The Location of Femoral and Tibial Tunnels in Anatomic Double-Bundle Anterior Cruciate Ligament Reconstruction Analyzed by Three-Dimensional Computed Tomography Models

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Background: Characterization of the insertion site anatomy in anterior cruciate ligament reconstruction has recently received increased attention in the literature, coinciding with a growing interest in anatomic reconstruction. The purpose of this study was to visualize and quantify the position of anatomic anteromedial and posterolateral bone tunnels in anterior cruciate ligament reconstruction with use of novel methods applied to three-dimensional computed tomographic reconstruction images.

Methods: Careful arthroscopic dissection and anatomic double-bundle anterior cruciate ligament tunnel drilling were performed with use of topographical landmarks in eight cadaver knees. Computed tomography scans were performed on each knee, and three-dimensional models were created and aligned into an anatomic coordinate system. Tibial tunnel aperture centers were measured in the anterior-to-posterior and medial-to-lateral directions on the tibial plateau. The femoral tunnel aperture centers were measured in anatomic posterior-to-anterior and proximal-to-distal directions and with the quadrant method (relative to the femoral notch).

Results: The centers of the tunnel apertures for the anteromedial and posterolateral tunnels were located at a mean (and standard deviation) of 25% ± 2.8% and 46.4% ± 3.7%, respectively, of the anterior-to-posterior tibial plateau depth and at a mean of 50.5% ± 4.2% and 52.4% ± 2.5% of the medial-to-lateral tibial plateau width. On the medial wall of the lateral femoral condyle in the anatomic posterior-to-anterior direction, the anteromedial and posterolateral tunnels were located at 23.1% ± 6.1% and 15.3% ± 4.8%, respectively. The proximal-to-distal locations were at 28.2% ± 5.4% and 58.1% ± 7.1%, respectively. With the quadrant method, anteromedial and posterolateral tunnels were measured at 21.7% ± 2.5% and 35.1% ± 3.5%, respectively, from the proximal condylar surface (parallel to the Blumensaat line), and at 33.2% ± 5.6% and 55.3% ± 5.3% from the notch roof (perpendicular to the Blumensaat line). Intraobserver and interobserver reliability was high, with small standard errors of measurement.

Conclusions: This cadaver study provides reference data against which tunnel position in anterior cruciate ligament reconstruction can be compared in future clinical trials.

Clinical Relevance: This study may help surgeons to evaluate tunnel position and facilitate anatomic tunnel placement in anterior cruciate ligament reconstruction.

Recent studies have contributed substantially to our understanding of anterior cruciate ligament anatomy and have revealed that common techniques for anterior cruciate ligament reconstruction may fail to replicate native ligament origins or insertions1. This has led to a growing interest in anatomic single-bundle and double-bundle anterior cruciate lig-
ament reconstruction, with the goal of better replicating the anatomy of the native anterior cruciate ligament\textsuperscript{9-11}. There is some evidence that graft placement aligned with native insertion sites results in superior clinical outcomes\textsuperscript{12,13}. A careful review of recently published articles, however, suggests that there is still no consensus regarding appropriate tunnel placement in anatomic anterior cruciate ligament reconstruction\textsuperscript{14-17}.

To characterize the anterior cruciate ligament footprint with its two bundles, a profound knowledge of the anterior cruciate ligament anatomy and its surrounding structures is necessary. Soft-tissue remnants from the anteromedial and posterolateral bundles, and anatomic structures such as the anterior horn of the lateral meniscus and the posterior cruciate ligament, are essential landmarks for anterior cruciate ligament bone-tunnel placement. Furthermore, topographical osseous anatomic landmarks that have recently been identified, such as the lateral intercondylar ridge and lateral bifurcate ridge on the femoral side\textsuperscript{2,18} and the medial and lateral intercondylar tubercles, and the anterior intertubercle ridge on the tibia\textsuperscript{4,19}, are utilized to guide bone-tunnel placement. Importantly, these latter structures are readily visualized on three-dimensional computed tomography reconstructions, making them ideal reference points for the evaluation of tunnel position\textsuperscript{4}. By combining three-dimensional imaging with meticulous, arthroscopic dissection, it is anticipated that anatomic anteromedial and posterolateral tunnel positions relative to osseous morphological landmarks can be identified arthroscopically.

The purpose of this study was to evaluate the position of anatomic femoral and tibial tunnels in anatomic double-bundle ACL reconstruction.

Fig. 1
Following careful arthroscopic dissection and removal of soft-tissue remnants, key insertion site anatomy was identified. On the femoral side, the lateral bifurcate and intercondylar ridges were identified. On the tibial side, the tibial spine, the medial and lateral intercondylar tubercles, and the posterior cruciate ligament (PCL) were identified. Corresponding three-dimensional computed tomography reconstructions delineate these topographical osseous landmarks. AM = anteromedial, PL = posterolateral, and ACL = anterior cruciate ligament.
standardization of surgical technique and thus lead to more accurate placement of anatomic anterior cruciate ligament bone tunnels and more accurate reporting of the results. Toward this end, we address two aims: (1) to establish a method to quantify tibial and femoral tunnel positions and (2) to define the location of anatomically positioned anteromedial and posterolateral tunnels on the femur and tibia with use of three-dimensional computed tomography models of cadaver knees.

**Materials and Methods**

Eight fresh-frozen cadaver knees were dissected and evaluated arthroscopically. The average age (and standard deviation) of the donors was 63 ± 4.4 years at the time of death; seven were male, and one was female (Committee for Oversight of Research Involving the Dead [CORID] No. 223). Cadaver knees with previous surgery, gross evidence of arthritis, or osteophyte formation were excluded from the study.

**Surgical Procedure**

Cadaver specimens were prepared with use of careful arthroscopic débridement, visualization, and identification of the intact anterior cruciate ligament bundles and surrounding anatomical structures (Fig. 1). Additionally, differential tensioning patterns of the intact ligament observed during range

\[\text{Fig. 2} \]

Following careful arthroscopic anatomic dissection, bone tunnels were drilled at the centers of the femoral and tibial anteromedial (AM) and posterolateral (PL) insertion sites. On the femoral side, the knee was flexed to 90° to demonstrate the area of nonanatomic tunnel positioning. On the tibial side, the relationship of the anteromedial and posterolateral guide-wires to the anterior horn of the lateral meniscus, the lateral intercondylar tubercle, and the posterior cruciate ligament (PCL) is shown. Note that in this specimen, the distance between the posterior cruciate ligament and the center of the posterolateral insertion measures 14 mm. The anteromedial tunnels appear anterior in the figure. However, a 6-mm drill-bit was used to drill the tunnel. Larger drill-bits used commonly during anterior cruciate ligament (ACL) reconstruction would enlarge the tunnel aperture, increasing its proximity to the posterolateral tunnel.
of motion of the knee and the figure-of-four position were used to distinguish between the two bundles. The insertion sites of the anteromedial and posterolateral anterior cruciate ligament bundles were identified and marked by electrocautery.

Femoral anteromedial and posterolateral bone tunnels were placed at the estimated centers of the marked anatomic insertion sites by means of an accessory anteromedial portal drilling technique. The tunnels were drilled at 110° and 130° of knee flexion, respectively. The tibial anteromedial and posterolateral tunnels were drilled with an anterior cruciate ligament tip guide (Smith and Nephew, Andover, Massachusetts) set to 55° and 45°, respectively, with the knee in 90° of flexion at their respective insertion sites under direct arthroscopic visualization (Fig. 2). Computed tomography scans were performed on all knees after the creation of the bone tunnels, with a field of view measuring 140 mm, a slice spacing of 0.6 mm, a pixel spacing of 0.27 × 0.27 mm, and a resolution of 512 × 512 pixels per image.

Three-Dimensional Reconstruction of Computed Tomography Scans
Bone was segmented from the axial computed tomography scan slices with use of Mimics (Materialise, Leuven, Belgium) and was processed into three-dimensional surface models with use of Geomagic Studio (Geomagic, Research Triangle Park, North Carolina). Since the computed tomography scans included only partial bones (middle of the tibia to the middle of the femur), the surface models from each specimen were coregistered with properly scaled male or female base models, which had been realigned to an anatomic coordinate system based on the femoral head and tibial malleoli centers as recommended by the International Society of Biomechanics.

Measurements on Three-Dimensional Images
The centers of the tibial tunnel apertures were determined with use of an anatomically aligned coronal plane grid, as previously described. The centers of the femoral tunnel apertures were measured with two different techniques. First, a new measurement system was developed with use of an anatomical coordinate system based on landmarks that can be determined either from three-dimensional computed tomography reconstruction images or by means of arthroscopy. Second, a system similar to the previously established quadrant method, which is based on a sagittal plane grid aligned to the Blumensaat line, was used (Fig. 3).

Tibial Tunnel Positions
With use of a true proximal-to-distal view on the tibial plateau, the anterior-to-posterior and medial-to-lateral
tunnel positions were determined (Fig. 4). Anterior-to-posterior positions were calculated as percentages of the distance from the line (T1) running through the anterior border of the tibial plateau (where the plateau edge drops down to the shaft) to the line (T2) running through the most posterior border of the tibial plateau. Medial-to-lateral positions were calculated as percentages of the distance from the line (T3) running through the medial border of the tibial plateau to the line (T4) running through the lateral border of the tibial plateau. The knee is in 90° of flexion.

Femoral anatomic coordinate axes posterior-to-anterior (P-A) measurements were made from the line (F1) running through the posterior border of the medial wall of the lateral condyle to the line (F2) running through the most anterior point of the notch. Proximal-to-distal (Pr-D) measurements were made from the line (F3) running through the proximal border of the notch to the line (F4) running through the distal point of the notch roof. Posterior-to-anterior measurements for anteromedial and posterolateral tunnels were calculated as B/C and A/C, respectively. Proximal-to-distal measurements were calculated as a/c and b/c, respectively. Note that the knee is in 90° of flexion. Tibial anterior-to-posterior (A-P) measurements were made from the line (T1) running through the anterior border of the tibial plateau (where the plateau edge drops down to the shaft) to the line (T2) running through the most posterior border of the tibial plateau. Medial-to-lateral (M-L) measurements were made from the line (T3) running through the medial border to the tibial plateau to the line (T4) running through the lateral border of the tibial plateau. Anterior-to-posterior (A-P) measurements for anteromedial and posterolateral tunnels were calculated as A/C and B/C, respectively. Medial-to-lateral measurements were calculated as a/c and b/c, respectively.
Femoral Tunnel Positions

Anatomic Coordinate Axes Method

The rationale for this anatomical method was to design a three-dimensional assessment of femoral tunnel position relative to structures that can be visualized arthroscopically through the medial portal (see Fig. 1)\(^1\). Thus, the measurements derived from three-dimensional computed tomography models could be applied during arthroscopy as a guide to anatomical tunnel placement. To improve visualization of the medial wall of the lateral femoral condyle, the medial condyle was removed from the three-dimensional computed tomography model at the most anterior aspect of the distal notch\(^3\). A true medial view of the femur (perpendicular to the medial-lateral femoral axis) was established at 90° of knee flexion, allowing standardized visualization of the medial wall of the lateral condyle (see Fig. 4). The tunnel positions were determined in the posterior-to-anterior and proximal-to-distal directions, parallel to the respective anatomical axes similar to published techniques\(^6\). More specifically, posterior-to-anterior positions were calculated as percentages of the distance from the line (F1) running through the posterior border of the medial wall of the lateral condyle to the line (F2) running through the most anterior point of the notch. Proximal-to-distal positions were calculated as percentages of the distance from the line (F3) running through the proximal border of the notch to the line (F4) running through the distal point of the notch roof.

Quadrant Method

A true medial view of the femur was established at 90° of knee flexion, as described above. Similar to the quadrant method for use on standard lateral radiographs, a 4 × 4 grid was applied to the three-dimensional computed tomography images (see Fig. 3). The grid was drawn, and measurements were performed as previously described\(^5\). On radiographs, the grid is aligned with the Blumensaat line, which is a projection of the femoral notch roof on the radiograph. However, since no such line exists on a three-dimensional computed tomography model, the most anterior edge of the femoral notch roof was chosen as the reference for the grid alignment. The segments of the grid along the Blumensaat line (t) were labeled from a to d. The segments of the grid perpendicular to the Blumensaat line (h) were labeled from 1 to 4.

All measurements were performed with use of ImageJ software (National Institutes of Health, Bethesda, Maryland), and all statistical analyses were performed with use of SPSS software (SPSS, Chicago, Illinois). Data for the location of the anteromedial and posterolateral femoral and tibial tunnels are presented as the mean and the standard deviation, with the range in parentheses. The interobserver and intraobserver reliability (intraclass correlation coefficient) was calculated for the anatomic coordinate axes method results with use of measures of absolute agreement. The two individuals (S.K. and A.K.W.) who performed the interobserver and intraobserver reliability tests were the same individuals who developed and agreed on the measurement technique together. A time period of three weeks elapsed between test and retest measurements. All observer-dependent steps in the analysis, including coregistration of the three-dimensional computed tomography models to the base models, establishment of the center of the tunnel apertures, and measurement and calculation of the position of all tibial and femoral bone tunnels, were repeated. For intraobserver and interobserver reliability, the intraclass correlation coefficient, 95% confidence interval for the intraclass correlation coefficient, and standard error of measurement were reported.

Source of Funding

The study was funded in part by the Smith and Nephew Research fund.

Results

Tibial Tunnel Positions

The mean anterior-to-posterior distances for the anteromedial and posterolateral tunnel center locations were 25% ± 2.8% (range, 21.1% to 29.5%) and 46.4% ± 3.7% (range, 40.1% to 51.5%), respectively, of the anterior-to-posterior depth of the tibia measured from the anterior border. The mean medial-to-lateral distances for the anteromedial and posterolateral tunnel center locations were 50.5% ± 4.2% (range, 44.1% to 54.7%) and 52.4% ± 2.5% (range, 49.5% to 56.1%), respectively, of the medial-to-lateral width of the tibia measured from the medial border.

Femoral Tunnel Positions

Anatomical Coordinate Axes Measurements

The mean posterior-to-anterior distances for anteromedial and posterolateral tunnel center locations were 23.1% ± 6.1% (range, 16.3% to 36.4%) and 15.3% ± 4.8% (range, 8.9% to 24.3%), respectively, of the posterior-to-anterior height of the medial wall of the lateral condyle measured from the posterior border (F1 in Fig. 4). The mean proximal-to-distal distances for the anteromedial and posterolateral tunnel center locations were 28.2% ± 5.4% (range, 20.1% to 36.2%) and 58.1% ± 7.1% (range, 50.2% to 73.1%), respectively, of the proximal-to-distal depth of the medial wall of the lateral condyle measured from the proximal border (F3 in Fig. 4). The reliability estimates for the anatomic coordinate axes method results are presented in Table I.

Quadrant Method Measurements

The mean distances of the anteromedial and posterolateral tunnel center locations parallel to the Blumensaat line were 21.7% ± 2.5% (range, 18.9% to 25.7%) and 35.1% ± 3.5% (range, 31.2% to 40.0%), respectively, along line t measured from the posterior border of the medial wall of the lateral condyle (see Fig. 3). The mean distances perpendicular to the Blumensaat line for anteromedial and posterolateral tunnel center locations were 33.2% ± 5.6% (range, 24.4% to 42.1%) and 55.3% ± 5.3% (range, 47.7% to 65.1%), respectively, along line h measured from the Blumensaat line. The center of the anteromedial bundle was located in box 1a for one cadaver and box 2a for the seven other cadavers. The center of the posterolateral bundle was located in box 2b for one cadaver and box 3b for the seven other cadavers.
In this study, the centers of the anteromedial and posterolateral bone tunnels in anatomic double-bundle anterior cruciate ligament reconstruction were identified and quantified on three-dimensional computed tomography reconstruction images on the basis of anatomic landmarks. Established radiographic measurement methods were adapted, and new measurement techniques were developed for three-dimensional model-based analysis of the bone tunnel positions. Through meticulous arthroscopic dissection, revealing the individual anterior cruciate ligament bundle anatomy and the surrounding native soft-tissue and osseous landmarks, bone tunnels were placed as closely as possible to the centers of the anteromedial and posterolateral bundle insertions. The position of these tunnels relative to known osseous landmarks was determined from three-dimensional bone models reconstructed from high-resolution computed tomography scans. The technique showed high reliability with regard to both intraobserver and interobserver variation. By defining anatomic locations for the anteromedial and posterolateral bundle insertion sites relative to easily identified anatomic landmarks, the results of this study may facilitate anatomic positioning of bone tunnels intraoperatively.

Tunnel locations have traditionally been determined from plain radiographs, which provide a two-dimensional projection of the three-dimensional bone geometry. Accurate measurements from two-dimensional radiographs are dependent on alignment of the bone with the imaging plane, which may be difficult to achieve reliably and can introduce errors in estimated tunnel position. Furthermore, potentially important osseous landmarks, such as the lateral intercondylar ridge or the lateral bifurcate ridge, are not visible on conventional radiographs.

Three-dimensional computed tomography reconstruction enables visualization of the bone model in its entirety. By selectively removing sections of the bone from the model and rotating the model view, regions of the bone that are traditionally difficult to see (e.g., the medial wall of the lateral femoral condyle) can be clearly visualized. Subtle bone surface features that were previously seen only during arthroscopy or gross dissection are easily discernible. Since each bone model is aligned with an anatomically defined coordinate system, measurements are independent of limb orientation during imaging. The methods employed to evaluate tunnel positions from three-dimensional computed tomography models were selected to be conceptually similar to radiographic and cadaver measurement techniques described in the literature. The quadrant method is one of the most commonly used techniques for measuring femoral tunnel position on standard lateral radiographs. However, this method references the Blumensaat line, which is not a fixed osseous landmark but rather a projection of the roof of the femoral intercondylar notch onto the radiograph. Because this so-called line does not...
actually represent a specific physical structure, it is difficult to define on three-dimensional computed tomography models. For this study, the problem was addressed by defining the Blumensaat line as the most anterior (superior) aspect of the notch (see Fig. 3).

The anatomic coordinate axes method for femoral tunnel measurements in this study was again based on a method reported in the literature by Watanabe et al., who described tunnel position relative to the border between the medial wall and the articular surface of the lateral condyle. Since this landmark is visible during arthroscopy, this position description may be easier to apply in an operative setting. Unlike the approach of Watanabe et al., the method used in the current study references the entire medial wall of the lateral femoral condyle, including areas both within and outside the anatomic anterior cruciate ligament insertion area. Additionally, in the current study, the rotation of the bone models within three-dimensional space was standardized to ensure standardized measurements.

We compared tunnel positions with data from previously published cadaver and radiographic studies (Table II). On the tibia, our three-dimensional computed tomography analysis yielded similarly positioned anteromedial and posterolateral tunnel positions in the medial-to-lateral direction but more anteriorly positioned anteromedial and posterolateral tunnels in the anterior-to-posterior direction compared with the previously published cadaver study. Of note, the aforementioned study measured the position of the native insertion site of the anterior cruciate ligament, while measures in the current study were based on anatomically positioned tunnels.

On the femur, our three-dimensional computed tomography analysis of the quadrant method yielded results, with regard to the distance parallel to the Blumensaat line (t), within the range of those in previously published cadaver studies. With regard to distances perpendicular to the Blumensaat line (h), our three-dimensional computed tomography analysis found the posterolateral tunnel locations to be nearly the same as those determined by Zantop et al., whereas the anteromedial tunnel locations in our study were slightly more distally and posteriorly placed.

The methods used to describe the location of the femoral and tibial tunnels based on three-dimensional computed tomography scans demonstrated high levels of intraobserver and interobserver reliability. Because only two observers were utilized to assess interobserver reliability, the reliability results can be generalized only to other individuals who have a similar level of experience with the software program and measurement methods that were utilized in this study. The time between repeat measurements was on the order of three weeks. As such, recall of the measurements may have artificially inflated the reliability estimates; however, given the nature of the measurements, we believe that this was unlikely. A sample size of only eight specimens should not appreciably affect the point estimates for the reliability coefficients, but it could affect the width of the confidence intervals for the reliability estimates. Therefore, because of the relatively small sample size, the lower bounds of the confidence intervals for the intraclass correlation coefficients may reflect a more conservative (i.e., worst case) estimate of the reliability of these measurement methods. Considering these limitations, we believe that the methods presented to measure the location of the femoral and tibial tunnels following anterior cruciate ligament reconstruction based on three-dimensional computed tomography scans are sufficiently reliable.

In this study, we visualized and quantified the position of anatomical double-bundle anteromedial and posterolateral tunnels, utilizing a novel three-dimensional computed tomography reconstruction measurement technique. Precise knowledge of tunnel locations is critical for our approach to anterior cruciate ligament surgery, which is based on the application of anatomical reconstruction concepts. Referencing anatomic landmarks, including anterior cruciate ligament remnants, osseous and surrounding soft-tissue landmarks, and insertion site anatomy, are crucial to achieving an anatomical anterior cruciate ligament reconstruction. These data provide a reference against which tunnel position can be judged in future clinical studies. By utilizing this method of three-dimensional computed tomography analysis to evaluate tunnel position in clinical scenarios, surgeons may be able to improve

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*AM = anteromedial, and PL = posterolateral.
anatomic tunnel positioning during anterior cruciate ligament reconstruction.

References


