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Research Advances in Anterior Cruciate Ligament Reconstructions with Remnant Preservation: A Review Article

Shashi Ranjan Tiwari, Biao Cheng*

Department of Orthopedic, Shanghai Tenth People's Hospital, Tongji University School of Medicine, Shanghai, PR China.

Abstract
This review summarizes the methods and research progress of reconstruction of the anterior cruciate ligament with the remnant preservation technique under arthroscopy for clinic reference. The related literature on the reconstruction of ACL with the remnant preservation technique under arthroscopy in recent years was reviewed and analyzed synthetically. There are some fibers left after the ACL injury, and that residual fiber could be divided into two types: residual bundle and residual stump. There are a number of techniques for reconstructing ACL under arthroscopy, including a single bundle of reconstructed remnants, retention of the tibia stump and recovery of stump structure by appropriate techniques. The preserved remnant provided synovium for the reconstructed ACL, which could accelerate revascularization of the graft, and be a benefit for the recovery of proprioception, besides the certain kinds of remnant could contribute to the stability of the knee joint, which can block the synovial fluid into the tunnel and prevent the tunnel to expand. However, the reconstruction of ACL surgery with the remnant preservation requires the high technique of surgery for the surgeon. At the same time, intercondylar notch impact and cyclops deformity and other complications may occur after surgery. The reconstruction of ACL with the remnant preservation can obtain a better clinical curative result, but the operation is difficult, the surgeon has high technical requirements. There should be more relevant basic research and clinical randomized controlled trials about remnant preservation in ACL reconstruction, which still need further study of its necessity and advantages and disadvantages.
Keywords: Anterior cruciate ligament, reconstruction, remnant preservation, arthroscopy, proprioception.

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***Correspondence:** Biao Cheng **Email** ortho_tenth@163.com, **Contact**: +8613681973702

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1. Introduction

Anterior cruciate ligament (ACL) injury causes knee joint anterior and posterior instability. ACL reconstruction is an effective means to restore knee joint stability [1, 2]. At present, ACL reconstruction is mainly focused on the postoperative biomechanical function, whereas the effect of biological healing and proprioception recovery on the motor function of the knee joint is little. The initial study shows that the ACL reconstructions with remnant preservation in part of ligament structure, synovial tissue, and remnant mechanoreceptors may promote the graft revascularization and ligament structure remodeling, improve the recovery ability and proprioception recovery [3–8]. In clinical practice, it is still controversial whether ACL reconstructions with remnant preservation can promote the healing and improve the clinical treatment effect. Therefore, ACL reconstructions with remnant preservation deserve to be further studied.

According to the condition of ACL residual fiber, ACL remnant reconstruction is mainly focused on two aspects: retained the stump reconstruction technique (remnant preserving technique) and retained residual bundle enhanced reconstruction (augmentation technique). In this review article, the biological characteristics, classification, reconstruction techniques and clinical effects of ACL residues were discussed. We have reviewed the current evidence to see whether the remnant preservation techniques could obtain better clinical outcomes rather than the standard anterior cruciate ligament reconstruction procedure.

2. Biological characteristics and effects of ACL remnant

2.1 Effects of ACL remnant on graft vascularization graft

After the rupture of ACL, the residual ACL could not form scar healing at the end of ruptured ligament fiber because of the effect of synovial fluid. Therefore, the use of tendon graft for ACL reconstruction is the best way to treat the injury. The success of tendon transplantation depends on the viability of the graft in the joint environment.

Revascularization is needed for the Grafts to survive, 4-6 weeks after reconstruction, a synovial membrane with vascular from the infrapatellar fat pad and synovial tissue wraps around the graft and produces synovial fluid [9]. Blood vessels from the infrapatellar fat pad and synovial membrane pass through the connective tissue of the graft to re-vascularize the graft, which promotes cell proliferation and eventually leads to the new connective tissue cells filled with the graft. Therefore, it is very important to retain the residual and the synovial membrane coverage on the surface of the graft to accelerate the process of ligament revascularization. Gohil et al. studied the degree of graft revascularization after ACL reconstruction by MRI (with residual ACL and non-residual ACL reconstruction) and found that the degree of vascularization was higher in the residual group than in the non-residual group after postoperative follow-up [10, 11-15]. In conclusion, the retention of ACL residues has a certain role in promoting the revascularization of the postoperative graft, which provides a theoretical basis for the retention of residual ACL bundle or residual ACL stump during the reconstruction. However, the remnant of a ruptured ACL can also increase the risk of impingement or a cyclops lesion, making proper tunnel placement difficult.

2.2 Effects of ACL remnant on the proprioception structure

Since Schultz et al [16] first reported the existence of mechanical receptors in human ACL, these mechanical receptor are present around the ACL stump and demonstrated a rich nerve supply and various types of sensory receptors in the knee joint ligament [17], such as Golgi tendon organs, Pacinian corpuscle, Ruffini peripheral structure and free nerve ending. Most of them are located in the synovial membrane structure near the tibial end point of ACL, which were thought to contribute to the proprioception by stimulating muscle coordinative contraction and tension, involve in the nerve reflex, sensor the direction of movement, position, and balance of the knee joint [18-20]. The previous study found, there was certain relevance between the ACL injury time and the amount of residual mechanical receptors if ACL injury time is shorter, the number of residual mechanical receptors is more. Therefore, it is possible to preserve the residual reconstruction in the early stage after an injury to retain the proprioceptive structure and improve the postoperative function [19]. Georgoulis et al. reported that residual mechanoreceptors could still be found in the stump of a ruptured ACL, attached to the posterior cruciate ligament (PCL), three years after ACL rupture [21]. So even chronic injuries should be retained remnant as far as possible. Because most of the acute ACL injuries occurred in the proximal and part of the femoral junction [22], and most mechanical receptors and proprioception structure have been reported to be located in the sub-synovial layer near the tibial insertion of the ACL, the residual tissue is not enough, but still need to be kept as much as possible [21, 23-25]. Lee, et al. [26], found that even with 20% of the ACL remnant, most mechanoreceptors could provide relatively good proprioception. Thus, after ACL injury, the majority of proprioception mechanoreceptor still remains in the stump tissue, to retain these mechanoreceptors as much as possible in the surgery, which is helpful for the recovery of proprioception of knee joint and accelerating the recovery of knee joint function.

3. Classification of ACL remnant tissue

In order to facilitate the description of traits of ACL residual tissue, Crain et al. according to the form of ACL stump, divided into 4 Groups: Group I: ACL stump attached to the PCL and the lateral wall of the femoral condylar notch is absent. Group II: the ACL stump attached high into the roof of the femoral condylar notch and the lateral wall of the femoral condylar notch ACL femoral attachment is absent. Group III: ACL stump attached to the lateral wall of the femoral condylar notch, and the attachment point is before the partial bais, the original ACL femur origin is absent. Group IV: ACL stump retraction or absorption. However, group I, II, III still hold 55% to 58% of ACL identifiable tissue remaining [27-30].

ACL residual tissue includes residual stump and residual bundle, which are different in the surgical procedure. In order to convenient, the selection of treatment programs, Kazusa et al. [4] included ACL partial rupture into the ACL residual classification, reformed the Crain classification method, and divided the ACL residual tissue into the following Groups: ***(1) Group 1:*** ACL is partially ruptured. Group 1a: posterior lateral (PL) bundle rupture, the anterolateral medial (AM) bundle is intact at the femoral attachment, to avoid injury. Group1b: partial rupture of AM bundle, PL bundle ligament tendon structure intact and attached to the femur origin, to avoid injury and well preserved. Group 1c: Partial rupture of the ACL but the remaining bundle could not be ascribed to either the AM or PL bundle.

(2) Group 2: ACL completely rupture. Group 2a: ACL remnants attached to PCL and tibia, The ACL of the lateral wall of the intercondylar notch was absent. Group 2b: ACL stump attached to the roof of the intercondylar notch and tibia, the lateral wall of the intercondylar notch ACL was absent from the femoral origin and the diameter of the stump was decreased. Group 2c: ACL remnant bridging lateral wall of the intercondylar notch and tibia. Attenuated ACL remnant healed to the lateral wall more arthroscopically anterior than its anatomic origin. There were no ligamentous continuous fibers in the normal attachment of the ACL to the femur. Group 2d: No substantial ACL remnants bridging the tibia and either the femur or the PCL. Among them, 1a and 1b group to retain residual bundle indications strengthen of ACL reconstruction.1c, 2a, 2b, and 2c are retention of stumped of ACL and its indications reconstruction of the single or double bundle. It should be noted that in the 1a and 1b types, the residual AM or PL bundle may not be complete and also lose some of the biomechanical function.

4. Method of Reconstruction of ACL with remnant preservation

4.1 Reserved stump reconstruction technique

ACL retention stump reconstruction refers to keeping the remaining ACL tissue as much as possible under the premise that the ACL is completely ruptured or most of the rupture and drilling the bone at the remaining tissue place, performing single or double beam reconstruction of ACL.

4.1.1 ACL Stump retention and method of reconstruction

Lee et al. [26, 31] and Ahn JH et al. [32-34] designed a surgical procedure that maximizes the retention of the tibial remnants under arthroscopy, but its need to completely clean the femoral attachment of the residual fibers to clearly show the roof of the intercondylar notch and facilitate the positioning of femoral tunnel. To achieve anatomical positioning, the tibial tunnel outlet must be located within the footprint of the tibial stump. The needle-pin point should be located in the footprint printing center and must be in the direction of the stump fiber to reduce the damage. When rebuilding an ACL bundle the tibial tunnel was first set at a 40° to 45° angle by ACL tibial guide (Linvatec) and prepared with a small drill (4.5 mm or 5.0 mm), drilling through bone and stump fiber and then gradually expand the tibial tunnel, when the tunnel is extended, it is advisable to drill through the bone hole to avoid the damage to the stump fiber and as well as form a cylindrical tunnel structure. Conventional methods for the preparation of femoral tunnel. A femoral tunnel was made from the 10 to 11-o'clock position for a right knee and 1 to 2-o'clock position for a left knee with a femoral guide through the transtibial tunnel. However, after over the procedure of making a tunnel, the graft passes through the center of the cylindrical stump end and it's surrounded by the residual stump, which increases the coverage of the synovial membrane of the graft and retains the proprioception in the stump. If the stump is torn, it can also under the arthroscopic suture repair. The technique can retain ACL tibial stump, but still, need to clean ACL femoral residual stump for easy to femoral tunnel positioning. Kim et al. [35] also used the same technique to preserve tibial stump reconstruction of ACL. Intraoperative tibial tunnel outlet located in the stump center, the key to the preservation is that the tibial drill bit does not drill through the stump, to reach the end of the tunnel after the start of anti-drilling and grinding off the stump attached to the bone. The graft passes through the residual stump center so that the stump is completely wrapped around the graft. Ahn JH et al [36] and Elazab A et al. [37] At the same time, reconstruction of ACL and posterior cruciate ligament also applied a similar reconstruction technique, to keep maintain blood vessels and nerve tissue in the remnants and after short- term follow-up finds curative effects was good.

Ahn et al. [38] thought that the retention of the stumps lost their tension and could be retracted to form a cyclops deformity, so they designed a technique to restore stump tension. The technique requires the tibial stump to be thick enough to suture traction. The suture hook enters from the distal anterior accessory approach and stitches in the stump. Combined 3 - 4 stitches, the tibial tunnel is prepared through the center of the tibial stump, and the transverse catheter is placed in the femoral tunnel. Wire insertion from the distal end of the femur, followed by the femoral tunnel and knee joint cavity, from the former approach traction straddle traction line, pull to the transverse nail catheter, traction line can restore remnants tension. ACL grafts are completely passed through and then straddle the traction line, and the traction line is squeezed in the bone tract to fix the stump. Finally, the synovial membrane and the remnants around the graft were sutured together with the graft under arthroscopy.

Superficially, it will be completely covered. The technique makes full use of the ACL fixture fixed

remnants fiber, does not need special additional equipment, and can retain maximum remnant fiber, with a wide range of indications, even if the short stump can also be retained. But the clinical application of the technique less, the current clinical efficacy reported rare at present, still need to further study [4, 34, 5].

4.1.2 Indications and precautions

The indications of ACL retention for reconstruction are for the patients whose ACL is a complete rupture or most of the rupture and out of function, which is suitable for ACL residual part of 1c and all 2 (or Grain type II) of the cases. The operation method is simple and easy, only to retain the residual as much as possible on the basis of ACL reconstruction method. Key points of surgery include: (1). A definite diagnosis, to find out whether the ACL completely ruptures and the attachment of the residual stump. (2). Need a clear surgical field of vision, observation of the femur head can use the middle of the auxiliary incision or 70 ° arthroscopies, the high lateral approach can be used to observe the tibial plateau point. (3). As much as possible to save the ACL residual tissue, if the ACL tibial stump is intact and the position of the tibial tunnel can transmit through the center footprint of the stump. If avulsion rupture, ACL stump was only removed from the femoral attachment and it can use ACL repair combined with reconstruction of the surgical approach (4). Dynamic exploration after reconstruction to prevent the impact caused by excessive retention. Kazusa et al. [4] gave a detailed description of the procedure, adding an intermediate auxiliary incision in order to clearly observe the femoral attachment position. Select the center of the femoral stump as the center footprint of the bone. ACL tibial stump was identified and the location of the center of the tibia was marked, the positioning guide was placed, the longitudinal incision of ligament and point it, exposing the guide pin, to complete the choice of tibial tunnel position. This procedure requires graft penetrates from the center of the stump and on the one hand makes the graft position is closer to the original anatomical point; on the other hand make more the stump and synovial tissue covering the graft. Ahn et al. [36] also invented another type of ACL reconstruction that maintains stump tension, remaining the stump in tension during graft fixation, simultaneous graft fixation, stump, and graft suture, fully covering the graft to avoid graft retraction and the formation of cyclops deformity.

4.1.3 Postoperative efficacy

Postoperative effects of reconstruction of reserved ACL stump not only could expand the volume of the graft, making the graft closer to the original ACL form, but also accelerate the rate of revascularization and promote the healing of graft. Therefore, theoretically, the remnant preserving ACL reconstruction technique can promote tissue healing, recover knee proprioception function and improve the function of the knee joint after ACL reconstruction, but the actual clinical efficacy still remains controversial. Dong Yi-Long et al [39] reported that 17 patients with ACL rupture were reconstructed and the functional score was evaluated after the operation. They suggested that the anatomic single-bundle reconstruction of the anterior cruciate ligament can achieve good clinical results. Ahn et al. [6, 36] reported that the use of 4 autologous hamstring tendon was performed on 41 patients in preserving remnant and compared with the non-preserving remnant group, patients were followed up for 6 ~ 9 months, MRI found that the diameter of graft group with remnant preservation was significantly higher than that of non-preserving remnant group, and there was no significant difference in signal intensity. Gohil et al. [10] used MRI to study the graft healing. At 6 months after ACL reconstruction, the MRI signal intensity of graft was significantly lower in the remnant group than in the non-remnant group. There was no significant difference in MRI signal intensity one year after the operation, suggesting that remnant reconstruction may promote graft healing in the early stages of reconstruction.

The ACL reconstruction of the retained stump can obtain good stability and a functional score of the knee joint, but the advantage is not clear compared with the traditional non-remnant reconstruction bundle. Lee et al [26] and Gohil et al [10] evaluated the remnant preservation group and control group respectively. It was found that there was no significant difference between the two groups in Lachman examination, pivot shift test, and anterior knee laxity, HSS, and IKDC scores after the operation. Lee et al [26] found that the remnant preservation group in the single foot skipping test score was significantly higher than the control group. Gao et al. [40] used LARS artificial ligament in the reconstruction of ACL in 159 patients, and the clinical effect was satisfactory in 81% of patients. Kim et al. [35] used the autologous quadriceps tendon reconstruction for double bundle

reconstruction and the stability of knee joint was significantly increased after the operation.

Ahn et al. [36] also evaluated the clinical value of ACL reconstruction of the remnant stump. It is suggested that the technique can construct a better cell regeneration framework, which maintains residual tension and the stability of the knee joint. However, there was no significant difference between the two groups in the evaluation of clinical efficacy. Jung et al. [41] suggested that this technique is suitable for the ACL stump of Crain type III, which not only can retain the stump tissue, but also can not affect the bone drilling. However, the method requires a higher surgical technique and a longer operation time, whether the clinical effect is better or not than the reserved remnant during ACL reconstruction is still controversial. However, the characteristics of stump reconstruction technique is to promote tissue healing and proprioception recovery, despite the current evaluation methods may not clearly reflect the advantages of preserving a remnant, the clinical results are still controversial, the preserving remnant can accelerate revascularization, ligament shaping and promote the recovery of proprioception potential function.

4.2 Reserved residual bundle ACL reconstruction technique

ACL enhanced reconstruction technique for preserving residual bundle or ACL reconstruction of the remnant bundle is also called selective bundle ACL reconstruction because it is based on the original anatomical point of single bundle reconstruction. Therefore, Fu et al [1] and van Eck et al [2] considered that the reconstruction method belongs to the category of ACL anatomical reconstruction.

4.2.1 Indications and precautions

ACL mainly includes AM and PL two functional bundles, the main function of AM is to control the forward and backward movement of the knee joint, PL mainly controls the knee rotation [1, 2]. Any injury of the bundle can cause the changes of knee joint function, so the main function of the ACL reconstruction is to restore the function of ACL damage bundle. This procedure is suitable for patients with ACL single bundle rupture and good residual function, which is ACL remnant cases with type 1a and type 1b [4].

Selective retention of the ACL for partial bundle reconstruction requires the basis of double bundle ACL anatomical reconstruction techniques based on surgical techniques, at the same time need to pay attention to two points: (1). Accurately select the bone position of the injured bundle; (2). Carefully protect the residual bundle to avoid further damage. Surgery required a definite arthroscopic diagnosis of partial rupture of ACL, single bundle injury was mostly located in the femoral attachment. When creating tension during the front drawer test and exploring the AM bundle that time can observe whether the AM bundle has attached to the lateral wall of the intercondylar notch or not. Exploring the PL bundle, the use of a probe to detect carefully and the foot position is like ‘4’ to observe the PL bundle in the femur attachment point [2]. If necessary, need to facilitate the middle of the auxiliary approach to observe the lateral wall of the intercondylar notch and Select the center location of the AM or PL stump.

If the femur attachment is poorly identified, it can be located according to the bony land marker. The both bundle are under the lateral wall horn of the bifurcation, whether AM bundle are located after the bifurcation of the intercondylar notch and PL bundle find before the lateral condyle of the intercondylar notch. If bony marker is not clear then it can be selected 30% ~ 35% below in lateral wall of the intercondylar notch, which is located in front or behind of lateral horn. Therefore, after performing the double-bundle reconstruction procedure of ACL can build a good tension and shape of both bundles [1, 2, 4**]**.

4.2.2 Postoperative efficacy

After the postoperative curative effect of ACL functional bundle rupture, the corresponding biomechanical function will be impaired. The purpose of reconstructing the remnant bundle is to restore the stability of the knee joint in order to restore the function of the damaged bundle. The reconstruction of the bundle is mainly to restore the stability of the knee joint. At the same time, due to the maximum retention of the original ACL structure, prevention of remnant bundle ACL surgery has the potential to improve the sensory function of the knee, graft revascularization, and enhance postoperative knee joint stability of the potential advantages.

First of all, the preserving remnant bundle of the ACL to strengthen the restore original biomechanical function. Preserving remnant bundle of ACL enhanced reconstruction due to the maximum remnant of the original ACL structure, therefore, can get better stability and improve the surgical results. Mifune et al. [42] confirmed by animal experiments

that preservation of remnant ACL reconstructions had better tensile strength compared with the non-remnant bundle reconstruction graft. Preservation of remnant bundle of ACL after surgery reconstruction is similar to the double-bundle anatomical reconstruction, but the former surgery is relatively simple, and less bone destruction. Whether the postoperative biomechanical function is different between the two groups, some scholars have also carried out related research. Park et al [43] made a comparative study on the double bundle reconstruction of ACL reconstruction with preserved remnant bundle and no remnant bundle. Clinical examination, functional score were no significant different in the two groups. However, the forward and backward stability is formerly better than passed, and the anti-rotation function of ACL is restored. The ACL reconstruction technique with remnant bundle is better than the single bundle reconstruction without remnant bundle, Adachi et al [44] performed ACL reconstruction in 40 patients with partial ACL injury, compared with 40 cases of ACL patients with single bundle reconstruction, it is found that the former can significantly improve the forward and backward stability, reduce the incidence of joint adhesion rate, increase the accurate of postoperative imaging examination.

The preservation of more ACL remnant tissue means that it retains more blood supply of the synovial membrane and proprioception, which can accelerate the revascularization of the graft and promote tissue healing. Despite the lack of clinical definite index [5, 8, 31], most researchers believe that preserving the remnant bundle strengthening reconstruction in biologically has the following advantages to promote the recovery of proprioception, retention of nerve fibers may exist the bundle, promote the regeneration of mechanoreceptors; can accelerate cell proliferation and graft revascularization of ACL bundle. Mifune et al. [42] confirmed by animal experiments that the ACL reconstruction was enhanced by retained residual bundle, and the expression of several cytokines was found around the graft, significantly different from the pure graft after ACL reconstruction.

Therefore, reconstruction technique preserving the remnant bundle ACL is not only beneficial to restore the stability of knee joint in biomechanics, but also could promote the healing of tissue and the recovery of proprioception in biology.

5. Complications of remnant reconstruction

Although ACL remnant reconstruction has many advantages, at the same time, due to increased graft volume and risk of 'impact', the major complications caused by the reconstruction technique were cyclops deformity and limited knee extension [45-47]. Gohil et al. [10] found that the incidence rate of cyclops deformity in the disabled group was higher than that in the control group after clinical follow-up. Kim et al. [35] reported one case of knee extension limitation of more than 5 degrees after ACL reconstruction. However, Ahn et al. [6] suggested that ACL remnant reconstruction does not increase the risk of a cyclops deformity and knee extension. At the same time, ACL reconstruction, especially the preservation of remnant bundle of ACL strengthen the reconstruction of the surgical technique requirements are higher, and knowledge of ACL anatomy is also higher. It is necessary to select the proper location and diameter of the bone graft to avoid further damage the residual tissue and hits on intercondylar fossa caused by excessive ligament volume.

6. Outlook and summary

In the reconstruction of ACL, it is always assumed that the residual reconstruction of ACL can promote the healing of the graft and improve proprioception. However, there is still a lack of clear and reliable evaluation criteria to evaluate the proprioception, and the current method of the scoring table cannot fully reflect the improvement of proprioception. Mechanoreceptors controlling proprioception not only exist in ACL, also exist around PCL, meniscus, articular capsule and muscle skin. Although ACL mechanoreceptor effect is not clear, it is certainly combined with the surrounding mechanical receptors to coordinate and control the proprioception of the knee joint [48-50].

Reider et al [51] regularly detected the positional sensation of the knee joint after the reconstruction of the ACL and found that the mechanical receptor of the joint capsule and other ligaments could counteract the effect of the lack of ACL receptor.

At present, the research on the promotion of healing is mainly in two aspects: on the one hand, the use of KT2000 by evaluating the stability of the indirect reaction healing process; on the other hand, the use of MRI and arthroscopy to directly observe. Therefore, it is necessary to find a more objective and effective index to evaluate the healing of ACL graft. In addition, the stability of the knee joint is mainly through the knee measuring instrument to measure the degree of forwarding and backward mobility, but the stability of knee joint also included the measurement of rotational stability. Therefore, the

objective evaluation of rotational instability in clinical follow-up can be used to evaluate the effect of surgery more comprehensively.

In summary, the main advantage of ACL reconstruction is to promote the healing of the graft tissue and to restore the proprioception of the knee joint. ACL stump retained mechanoreceptors controlling proprioception and re-vascularized synovial tissue, to make it possible to promote graft revascularization and ligament remodeling. Although there is no clear clinical conclusion that ACL preserving remnant can improve the knee joint stability and promote graft healing and improve knee proprioception, ACL in preserving remnant still have raised the potential role of these capabilities and needed to be to further confirmed by more objective evaluation methods.

7. References

[1] Fu FH, Karlsson J. A long journey to be anatomic. Knee Surg Sports Traumatol Arthrosc. 2010 Sep; 18(9):1151-3.

[2] van Eck CF, Lesniak BP, Schreiber VM, Fu FH. Anatomic single- and double-bundle anterior cruciate ligament reconstruction flowchart. Arthroscopy. 2010 Feb; 26(2):258-68.

[3] Papalia R, Franceschi F, Vasta S, Di Martino A, Maffulli N, Denaro V. Sparing the anterior cruciate ligament remnant: is it worth the hassle? Br Med Bull. 2012; 104:91-111.

[4] Kazusa H, Nakamae A, Ochi M. Augmentation technique for anterior cruciate ligament injury. Clin Sports Med. 2013 Jan; 32(1):127-40.

[5] Hong L, Li X, Zhang H, Liu X, Zhang J, Shen JW, Feng H. Anterior cruciate ligament reconstruction with remnant preservation: a prospective, randomized controlled study. Am J Sports Med. 2012 Dec; 40(12):2747-55.

[6] Ahn JH, Lee YS, Ha HC. Anterior cruciate ligament reconstruction with preservation of remnant bundle using hamstring autograft: technical note. Arch Orthop Trauma Surg. 2009 Aug; 129(8):1011-5.

[7] Yasuda K, Kondo E, Kitamura N, Kawaguchi Y, Kai S, Tanabe Y. A pilot study of anatomic double-bundle anterior cruciate ligament reconstruction with ligament remnant tissue preservation. Arthroscopy. 2012 Mar; 28(3):343-53.

[8] Nakamae A, Ochi M, Deie M, Adachi N, Shibuya H, Ohkawa S, Hirata K. Clinical outcomes of second-look arthroscopic evaluation after anterior cruciate ligament augmentation: comparison with single- and double-bundle reconstruction. Bone Joint J. 2014 Oct; 96-B (10):1325-32.

[9] Arnoczky SP. Blood supply to the anterior cruciate ligament and supporting structures. Orthop Clin North Am. 1985 Jan; 16(1):15-28.

[10] Gohil S, Annear PO, Breidahl W. Anterior cruciate ligament reconstruction using autologous double hamstrings: a comparison of standard versus minimal debridement techniques using MRI to assess revascularisation. A randomized prospective study with a one-year follow-up. J Bone Joint Surg Br. 2007 Sep; 89(9):1165-71.

[11] Min BH, Chung WY, Cho JH. Magnetic resonance imaging of reconstructed anterior cruciate ligament. Clin Orthop Relat Res. 2001; 393:237-243.

[12] Muramatsu K, Hachiya Y, Izawa H. Serial evaluation of human anterior cruciate ligament grafts by contrast-enhanced magnetic resonance imaging: comparison of allografts and autografts. Arthroscopy. 2008 Sep; 24(9):1038-44.

[13] Weiler A, Peters G, Mäurer J, Unterhauser FN, Südkamp NP. Biomechanical properties and vascularity of an anterior cruciate ligament graft can be predicted by contrast-enhanced magnetic resonance imaging. A two-year study in sheep. Am J Sports Med. 2001 Nov-Dec; 29(6):751-61.

[14] Ma Y, Murawski CD, Rahnemai-Azar AA, Maldjian C, Lynch AD, Fu FH. Graft maturity of the reconstructed anterior cruciate ligament 6 months postoperatively: a magnetic resonance imaging evaluation of quadriceps tendon with bone block and hamstring tendon autografts. Knee Surg Sports Traumatol Arthrosc. 2015 Mar; 23(3):661-8

[15] Ntoulia A, Papadopoulou F, Ristanis S, Argyropoulou M, Georgoulis AD. Revascularization process of the bone--patellar tendon--bone autograft evaluated by contrast-enhanced magnetic resonance imaging 6 and 12 months after anterior cruciate ligament reconstruction. Am J Sports Med. 2011 Jul; 39(7):1478-86.

[16] Schultz RA, Miller DC, Kerr CS, Micheli L. Mechanoreceptors in human cruciate ligaments. A histological study. J Bone Joint Surg Am. 1984 Sep; 66(7):1072-6.

[17] Aydog ST, Korkusuz P, Doral MN, Tetik O, Demirel HA. Decrease in the numbers of mechanoreceptors in rabbit ACL: the effects of ageing. Knee Surg Sports Traumatol Arthrosc. 2006 Apr; 14(4):325-9.

[18] Freeman MA, Wyke B. Articular contributions to limb muscle reflexes. The effects of partial neurectomy of the knee-joint on postural reflexes. Br J Surg. 1966 Jan; 53(1):61-8.

[19] Dhillon MS, Bali K, Vasistha RK. Immunohistological evaluation of proprioceptive potential of the residual stump of injured anterior cruciate ligaments (ACL). Int Orthop. 2010 Jun; 34(5):737-41.

[20] Bali K, Dhillon MS, Vasistha RK, Kakkar N, Chana R, Prabhakar S. Efficacy of immunohistological methods in detecting functionally viable mechanoreceptors in the remnant stumps of injured anterior cruciate ligaments and its clinical importance. Knee Surg Sports Traumatol Arthrosc. 2012 Jan; 20(1):75-80.

[21] Georgoulis AD, Pappa L, Moebius U, Malamou-Mitsi V, Pappa S, Papageorgiou CO, Agnantis NJ, Soucacos PN. The presence of proprioceptive mechanoreceptors in the remnants of the ruptured ACL as a possible source of re-innervation of the ACL autograft. Knee Surg Sports Traumatol Arthrosc. 2001 Nov; 9(6):364-8. Epub 2001 Sep 7.

[22] Sherman MF, Lieber L, Bonamo JR, Podesta L, Reiter I. The long-term followup of primary anterior cruciate ligament repair. Defining a rationale for augmentation. Am J Sports Med. 1991 May-Jun; 19(3):243-55.

[23] Kennedy JC, Alexander IJ, Hayes KC. Nerve supply of the human knee and its functional importance. Am J Sports Med. 1982 Nov-Dec; 10(6):329-35.

[24]. Krauspe R, Schmitz F, Zöller G, Drenckhahn D. Distribution of neuro filament-positive nerve fibres and sensory endings in the human anterior cruciate ligament. Arch Orthop Trauma Surg. 1995; 114(4):194-8.

[25] Schutte MJ, Dabezies EJ, Zimny ML, Happel LT. Neural anatomy of the human anterior cruciate ligament. J Bone Joint Surg Am. 1987 Feb; 69(2):243-7.

[26] Lee BI, Min KD, Choi HS, Kim JB, Kim ST. Arthroscopic anterior cruciate ligament reconstruction with the tibial-remnant preserving technique using a hamstring graft. Arthroscopy. 2006 Mar; 22(3):340.e1-7.

[27] 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 Jan; 21(1):19-24.

[28] Anderson AF, Snyder RB, Federspiel CF, Lipscomb AB. Instrumented evaluation of knee laxity: A comparison of five arthrometers. Am J Sports Med 1992; 20:135-140.

[29] Steiner ME, Brown C, Zarins B, Brownstein B, Koval PS, Stone P. Measurement of anterior-posterior displacement of the knee. A

comparison of the results with instrumented devices and with clinical examination. J Bone Joint Surg Am 1990; 72:1307-1315.
[30] Daniel DM, Stone ML, Dobson BE, Fithian DC, Rossman DJ, Kaufman KR. Fate of the ACL-injured patient. A prospective outcome study. Am J Sports Med 1994; 22:632-644.
[31] Lee BI, Kwon SW, Kim JB, Choi HS, Min KD. Comparison of clinical results according to amount of preserved remnant in arthroscopic anterior cruciate ligament reconstruction using quadrupled hamstring graft. Arthroscopy. 2008May; 24(5):560-8.
[32] Ahn JH, Lee YS, Ha HC. Anterior cruciate ligament reconstruction with preservation of remnant bundle using hamstring autograft: Technical note. Arch Orthop Trauma Surg 2009; 129:1011-1015.
[33] Ahn JH, Lee SH, Yoo JC, Ha HC. Measurement of the graft angles for the anterior cruciate ligament reconstruction with transtibial technique using postoperative magnetic resonance imaging in comparative study. Knee Surg Sports Traumatol Arthrosc 2007; 15:1293-1300.
[34] Ahn JH, Lee SH, Choi SH, Lim TK. Magnetic resonance imaging evaluation of anterior cruciate ligament reconstruction using quadrupled hamstring tendon autografts: Comparison of remnant bundle preservation and standard technique. Am J Sports Med 2010; 38:1768-1777.
[35] Kim SJ, Jo SB, Kim TW, et al. A modified arthroscopic anterior cruciate ligament double-bundle reconstruction technique with autogenous quadriceps tendon graft: remnant-preserving technique. Arch Orthop Trauma Surg, 2009, 129(3): 403-407.
[36] Ahn JH, Chung YS, Oh I. Arthroscopic posterior cruciate ligament reconstruction using the posterior trans-septal portal. Arthroscopy. 2003 Jan; 19(1):101-7.
[37] Elazab A, Lee YS, Kang SG. Femoral Footprint Reconstruction with a Direct Viewing of the Posterior Insertion Using a Trans-Septal Portal in the Outside-In Anterior Cruciate Ligament Reconstruction. Arthrosc Tech. 2015 Nov 17; 5(1):e49-54.
[38] Ahn JH, Wang JH, Lee YS, Kim JG, Kang JH, Koh KH. Anterior cruciate ligament reconstruction using remnant preservation and a femoral tensioning technique: clinical and magnetic resonance imaging results. Arthroscopy. 2011 Aug; 27(8):1079-89.
[39] Dong YL, Cai CY, Jiang GY, Zhang L, Jiang WH, Yang GJ. [Arthroscopic single bundle anterior cruciate ligament anatomical reconstruction with remnant preservation]. Zhongguo Gu Shang. 2013 Feb; 26(2):124-7.
[40] Gao K, Chen S, Wang L, Zhang W, Kang Y, Dong Q, Zhou H, Li L. Anterior cruciate ligament reconstruction with LARS artificial ligament: a multicenter study with 3- to 5-year follow-up. Arthroscopy. 2010 Apr; 26(4):515-23.
[41] Jung YB, Jung HJ, Siti HT, Lee YS, Lee HJ, Lee SH, Cheon HY. Comparison of anterior cruciate ligament reconstruction with preservation only versus remnant tensioning technique. Arthroscopy. 2011 Sep; 27(9):1252-8.
[42] Mifune Y, Ota S, Takayama K, Hoshino Y, Matsumoto T, Kuroda R, Kurosaka M, Fu FH, Huard J. Therapeutic advantage in selective ligament augmentation for partial tears of the anterior cruciate ligament: results in an animal model. Am J Sports Med. 2013 Feb; 41(2):365-73.
[43] Park SY, Oh H, Park SW, Lee JH, Lee SH, Yoon KH. Clinical outcomes of remnant-preserving augmentation versus double-bundle reconstruction in the anterior cruciate ligament reconstruction. Arthroscopy. 2012 Dec; 28(12):1833-41.
[44] 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 Surg. 2000; 120(3-4):128-33.
[45] McMahon PJ, Dettling JR, Yocum LA, Glousman RE. The cyclops lesion: a cause of diminished knee extension after rupture of the anterior cruciate ligament. Arthroscopy. 1999 Oct; 15(7):757-61.
[46] Tonin M, Saciri V, Veselko M, Rotter A. Progressive loss of knee extension after injury. Cyclops syndrome due to a lesion of the anterior cruciate ligament. Am J Sports Med. 2001 Sep-Oct; 29(5):545-9.
[47] Crawford R, Walley G, Bridgman S, Maffulli N. Magnetic resonance imaging versus arthroscopy in the diagnosis of knee pathology, concentrating on meniscal lesions and ACL tears: a systematic review. Br Med Bull. 2007; 84:5-23
[48] Ochi M, Iwasa J, Uchio Y, Adachi N, Kawasaki K. Induction of somatosensory evoked potentials by mechanical stimulation in reconstructed anterior cruciate ligaments. J Bone Joint Surg Br. 2002 Jul; 84(5):761-6.
[49] Fremerey RW, Lobenhoffer P, Zeichen J, Skutek M, Bosch U, Tscherne H. Proprioception after rehabilitation and reconstruction in knees with deficiency of the anterior cruciate ligament: a prospective, longitudinal study. J Bone Joint Surg Br. 2000 Aug; 82(6):801-6.
[50] Siebold R, Fu FH. Assessment and augmentation of symptomatic anteromedial or posterolateral bundle tears of the anterior cruciate ligament. Arthroscopy. 2008
Nov; 24(11):1289-98
[51] Reider B, Arcand MA, Diehl LH, Mroczek K, Abulencia A, Stroud CC, Palm M, Gilbertson J, Staszak P. Proprioception of the knee before and after anterior cruciate ligament reconstruction. Arthroscopy. 2003 Jan; 19(1):2-12.