29 ACL Augmentation

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29.1 Roles of Preserved ACL Remnant

There are three distinct reasons for which the preservation of ACL remnants may be beneficial for a successful ACL reconstruction.

The first reason is the biomechanical stability that may be enhanced by the presence of remnants. ACL remnants contribute to anteroposterior knee stability for up to 1 year after injury; however, beyond this time point, biomechanical function is lost [1].

Another reason that ACL should be retained during ACL reconstruction is the possible positive effect on the revascularization process. The vascular supply of the knee joint has been well described [2, 3]. The major supplying vessel of the intercondylar notch area, the human cruciate ligaments, and surrounding structures is the middle genicular artery [2, 3]. Prior studies have shown that the vascularization phase is one of the most important and sine qua non step in the ligamentization process [4, 5]. Revascularization of the substitute ACL graft occurs gradually along its length, with the intra-articular site being the first and the faster part to complete this phase, while both the intraosseous sites are still in progress throughout the first postoperative year [4]. Up to the second postoperative year, the intra-articular graft site reflected intense revascularization while a slower revascularization progress was noticed at the other two intraosseously enclosed sites [5]. Therefore the revascularization of the intra-articular part is an important link at the intrinsic healing chain of the ACL graft [4, 5]. In this context, the less damage of the ACL remnants that represent one of the important sites of the intra-articular native ACL part may be beneficial for the revascularization process.

The third reason for remnant preservation is the proprioception. It has been shown that in patients with ACL remnants adapted to the PCL, mechanoreceptors exist even 3 years after injury [6]. Since the restoration of proprioception is the result of reinnervation of the ACL, the preservation of ACL remnants as a source, if this is surgically possible without risk of a cyclops lesion, may be beneficial for the patient [6]. Actually, proprioceptive function was proved superior for patients with single-bundle (SB) augmentation reconstruction as compared to SB reconstruction at 6 and 12 months after surgery [7].

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Taken as a whole, relevant studies suggest that remnant-preserving ACL reconstruction would be favored for clinical and functional outcome since preservation of the ACL remnant may be beneficial in terms of proprioception, biomechanical functions, and vascularization of the graft. This evidence has influenced surgical techniques and remnant-preserving ACL reconstruction is used not only for partial rupture of the ACL but also for complete rupture.

29.2 ACL Augmentation Technique

29.2.1 Indications for ACL Augmentation

The decision as to whether the ACL remnant should be preserved and ACL augmentation performed is made after thorough consideration of clinical tests, laxity measurements, MRI, and arthroscopic findings [1, 8, 9]. Quantitative evaluation of anteroposterior knee laxity can aid in this decision. The patients are considered candidates for remnant-preserving ACL reconstruction when the side-to-side difference in the anterior displacement of the tibia is approximately less than 5 mm. MRI also provides important information regarding the condition of the proximal attachment of the ACL remnant. However, the final decision should be made after arthroscopic confirmation of the status of the injured ACL.

As stated in the former chapter (Diagnosis of Partial ACL Rupture), sometimes we encounter a partial rupture of the AM or PL bundle of the ACL during arthroscopy. Partial rupture of the ACL is an ideal indication for ACL augmentation. In these cases, single-bundle reconstruction of the ruptured bundle is desirable to preserve the femoral attachment of the remaining ACL bundle. In 2008, we began performing ACL augmentation even in patients with a continuous thick ACL remnant between the intercondylar notch and the tibia after complete rupture of the ACL. In this complete rupture group, the diameter of the proximal ACL remnant was greater than one-third of the original size and the femoral attachment of the ligamentous remnant was positioned abnormally. Anatomic central single-bundle or double-bundle [10] ACL reconstruction with the remnant-preserving technique is performed for the patients in this complete rupture group.

29.2.2 Surgical Technique

In this section, we describe surgical techniques of the single-bundle ACL augmentation as a standard procedure of remnant-preserving ACL reconstruction (Figs. 29.1 and 29.2). A four-strand gracilis and semitendinosus tendon or a quadrupled semitendinosus tendon is desirable as the graft for the augmentation. A three-portal technique (the anterolateral portal, the anteromedial portal, and the far-anteromedial portal) is used. The far-anteromedial portal is placed as inferior (close to the anterior portion of the medial meniscus) as possible, approximately 2.5 cm medial to the medial border of the patellar tendon.

29.2.2.1 Femoral Bone Tunnel

For femoral bone tunnel preparation, we regularly use the far-anteromedial portal technique, because this technique allows more flexibility in accurate anatomical positioning for femoral tunnel drilling than the transtibial technique. Excision of the femoral stump using a motorized shaver system is minimized. A delicate debridement and bone tunnel placement is important to minimize damage to the ACL remnant. It may be true that the main part of the femoral attachment of the ACL is on the resident's ridge from the biomechanical point of view, and the remaining part (fan-like extension fibers) is attached to the posterior portion of the ridge. However, we think that the center of the femoral tunnel opening should not be on the resident's ridge but should be placed just behind the resident's ridge when using the hamstring tendon for ACL reconstruction [9]. This is because the graft is pulled and shifts to the anterodistal side of the femoral tunnel opening in knee extension and mild flexion position. The center of the bone tunnel opening is not the central point of the application of force.

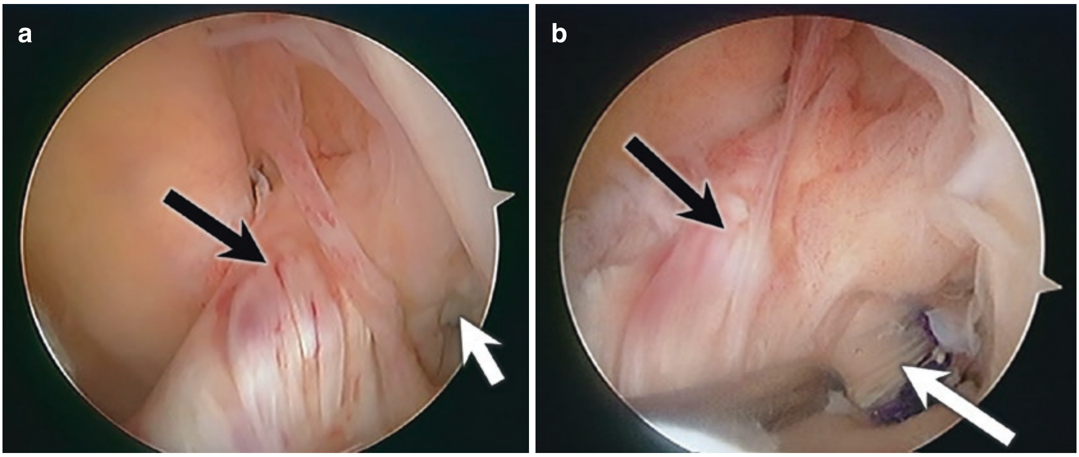

Fig. 29.1 (**a**) Partial rupture of the posterolateral (PL) bundle (*white arrow*). The anteromedial (AM) bundle (*black arrow*) of the ACL was well preserved although the remaining AM bundle is not completely intact. (**b**) AM bundle preserving ACL augmentation for the PL bundle rupture (*white arrow*, grafted tendon; *black arrow*, preserved AM bundle)

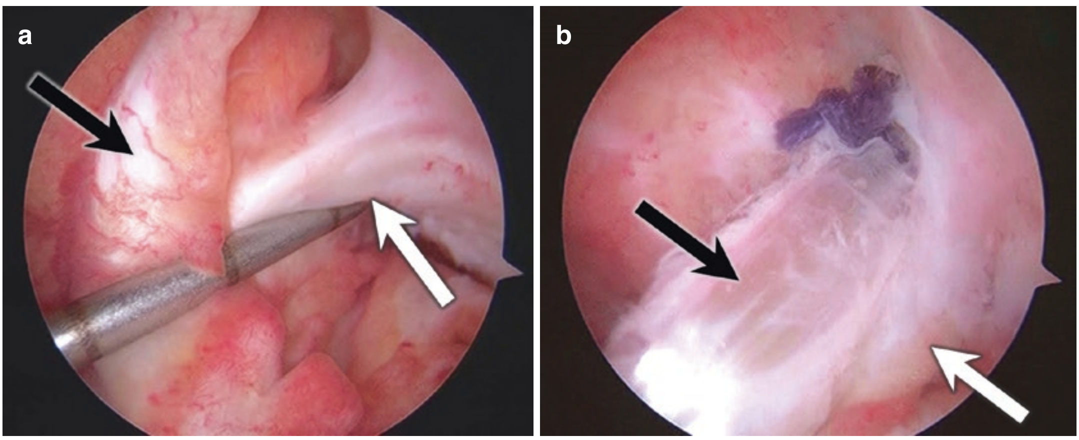

Fig. 29.2 (**a**) Partial rupture of the anteromedial (AM) bundle (*black arrow*). The posterolateral (PL) bundle (*white arrow*) of the ACL was preserved although the remaining PL bundle was not completely intact. (**b**) PL bundle preserving ACL augmentation for the AM bundle rupture (*black arrow*, grafted tendon; *white arrow*, preserved PL bundle)

In cases of PL bundle rupture, the central portion of the femoral tunnel is aimed at the clock position between 2 o'clock and 2:30 (left knee) or between 9:30 and 10 o'clock (right knee). At this position, approximately three-quarters of the femoral tunnel opening is occupied by the femoral attachment of the PL bundle and approximately one-quarter by the femoral attachment of the AM bundle. This is because we think that the remaining bundle is not intact and that the biomechanical function of the remaining bundle probably declines to some extent. In cases of AM bundle rupture, the central portion of the femoral tunnel was aimed at the clock position between 1:30 and 2 o'clock (left knee) or between 10 o'clock and 10:30 (right knee). In patients with a continuous thick ACL remnant between the intercondylar notch and the tibia after complete ACL rupture, the positions of the femoral bone tunnels is the same as used for standard anatomic single-bundle ACL reconstruction.

29.2.2.2 Tibial Bone Tunnel

In most cases, the tibial attachment of ACL remnant is normal. First, a longitudinal slit is made at the center of the ACL remnant through the anteromedial portal. The tip of the tibial drill guide, which is inserted through the anteromedial portal, is placed through the slit of the ACL remnant at an angle of 60–65° to the tibial plateau to allow visualization of the tip of the guide pin or Kirschner wire.

In cases of PL bundle rupture, the tip of the drill guide is positioned in the center of the tibial insertion of the whole ACL. In cases of AM bundle rupture and complete rupture, the tibial tunnel opening should be positioned as anterior as possible within the tibial footprint of the ACL. We recommend to check the position of the guide pin with the knee extended to see if the guide pin impinges on the roof of the intercondylar notch. When the position of the guide pin is satisfactory, the guide pin is advanced by a cannulated drill to create a tibial bone tunnel.

29.2.2.3 Graft Passage and Fixation

For cases such as the PL bundle rupture, if the graft passes above the ACL remnant, the positional relationship is anatomically incorrect. In such cases, pathologic impingement between the graft and the ACL remnant may occur. Therefore, in cases of PL bundle rupture and complete rupture, the graft should pass through the slit of the ACL remnant. As for the cases of AM bundle rupture, the graft should pass above the ACL remnant. The graft composites are introduced from the tibial tunnel to the femoral tunnel, and the proximal side of the graft is fixed to the lateral femoral cortex by flipping the endobutton. For graft fixation, we apply a tension force of 50 N to the distal endobutton tape connected to the graft and secure it with two staples at 30° of knee flexion.

29.3 Clinical Outcomes

29.3.1 Early History of ACL Augmentation

As detailed above, preserving the ACL remnant has great potential to contribute to knee function from several points of view. Therefore, in 1992, Ochi started performing ACL augmentation, when indicated, without sacrificing ACL remnant by using an autogenous hamstring tendon under arthroscopy. In 2000, Adachi et al. [11] reported that the proprioceptive function and joint stability of 40 patients who underwent arthroscopy-assisted ACL augmentation from 1992 to 1997 were superior to those of 40 patients who underwent standard single-bundle ACL reconstruction during the same period. However, in the early surgical procedure of ACL augmentation, the graft was passed through the over-the-top route for the femoral side. Therefore, the surgical technique needed two incisions at the medial aspect of the proximal tibia and also at the lateral femoral condyle. For this problem, Ochi started performing ACL augmentation with the one-incision technique using endobutton-CL and femoral bone tunnel and documented it as a report in 2006 [12]. The major indication for ACL augmentation was partial ACL rupture during the study period. In 2008, he started performing ACL augmentation even for patients with continuity of the ACL remnant between the femur and the tibia after complete ACL rupture. Anatomic central single-bundle ACL augmentation has been carried out for patients in this group.

29.3.2 Clinical Studies of ACL Augmentation

ACL augmentation has attracted much attention in the field of ACL reconstruction for this 10 years. Especially since 2006, a number of reports with regard to ACL augmentation has been published (Table 29.1) [13]. Several remnant-preserving techniques, including the remnant re-tensioning technique, selective AM or PL bundle reconstruction, and preservation of the ACL tibial remnant, have been described. To summarize the clinical results of ACL augmentation, we have reviewed the previous literature on ACL augmentation using a PubMed (1983–2014) and reported [13]. The review excluded case reports, literature review, animal studies, or current concepts. Table 29.1 [13] shows studies reporting arthroscopic remnant-preserving augmentation in ACL reconstruction. There are five different surgical techniques for ACL remnant preservation: (1) anatomic single-bundle ACL

Table 29.1 Studies reporting remnant-preserving augmentation in ACL reconstruction [13]

Study	Study design	Patient number[a]	Patient's age (years)[a]	Time from injury to reconstruction (months)[a]	Mean follow-up (months)[a]
Adachi and Ochi et al. (2000) [11]	Retrospective comparative study	40	25.8	4.2	38
Ochi et al. (2006) [12]	Technical note	17	31	Not reported	Not reported
Lee BI et al. (2006) [14]	Technical note	Not reported	Not reported	Not reported	Not reported
Buda et al. (2006) [15]	Case series	47	23.3	4.5	(More than 60)
Gohil et al. (2007) [16]	Randomized controlled trial	22	30.5	2	12
Buda et al. (2008) [17]	Case series	28	32.3	Not reported	27
Lee et al. (2008) [18]	Case series	16	35.1	5.5	35.1
Ochi et al. (2009) [8]	Case series	45	22	7.9	35
Yoon et al. (2009) [19]	Retrospective comparative study	82	28	7	24
Ahn et al. (2009) [20]	Technical note	65	Not reported	Not reported	Not reported
Kim et al. (2009) [21]	Technical note	21	Not reported	Not reported	12
Ahn et al. (2010) [22]	Cohort study	41	29.2	36.1	6.3
Sonnery-Cottet et al. (2010) [23]	Case series	36	32	6.6	24
Serrano-Fernandez et al. (2010) [24]	Case series	24	25	3	74
Ahn et al. (2011) [25]	Case series	53	32.2	28.2	27.7
Jung et al. (2011) [26]	Retrospective comparative study	76	32	2.5	31
Ochi et al. (2011) [10]	Technical note	Not reported	Not reported	Not reported	Not reported
Pujol et al. (2012) [27]	Randomized controlled trial	29	31.24	5.3	(More than 12)
Hong et al. (2012) [28]	Randomized controlled trial	39	34	10.3	25.8
Ohsawa et al. (2012) [29]	Case series	19	(15–57)	4.8	40.2
Yasuda et al. (2012) [30]	Case series	44	29	4	16.6
Park et al. (2012) [31]	Retrospective comparative study	55	30.4	7.0	34.1
Demirağ et al. (2012) [32]	Randomized controlled trial	20	28	2.3	24.3
Sonnery-Cottet et al. (2012) [33]	Case series	168	30	3	26

(continued)

Table 29.1 (continued)

Study	Study design	Patient number[a]	Patient's age (years)[a]	Time from injury to reconstruction (months)[a]	Mean follow-up (months)[a]
Cha et al. (2012) [34]	Retrospective comparative study	100	31.9	Not reported	Not reported
Muneta et al. (2013) [35]	Cohort study	88	22.1	6.7	(More than 24)
Kazusa and Ochi et al. (2013) [9]	Technical note	Not reported	Not reported	Not reported	Not reported
Maestro et al. (2013) [36]	Retrospective comparative study	39	28.1	1	31.7
Buda et al. (2013) [37]	Case series	52	23.3	4.3	(Up to 60)
Abat et al. (2013) [38]	Case series	28	30.4	2	37.3
Nakamae and Ochi et al. (2014) [39]	Retrospective comparative study	73	26.6	Not reported	28.9
Zhang et al. (2014) [40]	Randomized controlled trial	27	23.5	12.7	24.4
Lee et al. (2014) [41]	Retrospective comparative study	16	30.6	Not reported	29.5
Ahn et al. (2014) [42]	Technical note	Not reported	Not reported	Not reported	Not reported
Noh et al. (2014) [43]	Technical note	Not reported	Not reported	Not reported	Not reported
Sonnery-Cottet et al. (2014) [44]	Technical note	Not reported	Not reported	Not reported	Not reported
Muneta et al. (2014) [45]	Cohort study	200	Not reported	Not reported	Not reported
Kim et al. (2014) [46]	Retrospective comparative study	66	30	3	27
Taketomi et al. (2014) [47]	Technical note	47	31	4	Not reported

[a]Augmentation group only

augmentation preserving ACL remnant for complete rupture, (2) anatomic double-bundle ACL augmentation preserving ACL remnant for complete rupture, (3) single-bundle ACL reconstruction with remnant-tensioning technique, (4) selective AM or PL bundle augmentation for partial rupture, and (5) standard ACL reconstruction plus tibial remnant sparing. The ACL remnant in (1) and (2) maintains a bridge between the tibia and the intercondylar notch.

29.3.3 Clinical Outcomes of ACL Augmentation

Although there has been a growing interest in the potential advantages of ACL augmentation, a significant controversy remains regarding the use of remnant preservation techniques in ACL reconstruction. Thirteen clinical studies (Tables 29.2 and 29.3) [13] which compared the outcomes of ACL augmentation with those of the standard ACL reconstruction technique were selected from among studies in Table 29.1. Table 29.2 shows the characteristics of ACL remnant and type of graft in each study. Table 29.3 [13] shows clinical outcomes in each study. Several studies demonstrated favorable results using the ACL augmentation technique. Nakamae et al. report on the clinical outcomes and second-look arthroscopic findings of 216 patients who underwent ACL reconstruction (single or double bundle) or augmentation [39]. They concluded that patients in the ACL augmentation group exhibited better synovial

Table 29.2 Clinical studies which compared the ACL augmentation techniques with the standard ACL reconstruction technique [13]

Study	Conditions of ACL remnant for augmentation	Type of graft
Adachi and Ochi et al. (2000) [11]	ACL remnant bridging the femur and the tibia, with a diameter from one-third to one-half that of the normal ACL	Autogenous hamstring tendons or allogenic fascia lata
Gohil et al. (2007) [16]		Autologous hamstring tendons
Yoon et al. (2009) [19]	ACL remnant bridging the femur and the tibia anatomically, with a thickness of more than 50 % of that of the AM or PL bundle and laxity of less than 5 mm when drawn by a probe	Autologous hamstring tendons
Ahn et al. (2010) [22]	ACL remnant that could be tensioned toward the femoral bone tunnel	Autologous hamstring tendons
Pujol et al. (2012) [27]	Partial ACL tear; a well-inserted PL bundle	Autologous hamstring tendons or bone-patellar tendon bone
Hong et al. (2012) [28]	The remnant could be pulled to reach the femoral ACL insertion, and the remnant diameter was more than half of the native ACL	Allogeneic tibialis anterior or hamstring tendon
Park et al. (2012) [31]	Attachment of the remnant bundle between the femur and the tibia, the thickness of the ACL exceeding more than 50 % of that of the AM or PL bundle, and laxity of less than 5 mm when drawn by a probe	Autologous hamstring tendons
Demirağ et al. (2012) [32]	ACL remnant with more than one-half of its integrity preserved, bridging the tibia and the femur, and elongated no more than one-half of its length	Autologous hamstring tendons
Cha et al. (2012) [34]	ACL remnant that could be tensioned toward the femoral bone tunnel	Autologous hamstring tendons
Maestro et al. (2013) [36]	Partial ACL tear; a healthy bundle with a diameter equivalent to at least one-third of the original ACL was found, which was functional after palpation with a hook probe showing retention of its femoral and tibial insertions	Autologous hamstring tendons
Nakamae and Ochi et al. (2014) [39]	Partial rupture of the ACL; ligamentous fibers were seen to be in continuity from the femur to the tibia and the femoral attachment of those fibers was within the anatomical femoral insertion of the ACL	Autologous hamstring tendons
	Complete rupture of the ACL; thick ACL remnant (greater than one-third of the original size) maintaining a ligamentous bridge between the tibia and the femur and the femoral attachment of the ACL remnant was positioned non-anatomically	
Zhang et al. (2014) [40]		Autologous hamstring tendons
Lee et al. (2014) [41]	Partial ACL tear; there was a relatively intact bundle during surgery	Autologous hamstring tendons

AM anteromedial, *PL* posterolateral

Table 29.3 Outcomes in studies which compared the ACL augmentation techniques with the standard ACL reconstruction technique [13]

Study	The mean side-to-side difference in instrumented knee-laxity testing (anterior displacement of the tibia)	Pivot shift test (positive rate)	Other findings	Complications
Adachi and Ochi et al. (2000) [11]	0.7 mm in group A and 1.8 mm in group S ($P<0.05$)	8 % in group A and 4 % in group S (not significant)	Inaccuracy of joint position sense was 0.7° in group A and 1.7° in group S ($P<0.05$). ACL augmentation technique may contribute to restoring the proprioceptive function of the knee	
Gohil et al. (2007) [16]	3.2 (2–5) mm in group A and 2.75 (2–5) mm in group S		ACL augmentation technique appears to accelerate revascularization as indicated by increased signal intensity of MRI in the mid-substance of the graft at 2 months	No significant differences were found in incidence of cyclops lesions and ROM
Yoon et al. (2009) [19]	2.2 mm in group A and 1.9 mm in group S	12 % in group A and 12 % in group S		One case of limited ROM was observed in each group
Ahn et al. (2010) [22]			MRI showed significantly larger ACL grafts in group A than in group S, and these preserved remnant bundles showed progressive remodeling in the ACL graft	No significant difference was found in incidence of cyclops lesions
Pujol et al. (2012) [27]	1.24 mm in group A and 1.87 mm in group S ($P=0.03$)	17 % in group A and 28 % in group S ($P=0.4$)	There were no significant differences in subjective IKDC, KOOS, or Lysholm scores between the groups	One patient in group A developed a cyclops lesion
Hong et al. (2012) [28]	1.6 mm in group A and 1.8 mm in group S ($P=0.69$)	5 % in group A and 12 % in group S ($P=0.52$)	The passive angle reproduction test for proprioception measurements showed that there was no difference between both groups at final follow-up	In each group, cyclops lesion formation occurred in three patients
Park et al. (2012) [31]	1.5 mm in group A and 1.7 mm in group S (double bundle) ($P=0.69$)	9 % in group A and 11 % in group S (double bundle) ($P=0.74$)	There were no significant differences in the postoperative ROM, visual analog scale score, Lysholm score, Tegner score, and International Knee Documentation Committee knee evaluation form score between the two groups	

Demirağ et al. (2012) [32]		20 % in group A and 15 % in group S ($P = 0.5$)	Tibial and femoral tunnel widening was less in the augmentation group. This difference was more significant on the tibial side	One patient in group A developed a cyclops lesion confirmed by MRI
Cha et al. (2012) [34]			Eight cyclops lesions (3/20 (15.0 %) in group S and 5/41 (12.2 %) in group A) were found in the 61 patients who underwent second look ($P = 0.76$)	
Maestro et al. (2013) [36]	1.8 mm in group A and 2.3 mm in group S	13 % in group A and 36 % in group S		No postoperative complications
Nakamae and Ochi et al. (2014) [39]	0.4 mm in group A, 1.3 mm in single-bundle group, and 0.9 mm in double-bundle group ($P = 0.013$ between group A and the single-bundle group)	12 % in group A, 21 % in single-bundle group, and 15 % in double-bundle group ($P = 0.65$)	Second-look arthroscopy showed significantly better synovial coverage of the graft in group A than in the other groups. Improvement in proprioceptive function (threshold to detect passive motion) was seen in patients with good synovial coverage of the graft	
Zhang et al. (2014) [40]	1.4 mm in group A and 1.7 mm in group S (not significant)		The percentage of tibial tunnel enlargement was 25.7 % in group A and 34.0 % in group S ($P = 0.0004$)	
Lee et al. (2014) [41]	1.8 mm in group A and 1.9 mm in group S (double bundle) (not significant)	6 % in group A and 6 % in group S (not significant)	No statistical differences in the Lysholm, Tegner, and International Knee Documentation committee scores were observed between the two groups	ROM was not statistically different between the groups

Group A ACL augmentation (remnant-preserving ACL reconstruction) group, *group S* standard ACL reconstruction technique group, *ROM* range of motion coverage of the graft upon second-look arthroscopy than those in the single- and double-bundle reconstruction groups. Improvement in proprioceptive function was observed in patients with good synovial coverage of the graft. With regard to the mean side-to-side difference measured using the KT-2000 arthrometer, a significant difference was found between the augmentation group (0.4 mm) and the single-bundle group (1.3 mm). However, three studies concluded that ACL augmentation had no evident advantage in clinical outcome over the standard single-bundle ACL reconstruction [19, 28, 40]. One of these studies used allografts from the tibialis anterior or hamstring tendon. Furthermore, in these three studies, the average preoperative side-to-side difference in anterior knee laxity in the augmentation group was relatively large and almost same with those in the standard single-bundle reconstruction group. Indications for and concept of ACL augmentation may have differed from studies.

Among the 13 clinical studies, ten studies [11, 16, 19, 27, 28, 31, 36, 39–41] evaluated the side-to-side difference in instrumented anterior knee-laxity testing. Three studies concluded that patients in the ACL augmentation group exhibited better anterior knee stability than those in the single-bundle reconstruction group [11, 27, 39]. The remaining seven studies reported that there was no significant difference between the groups of surgical technique at final follow-up. Out of the seven studies, two studies showed similar anteroposterior knee stability between the ACL augmentation group and double-bundle reconstruction group [31, 41]. Lee et al. [41] concluded that selective bundle ACL reconstruction could be performed instead of double-bundle ACL reconstruction if some intact bundle exists. Nine studies evaluated results of the pivot shift test, and ten studies reported data on the clinical scores. With regard to the pivot shift test and clinical scores, none of the studies indicated that there were significant differences between the groups at final follow-up.

The currently available evidence suggests that clinical outcomes of patients with the ACL augmentation technique are comparable with that of patients who underwent double-bundle ACL reconstruction. A significant controversy still remains regarding the clinical superiority of ACL augmentation compared to standard single-bundle ACL reconstruction. Although longer follow-up studies and further comparative clinical studies with a sufficient number of patients are necessary before a definitive conclusion can be reached, we think that ACL augmentation is a reasonable treatment option for patients with favorable ACL remnants.

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