Technical Note

Computer-Assisted, Anatomic, Double-Bundle Anterior Cruciate Ligament Reconstruction

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Abstract: Accurate placement of the separate anteromedial bundle and posterolateral bundle bone tunnels required for anatomic, double-bundle anterior cruciate ligament reconstruction remains a concern, and the advantages the technique confers, in terms of laxity control, may be lost with incorrect tunnel positioning. We present an image-free, computer-assisted, double-bundle reconstruction technique using specifically designed software. This assists tunnel positioning and allows the behavior of virtual anteromedial and posterolateral bundle grafts to be modeled. Data on graft length change, obliquity, and possible notch impingement are fed back to the surgeon via the interactive, touch-screen navigation display. Tunnel length and obliquity may also be determined. In addition, the software allows preoperative and postoperative navigated laxity analysis, which includes objective measurement of pivot shift. **Key Words:** Computer-assisted—Anatomic—Double-bundle anterior cruciate ligament reconstruction.

It is now recognized that the native anterior cruciate ligament (ACL) does not behave as a simple bundle of fibers with constant tension, and the separation of the ligament into anteromedial (AM) and posterolateral (PL) fiber bundles has been widely accepted as the basis for the understanding of its function.[1] The AM bundle is relatively isometric, with little length change from full extension to 90°,[2] compared with the anisometric PL bundle that tightens toward knee extension and is also important in controlling the rotational component of pivot shift and coupled tibial rotational laxity.[1] Double-bundle ACL reconstruction has gained in popularity in an effort to better represent the normal anatomy and physiologic function of the ACL and improve control of knee joint laxity, particularly rotational stability and pivot shift.

However, despite the benefits, concern has been expressed about the increased number of bone tunnels required for anatomic double-bundle reconstruction.[3] Malpositioning of the bone tunnels remains the most common cause of single-bundle ACL graft failure[4] and is of particular concern in double-bundle reconstruction, where it has been shown that the biomechanical advantages of the technique may be lost with incorrect tunnel placement.[5]

Computer-assisted navigation is being increasingly used to assist single-bundle ACL reconstruction surgery and has already been shown to improve the accuracy of bone tunnel placement. In addition, knee kinematics can be assessed intraoperatively, and the effect of the reconstruction on controlling laxity assessed.

We introduce a computer-assisted surgical reconstruction technique specifically for anatomic double-bundle ACL reconstruction. This allows accurate navigated reconstruction of the 2 bundles by use of separate AM and PL bundle grafts, with independent

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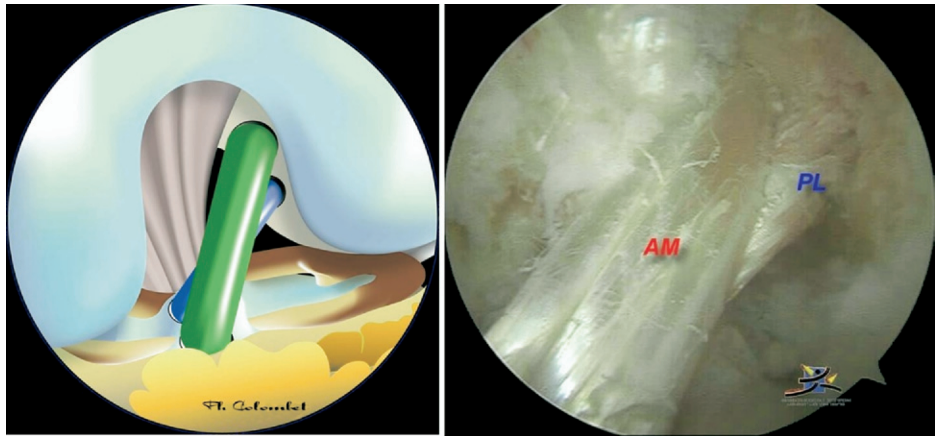

FIGURE 1. Schematic diagram of anatomic, double-bundle, 4-tunnel ACL reconstruction (left) and typical arthroscopic view of 2 grafts through AM portal (right).

bone tunnels (Fig 1). The software also allows assessment of the effect on knee kinematics provided by each graft in controlling knee laxity.

SURGICAL TECHNIQUE

Surgical Navigation System

The Praxim Medivision Surgetics system (Praxim, La Tronche, France) is a passive-optical, open-platform, image-free system that allows knee alignment, kinematics, and morphology to be measured. The Surgetics ACL Logics software (Praxim) was used for data acquisition. The Cartesian coordinate system is constructed from knee flexion/extension kinematic data and surface landmarks acquired by use of a pointer equipped with a navigation array. The surgeon uses a footswitch and a touch screen to control the system.

Patient Preparation

The patient is placed in the supine position on the operating room table with a pneumatic tourniquet applied to the proximal thigh. A foot support and lateral post are used to position the leg with the knee at 90° flexion and allowing movement from full extension to full flexion. The leg is then prepared and draped in the normal sterile fashion.

Graft Harvesting

A 3- to 4-cm skin incision is made over the AM surface of the tibia, at the level of the tibial tubercle midway between the tubercle and the posteromedial border of the tibia. This incision is used for harvesting and passage of the grafts as well as creation of the tibial tunnels. The incision may be used for placement of the tibial navigation array, but care must be taken that placement does not conflict with tunnel drilling. The gracilis and semitendinosus tendons are harvested with a closed tendon stripper, which allows the whole length of the tendons to be taken. After removal of the residual muscle from the tendons, each is doubled over a continuous-loop EndoButton CL (Smith & Nephew Endoscopy, Andover, MA). A 25-mm EndoButton CL is used for the AM bundle graft and a 15-mm EndoButton CL for the PL bundle graft. To maintain the morphometric ratio of the AM and PL bundles, the AM graft is generally made slightly larger than the PL graft. The AM bundle uses the doubled semitendinosus, resulting in a 7- to 9-mm graft diameter. The PL bundle uses the doubled or tripled gracilis, resulting in a 5- to 7-mm graft diameter. Minimal graft lengths of 26 cm for the gracilis tendon and 28 cm for the semitendinosus tendon are recommended for double or triple preparation. The doubled tendons are whipstitched, with an absorbable No. 1 suture, over 40 mm of their length, and their diameter is then measured (grafts and the corresponding tunnel diameters are sized in 0.5-mm increments).

Positioning of Navigation Arrays

The rigid-body navigation arrays are rigidly fixed to the tibia and femur (Fig 2) by use of a fixation nail that is triangular in cross section. These are both stiff and rotationally stable and provide a more minimally invasive alternative to the more traditional use of 2 bicortical Schanz screws with an external fixator–type attachment to secure the array. For the femoral array, a stab incision is made and a unicortical 3.2-mm pilot hole drilled. The femoral nail may be inserted percutaneously. Insertion of the fixation nail approximately 150 mm above the proximal border of the patella,

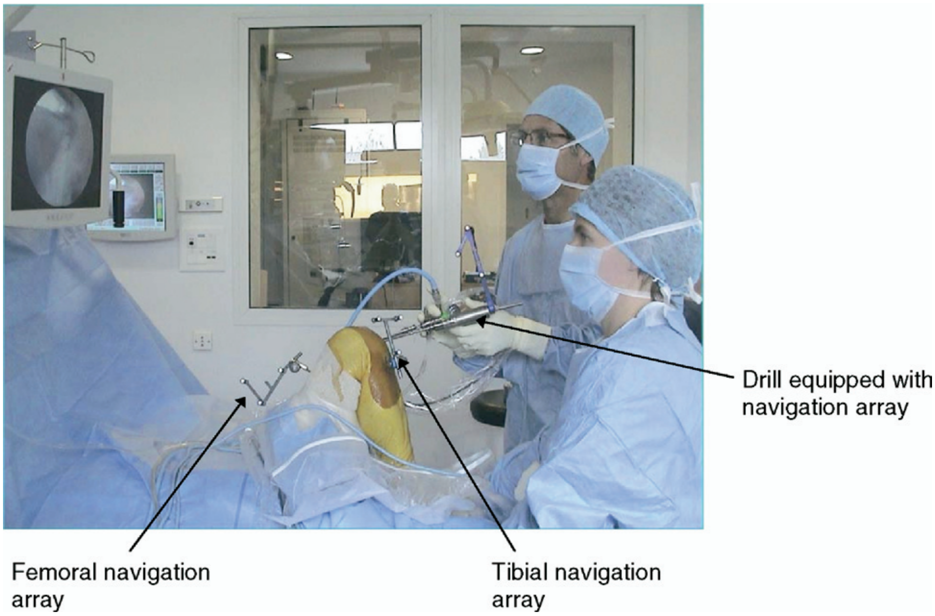

FIGURE 2. Surgeon drilling through AM portal using drill equipped with navigation array. The femoral (F) and tibial (T) navigation rigid-body arrays are shown in place.

slightly to 1 side of the midline, is usually satisfactory and will avoid transfixing the quadriceps tendon. On the tibial side, the nail can usually be inserted through the same incision used for the hamstring harvest or can be placed more distally, by use of a percutaneous stab incision. Both rigid bodies are carefully orientated toward the camera so that they can be visualized throughout the range of knee flexion/extension and during the clinical laxity testing maneuvers. The correct placement of navigation rigid-body markers is

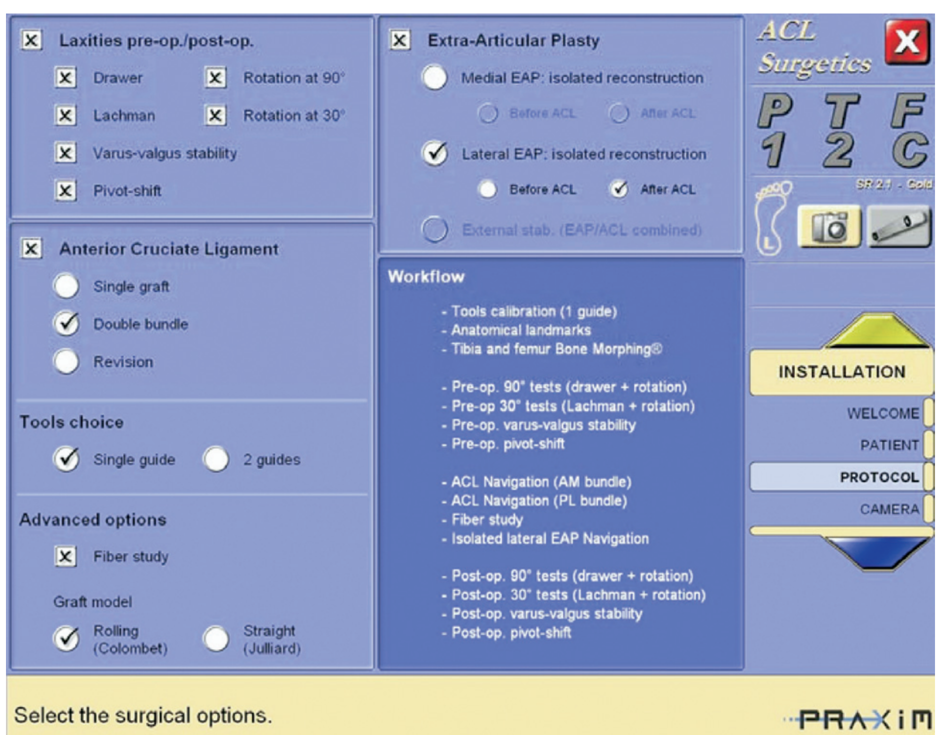

FIGURE 3. Touch-screen display for selecting surgical protocol and determining work flow. In this example, full preoperative and postoperative operative laxity assessment has been selected and a double-bundle ACL graft chosen. In addition, the option to perform a navigated lateral extra-articular plasty (EAP) has been selected.

critical, because once positioned, they cannot be moved. The rigid body must not obstruct the passage of arthroscopic instruments through the portals or impede drilling of the tibial tunnel.

Arthroscopic Portals

Anterolateral and AM arthroscopic portals are established immediately adjacent to the lateral and medial patella tendon borders at the level of the inferior pole of the patella to allow a downward view of the tibial footprint. A complete diagnostic arthroscopy is performed and any intra-articular pathology (i.e., meniscal or chondral injury) addressed. The femoral and tibial anatomic attachments of the AM and PL bundles of the ACL are identified on the lateral wall of the intercondylar notch and tibia. Their centers are marked with either a probe or an awl. It may be useful to switch the arthroscope from the anterolateral to the AM portal to allow a better view of the lateral wall of the intercondylar notch.

Navigation Protocol Selection, Calibration, and Registration

The touch-screen display (Fig 3) allows the surgical options to be selected and procedure to be customized to the surgeon's requirements. Options may be selected to allow knee laxity analysis and choice of stability tests, the use of 1 drill guide or 2, graft model, and whether an additional extra-articular plasty is to be performed. The technique we describe is for double-bundle reconstruction, measuring preoperative and postoperative knee laxities. We use a single guide: a drill equipped with a navigation array mounted directly onto it. Following the selected software protocol and onscreen instructions, the arthroscopic pointer and drill (with navigation array) are calibrated. Anatomic landmarks are then "digitized": the medial and lateral malleoli (acquired percutaneously with the pointer), the tips of the tibial spines, the center of the intermeniscal ligament, the center of the medial tibial plateau, and the center of the lateral tibial plateau (acquired arthroscopically with the pointer). The knee is then passively flexed and extended, allowing the software to calculate the midsagittal plane of the tibia and, from this, the orthogonal axes of knee motion. It is important to remember that this registration is an essential step and influences future calculations of graft behavior in the notch. Because the motion is performed without the ACL controlling anterior subluxation of the tibia, it is advisable to maintain light pressure on the tibial tuberosity to prevent any anterior tibial laxity. This better reproduces the motion of the

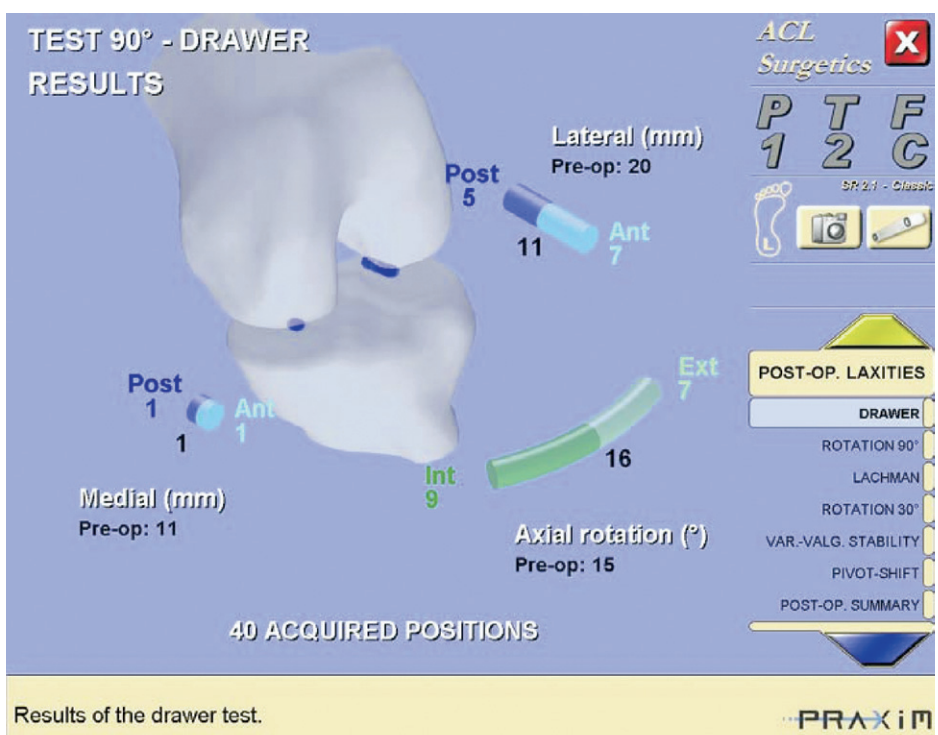

FIGURE 4. Navigation display showing anterior drawer test. Motion of the tibia is shown in real time. The coupled internal tibial rotation (9°) occurring with anterior translation is clearly shown. The anterior translation of the medial and lateral tibial condyles is also shown (1 mm and 7 mm, respectively).

intact knee and helps avoid erroneous calculations. The digitized points are tracked during clinical laxity testing, allowing 6-*df* kinematics to be computed.

Bone Morphing

Bone morphing is a process by which the pointer is moved over the intra-articular joint surfaces acquiring a series of data points allowing the Surgetics software to adapt its standard knee model to the individual 3-dimensional anatomy of the patient. In addition to the tibial spines, it is important to concentrate on the potential sites of graft impingement, particularly the medial edge of the lateral femoral condyle. The registration process takes approximately 1 minute for each bony surface (approximately 50 to 100 data points are acquired). The accuracy of the bone-morphed digital image should then be checked by placing the probe on the surface of the bone. This may be done anywhere within the registered area, but the medial edge of the lateral femoral condyle is recommended. Accuracy is verified if there is less than 1 mm between the tip of the probe and the bone surface. If there is more than 1 mm between the probe tip and the bone surface, then the process should be repeated to prevent inaccuracy.

Laxity Testing

After bone morphing and acquisition of predefined points, the navigation system can track and quantify 6-*df* knee kinematics in terms of rotations and translations. This allows real-time visualization of knee instabilities (Fig 4). We routinely measure the following before and after reconstruction:

- Anterior tibial translation and coupled internal rotation during the anterior drawer test
- Anterior tibial translation and coupled internal rotation during the Lachman test
- Maximum tibial internal/external rotation and anteroposterior tibial translation during the pivot-shift test (Fig 5)

To determine the contribution of each bundle to restraining knee instability, laxity analysis may be performed after fixation of each graft.[6]

Navigation of Femoral AM Tunnel

The Surgetics ACL Logics software allows simulation of a "virtual" graft in a digital model based on the patient's individual anatomy. It is possible to observe the behavior of this graft in real time. This includes

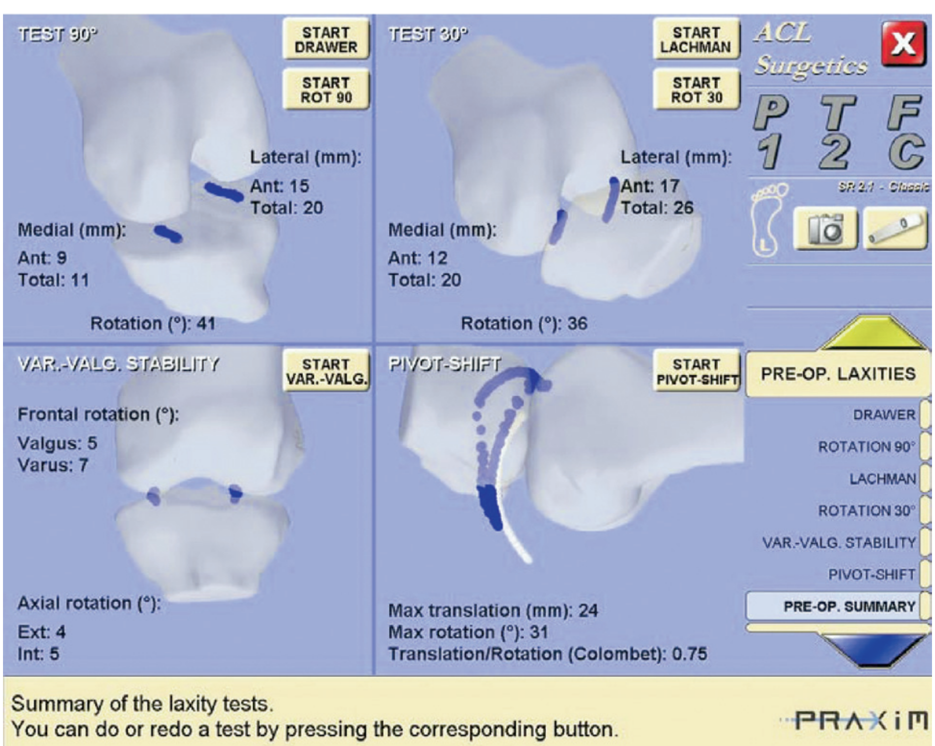

FIGURE 5. Navigation display summarizing laxity test data. Top left, Laxity at 90° knee flexion. The anterior laxity in both medial and lateral compartments is displayed. The "total" laxity in each compartment is the combined anteroposterior translation for the anterior and posterior drawer tests. Total internal/external passive rotation laxity is also shown. Top right, Laxity at 30°. The anterior laxity and total anteroposterior laxity are shown for each compartment. The combined internal/external rotation laxity is also shown. Bottom left, Varus/valgus (Var/Valg) stability. The varus and valgus rotation and coupled axial rotation are displayed. Bottom right, Pivot-shift laxity. The maximum tibial translation and axial rotation occurring during the pivot-shift test are displayed. A ratio of the degree of translation to rotation is also given; a value lower than 0.5 indicates relatively more rotation than translation.

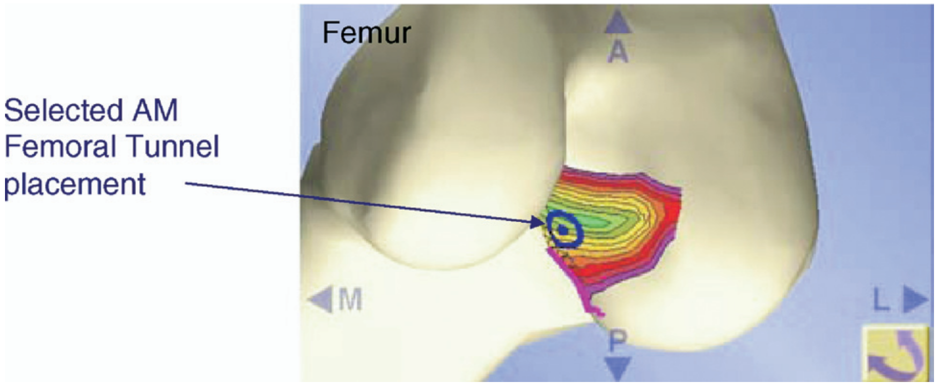

FIGURE 6. Computer screen showing isometry map that is displayed on lateral wall of intercondylar notch. Green indicates the most isometric femoral tunnel position; yellow, less isometric; and red, the least isometric (1-mm increments). In this case a femoral tunnel position just posterior to the most isometric position has been chosen. This position is advised when suspensory femoral fixation is used because the graft tends to lie against the anterior wall of the tunnel. Conversely, with interference screw fixation, the graft is pushed to the posterior aspect of the tunnel, so a femoral AM tunnel position just anterior to the most isometric point is selected.

identifying sites of potential graft impingement such as the roof of the intercondylar notch or the medial edge of the lateral femoral condyle, as well as assessing graft anisometricity. The center of the attachment of the AM bundle on the tibia is identified and the optimum position for the center of the tibial AM tunnel aperture digitized with the pointer. The graft diameter is then selected on the tough screen. The navigation software generates an "isometry map" projected onto a digital image of the PL aspect of the

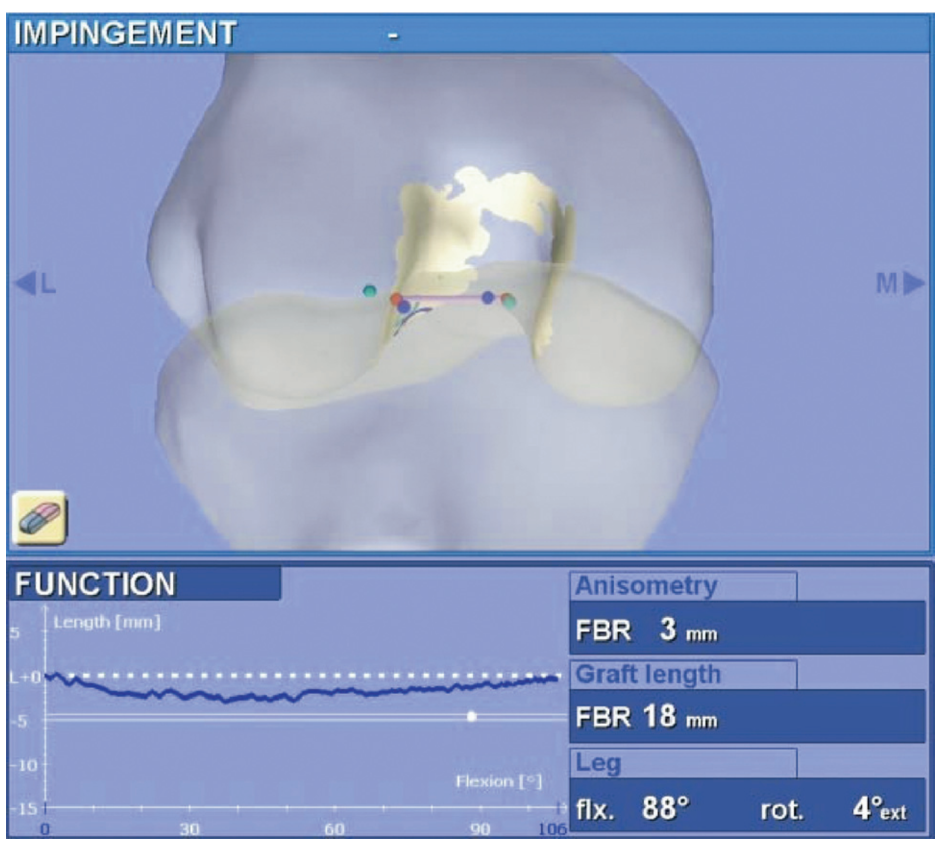

FIGURE 7. Example of navigation display screen showing typical isometry profile for AM bundle. The "function" box shows a graph of the length change between the selected femoral and tibial AM tunnel positions as the knee moves from 0° to 106° of flexion. A typical fiber-tensioning pattern for an AM bundle is shown, with minimal anisometry (3-mm length change). In the "impingement" section of the screen, the surgeon can assess the knee for evidence of impingement with the roof of the notch; in this case no impingement is shown.

intercondylar notch. This aids selection of the AM femoral tunnel position (Fig 6) to minimize graft anisometry. Once the tunnel positions have been chosen, the knee is passively flexed and extended. The software measures the change in distance between the 2 points, and an AM bundle "anisometry profile" is generated (Fig 7). Favorable AM bundle graft anisometry is achieved when the distance between the 2 tunnels slightly reduces as the knee progressively flexes; thus the graft becomes slightly more taut toward the last few degrees of knee extension. If this trend is reversed, it suggests incorrect tunnel positioning.[7] The virtual graft is also tested for possible impingement. In addition, the obliquity of the graft may be visualized in 3 planes.

Once the position is selected, the knee is slowly flexed to 120° to ensure proper orientation of the tunnel. The tunnel is drilled through the AM portal by use of the calibrated drill equipped with the navigation array (Fig 2). The computer guides drilling by displaying the position of the tip of the 4.5-mm drill relative to the selected position of the tunnel aperture (Fig 8). A reamer that

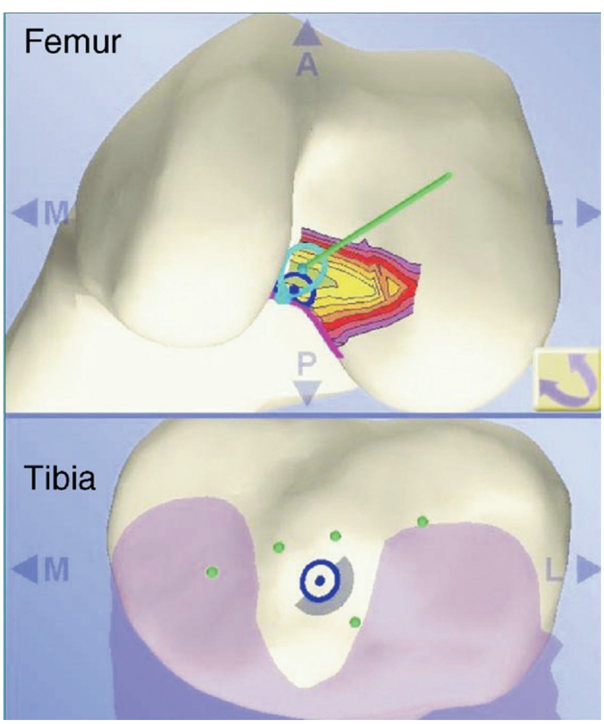

FIGURE 8. Navigated drilling of femoral AM tunnel. The software is able to precisely track the position of the drill. The green line on the display shows the alignment of the drill, and the tip is shown by the light blue dot and circle. The surgeon aims for the femoral AM tunnel aperture position that he or she has previously selected, shown by the dark blue circle and dot.

matches the graft diameter is then used to produce the AM femoral socket. Depth is regulated according to the desired insertion length.

Navigation of Femoral PL Bundle Tunnel

The center of the attachment of the PL bundle on the tibia is identified and the optimum position for the center of the tibial PL tunnel aperture digitized with the pointer (Fig 9). The navigation display also shows the position of the AM bundle tibial tunnel aperture so that the PL bundle position may be selected to maintain a bony bridge of approximately 2 mm between the apertures as they emerge into the joint. Previous studies have shown that this is possible, even in small knees, using a 7-mm-diameter AM bundle and 5-mm-diameter PL bundle graft.[8] The software then shows the position of the selected femoral PL tunnel aperture on the lateral notch wall, relative to the AM bundle aperture, with the 2-mm bony bridge represented in gray. After the tunnel positions have been selected, the knee is flexed and extended to model the PL bundle graft. The display again shows graft obliquity, possible areas of conflict, and the isometry profile.

Once the position is selected, the knee is flexed back to 120° and the tunnel is drilled with a 4.5-mm drill, guided by the navigation array, through the AM portal. Care should be taken to observe the obliquity of the tunnel to ensure that the AM and PL femoral tunnels diverge at approximately 15°. The tunnel is dilated with the appropriate-diameter router drilled to the desired depth.

Navigation of Tibial AM Bundle Tunnel

The drill, equipped with the navigation array and calibrated 4.5-mm drill bit, is used for the AM bundle tunnel. The computer display guides positioning by projecting a targeting circle onto the center of the anatomic attachment area of the native AM bundle (which has already been identified and digitized, as described previously). The computer is also able to calculate tunnel length and display this information to the surgeon in real time with drilling. Tunnel length can be adjusted simply by altering the tunnel entry point on the AM tibial cortex. We recommend that the AM tunnel aperture on the AM cortex is started approximately 1 cm medial to the tibial tuberosity. This position prevents having to position the PL bundle aperture too posterior (risking damage to the anterior fibers of the superficial medial collateral ligament) to maintain a sufficient bony bridge between the tunnels. The navigation array guides drilling so that the tip of

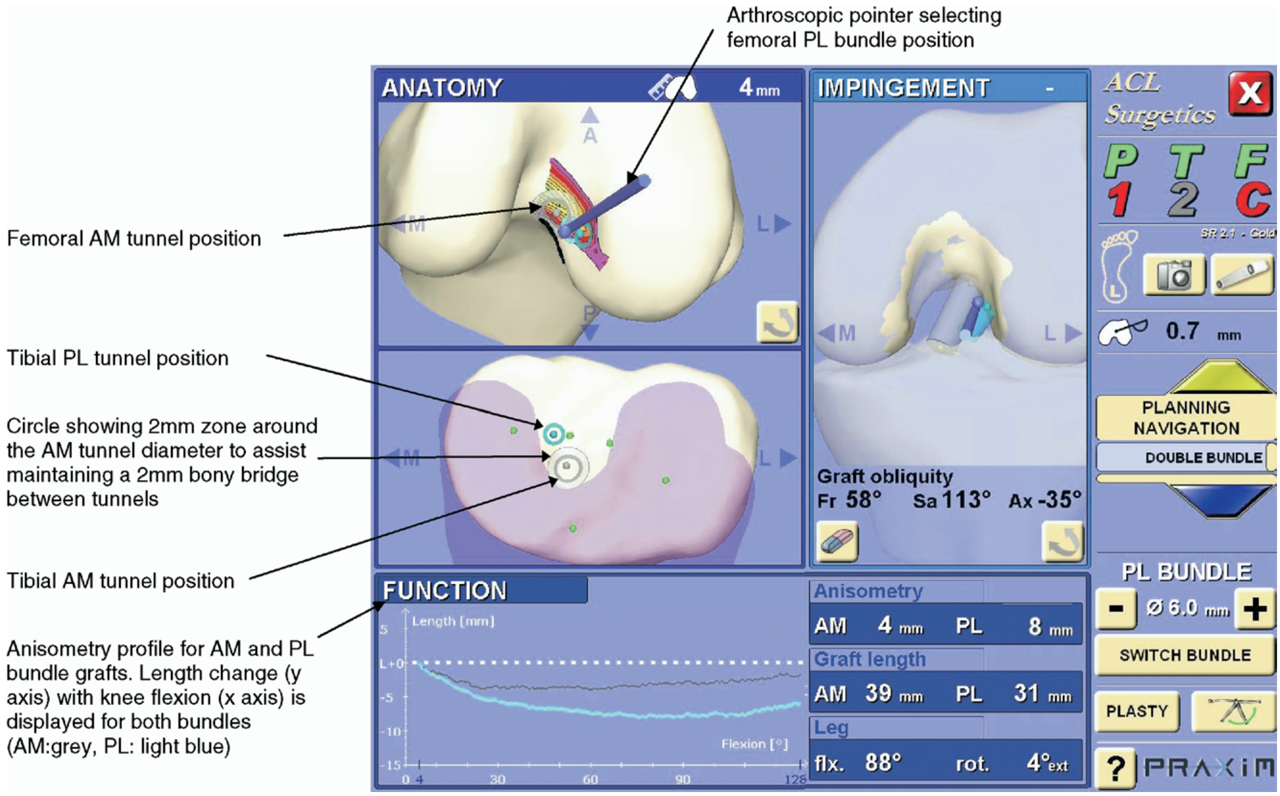

FIGURE 9. Navigation display assisting surgeon to select femoral PL tunnel position. The "anatomy" section shows the position of the arthroscopic pointer in real time. The previously selected AM tunnel placement is shown by the gray dot (center of the tunnel) and circle corresponding to the tunnel diameter. The position of the center of the PL bundle tunnel appears as a light blue dot surrounded by a light blue circle corresponding to the tunnel diameter. Data on the predicted graft obliquity and behavior for the selected tunnel position are shown in the "function" section. In this case the graph of predicted bundle length change shows typical PL bundle function (light blue): an anisometric graft, which tightens as the knee nears extension, relative to the function of the AM bundle (gray), which is relatively more isometric. Bundle obliquity in 3 planes is shown in the "impingement" section. The knee may be flexed and extended, and any areas of bony impingement are predicted. The appropriate PL graft diameter can be selected on the right side of the touch screen.

the drill emerges into the joint at the selected position. The tunnel is then dilated to the appropriate diameter corresponding to the diameter of the graft.

Navigation of Tibial PL Bundle Tunnel

The tibial PL bundle tunnel is similarly drilled, guided by the navigation array, so that the drill emerges into the joint at the preselected position. The tunnel aperture on the AM surface of the tibia lies just anterior to the anterior fibers of the superficial medial collateral ligament, approximately 2 cm from the AM tunnel aperture. With the tip of the drill resting against the cortex of the tibia, the length of the tunnel is displayed. Accurately determining tunnel length allows precise matching of interference screw length to tunnel length, thereby optimizing graft fixation. The tunnel is then dilated to the appropriate size. An osseous bridge of approximately 2 to 3 mm should remain between the 2 tunnels inside the joint.

Graft Passage and Fixation

A Beath pin, inserted through the AM portal, is used to insert 2 passing sutures of different colors (to ease identification) through the AM and PL femoral tunnels. By use of grasping forceps, the sutures are retrieved through the corresponding tibial tunnels. The PL bundle graft is passed and the EndoButton CL flipped. Next, the AM bundle graft is passed and the EndoButton CL flipped and fixation tested. The knee is cycled through a full range of motion from 0° to 120° approximately 20 to 30 times. The surgeon should mark the grafts that lie external to the tibia with a skin pen, close to the tunnel entrances, and visualize the variation of each bundle from full extension to full flexion. Generally speaking, the length variation on the AM bundle should range between 0 and 2 mm, whereas the PL bundle length variation ranges between 4 and 6 mm. These values are similar to those predicted by the navigated graft function tests.

The grafts may be fixed in any order. If required, laxity testing can be performed to assess the effect of the bundle on controlling knee laxity. The AM bundle is fixed with a bioabsorbable interference screw (BioRCI-HA; Smith & Nephew Endoscopy) while a posterior drawer force is applied to the tibia with the knee positioned at between 45° and 90° flexion. A screw 1 mm larger than the tunnel diameter and the longest screw possible is recommended. For the PL bundle, the larger the length variation of the graft in full range of motion is, the closer to full extension that fixation should be performed. An oversized interference screw is again used. Generally, fixation should occur between 30° and 10° of knee flexion. A fixation post or staple may also be used to augment the tibial fixation of the grafts.

After graft insertion, the laxity tests are repeated. All the navigation data are recorded onto a CD-ROM, along with any specific "screenshots" that the surgeon may also require. This allows for an operative report to be printed and for future detailed scientific analysis to be performed.

Double-bundle ACL reconstruction has been shown to better replicate the function of the native ligament and improve the control of knee laxity. Yet, the technique remains challenging. Accuracy in double-bundle reconstruction is essential, where it has been shown that the biomechanical advantages of the technique may be lost with incorrect tunnel placement.[5] Surgical technical error (including nonanatomic graft placement, graft impingement, and failure to address concurrent ligamentous laxities) remains the most common cause of single-bundle ACL graft failure.[9]

The computer-assisted anatomic double-bundle reconstruction technique we propose helps address these issues. Tunnel placement for the AM and PL bundle grafts can be accurately navigated and a "virtual" graft modeled to assess potential graft impingement. In addition, comprehensive knee laxity analysis can be performed intraoperatively to evaluate the effect of the reconstruction and to detect concomitant ligamentous laxities.

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