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Anatomic anterior cruciate ligament reconstruction: a changing paradigm

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Abstract Injury to the anterior cruciate ligament (ACL) of the knee is potentially devastating for the patient and can result in both acute and long-term clinical problems. Consequently, the ACL has always been and continues to be of great interest to orthopaedic scientists and clinicians worldwide. Major advancements in ACL surgery have been made in the past few years. ACL reconstruction has shifted from an open to arthroscopic procedure, in which a two- and later one-incision technique was applied. Studies have found that traditional, transtibial arthroscopic single-bundle reconstruction does not fully restore rotational stability of the knee joint, and as such, a more anatomic approach to ACL reconstruction has emerged. The goal of *anatomic* ACL reconstruction is to replicate the knee's normal anatomy and restore its normal kinematics, all while protecting long-term knee health. This manuscript describes the research that has changed the paradigm of ACL reconstruction from traditional techniques to present day anatomic and individualized concepts.

Keywords Anatomic · ACL · Anterior cruciate ligament · Paradigm

Introduction

Anterior cruciate ligament (ACL) rupture is one of the most frequent orthopaedic sports-related injuries, with a yearly incidence of 35 per 100,000 people [11]. An ACL injury can be devastating, particularly for a young athlete where high-level participation in strenuous sports is often not possible without surgical reconstruction of the ACL. Furthermore, the long-term development of knee osteoarthritis (OA) is common. One particular study with 12-year follow-up after ACL reconstruction showed that 50 % of patients had developed radiographic OA. These individuals had a mean age of only 31 years at follow-up [26, 28]; at this age, there are no good treatment options for a symptomatic osteoarthritic knee. It is therefore important to develop new approaches to reconstruct the ACL, aiming to maintain both long-term knee health and quality of life.

Historically, ACL reconstruction was performed via an arthrotomy, with the goal being to reproduce the native anatomy of the ACL. However, as with most modern surgery, minimally invasive surgical techniques were introduced for the knee, which subsequently led to the development of arthroscopically assisted ACL reconstruction. Arthroscopic ACL reconstruction was first performed using a two-incision technique, in which the femoral bone tunnel was drilled from the outside-in. Over time, a one-incision technique was adopted, where the femoral bone tunnel was drilled from the inside-out, through the tibial tunnel [13]. Both techniques were fast and efficient; unfortunately, neither consistently reproduced the native ACL anatomy.

Recognizing the problem

In the early 1990s, surgeons rapidly adopted the new, minimally invasive arthroscopic techniques. However, the major advancements made with the introduction of arthroscopic ACL surgery were associated with new problems, including the loss of knee range of motion [12], as well as

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impingement of the ACL graft [18–20]. In addition, as the number of primary ACL reconstructions increased, so too did the number of failed ACL reconstructions, resulting in an increased number of revision ACL surgeries [21].

Revisiting the anatomy

Although ACL anatomy was described in detail as early as 1836 by Weber and Weber [45], most early ACL reconstruction techniques did not accurately reproduce this native anatomy. For example, the Weber brothers described two functional bundles of the ACL, but techniques to reconstruct the ACL restored only one bundle. It was not until 1982 that Mott [31] described and published an open method to reconstruct both bundles of the ACL. In 1994, Rosenberg described an arthroscopic method for double-bundle ACL reconstruction, a procedure which was then popularized in Japan by Yasuda et al. [47] and Muneta et al. [32] in the late 1990s. The efforts of these leaders in the field allowed others to take a more critical look at ACL anatomy and subsequent reconstruction.

This critical evaluation of ACL anatomy began with careful anatomic dissection, during which it was confirmed that the location of the ligament had indeed been accurately reported by Weber and Weber [45]. In a study of 40 intact knee joints of 16–20-week-old human foetuses, the gross anatomy of the ACL was inspected under a stereomicroscope. The two bundles of the ACL, the anteromedial (AM) and posterolateral (PL) bundles, were divided by a well-defined septum and covered by a membrane, demonstrating that the two-bundle anatomy is already present during the foetal stage of life [7] (Figs. 1, 2). In a more recent study on the ACL in the foetal and adult knee, this septum was found to contain a population of vascular-derived stem cells, which may contribute to ligament regeneration and repair at the site of rupture, as well as to ligament strength [29]. Anatomic studies on adult cadaveric knees found that the apparent orientation of the two-bundle anatomy changed with different degrees of knee flexion [35, 49]. As a result, arthroscopic ACL reconstruction is now typically performed with the knee in 90° of flexion, rather than in full extension.

Traditional ACL reconstruction techniques were based on the assumption that all ACLs are of similar size and have the same distance to other anatomic structures, such as the posterior cruciate ligament and menisci. However, a recent study demonstrated that there is substantial variation in the size and shape of the ACL insertion site [25]. In 137 patients undergoing ACL reconstruction during the first 6 months after injury, the femoral and tibial ACL insertion sites were identified, marked with electrocautery, and measured with an arthroscopic ruler. The maximum width of the ACL insertion sites varied considerably, ranging from 12 to 22 mm [25].

To further characterize insertion site anatomy, a study was conducted to visualize and quantify the position of anatomically placed tunnels for AM and PL grafts [8]. Careful arthroscopic dissection and drilling of the tunnels for anatomic double-bundle ACL reconstruction were performed

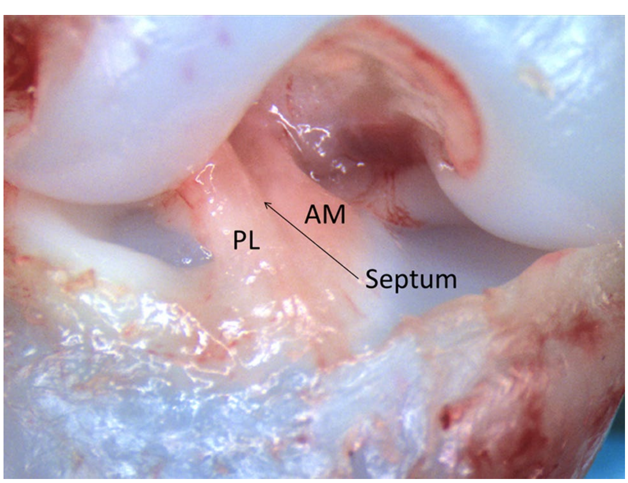

Fig. 1 Dissection of a right knee of a foetus showing that the ACL already has 2 bundles which are covered by a membrane and separated by a septum

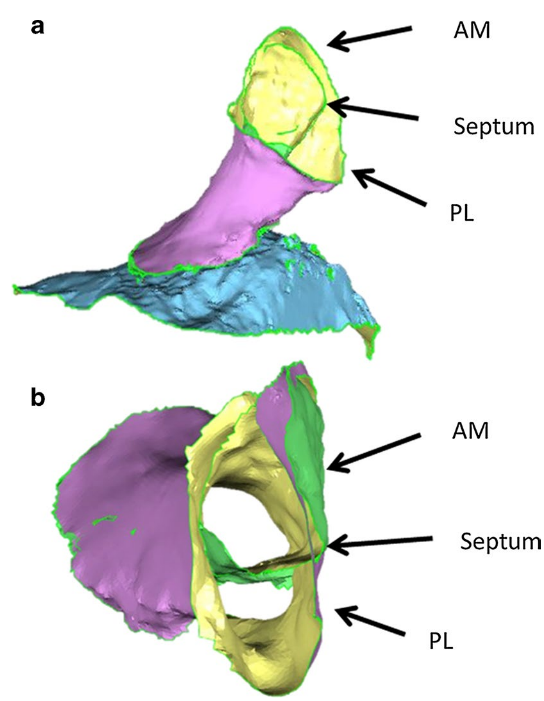

Fig. 2 3D laser scan of the ACL showing the 2 bundle anatomy as well as the membrane covering the two bundles (purple) and the septum separating them

using topographical landmarks in eight cadaver knees. CT scans were performed on each knee, and three-dimensional (3D) models were created and aligned into a 3D anatomic coordinate system. The centres of the tunnel apertures for the AM and PL tunnels were precisely mapped and objectively described. On the tibial side, the locations of the insertion sites were described as a percentage of the anterior-to-posterior and medial-to-lateral dimensions. On the femoral side, the insertion sites' location was described as a percentage of the distance both parallel and perpendicular to Blumensaat's line (Table 1). This cadaveric study provided some of the first reference data for comparing tunnel positions to native ACL insertion sites.

While it has been hypothesized that *traditional* single-bundle ACL reconstruction leads to non-anatomic tunnel positions, previous studies generally lacked objective data for assessing graft placement. In the second phase of the cadaveric study described above, 3D CT models were created to visualize and quantify the positions of femoral and tibial tunnels in 32 patients who underwent *traditional transtibial* single-bundle ACL reconstruction. Tunnel positions were compared to reference data on anatomic graft placement, using anatomically based coordinate systems derived from the CT bone models [22]. With the traditional transtibial arthroscopic ACL reconstruction technique, tibial tunnels were consistently positioned medial to the anatomic PL position (Table 2) and femoral tunnels were positioned anterior to both the AM and PL anatomic tunnel locations. This study was the first to demonstrate that transtibial ACL reconstruction fails to accurately place the femoral and tibial tunnels within the native ACL insertion sites [22, 23].

Table 1 Native ACL footprint location

	Native tibial footprint position		Native Femoral Footprint position	
	Anterior–posterior (%)	Medial–lateral (%)	Parallel to Blumensaat's line (%)	Perpendicular to Blumensaat's line (%)
AM	25.0	50.5	21.7	33.2
PL	46.4	52.4	35.1	55.3

Table 2 Tunnel locations of traditional compared to anatomic ACL reconstruction

	Transtibial (%)	Anatomic AM (%)	Anatomic PL (%)
Femoral			
Posterior–anterior	54.3 ± 8.3	23.1 ± 6.1	15.3 ± 4.8
Proximal–distal	41.1 ± 10.3	28.2 ± 5.4	58.1 ± 7.1
Tibial			
Anterior–posterior	48.0 ± 5.5	25.0 ± 2.8	46.4 ± 3.7
Medial–lateral	47.8 ± 2.4	50.5 ± 4.2	52.4 ± 2.5

Several landmarks have been identified that can aid the surgeon in placing the ACL femoral tunnels anatomically. The lateral intercondylar ridge was identified previously by Clancy as the most anterior border of the ACL insertion site on the femur [16]. More recently, the lateral bifurcate ridge was identified, which separates the AM and PL bundle insertion sites on the femur [6]. These ridges are both fundamental in placing the femoral tunnel(s) for ACL reconstruction in the anatomic footprint [9]. Our study showed that these ridges persist even in chronic ACL injuries, thereby confirming them as reliable landmarks in most cases, even when the soft tissue remnants of the chronically disrupted ACL are no longer apparent [42].

Two-bundle anatomy and knee function

To explore the two-bundle anatomy and function of the ACL, a cadaver study was conducted to determine the lengths and in situ loads of each bundle by combining kinematic data from the intact knee and load–length curves of the isolated ACL. These results demonstrated that load distribution within the ligament changes as a function of the knee flexion angle [37]. Unlike previous studies, this new robotic approach did not require surgical intervention, the attachment of mechanical devices to or near the ACL, and/or prior assumptions about the direction of in situ force. This study further demonstrated the functional differences between the AM and PL bundles of the ACL: the magnitude of the in situ force in the PL bundle was significantly affected by the knee flexion angle, whereas the magnitude of the in situ force in the AM bundle remained relatively constant [33]. These findings have provided valuable guidance for selecting knee flexion angles when tensioning one or two bundles during graft fixation.

These studies were the first to suggest that, for the ACL graft to reproduce the in situ forces of the native ACL, reconstruction techniques should take into account the roles of both bundles. Consequently, a study was initiated to determine whether reconstructing both bundles of the ACL would be more effective for restoring ACL-intact knee kinematics. A robotic cadaveric study was performed, in which knees were subjected to anterior tibial and combined rotatory loads. Knee kinematics and in situ force in the ACL and replacement graft were determined for intact, ACL deficient, single-bundle reconstructed and anatomic double-bundle reconstructed knees. Anterior tibial translation for the anatomic double-bundle reconstruction was significantly closer to that of the intact knee than the single-bundle reconstruction. Moreover, with a combined rotatory load, the in situ forces in the double-bundle reconstructed ACL more closely approximated that of the normal knee [46].

A follow-up study compared knee contact mechanics between single- and double-bundle ACL reconstruction and the native ACL. Contact area and pressure after double-bundle reconstruction were similar to those measured with the native ACL, whereas single-bundle reconstruction resulted in decreased cartilage contact area and increased joint contact pressure [38, 39, 48]. This finding is particularly significant, as increased joint pressure can lead to cartilage damage. Thus, double-bundle reconstruction may be advantageous for reducing the risk of osteoarthritis (OA) after ACL injury.

In addition to the number of bundles, the positioning of the bundles also plays an important role for restoring normal knee stability [24]. In a study comparing various positions of the femoral ACL tunnel, tunnel positions closest to the native femoral footprint were most effective for resisting rotatory loads [27].

Clinical application of anatomic ACL reconstruction

In order to assess the range of surgical techniques for ACL reconstruction, a systematic literature review was performed to identify all studies that described the technique for "anatomic double-bundle ACL reconstruction". Seventy-four studies were included in this review. The described surgical techniques for anatomic double-bundle ACL reconstruction varied widely, clearly delineating the lack of evidence and consensus on the most effective methods for anatomic ACL reconstruction [44].

With the increasing number of ACL reconstructions being performed, failures after ACL surgery are more common, leading to greater interest in the possible influence of surgical technique and patient-specific factors on failure risk. A recent study aimed to determine the failure rate and factors associated with graft failure after anatomic ACL reconstruction performed with allograft. Graft failure was defined as patient-reported instability, pathological laxity during physical examination, or evidence of a failed graft on magnetic resonance imaging or during arthroscopy. There were 206 subjects included in this study: 168 double-bundle and 38 single-bundle reconstructions. Overall, 27 (13 %) subjects experienced graft failure, of which 23 (14 %) were double-bundle. The characteristics associated with double-bundle graft failure were younger age (19 vs. 25 years, $P < 0.001$) and an earlier return to sports (after 222 vs. 267 days, $P = 0.007$). By comparison, 4 (11 %) single-bundle grafts failed. The characteristics associated with single-bundle graft failure were younger age (19 vs. 24 years, $P = 0.049$) and increased body mass (83 vs. 65 kg, $P = 0.031$). This study clearly showed that the failure rate after ACL reconstruction with *allograft* was as high as 13 % and that, depending on the technique utilized, a younger age, earlier return to sports and a higher body mass were associated with graft failure [43].

A caprine animal model for ACL healing

ACL grafts undergo extensive remodelling after implantation, resulting in early loss of graft strength and stiffness [2]. Various strategies have been suggested for improving the rate of graft healing, with the goal of reducing incidence of early graft failures. In an ongoing study, a caprine model was used to examine the effect of a fibrin clot on ACL graft healing. Eight Spanish boar goats underwent double-bundle reconstruction on the right hind limb utilizing an Achilles tendon autograft technique, while the left hind limb was observed as a normal control. Four goats underwent double-bundle reconstruction utilizing an autologous fibrin clot, and four goats underwent standard double-bundle reconstruction without fibrin clot. Animals were euthanized at 12 weeks and underwent 3T MRI for evaluation of graft signal intensity. Specimens were then cryo-sectioned and analysed by routine histological staining. Though the morphology and microstructure of the native caprine ACL was not achieved in either group by 12 weeks after surgery, haematoxylin and eosin (H&E) staining revealed consistently more organized and ligamentous-appearing tissue in those that underwent reconstruction with the fibrin clot. There was also a more pronounced septum between the AM and PL bundles in the fibrin clot group. The mean ligament tissue maturity index score was significantly higher for those that had a fibrin clot (15 ± 2.3) compared to those that did not (7.75 ± 5.19) ($P < 0.05$). On MRI, the signal intensity for the AM bundle was 1.1 ± 0.71 for those with a fibrin clot and 3.07 ± 1.76 for those without a fibrin clot (n.s.). The mean signal intensity for the PL bundle was significantly lower for the fibrin clot group (1.13 ± 0.68) compared to the no fibrin clot group (3.68 ± 1.34) ($P < 0.05$). This new study suggests that the addition of a fibrin clot results in improved ligamentous tissue maturity at early time points after double-bundle ACL reconstruction in a caprine model.

Clinical trials

There is convincing evidence that conventional, non-anatomic single-bundle ACL reconstruction fails to restore normal knee kinematics and leads to altered patterns of joint loading [38]. Although clinical studies have shown better joint laxity measurements with double-bundle

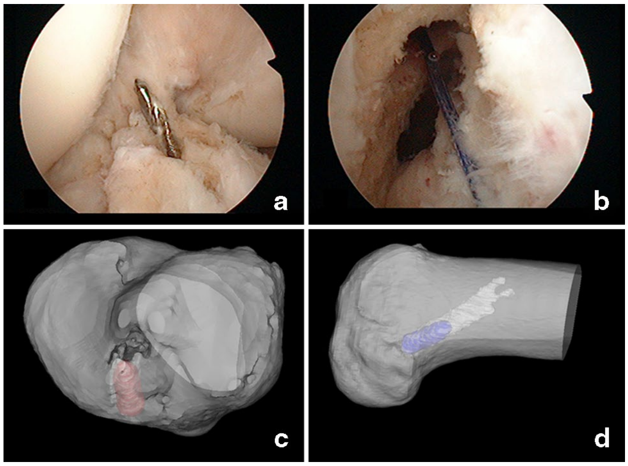

Fig. 3 Conventional single-bundle ACL reconstruction in a right knee. **a** The tibial tunnel is located in the PL bundle insertion site (arthroscopic view). The femoral tunnel is located at the high-AM position, above the native ACL insertion site (arthroscopic view). **c** and **d**. Tibial and femoral tunnel position on corresponding 3D CT scan

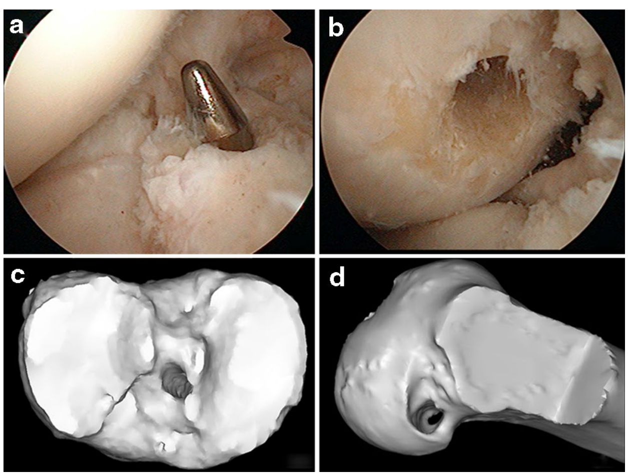

Fig. 4 Anatomic single-bundle ACL reconstruction in a right knee. **a** The tibial tunnel is located in the centre of the native ACL insertion site (arthroscopic view). **b** The femoral tunnel is located in the centre of the femoral insertion site (arthroscopic view). **c** and **d** Tibial and femoral tunnel position on corresponding 3D CT scan

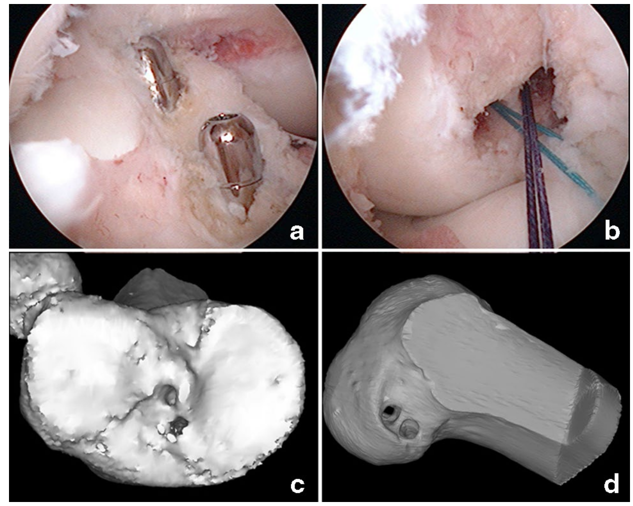

Fig. 5 Anatomic double-bundle ACL reconstruction in a right knee. **a** The tibial AM tunnel is located in the native tibial AM bundle insertion site and the tibial PL tunnel in the native tibial PL bundle insertion site (arthroscopic view). **b** The femoral AM tunnel is located in the native femoral AM bundle insertion site and the femoral PL tunnel in the native femoral PL bundle insertion site (arthroscopic view). **c** and **d** Tibial and femoral tunnel positions on corresponding 3D CT scan

reconstruction, it remained unclear if this effect is due to the addition of a second bundle or due to the more anatomic positioning of those bundles. A level I randomized clinical trial was performed to compare the clinical outcomes of three different ACL reconstruction techniques. Three-hundred and twenty patients were randomized into three groups: conventional single-bundle (Fig. 3), anatomic single-bundle (Fig. 4) and anatomic double-bundle reconstruction (Fig. 5). The average follow-up was 51 months (range 39–63 months), at which time 281 patients (88 %) were available for evaluation. Anatomic single-bundle reconstruction resulted in less anteroposterior and rotational laxity than conventional single-bundle reconstruction (average side-to-side difference for anterior tibial translation was 1.6 mm in the anatomic group versus 2.0 mm in the conventional group, $P = 0.002$; negative pivot shift was 66.7 versus 41.7 %, $P = 0.003$). In other parameters, the differences between groups were not statistically significant. The results of the anatomic double-bundle group were also superior to those of the anatomic single-bundle group for anteroposterior and rotational laxity (average side-to-side difference for anterior tibial translation was 1.2 mm in the double-bundle group versus 1.6 mm in the single-bundle group, $P = 0.002$; normal pivot shift was 93.1 versus 66.7 %, respectively, $P < 0.001$), and range of motion was also significantly better ($P = 0.005$). The Lysholm scores were 90.9, 91.8, and 93.0 in the conventional single-bundle, anatomic single-bundle, and anatomic double-bundle groups, respectively. The difference was only significant when anatomic double-bundle group was compared to conventional single-bundle group ($P = 0.025$). The IKDC Subjective Knee Form scores were 90.2, 90.6, and 92.1 in the conventional single-bundle, anatomic single-bundle, and anatomic double-bundle groups, respectively, which were not significantly different. This study demonstrated that anatomic single- and anatomic double-bundle ACL reconstructions are superior in terms of laxity, in contrast to conventional single-bundle ACL reconstruction [15].

In a follow-up study, it was hypothesized that there is no difference between the results of anatomic single-bundle and anatomic double-bundle reconstruction when the surgical technique is individualized with respect to the size of the ACL. Depending on intra-operative measurements of the ACL insertion site size, patients were selected for either single-bundle (<16 mm, $n = 32$) or double-bundle (>16 mm, $n = 69$) ACL reconstruction. The average follow-up was 30 months (range 26–34 months). There were no significant differences between the double- and single-bundle groups for the Lysholm score (93.9 vs. 93.5), IKDC Subjective Knee Form scores (93.3 vs. 93.1), anterior tibial translation (1.5- vs. 1.6-mm side-to-side difference), and pivot shift (92 vs. 90 % with normal pivot-shift examination). It was concluded that anatomic double-bundle reconstruction is not superior to anatomic single-bundle reconstruction when an individualized ACL reconstruction technique is used.

Recently, the National Institute of Arthritis and Musculoskeletal and Skin Diseases have provided funding for a prospective randomized double-blind clinical trial that compares anatomic single-bundle and anatomic double-bundle ACL reconstruction. The specific aims of this study are to determine whether anatomic double-bundle ACL reconstruction is better than anatomic single-bundle ACL reconstruction in terms of dynamic knee function and clinical outcomes. Fifty-seven subjects with an ACL injury involving both bundles of the ACL who participate in level I or II sports activities have been recruited and randomized to either anatomic single- or anatomic double-bundle ACL reconstruction. Knee joint kinematics and cartilage surface interactions during walking and running tasks are being measured 6 and 24 months after surgery using a unique combination of high-speed biplane radiography (for accurate assessment of knee kinematics) and three-dimensional imaging (MRI and CT), to define joint and cartilage morphology. Clinical outcomes are measured 3, 6, 12, and 24 months after surgery and include laxity, range of motion, and patient-reported symptoms, activity, and participation. Successful completion of this study will provide evidence of the efficacy of anatomic double-bundle ACL reconstruction for restoring normal knee mechanics and improving clinical outcomes. If the results show a clear benefit of this procedure, then a sound basis will have been established for future studies to assess the benefits of anatomic double-bundle ACL reconstruction for long-term clinical outcomes and joint health. This trial is the first of its kind and is the only trial comparing anatomic single-bundle to anatomic double-bundle reconstruction for a pre-defined ACL insertion site size range [14].

Meta-analysis

Recently, a meta-analysis of 12 studies was conducted to determine the degree to which SB and DB reconstruction restore anterior and rotational laxity, as well as ROM. There was a statistically significant difference in favour of double-bundle reconstruction for both anterior knee joint laxity (KT arthrometer difference −0.6 mm, 64 % risk reduction of positive Lachman) and the pivot-shift test (69 % risk reduction of positive shift). However, there were no significant differences between single-bundle and double-bundle reconstruction for the subgroup with non-anatomic reconstructions. Moreover, there was a 2.6 times risk increase in extension deficit with non-anatomic double-bundle reconstruction in comparison with non-anatomic single-bundle reconstruction. This may indicate that in the non-anatomic double-bundle group, the increased graft size combined with the non-anatomic positioning of the grafts leads to overcrowding of the notch, thereby resulting in impingement [41]. A more recent meta-analysis did find a better outcome for anatomic double-bundle reconstruction as compared to anatomic single-bundle reconstruction [5].

Imaging of the two-bundle anatomy, pre- and post-operatively

Advances in magnetic resonance imaging (MRI) have contributed to our understanding of ACL anatomy and provided new tools for pre- and post-operative assessment. Recent MRI protocols have been developed to distinguish both bundles [1, 3]. In a cadaveric study, the double-bundle structure of the ACL was mapped using 3-T ultra-high-field strength MRI, which allows faster imaging times, increased resolution and increased signal-to-noise ratio [36]. Using oblique sagittal and oblique coronal planes, it was possible to distinguish the double-bundle structure of the ACL in each knee. Further imaging studies focused on the diagnosis of one-bundle ruptures of the ACL, as well as the imaging of condition of the cartilage [4]. The ability to detect partial ACL injuries can facilitate surgical planning to augment the intact bundle rather than reconstructing the entire ACL (Fig. 6).

More recently, MRI studies have involved measuring the ACL insertion site size, length, and inclination angle (the sagittal-plane angle between the ACL and long axis of the leg with the knee in full extension) for pre-operative planning and post-operative evaluation [17] (Fig. 7c). To determine the clinical relevance of the inclination angle, MRI images were obtained from 12 intact cadaveric knees. The cadaveric knees were then subjected to loading in a robotic system. ACL reconstruction was then performed with an anatomically located tibial tunnel with three different locations of the femoral tunnel: (1) centre of the femoral

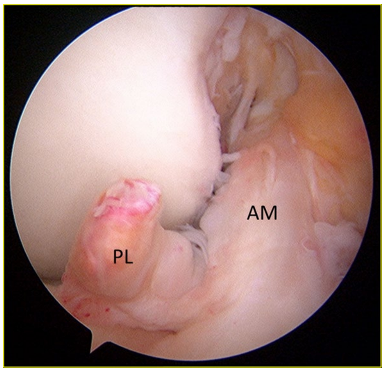

Fig. 6 Arthroscopic picture of a right knee showing an isolated *PL* bundle tear, while the *AM* bundle remains intact

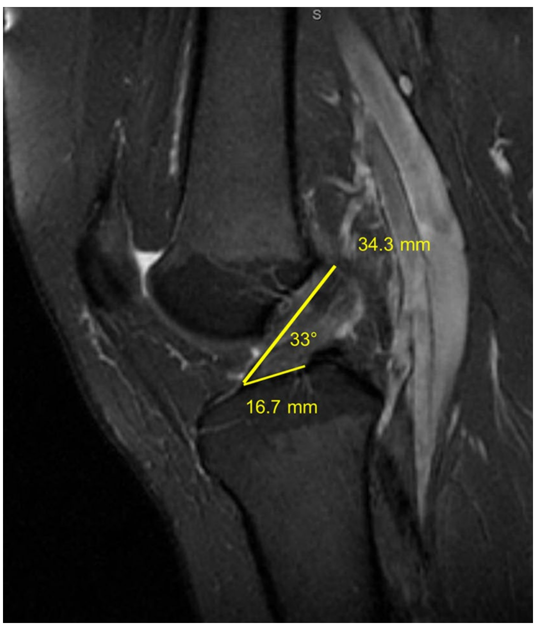

Fig. 7 MRI of a right knee showing the various measurements of the ACL that can be performed such as the insertion site size (16.7 mm), ACL length (34.3 mm), and inclination angle (33°)

insertion site (MID); (2) "high" femoral tunnel (S1); and (3) "higher" femoral tunnel (S2). A negative correlation was found between inclination angle and in situ force for all degrees of knee flexion under pivot shift loads and at 0° and 15° of flexion under anterior load. It was concluded that more anatomic ACL reconstructions (with lower graft inclination angles) resulted in higher in situ forces on the graft than non-anatomic reconstruction. While this may provide more natural load transmission in the knee (potentially protecting other structures, such as the meniscus and cartilage), it could contribute to early graft failure if individuals participate in strenuous activities prior to adequate graft healing.

From a 'Technique' to a 'Concept'

As knowledge on the anatomy and function of the ACL has improved, anatomic double-bundle reconstruction has grown from a technique to a concept aiming to restore ACL anatomy as closely as possible to the native knee. This concept is applicable to all methods of ACL surgery: single-bundle, double-bundle and one-bundle reconstruction (only the AM or PL bundle is reconstructed), as well as primary and revision surgeries [34]. To apply this concept universally, a rigorous, validated system is necessary to evaluate how "anatomic" a particular surgical procedure may be. The *Anatomic ACL Reconstruction Scoring System* has been developed by an international collaboration among key ACL thought leaders around the world. This scoring system was designed to grade ACL reconstruction procedures for individual patients, for comparative evaluation of the description of surgical methods in published studies on anatomic single- and anatomic double-bundle ACL reconstruction, and to enhance peer review of such papers. The scoring system uses 17 items that were determined to be primary indicators of the degree of "anatomic" ACL reconstruction by 32 experts in the field of ACL surgery and 329 experienced journal reviewers. The system was recently tested and found to be both reliable and valid with good internal consistency of the included items [40].

Return to sports

Return to sports (RTS) is a primary goal for ACL reconstruction, particularly among young active individuals and athletes. While there is a general perception that ACL reconstruction successfully enables most athletes to return to their sport of choice, the reality may be quite different; recent studies indicate that as few as 45 % of patients actually return to their pre-injury level of sports participation. We evaluated return to pre-injury level of sports participation after ACL reconstruction using a strict, comprehensive definition for RTS. Participants who were 1–5 years after ACL reconstruction completed a survey to determine their pre-and post-surgery sports activity levels. Comprehensive return to pre-injury level of sports (comprehensive RTS) was operationally defined as returning to the same type and frequency of sports and same Marx Activity Score as before injury. Patients also answered a global question on whether they had returned to their pre-injury level of sports (global RTS). The IKDC Subjective Knee Form was used to compare symptoms and function between patients who did and did not meet comprehensive RTS criteria. One hundred sixty eight participants (mean age, 28.8 ± 10.9 years) completed the survey. Using comprehensive RTS criteria, 69 (41.1 %) participants returned to their pre-injury level of sports. Based on the global RTS, 79 (47 %) reported they had returned to their pre-injury level of sports. Fifty nine (74.7 %) of the 79 individuals that reported global RTS met the comprehensive RTS criteria. Patients who met the comprehensive RTS criteria had fewer symptoms and better function based on the IKDC Subjective Knee Form than those who did not (87.5 ± 10.6 vs. 80.1 ± 13.7, $P < 0.001$). Of the 93 patients who did not meet comprehensive RTS criteria, 46 (49.5 %) did not return because of fear of re-injury, 32 (34.4 %) due to ongoing problems with their knee, 31 (31.3 %) lacked confidence in the knee, 20 (21.5 %) had conflicting work or family obligations, and 6 (6.5 %) were no longer eligible for participation in competitive sports. It was concluded that RTS is more common if based on a global RTS question than if measured by strict comprehensive criteria that combine return to the same type and frequency of sports and the Marx Activity Score. Patients who do not meet comprehensive RTS criteria demonstrate poorer function than those that do. A global rating of RTS may overestimate the true RTS rate by 25 %. Fear of re-injury, ongoing knee problems, and lack of confidence play a greater role in preventing RTS than lifestyle changes. These issues need to be addressed to improve RTS after ACL reconstruction.

Conclusion

In conclusion, anatomic anterior cruciate ligament (ACL) reconstruction has changed the paradigm of traditional ACL surgery. ACL reconstruction was traditionally based on standardized techniques that neglected the individual anatomy of the patient. In this manuscript, we have attempted to summarize a large body of research addressing ACL anatomy, function, biomechanics and imaging, and the implications of this work for our primary goal of improving medical care and outcomes for individuals who suffer an ACL injury. The combination of high-quality studies and the use of precise outcome measures has led to the advances in anatomic ACL reconstruction that have been made over the past several years. When arthroscopic ACL reconstruction was pioneered, 100 % of surgeons used a non-anatomic, transtibial drilling technique. A survey at a recent international meeting revealed that nearly 70 % of the surgeons utilize the anterior medial (AM) portal to drill the femoral tunnel. 22 % used both the AM portal technique and the transtibial technique to drill the femoral tunnel depending on whether or not anatomic tunnel placement can be achieved with the transtibial technique. No surgeon used *only* the transtibial drilling technique [30]. This is a significant change in the right direction, but we need to continue to modify our methods to anatomically reconstruct the ACL as more information about structure and function of the ACL becomes available. It is a long and continuing journey to be anatomic [10].

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