Preservation of the Anterior Cruciate Ligament: A Treatment Algorithm Based on Tear Location and Tissue Quality

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Abstract
The gold standard of anterior cruciate ligament (ACL) injuries is currently single-bundle autograft reconstruction. However, many disadvantages of reconstructive surgery exist, such as: anterior knee pain, muscle atrophy, and loss of range of motion. In addition, native kinematics are not restored, and osteoarthritis is not prevented. Finally, revision surgery, if necessary, can be problematic due to tunnel widening, tunnel malpositioning, and preexisting hardware.

Ligament preservation includes preservation of native tissues in order to optimize the biologic aspects, while decreasing the invasive nature of reconstructive surgery. In the 1970s and 1980s, ACL preservation via open primary repair was widely performed, but the technique was abandoned due to unpredictable results. Unfortunately, the influence of both tear location and tissue quality on primary repair outcomes was not adequately recognized. Augmented repair, essentially a combination of primary repair and reconstruction, was then performed in the 1980s and early 1990s. Despite excellent results, for multiple reasons the surgical community moved on to ACL reconstruction, which was adapted as the gold standard.

With the current knowledge of the role of tear location and tissue quality on outcomes of ACL preservation, in combination with modern advances of magnetic resonance imaging, arthroscopic technology, and the benefits of early rehabilitation, there is likely a role for ACL preservation today. In this article, we (I) discuss the history of ACL preservation, (II) discuss how modern advances alter the risk-benefit ratio for ACL preservation, and (III) propose a treatment algorithm for ACL injuries that is based on tear location and tissue quality.

Injury of the anterior cruciate ligament (ACL) is very common with over 200,000 annual injuries in the United States.1,2 There is a general consensus that these injuries should not be treated conservatively in patients that are younger, or who wish to remain active.3,4 Reconstructive surgery is currently the preferred treatment in these patients, and anatomic single-bundle reconstruction with autografts is considered the gold standard.5,6

Reconstruction of the ACL is, however, not a perfect treatment. Following single-bundle autograft reconstruction, revision rates of 3% to 8%,6,9 contralateral injury rates of 3% to 8%,10,11 and infection rates of 0.5% to 3%,12,13 have been reported. Furthermore, due to the invasive nature of graft harvesting and the surgical procedure, 10% to 25% of the patients are not satisfied following ACL reconstruction.14,15 This can often be explained by common complaints, such as anterior knee pain (13%-43%), kneeling pain (12%-54%), quadriceps muscle atrophy (20%-30%),16,17 and loss of range of motion (ROM) (12%-23%).18,19 Furthermore, as a result of the invasive nature of reconstructive surgery, revisions can be difficult due to compli-

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Preservation of the Anterior Cruciate Ligament: A Treatment Algorithm

The feasibility and applicability of these surgical techniques mainly depends on the tear type and tissue quality of the torn ligament. In this article we (I) discuss the history of ACL preservation, (II) discuss how modern advances alter the risk-benefit ratio for ACL preservation, and (III) propose a treatment algorithm for ACL injuries that is based on tear location and tissue quality.

History of ACL Preservation

The history of the surgical treatment of ACL injuries started in 1895 when Robson treated a 41-year-old male who tore both cruciate ligaments from the femoral wall. Performing primary repair with catgut ligatures, both cruciate ligaments were preserved and the patients had resolution of pain symptoms and full function at 6-year follow-up. Over the following decades, Palmer and O’Donoghue further popularized open primary repair for the treatment of ACL injuries, and this technique was the most commonly performed treatment in the 1970s and early 1980s. The initial short-term results of primary repair were excellent, but Feagin and Curl were the first to note that the results deteriorated at mid-term follow-up. Despite improvements in the surgical technique of repairing the ACL, such as the usage of nonabsorbable sutures and directly tying the sutures over bone, the results remained disappointing at longer-term follow-up.

In response to these disappointing results, surgeons sought to improve the surgical treatment by either augmenting the primary repair with a semitendinosus, a patella tendon graft or an augmentation device, or by performing primary repair also restores the native kinematics, and may prevent osteoarthritis. Furthermore, primary repair is a conservative approach in that no grafts need to be harvested, no tunnels need to be drilled, and revision surgery, if necessary, is more analogous to primary reconstructions.

In patients with partial tears, some surgeons have advocated preserving the anteromedial (AM) or posterolateral (PL) bundle and performing selective single-bundle augmentation. Others have augmented this repair technique with an internal brace or with a synthetic device. When performing primary repair, it is believed that proprioception is maintained, while experimental studies have suggested that primary repair also restores the native kinematics, and may prevent osteoarthritis. Furthermore, primary repair is a conservative approach in that no grafts need to be harvested, no tunnels need to be drilled, and revision surgery, if necessary, is more analogous to primary reconstructions.

Some authors have recently reported on arthroscopic primary repair of proximal ACL tears in which the ligament is reattached on the femoral wall using modern-day suture anchor technology. Others have augmented this repair technique with an internal brace or with a synthetic device. When performing primary repair, it is believed that proprioception is maintained, while experimental studies have suggested that primary repair also restores the native kinematics, and may prevent osteoarthritis.

Ligament preservation focuses on preserving the native tissues and biology, while minimizing the surgical morbidity to the patients.

Over the past decades, there has been an increasing interest in the preservation of the ACL in an attempt to ameliorate these issues. Ligament preservation focuses on preserving the native tissues and biology, while minimizing the surgical morbidity to the patients.

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The Important Role of Tear Location in Ligament Preservation

When taking a closer look at the outcomes of primary repair and augmented repair, it seems that the results of these preservation techniques were not as disappointing as was suggested. This can be explained, in large part, by the fact that the important roles of tear location and tissue quality were not widely recognized.

Sherman and colleagues reported in 1991 their mid-term results of open primary repair. Similar to others, they noted a deterioration of their results at mid-term follow-up. However, they uniquely performed an extensive subgroup analysis in order to find an explanation for this. In their study, considered a landmark paper on primary repair, they concluded that, “poor tissue quality is typical for midsubstance tears and that a repair of these injuries will predictably fail while type I tears (proximal), with better tissue quality, show a
definite trend towards better results.” With these findings, they confirmed the findings of others that had recognized a trend of better outcomes with proximal tears. 

A majority of the historical studies that were published before 1991 had not considered the role of tear location and tissue quality on outcomes of open primary repair. This was also true for the aforementioned randomized studies that compared primary repair with augmented repair and primary reconstruction. Because these studies randomized patients and did not take tear location into account, it can be expected that patients with midsubstance tears were included in the cohorts of primary repair and the outcomes of these studies were therefore confounded. 

Interestingly, and in contrast to the findings of Feagin and Curl, no deterioration of the outcomes at mid-term follow-up was noted in patients with proximal tears. Genelin and colleagues reported their results of 42 patients with proximal tears treated with open primary repair at 5- to 7-year follow-up. They found a negative pivot shift in 81%, stable or nearly stable Lachman test in 81%, and patient satisfaction in 86% of patients. Similarly, Bräm and colleagues found good results at mid-term follow-up with a good-excellent Lysholm score in 79%, return to a similar level of sports in 76%, stable or nearly stable Lachman test in 91%, and anterior drawer test in 94% of patients, along with an 88% satisfaction rate and 7% failure rate in patients who underwent open primary repair of proximal tears.

Open Primary ACL Repair Outcomes Stratified by Tear Location

When reviewing the literature of open primary repair outcomes stratified by tear location, it is noted that multiple studies reported excellent outcomes following primary repair of proximal ACL tears. Weaver and colleagues were among the first to stratify their results by tear location, and they found that more patients with proximal tears (52 of 66; 79%) were satisfied after the procedure when compared to patients with midsubstance tears (3 of 13; 23%) at 3.5-year follow-up. They concluded that, “selection can be made with some predictability of the type of injury to the ligament as to which patients will do better.” Kühne and colleagues reported the outcomes of 75 patients with proximal tears treated with open primary repair and noted no failures, negative pivot shift in 88% of patients, stable or nearly stable Lachman test in 87% of patients, and 89% return to sports rate at 4-year follow-up. Raunest and colleagues reported a negative pivot shift and negative anterior drawer test in 84%, return to sports in 71%, and satisfaction in 75% of 51 patients that underwent open primary repair of proximal tears at 3.5-year follow-up.

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On the contrary, when the outcomes of studies that performed open primary repair in mainly, or only, patients with midsubstance tears are reviewed, significantly inferior results are found. Frank and colleagues reported outcomes of 42 patients with midsubstance tears at 4-year follow-up. They reported that 56% had a stable or nearly stable anterior drawer test, 78% had a positive pivot shift, and that only 61% were satisfied with the procedure. Odensten and colleagues reported outcomes of open primary repair in a subgroup of 22 patients with midsubstance tears at 1.5-year follow-up, and noted a 14% failure rate.

When reviewing the mid-term results in patients with midsubstance tears, it seems that there was more deterioration in outcomes. Firstly, the aforementioned study by Sherman and colleagues showed poor results in the patients with (type IV) midsubstance tears at mid-term follow-up. Furthermore, Kaplan and colleagues reported the mid-term outcomes of 70 patients, of which 56 patients had midsubstance tears. After having reported good outcomes at short-term follow-up, they noted that 42% of patients had >3 mm anteroposterior stability when compared to the contralateral leg, only a 62% return to sport rate, and a 17% failure rate. They concluded that, “Although primary repair of the anterior cruciate ligament may work in some patients, it is an unpredictable operative procedure.”

These studies showed that the outcomes of open primary repair were significantly better in patients with proximal ACL tears and sufficient tissue quality when compared to midsubstance tears. This suggests that open primary ACL repair may have been prematurely abandoned as a treatment option for patients with proximal tears.

Augmented ACL Repair

There were several reasons why augmented repair became the preferred treatment in the early and
mid 1990s. First of all, the results of augmented repair were more consistent compared to primary repair in the aforementioned randomized and prospective studies,4,7,8,82, which is not surprising given the fact that the role of tear location was not widely recognized at the time. Secondly, in the 1970s and early 1980s, patients were treated postoperatively in a cast for 6 weeks, which led to problems, such as loss of ROM, pain, and decreased function.53,94 At the end of the 1980s and 1990s, the focus shifted from prolonged joint immobilization towards early postoperative ROM.95-97 Since many authors believed that primary repair of the ACL was not strong enough to tolerate early mobilization, an augmentation was added to the technique in order to fortify the repair and enable early ROM.96

Interestingly, augmented repair, which is essentially a combination of primary ACL repair and ACL reconstruction, was mainly performed in the 1990s and many surgeons did recognize the role of tear location in this treatment at this point.73,98-103 In these years, the treatment algorithm consisted of augmented ACL repair in patients with proximal tears in the acute setting and ACL reconstruction in patients with midsubstance or chronic tears. Several different augmentation techniques were used to reinforce the primary repair in these years including autograft tissues (semitendinosus tendon,103-106 patellar tendon,102 or iliotibial band [ITB]105) synthetic materials (polydioxanone [PDS],101,102,106 carbon fibre,74 and polyester [Trevira]97), augmentation devices (Kennedy Ligament Augmentation Device [LAD]96-101) and extra-articular augmentations.73

When reviewing the outcomes of augmented repair of the ACL, good to excellent results can be found in studies that used this technique in patients with proximal tears.73,98-106 Kdolsky and colleagues98 were in one of the first groups that reported their results of augmented repair in only patients with proximal tears. In 1993, they reported their mid-term outcomes (5 to 8 years) in 66 patients who underwent primary repair and augmentation with the Kennedy LAD and found that 97% of patients had stable knees (<3 mm on KT-1000 examination), 98% had a negative pivot shift, and 76% returned to previous level of sports. However, often-reported problems with the augmentation devices were found in this study with rupture of the device (12%) and decreased ROM (14%).98 In 1995, Grøntvedt and Engebretsen103 compared augmentation with the Kennedy LAD to patellar tendon augmentation in a randomized study of patients with acute proximal tears. They noted that 50% of the patients in the Kennedy LAD group had a positive pivot shift compared to 23% in the patellar tendon group. Furthermore, they found KT-1000 leg differences of <3 mm in 92% of the patellar tendon group and 54% of the Kennedy LAD group. Because the authors found significant differences between both groups at 1- and 2-year follow-up, they stopped the clinical trial.

Several authors in the following years reported good results of augmented repair using autograft tissues. Natri and colleagues105 reported the outcomes of 72 patients treated with primary repair of proximal tears augmented with the ITB at 3.5-year follow-up. They found 89% negative pivot shift rate, 93% stable or nearly stable Lachman test, 99% stable or nearly stable anterior drawer test, 79% satisfaction rate, and 91% return to previous level of sports rate. Krueger-Franke and colleagues104 reported the outcomes of primary repair of proximal tears with augmentation using the semitendinosus tendon. In a retrospective study of 76 patients, they noted that 96% of patients had a negative pivot shift, 75% of patients had stable or nearly stable Lachman test, 93% were satisfied with the procedure, a mean Lysholm score of 92, a Tegner score that only decreased from 7.2 to 7.1, and KT-1000 testing with 78% <4 mm leg difference with the contralateral leg. The authors concluded that patients with femoral ruptures could be treated with augmented repair when performed in the acute setting. As this study was published in 1998, they stated that magnetic resonance imaging and arthroscopy could be helpful in identifying the tear location.

Final Abandonment of ACL Preservation

Reviewing these outcomes raises the question as to why these techniques were ultimately abandoned in the treatment algorithm of proximal ACL injuries, especially given the aforementioned advantages of ACL preservation. One of the possible answers can be found in a landmark study on ACL reconstruction and rehabilitation published by Shelbourne and colleagues107 in 1991. At that time, arthrofibrosis and knee stiffness were frequently reported problems following ACL surgery, which could partially be explained by the standard conservative rehabilitation using postoperative joint immobilization.67,80,98

Shelbourne and colleagues107 aimed to assess the cause of arthrofibrosis and knee stiffness, and
Role for ACL Preservation with Modern Advances

As stated in the introduction, there has been a recent resurgence of interest in preservation of the native ligament.32-37 With the passage of time, many technologic advances have been made, which has allowed surgeons to reconsider the concept of ligament preservation.

First of all, appropriate patient selection was not applied historically, as the critical factors of tear location and tissue quality were not recognized in the era of open primary repair. In modern days, however, advances such as MRI have been developed, which can give the surgeon an idea of the status, and tear type of the ACL pre-operatively.108 This may help the orthopaedic surgeon to plan the surgery and make an assessment as to whether ACL preservation is possible. Secondly, in the historic literature the postoperative regimen consisted of casting for 5 or 6 weeks,67,70,80,88 while the focus later shifted towards early ROM.95-97 Modern day ACL rehabilitation focuses on immediate ROM to avoid the complications stiffness, pain and decreased function that plagued the outcomes when immobilization was used.93,94 Thirdly, historically small tunnels were drilled with primary repair and sutures had to be tied over bone,52,67 whereas currently suture anchors are available that prevent the need for tunnel drilling and enable direct suture tensioning.32,38 Finally, and most importantly, in the historic literature patients were treated with an invasive arthrotomy technique, while modern day arthroscopic techniques readily enable the surgeon to effectively suture the remnant arthroscopically. Interestingly, in 2005, in their 20-year follow-up of primary repair surgeries, Strand and colleagues109 stated, “if the same results could be accomplished by a smaller, arthroscopic procedure, primary repair might reduce the number of patients needing later reconstructions with small ‘costs’ in the way of risk and inconvenience for the patients. We therefore believe that further research and development of methods for closed (arthroscopic) repair are justified.”

Altered Risk-Benefit Ratio

Historically, the treatments of open primary repair and open ACL reconstruction were both invasive surgeries with an arthrotomy, drilling of bone tunnels, and postoperative joint immobilization for 4 to 6 weeks. However, with the modern-day advances, the risk-benefit ratio of both treatments has changed, as Strand and colleagues59 had already suggested. Although ACL reconstruction can be performed arthroscopically, it remains an invasive procedure, in which tunnels are drilled, patellar tendons or hamstring tendons are harvested, and complications, such as knee pain and quadriceps atrophy, are common. The surgery of primary ACL repair, however, has benefited significantly from the modern developments.32,38 Primary ACL repair can now be performed arthroscopically, and by using suture anchors no tunnels need to be drilled and the remnant can be tensioned directly. An additional benefit of the use of suture anchors is that revision surgery of a failed primary repair is analogous to primary reconstruction, whereas revision surgery of a failed ACL reconstruction can...
be problematic due to tunnel widening, tunnel malpositioning, and preexisting hardware.\textsuperscript{20,22}

Reviewing the differences between arthroscopic primary ACL repair and ACL reconstruction, it becomes clear that primary repair has benefited significantly from the modern advances and that the risk-benefit ratio for primary repair has been altered. This means that patients with proximal tears can be treated with a relatively straightforward, minimally invasive surgery, which has been shown to be effective in 85\% to 90\% of patients.\textsuperscript{32,38}

**Treatment Algorithm Based on Tear Location**

Since 2008, in the practice of the senior author (GSD), the surgical treatment algorithm for ACL injuries is completely based on the tear location and tissue quality of the ligament.\textsuperscript{110,111} To describe the different tear types, we use the modified Sherman classification in which we extended his classification towards the tibial side whereas Sherman and colleagues\textsuperscript{70} only described the femoral side of the tears (Figures A-F, Table). In this section, we will discuss the different tear types that are seen and the corresponding treatments that can be used to treat these injuries (Table). Furthermore, we discuss current research on these topics and the reported outcomes of these techniques. We will not provide the incidence of different tear types as the senior author’s practice is biased towards primary repair.

**Type I Tears: Primary Repair**

Type I tears are soft tissue avulsion type tears that can be easily treated with arthroscopic primary repair.\textsuperscript{107} The length of the distal remnant has to be...
at least 90% and the tissue quality has to be good to excellent in order to approximate the remnant towards the femoral wall (Table). The incidence of type I tears was 26% in the study of Sherman and colleagues, although recent studies showed a lower incidence (6% to 10%) in a larger population. Certainly, individual practices will see different percentages of type I tears based upon the mix of injury mechanisms they see most frequently. Over the last 2 years, with the recognition of the importance of tear type and tissue quality, there has been a renewed interest in arthroscopic primary ACL repair.

DiFelice and colleagues were the first to arthroscopically perform primary repair of the ACL in proximal tears using suture anchors. They reported the outcomes of the first 11 consecutive patients that underwent primary repair in a previously described technique. At mean 3.5-year follow-up, they noted only 1 failure (9%) due to re-injury; mean Lysholm score of 93.2; mean modified Cincinnati score of 91.5; pre- and postoperative Tegner score of 7.3 and 6.9, respectively; SANE score of 91.8; and subjective International Knee Documentation Committee (IKDC) score of 86.4. Of the patients with an intact repair, 9 patients had an objective IKDC rating A and 1 patient had B and all patients had KT-1000 leg differences of <3 mm with the contralateral side (three patients were not available for KT-1000 testing). The authors concluded that arthroscopic primary ACL repair could achieve short-term clinical success in a selected group of patients with proximal avulsion tears and excellent tissue quality. They further noted that mid-term outcomes are necessary given that the results of open primary repair deteriorated at longer-term follow-up in the historical literature. Recently, the senior author (GSD) has added an Internal Brace (Arthrex) to the primary repair with the goal of protecting the ligament in the first weeks to further promote healing of the ligament.

More recently, Achtnich and colleagues compared the treatment of arthroscopic primary ACL repair with primary ACL reconstruction in 41 patients with type I tears at 2.3-years follow-up. Twenty-one patients consented for primary repair while 20 patients declined this procedure and underwent primary reconstruction. They noted no significant differences in Lachman test, pivot shift test, objective IKDC score, and KT-1000 scores. Although not significant, the clinical failure rate in the primary repair group (15%) was higher than the reconstruction group (0%). Interestingly, despite the higher failure rate in the repair group, the authors concluded that primary ACL repair is recommended in a carefully selected group of patients with type I tears and excellent tissue quality, which can likely be explained by the differences in the risk-benefit ratio between both procedures.

Over the last decade, the research group led by Murray has performed experimental research on primary repair with a biological scaffold and reported many interesting findings that could be extrapolated to primary ACL repair. First of all, they compared bioenhanced primary repair with bioenhanced primary reconstruction in 64 Yucutan pigs and noted that there was significantly less macroscopic cartilage damage in the primary repair group at 1-year follow-up. They concluded that bioenhanced ACL repair may provide a new, less invasive treatment option that reduces cartilage damage following joint injury. This may suggest that primary repair may have a lower incidence of osteoarthritis when compared to ACL reconstruction, which is interesting as osteoarthritis is very common after ACL reconstruction. Further research in this area is certainly warranted.

In another study they compared bioenhanced primary repair in juvenile, adolescent and mature Yucutan pigs and noted that functional healing depended on the level of skeletal maturity with immature animals having a more productive healing response. This indicates that primary repair might be a good treatment option in skeletally immature patients, especially since reconstruction increases the risk of premature closure of the epiphysis and delaying treatment increases the risk of meniscus injury. Interestingly, a recent meta-analysis showed indeed that the risk of epiphysis closure was lower in primary repair when compared to ACL reconstruction and the rupture rate was also lower. Primary repair may be a good treatment option in children as the procedure has all the attributes that should be applicable to children: it is minimally morbid, tissue sparing, and it is a conservative approach that does not burn any surgical bridges for future reconstructive surgery if necessary.

Finally, the research group of Murray assessed the effect of surgical delay of primary repair following injury in Yucutan pigs and noted that better biomechanical outcomes were noted after delaying surgery for 2 weeks when compared to 6 weeks. This suggests that primary repair should preferably be performed in the acute setting, which has also been shown in historical studies since the liga-
One Bundle Type I Tears: Single Bundle Augmented Repair

In some cases, the tear locations of the AM and PL bundle are not at the same location and Zantop and colleagues\textsuperscript{120} reported in an arthroscopic study that this could be as frequent as in 30% of all complete tears. In some of these tears, one of the bundles can be avulsed of the femoral wall (type I tear) while the other bundle is not directly repairable (non-type I tear). In these cases, the senior author (GSD) will repair the type I tear bundle, whereas a hamstring augmentation is placed at the location of the other bundle. When reviewing the literature, a combination of primary repair of one bundle and reconstruction of the second bundle has not been described before. However, over the last decade several surgeons have performed augmentation of one bundle in the setting of partial tears.\textsuperscript{34,35,121,124}

Buda and colleagues\textsuperscript{34} were the first to perform selective AM or PL bundle reconstruction in the setting of partial tears.\textsuperscript{34} At 5-year follow-up, they reported no reruptures and only 1 patient with an IKDC C-score, although reoperation was necessary in 4 out of 47 patients (9%). Following this publication, many others reported on selective bundle reconstruction.\textsuperscript{35,121,124} However, with partial tears, the knee is often stable and a selective augmentation technique is utilized to prevent complete rupture of the ligament. The application of this technique is essentially different from reconstruction for complete ACL tears in which the knee is unstable, there is a giving way sensation and patients have problems participating in sports.

Type II Tears: Augmented Repair

Type II tears often have good or excellent tissue quality and can be pulled up towards the femoral footprint, but are too short to be firmly attached. Sherman and colleagues\textsuperscript{70} reported that approximately 22% patients had a type II tear, which corresponds to a tear located in the proximal part of the ligament. With this technique, multiple suture passes are used to stitch the remnant and, in addition, a smaller hamstring autograft or allograft is passed through the middle of the tibial remnant. A suture button is used proximally for the graft, and the tensioning repair sutures through the remnant are also passed through the suture button. The suture button is passed through the femoral tunnel and flipped so that the graft is proximally fixed. Then, the repair sutures of the remnant are tensioned, and the ligament is pulled towards the femoral wall as a sleeve around the graft. When the ligament is approximated to the femoral wall, the sutures are tied over the suture button. The graft is then tensioned distally to complete the augmented repair.

In the recent literature, the technique of augmentation of a primary repair using autograft tissue has not been reported. However, augmented repair using an internal brace\textsuperscript{35,40} or augmentation devices\textsuperscript{33,41} have been recently performed. MacKay and colleagues\textsuperscript{39} reported good outcomes of arthroscopic primary repair of proximal tears using an internal brace. Eggli and colleagues\textsuperscript{13} reported the results of the first 10 patients treated with ACL preservation using primary repair of the ligament with the addition of a dynamic screw-spring mechanism. The authors reported good preliminary results with one failure (10%) and good objective and subjective outcomes. In a next study, they reported the outcomes of 278 patients and although they reported good clinical outcomes and a revision rate of 4%, the reoperation rate for removal of the screw-spring mechanism was high (24%).\textsuperscript{41} This is not surprising when reviewing the historical literature in which high complication rates of the augmentation devices were reported.\textsuperscript{98,100} We were unable to identify any other studies reporting surgical techniques of augmenting primary repair in the literature.

Type III Tears: Reconstruction With Remnant Tensioning

In patients with type III tears, the ligament cannot be approximated to the wall and reconstruction is necessary in order to restore knee stability. However, in these cases the ligament has sufficient length (25%-75%) and can be tensioned along or around the graft. Preservation of the ligament remnant has several (theoretical) advantages, such as better proprioceptive function,\textsuperscript{42,49,50} vascularization and ligamentization of the graft,\textsuperscript{50,62} an optical guide for anatomic tunnel placement,\textsuperscript{53} and a decreased incidence of tunnel widening.\textsuperscript{54,55} Furthermore, tensioning of the remnant is thought to lower the risk of cyclops lesions when compared to remnant preservation.\textsuperscript{125} Although the difference between augmented repair and remnant tensioning seems small, the purpose of surgery is different. With augmented repair, the ligament can be approximated close to the femoral wall and the goal of surgery is to use the healing capacity that the ACL
has in the proximal part of the ligament, while with remnant tensioning the goal is only to benefit from some of the aforementioned advantages. Ahn and colleagues\textsuperscript{126} were the first to perform this technique and stated, “Our concept is that the remnant tissue has only an additive effect.” Furthermore, with augmented repair multiple sutures are passed through the AM and PL bundle in order to sufficiently approximate the ligament to the femoral wall, while with the remnant tensioning technique generally one or a few sutures or lasso loop are passed through the proximal part to tension the ligament, prevent sagging of the remnant, and decrease the risk of cyclops lesions.\textsuperscript{127,128}

Several authors have recently performed remnant tensioning during ACL reconstruction. Ahn and colleagues\textsuperscript{36} reported excellent objective and subjective outcomes following this procedure and found that with re-arthroscopy nearly all patients had fair synovialization of the graft. Others have reported similarly good outcomes of these techniques.\textsuperscript{125,129,130} However, studies comparing this treatment with normal ACL reconstruction and assessing outcomes, failure rates and proprioception are lacking.

**Type IV Tears: Reconstruction With Remnant Preservation**

Finally, in some patients the ligament is torn distally or the tissue quality is not optimal. In these patients, the remnant can be debrided to the part of good tissue quality in order to preserve the biology and minimize the risk for cyclops lesions. A standard reconstruction needs to be performed to restore the instability, but by preserving the remnant, advantages, such as proprioception,\textsuperscript{44,49,50} graft vascularization,\textsuperscript{50,52} an optical guide for tibial tunnel placement,\textsuperscript{53} and a decreased incidence of tunnel widening\textsuperscript{54,55} can be expected.

Lee and colleagues\textsuperscript{37} presented the tibial remnant technique in which standard reconstruction was performed, and the tibial tunnel was drilled through the center of the remnant. In a later study, they compared remnant preservation with a remnant of <20% of the total ACL length with >20% of the length and found that proprioception was better with more remnant volume.\textsuperscript{48} Similarly, Muneta and colleagues\textsuperscript{131} assessed the role of remnant length and found that remnant length is positively correlated with better stability measured on KT-1000 anteroposterior stability.

Several studies compared ACL reconstruction with remnant preservation vs conventional ACL reconstruction.\textsuperscript{52,54,129} Takazawa and colleagues\textsuperscript{52} performed a retrospective study of 183 patients and found that patients in the remnant preservation group had significantly better KT-2000 stability, while they also reported a significantly lower graft rupture rate in this group (1.1% vs 7.1%) at 2-year follow-up. Hong and colleagues\textsuperscript{129} performed a randomized clinical trial of 80 patients and did not find these differences, although there was a trend towards higher Lysholm scores in the remnant preservation group. Finally, Zhang and colleagues\textsuperscript{54} performed a randomized clinical trial and found a lower incidence and amount of tibial tunnel widening in the preserving-remnant group when compared to the removing-remnant group. These studies show that there is likely a role for remnant preservation.

**Type V Tears: Primary Repair**

In some patients, the ligament is torn in the distal 10% of the ligament, which can occur as a distal avulsion tear or as a distal bony avulsion fracture.\textsuperscript{132} Bony avulsion fractures are most commonly seen in children whereas true distal soft tissue avulsion tears are very rare.\textsuperscript{132}

Treatments of these tear types include antegrade screw fixation, pullout sutures or the use of suture anchors in case of bony avulsion fractures and pullout sutures with tying over a bony bridge or ligament button in case of soft tissue avulsions. Leeberg and colleagues\textsuperscript{132} recently performed a systematic review of all studies reporting on treatment of distal avulsion fractures. They noted that most treatments were currently performed arthroscopically and that outcomes were generally good. Another recent biomechanical study compared antegrade screw fixation with suture anchor fixation and pullout suture fixation.\textsuperscript{133} The authors noted that suture anchor fixation has slightly less displacement of the bony fragment when compared to screw fixation and pull-out sutures, and that the strength to failure was higher in the suture anchor fixation when compared to the pullout suture fixation. The outcomes of this study suggest that screw fixation and suture anchor fixation might be superior to pullout suture fixation, which might be interesting as with pullout suture fixation the ligament cannot be directly tensioned to the tibial footprint, which can lead to anteroposterior laxity.\textsuperscript{132} Clinical studies are necessary to assess the preferred treatment in these tear types but it seems that screw fixation is preferred in large bony avulsion fractures, while suture anchor fixa-
Preservation of the Anterior Cruciate Ligament: A Treatment Algorithm

Complex Tears or Poor Tissue Quality: Reconstruction

If the tear is complex, multiple tears are present, or the tissue quality is poor, then preservation of the ligament is not possible, and in these cases a standard reconstruction should be performed.

Conclusion

When reviewing the literature of ACL preservation, it becomes clear that the evolution of surgical treatment of ACL injuries was biased. Preservation of the native ligament has many advantages, such as better proprioception, graft vascularization, an optical guide for tibial tunnel placement, and a decreased incidence of tunnel widening that can be expected. Furthermore, arthroscopic primary ACL repair is minimally invasive and does not burn any bridges for future reconstructions, if necessary. This is in addition to the other (theoretical) advantages of primary repair, such as restoration of native kinematics and a decreased risk of osteoarthritis. Modern advances have significantly changed the risk-benefit ratio that should make us reconsider ACL preservation approaches. Certainly, further research in this area is warranted. In this article we have presented a treatment algorithm for ACL preservation, which is based on tear location and remnant tissue quality.

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