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 Status.[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%[7,12,13] 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%).[7,9,18,19] Furthermore, as a result of the invasive nature of reconstructive surgery, revisions can be difficult due to compli-

cations, such as tunnel widening, tunnel malpositioning, and preexisting hardware.[20-22] This can lead to inferior outcomes and higher rates (13%) of revision surgery compared to primary reconstruction.[23-26] Finally, reconstructive surgery does not restore native kinematics of the ACL,[27-29] which may partially explain why reconstructive surgery has not been shown to prevent osteoarthritis.[28-31]

Over the past decades, there has been an increasing interest in the preservation of the ACL in an attempt to ameliorate these issues.[32-37] Ligament preservation focuses on preserving the native tissues and biology, while minimizing the surgical morbidity to the patients.

Some authors have recently reported on arthroscopic primary repair of proximal ACL tears in which the ligament is reattached onto the femoral wall using modern-day suture anchor technology.[32,38] Others have augmented this repair technique with an internal brace[39,40] or with a synthetic device.[33,41] When performing primary repair, it is believed that proprioception is maintained,[42-44] while experimental studies have suggested that primary repair also restores the native kinematics,[45] and may prevent osteoarthritis.[46] 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.[32]

In patients with partial tears, some surgeons have advocated preserving the anteromedial (AM) or posterolateral (PL) bundle and performing selective single-bundle augmentation.[34,35] In addition, several authors have used remnant tensioning[36,47] or remnant preservation[37,48] in combination with reconstructive surgery in order to benefit from the biological characteristics of the remnant. These techniques lead to better proprioceptive function,[44,49,50] vascularization and ligamentization of the graft,[50-52] provide an optical guide for anatomic tunnel placement,[53] and decrease the incidence of tunnel widening.[54,55]

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[56] 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[57,58] and O'Donoghue[59,60] 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.[61-65] The initial short-term results of primary repair were excellent,[61,62] but Feagin and Curl[66] 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,[63,67] the results remained disappointing at longer-term follow-up.[68-70]

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,[71-74] or by performing primary reconstruction.[75-77] At the end of the 1980s and early 1990s, several randomized and prospective clinical trials were performed in order to compare the outcomes of these techniques.[74,78-82] Many studies showed that results of augmented repair were more reliable when compared to primary repair, which led to the abandonment of primary repair in favor of augmented repair, and eventually primary reconstruction.[65]

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[70] 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,[65,70] 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."[70] With these findings, they confirmed the findings of others that had recognized a trend of better outcomes with proximal tears.[64,67,83-85]

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.[74,78-82] If these studies would have been aware of the role that tear location plays on primary repair outcomes, different outcomes may have been found and different conclusions on the optimal treatment for different tear types may have been drawn.[86]

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.[73,83,84,87-90] Weaver and colleagues[64] 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."[64] Kühne and colleagues[89] 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[91] 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.

Interestingly, and in contrast to the findings of Feagin and Curl,[66] no deterioration of the outcomes at mid-term follow-up was noted in patients with proximal tears. Genelin and colleagues[88] 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[87] 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.

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[92] reported outcomes in 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[78] 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.[69,70] Firstly, the aforementioned study by Sherman and colleagues[70] showed poor results in the patients with (type IV) midsubstance tears at mid-term follow-up. Furthermore, Kaplan and colleagues[69] 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,[63,67] 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 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,[74,78-82] 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.[93,94] At the end of the1980s 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.[98]

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,[102-104] patellar tendon,[100] 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][98-100]) 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 colleagues[98] 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 Engebretsen[100] 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 colleagues[105] 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 colleagues[104] 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 colleagues[107] 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.[67,70,80,88]

Shelbourne and colleagues[107] aimed to assess the cause of arthrofibrosis and knee stiffness, and

divided the patients into groups by number of days between injury and surgery (<7, 7 to 21 days, and >21 days between injury and surgery). Furthermore, patients within these groups underwent either a conventional or accelerated rehabilitation program. The authors not only found that patients undergoing accelerated rehabilitation had less arthrofibrosis, but they also noted that less arthrofibrosis was seen when surgery was delayed. These findings, however, contrasted with the general perception that the ACL should be repaired in the first 3 weeks postinjury to ensure optimal tissue quality with an augmented approach. As a result, the treatment of ACL injuries shifted towards ACL reconstruction after these findings. Krueger-Franke and colleagues[104] commented on the trend after the study of Shelbourne and colleagues:[107] "Less consideration has been given to the importance of the proprioceptive receptors in the tibial remnants of the torn ACL and the value of their preservation as part of a primary reconstruction."

In addition to the trend away from an augmented repair approach due to the novel understanding of the importance of early mobilization, some discussion should focus on the technical limitations of arthroscopy at that time. While arthroscopy had been around for several decades, fluid management and arthroscopic instrumentation was slow to develop. All of the repair and augmentation techniques previously discussed had been performed via an open arthrotomy. Arthroscopic technologies of the time were not refined enough to enable surgeons to perform such complex, intra-articular techniques that would enable suturing of the ligament remnant. In this regard, arthroscopic ACL reconstruction was a much simpler technique to accomplish, and this also likely contributed to the final abandonment of the ligament preservation approach.

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-opera-

tively.[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,[57,67] 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 colleagues[109] 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 colleagues[109] 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
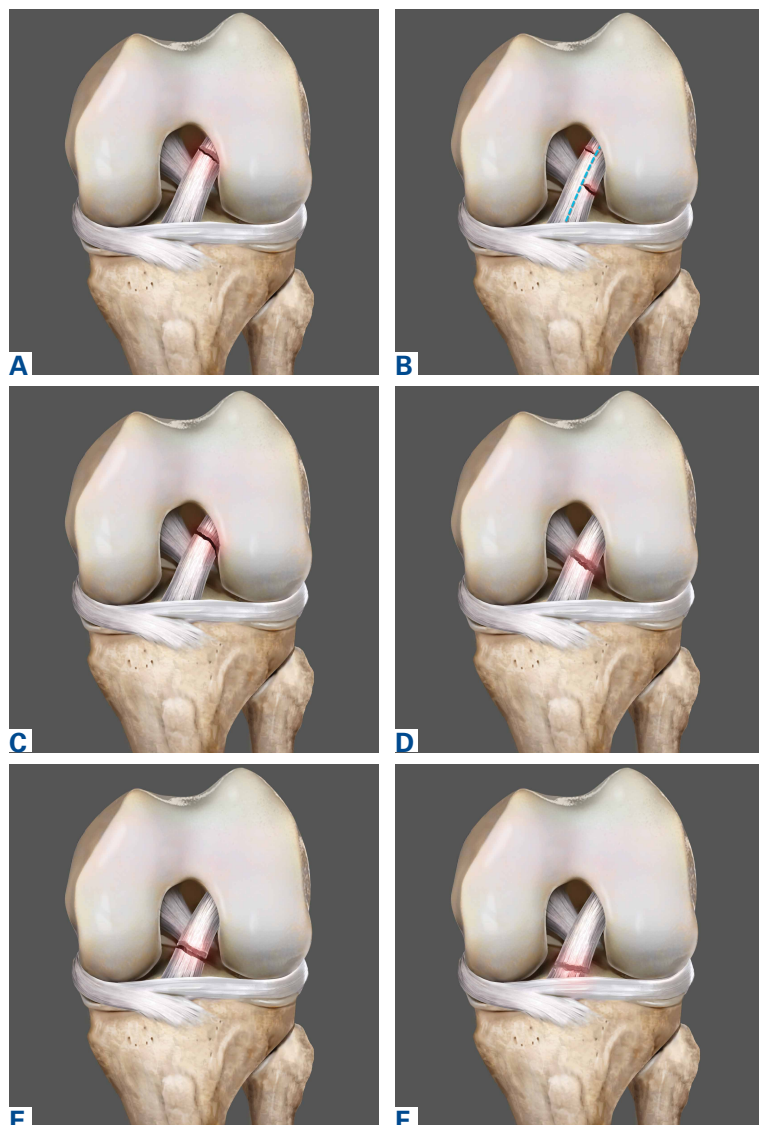
Figure. Illustrations of the new modified tear type classification.

be problematic due to tunnel widening, tunnel malpositioning, and preexisting hardware.[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 straight forward, minimally invasive surgery, which has been shown to be effective in 85% to 90% of patients.[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.[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[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.[107] The length of the distal remnant has to be

Table. Treatment Algorithm for Anterior Cruciate Ligament Preservation Based on the Different Tear Types

Tear Type	Description	Tear Location	Tissue Quality	Technique
Type I	Proximal avulsion	>90%	Good to excellent	Repair (two bundles/anchors) ± internal brace
One bundle Type I[a]	One bundle proximal avulsion[a]	>90%	Good to excellent	Repair (one bundle) + augmentation (other bundle)
Type II	Proximal	75%-90%	Good to excellent	Repair (two bundles) + augmentation
Type III	Midsubstance	25%-75%	Fair to good	Reconstruction + remnant tensioning
Type IV	Distal	10%-25%	Fair to good	Reconstruction + remnant preservation
Type V	Distal (bony) avulsion	<10%	Good to excellent	Distal repair (anchors/tunnels/screws)
Complex/multiple	—	—	Poor	Reconstruction

[a]With these tear types, one bundle (either anteromedial or posterolateral bundle) has a Type I tear that is amendable for repair while the other bundle is not repairable.

at least 90% and the tissue quality has to be good to excellent in order to approximate the remnant towards the femoral wall (Table).[112] The incidence of type I tears was 26% in the study of Sherman and colleagues,[70] although recent studies showed a lower incidence (6% to 10%) in a larger population.[32,38] 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.[32,38]

DiFelice and colleagues[32] 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.[113] 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.[39,40,114]

More recently, Achtnich and colleagues[38] 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[46,115,116] 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.[46] 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.[116] 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[117,118] and delaying treatment increases the risk of meniscus injury.[119] 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.[118] 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[115] 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-

ment in the acute setting has optimal tissue quality and the ligament is less likely to be retracted or reabsorbed.[59,60,115]

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[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.[34,35,121-124]

Buda and colleagues[34] were the first to perform selective AM or PL bundle reconstruction in the setting of partial tears.[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.[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[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[39,40] or augmentation devices[33,41] have been recently performed. MacKay and colleagues[39] reported good outcomes of arthroscopic primary repair of proximal tears using an internal brace. Eggli and colleagues[33] 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%).[41] This is not surprising when reviewing the historical literature in which high complication rates of the augmentation devices were reported.[99,100] 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,[42,49,50] vascularization and ligamentization of the graft,[50-52] an optical guide for anatomic tunnel placement,[53] and a decreased incidence of tunnel widening.[54,55] Furthermore, tensioning of the remnant is thought to lower the risk of cyclops lesions when compared to remnant preservation.[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,[126] while with remnant tensioning the goal is only to benefit from some of the aforementioned advantages. Ahn and colleagues[36] 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.[127,128]

Several authors have recently performed remnant tensioning during ACL.[36,47,125-127] Ahn and colleagues[47] 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.[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,[44,49,50] graft vascularization,[50-52] an optical guide for tibial tunnel placement,[53] and a decreased incidence of tunnel widening[54,55] can be expected.

Lee and colleagues[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.[48] Similarly, Muneta and colleagues[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.[52,54,129] Takazawa and colleagues[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[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[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.[132] Bony avulsion fractures are most commonly seen in children whereas true distal soft tissue avulsion tears are very rare.[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[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.[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.[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-

tion or pullout suture fixation can be used for soft tissue avulsion tears.

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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References

1. Mall NA, Chalmers PN, Moric M, et al. Incidence and trends of anterior cruciate ligament reconstruction in the United States. *Am J Sports Med.* 2014;42(10):2363-2370.
2. Sanders TL, Maradit Kremers H, Bryan AJ, et al. Incidence of anterior cruciate ligament tears and reconstruction: a 21-year population-based study. *Am J Sports Med.* 2016;44(6):1502-1507.
3. Ciccotti MG, Lombardo SJ, Nonweiler B, Pink M. Non-operative treatment of ruptures of the anterior cruciate ligament in middle-aged patients. Results after long-term follow-up. *J Bone Joint Surg Am.* 1994;76(9):1315-1321.
4. Sanders TL, Pareek A, Kremers HM, et al. Long-term follow-up of isolated ACL tears treated without ligament reconstruction. *Knee Surg Sports Traumatol Arthrosc.* 2016 May 24. [Epub ahead of print]
5. Irrázaval S, Kurosaka M, Cohen M, Fu FH. Anterior cruciate ligament reconstruction. *J ISAKOS.* 2016;1(1):38-52.
6. Gabler CM, Jacobs CA, Howard JS, Mattacola CG, Johnson DL. Comparison of graft failure rate between autografts placed via an anatomic anterior cruciate ligament reconstruction technique: a systematic review, meta-analysis, and meta-regression. *Am J Sports Med.* 2016;44(4):1069-1079.
7. Li S, Chen Y, Lin Z, Cui W, Zhao J, Su W. A systematic review of randomized controlled clinical trials comparing hamstring autografts versus bone-patellar tendon-bone autografts for the reconstruction of the anterior cruciate ligament. *Arch Orthop Trauma Surg.* 2012;132(9):1287-1297.
8. Rahr-Wagner L, Thillemann TM, Pedersen AB, Lind M. Comparison of hamstring tendon and patellar tendon grafts in anterior cruciate ligament reconstruction in a nationwide population-based cohort study: results from the danish registry of knee ligament reconstruction. *Am J Sports Med.* 2014;42(2):278-284.
9. Xie X, Liu X, Chen Z, Yu Y, Peng S, Li Q. A meta-analysis of bone-patellar tendon-bone autograft versus four-strand hamstring tendon autograft for anterior cruciate ligament reconstruction. *Knee.* 2015;22(2):100-110.
10. Andernord D, Desai N, Björnsson H, Gillén S, Karlsson J, Samuelsson K. Predictors of contralateral anterior cruciate ligament reconstruction: a cohort study of 9061 patients with 5-year follow-up. *Am J Sports Med.* 2015;43(2):295-302.
11. Maletis GB, Inacio MC, Funahashi TT. Risk factors associated with revision and contralateral anterior cruciate ligament reconstructions in the Kaiser Permanente ACLR registry. *Am J Sports Med.* 2015;43(3):641-647.
12. Kim SJ, Postigo R, Koo S, Kim JH. Infection after arthroscopic anterior cruciate ligament reconstruction. *Orthopedics.* 2014;37(7):477-484.
13. Makhni EC, Steinhaus ME, Mehran N, Schulz BS, Ahmad CS. Functional outcome and graft retention in patients with septic arthritis after anterior cruciate ligament reconstruction: a systematic review. *Arthroscopy.* 2015;31(7):1392-1401.
14. Kocher MS, Steadman JR, Briggs K, Zurakowski D, Sterett WI, Hawkins RJ. Determinants of patient satisfaction with outcome after anterior cruciate ligament reconstruction. *J Bone Joint Surg Am.* 2002;84-A(9):1560-1572.
15. Ardern CL, Österberg A, Sonesson S, Gauffin H, Webster KE, Kvist J. Satisfaction with knee function after primary anterior cruciate ligament reconstruction is associated with self-efficacy, quality of life, and returning to the preinjury physical activity. *Arthroscopy.* 2016;32(8):1631-1638.e3.
16. Grant JA, Mohtadi NG, Maitland ME, Zernicke RF. Comparison of home versus physical therapy-supervised rehabilitation programs after anterior cruciate ligament reconstruction: a randomized clinical trial. *Am J Sports Med.* 2005;33(9):1288-1297.
17. Lindström M, Strandberg S, Wredmark T, Felländer-Tsai L, Henriksson M. Functional and muscle morphometric effects of ACL reconstruction. A prospective CT study with 1 year follow-up. *Scand J Med Sci Sports.* 2013;23(4):431-442.
18. Biau DJ, Tournoux C, Katsahian S, Schranz PJ, Nizard RS. Bone-patellar tendon-bone autografts versus hamstring autografts for reconstruction of anterior cruciate ligament: meta-analysis. *BMJ.* 2006;332(7548):995-1001.
19. Spindler KP, Kuhn JE, Freedman KB, Matthews CE, Dittus RS, Harrell FE Jr. Anterior cruciate ligament reconstruction autograft choice: bone-tendon-bone versus hamstring: does it really matter? A systematic review. *Am J Sports Med.* 2004;32(8):1986-1995.
20. Aga C, Wilson KJ, Johansen S, Dornan G, La Prade RF, Engebretsen L. Tunnel widening in single- versus double-bundle

anterior cruciate ligament reconstructed knees. *Knee Surg Sports Traumatol Arthrosc.* 2016 Jun 21. [Epub ahead of print]

21. Maak TG, Voos JE, Wickiewicz TL, Warren RF. Tunnel widening in revision anterior cruciate ligament reconstruction. *J Am Acad Orthop Surg.* 2010;18(11):695-706.

22. Cheatham SA, Johnson DL. Anticipating problems unique to revision ACL surgery. S*ports Med Arthrosc.* 2013;21(2):129-134.

23. Kamath GV, Redfern JC, Greis PE, Burks RT. Revision anterior cruciate ligament reconstruction. *Am J Sports Med.* 2011;39(1):199-217.

24. Wright RW, Gill CS, Chen L, et al. Outcome of revision anterior cruciate ligament reconstruction: a systematic review. *J Bone Joint Surg Am.* 2012;94(6):531-536.

25. Andriolo L, Filardo G, Kon E, et al. Revision anterior cruciate ligament reconstruction: clinical outcome and evidence for return to sport. *Knee Surg Sports Traumatol Arthrosc.* 2015;23(10):2825-2845.

26. Grassi A, Ardern CL, Marcheggiani Muccioli GM, Neri MP, Marcacci M, Zaffagnini S. Does revision ACL reconstruction measure up to primary surgery? A meta-analysis comparing patient-reported and clinician-reported outcomes, and radiographic results. *Br J Sports Med.* 2016;50(12):716-724.

27. Ristanis S, Stergiou N, Patras K, Vasiliadis HS, Giakas G, Georgoulis AD. Excessive tibial rotation during high-demand activities is not restored by anterior cruciate ligament reconstruction. *Arthroscopy.* 2005;21(11):1323-1329.

28. Andriacchi TP, Mündermann A, Smith RL, Alexander EJ, Dyrby CO, Koo S. A framework for the in vivo pathomechanics of osteoarthritis at the knee. *Ann Biomed Eng.* 2004;32(3):447-457.

29. Imhauser C, Mauro C, Choi D, et al. Abnormal tibiofemoral contact stress and its association with altered kinematics after center-center anterior cruciate ligament reconstruction: an in vitro study. *Am J Sports Med.* 2013;41(4):815-825.

30. Ajuied A, Wong F, Smith C, et al. Anterior cruciate ligament injury and radiologic progression of knee osteoarthritis: a systematic review and meta-analysis. *Am J Sports Med.* 2014;42(9):2242-2252.

31. Chalmers PN, Mall NA, Moric M, et al. Does ACL reconstruction alter natural history?: A systematic literature review of long-term outcomes. *J Bone Joint Surg Am.* 2014;96(4):292-300.

32. DiFelice GS, Villegas C, Taylor SA. Anterior cruciate ligament preservation: early results of a novel arthroscopic technique for suture anchor primary anterior cruciate ligament repair. *Arthroscopy.* 2015;31(11):2162-2171.

33. Eggli S, Kohlhof H, Zumstein M, et al. Dynamic intraligamentary stabilization: novel technique for preserving the ruptured ACL. *Knee Surg Sports Traumatol Arthrosc.* 2015;23(4):1215-1221.

34. Buda R, Ferruzzi A, Vannini F, Zambelli L, Di Caprio F. Augmentation technique with semitendinosus and gracilis tendons in chronic partial lesions of the ACL: clinical and arthrometric analysis. *Knee Surg Sports Traumatol Arthrosc.* 2006;14(11):1101-1107.

35. Ochi M, Adachi N, Uchio Y, et al. A minimum 2-year follow-up after selective anteromedial or posterolateral bundle anterior cruciate ligament reconstruction. *Arthroscopy.* 2009;25(2):117-122.

36. 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(8):1011-1015.

37. 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;22(3):340.e1-e7.

38. Achtnich A, Herbst E, Forkel P, et al. Acute proximal anterior cruciate ligament tears: outcomes after arthroscopic suture anchor repair versus anatomic single-bundle reconstruction. *Arthroscopy.* 2016 Jun 17. [Epub ahead of print]

39. MacKay G, Anthony IC, Jenkins PJ, Blyth M. Anterior cruciate ligament repair revisited. Preliminary results of primary repair with internal brace ligament augmentation: a case series. *Orthop Muscul Syst.* 2015;4:188.

40. Mackay GM, Blyth MJ, Anthony I, Hopper GP, Ribbans WJ. A review of ligament augmentation with the InternalBrace™: the surgical principle is described for the lateral ankle ligament and ACL repair in particular, and a comprehensive review of other surgical applications and techniques is presented. *Surg Technol Int.* 2015;26:239-255.

41. Henle P, Röder C, Perler G, Heitkemper S, Eggli S. Dynamic intraligamentary stabilization (DIS) for treatment of acute anterior cruciate ligament ruptures: case series experience of the first three years. *BMC Musculoskelet Disord.* 2015;16:27.

42. Adachi N, Ochi M, Uchio Y, Iwasa J, Ryoke K, Kuriwaka M. Mechanoreceptors in the anterior cruciate ligament contribute to the joint position sense. *Acta Orthop Scand.* 2002;73(3):330-334.

43. Gao F, Zhou J, He C, et al. A morphologic and quantitative study of mechanoreceptors in the remnant stump of the human anterior cruciate ligament. *Arthroscopy.* 2016;32(2):273-280.

44. Georgoulis AD, Pappa L, Moebius U, et al. 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;9(6):364-368.

45. Fleming BC, Carey JL, Spindler KP, Murray MM. Can suture repair of ACL transection restore normal anteroposterior laxity of the knee? An ex vivo study. *J Orthop Res.* 2008;26(11):1500-1505.

46. Murray MM, Fleming BC. Use of a bioactive scaffold to stimulate anterior cruciate ligament healing also minimizes posttraumatic osteoarthritis after surgery. *Am J Sports Med.* 2013;41(8):1762-1770.

47. 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;27(8):1079-1089.

48. 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.* 2008;24(5):560-568.

49. Lee BI, Min KD, Choi HS, et al. Immunohistochemical study of mechanoreceptors in the tibial remnant of the ruptured anterior cruciate ligament in human knees. *Knee Surg Sports Traumatol Arthrosc.* 2009;17(9):1095-1101.

50. Takahashi T, Kondo E, Yasuda K, et al. Effects of remnant tissue preservation on the tendon graft in anterior cruciate ligament reconstruction: a biomechanical and histological study. *Am J Sports Med.* 2016;44(7):1708-1716.

51. Dong S, Xie G, Zhang Y, Shen P, Huangfu X, Zhao J. Ligamentization of autogenous hamstring grafts after anterior cruciate ligament reconstruction: midterm versus long-term results. *Am J Sports Med.* 2015;43(8):1908-1917.

52. Takazawa Y, Ikeda H, Kawasaki T, et al. ACL reconstruction preserving the ACL remnant achieves good clinical outcomes and can reduce subsequent graft rupture. *Orthop J Sports Med.* 2013;1(4):2325967113505076.

53. Shimodaira H, Tensho K, Akaoka Y, Takanashi S, Kato H, Saito N. Remnant-preserving tibial tunnel positioning using anatomic landmarks in double-bundle anterior cruciate ligament reconstruction. *Arthroscopy.* 2016;32(9):1822-1830.

54. Zhang Q, Zhang S, Cao X, Liu L, Liu Y, Li R. The effect of remnant preservation on tibial tunnel enlargement in ACL reconstruction with hamstring autograft: a prospective

randomized controlled trial. *Knee Surg Sports Traumatol Arthrosc.* 2014;22(1):166-173.

55. Tie K, Chen L, Hu D, Wang H. The difference in clinical outcome of single-bundle anterior cruciate ligament reconstructions with and without remnant preservation: A meta-analysis. *Knee.* 2016;23(4):566-574.

56. Robson AW. VI. Ruptured crucial ligaments and their repair by operation. *Ann Surg.* 1903;37(5):716-718.

57. Palmer I. On the injuries to the ligaments of the knee joint. *Acta Orthop Scand.* 1938;53.

58. Palmer I. On the injuries to the ligaments of the knee joint: a clinical study. 1938. *Clin Orthop Relat Res.* 2007;454:17-22.

59. O'Donoghue DH. An analysis of end results of surgical treatment of major injuries to the ligaments of the knee. *J Bone Joint Surg Am.* 1955;37-A(1):1-13.

60. O'Donoghue DH. Surgical treatment of fresh injuries to the major ligaments of the knee. *J Bone Joint Surg Am.* 1950;32 A(4):721-738.

61. Feagin JA, Abbott HG, Rokous JR. The isolated tear of the anterior cruciate ligament. *J Bone Joint Surg Am.* 1972;54-A:1340-1341.

62. England RL. Repair of the ligaments about the knee. *Orthop Clin North Am.* 1976;7(1):195-204.

63. Marshall JL, Warren RF, Wickiewicz TL, Reider B. The anterior cruciate ligament: a technique of repair and reconstruction. *Clin Orthop Relat Res.* 1979;(143):97-106.

64. Weaver JK, Derkash RS, Freeman JR, Kirk RE, Oden RR, Matyas J. Primary knee ligament repair–revisited. *Clin Orthop Relat Res.* 1985;(199):185-191.

65. Nogalski MP, Bach BR Jr. A review of early anterior cruciate ligament surgical repair or reconstruction. Results and caveats. *Orthop Rev.* 1993;22(11):1213-1223.

66. Feagin JA Jr, Curl WW. Isolated tear of the anterior cruciate ligament: 5-year follow-up study. *Am J Sports Med.* 1976;4(3):95-100.

67. Marshall JL, Warren RF, Wickiewicz TL. Primary surgical treatment of anterior cruciate ligament lesions. *Am J Sports Med.* 1982;10(2):103-107.

68. Straub T, Hunter RE. Acute anterior cruciate ligament repair. *Clin Orthop Relat Res.* 1988;227:238-250.

69. Kaplan N, Wickiewicz TL, Warren RF. Primary surgical treatment of anterior cruciate ligament ruptures. A long-term follow-up study. *Am J Sports Med.* 1990;18(4):354-358.

70. 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;19(3):243-255.

71. Paar O. Use of semitendinosus tendon to strengthen a freshly repaired anterior cruciate ligament. *Chirurg.* 1985;56(11):728-734.

72. Aglietti P, Buzzi R, Pisaneschi A, Salvi M. Comparison between suture and augmentation with the semitendinosus tendon in the repair of acute lesions of the anterior cruciate ligament. *Ital J Orthop Traumatol.* 1986;8(4):217-231.

73. Higgins RW, Steadman JR. Anterior cruciate ligament repairs in world class skiers. *Am J Sports Med.* 1987;15(5):439-447.

74. Harilainen A, Myllynen P. Treatment of fresh tears of the anterior cruciate ligament. A comparison of primary suture and augmentation with carbon fibre. *Injury.* 1987;18(6):396-400.

75. Jones KG. Results of use of the central one-third of the patellar ligament to compensate for anterior cruciate ligament deficiency. *Clin Orthop Relat Res.* 1980;(147):39-44.

76. Puddu G. Method for reconstruction of the anterior cruciate ligament using the semitendinosus tendon. *Am J Sports Med.* 1980;8(6):402-404.

77. Hefti F, Gächter A, Jenny H, Morscher E. Replacement of the anterior cruciate ligament. a comparative study of four different methods of reconstruction. *Arch Orthop Trauma Surg.* 1982;100(2):83-94.

78. Odensten M, Hamberg P, Nordin M, Lysholm J, Gillquist J. Surgical or conservative treatment of the acutely torn anterior cruciate ligament. A randomized study with short-term follow-up observations. *Clin Orthop Relat Res.* 1985;(198):87-93.

79. Andersson C, Odensten M, Good L, Gillquist J. Surgical or non-surgical treatment of acute rupture of the anterior cruciate ligament. A randomized study with long-term follow-up. *J Bone Joint Surg Am.* 1989;71(7):965-974.

80. Engebretsen L, Benum P, Fasting O, Mølster A, Strand T. A prospective, randomized study of three surgical techniques for treatment of acute ruptures of the anterior cruciate ligament. *Am J Sports Med.* 1990;18(6):585-590.

81. Jonsson T, Peterson L, Renström P. Anterior cruciate ligament repair with and without augmentation. A prospective 7-year study of 51 patients. *Acta Orthop Scand.* 1990;61(6):562-566.

82. Andersson C, Odensten M, Gillquist J. Knee function after surgical or nonsurgical treatment of acute rupture of the anterior cruciate ligament: a randomized study with a long-term follow-up period. *Clin Orthop Relat Res.* 1991;(264):255-263.

83. Heim U, Bachmann B, Infanger K. Reinsertion of the anterior cruciate ligament or primary ligamentous plasty? *Helv Chir Acta.* 1982;48(5):703-708.

84. Strand T, Engesaeter LB, Mølster AO, et al. Knee function following suture of fresh tear of the anterior cruciate ligament. *Acta Orthop Scand.* 1984;55(2):181-184.

85. Marcacci M, Spinelli M, Chiellini F, Buccolieri V. Notes on 53 cases of immediate suture of acute lesions of the anterior cruciate ligament. *Ital J Orthop Traumatol.* 1985;7(2):69-79.

86. van der List JP, DiFelice GS. Primary repair of the anterior cruciate ligament: a paradigm shift. *Surgeon.* 2016 Oct 6. [Epub ahead of print]

87. Bräm J, Plaschy S, Lütolf M, Leutenegger A. [The primary cruciate ligament suture–is the method outdated? Results in follow-up of 58 patients]. *Z Unfallchir Versicherungsmed.* 1994;87(2):91-109.

88. Genelin F, Trost A, Primavesi C, Knoll P. Late results following proximal reinsertion of isolated ruptured ACL ligaments. *Knee Surg Sports Traumatol Arthrosc.* 1993;1(1):17-19.

89. Kühne JH, Theermann R, Neumann R, Sagasser J. [Acute uncomplicated anterior knee instability. 2-5 year follow-up of surgical treatment]. *Unfallchirurg.* 1991;94(2):81-87.

90. Simonet WT, Sim FH. Repair and reconstruction of rotatory instability of the knee. *Am J Sports Med.* 1984;12(2):89-97.

91. Raunest J, Derra E, Ohmann C. [Clinical results of Palmer's primary cruciate ligament insertion without augmentation]. *Unfallchirurgie.* 1991;17(3):166-174.

92. Frank C, Beaver P, Rademaker F, Becker K, Schachar N, Edwards G. A computerized study of knee-ligament injuries: repair versus removal of the torn anterior cruciate ligament. *Can J Surg.* 1982;25(4):454-458.

93. Enneking WF, Horowitz M. The intra-articular effects of immobilization on the human knee. *J Bone Joint Surg Am.* 1972;54(5):973-985.

94. Millett PJ, Wickiewicz TL, Warren RF. Motion loss after ligament injuries to the knee. Part I: causes. *Am J Sports Med.* 2001;29(5):664-675.

95. Bilko TE, Paulos LE, Feagin JA Jr, Lambert KL, Cunningham HR. Current trends in repair and rehabilitation of complete (acute) anterior cruciate ligament injuries. Analysis of 1984 questionnaire completed by ACL Study Group. *Am J Sports Med.* 1986;14(2):143-147.

96. Paulos L, Noyes FR, Grood E, Butler DL. Knee rehabilitation after anterior cruciate ligament reconstruction and repair. *J Orthop Sports Phys Ther.* 1991;13(2):60-70.

97. Paessler HH, Deneke J, Dahners LE. Augmented repair and early mobilization of acute anterior cruciate ligament injuries. *Am J Sports Med.* 1992;20(6):667-674.

98. Kdolsky R, Kwasny O, Schabus R. Synthetic augmented repair of proximal ruptures of the anterior cruciate ligament. Long-term results of 66 patients. *Clin Orthop Relat Res.*

1993;(295):183-189.

99. Kdolsky RK, Gibbons DF, Kwasny O, Schabus R, Plenk H Jr. Braided polypropylene augmentation device in reconstructive surgery of the anterior cruciate ligament: long-term clinical performance of 594 patients and short-term arthroscopic results, failure analysis by scanning electron microscopy, and synovial histomorphology. *J Orthop Res*. 1997;15(1):1-10.

100. Grøntvedt T, Engebretsen L. Comparison between two techniques for surgical repair of the acutely torn anterior cruciate ligament. A prospective, randomized follow-up study of 48 patients. *Scand J Med Sci Sports*. 1995;5(6):358-363.

101. Hehl G, Strecker W, Richter M, Kiefer H, Wissmeyer T. Clinical experience with PDS II augmentation for operative treatment of acute proximal ACL ruptures–2-year follow-up. *Knee Surg Sports Traumatol Arthrosc*. 1999;7(2):102-106.

102. Schenk S, Landsiedl F, Enenkel M. Arthroscopic single-stranded semitendinosus tendon- versus PDS-augmentation of reinserted acute femoral anterior cruciate ligament tears: 7 year follow-up study. *Knee Surg Sports Traumatol Arthrosc*. 2006;14(4):318-324.

103. Zysk SP, Refior HJ. Operative or conservative treatment of the acutely torn anterior cruciate ligament in middle-aged patients. A follow-up study of 133 patients between the ages of 40 and 59 years. *Arch Orthop Trauma Surg*. 2000;120(1-2):59-64.

104. Krueger-Franke M, Siebert CH, Schupp A. Refixation of femoral anterior cruciate ligament tears combined with a semitendinosus tendon augmentation. Technique and results. *Arch Orthop Trauma Surg*. 1998;117(1-2):68-72.

105. Natri A, Järvinen M, Kannus P. Primary repair plus intra-articular iliotibial band augmentation in the treatment of an acute anterior cruciate ligament rupture. A follow-up study of 70 patients. *Arch Orthop Trauma Surg*. 1996;115(1):22-27.

106. Träger D, Pohle K, Tschirner W. Anterior cruciate ligament suture in comparison with plasty. A 5-year follow-up study. *Arch Orthop Trauma Surg*. 1995;114(5):278-280.

107. Shelbourne KD, Wilckens JH, Mollabashy A, DeCarlo M. Arthrofibrosis in acute anterior cruciate ligament reconstruction. The effect of timing of reconstruction and rehabilitation. *Am J Sports Med*. 1991;19(4):332-336.

108. Volokhina YV, Syed HM, Pham PH, Blackburn AK. Two helpful MRI signs for evaluation of posterolateral bundle tears of the anterior cruciate ligament: a pilot study. *Orthop J Sports Med*. 2015;3(8):2325967115597641.

109. Strand T, Mølster A, Hordvik M, Krukhaug Y. Long-term follow-up after primary repair of the anterior cruciate ligament: clinical and radiological evaluation 15-23 years postoperatively. *Arch Orthop Trauma Surg*. 2005;125(4):217-221.

110. van der List JP, DiFelice GS. Successful arthroscopic primary repair of a chronic anterior cruciate ligament tear 11 years following injury. *HSS J*. 2016. In press.

111. van der List JP, DiFelice GS. The role of ligament repair in anterior cruciate ligament surgery. In: Mascarenhas R, Bhatia S, Lowe WR, eds. *Ligamentous Injuries of the Knee*. 1st ed. Houston: Nova Science Publishers; 2016:199-220.

112. van der List JP, DiFelice GS. Gap formation following primary anterior cruciate ligament repair: a biomechanical study. *Knee*. 2016. In press.

113. DiFelice GS, van der List JP. Arthroscopic primary repair of proximal anterior cruciate ligament tears. *Arthrosc Tech*. 2016. In press.

114. Smith JO, Yasen SK, Palmer HC, Lord BR, Britton EM, Wilson AJ. Paediatric ACL repair reinforced with temporary internal bracing. *Knee Surg Sports Traumatol Arthrosc*. 2016;24(6):1845-1851.

115. Magarian EM, Fleming BC, Harrison SL, Mastrangelo AN, Badger GJ, Murray MM. Delay of 2 or 6 weeks adversely affects the functional outcome of augmented primary repair of the porcine anterior cruciate ligament. *Am J Sports Med*.

2010;38(12):2528-2534.

116. Murray MM, Magarian EM, Harrison SL, Mastrangelo AN, Zurakowski D, Fleming BC. The effect of skeletal maturity on functional healing of the anterior cruciate ligament. *J Bone Joint Surg Am*. 2010;92(11):2039-2049.

117. Werner BC, Yang S, Looney AM, Gwathmey FW Jr. Trends in pediatric and adolescent anterior cruciate ligament iInjury and reconstruction. *J Pediatr Orthop*. 2016;36(5):447-452.

118. Frosch KH, Stengel D, Brodhun T, et al. Outcomes and risks of operative treatment of rupture of the anterior cruciate ligament in children and adolescents. *Arthroscopy*. 2010;26(11):1539-1550.

119. Ramski DE, Kanj WW, Franklin CC, Baldwin KD, Ganley TJ. Anterior cruciate ligament tears in children and adolescents: a meta-analysis of nonoperative versus operative treatment. *Am J Sports Med*. 2014;42(11):2769-2776.

120. Zantop T, Brucker PU, Vidal A, Zelle BA, Fu FH. Intraarticular rupture pattern of the ACL. *Clin Orthop Relat Res*. 2007;454:48-53.

121. Yoon KH, Bae DK, Cho SM, Park SY, Lee JH. Standard anterior cruciate ligament reconstruction versus isolated single-bundle augmentation with hamstring autograft. *Arthroscopy*. 2009;25(11):1265-1274.

122 Demirağ B, Ermutlu C, Aydemir F, Durak K. A comparison of clinical outcome of augmentation and standard reconstruction techniques for partial anterior cruciate ligament tears. *Eklem Hastalik Cerrahisi*. 2012;23(3):140-144.

123. Sonnery-Cottet B, Zayni R, Conteduca J, et al. Posterolateral bundle reconstruction with anteromedial bundle remnant preservation in ACL tears: clinical and MRI evaluation of 39 patients with 24-month follow-up. *Orthop J Sports Med*. 2013;1(3):2325967113501624.

124. Sabat D, Kumar V. Partial tears of anterior cruciate ligament: results of single bundle augmentation. *Indian J Orthop*. 2015;49(2):129-135.

125. Jung YB, Jung HJ, Siti HT, et al. Comparison of anterior cruciate ligament reconstruction with preservation only versus remnant tensioning technique. *Arthroscopy*. 2011;27(9):1252-1258.

126. Nguyen DT, Ramwadhdoebe TH, van der Hart CP, Blankevoort L, Tak PP, van Dijk CN. Intrinsic healing response of the human anterior cruciate ligament: an histological study of reattached ACL remnants. *J Orthop Res*. 2014;32(2):296-301.

127. Boutsiadis A, Karampalis C, Tzavelas A, Vraggalas V, Christodoulou P, Bisbinas I. Anterior cruciate ligament remnant-preserving reconstruction using a "lasso-loop" knot configuration. *Arthrosc Tech*. 2015;4(6):e741-e746.

128. Noh JH, Yoon KH, Song SJ, Roh YH. Re-tensioning technique to cover the graft with remnant in anterior cruciate ligament reconstruction. *Arthrosc Tech*. 2014;3(6):e679-e682.

129. Hong L, Li X, Zhang H, et al. Anterior cruciate ligament reconstruction with remnant preservation: a prospective, randomized controlled study. *Am J Sports Med*. 2012;40(12):2747-2755.

130. Noh JH, Kyung HS, Roh YH, Kang TS. Remnant-preserving and re-tensioning technique to cover the graft in anterior cruciate ligament reconstruction. *Knee Surg Sports Traumatol Arthrosc*. 2015 Nov 12. [Epub ahead of print]

131. Muneta T, Koga H, Ju YJ, Horie M, Nakamura T, Sekiya I. Remnant volume of anterior cruciate ligament correlates preoperative patients' status and postoperative outcome. *Knee Surg Sports Traumatol Arthrosc*. 2013;21(4):906-913.

132. Leeberg V, Lekdorf J, Wong C, Sonne-Holm S. Tibial eminentia avulsion fracture in children - a systematic review of the current literature. *Dan Med J*. 2014;61(3):A4792.

133. In Y, Kwak DS, Moon CW, Han SH, Choi NY. Biomechanical comparison of three techniques for fixation of tibial avulsion fractures of the anterior cruciate ligament. *Knee Surg Sports Traumatol Arthrosc*. 2012;20(8):1470-1478.