Anatomic Double-Bundle Anterior Cruciate Ligament Reconstruction

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Summary: A review of the literature suggests that a significant number of patients undergoing anterior cruciate ligament (ACL) reconstruction continue to suffer residual pain and instability after surgery. Consequently, there remains considerable room for improvement in surgical ACL reconstruction. Anatomically, the ACL can be divided into 2 major functional bundles, the anteromedial and the posterolateral bundle. Biomechanical studies have shown that both bundles play important roles in providing anterior and rotational stability of the knee. In particular, it has been demonstrated that biomechanically, anatomic double-bundle ACL reconstruction results in a better restoration of the rotational stability of the knee joint. We suggest that anatomic ACL double-bundle reconstruction may result in a better restoration of the in vivo kinematics of the knee joint and can improve the clinical outcomes in ACL surgery. Currently, our preferred surgical technique uses 2 separate tibial and femoral tunnels using 2 tibialis anterior or tibialis posterior tendon allografts. Future clinical studies are necessary to evaluate the long-term functional outcomes after anatomic ACL double-bundle reconstruction. Key Words: ACL—Double-bundle—Anatomy—ACL technique—Rotational stability.

Approximately 250,000 anterior cruciate ligament (ACL) tears occur yearly in the United States. Over the past 2 decades, ACL reconstruction techniques have been improved, and surgical ACL reconstruction provides reproducibly satisfactory results in the majority of patients. However, recently published long-term outcome studies have shown that less than 50% of the patients return to their previous level of activity and more than 90% of the patients demonstrate degenerative changes on radiographs at 7 years after ACL reconstruction. These data suggest that there is still room for improvement of current treatment protocols and reconstruction techniques.

The optimal placement of the femoral and tibial tunnels is widely debated. Biomechanical cadaveric studies using robotic testing systems have shown that most single-bundle ACL reconstruction techniques yield satisfactory anteroposterior knee stability in different flexion angles. However, these ACL reconstruction techniques are usually unable to restore the rotational stability of the knee joint. Further clinical studies by Tashman et al evaluated the in vivo kinematics in patients undergoing single-bundle ACL reconstruction using high-speed stereoradiography. These authors demonstrated that single-bundle ACL reconstruction was able to restore the anteroposterior stability, but not the rotational stability, of the knee joint. This phenomenon may be associated with increased pressures in the medial compartment and may ultimately increase the risk of progressive cartilage degeneration after ACL reconstruction.

An alternative to traditional single-bundle ACL reconstruction may be offered by techniques that attempt to restore the normal anatomy of the ACL. It is well known that the ACL consists of 2 major functional bundles, the anteromedial (AM) bundle and the posterolateral (PL) bundle (Fig. 1). The goal of anatomic double-
bundle ACL reconstruction is to provide a close restoration of the normal knee kinematics and function and to decrease the risk of degenerative osteoarthritis of the knee joint after ACL injury.

Anatomy of the Anterior Cruciate Ligament

The ACL consists of 2 separate and functionally distinct anatomic bundles. Early anatomic descriptions of the 2 ACL bundles were published as early as in the 1930s by Palmer. The nomenclature of the 2 ACL bundles goes by their insertion on the tibial footprint. The AM bundle originates more proximally on the femoral side and inserts anteromedially on the tibia, whereas the PL bundle originates more distally on the femoral side and inserts posterolaterally on the tibia. The ACL attaches to the femur and the tibia, not as a singular cord, but rather as a collection of fascicles that fan out as they approach their insertion sites. The insertion site of the ACL is 3 to 3.5 times larger than the cross-sectional area of the ligament midsubstance. Therefore, single-bundle reconstructions must aim for a “compromise” position of the ACL graft and can not restore the anatomic footprint of the ACL.

Biomechanics of the 2 Anterior Cruciate Ligament Bundles

Biomechanical investigations have demonstrated that the ACL fiber bundles are not isometric throughout flexion and extension. During knee flexion, the tension in the AM bundle increases while the PL bundle relaxes. During knee extension, the PL bundle tightens while the tension in the AM bundle decreases. This reciprocal length and tension pattern of the AM and the PL bundles is of great clinical importance, because in any position of the knee, a portion of the ACL remains under tension. This provides sufficient knee stability throughout range of motion.

On application of mechanical loads to the knee joint, the forces are distributed between the AM and the PL bundles. Gabriel et al investigated the distribution of the in situ forces of the ACL in response to both anterior and combined rotatory loads. In response to anterior tibial loads, the in situ force in the PL bundle was the highest in extension and decreased with increasing flexion. The in situ force in the AM bundle was lower than in the PL bundle at full extension but increased with increasing knee flexion. In response to combined rotatory load of 10 Nm valgus torque and 5 Nm internal tibial torque, both the AM and the PL bundles demonstrated significant in situ forces, especially at 15° of knee flexion. These biomechanical investigations suggested that each bundle may play a separate but equally important role for the stability of the knee joint. In particular, these studies established the important role of the PL bundle as a stabilizer against rotatory and anterior loads.

Biomechanics and In Vivo Kinematics of Single-Bundle versus Double-Bundle Anterior Cruciate Ligament Reconstruction

Biomechanical cadaver studies demonstrated that anatomic double-bundle ACL reconstruction restores the knee stability more closely to normal than conventional single-bundle ACL reconstruction. Yagi et al demonstrated that on the application of anterior tibial loads, anterior tibial translation was significantly closer to normal with double-bundle reconstruction than with single-bundle reconstruction. More importantly, the anatomic double-bundle ACL reconstruction technique provided significantly higher rotational stability of the knee joint. On the application of a combined rotatory loads of 10 Nm valgus torque and 5 Nm internal tibial torque at 30° of knee flexion, the normalized in situ force for the single-bundle and the double-bundle reconstruction group averaged 66% and 91%, respectively. Recently, Yamamoto et al compared the knee kinematics after anatomic double-bundle ACL reconstruction with single-bundle ACL reconstruction of the PL bundle alone. They reported that in response to combined rotatory loads, there were no significant differences between these 2 groups. However, the single-bundle ACL reconstruction of the PL bundle only was associated with increased...
anterior tibial translation on application of anterior loads at higher knee flexion angles.\textsuperscript{21}

A thorough outcome assessment of patients undergoing ACL reconstruction should include the evaluation of the 3-dimensional in vivo kinematics of the knee joint, including the rotational stability of the knee joint. Recent reports by Tashman et al\textsuperscript{18} have provided important information on the 3-dimensional in vivo kinematics of the knee joint after ACL reconstruction using high-speed stereoradiography.\textsuperscript{18} These investigations demonstrated that single-bundle ACL reconstruction sufficiently restored the anteroposterior tibial translation but was associated with increased internal tibial rotation.

These data from cadaveric and in vivo studies emphasize that single-bundle ACL reconstruction may not restore normal knee kinematics. Biomechanical cadaver studies have suggested that anatomic double-bundle ACL reconstruction may restore the knee stability more closely to normal than single-bundle ACL reconstruction. Future studies will need to focus on the investigation of the 3-dimensional in vivo knee kinematics after anatomic double-bundle ACL reconstruction.

**SURGICAL TECHNIQUE OF ANATOMIC ANTERIOR CRUCIATE LIGAMENT DOUBLE-BUNDLE RECONSTRUCTION**

The patient is positioned supine on the operating table and the nonoperative leg is placed in a well-leg holder in the abducted position. A pneumatic tourniquet is applied around the upper thigh of the operative leg; the operative limb is exsanguinated by elevation for 3 minutes; and the tourniquet is insufflated to 300 to 450 mm Hg depending on the patient’s size. The limb is positioned in an arthroscopic leg holder and the operative leg is prepared and draped.

Standard anteromedial and anterolateral portals immediately adjacent to the patella tendon are used to perform the arthroscopic inspection of the knee joint. Associated meniscal or chondral lesions are addressed before the ACL reconstruction. The torn ACL is carefully dissected with special attention to the anatomic footprints of the 2 ACL bundles on the lateral wall of the intercondylar notch and on the tibial side. The tibial footprints are left intact because of their proprioceptive and vascular contributions.

First, we drill the PL femoral tunnel through an accessory anteromedial portal. This portal is established with an 18-gauge spinal needle inserted medially and distally to the standard anteromedial portal just above the meniscus (Fig. 2A, B). For better visualization of the lateral wall of the intercondylar notch, we switch the arthroscope into the standard anteromedial portal. A 3.2-mm guide wire is inserted through the accessory portal and the tip of the guide wire is placed on the femoral footprint of the PL bundle on the lateral wall of the intercondylar notch (Fig. 3A, B). It is important to note that the knee is positioned at 90° of flexion, which brings the posterior–distal part of the lateral wall of the intercondylar notch more forward. Once the tip of the guide wire is malleted in the correct position, the femoral PL tunnel is drilled with an acorn drill that is inserted over the guide wire. The PL tunnel is drilled to a depth of 25 mm to 30 mm. Then the far cortex is breached with a 4.5-mm Endo-button drill (Smith & Nephew, Andover, MA), and the depth gauge is used to measure the distance to the far cortex.

To establish the 2 tibial tunnels, a 4-cm skin incision is made over the anteromedial surface of the tibia at the level of the tibial tubercle. For the PL tibial tunnel, the elbow ACL tibial drill guide is set at 55° and the tip of the drill guide is placed intraarticularly on the tibial footprint of the PL bundle. On the tibial cortex, the tibial drill starts just anterior to the superficial medial collateral...
ligament fibers. A 3.2-mm guide wire is passed into the stump of the PL tibial footprint. The AM tibial tunnel is drilled with the elbow ACL tibial drill guide set at 45°. The tip of the drill guide is placed on the tibial footprint of the AM tunnel. The starting point of the AM tunnel on the tibial cortex is more anterior, central, and proximal than the starting point of the PL tunnel. Once the elbow ACL tibial drill guide is in the desired position, a 3.2-mm guide wire is passed into the stump of the AM tibial footprint (Fig. 4). After bringing the 2 tibial guide wires in a satisfactory position, the 2 tibial tunnels are established using a cannulated drill.

The femoral AM tunnel is the last tunnel to be drilled. A transtibial technique is used in a similar fashion that a femoral tunnel for ACL single-bundle reconstruction is performed. We pass the guide wire through the AM tibial tunnel and place the tip of the guide wire on the femoral footprint of the AM bundle. Once the tip of the guide wire is malletted in the desired position, an acorn drill is inserted over the guide wire and the AM femoral tunnel is drilled to a depth of 35 mm to 40 mm. The far cortex of the AM femoral tunnel is breached with a 4.5-mm Endo-button drill (Smith & Nephew), and the depth gauge is used to measure the distance to the far cortex. The directions of the PL femoral and the AM femoral tunnels are divergent (Fig. 5).

During the arthroscopic procedure, the ACL grafts are prepared on the back table. We prefer the use 2 separate tibialis anterior or tibialis posterior tendon allografts. These grafts are usually 24 cm to 30 cm in length, and we fold each tendon graft to obtain 12 cm to 15 cm double-stranded grafts. First, the tendon grafts are trimmed and the diameters of the double-stranded grafts are adjusted. The AM tendon graft is trimmed such that the diameter of the double-stranded graft is 8 mm to 9 mm; the PL graft is trimmed such that the diameter of the double-stranded graft is 7 mm to 8 mm. The ends of the tendon grafts are sutured using a baseball stitch with 2–0 Tycron sutures. Each graft is looped around an Endo-button CL (Smith & Nephew) to obtain double-stranded grafts (Fig. 6). The length of the Endo-button loop is chosen according to the measured length of the femoral tunnels.

We first pass the PL bundle graft. A Beath pin with a

FIG. 3. (A and B). The posterolateral bundle femoral tunnel is drilled through the accessory anteromedial portal. For better visualization of the lateral wall of the intercondylar notch, the arthroscope is inserted into the standard anteromedial portal. LFC indicates lateral femoral condyle.

FIG. 4. Two separate tibial tunnels are established. AM indicates anteromedial bundle; PL, posterolateral bundle; LFC, lateral femoral condyle.
long looped suture attached to the eyelet is passed through the accessory anteromedial portal and out through the PL femoral tunnel. The looped suture is visualized within the joint and retrieved with an arthroscopic suture grasper through the PL tibial tunnel. The graft is passed and the Endo-button is flipped in a standard fashion to establish femoral fixation of the PL bundle graft. Then, the AM bundle graft is passed using the transtibial technique through a Beath pin with a loaded looped suture (Fig. 7A–C). The Endo-button is flipped in a standard fashion to establish femoral fixation of the AM bundle graft. Preconditioning of the grafts is performed by flexing and extending the knee through a range of motion from 0° to 120° approximately 20 to 30 times. On the tibial side, we prefer the use of a bioabsorbable interference screw fixation combined with a staple fixation for each graft (Fig. 8). The PL bundle graft is tensioned and fixed between 0° and 10° of flexion; the AM bundle graft is tensioned and fixed between 60° and 90° of flexion.

Our postoperative rehabilitation follows the same standard protocol that we have used for patients undergoing ACL single-bundle reconstruction using soft tissue grafts. Postoperatively, the patients wear a hinged knee brace for 6 weeks. For the first week, the brace is locked in extension. Continuous passive motion is started immediately after surgery from 0° to 45° of flexion and increased by 10° per day. The patients use crutches for 4 weeks postoperatively. From the first postoperative day, the patients are allowed full weight bearing as tolerated. Noncutting and nontwisting sports such as swimming, biking, and running in a straight line are allowed at 12 weeks after surgery. Return to full activity level is usually allowed at 6 months postoperatively.

**CLINICAL OUTCOMES**

Data on the clinical long-term functional outcome after anatomic double-bundle ACL reconstruction is limited. Yasuda et al reported a case series of 57 consecutive patients undergoing anatomic double-bundle ACL reconstruction. In their series, no major complications were recorded at a minimum follow up of 24 months, and they suggested that anatomic double-bundle ACL reconstruction appears to be a safe and practicable technique. The clinical outcomes were compared with a historic control group of patients who had undergone single-bundle ACL reconstruction in the same institution. They documented a trend toward better anteroposterior stability as measured by the KT-2000 in patients with anatomic double-bundle ACL reconstruction.

In a prospective, randomized clinical trial including 108 patients, Adachi et al compared the knee function of patients undergoing anatomic double-bundle ACL reconstruction versus single-bundle ACL reconstruction. Their only measures of outcome included the anteroposterior knee stability, as measured by the KT-2000, and the joint position sense. At a mean follow up of 32 months, no difference between the single-bundle and the double-bundle groups was recorded using these outcome measures.

These studies did not include any measures of outcome for the rotational stability of the knee joint and they did not test overall functionality of the limb and return to sports activities. Because the major potential advantage of anatomic double-bundle ACL reconstruction lies in a superior restoration of the rotational knee stability, valid outcome studies comparing single- versus double-bundle reconstruction should include the evaluation of rotational knee stability. However, such outcome measures have
been poorly established in the clinical setting. Possible techniques include video motion analysis and electromagnetic tracking devices that are applied to the skin, weight bearing and dynamic magnetic resonance imaging (MRI), high-speed stereoradiography, and fluoroscopy and MRI-based computer models. The goal of future investigations should be to establish measures of outcome for rotational knee stability and incorporate them into clinical trials that are comparing the outcomes of single-bundle versus double-bundle reconstruction.

**DISCUSSION**

The overall clinical outcomes of single-bundle ACL reconstructions have been satisfactory with restoration of the anteroposterior knee stability in most patients. However, recent long-term outcome data have suggested that the overall progression of degenerative osteoarthritis of the knee joint after ACL injury is not stopped. The reasons for progressive osteoarthritis are varied and may include associated injuries to the knee joint, abnormal knee kinematics, and biologic factors.

The impact of the initial trauma after ACL injury may set off a cascade of humoral changes within the joint that ultimately leads to osteoarthritis. Cameron et al have pointed out that synovial fluid from arthritic knees contains high concentrations of cytokines as well as degradative enzymes that may play a role in early cartilage damage. Some of these factors may be released early on in the process after a knee ligament injury and may be irreversible by the time an ACL reconstruction is performed.

A major goal of surgical ACL reconstruction is the restoration of normal knee stability and normal knee kinematics. Although it has been well known for many years that the ACL consists of 2 major functional bundles, most surgical ACL reconstruction techniques have focused on the reconstruction of the AM bundle only. Cadaveric studies clearly have indicated that the AM bundle is the primary restraint of anteroposterior knee stability and therefore has been the focus of our efforts to replace the ACL. However, the rotational stability of the knee joint has often been neglected in our assessment of patients with ACL injuries. Cadaveric studies using ro-

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**FIG. 7.** (A–C) First, we pass the posterolateral (PL) bundle graft (A). After passage of the anteromedial (AM) bundle graft, the PL bundle graft disappears behind the AM bundle (B). Retraction of the AM bundle allows visualization of the PL bundle (C).

**FIG. 8.** On the tibial side, the grafts are fixed with biointerference screws in combination with a staple fixation.
biomechanic testing systems have shown that single-bundle ACL reconstruction can only partially restore the rotational stability of the knee joint. In contrast, anatomic double-bundle ACL reconstruction restores the knee function more closely to normal in all 6 degrees of freedom. These biomechanical data from cadaveric studies support the use of double-bundle ACL reconstruction. Future studies need to investigate if anatomic double-bundle ACL reconstruction will result in improved restoration of the 3-dimensional in vivo knee kinematics, and more importantly, if these improvements will correlate with superior functional long-term outcomes and a decreased risk of degenerative osteoarthritis of the knee joint.

CONCLUSIONS

It is well known that the ACL consist of 2 major functional bundles, the AM and the PL bundles. Our suggested surgical concept attempts to restore the anatomic footprints of both functional ACL bundles. Cadaveric studies have shown that anatomic double-bundle ACL reconstruction provides better restoration of the rotational stability of the knee joint than single-bundle ACL reconstruction. Future clinical trials are necessary to investigate whether this potential advantage will translate into improved clinical outcomes. These trials must include valid measures of outcome for the rotational stability of the knee joint.

REFERENCES