The Knee 20 (2013) 332–338

Contents lists available at ScienceDirect

The Knee

Promising short-term results following selective bundle reconstruction in partial anterior cruciate ligament tears

Ferran Abat [a], Pablo Eduardo Gelber [a,b,*], Juan I. Erquicia [b], Xavier Pelfort [b], Marc Tey [b], Juan Carlos Monllau [a,b]

[a] *Department of Orthopaedic Surgery, Hospital de la Santa Creu i Sant Pau, Universitat Autònoma de Barcelona, Sant Quintí 89, 08041 Barcelona, Spain*
[b] *ICATME—Institut Universitari Dexeus, Universitat Autònoma de Barcelona, Sabino de Arana 5-19, 08028 Barcelona, Spain*

A R T I C L E I N F O

Article history:
Received 15 October 2012
Received in revised form 11 May 2013
Accepted 24 May 2013

Keywords:
Anterior cruciate ligament
Augmentation
Selective reconstruction
Partial tear

A B S T R A C T

Background: The different functions of the two anterior cruciate ligament (ACL) bundles have increased interest in tears of only one of these two bundles. The purpose of this study was to assess the outcome of selective reconstruction of an injured bundle of isolated anteromedial bundle (AMB) or posterolateral bundle (PLB) tears.
Methods: Consecutive series of 147 ACL reconstructions was prospectively analyzed. Patients with partial ACL tears who underwent selective bundle reconstructions were studied. Stability was assessed with the Lachman, anterior-drawer and pivot-shift tests and KT-1000. Functional assessment was performed with Lysholm and Tegner questionnaires. The preoperative MRI was analyzed to detect differences from arthroscopic findings.
Results: Twenty-eight patients (19%) were included. The minimum follow-up period was 30 months. Eighteen had AMB and 10 PLB tears. Only 19% of their MRI's were categorized as partial ACL tears.
The Lysholm score improved from 66.1/65.5 to 96.6/95.2 in the AMB/PLB groups, respectively ($p < 0.001$). The same or no more than one level lower Tegner score was restored. The pivot-shift, Lachman and anterior-drawer tests were negative in all cases ($p < 0.001$). Two reconstructed AMBs developed extension loss due to Cyclops lesions and were resolved surgically.
Conclusions: The technique provided excellent functional scores with normalized stability and a return to previous level of activity with a low rate of minor complications at a minimum 2.5 years' follow-up. Arthroscopic examination was the most reliable tool for properly diagnosing and treating a condition observed in almost one out of every five ACL reconstructed knee in this series.
Level of evidence: Therapeutic case series; level 4.

1. Introduction

The different functional roles of the two recognized anterior cruciate ligament (ACL) bundles have been widely studied over the last decade. While the anteromedial bundle (AMB) is taut throughout ROM with maximum tension between 45° and 60° of knee flexion, the posterolateral bundle (PLB) is primarily tight in extension [1,2]. In addition, the PLB has a crucial role in the rotational stability of the knee joint [3]. These different functions of the two ACL bundles have increased interest in isolated tears of one of the two bundles of the anterior cruciate ligament (ACL). Three decades ago, Mott [4] was the first to describe how to surgically reconstruct the ruptured fibers of the ACL while preserving its remnants. They defined it as an augmentation ACL technique. However, this technique has been more frequently performed only in the last few years, once the double bundle technique had been popularized.

Preserving the uninjured bundle at least has some theoretical advantages. First, ACL remnants may add biomechanical strength and stability to the reconstruction in the immediate post-operative period [5], while graft strength primarily depends on the fixation device. Moreover, the residual portion of the ACL may maintain its blood supply and thus provide support to the healing process of the graft [5–7]. In addition, maintaining some of its proprioceptive innervation might allow for a faster return to sport [8]. Finally, the intact bundle might help to optimize the accuracy of bone tunnel placement by serving as a landmark.

Controversies exist regarding the reported incidence of partial tears of the ACL in all the cases of ACL ruptures. They range from as low as 5% to as high as 25% depending on the series [3,9–11]. These differences might be due to the fact that partial ruptures of the ACL may evolve to complete tears secondary to necrosis of the intact fibers produced by blood supply interruption [9,12]. The lack of an accurate and reproducible tool to properly diagnose partial ACL ruptures might further explain these different reported incidences. Clinically, an isolated AMB tear will theoretically show a highly positive anterior drawer test and a mildly positive Lachman test with a negative pivot-shift test [13]. In contrast, patients with a symptomatic PLB rupture will complain of rotational

* Corresponding author at: Department of Orthopaedic Surgery, Hospital de la Santa Creu i Sant Pau, Universitat Autònoma de Barcelona, Sant Quintí, 89, 08041 Barcelona, Spain. Tel.: +34 93 553 70 31; fax: +34 93 553 70 33.
E-mail address: personal@drgelber.com (P.E. Gelber).

0968-0160/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.knee.2013.05.006

instability with small anterior laxity and a clearly positive pivot shift maneuver [13]. However, this is not always as clearly seen in the clinical setting. In addition, the accuracy of standard magnetic resonance imaging (MRI) might be as low as 25% to 53% [14]. Thus, while a partial ACL rupture may be suspected from the physical examination and MRI evaluation, an accurate arthroscopic assessment performed by an experienced surgeon is currently considered the approach to take to confirm the diagnosis [15]. While Adachi et al. [16] reported the first short-term results of an augmentation technique; few other studies have been published in recent years that report on the results of ACL augmentation procedures. They have mostly observed that it provides excellent joint stability, joint position sense and functional scores after few years of follow-up [5,11,17]. However, studies that report on the ability of this surgical technique to restore the pre-injury activity level of the patients are almost inexistent.

The purpose of this study was to assess the functional results and the activity level after selective reconstruction of the injured bundle of isolated AMB or PLB tears and to investigate the incidence in a consecutive series of ACL reconstructions. The first hypothesis was that this surgical procedure would provide optimal joint stability and functionality so as to restore pre-injury activity levels with a low rate of complications at short-term follow-up. The second hypothesis was that the incidence would be closer to those highest reported rates.

2. Materials and methods

From October 2008 to February 2010, a consecutive series of 147 ACL reconstructions was prospectively analyzed. Patients complaining of knee instability due to partial ACL tears that were operated on with selective reconstruction of the injured bundle were included in the study. Exclusion criteria were patients with either a concomitant injury or previous surgery of any other major ligament in the knee. Patients with any surgical treatment of associated chondral injuries were also excluded from the study.

The clinical research ethics committee of our institution approved the study (11/145/1350). All the patients signed informed consent to participate in the study as well as for evaluation and publication of their results.

The diagnosis of partial tears was suspected from the physical examination and MRI assessment. However, tears of a single bundle were only confirmed arthroscopically.

2.1. Clinical and functional evaluation

The evaluation included the Lachman test and the anterior drawer test at 90° of knee flexion and the pivot-shift maneuver to assess the rotational stability. All these three parameters were qualified using the International Knee Document Committee criteria as grades 0, 1+, 2+ and 3+. These data were first obtained at the office and confirmed before surgery in an exam under anesthesia. Quantitative assessment of anterior tibial translation was performed at the office with the laximeter KT-1000 (Medmetric, San Diego, CA, USA) at 30 lb to find side-to-side differences. Clinical and functional follow-up also included the objective IKDC ligament evaluation form, the Lysholm questionnaire and the Tegner activity score. The physical examination as well as the functional evaluation of every patient was performed preoperatively and at final follow-up by a single sports medicine surgeon who was independent of the study and blinded to the type of ACL surgery (i.e. AMB, PLB or total ACL reconstructions) that had been performed.

2.2. MRI evaluation

Magnetic resonance images with standard axial, coronal and parasagittal images were obtained for every patient. All studies were performed with a 1.5-T superconducting magnet (Prestige 2 T; Elscint, Haifa, Israel) using a knee specific circular coil. A positioning device for the ankle was used to ensure uniformity. The standard knee protocol for each subject consists of the following sequence: Axial fast-spin-echo T2-weighted with fat saturation (TR: 2300 ms; TE: 30 ms; FA: 90°; ST: 3 mm; FOV: 20 cm), coronal fast spin-echo intermediate-weighted (TR: 2500 ms; TE: 30 ms; FA: 90°; ST: 4 mm; FOV: 18 cm), sagittal spin-echo intermediate-weighted (TR: 700 ms; TE: 14 ms; FA: 90°; ST: 4 mm; FOV: 18 cm) and sagittal fast spin-echo T2-weighted with fat saturation (TR: 2500 ms; TE: 85 ms; FA: 90°; ST: 4 mm; FOV: 18 cm).

A diagnosis of a partial ACL rupture was suspected when any of the following signs were observed in the magnetic resonance images [14]: a, hyperintense signal within the ACL substance; b, distortion of fibers without obvious discontinuity; and c, attenuation and/or abnormal orientation of the ACL with respect to Blumensaat's line. When either complete discontinuity or a complete absence of the ACL fibers was observed, the diagnosis of a total ACL tear was made. The same radiologist, experienced in musculoskeletal diagnosis, performed the evaluation of the images for every patient.

2.3. Arthroscopic evaluation and surgical technique

All the surgeries were performed or supervised by the same surgeon. A high anterolateral viewing portal was first established. This high portal allowed a better assessment of the tibial side of the ACL [18]. Either a high medial parapatellar portal or a transpatellar medial portal was then conveniently established as a viewing portal for the midsubstance and proximal aspect of the ACL. Finally, an accessory low anteromedial portal was performed. Concomitant meniscal lesions were addressed before the ACL procedure.

The visual aspect of the remnants was studied with the arthroscope from the central portal to confirm that the remaining tibial and femoral fiber attachments were located inside the anatomic ACL footprints. Both bundles were routinely examined at various knee flexion angles to consider the different tension patterns of the two bundles. The AMB has relatively constant levels of in situ forces during knee flexion and it was best tested arthroscopically between 70° and 90° [3,13]. Conversely, the highest in situ forces of the PLB are seen between 0° and 30° of knee flexion [3,13], but the intercondylar notch cannot be examined arthroscopically close to extension [15]. Thus, in the figure-of-4 position the PLB is more easily identified as the femoral PLB footprint is usually rotated and exposed in the anterior aspect of the intercondylar wall [15]. Bleeding and discontinuity are signs of rupture. A lax PLB is not a sign of rupture, because it is normally lax at 90° of knee flexion. This is crucial to avoid overdiagnosis of PL bundle tears. In addition, we systematically performed what we call the *extension–flexion PLB test*. Handling the probe firmly under the PLB at 90° of knee flexion, we start to extend the knee progressively. In intact PLBs, the extra-articular end of the probe will be forced in an upward direction due to the progressive tightening of the bundle. In contrast, when facing a PLB rupture, the probe will be easily kept in the starting position, because the ruptured ligament will not sufficiently tighten to push against the probe.

Once the isolated bundle rupture of the ACL was confirmed, the graft was harvested. From a longitudinal incision 2 cm long and 2 cm medially to the medial border of the tibial tuberosity (TT), the ipsilateral semitendinosus tendon (ST) was harvested and routinely triplicated. In cases of an AMB reconstruction with a triplicated ST graft thinner than 7 mm or a PLB reconstruction with a triplicated ST graft thinner than 6 mm, following an arbitrary cut-off regardless the height of the patient or the size of the intercondylar notch, the graft construction was augmented with a gracilis tendon (GT). Fixation at the femoral side was obtained with an extracortical fixation implant (XoButton device, ConMed Linvatec, Largo, FL, USA) whereas it was accomplished with a 2 mm-oversized bioabsorbable interference screw (BioScrew, ConMed Linvatec) on the tibial side.

2.3.1. AMB reconstruction

The center of the femoral AMB bone tunnel was located either with the help of a femoral offset guide (ConMed Linvatec) (Fig. 1a) or with a freehand technique. For the tibial AMB bone tunnel, the tibial drill guide (ConMed Linvatec) was set at between 55° and 60° and it was placed 2 cm medial to the TT on the distal tibial cortex. The intra-articular tip was positioned in the anteromedial part of the tibial footprint of the medial tibial plateau and 4 to 5 mm posterior to the anterior rim of the ACL stump. A guidewire was overdrilled by a conventional reamer 1 mm smaller than the diameter of the graft without compromising the intact insertion of the PL bundle. The soft trabeculae of the tibia were finally compressed with a dilator that matched the graft diameter to help compact the surface of the tunnel. Fixation of the graft was done between 20° and 30° of knee flexion (Fig. 1b).

2.3.2. PLB reconstruction

The intact AMB was used as a landmark for orientation (Fig. 2a). Special care was taken to preserve these intact ACL fibers. While viewing through the high AM or transpatellar portal, the center of the femoral footprint of the PLB was located and marked either with the tip of a curved awl or with the help of the BullsEye femoral guide [19] (ConMed Linvatec) (Fig. 2b). The knee was then further flexed at a minimum of 110° and the femoral tunnel was drilled. The tibial tunnel was performed with the ACL tibial drill guide set at between 55° and 65°. It was placed 3 cm medial to the TT on the distal tibial cortex. The intra-articular tip of the guide was positioned in the posterolateral aspect of the tibial ACL insertion at an average of 4 to 5 mm medial to the lateral eminentia intercondylaris and 4 to 5 mm anterior to the posterior root of the lateral meniscus. The intact AMBs were retracted with a probe through the accessory AM portal to protect it during the tibial tunnel drilling (Fig. 2c). A conventional reamer carefully overdrilled the guide with the same technique as that described for the AMB tibial tunnel. Fixation of the graft was also performed between 20° and 30° of knee flexion (Fig. 2d) because it has been shown that both bundles carry approximately the same load within this 10° of motion [20].

2.4. Rehabilitation protocol

All the patients followed the same rehabilitation program, similar to the one recommended for standard ACL reconstructions. However, the physiotherapists were allowed to gently accelerate restoration of full extension and quadriceps function of the patients. Full weight-bearing and full range of motion was then encouraged from that beginning. Apart from isometric exercises with the knee in full extension, quadriceps-strengthening exercises were restricted to closed kinetic chain exercises during the first 12 weeks. Sport-specific drills were started and gradually progressed after 3 months. Full activities and a return to contact sport were only allowed at least 6 months after surgery depending on the physical examination, strength and the MRI aspect of the graft.

2.5. Statistical analysis

Continuous variables are presented as mean, standard deviation (SD), maximum and minimum. Categorical variables are presented as percentages and frequencies.

Because of the small sample number, statistical tests were not utilized to evaluate normality. Instead, the assessment was performed with non-parametric equivalents, which showed no discrepancies in terms of significance. The relationship between the variables was described with contingency tables for the categorical one, and the inference was studied with the chi-square test or Fisher's exact test depending on what corresponded. The inference in continuous variables was calculated with the paired-samples *T*-test and their results are presented with their 95% confidence interval (95% CI). The level of significance was set at 5% ($\alpha = 0.05$), bilateral approximation. All the analyses were performed with the SPSS 19 (SPSS Inc., Chicago, Illinois).

3. Results

From a total of 147 ACL procedures, 28 cases corresponded to selective reconstructions of the injured bundle. This represented an incidence of 19% of all the performed ACL reconstructions. At an average of 37.3 months (range, 30–46), all the 28 cases were available for follow-up. Eighteen of those 28 cases (64.3%) were AMB reconstructions and the remaining 10 cases (35.7%) were PLB augmentation procedures. The series comprised 21 men (75%) and 7 women (25%) with a mean age of 30.4 years (range, 16 to 47) at the time of surgery. Twelve surgeries (42.9%) were performed on the right knees whereas the remaining 16 cases (57.1%) were done on the left knee. The median time period from injury to operation was 68 days (range, 15–280 days). All the injuries were sustained during sport activities, most commonly soccer ($n = 13$), skiing ($n = 8$) and basketball ($n = 5$).

In 20 patients, the ACL reconstructions were performed with a triplicated semitendinosus tendon with a mean diameter of 7.1 mm (SD, 0.6 mm). In the remaining 8 patients, a double semitendinosus and gracilis tendon grafts (quadrupled hamstring graft) were used. Their mean diameter was 8.4 mm (SD, 0.9 mm). Those grafts used in AM bundle reconstructions had a mean diameter of 7.4 mm (SD, 0.9 mm) while those grafts corresponding to PL bundle reconstructions had a mean of 6.5 mm (SD, 1.1 mm). Relative to concomitant lesions, eight patients had meniscal tears that were treated with partial meniscectomy. Only two of the patients had minor injuries in the articular cartilage that were left untreated. The operation time had a mean of 64 min (SD, 6 min). No complications were observed during the surgeries.

The radiologist found at least one sign [36] of a partial ACL rupture in only six cases (21.4%) of the preoperative MRI analyzed (Fig. 3a). The radiologist described a total ACL tear in the remaining 22 cases (78.6%) (Fig. 3b).

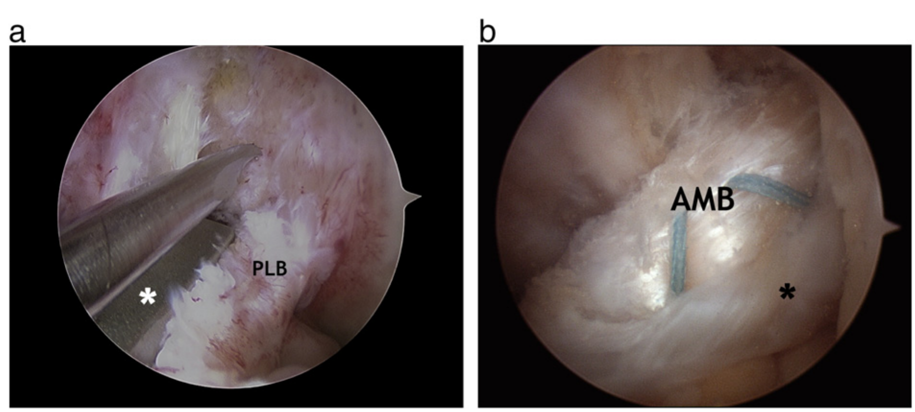

Fig. 1. Reconstruction of the anteromedial bundle (AMB) of the ACL in a left knee. a, Arthroscopic view from a medial parapatellar portal. The drill guide was placed at the center of the AMB footprint with the help of an offset-guide (*). The intact PLB was a useful landmark to improve accurate placement of the AMB tunnel. b, The reconstructed AMB is seen from the high anterolateral portal.

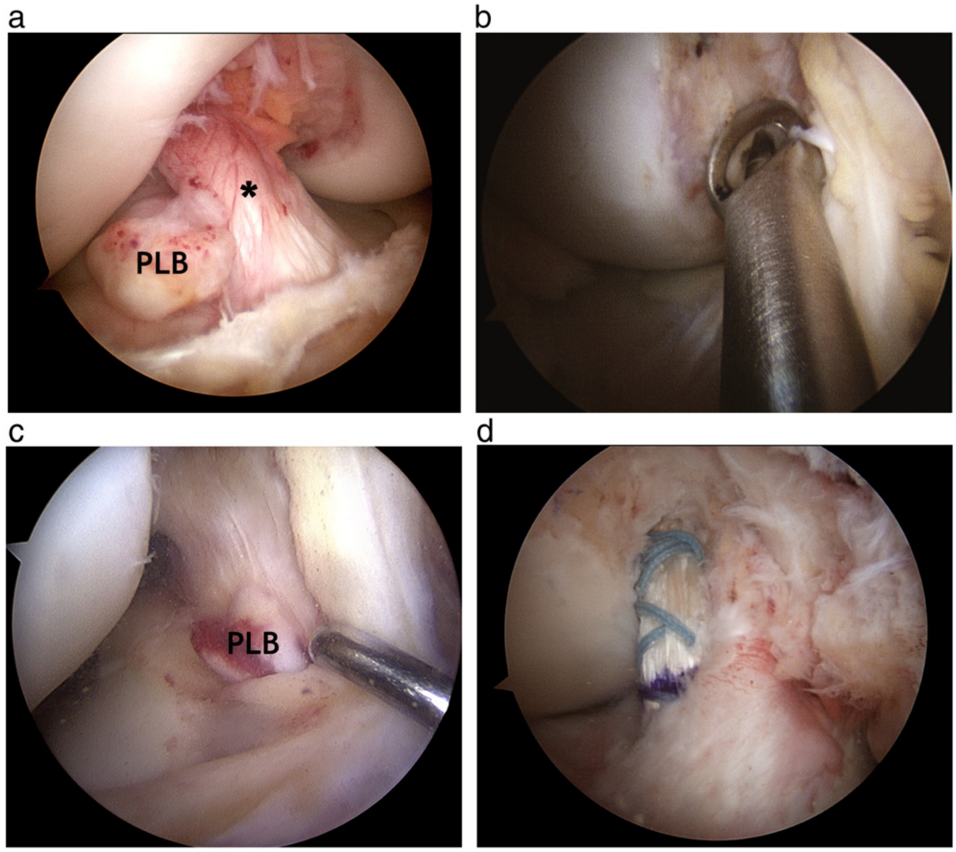

Fig. 2. Isolated tear of the posterolateral bundle (PLB) of the ACL in a right knee. a, Arthroscopic view from the high anterolateral portal. The PLB was observed clearly ruptured while the anteromedial bundle (*) was seen intact. b, Arthroscopic view through a transpatellar portal. The BullsEye guide (ConMed Linvatec) helped to calculate the limits of the posteriorly drilled PLB tunnel. c, The intact AMB is pulled from the accessory AM portal with a probe to improve visualization of the PLB tibial footprint. d, A reconstructed PLB is seen from the transpatellar portal.

3.1. Clinical and functional evaluation

All the patients complained, preoperatively, of recurrent giving-way episodes. The pivot-shift test was positive in 15 out of 18 (83.3%) AMB reconstructions and in eight out of 10 (80%) PLB reconstructions. With regard to the Lachman test, it was positive in 17 cases in the AM bundle group (94.4%) and in six cases in the PL bundle group (60%). No patient had both negative pivot-shift and Lachman tests. No differences were observed between the AMB and PLB groups (Table 1) or between the results of the examination at the office and under anesthesia. In all cases, the pivot-shift, the Lachman and the anterior drawer tests were negative at final follow-up ($p < 0.001$).

An overall improvement was obtained in terms of the objective IKDC, the Lysholm questionnaire and the Tegner activity score. Postoperatively, 25 patients were classified as IKDC grade A and the remaining three patients as IKDC grade B ($p < 0.001$) (Table 2). The Lysholm score improved from a mean 66.1 (SD, 1.3) to 96 (SD, 1.4) in

Fig. 3. a, MRI that reported a partial ACL injury. An isolated tear of the PLB was later confirmed during the arthroscopic procedure. The AMB is seen intact. b, MRI which had reported a complete ACL tear but which was arthroscopically diagnosed with an isolated PLB tear. c, In the MRI of the same patient after 8 months of the isolated reconstruction of the PLB (*), the intact AMB was also clearly seen (arrow).

the AMB group and from 63.5 (SD, 5.4) to 95.6 (SD, 0.6) in the PLB group ($p < 0.001$). All the patients' scores were either restored or decreased a single level in comparison to the pre-injury Tegner activity score ($p = 0.42$) (Table 3). The mean side-to-side difference observed during the instrumented laxity testing dropped down from 3.5 mm (SD, 0.5 mm) preoperatively to 0.6 mm (SD, 0.6 mm) postoperatively ($p < 0.001$) (Table 1). All the patients had postoperative laxity lower than 3 mm than that measured in the non-injured knee.

3.2. Complications

Complications were observed in three patients (10.7%). Two out of 18 of the AMB reconstructions (11.1%) had a persistent extension deficit. In both cases, full knee range of motion had been confirmed at the end of the surgical procedure. The postoperative radiographs confirmed that the tibial as well as the femoral tunnels were properly placed. The extension loss was attributed to Cyclops-like lesions in both patients (Fig. 4). They were successfully treated with arthroscopic resection. These two cases occurred in the first five patients of the series operated on. The remaining patient, with a PLB reconstruction that had been operated on nine days earlier, developed septic arthritis. The patient was treated with arthroscopic debridement and specific antibiotic therapy for 6 weeks. All three patients regained full range of motion and showed no differences in any of the studied variables of the other 22 cases.

4. Discussion

The anatomic augmentation of ACL partial injuries with the described technique showed significant improvement in the Lysholm scores and in joint stability. It also was shown to restore to the same Tegner score level or only one score lower, which is even superior to the 76% of full returns reported in one of the few previous studies reporting level of activity [5]. These findings confirmed the first hypothesis. In addition, the incidence rate of only one injured bundle among all the ACL injuries was within the rate that has been previously reported. While Kaz et al. [21] reported 5% partial tears, Sonnery-Cottet et al. [17] reported 7.1%, Ochi et al. [10] 10%, Crain et al. [22] 20% and Zantop et al. [3] 25%. Thus, the 19% incidence observed in the current investigation was closer to the highest reported rate, which confirmed the second hypothesis. Some of these differences in the reported incidences of partial ACL tears might be explained, to a certain degree, by the difficulty in finding universal agreement as to the best definition of partial ACL tears [15]. Whereas Noyes et al. [23] defined a partial tear as those involving less than 25% of the ligament, Hong et al. [24] considered partial ACL tear as those that show less than 50% of the fibers torn. DeFranco and Bach [25] proposed a multifactorial definition with an asymmetric Lachman test, a negative pivot shift, differential KT-1000 laxity equal to or less than 3 mm and the results of an arthroscopic examination. It is the author's opinion that this is the best way to classify partial ACL tears emphasizing the definitive value of arthroscopic assessment. However, the preoperative and arthroscopic diagnosis of partial tears of the ACL is still challenging and might be another crucial factor to explain the differences in the published incidences.

An experienced surgeon is considered critical to a more accurate arthroscopic assessment and diagnosis of partial ACL injuries and also to maintaining the uninjured fibers intact [15]. Saving ACL remnants during ACL reconstruction has some hypothetical biomechanical, vascular and proprioceptive advantages for the patient. First, the uninjured bundle may also allow optimized accuracy of bone tunnel placement at the insertion sites. The intact bundle may serve as a guide for orientation and a point of reference for the proper placement of the graft [15]. Secondly, the remnant may add strength to the bundle during the rehabilitation process, while graft strength depends essentially on the fixation device [5]. Thirdly, the residual bundle of the ACL may maintain the blood supply as was shown in different animal studies [5–7]. In one of those studies, Bray et al. [6] showed that surgically induced partial injuries promote a significant increase in blood flow and vascular volume. However, that the time interval for maturity and remodeling is shortened due to this phenomenon is yet to be proven. And finally, preservation of some ACL fibers may maintain some proprioceptive innervation increasing joint proprioception. The human ACL is extensively innervated and neural elements comprise approximately 1% of the area of the ligament [26]. Maintaining ACL remnants suggests, theoretically, that joint position sense may be increased, which may allow a faster return to sport [8]. However, the lack of studies specifically on ACL partial ruptures in addition to the difficulty in objectively assessing proprioception and the biological status of the graft make all these theories an as yet an unproven matter.

With regard to the few complications observed in the study, the most relevant from a surgical point of view were the two out of the 18 cases of AMB reconstruction that developed extension loss due to a Cyclops syndrome. Cyclops lesions leading to extension loss have previously been described in isolated tears of the AMB secondary to notch impingement of a pedunculated nodule of the anteromedial

Table 1
Preoperative clinical findings.

	AMB group	PLB group	Sig. (p)
Lachman test			
Negative	1 (5.5%)	4 (40%)	0.064
1+	16 (89%)	6 (60%)	
2+	1 (5.5%)	None	
3+	None	None	
Anterior drawer test			
Negative	1 (5.5%)	7 (70%)	0.001
1+	13 (72.3%)	3 (30%)	
2+	4 (22.2%)	None	
3+	None	None	
Pivot-shift test			
Negative	3 (16.7%)	2 (20%)	0.128
1+	15 (83.3%)	6 (60%)	
2+	None	2 (20%)	
3+	None	None	
KT-1000 test (mm)			
Pre	3.6 (3.30, 3.81)	3.5 (3.12, 3.88)	0.790
Post	0.8 (0.64, 1.02)	0.2 (−0.25, 0.65)	0.013
MRI diagnosis			
Partial tears signs	3 (16.7%)	3 (30%)	0.634
Total tears signs	15 (83.3%)	7 (70%)	

The statistical analysis was performed with the chi-square test, except KT-1000 values that were analyzed with independent *T*-test. Values are presented as number of cases (percentages). KT-1000 values are presented as mean (95% CI). Significance (p) comparing both groups.

Table 2
Objective IKDC evaluation.

Grade	Preoperative		Postoperative	
	AMB group	PLB group	AMB group	PLB group
A	0	0	16 (88.9%)	9 (90%)
B	3 (16.7%)	2 (20%)	2 (11.1%)	1 (10%)
C	14 (77.8%)	7 (70%)	0	0
D	1 (5.6%)	1 (10%)	0	0

Comparison between preoperative and postoperative values showed statistical differences ($p < 0.001$). Analysis was performed with the McNemar test. Values are presented as number of cases (percentages).

Table 3
Functional evaluation.

AMB				PLB			
Lysholm		Tegner		Lysholm		Tegner	
Preop.	Postop.	Pre-inj.	Postop.	Preop.	Postop.	Pre-inj.	Postop.
66.1 ± 1.3 (65.5–66.8)	96.0 ± 1.4 (95.3–96.7) $p < 0.001$	3.3 ± 0.5 (3.09–3.57)	7.0 ± 0.8 (6.62–7.38) $p < 0.001$	63.5 ± 5.4 (59.7–67.3)	95.6 ± 3.2 (93.3–97.9) $p < 0.001$	3.1 ± 0.6 (2.69–3.51)	7.5 ± 0.8 (6.89–8.11) $p < 0.001$

Statistical analysis was conducted with the paired-samples *T*-test. Results are expressed as mean ± SD (95% CI). Significance comparing the preoperative to the postoperative status.

Fig. 4. MRI of a patient with 5° of knee extension loss who underwent isolated reconstruction of the AMB of the ACL 5 months before. In this T2 view, a Cyclops nodule was detected (arrow).

remnant [27,28]. This phenomenon has also been described after standard single as well as double bundle ACL reconstruction technique [29]. Although the Cyclops nodule has also been observed in MRI following the remnant bundle preservation technique [30], this is the first report on such a complication that has led to extension loss in an isolated reconstruction of the AMB. These two cases, although the tunnels were correctly placed as it was assessed in their radiological as well as in their arthroscopic revisions, might be an example of the difficulty of the technique in resecting all the injured tissue while only preserving the intact ACL fibers. The fact that the two patients who developed this complication were some of the first patients operated on with this technique might be due to a learning curve period, which further stresses the difficulty of the procedure. In our experience, the tibial AMB stump was left in situ with the intent to maintain the high density of mechanoreceptors in that area during the first cases of selective AMB reconstructions [8]. After these two extension losses due to Cyclops lesions, the tibial stump of the AMB was instead more generously debrided and this type of complication has not been observed again since then. Sonnery-Cotter et al. [29] suggested that a 8 mm AM bundle graft along with a large PLM remnant contributed to the lack of extension, and thus they recommended keeping the size of the individual bundles in mind. However, the AML graft in those two patients from the present study who developed extension loss due to a Cyclops lesion had a diameter of 7 mm and 7.5 mm and no bulking of the remnant PLB on the AML grafts was observed in the revision surgery.

With regards to the clinical findings, Akgun et al. [13] performed an interesting experimental study in which the fibers of the AMB and PLB were resected in alternating order. They found that after isolated AM bundle transection, the anterior drawer test and Lachman test were highly positive, whereas the pivot shift test was always negative. On the other hand, isolated PL bundle-resected knees usually showed anterior drawer and Lachman tests as negative, whereas the pivot-shift maneuver was systematically positive. Although the Akgun et al. [13] study gives a comprehensive idea of the physical examination of isolated bundle tears, this pure split of only one of the two bundles is only feasible in an experimental model. Unfortunately, this is not always as clearly seen as in the aforementioned study in patients with symptomatic AMB or PLB tears who usually complain of non-specific symptoms like recurrent pain and swelling in clinical practice. All the patients in this investigation also complained for some degree of giving way episodes in pivoting activities regardless of the objective clinical examination. In addition and in contrast to the Akgun et al. study [13], most of the patients with isolated tear of the AMB had a positive pivot shift test and most of the patients with isolated tear of the PLB had a positive Lachman test. In fact, no differences in the results of any of these tests between AMB and PLB injured knees were observed.

Some studies have been published in the last few years that report the results of ACL augmentation procedures. Adachi et al. [16] published the first results of an augmentation technique, which was first described by Mott [4] in the early 80's. They showed better results in terms of residual laxity in comparison to a classic ACL reconstruction. More recently, Ochi et al. [5,10] and Sonnery-Cottet et al. [17] have reported excellent joint stability, joint position sense and Lysholm scores at short-term follow-up after selective AM and PL bundle reconstructions. These findings were in agreement with the excellent results observed in this study regarding functional scores, clinical evaluation for rotational and anterior stability of the knee including KT-1000 assessment and return to previous activity levels. These postoperative values are similar to the reported values after ACL double-bundle reconstruction [31–33].

With regard to MRI evaluation, the previously performed MRI diagnosed the ACL as partially injured instead of a total ACL tear in only 21.4% of the arthroscopically confirmed partial ACL ruptures. This low accuracy of standard MRI in terms of properly diagnosing a partial ACL tear has already been reported [14]. Steckel et al. [34,35] have shown that characterization of the two distinct bundles and diagnosis of isolated bundle tears can be highly improved by establishing ideal oblique planes in combination with a 3 T ultra-high-field strength MRI.

One of the most relevant limitations of the current study is the lack of a control group. Comparison with a conservatively treated group of patients, or better with a standard-reconstructed ACL group might have allowed for arriving at much stronger conclusions. Although a conservative treatment might have been followed, especially in those few patients who had normal Lachman test, they were active athletes who complained of some degree of instability with their pivoting activities. The low number of patients and the short-term follow-up are two other relevant weaknesses. However, this limitation is also observed in most of the currently available studies evaluating this technique [5,10,17]. The fourth limitation was that no functional and proprioceptive evaluation of the patients during the first 6 months postoperatively was done. Comparison of such findings with standard ACL reconstructions may be of utmost relevance to better reveal whether faster recovery may be expected after an ACL augmentation procedure. Another limitation was that rotational stability was only tested with the pivot-shift test. Although we are currently using a non-invasive pivot-shift accelerometer, which objectively compare the injured knee with the contralateral knee (KIRA device, Orthokey, Italy) [36], the device has yet to be validated for differentiating partial from total ACL ruptures.

Although these weaknesses do not allow for the verification of whether there is any superiority of isolated reconstruction of the injured bundle over standard ACL reconstructions, the results of this study showed that this technique was effective in restoring to the previous level of activity and in providing excellent functional results for the patients with an acceptable rate of minor complications. In addition, the low accuracy of the standard MRI in properly distinguishing partial from total ACL tears plus the variability in the clinical findings from patients with ACL tears shed light on the crucial role of the arthroscopic examination in the diagnostic chart of isolated injuries of one of the two ACL bundles.

In conclusion, selective reconstruction of the injured ACL bundle showed excellent functional scores with normalized stability and a return to the previous level of activity with a low-rate of minor complications at a minimum 2.5 years' follow-up. Arthroscopic examination was the most reliable tool for properly diagnosing and treating a condition observed in almost one out of every five ACL reconstructed knee in this series.

Conflict of interest statement

There are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

Acknowledgments

We are grateful to Ignasi Gich for assisting in the statistical analysis. We also thank Eric Goode for his help in correcting the manuscript.

References

[1] Furman W, Marshall JL, Girgis FG. The anterior cruciate ligament. A functional analysis based on postmortem studies. J Bone Joint Surg Am 1976;58:179–85.
[2] Weber E, Weber W. Über die Mechanik der menschlichen Gehwerkzeuge. Göttingen: Dieterich; 1836 .
[3] Zantop T, Herbort M, Raschke MJ, Fu FH, Petersen W. The role of the anteromedial and posterolateral bundles of the anterior cruciate ligament in anterior tibial translation and internal rotation. Am J Sports Med 2007;35:223–7.
[4] Mott HW. Semitendinosus anatomic reconstruction for cruciate ligament insufficiency. Clin Orthop Relat Res 1983;172:90–2.
[5] Ochi M, Adachi N, Uchio Y, Deie M, Kumahashi N, Ishikawa M, et al. A minimum 2-year follow-up after selective anteromedial or posterolateral bundle anterior cruciate ligament reconstruction. Arthroscopy 2009;25:117–22.
[6] Bray RC, Leonard CA, Salo PT. Vascular physiology and long-term healing of partial ligament tears. J Orthop Res 2002;20:984–9.
[7] Cray RC, Leonard CA, Salo PT. Correlation of healing capacity with vascular response in the anterior cruciate and medial collateral ligaments of the rabbit. J Orthop Res 2003;21:1118–23.
[8] Adachi N, Ochi M, Uchio Y, Iwasa J, Ryoke K, Kuriwaka M. Mechanoreceptors in the anterior cruciate ligament contribute to the joint position sense. Acta Orthop Scand 2002;73:330–4.
[9] Borbon CA, Mouzopoulos G, Siebold R. Why perform an ACL augmentation? Knee Surg Sports Traumatol Arthrosc 2012;20:245–51.
[10] Ochi M, Adachi N, Deie M, Kanaya A. Anterior cruciate ligament augmentation procedure with a 1-incision technique: anteromedial bundle or posterolateral bundle reconstruction. Arthroscopy 2006;22(463):e1–5.
[11] Siebold R, Fu FH. Assessment and augmentation of symptomatic anteromedial or posterolateral bundle tears of the anterior cruciate ligament. Arthroscopy 2008;24:1289–98.
[12] Noyes FR, Bassett RW, Grood ES, Butler DL. Arthroscopy in acute traumatic hemarthrosis of the knee. Incidence of anterior cruciate tears and other injuries. J Bone Joint Surg Am 1980;62:687–95.
[13] Akgun I, Can Unlu M, Edipoglu E, Uzun I. Evaluation of the functional effects of anterior cruciate ligament bundles. A cadaveric experiment. J Knee Surg 2009;22:317–24.
[14] Van Dyck P, De Smet E, Veryser J, Lambrecht V, Gielen JL, Vanhoenacker FM, et al. Partial tear of the anterior cruciate ligament of the knee: injury patterns on MI images. Knee Surg Sports Traumatol Arthrosc 2012;20:256–61.
[15] Colombet P, Dejour D, Panisset JC, Siebold R. Current concept of partial anterior cruciate ligament ruptures. Orthop Traumatol Surg Res 2010;96:109–18.
[16] Adachi N, Ochi M, Uchio Y, Sumen Y. Anterior cruciate ligament augmentation under arthroscopy. A minimum 2-year follow-up in 40 patients. Arch Orthop Trauma Surf 2000;120:128–33.
[17] Sonnery-Cottet B, Lavoie F, Ogassawara R, Scussiato RG, Kidder JF, Chambat P. Selective anteromedial bundle reconstruction in partial ACL tears: a series of 36 patients with mean 24 months follow-up. Knee Surg Sports Traumatol Arthrosc 2010;18:47–51.
[18] Cohen SB, Fu FH. Three-portal technique for anterior cruciate ligament reconstruction: use of a central medial portal. Arthroscopy 2007;23:325.e1–5.
[19] Gelber PE, Erquicia J, Abat F, Torres R, Pelfort X, Rodriguez-Baeza A, et al. Effectiveness of a footprint guide to establish an anatomical femoral tunnel in anterior cruciate ligament reconstruction. Computed tomography evaluation in a cadaveric model. Arthroscopy 2011;27:817–24.
[20] Miura K, Woo SL, Brinkley R, Fu YC, Noorani S. Effects of knee flexion angles for graft fixation on force distribution in double-bundle anterior cruciate ligament grafts. Am J Sports Med 2006;34:577–85.
[21] Kaz R, Starman JS, Fu FH. Anatomic double-bundle anterior cruciate ligament reconstruction revision surgery. Arthroscopy 2007;23(1250):e1–3.
[22] Crain EH, Fithian DC, Paxton EW, Luetzow WF. Variation in anterior cruciate ligament scar pattern: does the scar pattern affect anterior laxity in anterior cruciate ligament-deficient knees? Arthroscopy 2005;21:19–24.
[23] Noyes FR, Mooar LA, Moorman III CT, McGinniss GH. Partial tears of the anterior cruciate ligament. Progression to complete ligament deficiency. J Bone Joint Surg Br 1989;71:825–33.
[24] Hong SH, Choi JY, Lee GK, Choi JA, Chung HW, Kang HS. Grading of anterior cruciate ligament injury. Diagnostic efficacy of oblique coronal magnetic resonance imaging of the knee. J Comput Assist Tomogr 2003;27:814–9.
[25] DeFranco MJ, Bach Jr BR. A comprehensive review of partial anterior cruciate ligament tears. J Bone Joint Surg Am 2009;91:198–208.
[26] Schutte MJ, Dabezies EJ, Zimny ML, Happel LT. Neural anatomy of the human anterior cruciate ligament. J Bone Joint Surg Am 1987;69:243–7.
[27] Irisawa H, Takahashi M, Hosokawa T, Nagano A. Cyclops syndrome occurring after chronic partial rupture of the anterior cruciate ligament without surgical reconstruction. Knee Surg Sports Traumatol Arthrosc 2007;15:144–6.
[28] Runyan BR, Bancroft LW, Peterson JJ, Kransdorf MJ, Berquist TH, Ortiguera CJ. Cyclops lesions that occur in the absence of prior anterior ligament reconstruction. Radiographics 2007;27:e26.
[29] Sonnery-Cottet B, Lavoie F, Ogassawara R, Kasmaoui H, Scussiato RG, Kidder JF, et al. Clinical and operative characteristics of Cyclops syndrome after double-bundle anterior cruciate ligament reconstruction. Arthroscopy 2010;26:1483–8.
[30] Cha J, Choi SH, Kwon JW, Lee SH, Ahn JH. Analysis of Cyclops lesions after different anterior cruciate ligament reconstructions: a comparison of the single-bundle and remnant bundle preservation techniques. Skeletal Radiol 2012;41:997–1002.
[31] Colombet P, Robinson J, Jambou S, Allard M, Bousquet V, de Lavigne C. Two-bundle, four-tunnel anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc 2006;14:629–36.
[32] Järvelä T. Double-bundle versus single-bundle anterior cruciate ligament reconstruction: a prospective, randomize clinical study. Knee Surg Sports Traumatol Arthrosc 2007;15:500–7.
[33] Otsubo H, Shino K, Nakamura N, Nakata K, Nakagawa S, Koyanagi M. Arthroscopic evaluation of ACL grafts reconstructed with the anatomical two-bundle technique using hamstring tendon autograft. Knee Surg Sports Traumatol Arthrosc 2007;15:720–8.
[34] Steckel H, Vadala G, Davis D, Fu FH. 2D and 3D 3-tesla magnetic resonance imaging of the double bundle structure in anterior cruciate ligament anatomy. Knee Surg Sports Traumatol Arthrosc 2006;14:1151–8.
[35] Steckel H, Vadala G, Davis D, Musahl V, Fu FH. 3-T MR imaging of partial ACL tears: a cadaver study. Knee Surg Sports Traumatol Arthrosc 2007;15:1066–71.
[36] Lopomo N, Signorelli C, Bonanzinga T, Marcheggiani Muccioli GM, Visani A, Zaffagnini S. Quantitative assessment of pivot-shift using inertial sensors. Knee Surg Sports Traumatol Arthrosc 2012;20:713–7.