Anterior cruciate ligament reconstruction failure and revision surgery: current concepts

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ABSTRACT

Anterior cruciate ligament reconstruction (ACLR) is one of the most commonly performed procedures in orthopaedic sports medicine. Despite developments in understanding the anatomy and biomechanics of the knee joint, a fairly large subset of patients has ACLR failure. Outcomes after revision ACLR are historically inferior to primary ACLR. Thus, a systematic approach is necessary to identify all potential causes of failure and addressing them in conjunction with a revision ACLR to mitigate the risk of revision failure and to maximise improved patient outcomes.

Current concepts

- The rate of return to high-level sports and clinical outcomes of revision anterior cruciate ligament reconstruction (ACLR) are inferior to primary ACLR.
- Understanding anterior cruciate ligament (ACL) quantitative and radiographic anatomy and clinically relevant biomechanics is crucial for anatomic reconstructions and to improve clinical outcomes.
- Revision ACLR are challenging and should be approached as a different entity than primary cases (they require a more detailed assessment of tibial slope, coronal plane alignment and tunnel malposition/osteolysis); hence, a proper diagnosis, failure cause assessment and planning is the cornerstone of patient success.

Future perspectives

- Revision ACLR are challenging and rely on addressing the cause of failure, and other potential relevant contributing factors would clarify this issue to improve patient outcomes.
- Future prospective high-level studies would help to better elucidate clinical outcomes regarding single-stage versus two-stage revision ACLR, bone grafting technique, graft selection and alignment approach among other issues.
- Further work using the proposed Failed ACLR Workup Algorithm should be done in order to improve clinical outcomes in this patient subset.
- Improving return to high-level sports as well as decreasing the revision ACLR failure rates compared with primary cases will be a source of continuous research on this field.

INTRODUCTION

Anterior cruciate ligament reconstruction (ACLR) is a common procedure in sports medicine, and revision ACLR accounts for 4.1% to 13.3% of these procedures.[1 2] Despite improved surgical techniques and fixation devices, a subset of patients has inferior outcomes and persistent instability. Return to preinjury-level sport has been recently reported to be between 13% and 69% at an average of 6.7 to 12 months' follow-up, although the group who obtained the least percentage had a relatively short follow-up period (1 year) and the method of evaluation was patient self-assessment.[3] Furthermore, this systematic review reported a 20% revision graft re-rupture rate. However, ACLR failure definition was not detailed.[3] Therefore, a significant number of young and active population who undergo ACLR will require a revision surgery.[4]

The goals of revision ACLR are to restore knee function, improve patient-reported outcomes, provide adequate knee stability, and protect the articular cartilage and menisci from further injury. The success of revision ACLR surgery depends on determining and addressing the cause of failure of the index surgery. As ACLR failure has heterogeneous definitions, ACLR clinical failure can be defined as a combination of persistent rotational laxity evidenced with pivot-shift manoeuvre or a graft rupture; being this confirmed by clinical examination, MRI or arthroscopic examination.[5 6] A proper work-up and all potential causative factors should be identified to achieve optimal clinical results. Revision ACLR can be challenging and should be approached as a different entity than primary ACL reconstructions. The purpose of this review was to describe our applied algorithm to treat this patient subset to maximise revision ACLR success.

ANATOMY AND RADIOGRAPHIC OVERVIEW

Placement of the ACL femoral tunnel is one of the most important factors in restoring knee kinematics and improving clinical outcomes. With the improved understanding of quantitative ACL anatomy, surgical techniques have been modified to a more anatomical single-bundle reconstruction by creating a femoral tunnel from an accessory anteromedial portal or an outside-in technique.[7]

On the femur, the ACL attachment centre is essentially adjacent to the posterior lateral femoral condyle articular cartilage margin at 6.1 mm posterior to the lateral intercondylar ridge and 8.5 mm anterior to the posterior margin cartilage[7] (figure 1). Radiological studies have reported that the centre of the single-bundle ACL insertion on the femoral side is 29% from proximal to distal and 25%

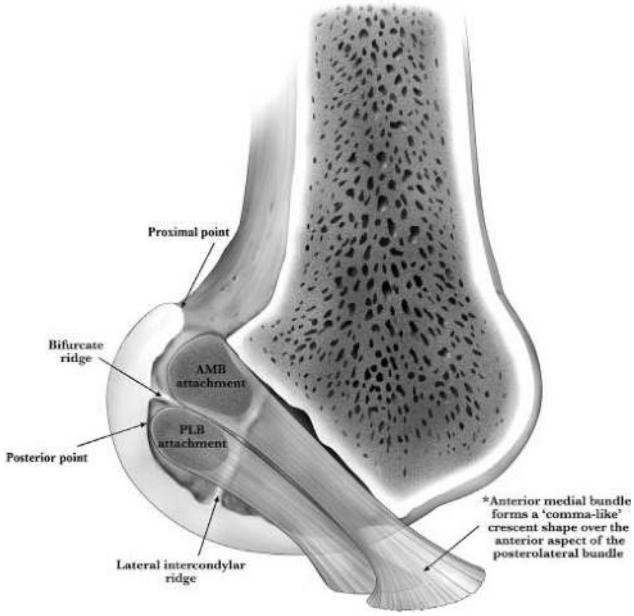

Figure 1 Illustration of a left knee in extension lateral femoral condyle view demonstrating the relationship of the anteromedial bundle (AMB) and posterolateral bundle (PLB) to pertinent bony landmarks. Reproduced with permission from Ziegler *et al*.[7]

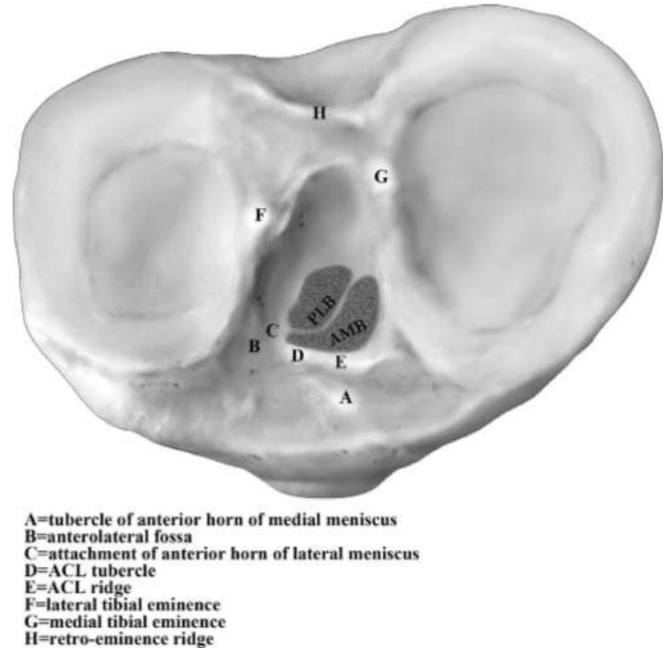

Figure 2 Illustration of both anteromedial bundle (AMB) and posterolateral bundle (PMB) of the anterior cruciate ligament (ACL) footprint on a right tibia and key anatomical landmarks. Reproduced with permission from Ziegler *et al*.[7]

from posterior to anterior according to the Bernard and Hertel method with the knee in 90° of flexion.[8] Meanwhile, Pietrini *et al* reported that the ACL should be anatomically positioned at 28.75% from proximal to distal ('maximal notch height') on average between the anteromedial bundle (AMB) and posterolateral bundle (PLB) attachments with a knee flexion angle of 90°.[9]

The ACL tibial attachment is 7.5 mm medial to the anterior root attachment of the lateral meniscus.[7] Histological and electron microscopy studies have demonstrated a significant overlap between the ACL tibial insertion and the anterolateral meniscal root (ALMR). The overlap of the ACL attachment comprises 63.2% of the ALMR insertion area, while the overlap of the ALMR attachment on the ACL comprises 41% of the ACL insertion site.[10] This is important during ACL tibial tunnel reaming to avoid iatrogenic injury to the ALMR which can lead to lateral meniscal extrusion and predispose the knee to degenerative arthritis.[11 12] Radiologically, the ACL footprint on the tibial side was reported to be at 44% anterior to posterior on the lateral view and at 47.15% from medial to lateral on the anteroposterior view[9] (figure 2).

Recently, there has been significant interest in the anatomy of the anterolateral structures of the knee, known as the anterolateral complex (ALC), and their role in the control of knee internal rotation. These structures include the anterolateral capsule, incorporating the anterolateral ligament (ALL), the iliotibial band (ITB), including the distal Kaplan fibres attachment to the distal femur and the lateral meniscus with its capsular attachments.[13–17] Residual anterolateral subluxation, as measured by the pivot-shift test, is a clinical manifestation of internal rotational laxity and is associated with poorer outcomes and reduced patient satisfaction.[18] Furthermore, persistent instability may contribute to the development of post-traumatic osteoarthritis (OA).[19]

CLINICALLY RELEVANT BIOMECHANICS

Isolated ACL biomechanical function

The ACL is the primary static stabiliser against anterior tibial translation (ATT), providing up to 86% of the total force resisting ATT.[20 21] The AMB and PLB of the ACL provide key roles in both anteroposterior and rotational stability of the knee. Some authors advocate for a double bundle (DB) ACLR to better reproduce these anatomical structures. In a systematic review of 60 papers comparing SB versus DB, 23 studies reported on graft failures (as graft re-ruptures), whereas two of them (the same group) reported significant differences in favour of DB ACLR. Superior results with DB ACLR in terms of anteroposterior and rotatory laxity were also reported. However, no significant differences in clinical subjective outcome were reported. Meanwhile, a more recent level II prospective randomised trial at 10 years reported a significantly fewer graft failure rate (graft re-rupture undergoing revision ACLR) with DB ACLR technique.[22 23]

The ACL has also an important role as a secondary restraint against varus forces. When a posterolateral corner (PLC) or mainly a fibular collateral ligament (FCL) tear is present, forces on the ACL are increased significantly, predisposing an ACL graft to early failure.[24 25]

Secondary restraints in the ACL-deficient knee

Secondary restraints in the ACL-deficient knee are those structures whose injury increase knee instability only when the ACL is concomitantly deficient to resist the same externally applied load.[24] Injury to secondary stabilisers can cause persistent knee instability after an ACLR and can lead to an indirect ACL graft rupture. These secondary restraints include the medial collateral ligament (MCL), posteromedial corner, lateral meniscus, posterior horn of medial meniscus (PHMM) and the ALC of the knee.

On the medial side, at 90° of knee flexion, the deep MCL and superficial MCL provide stability against ATT.[26] Anteromedial rotational and valgus instability due to MCL injury can cause subjective instability and increased forces on the ACL graft which can ultimately lead to ACLR failure.

A recent study from the Swedish Knee Ligament Registry compared patients with isolated ACL and combined ACL–MCL injuries. When stratifying by type of MCL treatment, the isolated ACL group had a significantly reduced risk of ACLR revision compared with the combined ACL and MCL tears managed conservatively (HR 0.61 (95% CI 0.41 to 0.89), p=0.0097), but not compared with surgically managed MCL tears.[27] However, it was observed that surgical treatment of the MCL injury was associated with a worse 2-year patient-reported knee function.[27] Although no recent high-level studies have been reported regarding combined ACL–MCL tears and at least for ACL revision cases, it is well accepted that high-grade MCL tears, especially with posterior structure compromise (posterior oblique ligament (POL)), may lead to an anteromedial rotational instability and thus surgical management is preferred. Stress X-rays are especially useful to assess the degree of MCL insufficiency. Chronic valgus instability, especially persistent after revision ACLR graft fixation, is another factor to be considered for MCL surgical management.[28]

The lateral meniscus plays an important role by providing restraint to both tibial internal rotation and also against ATT during a pivot-shift manoeuvre.[29] Recent biomechanical studies have also demonstrated the importance of the posterolateral meniscal root and the meniscofemoral ligaments as primary and secondary stabilisers for the pivot-shift phenomenon.[30 31] Injuries to the PHMM, including ramp lesions, have been reported to increase ATT and the pivot shift in ACL-deficient knees, as well as a restraint role for external rotation, with stability being restored after ACLR with a posteromedial meniscocapsular junction repair.[32]

Anterolateral rotational stability varies with knee flexion angle. While the ACL is the main stabiliser for internal rotation at 0–30°, the ALL, ITB and MCL have important roles at higher flexion angles of beyond 60°, while the POL and posteromedial capsule are important close to full knee extension.[33]

Biomechanical effects of bone morphology

Sagittal plane tibial slope has been reported to influence the forces acting on the ACL and the risk of ACLR failure.[34 35] Salmon *et al* described the catastrophic effect of combined young age (<18 years) and high tibial slope (>12°) on ACLR outcomes in a prospective study with 20 years of follow-up.[36] Only 20% of the population had an increased tibial slope, but there was an ACL graft rupture rate at 5 and 20 years in this subset of patients as high as 55% and 78%, respectively. In conclusion, they observed that adolescents with >12° tibial slope were 11 times more likely to rupture their ACL graft and 7 times more likely to rupture their contralateral ACL than adults with normal tibial slope.[36] Furthermore, increases in tibial slope lead to a linear increase in ACLR graft forces, which is magnified when a posteromedial meniscal root tear is present.[35 37]

Coronal plane mechanical axis alignment is also important because significant varus or valgus malalignment may put the ACL under increased forces and predispose the ACLR graft to failure.[38 39] Corrective osteotomies for coronal and sagittal malalignment are performed to mitigate the risk of ACLR failure.

AETIOLOGIES OF ACLR FAILURE

Classically, three main categories including surgical technique, graft incorporation and trauma-related factors were reported as the main contributors for persistent knee instability after primary ACLR.[40] Graft overtensioning, immobilisation, infection and immunological reaction may be causes of detrimental graft vascularity and delayed incorporation.[41] Time to return to high-level sports and quadriceps strength are important factors in preventing knee reinjury.[42] However, the most common cause of ACLR failure is related to errors in surgical technique (70% to 80%), such as tunnel malposition, especially on the femoral side.[43 44] Poor tunnel placement in a non-anatomic position may lead to excessive graft forces due to changes of graft length throughout knee range of motion, leading to plastic deformation of the graft and ultimately ACLR failure. A femoral tunnel that is too close to the central axis of the femur may result in adequate anterior restraint, but poor rotational stability.[45] Some studies have reported decreased graft re-rupture rates with transtibial ACLR compared with transportal technique.[46] However, significantly higher odds of OA and repeat surgery in transtibial techniques have been reported, probably secondary to a decreased loading of a non-anatomic ACL graft and decreased rotational control, resulting in higher forces on the meniscus and altered pressure distribution on the articular cartilage.[47]

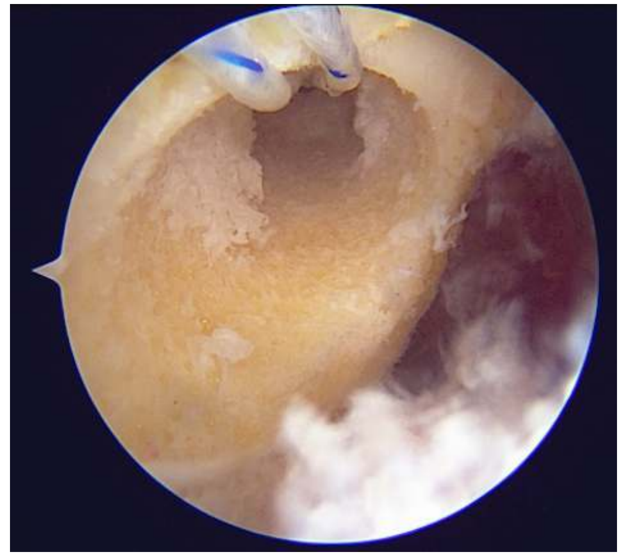

Figure 3 Right knee. Arthroscopic view from the anteromedial portal of an anterior cruciate ligament reconstruction procedure. A transportal 10 mm diameter and anatomically placed femoral tunnel with 2 mm bone-bridge backwall is visualised. A correct arthroscopic visualisation of the femoral backwall is determinant to achieve an anatomic femoral tunnel.

The ideal placement of the femoral tunnel is midway between the AMB and PLB, posterior to the lateral intercondylar ridge, as far posteriorly in the notch as possible, without violation of the posterior cortical wall (figure 3). On a full extension profile lateral view radiograph, the tibial tunnel should be posterior to Blumensaat's line.

Other causes of ACLR failure may be due to missed or untreated concomitant ligament injuries, insufficient meniscal volume or meniscal tears, and bony geometry issues given the important biomechanical function and tear consequences mentioned. Graft impingement on the intercondylar roof secondary to an oversized graft and inadequate notchplasty in chronic cases with osteophytes may also result in a poor outcome.[40]

CLINICAL AND RADIOGRAPHIC EXAMINATION OF THE FAILED ACLR

A thorough clinical history and physical examination are performed. The operative report and intraoperative images from the index surgery should be obtained when possible. ACL tears risk factors such as female sex, age, sport level, generalised joint laxity, tibial and meniscal slope, and notch width index are also assessed.[48 49] It is also important to determine if the patient has had persistent instability or whether there has been

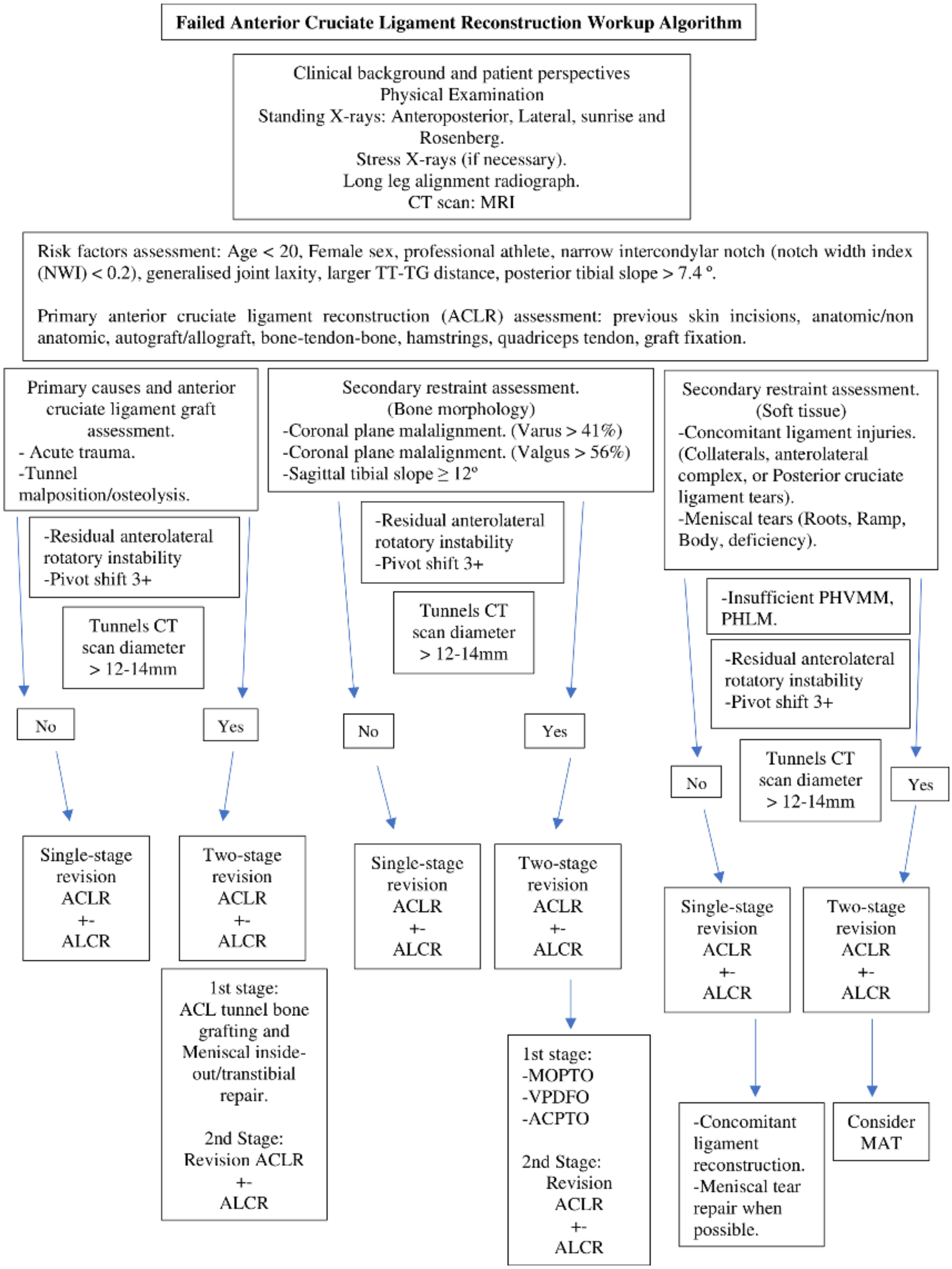

Figure 4 Failed anterior cruciate ligament reconstruction (ACLR) workup algorithm.[5 49 55 59 61 72] ALCR, Anterolateral complex reconstruction; PHVMM, Posterior horn volume of medial meniscus; MOPTO, Medial open wedge proximal tibial osteotomy; VPDFO, Varus-producing distal femoral osteotomy; ACPTO, Anterior closing wedge proximal tibial osteotomy; MAT, Meniscal allograft transplantation.

a new traumatic episode. Early failure usually within the first 6 months postoperatively is more related to non-anatomic ACLR graft positioning, biologic issues such as graft incorporation, too aggressive rehabilitation or a premature return to sports.[42] Later failure (>1 year) is more consistent with a traumatic event. A comprehensive algorithm flowchart approach based on many factors over the past two decades since the study by Johnson and Fu is illustrated[40] (figure 4).

Preoperative clinical evaluation includes mechanism of injury, preferred sport(s), level of participation, patient expectations and knee function after index ACL surgery. Physical examination includes limb alignment, range of motion, Lachman test and anterolateral rotational laxity with the pivot-shift manoeuvre. Patients with a high-grade Lachman and pivot-shift test should be evaluated for possible meniscus and/or meniscus root tears which should be repaired when possible to prevent increased graft forces.

Collateral ligament stability should be assessed with varus and valgus stress testing at 0° and 30° of knee flexion. The PLC integrity is examined, and it is important to be aware of a pseudo-positive Lachman caused by PLC insufficiency. Integrity of the PLC should be confirmed with the posterolateral drawer test and the dial test for external rotation asymmetry at 30° and 90° of knee flexion. A positive external recurvatum test usually indicates a combined ACL and PLC tears, and increased heel height with a side-to-side difference >2.5 cm has been reported to be present with a combined ACL and FCL injury.[50 51]

Gait examination should be performed to evaluate for a varus, or valgus, thrust or abnormal tibial rotation.[52] When a concomitant ligament injury is suspected on clinical examination, bilateral varus, valgus and/or posterior knee stress radiographs should be performed.[53] Chronic FCL and posterior cruciate ligament (PCL) tears may not be accurately diagnosed on MRI alone, with a sensitivity as low as 48% and 62.5%, respectively[51 54]

We recommend obtaining plain anteroposterior, lateral radiographs, Rosenberg views and systematically long leg alignment radiographs to assess coronal plain alignment and tibial slope. An MRI is performed to evaluate graft integrity and concomitant meniscal and chondral injuries. A CT scan is also systematically obtained to evaluate reconstruction tunnel diameter, given its higher reliability than other image methods.[55 56]

ONE-STAGE VERSUS TWO-STAGE REVISION ACLR RECONSTRUCTION PROCEDURE

A well-positioned tunnel with less than 12–14 mm diameter is revised with a single-stage revision. If previous fixation graft hardware interferes with the anatomic tunnel placement, it should be removed. Indications for a two-stage ACL revision procedure include (1) malpositioned bone tunnels that will interfere with new revision reconstruction tunnel placement or (2) the presence of tunnel osteolysis in which the tunnel diameters are too large (≥14 mm) to securely place a new reconstruction graft, without a risk of a lack of biological incorporation. Graft incorporation may be put at risk if limited contact exists between the surrounding bone and graft tissue.

Coronal plane malalignment in ACL-deficient knees with concomitant medial knee compartment OA, chronic PLC, concurrent cartilage restoration procedure and meniscal allograft transplantation is corrected when indicated. Our aim with realignment is to restore the mechanical axis through the apex of the lateral tibial eminence (56% across the tibial plateau).[57] The main indication for an anterior closing wedge high tibial osteotomy (HTO) is an increased sagittal plane posterior slope of ≥12° in patients with failed ACLR, aiming to achieve 6° to 8° posterior tibial slope (figure 5). Hypercorrection may increase the risk of a PCL tear.[58 59]

Staging the surgery may provide better conditions for anatomic revision ACLR with well-placed tunnels, and good incorporation and fixation of the graft.[60 61] It promotes and enhances a biological bone healing environment, preserves bone stock and allows a precise anatomic tunnel placement for the definitive revision ACLR, typically performed after 4 to 6 months after first-stage procedure[61] (figure 6).

REVISION ACLR GRAFT SELECTION

Our preference is to use an ipsilateral or contralateral bone patellar–tendon bone (BTB) autograft when possible, especially in patients younger than 50 years.[62] Other options include an ipsilateral or contralateral hamstring or quadriceps tendon autograft. A BTB allograft is considered in patients older than 50 years, any patient with an insufficient patellar tendon or patients who choose not to have their contralateral patellar tendon harvested.

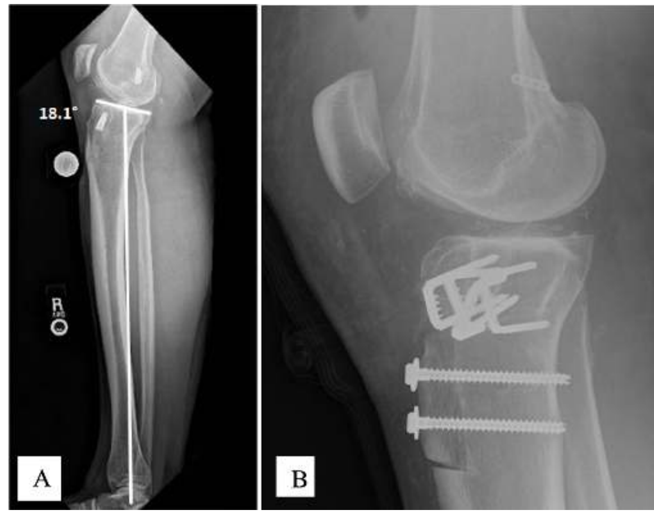

Figure 5 (A) Sagittal view of a right leg radiograph of a failed anterior cruciate ligament patient case. This image demonstrates a significant increased sagittal tibial slope (>12°). (B) An example case of a postoperative radiograph of an anterior closing wedge high tibial osteotomy. This procedure is indicated in revision cases with these bony characteristics to achieve better clinical outcomes.

ANTEROLATERAL COMPLEX RECONSTRUCTION/REPAIR

Surgical treatment of the ALC can consist of a lateral extra-articular tenodesis (LET), an ALL reconstruction (ALLR) and/or a distal Kaplan fibre repair.[63] We prefer to perform a combined ACLR and an anatomic ALLR or a LET of the knee in selected cases: residual anterolateral rotatory instability after anatomic ACLR, generalised ligamentous laxity, and in patients with ACL deficiency and a 3+ pivot shift on examination without associated meniscal, collateral or PLC injury. An additional indication is in the setting of a primary ACL tear with a tibial slope >12°, especially in younger patients.[5 63 64]

Furthermore, we advocate to perform meniscal repair with an inside-out and/or transtibial repair for meniscal root tears whenever possible on the first stage of a two-stage procedure. There have been good clinical outcomes reported with this approach, with the additional advantages of second-look and revising the repair at the second-stage surgery if the procedure has failed, or an immediate transitioning to protected weightbearing after second-stage ACLR.[65]

Figure 6 Left knee CT scan showing tibial tunnel enlargement (>14 mm) in sagittal and axial plane (A and B). X-Ray of the same knee 4 months after first stage anterior cruciate ligament revision showing bone graft incorporation in tibial tunnel (C).

DISCUSSION

Several studies have reported improved clinical outcomes in revision ACLR with the use of autografts in addition to primary ACLR.[62 66] Results reported by the MARS group on revision ACLR (level II study) showed significant better functional outcomes and 2.78 times less likely to sustain a subsequent ACL graft rupture with autografts compared with allografts.[67] Meanwhile, Legnani *et al*[68] reported that patients undergoing revision ACLR with autografts experienced a quicker return to sports compared with patients who underwent allograft revision surgery. On another study, Mayr *et al*[69] reported greater extension deficits in patients who underwent revision ACLR with autografts compared with patellar tendon allografts. Although reharvesting the BTB is an option when allografts are not available, the reharvested tissue has been reported to have inferior tissue quality for revision cases and it is not generally recommended.[70]

Regarding meniscal volume, no high-level studies have been reported to date, although a meniscal allograft transplantation (MAT) should be considered as a concomitant procedure for revision ACLR to aid in joint stability when meniscus deficiency is believed to be a contributing factor to failure.[71 72] There are no high-level studies to support one-stage or two-stage surgery for concomitant MAT or HTO and ACLR. Performing MAT with a revision ACLR is possible and recommended to stabilise the knee after MAT. A second stage is sometimes not necessary for HTO patients who achieve adequate stability, and additionally, hardware from HTO may interfere with tunnel reaming for revision ACL.[73]

Although there has historically been controversy regarding ALC surgical management, many authors have reported no significant benefits for this procedure in a primary ACLR setting.[74] However, recent studies have reported significant lower graft re-rupture rates and higher rate of return to the preinjury level with the use of hamstring autograft and ALL reconstruction.[64] Cadaveric studies demonstrated increased rotational knee laxity with combined ACL and ALC knee injury.[17] Moreover, normal knee kinematics were not restored after isolated ACLR in presence of an ACL-deficient knee combined to ALC tears.[75] Although some studies have reported an over-constrained knee secondary to ALLR, a recent meta-analysis found no correlation between LET and OA.[14 76] Moreover, in a recent level I prospective randomised clinical trial, Getgood *et al* compared ACLR and ACLR with concurrent LET using hamstring autografts. They demonstrated a significantly higher rate of clinical ACLR failure (40% vs 25%; $p<0.0001$) and graft rupture rates (11% vs 4%; $p<0.001$) with ACLR without LET, with a minimum 24 months' follow-up and an average age of 18.9 years.[5]

Although there are no high-level comparative studies in the setting of significant tunnel enlargement, there has been a trend towards a two-stage surgery when trying to optimise patient outcomes.[77] Several factors including the surgeon's experience, team, tunnel diameter and position, concomitant pathology such as alignment, and meniscus loss/insufficiency play a role on the choice of two-stage versus single-stage surgery. Even in the presence of these pathologies, it is still often possible to perform a single-stage revision. The advantages of single-stage revision are one surgery to avoid multiple trauma to the knee with multiple surgeries and a shorter rehabilitation time frame. In order to avoid two stages, various surgical techniques have been described for a single-stage basis including cylindrical autograft, corticocancellous shims, retention of interference screws, larger interference screws, dilation of a new tunnel, bone dowel or a divergent tunnel concept technique.[78–81]

Nevertheless, we acknowledge revision ACLR surgery is challenging, and it is important to optimise outcomes after an already failed surgery. Studies have demonstrated that outcomes after revision ACLR surgery are inferior to primary ACLR surgery.[3] With that in mind, staging the surgery may provide better conditions for anatomic revision ACLR with well-placed tunnels, and good incorporation and fixation of the graft. The over the top (OTT) technique is another option for single-stage revision ACLR and no high-level studies have been compared with an anatomic ACLR.[82] However, a trend towards anatomical techniques have been emphasised because anteroposterior and rotational stability are restored closer to knee intact kinematics, being considered more as a salvage open physis option. We also acknowledge that an OTT position tends to achieve an ACL graft that is potentially too tight in extension and too loose in flexion.[43]

The senior author advocates a two-stage procedure with tunnel enlargement greater than 14 mm and found no significant clinical differences compared with the single-stage (no significant osteolysis) revision group. In this study, undergoing a two-stage procedure has not been reported to be a significant concern compared with the single-stage group of patients, but to have a more functional and healthier knee without subsequent failures.[61] Although staging takes longer rehabilitation time and involves several surgeries, it is important to remember that it is a good option when conditions are not optimal. Ultimately, achieving a stable and functional knee is the goal, whether with a single-stage or two-stage procedure.

Failure rates of revision ACLR have been reported to be three to four times higher than primary ACLR.[83] Moreover, subsequent re-revision for revision ACLR patients is 6.5% at 5 years and 9.0% at 8 years.[84] A systematic review of the literature on revision ACLR by Liechti *et al* reported that although re-revision ACLR could restore stability and improve functional outcomes compared with the preoperative state, outcomes were inferior when compared with primary ACLR regarding ability to return to pre-injury level of activity.[85] Therefore, identifying patients who are at risk of ACLR failure and adequate preoperative counselling is important.

Rehabilitation does not differ much from a primary ACLR other than progression through stages is slower to allow for graft incorporation; however, there are insufficient data on rehabilitation following revision surgery. It is known that aggressive early rehabilitation may result in early ACLR failure and a generally accepted return-to-sport (RTS) period is between 8 and 12 months.[86] RTS is slower than primary cases and sometimes depends on addressing concomitant lesions present at the revision stage and on graft selection. On a recent level I study, it was reported that immediately postoperatively weight-bearing is recommended while evidence for the use of motion control and functional derotation bracing is sparse and contradictory.[87]

CONCLUSIONS

Revision ACLR are challenging and require a thorough and systematic approach to identify the causes of primary ACLR failure to be addressed when possible. Causes of ACLR failure include surgical technique, failure of graft incorporation, trauma-related factors and unaddressed concomitant pathology. Imaging should be performed to diagnose concomitant pathology, alignment and tunnel size in order to plan surgery and optimise outcomes. Two-stage surgery is recommended if the bony morphology including tunnel size (>14 mm) and limb alignment tibial slope (>12°) are not optimal. Staging revision ACLR has not been demonstrated to affect outcomes, although higher-level comparative studies are needed. In a selected subset of patients, a concurrent ALC procedure can improve outcomes.

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REFERENCES

1 van Eck CF, Schkrohowsky JG, Working ZM, *et al*. Prospective analysis of failure rate and predictors of failure after anatomic anterior cruciate ligament reconstruction with allograft. *Am J Sports Med* 2012;40:800–7.
2 Granan L-P, Forssblad M, Lind M, *et al*. The Scandinavian ACL registries 2004–2007: baseline epidemiology. *Acta Orthop* 2009;80:563–7.
3 Glogovac G, Schumaier AP, Grawe BM. Return to sport following revision anterior cruciate ligament reconstruction in athletes: a systematic review. *Arthroscopy* 2019;35:2222–30.
4 Lefevre N, Klouche S, Mirouse G, *et al*. Return to sport after primary and revision anterior cruciate ligament reconstruction: a prospective comparative study of 552 patients from the FAST cohort. *Am J Sports Med* 2017;45:34–41.
5 Getgood AMJ, Bryant DM, Litchfield R, *et al*. Lateral extra-articular tenodesis reduces failure of hamstring tendon autograft anterior cruciate ligament reconstruction: 2-year outcomes from the stability study randomized clinical trial. *Am J Sports Med* 2020;48:285–97.
6 Scholten RJPM, Opstelten W, van der Plas CG, *et al*. Accuracy of physical diagnostic tests for assessing ruptures of the anterior cruciate ligament: a meta-analysis. *J Fam Pract* 2003;52:689–94.
7 Ziegler CG, Pietrini SD, Westerhaus BD, *et al*. Arthroscopically pertinent landmarks for tunnel positioning in single-bundle and double-bundle anterior cruciate ligament reconstructions. *Am J Sports Med* 2011;39:743–52.
8 Bernard M, Hertel P. [Intraoperative and postoperative insertion control of anterior cruciate ligament-plasty. A radiologic measuring method (quadrant method)]. *Unfallchirurg* 1996;99:332–40.
9 Pietrini SD, Ziegler CG, Anderson CJ, *et al*. Radiographic landmarks for tunnel positioning in double-bundle ACL reconstructions. *Knee Surg Sports Traumatol Arthrosc* 2011;19:792–800.
10 Steineman BD, Moulton SG, Haut Donahue TL, *et al*. Overlap between anterior cruciate ligament and anterolateral meniscal root insertions: a scanning electron microscopy study. *Am J Sports Med* 2017;45:362–8.
11 LaPrade CM, Smith SD, Rasmussen MT, *et al*. Consequences of tibial tunnel reaming on the meniscal roots during cruciate ligament reconstruction in a cadaveric model, part 1: the anterior cruciate ligament. *Am J Sports Med* 2015;43:200–6.
12 Pache S, Aman ZS, Kennedy M, *et al*. Meniscal root tears: current concepts review. *Arch Bone Jt Surg* 2018;6:250–9.
13 Godin JA, Chahla J, Moatshe G, *et al*. A comprehensive reanalysis of the distal Iliotibial band: quantitative anatomy, radiographic markers, and biomechanical properties. *Am J Sports Med* 2017;45:2595–603.
14 Schon JM, Moatshe G, Brady AW, *et al*. Anatomic anterolateral ligament reconstruction of the knee leads to overconstraint at any fixation angle. *Am J Sports Med* 2016;44:2546–56.
15 Kaplan EB. The iliotibial tract; clinical and morphological significance. *J Bone Joint Surg Am* 1958;40-A:817–32.
16 Hughston JC, Andrews JR, Cross MJ, *et al*. Classification of knee ligament instabilities. Part II. The lateral compartment. *J Bone Joint Surg Am* 1976;58:173–9.
17 Geeslin AG, Chahla J, Moatshe G, *et al*. Anterolateral knee extra-articular stabilizers: a robotic sectioning study of the anterolateral ligament and distal Iliotibial band Kaplan fibers. *Am J Sports Med* 2018;46:1352–61.
18 Ayeni OR, Chahal M, Tran MN, *et al*. Pivot shift as an outcome measure for ACL reconstruction: a systematic review. *Knee Surg Sports Traumatol Arthrosc* 2012;20:767–77.
19 Haughom B, Schairer W, Souza RB, *et al*. Abnormal tibiofemoral kinematics following ACL reconstruction are associated with early cartilage matrix degeneration measured by MRI T1rho. *Knee* 2012;19:482–7.
20 Odensten M, Gillquist J. Functional anatomy of the anterior cruciate ligament and a rationale for reconstruction. *J Bone Joint Surg Am* 1985;67:257–62.
21 Chhabra A, Starman JS, Ferretti M, *et al*. Anatomic, radiographic, biomechanical, and kinematic evaluation of the anterior cruciate ligament and its two functional bundles. *J Bone Joint Surg Am* 2006;88 Suppl 4:2.
22 Björnsson H, Desai N, Musahl V, *et al*. Is double-bundle anterior cruciate ligament reconstruction superior to single-bundle? A comprehensive systematic review. *Knee Surg Sports Traumatol Arthrosc* 2015;23:696–739.
23 Järvelä S, Kiekara T, Suomalainen P, *et al*. Double-bundle versus single-bundle anterior cruciate ligament reconstruction: a prospective randomized study with 10-year results. *Am J Sports Med* 2017;45:2578–85.
24 Takeda Y, Xerogeanes JW, Livesay GA, *et al*. Biomechanical function of the human anterior cruciate ligament. *Arthroscopy* 1994;10:140–7.
25 LaPrade RF, Resig S, Wentorf F, *et al*. The effects of grade III posterolateral knee complex injuries on anterior cruciate ligament graft force. A biomechanical analysis. *Am J Sports Med* 1999;27:469–75.
26 Griffith CJ, LaPrade RF, Johansen S, *et al*. Medial knee injury: Part 1, static function of the individual components of the main medial knee structures. *Am J Sports Med* 2009;37:1762–70.
27 Svantesson E, Hamrin Senorski E, Alentorn-Geli E, *et al*. Increased risk of ACL revision with non-surgical treatment of a concomitant medial collateral ligament injury: a study on 19,457 patients from the Swedish National Knee Ligament Registry. *Knee Surg Sports Traumatol Arthrosc* 2019;27:2450–9.
28 Dale KM, Bailey JR, Moorman CT. Surgical management and treatment of the anterior cruciate ligament/medial collateral ligament injured knee. *Clin Sports Med* 2017;36:87–103.
29 Musahl V, Citak M, O'Loughlin PF, *et al*. The effect of medial versus lateral meniscectomy on the stability of the anterior cruciate ligament-deficient knee. *Am J Sports Med* 2010;38:1591–7.
30 Geeslin AG, Civitarese D, Turnbull TL, *et al*. Influence of lateral meniscal posterior root avulsions and the meniscofemoral ligaments on tibiofemoral contact mechanics. *Knee Surg Sports Traumatol Arthrosc* 2016;24:1469–77.
31 Frank JM, Moatshe G, Brady AW, *et al*. Lateral meniscus posterior root and meniscofemoral ligaments as stabilizing structures in the ACL-deficient knee: a biomechanical study. *Orthop J Sports Med* 2017;5:232596711769575.
32 DePhillipo NN, Moatshe G, Brady A, *et al*. Effect of meniscocapsular and meniscotibial lesions in ACL-deficient and ACL-reconstructed knees: a biomechanical study. *Am J Sports Med* 2018;46:2422–31.
33 Vap AR, Schon JM, Moatshe G, *et al*. The role of the peripheral passive rotation stabilizers of the knee with intact collateral and cruciate ligaments: a biomechanical study. *Orthop J Sports Med* 2017;5:232596711770819.
34 Giffin JR, Vogrin TM, Zantop T, *et al*. Effects of increasing tibial slope on the biomechanics of the knee. *Am J Sports Med* 2004;32:376–82.
35 Bernhardson AS, Aman ZS, Dornan GJ, *et al*. Tibial slope and its effect on force in anterior cruciate ligament grafts: anterior cruciate ligament force increases linearly as posterior tibial slope increases. *Am J Sports Med* 2019;47:296–302.
36 Salmon LJ, Heath E, Akrawi H, *et al*. 20-Year outcomes of anterior cruciate ligament reconstruction with hamstring tendon autograft: the catastrophic effect of age and posterior tibial slope. *Am J Sports Med* 2018;46:531–43.
37 Samuelsen BT, Aman ZS, Kennedy MI, *et al*. Posterior medial meniscus root tears potentiate the effect of increased tibial slope on anterior cruciate ligament graft forces. *Am J Sports Med* 2020;48:334–40.
38 Phisitkul P, Wolf BR, Amendola A. Role of high tibial and distal femoral osteotomies in the treatment of lateral-posterolateral and medial instabilities of the knee. *Sports Med Arthrosc Rev* 2006;14:96–104.
39 Cantin O, Magnussen RA, Corbi F, *et al*. The role of high tibial osteotomy in the treatment of knee laxity: a comprehensive review. *Knee Surg Sports Traumatol Arthrosc* 2015;23:3026–37.
40 Johnson DL, Fu FH. Anterior cruciate ligament reconstruction: why do failures occur? *Instr Course Lect* 1995;44:391–406.
41 Harner CD, Giffin JR, Dunteman RC, *et al*. Evaluation and treatment of recurrent instability after anterior cruciate ligament reconstruction. *Instr Course Lect* 2001;50:463–74.
42 Grindem H, Snyder-Mackler L, Moksnes H, *et al*. Simple decision rules can reduce reinjury risk by 84% after ACL reconstruction: the Delaware-Oslo ACL cohort study. *Br J Sports Med* 2016;50:804–8.
43 George MS, Dunn WR, Spindler KP. Current concepts review: revision anterior cruciate ligament reconstruction. *Am J Sports Med* 2006;34:2026–37.
44 Duffee A, Magnussen RA, Pedroza AD, *et al*. Transtibial ACL femoral tunnel preparation increases odds of repeat ipsilateral knee surgery. *J Bone Joint Surg Am* 2013;95:2035–42.
45 Ristanis S, Giakas G, Papageorgiou CD, *et al*. The effects of anterior cruciate ligament reconstruction on tibial rotation during pivoting after descending stairs. *Knee Surg Sports Traumatol Arthrosc* 2003;11:360–5.

46 Clatworthy M, Sauer S, Roberts T. Transportal central femoral tunnel placement has a significantly higher revision rate than transtibial AM femoral tunnel placement in hamstring ACL reconstruction. *Knee Surg Sports Traumatol Arthrosc* 2019;27:124–9.
47 Rothrauff BB, Jorge A, de Sa D, *et al*. Anatomic ACL reconstruction reduces risk of post-traumatic osteoarthritis: a systematic review with minimum 10-year follow-up. *Knee Surg Sports Traumatol Arthrosc* 2020;28:1072–84.
48 Cheung EC, Boguszewski DV, Joshi NB, *et al*. Anatomic factors that may predispose female athletes to anterior cruciate ligament injury. *Curr Sports Med Rep* 2015;14:368–72.
49 Zeng C, Gao S-guang, Wei J, *et al*. The influence of the intercondylar notch dimensions on injury of the anterior cruciate ligament: a meta-analysis. *Knee Surg Sports Traumatol Arthrosc* 2013;21:804–15.
50 LaPrade RF, Ly TV, Griffith C. The external rotation recurvatum test revisited: reevaluation of the sagittal plane tibiofemoral relationship. *Am J Sports Med* 2008;36:709–12.
51 Cinque ME, Geeslin AG, Chahla J, *et al*. The heel height test: a novel tool for the detection of combined anterior cruciate ligament and fibular collateral ligament tears. *Arthroscopy* 2017;33:2177–81.
52 Roessler PP, Getgood A. The role of osteotomy in chronic valgus instability and hyperextension valgus thrust (medial closing wedge distal femoral varus osteotomy and lateral opening wedge high tibial osteotomy). *Clin Sports Med* 2019;38:435–49.
53 Kane PW, Cinque ME, Moatshe G, *et al*. Fibular collateral ligament: varus stress radiographic analysis using 3 different clinical techniques. *Orthop J Sports Med* 2018;6:232596711877017.
54 DePhillipo NN, Cinque ME, Godin JA, *et al*. Posterior tibial translation measurements on magnetic resonance imaging improve diagnostic sensitivity for chronic posterior cruciate ligament injuries and graft tears. *Am J Sports Med* 2018;46:341–7.
55 de Beus A, Koch JE, Hirschmann A, *et al*. How to evaluate bone tunnel widening after ACL reconstruction—a critical review. *Muscles Ligaments Tendons J* 2017;7:230.
56 Parkar AP, Adriaensen MEAPM, Fischer-Bredenbeck C, *et al*. Measurements of tunnel placements after anterior cruciate ligament reconstruction—a comparison between CT, radiographs and MRI. *Knee* 2015;22:574–9.
57 Laprade RF, Spiridonov SI, Nystrom LM, *et al*. Prospective outcomes of young and middle-aged adults with medial compartment osteoarthritis treated with a proximal tibial opening wedge osteotomy. *Arthroscopy* 2012;28:354–64.
58 Chahla J, Dean CS, Mitchell JJ, *et al*. Medial opening wedge proximal tibial osteotomy. *Arthrosc Tech* 2016;5:e919–28.
59 DePhillipo NN, Kennedy MI, Dekker TJ, *et al*. Anterior closing wedge proximal tibial osteotomy for slope correction in failed ACL reconstructions. *Arthrosc Tech* 2019;8:e451–7.
60 Thomas NP, Kankate R, Wandless F, *et al*. Revision anterior cruciate ligament reconstruction using a 2-stage technique with bone grafting of the tibial tunnel. *Am J Sports Med* 2005;33:1701–9.
61 Mitchell JJ, Chahla J, Dean CS, *et al*. Outcomes after 1-stage versus 2-stage revision anterior cruciate ligament reconstruction. *Am J Sports Med* 2017;45:1790–8.
62 Keizer MNJ, Hoogeslag RAG, van Raay JJAM, *et al*. Superior return to sports rate after patellar tendon autograft over patellar tendon allograft in revision anterior cruciate ligament reconstruction. *Knee Surg Sports Traumatol Arthrosc* 2018;26:574–81.
63 Mathew M, Dhollander A, Getgood A. Anterolateral ligament reconstruction or extra-articular tenodesis: why and when? *Clin Sports Med* 2018;37:75–86.
64 Sonnery-Cottet B, Saithna A, Cavalier M, *et al*. Anterolateral ligament reconstruction is associated with significantly reduced ACL graft rupture rates at a minimum follow-up of 2 years: a prospective comparative study of 502 patients from the SANTI Study Group. *Am J Sports Med* 2017;45:1547–57.
65 DePhillipo NN, Dekker TJ, Aman ZS, *et al*. Incidence and healing rates of meniscal tears in patients undergoing repair during the first stage of 2-stage revision anterior cruciate ligament reconstruction. *Am J Sports Med* 2019;47:3389–95.
66 Bottoni CR, Smith EL, Shaha J, *et al*. Autograft versus allograft anterior cruciate ligament reconstruction. *Am J Sports Med* 2015;43:2501–9.
67 Wright RW, Huston LJ, Haas AK, *et al*. Effect of graft choice on the outcome of revision anterior cruciate ligament reconstruction in the multicenter ACL revision study (MARs) cohort. *Am J Sports Med* 2014;42:2301–10.
68 Legnani C, Zini S, Borgo E, *et al*. Can graft choice affect return to sport following revision anterior cruciate ligament reconstruction surgery? *Arch Orthop Trauma Surg* 2016;136:527–31.
69 Mayr HO, Willkomm D, Stoehr A, *et al*. Revision of anterior cruciate ligament reconstruction with patellar tendon allograft and autograft: 2- and 5-year results. *Arch Orthop Trauma Surg* 2012;132:867–74.
70 LaPrade RF, Hamilton CD, Montgomery RD, *et al*. The reharvested central third of the patellar tendon. A histologic and biomechanical analysis. *Am J Sports Med* 1997;25:779–85.
71 Zaffagnini S, Grassi A, Romandini I, *et al*. Meniscal allograft transplantation combined with anterior cruciate ligament reconstruction provides good mid-term clinical outcome. *Knee Surg Sports Traumatol Arthrosc* 2019;27:1914–23.
72 Getgood A, LaPrade RF, Verdonk P, *et al*. International meniscus reconstruction experts forum (IMREF) 2015 consensus statement on the practice of meniscal allograft transplantation. *Am J Sports Med* 2017;45:1195–205.
73 Noyes FR, Barber-Westin SD, Hewett TE. High tibial osteotomy and ligament reconstruction for varus angulated anterior cruciate ligament-deficient knees. *Am J Sports Med* 2000;28:282–96.
74 Rezende FC, de Moraes VY, Martimbianco ALC, *et al*. Does combined intra- and extraarticular ACL reconstruction improve function and stability? A meta-analysis. *Clin Orthop Relat Res* 2015;473:2609–18.
75 Inderhaug E, Stephen JM, Williams A, *et al*. Biomechanical comparison of anterolateral procedures combined with anterior cruciate ligament reconstruction. *Am J Sports Med* 2017;45:347–54.
76 Devitt BM, Bouguennec N, Barfod KW, *et al*. Combined anterior cruciate ligament reconstruction and lateral extra-articular tenodesis does not result in an increased rate of osteoarthritis: a systematic review and best evidence synthesis. *Knee Surg Sports Traumatol Arthrosc* 2017;25:1149–60.
77 Burnham JM, Herbst E, Pauyo T, *et al*. Technical considerations in revision anterior cruciate ligament reconstruction for operative techniques in orthopaedics. *Oper Tech Orthop* 2017;27:63–9.
78 Werner BC, Gilmore CJ, Hamann JC, *et al*. Revision anterior cruciate ligament reconstruction. *J Am Acad Orthop Surg* 2016;24:581–7.
79 Bach BR. Revision anterior cruciate ligament surgery. *Arthroscopy* 2003;19(Suppl 1):14–29.
80 Dragoo JL, Kalisvaart M, Smith KM, *et al*. Single-stage revision anterior cruciate ligament reconstruction using bone grafting for posterior or widening tibial tunnels restores stability of the knee and improves clinical outcomes. *Knee Surg Sports Traumatol Arthrosc* 2019;27:3713–21.
81 Demyttenaere J, Claes S, Bellemans J. One-stage revision anterior cruciate ligament reconstruction in cases with excessive tunnel osteolysis. Results of a new technique using impaction bone grafting. *Knee* 2018;25:1308–17.
82 Usman MA, Kamei G, Adachi N, *et al*. Revision single-bundle anterior cruciate ligament reconstruction with over-the-top route procedure. *Orthop Traumatol Surg Res* 2015;101:71–5.
83 Wright RW, Gill CS, Chen L, *et al*. Outcome of revision anterior cruciate ligament reconstruction: a systematic review. *J Bone Joint Surg Am* 2012;94:531–6.
84 Vap AR, Persson A, Fenstad AM, *et al*. Re-revision anterior cruciate ligament reconstruction: an evaluation from the Norwegian knee ligament registry. *Arthroscopy* 2019;35:1695–701.
85 Liechti DJ, Chahla J, Dean CS, *et al*. Outcomes and risk factors of rerevision anterior cruciate ligament reconstruction: a systematic review. *Arthroscopy* 2016;32:2151–9.
86 Wright RW, Haas AK, Anderson J, *et al*. Anterior cruciate ligament reconstruction rehabilitation. *Sports Health* 2015;7:239–43.
87 MARS Group. Rehabilitation predictors of clinical outcome following revision ACL reconstruction in the Mars cohort. *J Bone Joint Surg* 2019;101:779–86.