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Bony Landmarks of the Anterior Cruciate Ligament Tibial Footprint

A Detailed Analysis Comparing 3-Dimensional Computed Tomography Images to Visual and Histological Evaluations

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Background: Although the importance of tibial tunnel position for achieving stability after anterior cruciate ligament (ACL) reconstruction was recently recognized, there are fewer detailed reports of the anatomy of the tibial topographic footprint compared with the femoral side.

Hypothesis: The ACL tibial footprint has a relationship to bony prominences and surrounding bony landmarks.

Study Design: Descriptive laboratory study.

Methods: This study consisted of 2 anatomic procedures for the identification of bony prominences that correspond to the ACL tibial footprint and 3 surrounding landmarks: the anterior ridge, lateral groove, and intertubercular fossa. In the first procedure, after computed tomography (CT) was performed on 12 paired, embalmed cadaveric knees, 12 knees were visually observed, while their contralateral knees were histologically observed. Comparisons were made between macroscopic and microscopic findings and 3-dimensional (3D) CT images of these bony landmarks. In the second procedure, the shape of the bony prominence and incidence of their bony landmarks were evaluated from the preoperative CT data of 60 knee joints.

Results: In the first procedure, we were able to confirm a bony prominence and all 3 surrounding landmarks by CT in all cases. Visual evaluation confirmed a small bony eminence at the anterior boundary of the ACL. The lateral groove was not confirmed macroscopically. The ACL was not attached to the lateral intercondylar tubercle, ACL tibial ridge, and intertubercular space at the posterior boundary. Histological evaluation confirmed that the anterior ridge and lateral groove were positioned at the anterior and lateral boundaries, respectively. There was no ligament tissue on the intercondylar space corresponding to the intercondylar fossa. In the second investigation, the bony prominence showed 2 morphological patterns: an oval type (58.3%) and a triangular type (41.6%). The 3 bony landmarks, including the anterior ridge, lateral groove, and intertubercular fossa, existed in 96.6%, 100.0%, and 96.6% of the cases, respectively.

Conclusion: There is a bony prominence corresponding to the ACL footprint and bony landmarks on the anterior, posterior, and lateral boundaries.

Clinical Relevance: The study results may help create an accurate and reproducible tunnel, which is essential for successful ACL reconstruction surgery.

Keywords: anterior cruciate ligament; bony landmark; tibial footprint; 3-dimensional computed tomography

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bundle (AMB) and posterolateral bundle (PLB) in the femoral ACL footprint; these bony protrusions were coined the “intercondylar ridge” and “bifurcate ridge,” respectively. Iwahashi et al\textsuperscript{15} compared 3-dimensional computed tomography (3D-CT) images and histological findings to assess their detailed bony border. Moreover, Shino et al\textsuperscript{27} described the ability to arthroscopically identify the intercondylar ridge as a precise intraoperative landmark when creating a femoral tunnel. These findings would standardize the view on the position of the femoral ACL attachment and be beneficial for reproducible femoral tunnel placement at the time of anatomic ACL reconstruction.

Compared with the femoral attachment, there are no general standard guidelines and fewer reports on the bony landmarks for anatomic placement of the tibial tunnel. The CT study reporting on tibial bony landmarks by Purnell et al\textsuperscript{26} is widely known. In this study, the authors reported that the posterior and medial boundaries of bone are the tibial ridge and medial intercondylar eminence, respectively; there is no bony landmark in the anterior and lateral boundaries. However, because their study used only 3D-CT images adjusted by a volume-rendering technique to determine the border of the footprint, their detailed result was unclear. Recent studies showed the importance of tibial tunnel location in terms of translational control and rotational stability after ACL reconstruction.\textsuperscript{2,3,9,13,21,24} Bedi et al\textsuperscript{3} reported that more anterior tibial tunnel placement significantly reduced anterior tibial translation and pivot-shift movement compared with posterior tunnel placement in a cadaveric study. Mall et al\textsuperscript{21} revealed that less oblique grafts were associated with greater anterior translation and that graft obliquity was particularly influenced by tibial tunnel position. Accordingly, based on these reports, it is important for postoperative knee stability to determine anteromedial placement of the tibial tunnel within anatomic footprints, and there is a need for the accurate identification of bony or soft tissue landmarks for creating an ideal tibial tunnel that is compatible with the diverse shape of the tibial footprint.

We performed a preliminary investigation using preoperative 3D knee imaging to identify bony landmarks for the tibial attachment of the ACL. We identified a bony prominence in front of the medial and lateral intercondylar tubercles and the medial side of the medial intercondylar ridge as a bony landmark (Figure 1) that is distinguished from the surrounding area by the clear bony eminence of the anterior side, which connected to the anterior edge of the medial intercondylar eminence, a small groove that runs back and forth on the lateral side, and a small pit between the medial and lateral intercondylar tubercles on the posterior side. These bony landmarks were named as the anterior ridge, lateral groove, and intertubercular fossa, respectively. In this study, we focused on these bony structures that correspond to the ACL tibial footprint and its surrounding boundaries by a combination of visual, histological, and imaging findings to determine the ideal tibial tunnel position.

\textbf{MATERIALS AND METHODS}

Cadaveric Assessment of the Tibial Attachment of the ACL by Macroscopic, Microscopic, and CT Evaluations

To investigate the correlation between the bony landmark and ACL tibial attachment, an anatomic study was performed. Twenty-four paired knees from 12 adult embalmed cadaveric specimens (8 male and 4 female) with no...
macroscopic degenerative or traumatic changes were donated and used in this study. The mean age of the cadaveric specimens was 82.7 years (range, 45-94 years).

The muscles and capsule around the knee joint were removed. The posterior cruciate ligament (PCL) and patella were also removed. The proximal tibia was cut with a bone saw 4 cm below the articular surface, and the ACL was cut at the femoral attachment from the roof of the intercondylar notch to allow macroscopic and microscopic examination of the ACL tibial attachment. Then, all knees were scanned at a slice thickness of 1 mm with a CT scanner (SOMATOM Sensation 16, Siemens Medical Solutions, Erlangen, Germany). The CT data were reconstructed with software for image analysis (OsiriX version 5.5, Apple, Cupertino, California, USA), and 3D images of the proximal tibial condyle were reconstructed from CT data using a 3D volume-rendering technique. The presence of each previously described bony landmark was evaluated by 3D imaging from multiple orientations.

These paired knees were randomly divided into 2 groups for macroscopic and microscopic evaluation. In terms of the macroscopic evaluation group, the overlying synovium and fat tissue around the ACL were carefully removed to expose the surface of the ligament. Gross macroscopic evaluation was performed with special attention to the relationship between the bony/anatomic landmarks and margins of the ACL footprint. In terms of the microscopic evaluation group, the soft tissue around the ACL was not touched for the assessment of its natural status. To identify the relationship between the ACL attachment and bony landmarks, we cut 3 specimens from a cadaveric knee through corresponding planes, including the insertion of dense collagen fibers and the surrounding soft and bony tissue: the sagittal plane for the anterior ridge, coronal plane for the lateral groove, and axial plane for the intercondylar fossa. Because a single knee cannot sufficiently yield 3 specimens, the lateral groove specimen was prepared using a knee from the macroscopic group. Delipidation was performed in methyl alcohol for 3 days. Decalcification was performed in K-CX solution (Falma, Tokyo, Japan) for 3 to 7 days, dependent on bone quality. Dehydration was performed in a series of graded methyl alcohol. The anterior ridge and lateral groove were both sampled from the center of the bony landmark, while the intercondylar fossa was sampled from the tip, center, and base of the tubercle. Sections were sliced into 5-µm specimens and stained with hematoxylin and eosin (H&E). To evaluate the relationship between the bony landmark and ligament border, each specimen was carefully inspected with a light microscope (NECLIPSE E800M, Nikon, Tokyo, Japan). Visual and histological evaluations were assessed through their comparison to 3D-CT images.

In Vivo Assessment of ACL Tibial Insertion Characteristics and Bony Landmarks With High-Resolution CT

Sixty consecutive patients undergoing surgery around the knee were involved (Table 1). There were 31 female and 29 male patients with a mean age of 28.8 ± 15.0 years (range, 13-70 years). All patients underwent CT preoperatively for clinical evaluation. The preoperative diagnoses are shown in Table 1. For ACL cases, CT imaging within 6 months of injury was used. Those who had undergone a previous surgery to the index knee, those who radiographically showed bone surface changes, or those with a tumor lesion that invaded the articular surface were excluded in this study.

Three-dimensional images of the proximal tibial condyle were reconstructed from CT data by a 3D volume-rendering technique following the same protocol of the cadaveric investigation, and the shape, length, and width of the bony prominence were measured. Measurement of the tibial bony prominence was achieved while visualizing the tibial plateau in the axial plane (Figure 2). Anteroposterior lengths of the bony prominence were measured by the distance between the most anterior elevated points and anterior margin of the intertubercular fossa (A1) and ACL tibial ridge (A2) in the anteroposterior direction, respectively. Mediolateral widths were measured by the distance between the medial intercondylar eminence and medial margin of the bony prominence (B1) and deepest point of the lateral groove (B2) in the mediolateral direction, respectively. The incidence of each bony landmark, including the anterior ridge, lateral groove, and intertubercular fossa, was evaluated. The anterior ridge was measured in its length (C), and the lateral groove was measured in its length (D1) and width (D2).

Ethical approval for the study was obtained from the institutional review board.

RESULTS

Tibial Attachment of the ACL in Cadaveric Specimens

In all cases, we were able to confirm a bony prominence that corresponded to the ACL footprint and all 3
landmarks, including the anterior ridge, lateral groove, and intercondylar fossa, by 3D-CT imaging. All descriptions of the gross appearance are compiled and presented in Table 2. Visual observation and palpation confirmed the ACL in the medial margin of the medial intercondylar eminence of the tibia. Synovium and fat tissue were not present on the anterior side, and direct tactile confirmation of a small bony eminence was made on the anterior margin with a longitudinal ligament-splitting incision, closely matching the anterior ridge observed on 3D-CT images. Furthermore, the ACL was attached posterior to this bony eminence. Consequently, the lateral margin of the ACL was adjacent to the anterior horn of the lateral meniscus, and the visual border was obscured by the attached ligament fiber that consisted of one half to one third of the width of the meniscoid surface. Fat and fibrous tissue were found between the medial and lateral intercondylar tubercles, and careful removal of these tissues revealed the ligament fiber attached to the tip of the medial intercondylar tubercle; however, they were not attached to the lateral intercondylar tubercle, ACL tibial ridge, and intertubercular space, which corresponded to the intertubercular fossa on 3D-CT imaging (Figure 3).

Histological evaluation confirmed an anterior ridge in all cases, and the ACL was attached posterior to the border of this protrusion (Figure 4A). On the lateral aspect, ligament tissue was attached to the bottom of the lateral groove in all but 1 case, and all cases were positioned adjacent to the anterior horn of the lateral meniscus (Figure 4B). Similarly to the macroscopic evaluation, there were

Figure 2. The 3-dimensional image measurements were performed in a tibial axial plane in a right knee based on the morphological characteristics of each bony landmark. (A) A1, distance from the anterior ridge to the anterior margin of the intertubercular fossa; A2, distance from the anterior ridge to the anterior cruciate ligament tibial ridge; B1, distance from the medial intercondylar ridge to the medial margin of the lateral groove; B2, distance from the medial intercondylar ridge to the lateral margin of the lateral groove. (B) C, length of the anterior ridge; D1/D2, length and width of the lateral groove, respectively.

Figure 3. Gross appearance and 3-dimensional computed tomography (3D-CT) images in the posterosuperior view of the tibial anterior cruciate ligament (ACL) insertion of the left knee. (A) The ACL fiber was attached to the medial intercondylar tubercle (a) but not attached to the lateral intercondylar tubercle (b), ACL tibial ridge (c), and bottom of the intertubercular space corresponding to the fossa (white dot circle), respectively. (B) The bony landmarks were observed on 3D-CT.
and bony landmarks are reported in Tables 3 and 4. This prominence showed 2 morphological patterns: an oval type with the longer axis oriented in the anteroposterior direction and a triangular type with the base opened anteriorly. The anterior ridge was located on the anterior margin of this prominence, and the medial margin of this prominence was adjacent to the anterior horn of the lateral meniscus.

**Figure 4.** Histological evaluation of the anterior cruciate ligament (ACL) tibial insertion (H&E stain). (A) Sagittal section of the anterior ridge (original magnification ×4); the presence of the ridge at the anterior border of the ACL (black arrow) is shown. (B) Coronal section of the lateral groove (original magnification ×4); the ACL was attached to the bottom of the groove (arrowheads), which was adjacent to the anterior horn of the lateral meniscus.

**Figure 5.** There were fat, blood vessels, and fibrous tissue; however, there was no ligament tissue between the lateral and medial intercondylar tubercles. (A) Coronal section of the intertubercular fossa on 3-dimensional computed tomography imaging. Lines indicate slices of the tip (b), midbody (c), and bottom (d) of the medial and lateral intercondylar tubercles. (B, C, D) Histological evaluation of the anterior cruciate ligament tibial insertion (H&E stain) (original magnification ×4).


table:TABLE 2  

<table>
<thead>
<tr>
<th>Macroscopic Evaluation</th>
<th>Tactile Evaluation</th>
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<tr>
<td>Anterior Border was obscured</td>
<td>Small ridge was palpable with a slit in the ligament</td>
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<tr>
<td>Lateral Adjacent to the lateral meniscus; ligament fiber was attached to the meniscoid surface (border was obscured)</td>
<td>Bony structure was not confirmed (without resection of the lateral meniscus)</td>
</tr>
<tr>
<td>Posterior Border was obscured (without resection of soft tissue)</td>
<td>Ligament was attached to the tip of the medial intercondylar tubercle but not attached to the lateral intercondylar tubercle and intertubercular space (with resection of soft tissue)</td>
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**ACL Tibial Insertion Characteristics and Bony Landmarks in Patients**

In addition to the results from the preliminary investigation, the bony prominence was confirmed in front of the medial and lateral intercondylar tubercles in all cases by images of the tibial condyle's articular surface. Morphological patterns of the bony prominence, incidence of the 3 bony landmarks, and measurements of the bony prominence and bony landmarks are reported in Tables 3 and 4. This prominence showed 2 morphological patterns: an oval type with the longer axis oriented in the anteroposterior direction and a triangular type with the base opened anteriorly. The anterior ridge was located on the anterior margin of this prominence, and the medial margin of this
DISCUSSION

While much attention has been paid to surgical methods for more accurate re-creation of femoral tunnel placement, considerably less focus has been placed on the tibial tunnel position. The purpose of this study was to provide new basic anatomic data for tibial tunnel creation. There are 2 new points raised in our present study. First, there is a bony prominence at the center of the tibial plateau that nearly overlaps with the ACL attachment site. Macroscopic and microscopic findings present a bony landmark found in the periphery of this prominence, and the bony landmark serves as a border between ligament tissue and its surroundings; the high incidence of this landmark is demonstrated by 3D-CT imaging. Second, there is a relationship between these bony landmarks and anatomic landmarks, which could be endoscopically conferred and confirmed as an indicator for bone tunnel creation.

The size of the tibial attachment site can vary widely according to different reports (see the Appendix, available online at http://ajsm.sagepub.com/supplemental). Our findings showed that the anteroposterior length was comparatively shorter than that in other reports. We thought that the sex, physique, and racial makeup of research participants had a great influence on both their findings and our results.18,23 Furthermore, most research on attachment sites visually assesses cadaveric ligament attachment sites. There are fibrous, synovial, and fat tissues surrounding the surface of the ligament, and results can vary widely, depending on how these tissues are treated and how the examiner defines the essential components of the ligament. In terms of ACL length, the anteroposterior measurement varies according to the interpretation of the posterior boundary; taking into account our histological observations, the posterior boundary of the tibial attachment site was positioned at the anterior border of the intertubercular fossa, which may explain the smaller anteroposterior diameter in our study in comparison with those of other reports.

There were a few reports on the posterior boundary of the ACL tibial footprint. Purnell et al26 found that the posterior attachment of the ACL lies on the tibial ridge in between the medial and lateral intercondylar tubercles. Ferretti et al16 reported that no ACL insertion was posterior to the posterior edge of the lateral tibial eminence. In this study, our visual and histological findings showed that the ACL is attached to the medial intercondylar tubercle in the posterior aspect but not attached to the lateral intercondylar tubercle, intertubercular fossa, and tibial ridge that Purnell et al26 have described. We believe that the posterior border of the main fiber is attached more anteriorly than previously described. Hara et al8 have reported there is a bare area on the posterior side of the tibial attachment where no ligament exists by microscopic evaluation, and the intertubercular fossa that we observed would correspond to this area. The posterior border of the ACL was bounded by the anterior border of the intertubercular fossa; moreover, this approximately overlapped with the anterior border of the medial and lateral intercondylar tubercles as anatomic landmarks that could be referred during arthroscopic surgery.

There have been several reports in terms of anatomic landmarks located anterior to the ACL tibial attachment site. Recently, several studies regarding the intermeniscal ligament as the anterior ACL tibial landmark have been published.6,17 Kongcharoensombat et al17 reported that the transverse ligament was positioned at the anterior margin of the ACL tibial footprint. However, the transverse ligament was covered with fatty tissue, had some anatomic variations, and was only found in 62.2% to 94.4% of patients.1 Berg4 reported an anterior bone bulge of the ACL attachment, called the Parsons knob, which was confirmed on a lateral radiograph of the knee at 30% of the knee joint. We believe that the anterior ridge detailed in this report could be the same bony structure. Unlike the intermeniscal ligament, the landmark directly indicates the anterior boundary and can be confirmed in almost every case.

Moreover, we propose that the medial intercondylar eminence and anterior ridge are joined at their anteromedial edge, and these 2 bony landmarks form the anteromedial boundary of the ACL tibial footprint, which we named the “L-shaped ridge.” Recent studies have reported that graft obliquity in the coronal and sagittal planes strongly influenced better anteroposterior rotational knee stability.2,19,21,31 Also, Kato et al16 evaluated the stability of different femoral and tibial bone tunnel positions in single-bundle reconstruction, and they found that the anteromedial-anteromedial position for bone tunnel placement demonstrated optimal knee kinematics. Furthermore, Plaweski et al25 have reported in a computer navigation study that previously described graft impingement on the intercondylar notch did not occur in tibial tunnel placement within the anteromedial attachment site. With that point in mind, the tibial bone tunnel should be placed more anteromedially within the anatomic footprint, and we believe that this landmark that we proposed is a good indicator for defining the anteromedial position of the tibial tunnel.

| TABLE 3 |
| Shape of the Bony Prominence and Incidence of 3 Bony Landmarks (N = 60 Knees) |
| Shape of bony prominence | n (%) |
| Oval | 35 (58.3) |
| Triangular | 25 (41.6) |
| Presence of bony landmark | |
| Anterior ridge | 58 (96.6) |
| Lateral groove | 60 (100.0) |
| Intertubercular fossa | 58 (96.6) |
For tibial tunnel creation, various anatomic reference landmarks, including the anterior border of the PCL, posterior border of the anterior horn of the lateral meniscus, medial tibial eminence, and over-the-back ridge, were used for anatomic tibial tunnel placement and the 2-tunnel arrangement, using distance from the ideal tunnel placement to the tibial tunnel as a point of comparison. However, because these landmarks have some variability in the distance between the reference point and insertion point, it is difficult to endoscopically determine the bone tunnel position with accurate reproducibility under this criterion, making the landmark ineffective for anteromedial tibial tunnel placement. In this study, we suggested that the anterior ridge approximately corresponds to the anterior boundary, the anterior horn of the lateral meniscus to the lateral boundary, and the anterior border of the medial and lateral intercondylar tubercles to the posterior boundary. These 3 landmarks, in addition to the medial intercondylar eminence as the medial boundary, form a square outline for placement of the tibial tunnel, with the periphery of the tunnel positioned to meet the “L-shaped ridge.” We strongly believe that these criteria based on bony/anatomic landmarks are useful for creating tunnels in reproducible anatomic and functional positions, regardless of morphological variations. Siebold et al endorsed a similar square model for the ACL tibial attachment site, defining the anterior aspect of the tibial plateau and its surrounding border. Although the definition of the surrounding boundary may differ slightly, our concept corresponds directly with theirs.

This study has several limitations. First, we were unable to provide a landmark in determining the tunnel position arrangement of the AMB and PLB for a double-bundle procedure. However, a narrower anteroposterior boundary was measured in this study (mean, 13.7 mm) than previously reported. If a conventional size of the tibial bone tunnel is placed in the anteroposterior position, most of the hypothetical attachment site could be covered. Second, many of the cases using 3D-CT image analysis had some kind of pathological condition, which may have influenced the results.

However, there have been previous reports observing that the identification of bony landmarks is not affected after an ACL injury, and strict measures were taken to select patients with no arthrosis and to detect ligament degeneration. Because the objective of this study was to provide an evaluation of the morphological patterns of the bony surface, we believe that there is a low probability of these factors influencing our results.

### CONCLUSION

We found that there was a bony prominence in the center of the tibial plateau that corresponds to the ACL attachment site. Using macroscopic and microscopic evaluations combined with 3D images, we clarified the presence of bony landmarks, including an anterior ridge on the anterior boundary, a lateral groove on the lateral boundary, and an intertubercular fossa on the posterior boundary. The anterior ridge was palpable with a probe by slitting the anterior margin of the ligament, but the lateral groove and intertubercular fossa may not be arthroscopically confirmed. However, we found that the anterior horn of the lateral meniscus and the anterior border of the medial and lateral intercondylar tubercles can be considered the anatomic landmark of that boundary. Additionally, we have confirmed that these landmarks can be arthroscopically identified and possibly serve as useful tools for creating bone tunnels.

Our research results provided the preoperative estimation of the size and shape of the tibial attachment site by CT images and should be valuable information for preoperative planning of surgeries using CT-based navigation. We believe that our results could be used to enhance the arthroscopic assessment of the tibial footprint and may...
help anatomic and functional tunnel creation, which is essential to successful ACL reconstruction surgery.

REFERENCES


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