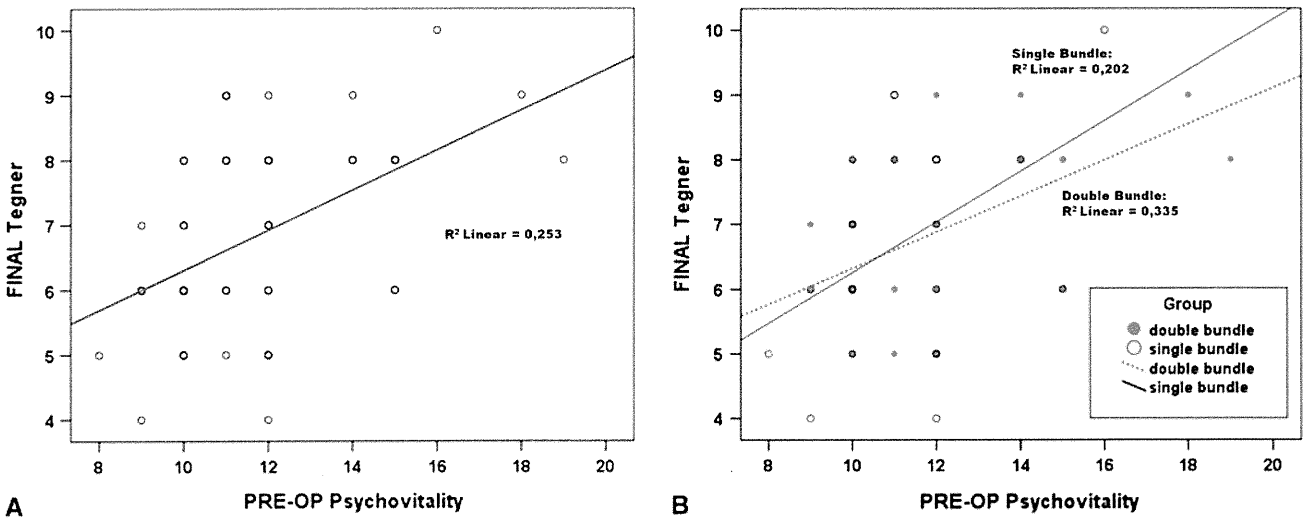

Fig. 4A–B Scatterplot showing a correlation between preoperative psychovitality and Tegner score at last followup for all the patients (**A**) as well as for each group separately (**B**).

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

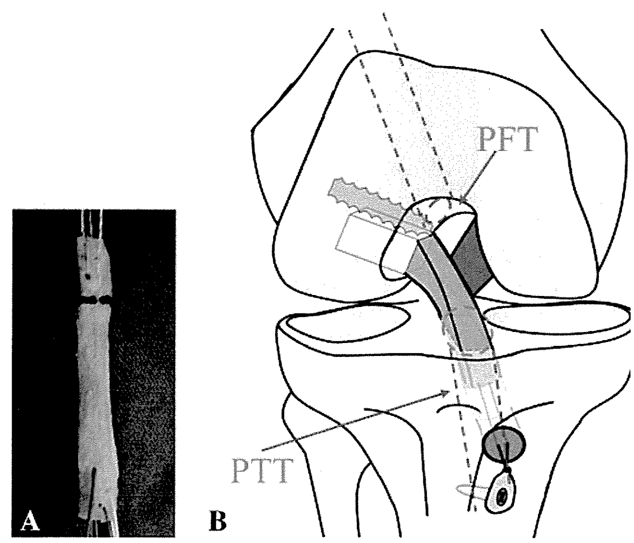

Fig. 2A–B (**A**) A prepared bone-patellar tendon-bone (BTB) graft of 10-mm width. (**B**) Schema of revision rectangular tunnel ACL reconstruction (RT ACLR) with BTB graft. The bone plug is fixed to the femur with a 6-mm interference screw, whereas tibial fixation is achieved with a modified pullout 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.

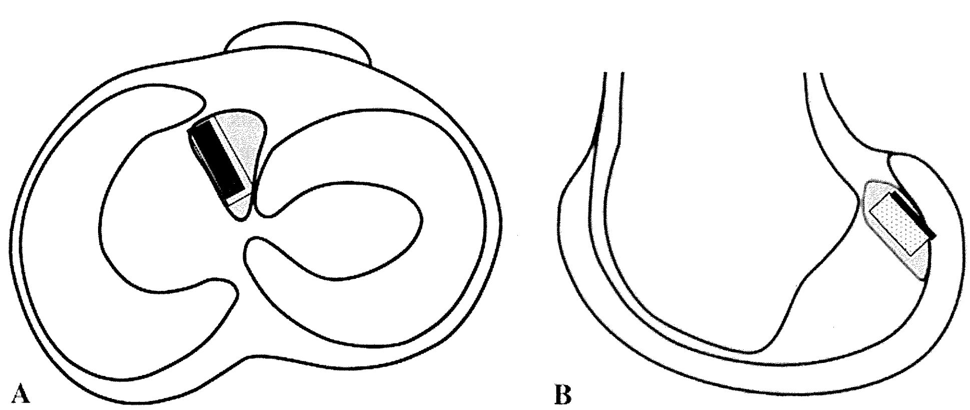

Fig. 1A–B Intra-articular tunnel apertures of the tibia (**A**) and the femur (**B**) in rectangular tunnel ACL reconstruction (RT ACLR). (**A**) The tibial tunnel aperture is almost filled with the tendon (black-painted area); (**B**) note the tendinous side of the bone plug (black-painted area) located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

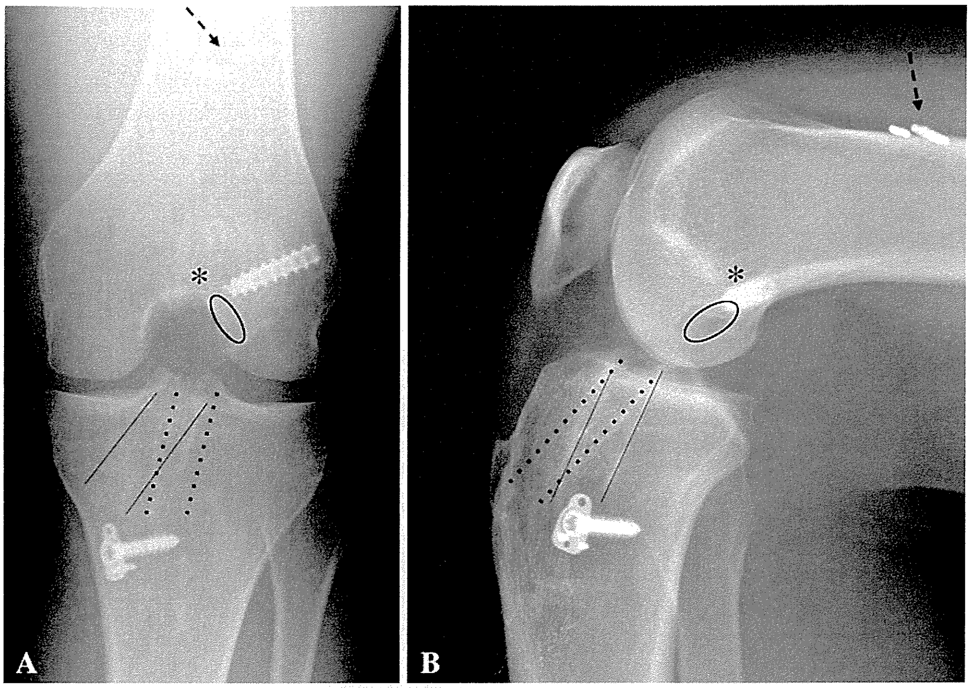

Fig. 3A–B Radiographs of a case with previous improperly placed tunnels (Case 3 in table 1). (**A**) Posteroanterior 45° flexion weightbearing view; (**B**) lateral view. The primary surgery had been performed with a hamstring tendon graft through two high femoral tunnels (*) and a single central tibial tunnel (dotted line). Note two residual Endobuttons used for femoral fixation at the time of primary ACL reconstruction (ACLR) (dotted arrow). A rectangular new femoral tunnel was created in a proper place, whereas the direction of the tibial tunnel was changed to obtain a new tunnel wall of fresh cancellous bone. Note the solid lines of the new tibial tunnels and fixation hardware on the femur and the tibia. The circles show the aperture locations of the new properly placed tunnels.

[2, 14, 37]. However, we recommend grafting over the top of the lateral condyle for those with severe tunnel widening around the original femoral attachment (Fig 7).

On the tibial side, a tunnel placed too anteriorly is easily revisable, whereas a tunnel placed too posteriorly is not. For the latter, the direction of the tunnel should be changed to obtain a new posterior tunnel wall of fresh cancellous bone using a divergent tunnel technique (Fig. 3). This should help the graft to heal to the tunnel wall and resist anterior tibial force. With a tunnel malpositioned by 1 cm or less posteriorly, it may be reasonable to reuse the same tunnel aperture, to avoid merging the two tunnel apertures. When the posterior malpositioning exceeds 1 cm, however, the previous tunnel may be filled with a bone graft or its substitute.

Femoral graft fixation is usually achieved with a 6-mm interference screw (Fig. 3), although additional cortical suspensory fixation may be considered if the fixation is questionable as a result of the previous tunnel.

Tibial fixation is achieved with a modified pullout suture technique using DSP (Double Spike Plate; Smith-Nephew Endoscopy, Andover, MA) and a screw. This technique makes it possible to fix the graft under a predetermined amount of tension [34].

The knee is immobilized in 10° flexion for 1 week with a brace for BTB grafts, whereas the immobilization is continued up to 2 weeks for SMT grafts. After that, passive and active ROM exercises are followed. Partial weightbearing is allowed at 2 to 3 weeks followed by full weightbearing at 4 to 5 weeks. Full extension or flexion exceeding 130° is not permitted until 5 weeks. Jogging is recommended at 3 to 4 months. Return to strenuous activity is not allowed until 6 months.

Patients and Methods

From June 2004 to December 2008, we treated 31 patients with failed ACLR using the described technique. Our indications for revision ACLR were (1) subjective instability or giving way during strenuous activity or daily activities; (2) positive Lachman and pivot shift tests; and (3) more than 3 mm side-to-side difference with KT-1000 at maximum manual force. The contraindications were: (1) arthrofibrosis: ROM deficit such as an extension or flexion deficit exceeding 10°; (2) deep infection; and (3) severe osteoarthritis. In one patient with massive bone loss, we chose the graft fixation over top of the lateral femoral condyle; this

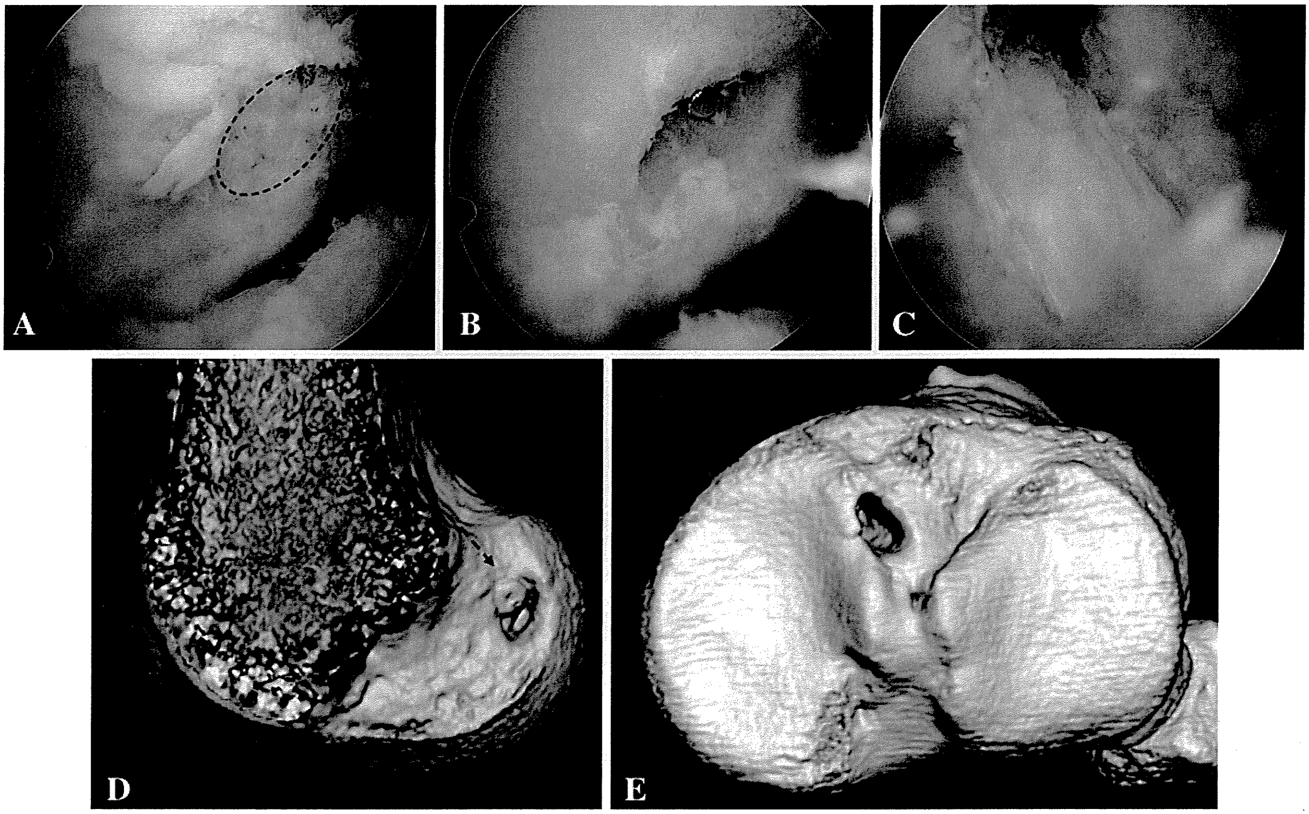

Fig. 4A–E A case with previous proper rectangular tunnels (Case 12 in Table 1). (**A**) Arthroscopic view of the previous femoral tunnel was densely filled with tendon and bone plug; (**B**) arthroscopic view of the new rectangular femoral tunnel recreated in the same place as that in the previous surgery. The bone-patellar tendon-bone (BTB) graft from the contralateral side was introduced through the same rectangular tibial tunnel after curettage, and the bone plug was fixed to the femoral tunnel with an interference screw. (**C**) Arthroscopic view of BTB graft in situ after fixation. (**D**) Three-dimensional CT of the lateral femoral condyle at 4 weeks after the revision. Note the bone plug fixed with an interference screw (dotted arrow) inside the femoral tunnel; (**E**) three-dimensional CT of the tibial plateau. Note the bone plug located medially inside the properly placed tibial tunnel.

patient was excluded. We also excluded 12 patients who were lost to followup between 1 and 18 months. This left 18 patients' one of whom was excluded because of retear of the graft at 28 months. Thus, the remaining 17 with a mean followup of 38 months with a range from 24 to 73 months were evaluated (Table 1). There were 10 male and seven female patients with a mean age at the revision of 23 years (range, 15–34 years). The mean time from diagnosis of the failure to revision was 2.3 months. No patients were recalled specifically for this study; all data was obtained from medical records and radiographs.

Our followup routines recommended to patients are as follows: (1) a monthly examination including ROM and Lachman and pivot shift tests up to 12 months; (2) examination every 3 months after 12 months to 24 months; (3) examination and plain radiographs at 24 months; and (4) annual examinations from 24 to 60 months. At each examination we completed the IKDC evaluation form [21] and obtained laxity measurement with KT-1000 (MEDmetric Corp, San Diego, CA). There were no missing data from these examinations. Radiographs were taken at followup between 24 and 60 months in 17 patients in whom we obtained the following views: 45° posterior-anterior flexion weightbearing view, lateral view at 90°, and Merchant view.

Results

The femoral tunnel could be created in the center of the anatomic attachment area in 30 of the 31 patients using the RT ACLR technique, whereas the technique could not be applied in one (Fig. 7). The tibial tunnel was successfully created within the tibial attachment area in 29 of the 30 patients, whereas the remaining one required bone grafting to fill out the previous tunnel because of its posterior location. None of the patients underwent staged surgeries.

Of the 18 patients followed for a minimum of 24 months, none reported giving way or subjective

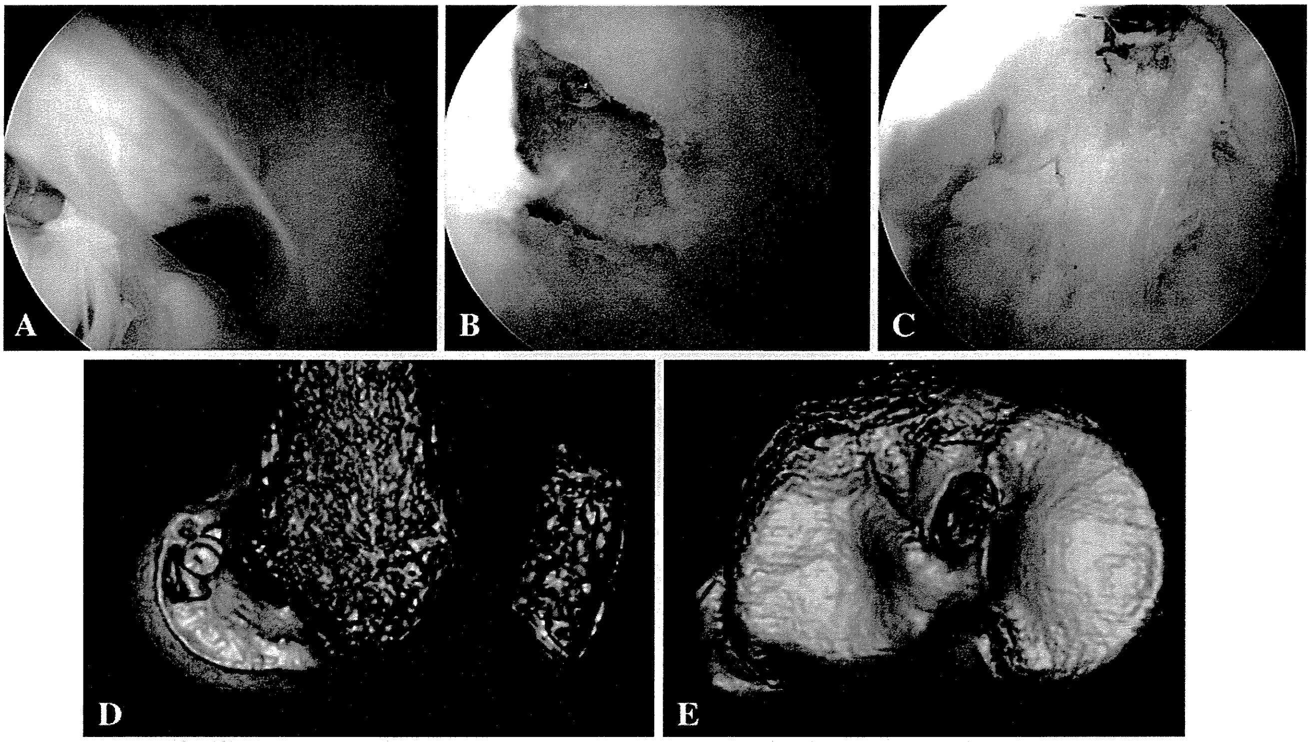

Fig. 5A–E A case with previous properly placed tunnels for double-bundle graft (Case 16 in Table 1). (**A**) Arthroscopic view of the hamstring graft resulting from stretch-out; (**B**) arthroscopic view of the rectangular femoral tunnel aperture created by dilation after graft removal. The bone-patellar tendon-bone (BTB) graft was introduced through the rectangular tibial tunnel created by dilating the previous two tunnels, and the bone plug was fixed to the femoral tunnel with a 7-mm interference screw. (**C**) Arthroscopic view of the revision BTB graft in situ. Note the interference screw used for femoral fixation (dotted arrow). (**D**) Three-dimensional CT at 4 weeks after the revision showing the bone plug fixed with an interference screw inside the femoral tunnel; (**E**) three-dimensional CT at 4 weeks showing the bone plug located medially inside the tibial tunnel.

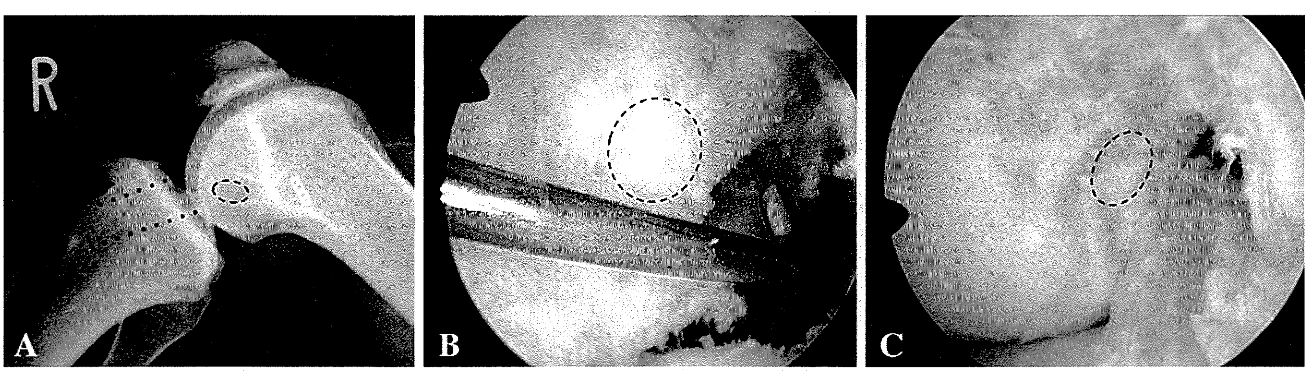

Fig. 6A–C An illustrative case with previous improperly placed tunnels using a hamstring tendon graft. (**A**) A lateral radiograph showing an improperly placed anterior femoral and slightly posterior tibial tunnels (dotted lines); (**B**) arthroscopic view through the anteromedial portal of the femoral attachment area. Dotted circle shows the previous anterior femoral tunnel aperture, whereas the probe tip denotes the new properly placed tunnel aperture. Note there is no overlapping tunnels; (**C**) a new bone-patellar tendon-bone (BTB) graft was introduced and fixed with an interference screw. Note more than 5-mm distance between the previous tunnel aperture (dotted circle) and the anterior border of the new tunnel. Unfortunately, this patient had undergone an accident leading to femoral bone plug slippage out of the tunnel at 3 weeks and had further surgery to refix the bone plug.

instability. One patient had a tear of the graft at 28 months. Of the remaining 17 patients, 11 were classified as normal and six were categorized as nearly normal by the IKDC evaluation form. Quantitative anterior laxity measurement with KT-1000 showed the mean side-to-side difference at maximum manual drawer force improved to 1.0 ± 1.5 mm with a range from -1 to 4 mm. Fifteen of the 17 patients had no loss of motion or effusion, while the other two

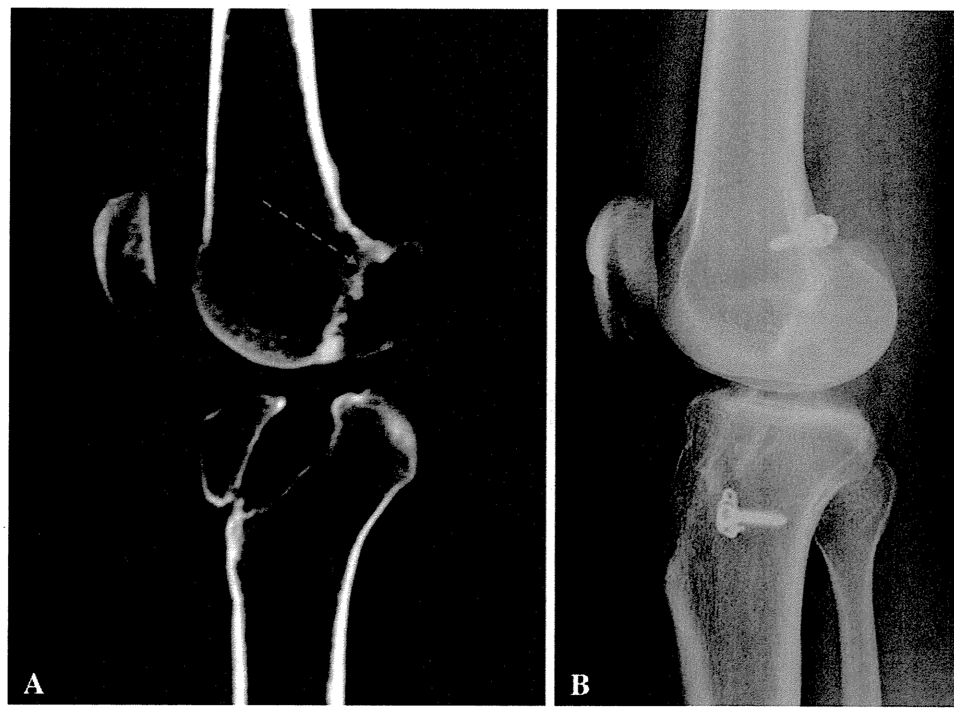

Fig. 7A–B An illustrative case with bone absorption. (**A**) CT of the right knee before revision. Note the severe bone absorption around the anatomic femoral attachment (dotted line); (**B**) postoperative lateral radiograph showing femoral graft fixation over top of the lateral condyle.

patients had mild pain and swelling after strenuous activity and showed loss of 5°flexion (Cases 8, 17). Two had a mildly positive Lachman sign with a firm end point and pivot shift test (Cases 1, 2), whereas the remaining 15 were negative on both tests. Of the 12 patients lost to followup at 13 months ranging from 1 to 18 months, none reported subjective instability, limitation of motion, or pain on daily activities at the last examination according to the medical record (Table 2).

One patient sustained a tear of the revision graft and underwent a second revision ACLR with the ipsilateral QTB graft and was not listed in Table 1. Another17-year-old male patient had a fall with the knee hyperflexed, resulting in femoral bone loosening from the tunnel at 3 weeks and underwent refixation of the bone plug. He resumed soccer by 8 months, was playing soccer without instability as of 13 months, and was lost to followup thereafter (not listed in the table) (Fig. 6).

Discussion

Revision ACLR is technically difficult because of preexisting tunnels in the primary ACLR. Recent published studies suggest the femoral ACL attachment area is crescent-shaped with a maximum width of less than 1 cm [9, 22, 31]. The rectangular tunnel aperture of 5-mm width (50 mm^2 in cross-sectional area) in the RT ACLR as well as the two-tunnel technique is advantageous compared with a single round one of 10 mm (79 mm^2 in cross-sectional area) to avoid overlapping tunnels at the time of revision ACLR [43, 45]. The femoral tunnel was created in the anatomic center of the attachment area in 97% of our series. In addition, the RT ACLR technique is useful to revise failure after double-bundle ACLR in which two tunnels were properly created along the long axis of the ACL attachment areas. A new rectangular tunnel can be easily created by dilating previous two tunnels (Fig. 5).

We acknowledge limitations of our study. First, we located only 18 of the 30 patients (60%) for followup examination at 24 months or longer. Thus, our observations may not represent those for the larger group. Second, the followup evaluation was performed retrospectively. Third, the minimum followup was relatively short. However, we found the procedure reliably restored stability without substantial loss of motion.

A number of reports describe revision ACLR through a single round tunnel using various kinds of graft including autogenous hamstring, BTB, QTB, or allograft (Table 3). In these studies, 2.1% to 8.2% of the patients showed side-to-side differences in KT measurement greater than 5 mm, whereas none of the patients in our series had values greater than 5 mm or a 2+ pivot shift [44]. Comparing IKDC scores of their studies with those of ours, their results showed 56% to 93% of patients were in the A or B category, whereas 100% of our patients were classified into these categories. Loss of ROM exceeding 5°was reported in 2% to 4% of the patients in several studies [25, 29, 32], whereas no patient lost ROM exceeding 5° in the current study. One possible explanation for this difference could be

Table 1. List of patients with a followup of 24 months or longer

Patient number	Age at revision (years)	Followup (years)	Time from first ACL reconstruction to revision (years)	Diagnosis of graft failure to revision (months)	Cause for revision	Preoperative KT (mm)	Grafts for revision	Meniscal injury at revision	Previous grafts	Previous tunnel aperture position	
										At the tibia	At the femur
1	22	6.1	2.4	1.2	New trauma	10	BTB	LM	SMT	Anatomic × 2	Anatomic × 2*
2	16	5.8	1.8	0.5	New trauma	4	BTB	None	SMT	Anatomic × 2	Anatomic × 2*
3	34[1]	5.7	5.9	4.0	New trauma	4	BTB	None	SMT	Anatomic × 1	High × 2
4	21	2.1	2.1	1.7	Technical failure	6	BTB	LM	SMT	Posterior × 1	High, anterior × 1
5	21	2	2	1.4	Technical failure	16	BTB	MM	SMT	Posterior × 1	High, anterior × 1
6	17	2	1.7	2.9	New trauma	5	BTB	None	SMT	Anatomic × 2	Anatomic × 2*
7	20	2	0.4	3.3	New trauma	10	SMT	LM	BTB	Anatomic × 1	Anatomic × 1
8	32	3.3	3.8	1.5	New trauma	12	BTB	LM	SMT	Anatomic × 2	Anatomic × 2*
9	34	3	8	2.1	Technical failure	5	QTB	None	BTB	Posterior × 1	High, anterior × 1
10	15	2	1	3.5	New trauma	7	BTB	None	SMT	Anatomic × 3	Anatomic × 2*
11	22	2	2.3	2.3	New trauma	9	BTB (contralateral)	LM	BTB	Anatomic × 1	Anatomic × 1
12	19[2]	2.2	8.3	1.9	New trauma	5	BTB (contralateral)	None	BTB	Anatomic × 1	Anatomic × 1
13	20	5.3	2	4.7	New trauma	12	BTB	None	SMT	Anatomic × 2	Anatomic × 2*
14	19	3.5	1.1	1.5	New trauma	7	BTB	MM	SMT	Anatomic × 3	Anatomic × 2*
15	28	2	11.5	1.8	New trauma	4	BTB	MM + LM	SMT	Anatomic × 1	High × 2
16	28[3]	5	3.5	2.0	New trauma	5	BTB	MM	SMT	Anatomic × 2	Anatomic × 2*
17	18	5.5	2.3	2.5	New trauma	4	BTB	None	SMT	Anatomic × 2	Anatomic × 2
Mean ± SD	22.7 ± 6.2	3.5 ± 1.7	3.5 ± 3.1	2.3 ± 1.1	NA	7.4 ± 3.6	NA	NA	NA	NA	NA

[1]Fig. 3; [2]Fig. 4; [3]Fig. 5; * anterior widening of femoral tunnel aperture; BTB = bone-patellar tendon-bone autograft; QTB = quadriceps tendon-bone autograft; SMT = two double-looped semitendinosus tendon autograft; KT = side-to-side difference at manual maximum force with KT-1000 arthrometer; NA = not applicable; MM = medial meniscus; LM = lateral meniscus; contralateral = contralateral leg.