Revision anterior cruciate ligament surgery: state of the art

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ABSTRACT

With the increase in number of anterior cruciate ligament (ACL) reconstructions being performed, and with patients’ desire to return to high-level sports activities, the prevalence of ACL revision has been rising despite recent improvements in ACL reconstruction technique. ACL reconstruction failures can be classified into 3 general categories: recurrent instability, postoperative complications and patient comorbidities. Of these 3 categories, recurrent instability is the most common cause for revision surgery. Cases of recurrent instability can be further subdivided into 2 groups: traumatic and atraumatic. Causes of atraumatic failure include technical errors, missed associated injuries, biological factors and infection. Careful preoperative evaluation and planning, sophisticated surgical technique (including individualised graft selection, anatomical tunnel placement and secure fixation), careful evaluation and treatment of all associated injuries, and individualised rehabilitation are all essential for successful revision ACL surgery. There have been very few high-level studies in the field of revision ACL surgery, therefore, accumulating more evidence for clinical outcomes and prognostic factors to improve revision surgery procedure will be necessary. Both primary ACL injury prevention and reinjury prevention, as well as individualised anatomical primary ACL reconstruction, are critical to reduce the incidence of revision ACL surgery.

INTRODUCTION

Revision anterior cruciate ligament surgery: prevalence and societal impact

Anterior cruciate ligament (ACL) injury is one of the most frequent sports-related injuries that require surgery. An estimated 200 000 ACL injuries occur annually in the USA alone,1 and the incidence of ACL reconstruction has increased, particularly in females as well as in those younger than 20 and older than 40.2 Conventional single-bundle techniques for ACL reconstruction had been considered successful, as anterior stability was restored and the majority of athletes were able to return to sports. However, both biomechanical and clinical studies have revealed that conventional non-anatomic single-bundle reconstruction fails to restore normal knee kinematics, especially in terms of rotational stability.3–5 Therefore, recent ACL reconstruction strategies have been shifting towards anatomic reconstruction, aiming to reproduce the native anatomy and normal kinematics of the knee. On the other hand, with the increase in number of ACL reconstructions being performed and with patients’ desire to return to high-level sports activities, the prevalence of ACL revision has been rising despite the recent improvement in ACL reconstruction technique.6 The reported rate of revision ACL reconstruction is between 4% and 25%, depending on the criteria for revision and the graft used for primary reconstruction.6–9 Most revisions occur between 1 and 2 years after the primary surgery.6 Consequently, surgeons and researchers should take a great interest in preventing the original ACL injury as well as reinjury after ACL reconstruction.

Reviews and state of the art or current concept articles

Systematic reviews of the literature on ACL revision surgery have mostly focused on causes/risks of failure in primary ACL reconstruction, indications/strategies of revision, technical considerations and clinical outcomes. Eleven review articles were identified from the past 10 years on the topic of revision ACL surgery and related subjects. Five reviews focused on risks and causes of primary ACL reconstruction failure,8–10 13 four on indications/strategies and techniques of revision surgeries,8 10 14 15 and four on clinical outcomes;16–19 two of them focused on return to sports.17 18 In addition, one recent article described strategies for revision surgery after primary double-bundle (DB) ACL reconstruction.20 Moreover, it should be noted that the Multicenter ACL Revision Study (MARS) was developed in 2006 to create a multisurgeon, multicentre prospective longitudinal study. The goal of MARS was to obtain sufficient participants to allow multivariable analysis and determine predictors of clinical outcome after revision ACL reconstruction. The MARS group has already published 13 articles regarding revision ACL reconstruction.21–33 Although most of the articles have thus far focused on preoperative/intraoperative factors, one article has recently been published focusing on meniscal and articular cartilage predictors of clinical outcome after revision ACL reconstruction.21 More articles regarding clinical outcomes are expected in the near future (box 1).

CURRENT STATE OF THE ART

Causes of primary ACL reconstruction failure

In spite of recent improvements in surgical technique, ACL reconstructions are still susceptible to fail for a variety of reasons. The definitions of the ACL reconstruction failures can be (1) knees that require revision ACL reconstruction, and (2) knees with low quality of life, represented by a low score on the Knee Injury and Osteoarthritis Outcome Score (KOOS) activities of daily living (ADL) subscale. These failures can be classified into three general categories: recurrent instability,
Technical errors
Technical error is the most common cause of failed ACL reconstruction. Technical error has been thought to contribute to failure in 22–79% of cases.8 Technical errors include non-anatomic tunnel placement, incorrect graft choice, improper graft tensioning and inadequate graft fixation.

Tunnel placement
Non-anatomic tunnel placement is the most common technical error that leads to failure of ACL reconstruction. Failure to reproduce the native ACL anatomic footprints can lead to increased graft stress and eventual graft loosening. Femoral tunnel malposition, particularly anterior tunnel placement, is the most common culprit. Anterior femoral tunnel placement results in excessive graft tension in flexion, leading to either reduced knee flexion or graft failure. Vertical femoral tunnel placement in the coronal plane with anterior tibial tunnel placement will lead to graft impingement against the intercondylar notch, also leading to graft failure. Therefore, posterior tibial tunnel placement and notchplasty have been recommended in some cases to avoid graft impingement.34 However, the resulting vertical graft placement often results in residual rotational instability with a positive pivot shift,35 and notchplasty is at risk of regrowth (figure 1). The recent strategy of anatomic ACL reconstruction with more posterior femoral tunnel placement and anterior tibial tunnel placement, within a native ACL footprint, has reduced the risk of graft impingement without needing notchplasty and with better rotational stability (figure 2).36 Furthermore, DB reconstruction has been shown to more accurately reproduce native knee stability, resulting in a decreased repeat ACL rupture as compared with single-bundle reconstruction.37

Graft selection
In terms of graft selection, artificial ligaments such as Dacron (Stryker, KalamaZoo, Michigan, USA), GORE-TEX (WL Gore and Associates, Flagstaff, Arizona, USA), Kennedy ligament augmentation device (3M, St Paul, Minnesota, USA) and Lees-Keio (Xiros, Leeds, England) have demonstrated a high risk of complications including recurrent pain, mechanical failure, infection, tunnel osteolysis and massive effusions.38 39 However, newer generation devices such as Ligament Augmentation and Reconstruction System (LARS; Surgical Implants and Devices, Arc-sur-Tille, France) have been reported with lower rates of failure, revision and sterile effusion/synovitis.40 Patients with failed artificial grafts often present with recurrent instability, pain, swelling or effusions. Revision surgery in these cases requires careful preoperative evaluation and planning. The use of allografts has also been shown to have a higher risk of revision compared with autografts, especially in younger patients.41 42 Allografts have a longer and less complete course of incorporation and remodelling than autografts, and are biomechanically inferior to autografts.43 Among allografts, graft irradiation >1.8 Mrad, BioCleanse graft processing and bone-patellar tendon-bone (BPTB) graft compared with soft tissue postoperative complications (stiffness, infection, etc) and patient comorbidities (muscle dysfunction, pain, arthritis, etc).8 The most common reason for revision ACL reconstruction is recurrent instability, defined as failure of the reconstructed ACL to provide adequate anterior and/or rotational stability to the knee. The reasons for this recurrent instability can be further subdivided into two additional categories: traumatic and atraumatic.

Traumatic failure
Traumatic failure is due to simple reinjury with obvious trauma, similar to primary ACL tear after return to sports activities, as well as to chronic repetitive trauma to the graft, trauma to the graft before complete graft incorporation, inappropriate accelerated rehabilitation postoperatively and premature return to sports before complete restoration of neuromuscular control.8 10

Atraumatic failure
ACL reconstruction can also fail for reasons other than a traumatic event. In most cases, the reasons for failure are multifactorial: a combination of factors contributes to failure of the graft. Recurrent instability in the early (<6 months) postoperative period is typically related to poor surgical technique, failure of graft fixation and failure of graft incorporation, in addition to mechanical overloads during early rehabilitation. On the other hand, the most common reason for late (more than 6 months) failure is traumatic reinjury as already mentioned; however, other factors such as poor surgical technique, missed associated injuries and anatomic factors also play important roles in the failure of reconstructed ACL.8 10 12

Box 1 Key articles on anterior cruciate ligament (ACL) revision surgery

motion, graft failure or articular cartilage degeneration in single-constrained knee joint, resulting in loss of range of motion. It has been reported that excessive initial tension might lead to graft tensioning

In terms of autografts, recent studies from Scandinavian registries showed that hamstring tendon grafts had higher revision rates than BPTB grafts; however, no systematic reviews or meta-analyses of randomised or prospective studies showed any difference in the revision rate between hamstrings and BPTB grafts.64–62

Graft fixation During the immediate postoperative period, the graft fixation site has a lower load to failure than the graft itself. Solid graft fixation is essential to keep the graft in place during the process of graft incorporation.64 The resistance of fixation depends on the type of the graft and fixation used, and on the quality of the bone. The fixation of the BPTB graft seems more secure than hamstrings. With regard to the BPTB graft fixation, interference screws have proven to be more effective than other devices, although screw fixation could cause some problems such as graft divergence, and rupture or damage of the bone plug/tendon. For a hamstrings graft, extracortical suspensory fixation such as EndoButton (Smith & Nephew Endoscopy, Andover, Massachusetts, USA) is usually used for the femoral side, whereas various devices are used for the tibial side. A recent study from the Norwegian registry showed that the use of EndoButton had the highest revision rate among several femoral fixation devices for hamstring graft.64 Further investigations with randomised or high-quality prospective studies will be necessary to determine optimal graft fixation for hamstring graft.

Missed associated injuries ACL injuries frequently occur concomitantly with other ligament, capsular and meniscus injuries in the knee. An assessment of such injuries is essential, as failure to recognise and treat these injuries can cause increased loads on the reconstructed ACL.

Medial side of the knee It is generally accepted that grade 2 or lower medial collateral ligament (MCL) injury concomitant with ACL injury can be treated by ACL reconstruction alone, as the MCL has excellent healing capacity.65,66 On the other hand, in case of complete medial knee injury combined with ACL injury, complex and problematic instability could be pronounced, because the functional deficiency of one ligament might affect the healing of the others.67 In that case, both ACL and MCL should also be reconstructed. In terms of MCL reconstruction, superficial and deep MCL, as well as posterior oblique ligament (POL), must be treated.68,69 The importance of POL has been recently

Grafts were associated with a higher risk of revision surgery.44 In terms of autografts, recent studies from Scandinavian registries and the Kaiser Permanente registry showed that hamstring tendon grafts had higher revision rates than BPTB grafts; however, no systematic reviews or meta-analyses of randomised or prospective studies showed any difference in the revision rate between hamstrings and BPTB grafts.64–62

Figure 1 CT scan of a patient with a low intercondylar notch and notchplasty during primary ACL reconstruction. The 3D-CT scan demonstrates reossification of the notchplasty (black dotted line) with resultant lower notch volume and higher risk for ACL reinjury. 3D-CT, three-dimensional CT; ACL, anterior cruciate ligament.

Figure 2 Postoperative CT scan and MRI of two patients with a high intercondylar notch. (A) High intercondylar notch with an intact vertical graft (white dotted line) and consequently lower in situ forces in the ACL. (B) High intercondylar notch with anatomical tunnel placement. This restores the in situ forces within the ACL graft. However, in such cases, the graft will be at risk for failure and return to sports should be delayed until adequate graft maturation. ACL, anterior cruciate ligament.
recognised as a primary restraint to the valgus torque at full extension as well as the internal rotation torque.\textsuperscript{70,71}

**Posterolateral corner**
Instability of the posterolateral corner, including the lateral collateral ligament, popliteus tendon and popliteofibular ligament, is often overlooked when combined with ACL injury, and the estimated incidence of posterolateral instability in patients with chronic ACL deficiency was reported to be 10–15\%\textsuperscript{72}. When both the ACL and posterolateral corner are injured, a simultaneous reconstruction is recommended.

**Anterolateral structures**
With the renewed focus on rotational knee stability, the anterolateral structures of the knee have recently attracted more attention.\textsuperscript{73} It has been reported that resection of a ligamentous structure referred to as the anterolateral ligament (ALL) increased rotational instability in ACL-deficient knees,\textsuperscript{74} and ALL reconstruction combined with ACL reconstruction significantly improved rotational stability compared with ACL reconstruction alone.\textsuperscript{75} However, the role, anatomy and even existence of the ALL are still controversial. Nevertheless, the importance of the anterolateral structures should be recognised, and additional procedures may be necessary in patients with a large residual pivot shift.

**Meniscus**
The medial meniscus acts as a secondary restraint for AP stability, and resection of the medial meniscus increases anterior translation in ACL-deficient knees.\textsuperscript{76} In addition, recent studies have reported that the peripheral attachment tear of the posterior horn of the medial meniscus, coined the ‘ramp lesion’, is commonly associated with ACL injury, and this ramp lesion increases anterior translation as well as rotational instability in ACL-deficient knees.\textsuperscript{77,78} In addition, the posterior root of the lateral meniscus has also been recognised to play an important role in anterolateral rotational stability in ACL-deficient knees.\textsuperscript{79} Surgeons should endeavour to repair all meniscal tears associated with ACL reconstructions, as it has been reported that patients were 4.9 times more likely to fail if they had a deficient medial or lateral meniscus compared with those with an intact meniscus, and those patients who underwent meniscal repair did not demonstrate any increased risk of failure.\textsuperscript{80}

**Biological factors**
When recurrent instability following ACL reconstruction is observed and there is no history of new trauma, no laxity of the secondary restraint and no identifiable technical error, biological failure should be considered.\textsuperscript{11} Biological failure can be defined as a failure in the completion of the ligamentisation process of the graft, which includes avascular necrosis, revascularisation, cellular repopulation, collagen remodelling and maturation.\textsuperscript{81} Therefore, a microscopic definition of biological failure appears more reliable and appropriate. However, at this moment, the concept of biological failure is still under investigation and is more of diagnosis of exclusion. In any case, the biological response of the graft is linked to the biomechanical and biochemical environment into which the graft is placed. The ACL graft heals only if the reconstruction can restore the anatomy and biomechanical environment.\textsuperscript{82}

**Infection**
Most infections after ACL reconstruction can be treated non-operatively or operatively without removing the ACL graft. However, graft removal is sometimes necessary depending on the extension of the infection, causal bacteria and type of graft (especially artificial ligaments). In cases with recurrent instability after graft removal, the revision surgery should not be considered until the laboratory data have returned to normal and any signs and symptoms of infection have subsided.\textsuperscript{83}

**Other factors**
Recent meta-analyses and registry studies have demonstrated that male gender, younger age and a return to high level of activity were risk factors of secondary injury after ACL reconstruction.\textsuperscript{11,41,84} A recent prospective cohort study has shown that return to sports 9 months or later after surgery and symmetrical quadriceps strength prior to return can reduce the reinjury rate.\textsuperscript{85}

A difference in the femoral tunnel drilling technique can also be a factor. While one study reported that the transportal technique was associated with a higher revision rate than the transtibial technique (Danish registry data),\textsuperscript{86} other studies showed equivalent clinical outcomes.\textsuperscript{87,88} Additional studies demonstrated that the transportal technique achieves improved anatomic tunnel placement, superior rotational stability and better clinical outcomes than the transtibial technique.\textsuperscript{89,90} The reasons for higher revision rates in the transportal technique could be technical failures resulting from a more complex procedure or by greater force placed on the grafts due to a more accurate reproduction of the strains placed on the native ACL.\textsuperscript{45}

Anatomic factors should also be considered. A narrow or low intercondylar notch and/or large posterior slope of the lateral tibial plateau have been reported as risk factors for ACL injuries.\textsuperscript{91} Likewise, these factors have been associated with graft failure after ACL reconstruction. The narrow intercondylar notch should be treated with notchplasty if graft impingement is observed during surgery, and posterior slope can be corrected via osteotomy in cases of excessively large slope. Care must also be taken to choose the proper graft type when dealing with a low notch. For example, a large BPTB graft may not be appropriate in a low notch, while a smaller hamstring graft may be used without impingement (figure 3). A larger notch will allow

**Figure 3** Postoperative CT scan including intraoperative measurements of a low and a high intercondylar notch. A low intercondylar notch (A) is a risk factor for ACL rupture, especially when a large graft is used. This patient sustained a second reinjury following ACL reconstruction using a 10 mm bone-patellar tendon-bone graft. A high intercondylar notch (B) allows a larger graft. ACL, anterior cruciate ligament.
more options including a traditional 10 mm BPTB graft. Furthermore, varus malalignment with a lateral thrust can lead to a chronic repeated stretch of the ACL graft, and valgus tibial osteotomy might be considered at the time of ACL reconstruction in these cases (table 1).92

Preoperative evaluation and planning
Careful preoperative evaluation is critical for successful revision ACL surgeries. It is important to identify the cause(s) of primary ACL reconstruction failure as outlined above, and then to develop appropriate plans for the revision surgery based on the causes of failure.

History taking and assessment of patient symptoms
Thorough history taking regarding the primary injury pattern, associated ligamentous/ meniscal/articular cartilage injuries, prior procedures performed, postoperative course, as well as reinjury pattern, is necessary. Patient activity level, patients' symptoms and patients' subjective evaluations should also be considered. The patients’ symptoms may include pain, swelling, instability (including fear and actual giving way), locking, stiffness or inability to return to physical activities as expected. The use of subjective evaluation forms such as Tegner activity scale, Lysholm score, KOOS and International Knee Documentation Committee (IKDC) subjective score are helpful for quantitative evaluation.

All previous medical records such as surgical records and preoperative/postoperative imaging should be obtained when possible (especially when prior surgeries were performed at other hospitals), and relevant surgical details, including associated injuries and treatments, type of graft, type of fixation, tunnel placement and other surgical techniques, should be carefully reviewed. In terms of graft type, special attention should be given to the artificial ligaments, as staged surgery might be necessary in cases with tunnel osteolysis and massive effusion caused by implant debris.

Physical examination
A thorough physical examination includes an assessment of range of motion, joint effusion, ACL-related instability and other symptoms related to other ligament deficiencies, and secondary restraint failures such as meniscus and capsule. ACL deficiency can be evaluated by AP instability (Lachman test, anterior drawer test, knee arthrometer) and anterolateral rotational instability (pivot shift tests). Evaluation of the pivot shift test is particularly important because the pivot shift test has been shown to be superior to AP instability tests when it comes to predicting patient-reported instability and poor subjective and outcome scores.93

Radiographic evaluation
Radiographic evaluation is critical for preoperative planning prior to revision surgery, as it provides the graft status and placement, tunnel positioning and expansion, and the presence of hardware that will interfere with the revision surgery. Hardware removal is not always necessary if new tunnel creation will not be affected by the location of the devices; however, if hardware removal is required to create a new tunnel, a complete set of hardware removal instruments must be available at the time of revision surgery.

Routine knee X-rays should be obtained. We routinely take a standing AP view in extension, a Rosenberg view (a standing 45° flexion posteroanterior view), a lateral view in maximum extension and a tangential view of the patellofemoral joint for both knees. A full-length standing AP view is also recommended if varus or valgus alignment is suspected. Stress X-rays (varus, valgus and posterior) help to quantitatively evaluate corresponding instabilities.

MRI of the current as well as the initial injury should be reviewed. If possible, MRI of the initial injury should be obtained to evaluate initial injuries, including ACL, meniscus, cartilage and other ligamentous injuries, especially ones that might have been misdiagnosed. The current MRI provides information regarding the status of the reconstructed graft, whether it is torn, elongated, degenerated or disappeared, as well as its orientation and positioning. In some cases with a vertical graft with a posterior tibial tunnel and anterior femoral tunnel placement, the graft looks intact in spite of gross rotational instability. The current MRI also provides information on the status of other concomitant injuries such as meniscus, cartilage and other ligamentous injuries, as well as on the quality of other soft tissues.

Three-dimensional CT (3D-CT) provides valuable information on the precise location and size of prior tunnels and hardware, and on the extent of residual tunnel expansion.94 95 Evaluation of 3D-CT is essential for surgeons to determine how to create new tunnels at the time of revision surgery or if staged surgery is required (table 2).

Surgical procedures
Graft selection
Graft selection should be individualised; it could be affected by such factors as the graft used in the primary surgery, sex, age, patient’s activity level, and other patient needs and demands. The senior author currently uses the DB technique with hamstring (only the semitendinosus tendon in most cases) in patients after primary BPTB reconstruction, patients with failure of the primary hamstrings tendon reconstruction due to apparent technical errors, and patients planning to participate in repetitive jumping. In these cases, if the primary surgery is hamstring tendon reconstruction, the graft for revision surgery is harvested from the contralateral side. On the other hand, our current indications for use of BPTB graft are patients after primary hamstrings tendon reconstruction who do not want to have an incision in the healthy limb, and those without apparent technical errors. While lacking scientific data, surgeons tend to

### Table 1 Causes of primary ACL reconstruction failure

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<thead>
<tr>
<th>Type</th>
<th>Cause</th>
<th>Cause</th>
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<tr>
<td>Traumatic failure</td>
<td>Inappropriate accelerated rehabilitation</td>
<td>Trauma before graft incorporation</td>
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<td>Premature return to sports</td>
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<td>Traumatic event after return to sports</td>
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<td>Chronic repetitive trauma</td>
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<td>Atraumatic failure</td>
<td>Technical error</td>
<td>Tunnel placement</td>
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<td>Graft selection</td>
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<td>Graft tensioning</td>
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<td>Graft fixation</td>
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<td>Missed associated injuries</td>
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<td>Posterolateral corner</td>
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<td>Anterolateral structures</td>
<td>Meniscus</td>
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<td>Biological factors</td>
<td>Infection</td>
<td>Age, sex, sports activity level</td>
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<td>Other factors</td>
<td>Femoral tunnel drilling technique</td>
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hesitate to perform the revision surgery with the same graft, especially when there is no apparent technical error. Other choices could be the quadriceps tendon and iliotibial band, and in any case the use of autografts is preferred as the use of allografts has been associated with a higher incidence of graft failure.42 Indications for an allograft could be patients with a shortage of autograft (after multiple ligament reconstruction or multiple revision case), low-demanding elderly patients or patients who are reluctant to have an autograft harvest; however, in some countries such as Japan the availability of allografts is limited.

Tunnel creation

Tunnel placement should be rigorously planned based on preoperative imaging, especially 3D-CT. Tunnel placement can be categorised according to the position of previous tunnels: (1) anatomically correct position, (2) complete-incorrect position and (3) incomplete-incorrect position.20

Femoral tunnel

Anatomically correct femoral tunnel creation in the revision surgery is theoretically possible through any of the femoral tunnel drilling techniques, such as transtibial, transportal and outside-in techniques. Surgeons can use any preferred techniques. However, the outside-in technique would be the best, especially when tunnel direction should be controlled.

Correct femoral tunnel position

If the previous surgery is anatomic DB reconstruction without significant tunnel enlargement, these tunnels can be reused for either DB or BPTB revision reconstruction with the same aperture but different tunnel direction (figure 4). Even after anatomic single-bundle or BPTB reconstruction without significant tunnel enlargement, either the hamstring tendon with the DB technique or the BPTB graft can be used without compromising graft function with the tunnel merging with the previous one. If significant tunnel enlargement is observed, surgical options could be (1) two-stage surgery with bone grafting, (2) one-stage surgery using the BPTB graft and an interference screw to fill the previous tunnel as well as to keep the graft in an anatomic position, and (3) the over-the-top procedure. Since we strive to avoid multiple surgeries and prefer anatomic graft placement, our preference is option (2).

Table 2  Key issues for preoperative evaluations

<table>
<thead>
<tr>
<th>History taking</th>
<th>Patients’ symptoms</th>
<th>Physical examination</th>
<th>Primary surgery information</th>
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<td>Radiographic evaluation</td>
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<td>◀ Associated injuries</td>
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<tr>
<td>◀ Associated injuries</td>
<td>◀ Other ligamentous instability</td>
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<td>◀ Quality of other soft tissues</td>
<td>◀ Meniscus</td>
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3D-CT, three-dimensional CT; ACL, anterior cruciate ligament; IKDC, International Knee Documentation Committee; KOOS, Knee Injury and Osteoarthritis Outcome Score.

Figure 4  A case with correct femoral tunnel position. (A) Preoperative 3D-CT of the femur showed correct femoral tunnel position after primary DB ACL reconstruction with a merge of the two tunnels. (B) Preoperative 3D-CT of the tibia showed a medially placed AMB tunnel and correct PLB tunnel. (C) Preoperative MRI showed a torn reconstructed ACL graft. In this case, revision surgery was performed using a BPTB graft with rectangular femoral (D) and tibial (E) tunnels with the tunnels merging with the previous ones. 3D-CT, three-dimensional CT; ACL, anterior cruciate ligament; AMB, anteromedial bundle; DB, double-bundle; PLB, posterolateral bundle.
Complete-incorrect femoral tunnel position
In such cases, two isolated anatomic DB tunnels can usually be created unless the old tunnel is significantly enlarged (figure 5). In cases where the BPTB graft is used, rectangular tunnel creation has the advantage of avoiding tunnel encroachment, as reduced tunnel size with the rectangular aperture would be more suitable in revision surgery with previous improperly placed, enlarged tunnels. If an old tunnel is significantly enlarged and there is a risk of tunnel encroachment or collapse between the old tunnel and the new tunnel, filling the old tunnel with an interference screw or bone graft is useful.

Incomplete-incorrect femoral tunnel position
Sometimes, this is the most technically demanding case, as there is a potential risk of tunnel communication between the new tunnel and the old tunnel, possibly leading to an extensive bone defect. In such cases, femoral tunnel creation should be planned very rigorously, and surgical options consist of (1) two-stage surgery with bone grafting, (2) one-stage surgery using the BPTB graft with a rectangular femoral tunnel, and the use of an interference screw to fill the previous tunnel as well as to keep the graft in an anatomic position if necessary (figure 6), and (3) the over-the-top procedure.

Tibial tunnel
In terms of the tibial tunnel, a complete-incorrect tunnel position is less common than in the femoral side. However, massive tunnel enlargement and/or posteriorly and laterally placed non-anatomic previous tunnels can be a challenge for surgeons. In such cases, surgeons can try to create a new tunnel at the anatomic position with the different tunnel route first. Then if the graft is deviated to the old tunnel, an interference screw or bone graft is useful to fill the previous tunnel as well as to keep the graft in an anatomic position. If tunnel enlargement is so massive and the tibial side fixation seems unstable, two-stage surgery with bone grafting could be considered. If tibial tunnels are anatomically placed without significant enlargement, a different tunnel route with the same aperture can be created.

Associated injuries
Again, if concomitant secondary stabiliser instability is identified, simultaneous reconstruction should be performed. Meniscus injury or dysfunction should be treated according to the injury status; it should be repaired wherever possible (figure 5), and in some cases with meniscus dysfunction or after meniscectomy, meniscal transplantation should also be considered. After all associated ligament injuries and meniscus injuries are treated, if the patient still has large anterolateral rotational instability, extra-articular augmentation (anterolateral structure reconstruction) may be added. However, caution should be exercised to first ensure that the ACL reconstruction is anatomic, and then to ensure that any additional procedures do not overconstrain the lateral compartment.

Postoperative care and rehabilitation
Patients with revision ACL generally need closer care than those after primary ACL reconstruction. They frequently have combined meniscus and articular injuries as well as secondary restraint damages, which cause prolonged joint inflammation and permanent knee kinematic changes. In addition, patients after revision surgery can be considered to have a higher risk of reinjury and graft failure. Therefore, slower rehabilitation with a longer period of knee brace wearing and crutch usage in the early postoperative period should be considered for preventing recurrent instability in such high-risk patients. In the late postoperative period before returning to sports activities, more careful exercises and stricter criteria for return to sports are necessary to prevent reinjury. Stereotype progression of the postoperative schedule should not be applied; individualised rehabilitation protocol and goal setting are important for patients after revision surgery (boxes 2 and 3).
Clinical outcomes after ACL revision surgery

Recent systematic reviews and meta-analyses have revealed that revision ACL reconstruction has inferior outcomes compared with primary ACL reconstruction. Wright et al. concluded that revision ACL reconstruction resulted in worse outcomes compared with primary ACL reconstruction, in terms of patient-reported outcome scores and graft failure. In particular, a dramatically elevated failure rate was noted—nearly 3–4 times higher compared with a prospective series of primary ACL reconstruction. An inferior rate of return to the same preinjury sport level has also been reported. Andriolo et al. reported that 57% of patients after revision surgery did not return to the same level of sports activity, which was significantly inferior to that of those after primary reconstruction. Grassi et al. also reported that, in spite of almost 80% of patients returning to sports after revision ACL surgery and showing good stability, only half of the patients returned to the same preinjury sport.

**Box 2** Tips and tricks for successful revision anterior cruciate ligament (ACL) surgery

1. **Graft selection**: graft selection should be individualised according to primary surgery, sex, age, patient’s activity level and other factors. Either autogenous hamstrings tendon (possibly double-bundle technique) or bone-patellar tendon-bone is recommended.

2. **Tunnel creation**: both femoral and tibial tunnels should be rigorously planned based on three-dimensional CT. The tunnels should be placed within an anatomical footprint, and if anatomical placement and secure graft fixation are difficult because of massive tunnel enlargement, two-stage surgery with bone grafting can be considered.

3. **Associated injuries**: Associated injuries should be treated according to the injury status. If large anterolateral rotational instability exists even after all associated injuries have been treated, additional extra-articular augmentation can be considered.

4. **Individualisation**: careful and slower rehabilitation should be applied for preventing re-injury and graft failure after revision ACL surgery.

**Box 3** Major pitfalls

1. **Use of allografts** should be limited. The use of allografts has been associated with a higher incidence of graft failure. Indications for an allograft could be patients with a shortage of autograft, low-demanding elderly patients or patients who are reluctant to have an autograft harvest.

2. **If a significant tunnel enlargement is observed** and there is a risk of tunnel encroachment or collapse between the old tunnel and the new tunnel, surgical options could be (1) two-stage surgery with bone grafting, (2) one-stage surgery using a bone-patellar tendon-bone graft and an interference screw to fill the previous tunnel as well as to keep the graft in an anatomical position, and (3) the over-the-top procedure.

3. **If the patient has large anterolateral rotational instability**, additional extra-articular augmentation (anterolateral structure reconstruction) may be considered. However, caution should be exercised to first ensure that the anterior cruciate ligament reconstruction is anatomically correct and all associated ligament injuries and meniscus injuries are properly treated, and then to ensure that any additional procedures do not overconstrain the lateral compartment.

4. **Stereotype progression of the postoperative schedule should not be applied**; individualised rehabilitation protocol and goal setting are important for patients after revision surgery.

**Figure 6** In cases where the BPTB graft is used, rectangular tunnel creation has advantages in avoiding tunnel encroachment with a previous improperly placed, enlarged tunnel. (A) Preoperative 3D-CT of the femur showed incompletely incorrect, anterior and high femoral tunnel positions after primary DB ACL reconstruction. The prior PLB tunnel was partially overlapped with the anatomical AMB attachment site. (B) The preoperative 3D-CT of the tibia showed correct AMB and PLB tunnels. (C) The preoperative MRI showed a vertical graft without a tear, although not functional. In this case, revision surgery was performed using the BPTB graft with rectangular femoral (D) and tibial (E) tunnels. As for the femoral tunnel, a new rectangular tunnel could be created posterior to prior tunnels without merging; the use of the interference screw was not necessary. 3D-CT, three-dimensional CT; ACL, anterior cruciate ligament; AMB, anteromedial bundle; DB, double-bundle; PLB, posterolateral bundle.
level. Regarding prognostic factors after revision ACL surgery, a recent study from the MARS group revealed that prior lateral meniscectomy and current grade 3–4 changes of the trochlear cartilage were associated with worse outcomes in terms of decreased sports participation, more pain, more stiffness and more functional limitation at 2 years after revision surgery. 21

Geographical differences

As already mentioned, in some countries such as Japan, the use of allografts is very limited. In these countries, only autografts are available. Graft choice is especially difficult in cases with multiple ligament injuries and multiple revision surgeries, and all possible autografts should be considered. However, in very rare cases, the use of artificial ligaments can be also considered, although we have not had such experiences.

Since the renewed focus on the anterolateral knee structures, extra-articular augmentation or ALL reconstruction in addition to revision ACL reconstruction has regained popularity, especially in European countries. 13 98 99 Although the role, anatomy and even existence of the ALL are still controversial, if large anterolateral rotational instability still exists even after all associated injuries have been treated, additional extra-articular augmentation may be considered. However, the goal of any ACL reconstruction surgery should be to recreate the native anatomy of the ACL to the greatest degree possible. In addition, more research is needed to investigate which patients might benefit from additional extra-articular procedures.

CONCLUSIONS AND FUTURE PERSPECTIVES

As already mentioned, revision ACL reconstruction results in inferior outcomes compared with primary ACL reconstruction. Careful preoperative evaluation and planning, sophisticated surgery (including individualised graft selection, anatomical tunnel placement and secure fixation) and individualised rehabilitation are essential keys to successful revision ACL surgery. There have been very few high evidence-level studies in the field of revision ACL surgery; therefore, more evidence with high-quality studies is necessary. The relatively recent development of MARS will give us more evidence regarding clinical outcomes and prognostic factors, which will contribute to improving revision surgery procedures. On the other hand, surgeons should also pay more attention to prevention. First of all, primary ACL injury should be prevented by means of preventive intervention. 100 If a patient has an ACL injury, surgeons should perform anatomic ACL reconstruction as perfectly as possible, and any associated ligament, meniscus and cartilage injuries should be treated accordingly. Careful rehabilitation and preventive training for reinjury should also be conducted after primary ACL reconstruction. After all, reducing the incidence of revision ACL surgery, as well as primary ACL injury, is essential for the sake of all athletes.

Contributors

HK drafted the manuscript. LE, FHF and TM completed the final manuscript.

Competing interests

None declared.

Provenance and peer review

Commissioned; externally peer reviewed.

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Revision anterior cruciate ligament surgery: state of the art

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J ISAKOS 2017 2: 36-46 originally published online December 16, 2016
doi: 10.1136/jisakos-2016-000071

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