(iii) Anterior cruciate ligament reconstruction — evolution and current concepts

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Abstract

Since the early 20th century, the considerable evolution of anterior cruciate ligament reconstruction has been an essential impetus for our understanding of knee anatomy and biomechanics, and their relation to function, injury and rehabilitation. Traditional use of non-anatomic intra- and extra-articular reconstructions has moved to an emphasis on restoring anatomy and native knee kinematics whilst preserving biology. With new evidence and technology, old concepts such as ACL repair and lateral procedures are being revisited with a fresh perspective in an attempt to restore normal knee function. Every aspect of the technique is a source of constant innovation with new concepts and controversy. This review describes the key milestones of this evolution then provides an appraisal overview of current concepts and the rationale for variations in technique.

Keywords anatomic; anterior; cruciate; fixation; graft

Introduction

Anterior cruciate ligament (ACL) injuries are one of the most common knee injuries, with an annual incidence of 100 000 –200 000 in the US.[1] Non-surgical management of this injury may be appropriate in certain instances; however, it is widely accepted that for symptomatic instability an ACL reconstruction is critical for the prevention of secondary injury and long-term morbidity.

The goals of ACL reconstruction (ACLR) are to stabilize the knee joint, restore normal kinematics and prevent early onset degenerative arthrosis. Unfortunately, despite extensive anatomical, biomechanical and clinical research, this has not yet enabled us to fully restore normal knee function. However, this has led to constant improvements in our understanding with regards to ACLR over the last 30 years, which in turn has yielded significant improvements in the clinical outcomes following ACL injury. ACLR continues to dominate both the literature and clinical forums in the field of soft-tissue knee surgery. A recent PubMed search for 'anterior' 'cruciate' 'ligament' revealed over 14 000 results, with 1050 in 2013 alone. However, a recent meta-analysis concluded that the majority of the evidence is below Level II and must be considered carefully.[2]

Advances have come largely from a better understanding of ACL anatomy; in particular, the anteromedial (AM) and posterolateral (PL) bundles, their inherent anisometry, the morphology of their bony insertions and how these relate to surrounding structures.[3–5] Historically, reconstructions placed a bone-patellar tendon-bone (BPTB) graft in a non-anatomic, isometric position, high and deep in the notch outside of the femoral footprint. Biomechanical and clinical studies observed a lack of rotational control and persistent pivot-shift, leading surgeons to re-examine the anatomy and the unaddressed role of the PL bundle. This prompted the advent of anatomic double-bundle (DB) and mid-bundle ACLR.[6]

More recently, the importance of the lateral side of the knee has also been revisited, with the possibility of an anatomic reconstruction of the 'anterolateral' ligament replacing traditional tenodesis procedures. The biological and mechanical advantages of ACL remnant preservation have also been highlighted in the context of complete and partial rupture.[7]

Here, we present an overview of the current concepts in ACLR, focussing on anatomy, graft selection, tunnel position, fixation and control of rotational stability.

Evolution

At the dawn of the 20th century, operative treatment of ACL rupture focused on direct repair. The first ACL reconstruction used tensor fascia lata autograft and was performed in 1912 by Giertz. In 1917, Hey-Groves attempted to reconstitute the anatomy of the ACL, drilling inside-out in an open procedure. In 1938, Palmer proposed the idea of double-bundle reconstruction in his thesis on the ACL, but this was widely unaccepted at the time.[6]

Up until the mid-1970s, the diagnosis of ACL injury was difficult to elicit and relied on discernable laxity at 90° of flexion with the foot in varying degrees of rotation. Naturally, this did not identify isolated ACL injuries and only tended to be positive when other ligamentous or meniscal structures were damaged. Classic studies, such as those of Girgis et al.,[3] described the relationship between knee laxity and flexion angle as well as identifying the ACL's role in controlling tibial rotation. Such

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biomechanical awareness led to descriptions of the 'pivot shift' (Galway et al. 1972) and later the 'Lachman Test' (Torg et al. 1976). The need to control rotation and the difficulty of intra-articular reconstruction led to a series of extra-articular lateral procedures being described. Pioneered by Strickler (1937) initially, then by Lemaire (1960) and MacIntosh (1970s), these used a lateral tenodesis to control anterolateral tibial subluxation. However, these procedures in isolation resulted in residual instability and subsequent early degenerative change.[8] This failure directed attention towards intra-articular reconstruction of the ACL.

The 1980s saw the uptake of arthroscopy as both a diagnostic tool and an adjunct to open ACLR. Transtibial drilling of tunnels/sockets was the 'gold-standard' throughout the 1980s and 1990s. This technique produced a reconstruction that resisted anterior tibial displacement relatively well but with only limited rotational stability.[9] Initial wire fixation of the bone plugs was replaced with interference screws.

In the early 21st century, studies noted that up to 25% of patients had a persistent pivot shift following transtibial ACLR, going on to develop secondary meniscal and chondral injuries which are likely to propagate to degenerative arthrosis.[10] Up until now, a 'non-anatomic' isometric position was sought after on the femur, as one graft had to resist tibial translation at all flexion angles. This leads to the function of the PL bundle being considered and the concept of anatomical DB-ACLR being defined by Yasuda et al., 2004.[11] This technique has gained popularity over the last decade, due to a perceived improvement in reproduction of anatomy and rotational stability when compared to traditional ACLR.[6,12,13] However, 'anatomic' placement of single bundle (SB) ACLR in a more oblique position, 'down the clock face' and within the femoral footprint, has been more widely accepted. There is a general consensus in the literature that both of these 'anatomic' techniques more closely restore normal knee kinematics than the traditional 'over the top' technique. However, given the complexity of DB reconstruction, 'anatomic' SB — ACLR is now considered the new gold standard by many.[6]

At present, no ACLR technique restores normal anatomy, kinematics and function to the knee. Whilst there is consensus on the indications for ACLR, controversy persists surrounding the optimal reconstructive technique; tunnel placement, graft selection and fixation method.

Anatomy

The ACL is an intra-articular but extra-synovial structure with a blood supply predominantly from the middle genicular artery, arising from the popliteal artery. A functional native ACL provides proprioceptive feedback that is protective to the knee but which is lost, at least in the short term, following reconstruction. The ACL has a mean length of 31—38 mm and width of 11 mm. It is a strong structure with a mean tensile strength of 2150 N and stiffness of 242 Nmm^{-2}.[3]

The ACL originates from the medial border of the lateral femoral condyle and inserts in proximity to the tibial spines. It does not function as a simple tube of fibres with a constant tension, but rather consists of fibre groups that are subjected to episodes of lengthening and slackening throughout the range of motion; i.e. it is anisometric. This has advocated the functional subdivision of the ACL into an AM and a PL bundle, named according to their relative insertions on the tibia. The AM bundle is tighter with the knee in flexion and the PL tighter in extension (Figure 1). However, the description of two bundles may be somewhat of an oversimplification, and current anatomical studies suggest a ribbon-like structure that inserts as a 'C'-shape onto the tibia.[14] This 'ribbon' is not separated into two distinct bundles in the proximal half of the ACL.[15]

In addition to the ACL, it is now evident that other structures provide significant rotational stability. This concept has recently been revisited by Claes et al[16] describing a well-defined ligamentous structure clearly distinguishable from the anterolateral capsule and the iliotibial band: the anterolateral ligament (ALL).

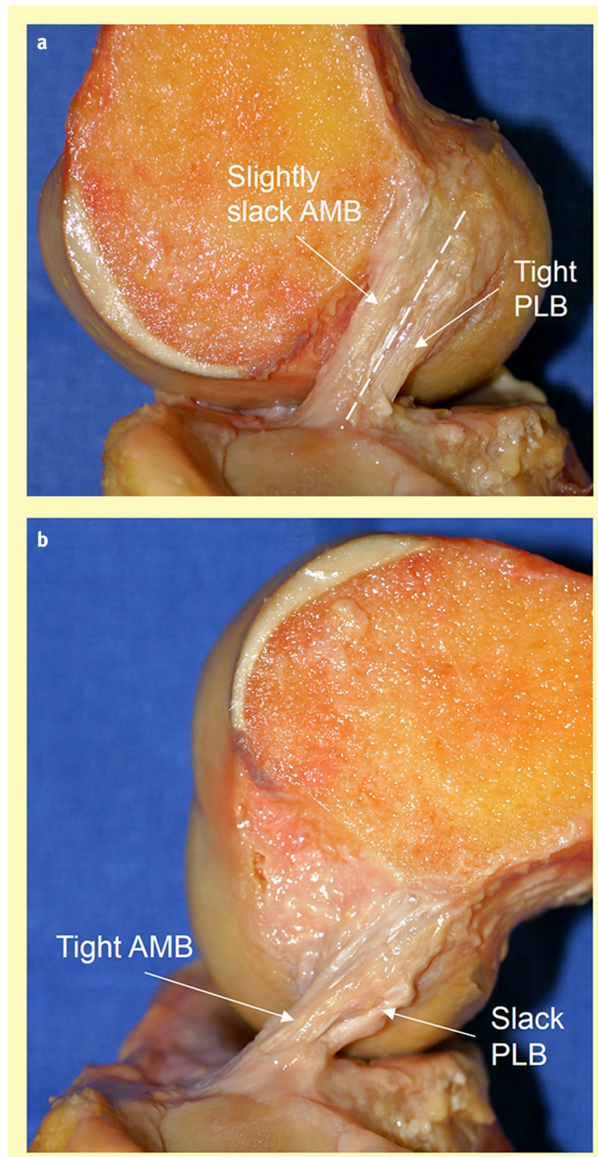

Figure 1 Lateral view of the native ACL depicting the nominally divided anteromedial (AMB) and posterolateral (PLB) bundles. (**a**) The PLB is tight whilst the AMB is slightly slack in extension. (**b**) The AMB is tight whilst the PLB is slack during flexion. *Images courtesy of Dr Charles Brown, Abu Dhabi Knee & Sports Medicine Centre*.

This is supported by the findings of Caterine et al., who clearly identified the ALL on MRI as well as verifying a histological appearance consistent with ligamentous tissue.[17] The exact course of this ligament is contested: Claes et al. reported the ALL origin at the prominence of the lateral femoral epicondyle 2–3 mm anterior and distal to the origin of the lateral collateral ligament (LCL); Dodds et al.[18] described the ALL origin to be 8 mm proximal and 4.3 mm posterior to the lateral epicondyle and proximal to the LCL. The fibres follow an oblique path, inserting on the anterolateral aspect of the tibia, mid-way between the tip of the fibula head and Gerdy's tubercle, with attachments to the lateral meniscus.[16,18]

Injury and prevention

Anterior cruciate ligament injuries are commonly sustained in non-contact situations when the knee pivots under axial force. Sports associated with this injury include soccer, netball, handball, hockey and basketball. Females are at higher risk of injury, with a relative risk ratio of 2–6 times that of their male counterparts.[19] Risk factors include hyper-laxity, genetic predisposition, raised BMI and hormones.[19] Active prevention such as the FIFA 11+ programme has been shown to reduce risk of injury by 40% in soccer players[20] by using a comprehensive warm-up with improved strength, awareness and neuromuscular control. Tensile forces in the ACL are highest with the knee in full extension[3]; therefore, players can be taught to bend their knees when they land from a jump. The goal is a decreased peak vertical ground reaction force, increased knee flexion angle and decreased knee valgus.

ACL reconstruction

Femoral tunnel/socket preparation

Correct positioning of bone tunnels is critical to a successful clinical outcome following ACLR. Malposition of the graft is the most common technical error, leading to impingement, deficits in range of motion, recurrent instability and ultimately graft failure.[21]

The clockface method for femoral tunnel positioning is based on the morphology of the intercondylar notch; a notoriously imprecise arthroscopic landmark. Furthermore, it does not take into account the depth of the femoral footprint and it cannot be viewed from the AM portal (AMP).

The ACL femoral attachment is oval in appearance and is defined by two bony ridges, the lateral intercondylar and the bifurcate ridge (Figure 2). The lateral intercondylar ridge is a consistent bony landmark, with all the ACL fibres inserting posterior to it. The bifurcate ridge runs perpendicular to the lateral intercondylar ridge, dividing the footprint into the insertion sites for the AM and PL bundles. The centres of the AM, PL and mid-bundle points were described by Ziegler et al. in terms of these bony landmarks.[22] However, their identification often requires extensive soft tissue resection, compromising the remnants of the native ACL. Remnant preservation gives further indication as to correct tunnel position, enhances biological healing and proprioception, and provides mechanical support to the ACLR graft.[7]

Piefer et al.[5] performed a systematic review of recent literature defining the central points of the AM, PL and mid-bundle positions in terms of their relationship to the articular cartilage along the long axis of the femur. The AM, mid- and PL bundle centres were 29.5%, 43% and 50% respectively along a line from the proximal to the distal articular cartilage margins and 2.5 mm plus the femoral socket radius from the posterior articular cartilage.

These findings support the 'direct measurement' technique described by Bird et al.,[23] using a calibrated measuring tool. This technique is particularly useful in the context of revision ACLR, where there is often no ACL remnant or bony landmark present.

The use of intra-operative fluoroscopy with a true lateral radiograph is an accurate way to initially determine, implement and evaluate ACL femoral tunnel placement. This is especially

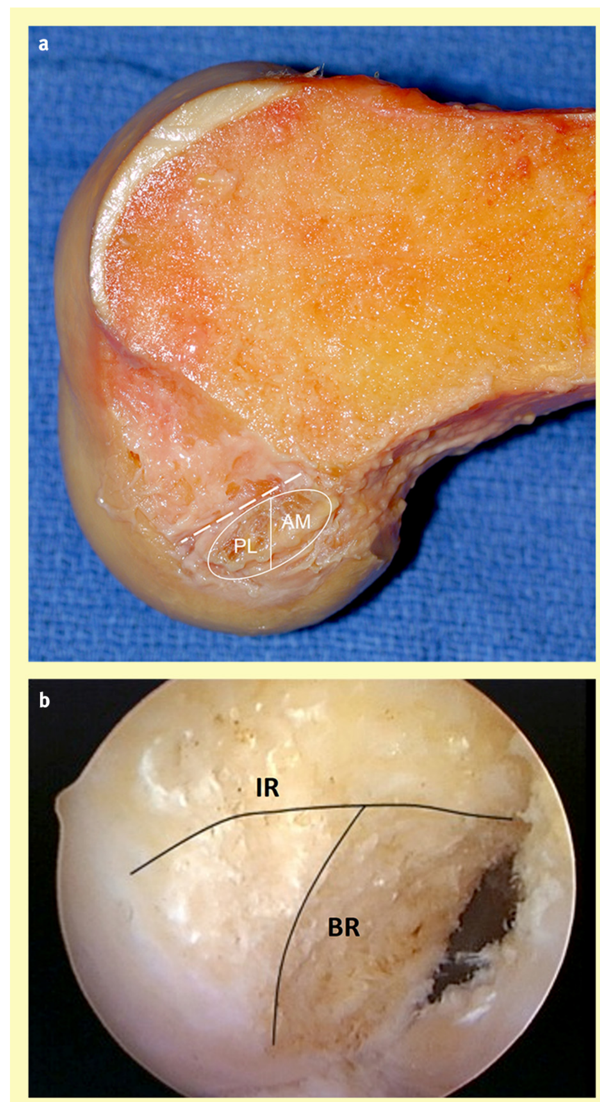

Figure 2 (**a**) Lateral view of the ACL footprint depicting the superior limit of the insertion (dashed line), the oval shape and the broad nominal division into AM and PL bundle insertion sites. Despite ACL resection, the remnants obscure the underlying bony landmarks. (**b**) Arthroscopic view of the medial wall of the lateral femoral condyle, depicting the shallow to deep lateral intercondylar ridge (IR) and the bifurcate ridge (BR), following resection of the ACL remnant *Images courtesy of Dr Charles Brown, Abu Dhabi Knee & Sports Medicine Centre*.

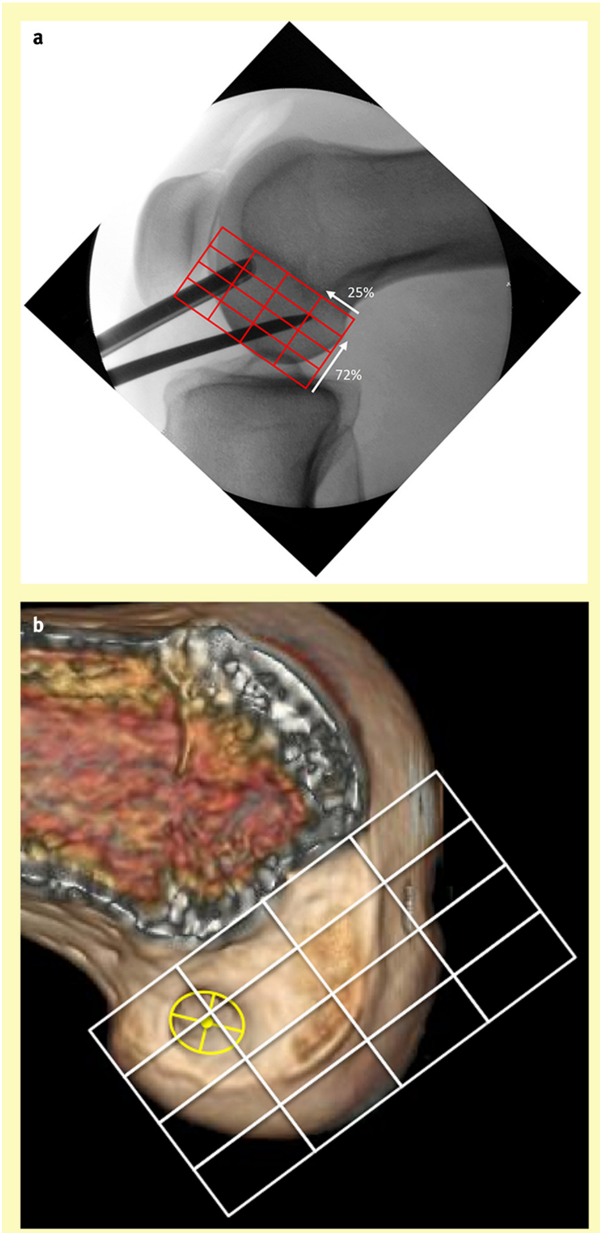

Figure 3 (**a**) Lateral radiograph of the knee with the Hertel grid overlaid. The centre of the ACL femoral attachment is a point 24.8% by depth along Blumensaat's line and 71.5% of the lateral wall height perpendicular to Blumensaat's line. The ACL drilling guide (shown) can be accurately positioned to ensure optimal tunnel placement. *Images courtesy of Dr Charles Brown, Abu Dhabi Knee & Sports Medicine Centre*. (**b**) Sagittal section through a 3D reconstruction of post-operative CT images showing optimal tunnel placement within the Hertel grid. *Image courtesy of Parkinson and Spalding, University Hospital of Coventry and Warwickshire*.

valuable in the context of ACL augmentation, remnant preserving ACLR and revision procedures. This utilizes the grid system proposed by Bernard and Hertel[24]: the centre of the ACL femoral attachment is a point 24.8% by depth (deep to shallow) along Blumensaat's line and 28.5% of the lateral wall height (high to low) perpendicular to Blumensaat's line (Figure 3).

Historically, the femoral tunnel has been drilled using over the top guides up the tibial tunnel in a transtibial technique. However, this restricts tunnel placement, resulting in non-anatomic vertical grafts. With the advent of anatomic ACLR, inside-out drilling through the AMP has removed the constraint of transtibial drilling. However, visualization and depth perception within the ACL femoral footprint is impaired, increasing the chance of tunnel malposition.

Recognizing this, Cohen et al. proposed an accessory medial portal, to allow concurrent visualization and drilling from the medial side.[25] Although popular, instrument overcrowding is challenging and knee hyperflexion can be disorientating. The latter is often not possible in the obese patient and the surgeon may be restricted to the transtibial technique. Despite the use of low profile reamers (Figure 4), medial femoral condyle scuffing is another potential hazard, in addition to shorter femoral tunnel length (less than 20 mm), posterior blow-out and inferior exit of

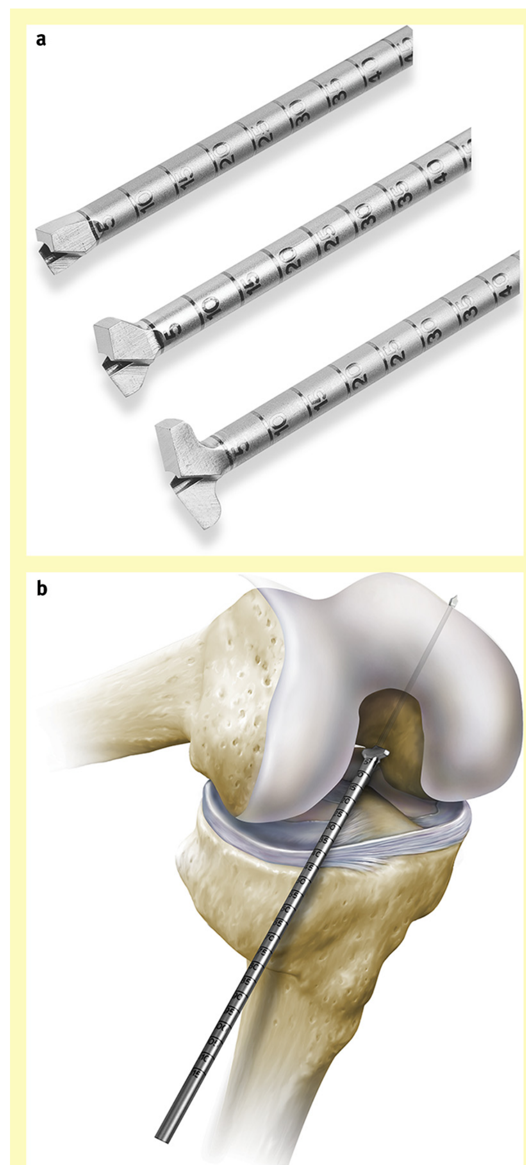

Figure 4 (**a**–**b**). Low profile reamers to protect the chondral surface of the medial femoral condyle during tunnel preparation using (accessory) medial portal drilling (Arthrex, Naples, Fl).

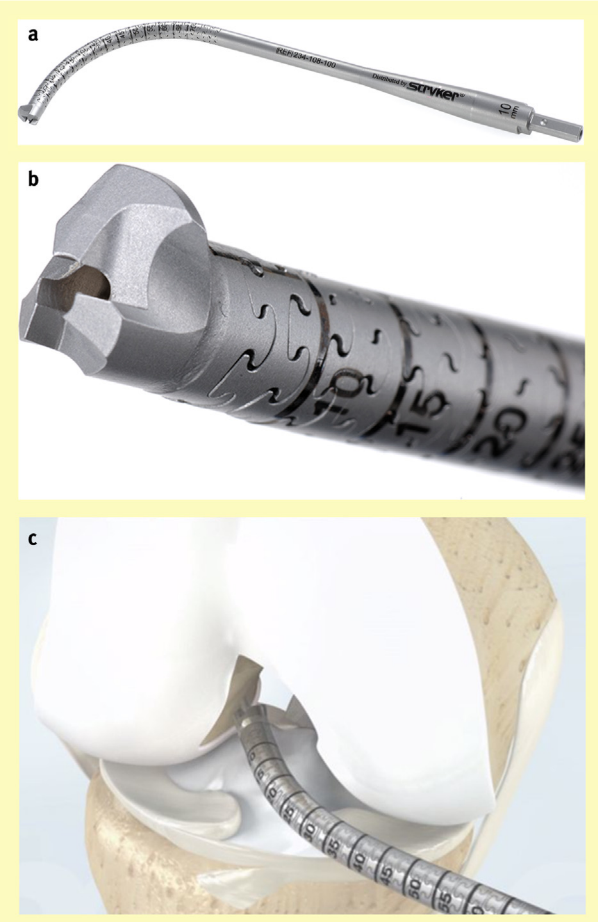

Figure 5 (**a**–**c**). VersiTomic Flexible Reaming System (Stryker, Kalamazoo, MI). This system allows for femoral socket positioning using (accessory) medial portal drilling without the difficulties associated with hyperflexion of the knee.

the guidewire from the lateral thigh approaching critical neurovascular structures. Flexible reamers are now available to circumvent these problems (Figure 5), but issues with instrument overcrowding persist.

Advances in retrograde socket drilling technology now enable accurate and reliable minimally invasive retro-socket creation, facilitating the 'all-inside' approach. An initial small pilot hole (3.5 mm) is made and then retro-reaming is carried out with a FlipCutter (Arthrex, Naples, Fl, USA) selected to the size of the graft (Figure 6). The TransLateral ACLR technique uses this technology combined with anatomically contoured instruments to navigate around the lateral femoral condyle, facilitating medial viewing with lateral working.[26] This alleviates the problems associated with hyperflexion and the 3-portal technique. The TransLateral method for femoral socket preparation uses adjustable cortical suspensory fixation on the femur, such as the ACL-TightRope (Arthrex, Naples, Fl, USA). This fixation can also be used on the tibia in the TransLateral 'all-inside' ACLR technique.[27] This technique has been reported to have a low complication rate and low graft failure rate of only 4.3% in over 200 cases (Yasen & Wilson et al., article in press).

The results of a recent Cochrane review into ACL Navigation or computer assisted surgery (CAS) revealed a non-significant improvement in patient outcome scores but longer operative times. The authors concluded that CAS could not be recommended at this time, but that further studies would be beneficial.[28]

Tibial socket preparation

As with the femur, the evolution of tibial tunnel placement has seen a move away from a primary focus of isometric positioning and evasion of graft impingement towards anatomic ACLR with better restoration of anterior translation and rotational stability.[21]

The tibial insertion of the ACL is larger than the femoral origin and has traditionally been described as 'oval'. However, several recent anatomical and histological studies have described a 'ribbon-like' mid-substance to the ACL, corresponding with a 'C-shaped' insertion from the medial tibial spine to the anterior aspect of the anterior horn of the lateral meniscus.[29]

A high anteromedial portal position allows excellent visualization of the tibial footprint, to facilitate appropriate positioning. Key arthroscopic landmarks are outside the tibial insertion, enabling accurate positioning whilst preserving the ACL remnant. There is some controversy as to the optimal position in relation to these landmarks. Hwang et al. performed a systematic review of the recent literature, reporting the bundle positions relative to the anterior border of the PCL and the medial and lateral tibial spines.[4] The mid-bundle position was reported as 15 mm anterior to the anterior border of the PCL and 40% the medial to lateral distance between the tibial spines. The PL bundle was 11 mm anterior to the PCL and 50% the medial to lateral distance between the tibial spines. The AM bundle was 4 mm medial to the PL, 20 mm anterior to the PCL border and 25% the medial to lateral distance between the tibial spines. Another useful reference guide is the axis between the medial tibial spine and the root of the anterior horn of the lateral meniscus. The PL bundle should be posterolateral to this, the AM anteromedial and the mid-bundle on this line.

Fluoroscopic guidance has been quantified by a variety of studies using the Amis and Jakob line (Figure 7).[30] Kasten et al. performed an in vivo study reporting the AM and PL bundles to be at 35% and 48% of the AP distance along this line, with the mid-bundle position being at 41%. In the coronal plane, the mid-bundle position was 42% from the medial joint line.[31]

The 'all-inside' approach has many advantages in terms of tibial socket preparation during complex ACLR. Examples include when performing ACLR in conjunction with simultaneous high tibial osteotomy. Here, it is easier to maintain cortical integrity between the osteotomy site and the tibial tunnel using a small pilot hole. The pilot hole can be placed away from the osteotomy site and cortical fixation achieved with a TightRope button. In the paediatric patient, the retrosocket can be made all-epiphyseal or the surgeon can choose to make the pilot hole transphyseal but only make the retrosocket within the epiphysis, minimizing the amount of physis that is compromised by the socket preparation. For Revision ACLR, the 3.5 mm pilot drill can be placed away from existing metalwork and hardware circumvented without the time and morbidity associated with metalwork removal.

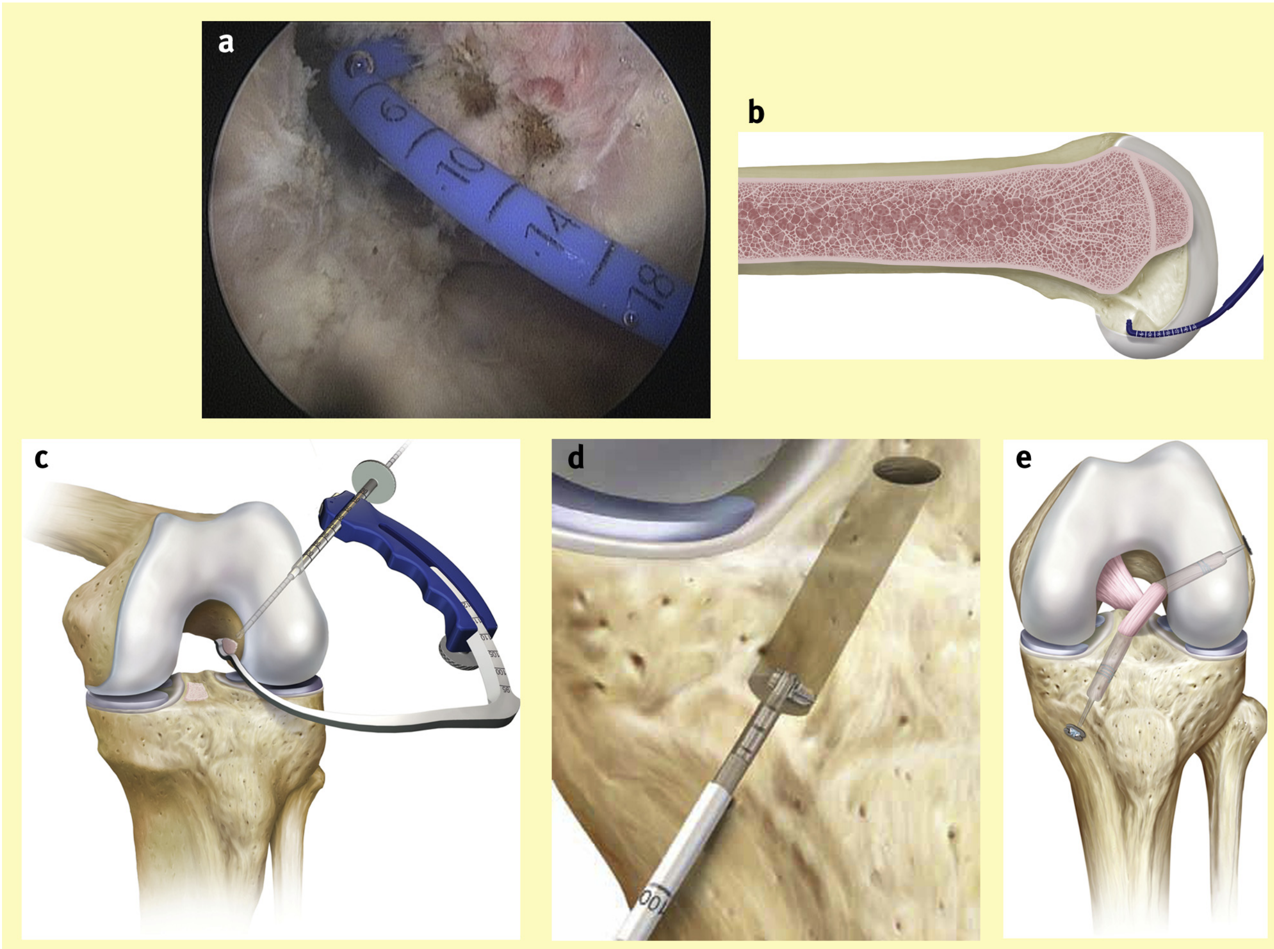

Figure 6 TransLateral instruments for all-inside ACL reconstruction (**a**–**d**), Arthrex, Naples, Fl. (**a**–**b**) Calibrated radiofrequency device for simultaneous soft tissue clearance and socket marking; CoolCut Caliblator. (**c**) Contoured drill guide to negotiate the lateral femoral condyle with step sleave guide to protect the cortical bridge. (**d**) Tibial retrosocket preparation. (**e**) Completed all-inside ACLR, here using a BTB TightRope (Arthrex). This can be threaded through the graft including bone plugs.

Graft selection

Surgical preference is certainly important; however, inherent laxity, associated injuries, biology and physical demand of the patient are crucial factors. Autograft tissue is the gold standard and most common choice, followed by allograft, with a variety of ligament augmentations coming into vogue.

Autograft

The most common autografts are hamstring (HS) and bone-patella tendon-bone (BPTB) although quadriceps tendon, with or without a bone block, is another option that is often considered in revision cases. Autografts have the advantage of being readily available and biologically favourable, with no risk of disease transmission and no additional cost.

For many years, BPTB graft was considered to be the gold standard in ACLR due to superior biomechanical properties and bone-to-bone healing, with high initial fixation strength. The Scandinavian ACL registry has shown higher revision rates with hamstring grafts, especially in the first year.[32] However, a systematic review comparing these grafts showed no difference in terms of survivorship or functional outcomes.[33]

As complications related to BPTB graft harvest and donor site morbidity are a concern, the trend has now shifted towards using HS grafts for uncomplicated ACLRs. These can be harvested through a small cosmetically pleasing incision with less pain and with easier graft passage, and they are suitable for multi-bundle ACLR. Hamstrings are the graft of choice for patients with an occupation that requires kneeling or for those with a history of anterior knee pain. An oblique incision improves visualization of the vinculae during HS harvest, but the infra-patellar branch of the saphenous nerve remains at risk. An alternative posterior approach may avoid this. In athletes, loss of hamstring proprioception and power after HS harvest can be detrimental, and BPTB grafts, which incorporate more quickly at the osseous interface, may allow accelerated rehabilitation and earlier return to full activity.[34]

Traditionally, both the semitendinosus and gracilis are harvested and doubled over to create a 4-strand ACL graft. This often produces a graft less than 8 mm in diameter, compromising mechanical strength. In the USA, smaller diameter grafts are often supplemented with allograft to increase diameter beyond 8 mm. This can be circumvented by tripling or quadrupling a single

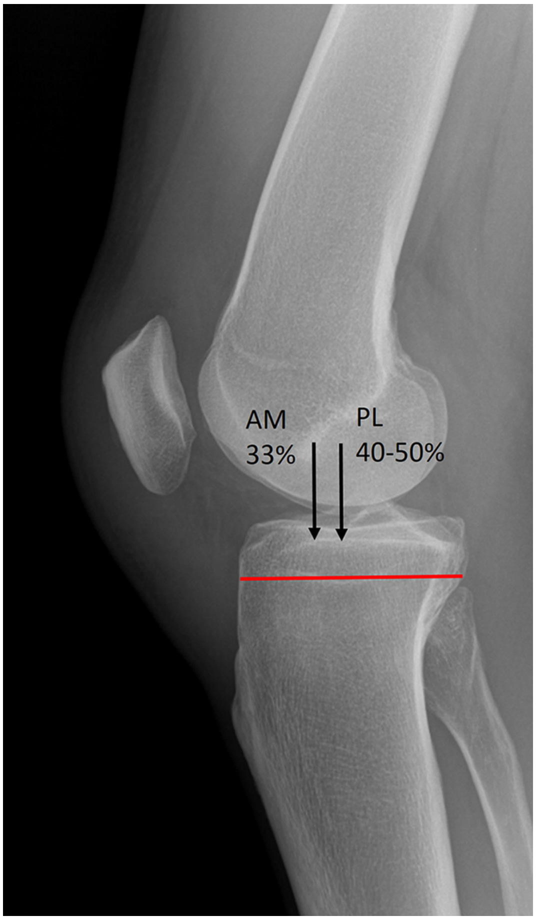

Figure 7 Lateral radiograph depicting the proximal tibial line of Jakob and Amis[30] parallel to the tibial joint surface. This can be a useful adjunct to traditional arthroscopic landmarks in order to evaluate the tibial tunnel position.

semitendinosus tendon using a variety of techniques, including the all-inside. This preserves the mechanical and proprioceptive function of the gracilis or makes it available for an extra-articular reconstruction, where required.

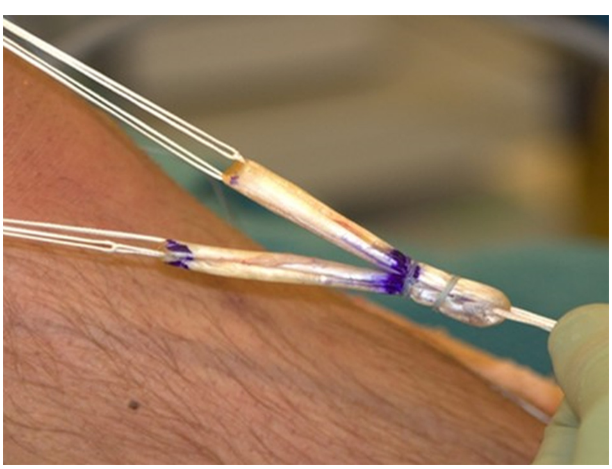

Figure 8 TriLink: a novel 3-socket anatomic double-bundle reconstruction using a single bifurcate hamstring tendon. Complete adjustable cortical suspensory fixation allows the differential tensioning patterns of a conventional double-bundle reconstruction whilst simplifying the technique with a single tibial socket.

The functional anisometry of the native ACL is well documented, with the majority of length change being dependent upon the position within the femoral footprint.[35] Evidence from cadaveric and clinical biomechanical studies has suggested improved kinematic restoration using DB–ACLR techniques. However, DB surgery is technically challenging, has a steep learning curve, can complicate future revision surgery and incurs greater cost.[36]

A novel 3-socket approach has been proposed for anatomic all-inside double-bundle reconstruction, using a single bifurcate hamstrings graft: the 'TriLInk' (TL) technique (Arthrex, Naples, Fl, USA) (Figure 8). Complete suspensory fixation enables differential tensioning of the AM and PL bundles on the femur, aiming to replicate native ACL behaviour. A single tibial socket simplifies the technique whilst conserving bone stock. The use of DB surgery is controversial, and current opinion amongst many is that given the potential difficulties, anatomic SB-ACLR is an adequate compromise. However, in high demand patients with large femoral footprints, the difference in rotational stability and control of the pivot-shift may be enhanced. In this demographic, TriLink may offer a better compromise by improving stability using a simplified technique. Early clinical results have been encouraging in a series of 21 patients, with a kinematic study in press.

Harvesting the quadriceps tendon has the advantage of producing a large graft with excellent biomechanical properties. Advances in minimally invasive techniques now enable adequate length and diameter of the quadriceps tendon to be harvested with a pleasing cosmetic result (Figure 9). Clinical outcomes are comparable to other autografts whilst post-operative anterior knee pain is similar to HS-ACLR.[37] The quadriceps tendon may be harvested with a patellar bone block, which can be complimented with an additional bone block harvested via use of a coring reamer to create the tibial tunnel.[38]

Allograft

The use of allografts has been popular in the US for many years for both primary and revision ACL surgery. Their use for primary ACLR is relatively uncommon in the UK, with the majority of surgeons restricting use to revision and complex multiligament reconstructions. The most commonly used allograft tendons are peroneus longus, tibialis posterior/anterior, tendo-Achilles and, less commonly, patellar tendon and hamstring tendons.

Inherent advantages of these grafts include no limit on number, size or shape. A large bone plug can be contoured to the specific shape required for a 'press-fit' fixation within the tunnel. Allografts require shorter operating time, exclude complications related to graft harvesting and donor site morbidity and are associated with less immediate post-operative pain, enabling faster mobilization and initial rehabilitation. This has obvious cost saving implications, which offsets the cost of the graft itself. Conversely, biological incorporation is slower, so rehabilitation may need to be modified in the medium-term.

For grafts harvested under the American Association of Tissue Bank's (AATB) guidelines, the potential for disease transmission still exists; however, the risk is now considered negligible. The potential for immunogenic reaction is also a concern to both patient and surgeon. Concerns also exist regarding the biomechanical properties of allografts following sterilization with gamma irradiation. Thanks to innovative non-irradiating

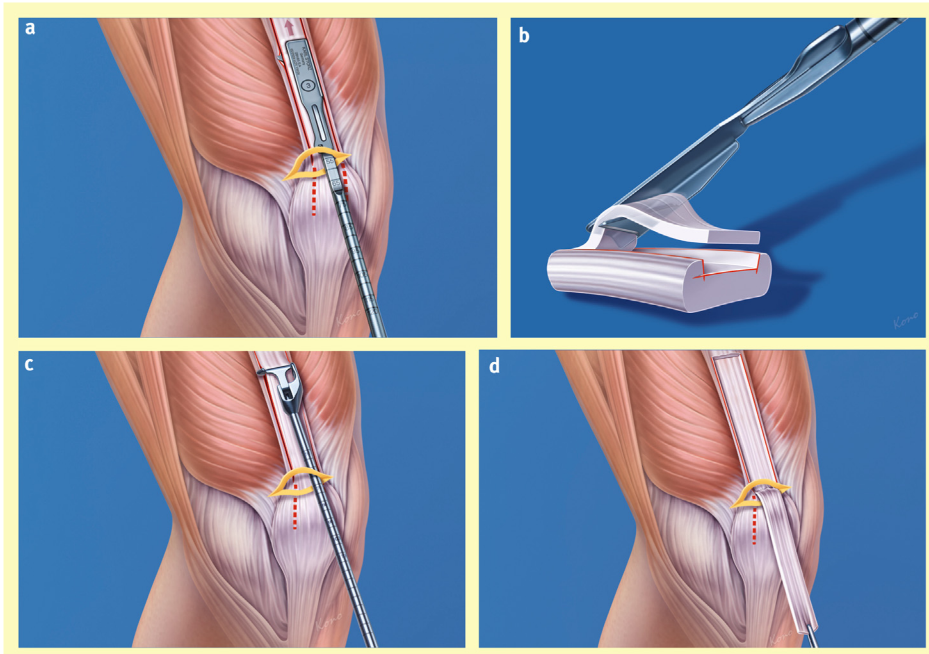

Figure 9 (**a**–**d**) Quadriceps Tendon Harvesting System (STORZ, Tuttlingen, Germany): a minimally invasive technique. (**a**) Sagittal cut, (**b**) coronal cut, (**c**) proximal cut and (**d**) removal of graft with or without bone block.

sterilization treatments, these concerns are largely historic. A recent meta-analysis compared auto- and allografts and showed no significant differences in laxity, PROMS data or failure rates.[39] The current practice for most surgeons is to use fresh frozen non-irradiated grafts.

Fixation

The optimal form of graft fixation in ACLR is one of the most investigated topics in sports medicine, with fixation dictating the mechanical properties of the graft during the critical early healing phase. Fixation must maintain graft position and tension until full biological integration within the socket has occurred. Fixation devices must be strong enough to avoid failure, stiff enough to restore stability and must allow graft incorporation. The rate of incorporation varies considerably depending upon the type of ACL graft. Animal models suggest 6 weeks for BPTB graft, 8–12 weeks for soft tissue autograft and up to 6 months for allograft.[40,41]

Bone-tendon-bone graft

High fixation strength is achieved using a variety of fixation methods, with interference compression screws being considered the gold standard. Screw diameter is important in cases of graft-tunnel mis-match, when a gap requires a larger screw.

Traditional metal screws have been largely superseded by biocomposite screws, which rapidly degrade whilst promoting bony ingrowth, graft incorporation and minimal MRI interference. Initial fixation strength is comparable to metal screws, without the need for removal in the context of revision.[42] However, these are not without their limitations, as concerns exist regarding screw breakage, migration into the joint, degradation induced inflammatory synovitis and graft slippage.

In an attempt to avoid interference with bone-graft healing, other fixation devices have been developed, with no difference reported in biomechanical comparisons with interference screws.[43] Transverse suspension such as Rigid-Fix (DePuy Mitek, Raynham, Ma) use cross pins to secure the bone plug. Transcondylar screws uses lateral compression of the bone plug against the medial tunnel wall.

Autologous bone from tunnel preparation can be used for 'press-fit' fixation on either the femur or the tibia. Likewise, a bulky bone block on an allograft can be contoured for this purpose. A recent study reported no difference in clinical outcome between 'press-fit' fixation and interference screws but there was a significant reduction in complication rate and tibial tunnel widening on MRI.[44]

Soft tissue graft fixation

An interference compression screw on both the femur and tibia has historically been the standard fixation. This provides an 'anatomic' fixation at the aperture of the bone-tunnel, reducing working graft length, potentially stiffening the construct and reducing the longitudinal 'bungee-cord' and 'windscreen-wiper' effect associated with 'non-anatomical' extra-articular fixation. However, cancellous bone is more susceptible to changes in bone mineral density, age, smoking and other co-morbidities when compared to cortical bone. Concerns about graft laceration, slippage and bio-integration have led to a great deal of innovation in terms of femoral fixation.

Cortical suspensory fixation is popular, with a variety of fixed length devices available, such as the EndoButton (Smith & Nephew, Andover, Ma) and RetroButton (Arthrex, Naples, Fl, USA). These consist of a metal button with a suture loop mounted on the anterolateral femoral cortex. This method is bone preserving as it only requires a small pilot hole through the cortex and allows greater bone-tendon interaction with circumferential contact promoting faster healing. Adjustable devices such as ToggleLoc (Biomet, Warsaw, Indiana) and

TightRope (Arthrex, Naples, Fl, USA) remove the need to calculate socket and graft-button length. With these suspensory fixation devices the ACL graft has been shown to lengthen after initial fixation and cycling of the knee.[45] Adjustable button loops enable independent tensioning on the femur so the graft can be re-tensioned following initial fixation and cycling. This ability enables the AM and PL bundles in DB surgery or with the 'TriLink' graft to be individually tensioned at 30° and 0° respectively.

Graft fixation on the tibia is often considered to be the weak link in any ACLR, as the graft axis is parallel to the applied force whilst it's bone mineral density (BMD) is considerably less than the distal femur. Although cortical bone is 30 times stronger than cancellous bone, clinical studies comparing cortical fixation alone with interference screws and expansion devices show no significant clinical differences.[46] In addition, the minimal soft tissue cover over the anteromedial tibia can lead to local skin irritation and pain. However, cortical devices are often used as secondary fixation on the tibia in high demand, osteoporotic or poorly compliant patients and in revision cases. Cortical devices include staples, sutures over posts and screws with spiked washers, such as WasherLoc (Biomet). Newer anchor devices such as SwiveLock (Arthrex, Naples, Fl, USA) can also be useful, especially in revision situations.

Animal studies have shown a higher ultimate load to failure and a reduced amount of cyclic displacement using expansion devices such as the Intrafix (DePuy, Mitek), whilst human cadaveric experiments support the use of interference screws over this device.[47] This may be due to the poorer quality of cadaveric cancellous bone. Unlike the femur, longer and wider screws (28–35 mm) have been shown to reduce slippage and increase ultimate failure when the head of the screw engages the tibial cortex.[48] With lower BMD, the general consensus is to use a screw diameter of 1 mm greater than that of the tibial tunnel. As with BPTB grafts, screw divergence of 15° or more significantly decreases fixation strength.[49]

Graft reinforcement and internal bracing

Historically, synthetic material has fallen out of favour due to particulate induced synovitis and failure. However, a third generation of ultra-high molecular weight polyethylene terephthalate products have seen widespread use in shoulder and ankle surgery. These are now being re-popularized to reinforce soft tissue reconstructions around the knee, promoting graft stability in the critical early healing phase whilst a similar strain pattern to the native ACL prevents stress-shielding. In the case of FiberTape, over 700 000 units have been sold (Arthrex Data), with only six (<0.001%) 'suture reactions' being reported to Medical Device Reporting (MDR — US Food and Drug Administration) and no synovitic or bone reactions reported.

FiberTape can be employed as an 'internal brace' to acutely repair the ACL, or more commonly the posterior cruciate ligament (PCL), following partial or complete rupture. Likewise, the medial collateral ligament (MCL), PCL or posterolateral corner (PLC) can be 'internally braced', sparing autograft for treatment of multi-ligament injuries. A small or inadvertently short semitendinosis can be reinforced/lengthened with FiberTape and fashioned into a GraftLink.[27]

ACLR and the anterolateral ligament

The biomechanical results presented by Claes et al. at the ISAKOS 2013 and ESSKA 2014 meetings have shown that selective sectioning of the ALL causes significant increases in internal rotation in both the ACL-deficient and ACL-intact knee.[50] Sectioning the AM and PL bundles did not result in a positive pivot shift on whole cadaveric knees. Subsequent sectioning of the ALL did cause significant rotatory instability in both the ACL-deficient and intact knee. Furthermore, sectioning of the ALL was vital to the occurrence of an IKDC grade III pivot-shift in the ACL-deficient knee, whilst cutting of the ACL alone produced only an IKDC grade I pivot shift in 40% of cases.

Historically, cases of chronic ACL deficiency with IKDC grade III pivot shift received extra-articular surgery in combination with intra-articular ACLR, with a significant increase in observed stability.[51] The senior author, working in collaboration with Stephen Claes and his team, have devised a minimally invasive anatomic reconstruction based on the anatomy proposed by Claes et al. A case series of over 50 patients (30 with >12-month follow-up) has produced encouraging early clinical results, with no detrimental outcomes observed when compared to the isolated ACLR series. The long-term results of such a series and further biomechanical testing are essential to determine the importance of this strategy.

The paediatric ACL

ACL rupture has been perceived as a relatively uncommon injury. With increased awareness, ACL tears have become increasingly recognized in children involved in competitive sports, accounting for 0.5–3% of all ACL injuries.[52]

Traditional management involves rehabilitation and activity modification followed by delayed reconstruction when skeletally mature, if still symptomatic. However, compliance with bracing and limitation of activity is a problem. The resultant chronic instability has a poor outcome, being associated with further meniscal and chondral injury in the active child.[53] Consequently, there has been a drive towards reconstruction of ACL injuries in children.

Consideration of the physis is critical when planning ACLR in children, as damage to this can result in growth abnormalities. The remaining expected growth at the physis can guide surgical choices. The Tanner staging is useful in predicting risk of growth disturbances. Tanner 3 and above have less chance of significant issues due to their reduced growth potential.[54]

It has been demonstrated that crossing the physis with an ACL drill will not cause disruption of growth if a single pass is performed relatively perpendicular to the axis of the physis. In this position, typically less than 3% of the physis is damaged, which is below the 7–9% threshold that can cause growth arrest.[55] The tibial tubercle apophysis must be avoided. If using inside-out drilling, the femoral socket or tunnel should not be anatomic, but in the 'classic' high and deep position to avoid obliquity whilst crossing the physis.

Within the mêlée of physeal concern, there are enthusiasts for all-epiphyseal techniques, where drilling is performed under strict image-guidance. This technique can either be performed using an outside-in or inside-out drilling method. Using the all-inside technique, the femoral physis, where the majority of

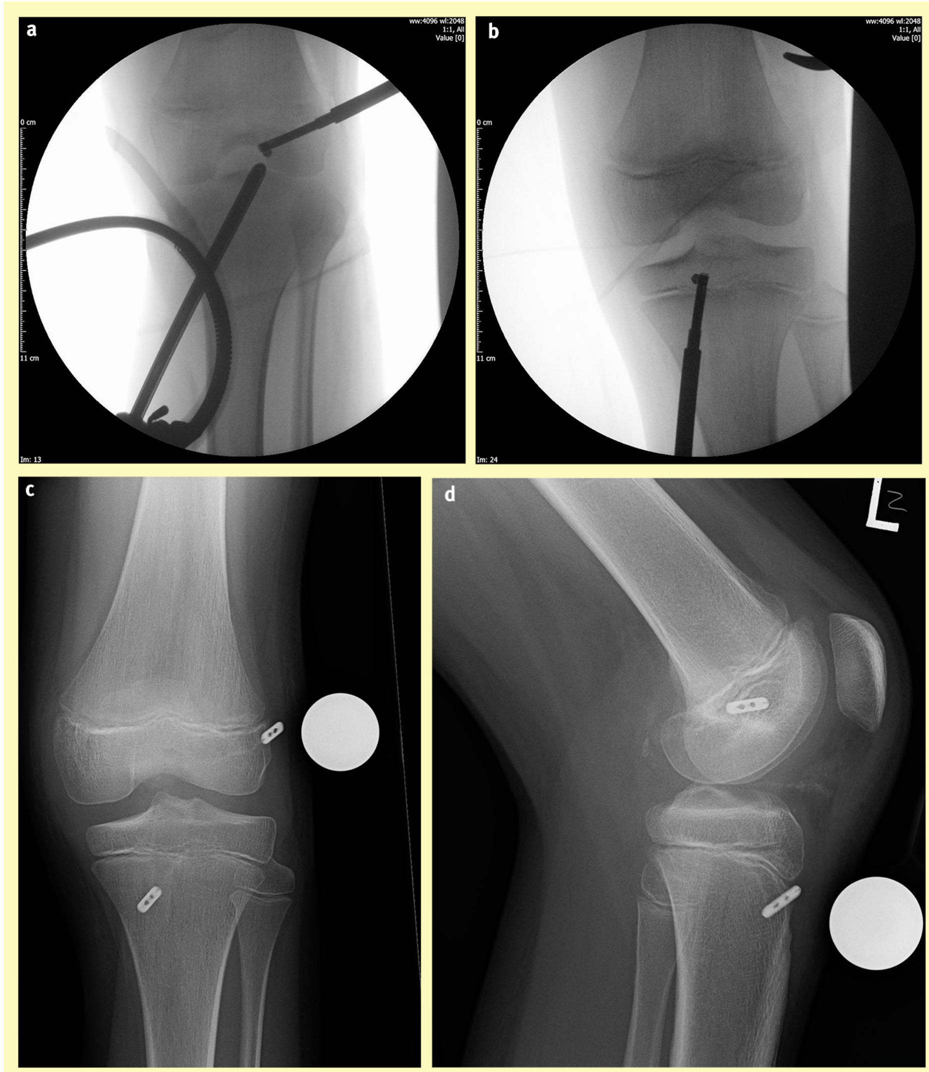

Figure 10 (**a**–**b**) Intra-operative AP radiographs of a physeal sparing all-inside ACL reconstruction in an 11 year old female. (**a**) All epiphyseal femoral retrosocket preparation. (**b**) Epiphyseal retrosocket creation in the tibia with a 3.5 mm pilot hole through the physis. (**c**–**d**) Post-operative AP (**c**) and lateral (**d**) radiographs of the same patient depicting cortical suspensory fixation and socket position.

growth occurs, is entirely spared (Figure 10). The tibial socket can be made all epiphyseal or trans-physeal where the pilot hole (3.5 mm) passes through the tibial physis in a vertical direction.

Hamstring grafts should be used, as bone blocks can cause a physeal bar and the harvest of any BTB autograft could potentially damage the tibial apophysis. Donated parental allograft is an alternative source; it reduces the child's morbidity and can be particularly useful where autogenous graft is of insufficient size. Goddard & Pinczewski reported a case series of 32 skeletally immature patients (mean age 13 years) who received parental-graft transphyseal ACLR. Of the 29 followed-up at 2 years, 28 patients (97%) had a normal or nearly normal IKDC ligament grade, 28 said they would undergo the same procedure again under the same circumstances and there were no cases of limb malalignment.[56]

Conclusion

The treatment of ACL injury has evolved considerably since Galway et al. first described the pivot-shift test and Girgis et al. related anatomy to function. ACLR techniques have advanced, but the principles remain the same. A greater understanding of knee anatomy and biomechanics is central to improving long-term outcomes following ACLR. Despite a vast amount of research and innovation, there are a number of exciting new prospects in ACLR today.

Adhering to the 'anatomic' philosophy and new remnant preserving techniques may allow ACL repair or enhance graft biology. Acute repair and physeal sparing techniques have removed the stigma of ACLR in the skeletally immature, reducing the risk of secondary injury, with the possibility of parental donation reducing morbidity for the child. Minimally invasive ACLR techniques reduce morbidity and preserve soft tissue. Non-irradiated allografts and advances in synthetic materials offer greater graft choice, especially in revision cases or multi-ligament injuries. Finally, evidence strongly suggests that the ALL not only exists, but that it also has a defined effect on the rotational stability of the knee. It can be imaged on ultrasonography and this, in addition to clinical examination, opens the possibility of identifying ALL injury in the outpatient setting. Early results combining this approach are encouraging, but studies with longer follow-up are required to assess the clinical importance of this management strategy. ◆

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