Bony Landmarks of the Anterior Cruciate Ligament Tibial Footprint: A Detailed Analysis Comparing Three-Dimensional Computed Tomography Images to Visual and Histological Evaluations

ABSTRACT

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

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

Study design: Descriptive laboratory study

Methods: We planned two anatomical studies for the identification of bony prominences that correspond to the ACL tibial footprint and three surrounding landmarks: anterior ridge, lateral groove, and intertubercular fossa. In the first study, after computed tomography (CT) scanning performed on 12 paired embalmed cadaveric knees, 12 knees were visually observed, while their contralateral knees were histologically observed. Comparisons were made between macroscopic/microscopic findings and three-dimensional (3D) CT images of these bony landmarks. In the second study, the morphology 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 study, we were able to confirm a bony prominence and all three surrounding landmarks by CT imaging 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 an anterior ridge and lateral groove was positioned at the anterior and lateral boundary. There was no ligament tissue on the intercondylar space corresponding to the intercondylar fossa. In the second study, the bony prominence shows two morphological patterns: an oval type (58.3%) and triangular type (41.6%). The three bony landmarks including the anterior ridge, lateral groove, and intertubercular fossa existed in 96.6%, 100%, and 96.6% of our cases, respectively.

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

Clinical relevance: Our results may help create an accurate and reproducible tunnel, which is essential to the successful ACL reconstruction surgery.

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

What is known about the subject: There is very little documentation available on bony landmarks surrounding the tibial ACL attachment site. Most existing literature continues to provide limited evaluations, either through CT or visual images, and comprehensive evaluations utilizing multiple methodologies have not been reported. Although the discovery of bony landmarks led to the standardization of femoral bone tunnel construction, there are still no standardized methods for tibial tunnel construction.

What this study adds to existing knowledge: The present study on ACL tibial attachment site and bony landmarks compared 3D images with visual and histological evaluations. The results from this study found a unique bony landmark surrounding the ACL attachment site that was never previously described. Moreover, by showing the relationship of these bony landmarks and surrounding anatomical landmarks, we were able to document a useful indicator for determining tunnel positions during arthroscopic surgery. The tibial attachment site is narrower than had previously thought, and we believe tunnel construction within the boundaries (indicator) described in our study will make reproducibility and anatomical positioning possible for tunnel construction. There have been many recent biomechanical research studies that report the importance of tibial tunnel positioning, and the consideration of both anatomical and biomechanical factors are necessary for determining tunnel positions. We believe that our proposed landmarks are useful in fulfilling both of these considerations.

INTRODUCTION

The current operation for anterior cruciate ligament (ACL) injury has shifted to the anatomical ACL reconstruction, which mimics the original anatomy of the ACL. A recent study suggested that a more anatomical approach to replicate the original ACL anatomy should be of benefit to knee stability.[11, 20, 33, 34] For that reason, optimal anatomic replacement of ACL graft is essential for improving patient clinical outcome. Therefore, in performing an anatomic ACL reconstruction, detailed knowledge of native insertions are critical.

Ferretti et al. reported two bony prominences that exist in the anterior edge and partitions the anteromedial bundle (AMB) and posterolateral bundle (PLB) in the femoral ACL footprint; these bony protrusions were coined the “intercondylar ridge” and “bifurcate ridge”, respectively.[7] Iwahashi, et al. compared three dimensional computed tomography (3D-CT) images and histological findings to assess their detailed bony border.[15] Moreover, Shino et al. described the ability to arthroscopically identify the intercondylar ridge as a precise intraoperative landmark when creating a femoral tunnel.[27] These findings would standardize the view on the position of femoral ACL attachment, and be beneficial for reproducible femoral tunnel placement at the time of anatomical ACL reconstruction.

Compared to the femoral attachments, there are no general standard guidelines and fewer reports on the bony landmarks for the anatomical placement of the tibial tunnel. The CT study related on tibial bony landmarks by Purnell et al. is widely known.[26] In this report, the authors reported that the posterior and medial boundaries of bone are the tibial ridge and the medial intercondylar eminence; there is no bony landmark in the anterior and lateral boundary. 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 show the importance of tibial tunnel location in terms of translational control and rotational stability after ACL reconstruction.[2, 3, 8, 13, 21, 24] Bedi et al. reported more anterior tibial tunnel placement significantly reduced anterior tibial translation and pivot shift movement compared with posterior tunnel placement in a cadaveric study.[3] Mall et al. revealed less oblique grafts were associated with greater anterior translation, and graft obliquity is particularly influenced by tibial tunnel position.[21] Accordingly, based on these reports, it is important for postoperative knee stability to create the anteromedial placement of tibial tunnel within anatomical footprints, and there is a need for accurate identification of bony or soft tissue landmarks for creating an ideal tibial tunnel that is compatible with the diverse morphology of the tibial footprint.

We performed a preliminary investigation using preoperative 3D knee imaging in order to identify bony landmarks for the tibial attachment of the ACL. We identified a bone prominence in front of the medial/lateral intercondylar tubercles and medial side of medial intercondylar ridge as a bony landmark (Figure1) that is distinguished from the surrounding area by the clear bone eminence of the anterior side which connected to the anterior edge of 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, through a combination of visual, histological and image findings in order to determine the ideal tibial tunnel position.

MATERIALS AND METHODS

Assessment of Tibial Attachment of the ACL in Cadavers by Macroscopic and Microscopic and CT Images Evaluation

To investigate the correlation between the bony landmark and ACL tibial attachment, an anatomic study was performed. Twenty four paired knees (eight men and four women) from twelve adult embalmed cadavers, with no macroscopic degenerative or traumatic changes, were donated and used in this study. The mean age of the cadavers was 82.7 years (range, 45 to 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 4cm 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 tibial ACL attachment. Then all knees were scanned at slice thickness of 1 mm with a CT scanner (SOMATOM Sensation16; Siemens Medical Solutions, Erlangen, Germany). The CT data were reconstructed with software for image analysis (Osiri X version 5.5; Apple, CA). 3D images of the proximal tibial condyle were reconstructed from CT data by a 3D volume rendering technique. Presence of each previously described bony landmark was evaluated by 3D imaging from multiple orientations.

These paired knees were randomly divided into two groups for macroscopic and microscopic evaluation, respectively. 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/anatomical 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 evaluation of its natural status. To identify the relationship between the ACL attachment and bony landmarks, we cut 3 specimens from a cadaver 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 one knee cannot sufficiently yield three 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, stained with H&E stain. 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 its comparison to 3D-CT images.

Assessment of ACL Tibial Insertion Morphology and Bony Landmark with High Resolution CT in Patients

Sixty consecutive patients undergoing surgery around the knee were involved (Table1). They consisted of 31 females and 29 males with a mean age of 28.8 ± 15.0 years ranging from 13 to 70 years. All of them underwent CT scan preoperatively for clinically evaluation. The preoperative diagnosis was shown in Table 1. For ACL cases, CT imaging within 6 months of injury were used. Those who had undergone a previous surgery to the index knee, those who showed radiographically bone surface changes, or those with a tumor lesion that invaded the articular surface were excluded in this study.

3D images of the proximal tibial condyle were reconstructed from CT data by a 3D volume rendering technique in the same protocol of cadaver study, and the shape, length, and width of the bone prominence were evaluated. 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)/ACL tibial ridge (A2) in the AP direction, respectively. Medial-lateral widths were measured by the distance between the medial intercondylar eminence and medial margin of bony prominence (B1), the deepest point of lateral groove (B2) in ML direction, respectively. Incidence of each bony landmark, including the anterior ridge, lateral groove, and intertubercular fossa were 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 each study was obtained from the Institutional Review Board.

RESULTS

Tibial Attachment of the ACL in Cadavers.

In all cases, we were able to confirm a bone prominence that corresponded to ACL footprint and all three landmarks, including the anterior ridge, lateral groove, and intertubercular fossa by 3D-CT imaging. All descriptions of 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 in 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 in 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 1/2 to 1/3 the width of the meniscoid surface. Fat and fibrous tissues were found between the medial/lateral intercondylar tubercle, and careful removal of these tissue revealed 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 intertubercular fossa on 3D-CT image (Figure 3).

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

Similarly to the macroscopic evaluation, there were fat, blood vessel, and fibrous tissue; however, no ligament tissue between the lateral and medial intercondylar tubercle that corresponds to the intercondylar fossa on 3D-CT image, aside from one case in which we could not create sufficient specimen for histological evaluation (Figure 5).

ACL Tibial Insertion Morphology and Bony Landmark in Patients

In addition to the result of the preliminary study, the bony prominence was confirmed in front of the medial and lateral intercondylar tubercle in all cases through the images of the tibial condyle articular surface. Morphological patterns of the bony prominence, incidence of the three bony landmarks, and measurements of the bony prominence and bony landmarks are reported in Table 3 and 4. This prominence showed 2 morphological patterns: an oval type with the longer axis oriented in the AP 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 ridge was all connected to the anterior edge of the medial intercondylar ridge. The lateral groove was located on the anterior side of the lateral intercondylar tubercle in the AP direction, and opened anteriorly. The intertubercular fossa existed between the medial-lateral intercondylar tubercule and anterior margin of this fossa corresponded to the anterior margin of the medial/lateral intercondylar tubercle.

DISCUSSION

Whereas much attention has been paid to surgical methods for more accurate recreation of the femoral tunnel placement, considerably less focus has been placed on the tibial tunnel position. The purpose of this study was to provide new basic anatomical data for tibial tunnel creation. There are two new points raised in our present study. Firstly, there is a bony prominence at the center of the tibial plateau, which nearly overlaps with the ACL attachment site. Macroscopic and microscopic findings present us with a bony landmark found in the periphery of this prominence, and the bony landmark serves as a border between the ligament tissue and its surroundings; the high incidence of this landmark is demonstrated by 3D-CT imaging. Secondly, there is a relationship between these bony landmarks and anatomical 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 (Table 5). Our findings showed that the anteroposterior length was comparatively shorter than other reports. We thought that the sex, physique, and racial makeup of research subjects had a great influence on both their 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 account for the smaller anteroposterior diameter in our study in comparison to other reports.

There were a few reports about the posterior boundary of the ACL tibial footprint. Purnell et al. found the posterior attachment of the ACL lies on the tibial ridge in between the medial and lateral intercondylar tubercle[26]. Ferretti et al. reported that no ACL insertion was posterior to the posterior edge of lateral tibial eminence.[6] In this study, our visual and histological findings show 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 the tibial ridge that Purnell et al. have described. We believe the posterior border of the main fiber is attached more anteriorly than previously described. Hara et al. have reported there is a bare area on the posterior side of the tibial attachment where no ligament exists at microscopic evaluation, and the intertubercular fossa we observed would correspond to this same area.[9] 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/lateral intercondylar tubercle as anatomical landmarks which could be referred at the arthroscopic orientation.

There are several reports in terms of anatomical landmarks anterior to the ACL tibial attachement site. Recently, several studies about the intermeniscal ligament as the anterior ACL tibial landmark was proposed.[6, 17] Kongcharoensombat et al. reported that the transverse ligament was positioned at the anterior margin of the tibial ACL footprint.[17] However, the transverse ligament was covered with fatty tissue and had some anatomical variations, and was only found in 62.2-94.4%.[1] Berg et al. reported an anterior bone bulge of the ACL attachment, named the Parson’s knob, which was confirmed at lateral X-ray of the knee at 30% of the knee joint.[4] We believe the anterior ridge detailed in this report could be the same bony structure. Unlike the intermeniscal ligament, the landmark directly indicates to 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 two bony landmarks form the anteromedial boundary of the ACL tibial footprint, which we termed the “L-shaped ridge”. Recent studies reported that graft obliquity on the coronal and saggital plane strongly influenced better anteroposterior-rotational knee stability.[2, 19, 21, 32] Also, Kato et al. evaluated the stability of different femoral and tibial bone tunnel positions in single-bundle reconstruction, and they found that the AM-AM position for bone tunnel placement demonstrated optimal knee kinematics.[16] Furthermore, Plaweski et al. have reported in a computer navigation study that previously described graft impingement on the intercondylar notch did not occur in the tibial tunnel placement within the anteromedial attachment site.[25] With that point in discussion, the tibial bone tunnel should be placed more anteromedially within the anatomical footprint, and we believe this landmark we proposed is a good indicator for defining the anteromedial position of the tibial tunnel.

For the tibial tunnel creation, various anatomic reference landmarks, including the anterior border of PCL, posterior border of anterior horn of lateral meniscus, medial tibial eminence, and over-the-back ridge were used for anatomical tibial tunnel placement and the two-tunnel arrangement, using distance from the ideal tunnel placement to the tibial tunnel as a point of comparison.[5, 6, 10, 12, 14, 22, 35] 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 lateral meniscus to the lateral boundary, and the anterior border of medial/lateral intercondylar tubercle to the posterior boundary, respectively. These three landmarks, in addition to the medial intercondylar eminence as the medial boundary, form a square boundary for the placement of tibial tunnel, and the periphery of the tunnel positioned to meet the "L-shaped ridge". We strongly believe these criteria based on bony/anatomical landmarks are useful for creating tunnels on reproducible anatomical 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.[28] Although the definition of the surrounding boundary may differ slightly, our concept corresponds directly with theirs.

This study has several limitations. Firstly, 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 (average: 13.7 mm) than previously reported. If the conventional size of the tibial bone tunnel is placed in the anteroposterior position, most of the hypothetical attachment site could be covered. Secondly, 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 that the identification of bony landmarks is not affected after ACL injury [31], and strict measures were taken to select patients with no changes in their tibial articular surface; thus, we consider these factors presented minimal influence on the results. Thirdly, many of the subjects for the visual and histological study were embalmed geriatric cadavers. However, a strict selection process was implemented to choose patients with no arthrosis and detection of ligament degeneration. Because the objective of this study is to provide an evaluation of bony surface morphology, we believe there is a low probability of these factors to influence our results.

CONCLUSION

There was a bony prominence in the center of the tibial plateau that corresponds to the ACL attachment site. Through 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 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/lateral intercondylar tubercle can be considered the anatomical landmark of that boundary. Additionally, we have confirmed that these landmarks can be arthroscopically identified and possibly serve as a useful landmark for creating bone tunnels.

Our research results have made the preoperative estimation of the size and morphology of the tibial attachment site by CT images, and should be valuable information for preoperative planning of surgeries using CT-based navigation.[30] We believe that our results could be used to enhance the arthroscopic assessment of tibial footprint and may help anatomical and functional tunnel creation, which is essential to the successful ACL reconstruction surgery.

REFERENCES

1. Aydin AT, Ozenci AM, Ozcanli H, Ozdemir H, Urgüden M. The reference point to measure the anterior intermeniscal ligament's thickness: an MRI study. Knee Surg Sports Traumatol Arthrosc. 2002;10(6):343-346.
2. Ayerza MA, Múscolo DL, Costa-Paz M, Makino A, Rondón L. Comparison of sagittal obliquity of the reconstructed anterior cruciate ligament with native anterior cruciate ligament using magnetic resonance imaging. Arthroscopy. 2003;19(3):257-261.
3. Bedi A, Maak T, Musahl V, Citak M, O'Loughlin PF, Choi D, Pearle AD. Effect of tibial tunnel position on stability of the knee after anterior cruciate ligament reconstruction: is the tibial tunnel position most important? Am J Sports Med. 2011;39(2):366-373.
4. Berg EE. Parsons' knob (tuberculum intercondylare tertium). A guide to tibial anterior cruciate ligament insertion. Clin Orthop Relat Res. 1993;(292):229-231.
5. Edwards A, Bull AM, Amis AA. The attachments of the anteromedial and posterolateral fibre bundles of the anterior cruciate ligament: Part 1: tibial attachment. Knee Surg Sports Traumatol Arthrosc. 2007;15(12):1414-1421.
6. Ferretti M, Doca D, Ingham SM, Cohen M, Fu FH. Bony and soft tissue landmarks of the ACL tibial insertion site: an anatomical study. Knee Surg Sports Traumatol Arthrosc. 2012;20(1):62-68.
7. Ferretti M, Ekdahl M, Shen W, Fu FH. Osseous landmarks of the femoral attachment of the anterior cruciate ligament: an anatomic study. Arthroscopy. 2007;23(11):1218-1225.

8. Hatayama K, Terauchi M, Saito K, Higuchi H, Yanagisawa S, Takagishi K. The importance of tibial tunnel placement in anatomic double-bundle anterior cruciate ligament reconstruction. Arthroscopy. 2013;29(6):1072-1078.
9. Hara K, Mochizuki T, Sekiya I, Yamaguchi K, Akita K, Muneta T. Anatomy of normal human anterior cruciate ligament attachments evaluated by divided small bundles. Am J Sports Med. 2009;37(12):2386-2391.
10. Heming JF, Rand J, Steiner ME. Anatomical limitations of transtibial drilling in anterior cruciate ligament reconstruction. Am J Sports Med. 2007;35(10):1708-1715.
11. Hussein M, van Eck CF, Cretnik A, Dinevski D, Fu FH. Prospective randomized clinical evaluation of conventional single-bundle. anatomic single-bundle. and anatomic double-bundle anterior cruciate ligament reconstruction: 281 cases with 3- to 5-year follow-up. Am J Sports Med. 2012;40(3):512-520.
12. Hutchinson MR, Bae TS. Reproducibility of anatomic tibial landmarks for anterior cruciate ligament reconstructions. Am J Sports Med. 2001;29(6):777-780.
13. Inderhaug E, Strand T, Fischer-Bredenbeck C, Solheim E. Effect of a too posterior placement of the tibial tunnel on the outcome 10-12 years after anterior cruciate ligament reconstruction using the 70-degree tibial guide. Knee Surg Sports Traumatol Arthrosc. 2013 [Epub ahead of print]
14. Iriuchishima T, Ingham SJ, Tajima G, Horaguchi T, Saito A, Tokuhashi Y, Van Houten AH, Aerts MM, Fu FH. Evaluation of the tunnel placement in the anatomical double-bundle ACL reconstruction: a cadaver study. Knee Surg Sports Traumatol Arthrosc. 2010;18(9):1226-1231.
15. Iwahashi T, Shino K, Nakata K, Otsubo H, Suzuki T, Amano H, Nakamura N.

Direct anterior cruciate ligament insertion to the femur assessed by histology and 3-dimensional volume-rendered computed tomography. Arthroscopy. 2010;26(9 Suppl):S13-20.

16. Kato Y, Maeyama A, Lertwanich P, Wang JH, Ingham SJ, Kramer S, Martins CQ, Smolinski P, Fu FH. Biomechanical comparison of different graft positions for single-bundle anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc. 2013;21(4):816-823.

17. Kongcharoensombat W, Ochi M, Abouheif M, Adachi N, Ohkawa S, Kamei G, Okuhara A, Shibuya H, Niimoto T, Nakasa T, Nakamae A, Deie M. The transverse ligament as a landmark for tibial sagittal insertions of the anterior cruciate ligament: a cadaveric study. Arthroscopy. 2011;27(10):1395-1399.

18. Kopf S, Pombo MW, Szczodry M, Irrgang JJ, Fu FH. Size variability of the human anterior cruciate ligament insertion sites. Am J Sports Med. 2011;39(1):108-113.

19. Lee MC, Seong SC, Lee S, Chang CB, Park YK, Jo H, Kim CH. Vertical femoral tunnel placement results in rotational knee laxity after anterior cruciate ligament reconstruction. Arthroscopy. 2007;23(7):771-778.

20. Lim HC, Yoon YC, Wang JH, Bae JH. Anatomical versus non-anatomical single bundle anterior cruciate ligament reconstruction: a cadaveric study of comparison of knee stability. Clin Orthop Surg. 2012;4(4):249-255.

21. Mall NA, Matava MJ, Wright RW, Brophy RH. Relation between anterior cruciate ligament graft obliquity and knee laxity in elite athletes at the National Football League combine. Arthroscopy. 2012;28(8):1104-1113.

22. Morgan CD, Kalman VR, Grawl DM. Definitive landmarks for reproducible tibial tunnel placement in anterior cruciate ligament reconstruction. Arthroscopy.

1995;11(3):275-288.

23. Papachristou G, Sourlas J, Magnissalis E, Plessas S, Papachristou K. ACL reconstruction and the implication of its tibial attachment for stability of the joint: anthropometric and biomechanical study. Int Orthop. 2007;31(4):465-470.

24. Pinczewski LA, Salmon LJ, Jackson WF, von Bormann RB, Haslam PG, Tashiro S. Radiological landmarks for placement of the tunnels in single-bundle reconstruction of the anterior cruciate ligament. J Bone Joint Surg Br. 2008 90(2):172-179.

25. Plaweski S, Rossi J, Merloz P, Julliard R. Analysis of anatomic positioning in computer-assisted and conventional anterior cruciate ligament reconstruction. Orthop Traumatol Surg Res. 2011;97(6S):S80-5.

26. Purnell ML, Larson AI, Clancy W. Anterior cruciate ligament insertions on the tibia and femur and their relationships to critical bony landmarks using high-resolution volume-rendering computed tomography. Am J Sports Med. 2008;36(11):2083-2090.

27. Shino K, Suzuki T, Iwahashi T, Mae T, Nakamura N, Nakata K, Nakagawa S. The resident's ridge as an arthroscopic landmark for anatomical femoral tunnel drilling in ACL reconstruction. Knee Surg Sports Traumatol Arthrosc. 2010;18(9):1164-1168

28. Siebold R, Ellert T, Metz S, Metz J. Tibial insertions of the anteromedial and posterolateral bundles of the anterior cruciate ligament: morphometry, arthroscopic landmarks, and orientation model for bone tunnel placement. Arthroscopy. 2008;24(2):154-161..

29. Tállay A, Lim MH, Bartlett J. Anatomical study of the human anterior cruciate

ligament stump's tibial insertion footprint. Knee Surg Sports Traumatol Arthrosc. 2008;16(8):741-746.

30. Tensho K, Kodaira H, Yasuda G, Yoshimura Y, Narita N, Morioka S, Kato H, Saito N. Anatomic double-bundle anterior cruciate ligament reconstruction, using CT-based navigation and fiducial markers. Knee Surg Sports Traumatol Arthrosc. 2011;19(3):378-383.

31. van Eck CF, Morse KR, Lesniak BP, Kropf EJ, Tranovich MJ, van Dijk CN, Fu FH. Does the lateral intercondylar ridge disappear in ACL deficient patients? Knee Surg Sports Traumatol Arthrosc. 2010;18(9):1184-1188.

32. Voos JE, Musahl V, Maak TG, Wickiewicz TL, Pearle AD. Comparison of tunnel positions in single-bundle anterior cruciate ligament reconstructions using computer navigation. Knee Surg Sports Traumatol Arthrosc. 2010;18(9):1282-1289.

33. Yasuda K, Kondo E, Ichiyama H, Tanabe Y, Tohyama H. Clinical evaluation of anatomic double-bundle anterior cruciate ligament reconstruction procedure using hamstring tendon grafts: comparisons among 3 different procedures. Arthroscopy. 2006;22(3):240-251.

34. Zantop T, Diermann N, Schumacher T, Schanz S, Fu FH, Petersen W. Anatomical and nonanatomical double-bundle anterior cruciate ligament reconstruction: importance of femoral tunnel location on knee kinematics.Am J Sports Med. 2008;36(4):678-685.

35. Zantop T, Wellmann M, Fu FH, Petersen W. Tunnel positioning of anteromedial and posterolateral bundles in anatomic anterior cruciate ligament reconstruction: anatomic and radiographic findings. Am J Sports Med. 2008;36(1):65-72.

FIGURE LEGENDS

Figure 1.

3D images of right knee tibial plateau. (A) Axial view and expansion of the central part. (B) Antero-superior view of tibial plateau and expansion of the central part. Demarcations: a, lateral intercondylar tubercle; b, medial intercondylar tubercle; c, medial intercondylar ridge; d, anterior ridge; e, ACL tibial ridge; White dot circle, bony prominence of ACL footprint; Red dot circle, lateral groove; Gray dot circle, intertubercular fossa.

Figure 2.

The 3D image measurements were performed on a tibial axial plane in a right knee based on the morphology of the each bony landmark. (A) Demarcations: A1, distance from anterior ridge to anterior margin of intertubercular fossa; A2, distance from anterior ridge to ACL tibial ridge; B1, distance from medial intercondylar ridge to medial margin of lateral groove; B2, distance from medial intercondylar ridge to lateral margin of lateral groove. (B) Demarcations: C, length of anterior ridge; D1/2, length and width of lateral groove.

Figure 3.

Gross appearance and 3D-CT image of the posterosuperior view of tibial ACL insertion of left knee. (A) ACL fiber was attached to the medial intercondylar tubercle(a), but not attached to lateral intercondylar tubercle(b), ACL tibial ridge(c), bottom of intertubercular space corresponding to fossa (white dot circle), respectively. (B) The bony landmarks were observed in 3D CT image.

Figure 4.

Histology of tibial ACL insertion (H&E stain). (A) Sagittal section of anterior ridge (original magnification ×4); the presence of ridge at anterior border of ACL (black arrow). (B) Coronal section of lateral groove (original magnification ×4); ACL was attach to the bottom of the groove (arrowheads) which adjacent to the anterior horn of lateral meniscus.

Figure 5.

There were fat, blood vessel, and fibrous tissue; however, there was no ligament tissue between the lateral and medial intercondylar tubercle. (A) Coronal section of intertubercular fossa in 3D-CT image. (B-C) Histology of tibial ACL insertion (H&E stain) (original magnification ×4). (B) Slice of tip of medial/lateral intercondylar tubercle. (C) Slice of midbody of medial/lateral intercondylar tubercle. (D) Slice of bottom of medial/lateral intercondylar tubercle.

Table 1

Patients' Demographic Data of CT Evaluation

No. of knees (n=60)	
ACL rupture	31
Osteochondritis dissecans of femur	7
Acute/recurrence patellar dislocation	11
Soft tissue tumor around knee joint	3
Fracture around knee joint	5
Avascular necrosis of medial femoral condyle	3
Mean Age (range) (yr)	28.8±15.0 (13-70)
Male/Female	35/25
Right/Left	23/37
Weight (kg)/Height (cm)	58/168

Table 2

Summary of Macroscopic and Tactile Evaluation

	Macroscopic evaluation	**Tactile evaluation**
Anterior	Border obscured	Small ridge was palpable with a slit in the ligament
Lateral	Adjacent to lateral meniscus Ligament fiber was attached to the meniscoid surface (border obscured)	Bony structure not confirmed (without resection of lateral meniscus)
Posterior	Border obscured (without resection of soft tissue)	Ligament was attached to the tip of the medial intercondylar tubercle, not attached to lateral intercondylar tubercle and intertubercular space (with resection of soft tissue)

Table 3

Morphology of Bony Prominence and Incidence of Three Bony Landmarks

	Incidence (%)	
n=60		
Morphology of bony prominence		
Oval	58.3	(35/60)
Triangular	41.6	(25/60)
Presence of bony landmark		
Anterior ridge	96.6	(58/60)
Lateral groove	100	(58/60)
Intertubercular fossa	96.6	(58/60)

Table 4

Measurement of ACL Tibial Bony Landmark

Measurement	Average ± SD* (mm)	Range (mm)	95% confidence interval (mm)	Figure correlation
n=58				
Distance from anterior ridge to anterior margin of intertubercular fossa (A1)	13.5 ± 1.7	10.7 - 18.1	13.08 – 13.9	Figure 2 (A1)
Distance from anterior ridge to ACL tibial ridge (A2)	17.2 ± 2.1	14.3 - 22.7	16.9 – 17.8	Figure 2 (A2)
n=60				
Distance from medial intercondylar ridge to medial margin of lateral groove (B1)	9.1 ±1.6	5.8 − 13.3	8.7 – 9.5	Figure 2 (B1)
Distance from medial intercondylar ridge to lateral margin of lateral groove (B2)	11.7 ±1.7	8.6 − 16.8	11.3 – 12.2	Figure 2 (B2)
n=58				
Length of anterior ridge (C)	10.9 ±2.8	7.2 – 14.9	10.2 – 11.7	Figure 2 (C)
n=60				
Length of lateral groove (D1)	10.3 ±1.9	6.2 – 14.9	9.8 – 10.8	Figure 2 (D1)
Width of lateral groove (D2)	5.3 ±1.1	3.5 – 8.9	5.0 – 5.6	Figure 2 (D2)

*SD: standard deviation.

Table 5

ACL Tibial Insertion Size and Anatomical Landmark by Previous Study

Author	Mean length ± SD* (mm) (range)	Mean width ± SD* (mm) (range)	Anatomical landmark for tunnel positioning
Siebold et al.[28]	14±2mm (9-18)	10±2mm (7-15)	Square model: anterior/posterior border of ACL remnant, antero-medial/-lateral border rim of articular surface
Tállay et al.[29]	19.5±2.6 mm (14.5-24.7)	10.3±1.9mm (7.1-15.1)	Distance from anterior edge of tibia (AM: 17.2±4.1 mm, PL: 25.6±14.8mm)
Morgan et al.[22]	18 mm (14-21)	10mm (8-12)	Distance from PCL (center: 6-7mm)
Ferretti et al.[6]	18.1±2.8 mm (13.7-22.1)	10.7±1.9mm (7.4-13.1)	Anterior: intermeniscal ligament Posterior: medial tibial eminence
Edwards et al.[5]	18±2 mm (11-23)	Not described	Distance from the over the back ridge (AM: 17±2 mm anterior, PL: 10±1 mm anterior)
Heming et al.[10]	18.5 mm	10.3 mm	Tibial notch of PCL Center: 15.0 mm anterior
This study	13.5 ±1.7 mm (10.7-18.1)	11.7±1.7mm (8.6-16.8)	Anteromedial: L-shaped ridge Lateral: anterior horn of lateral meniscus Posterior: medial/lateral intercondylar tubercle

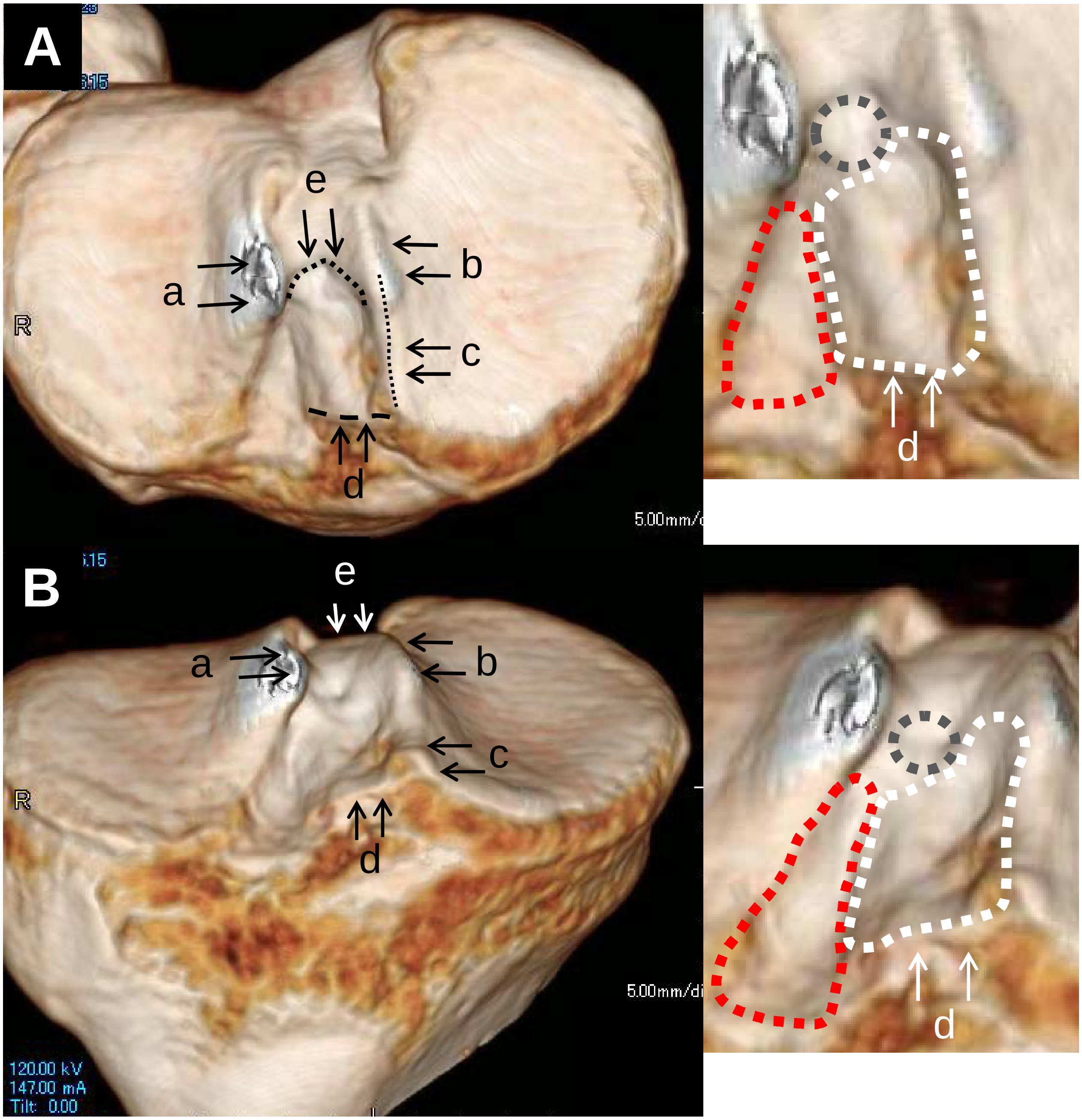

Figure 1

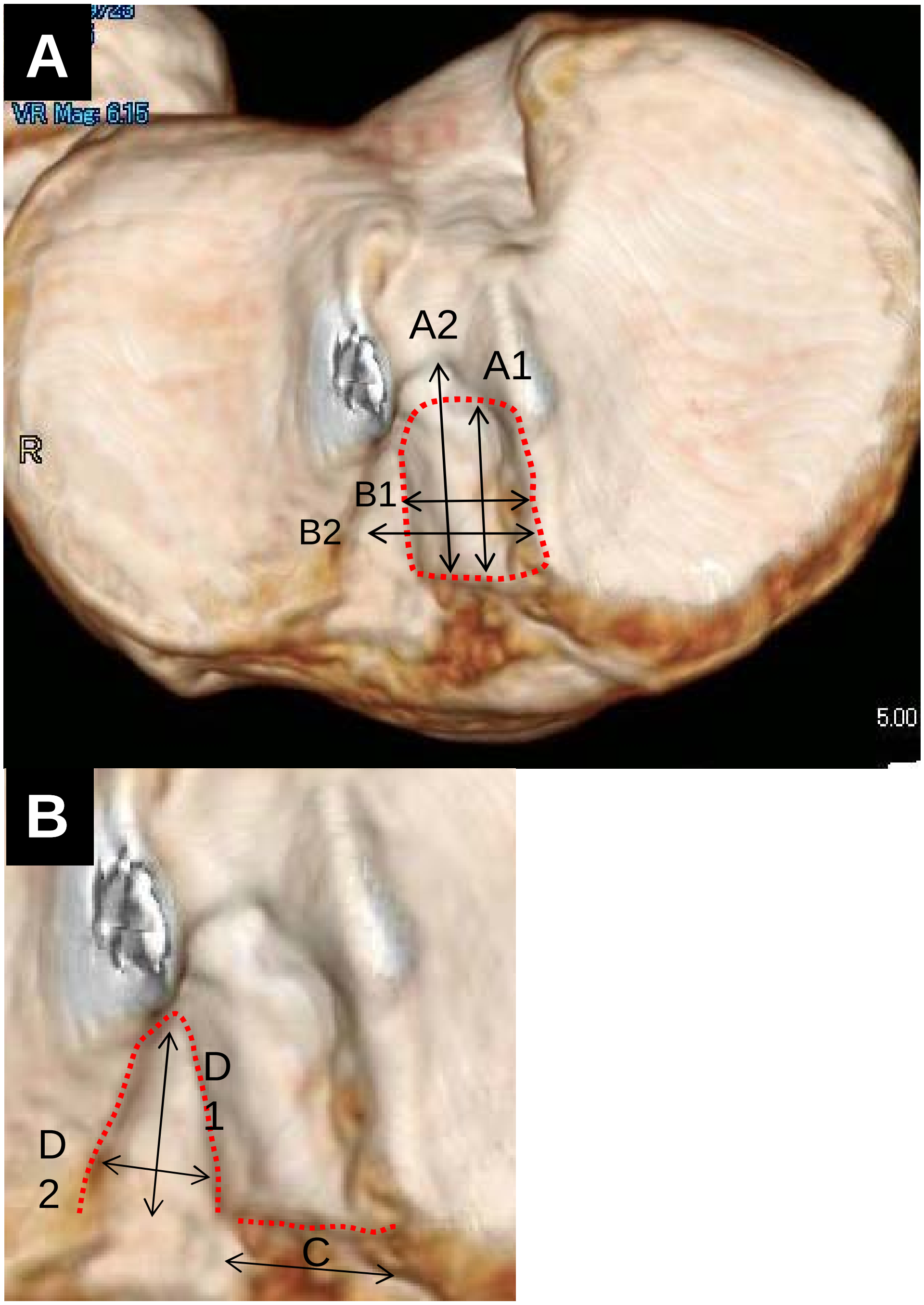

Figure 2

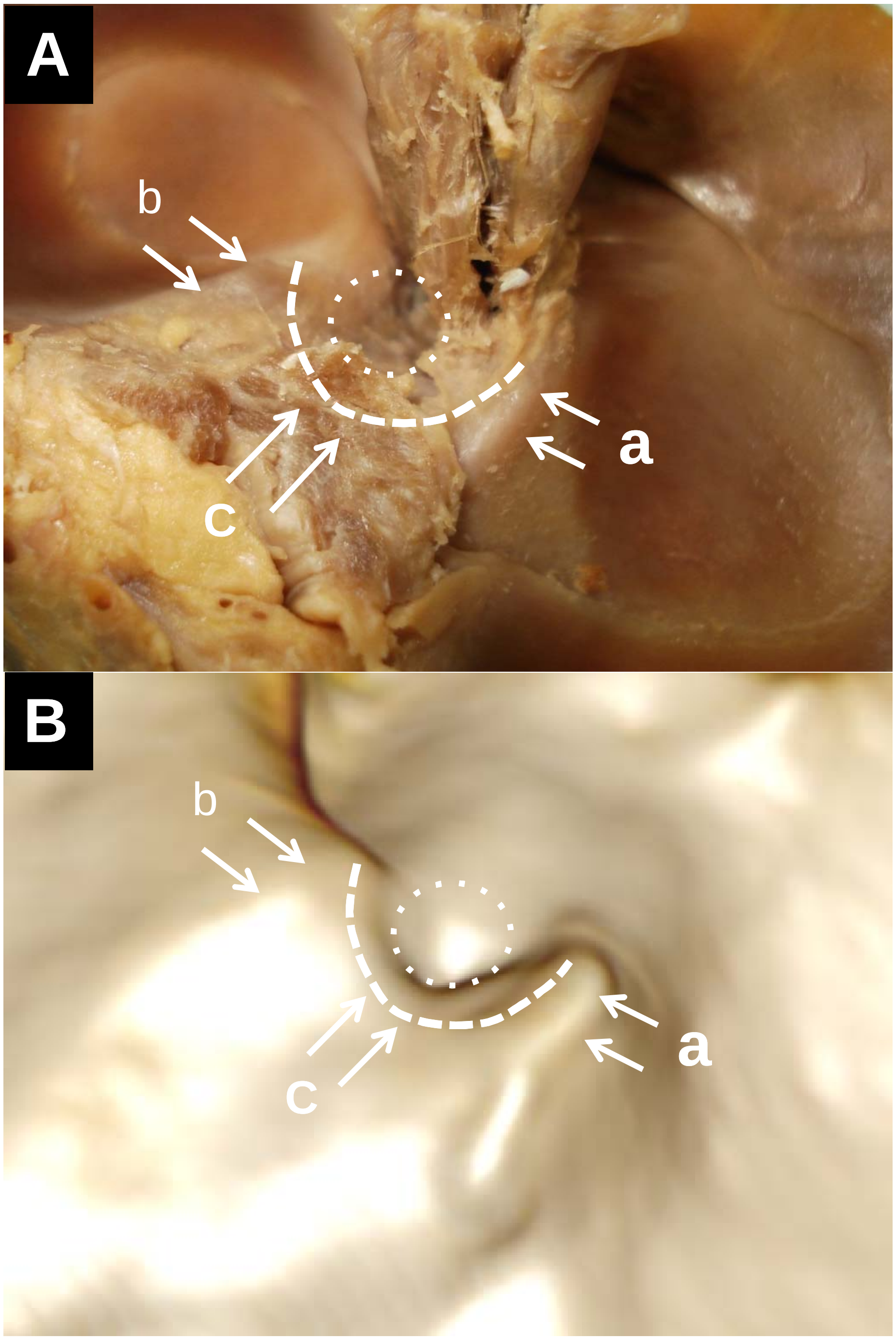

Figure 3

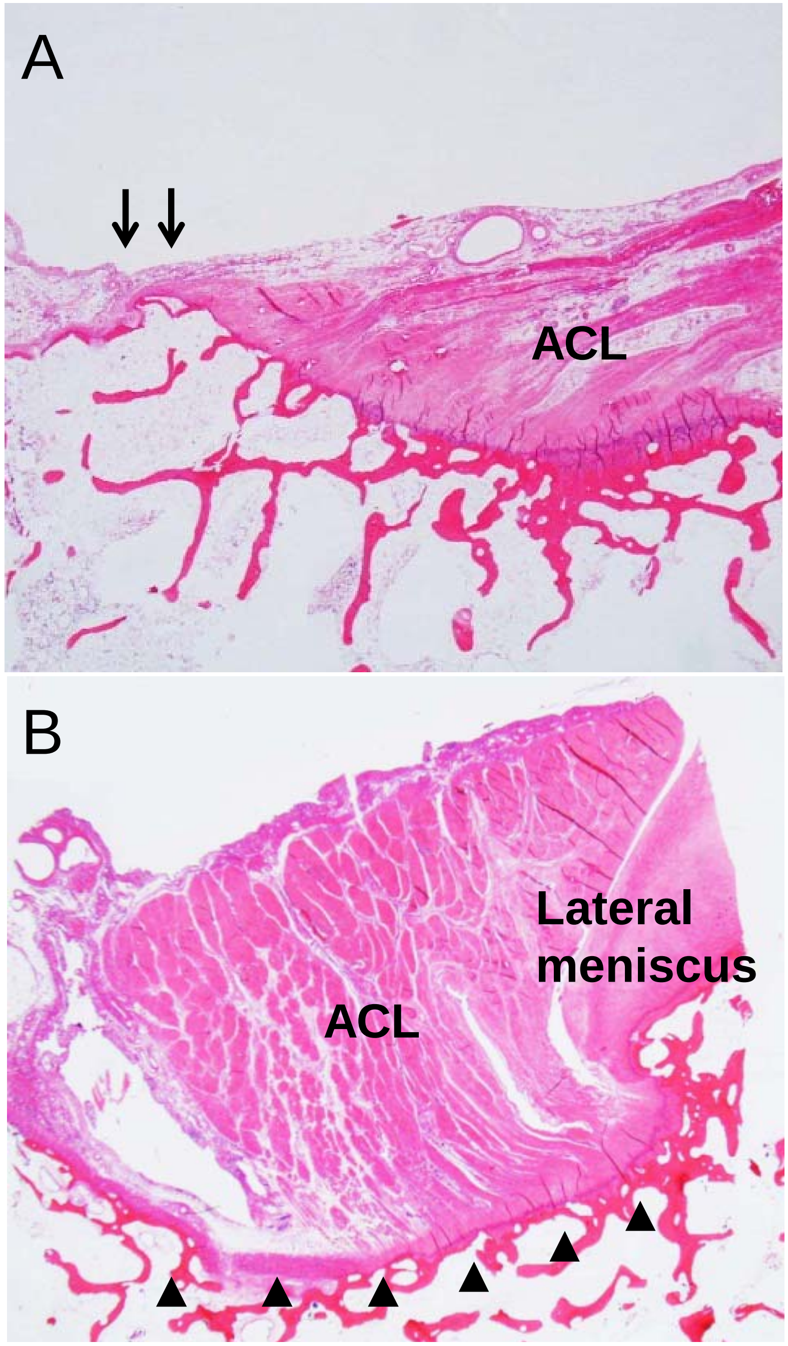

Figure 4

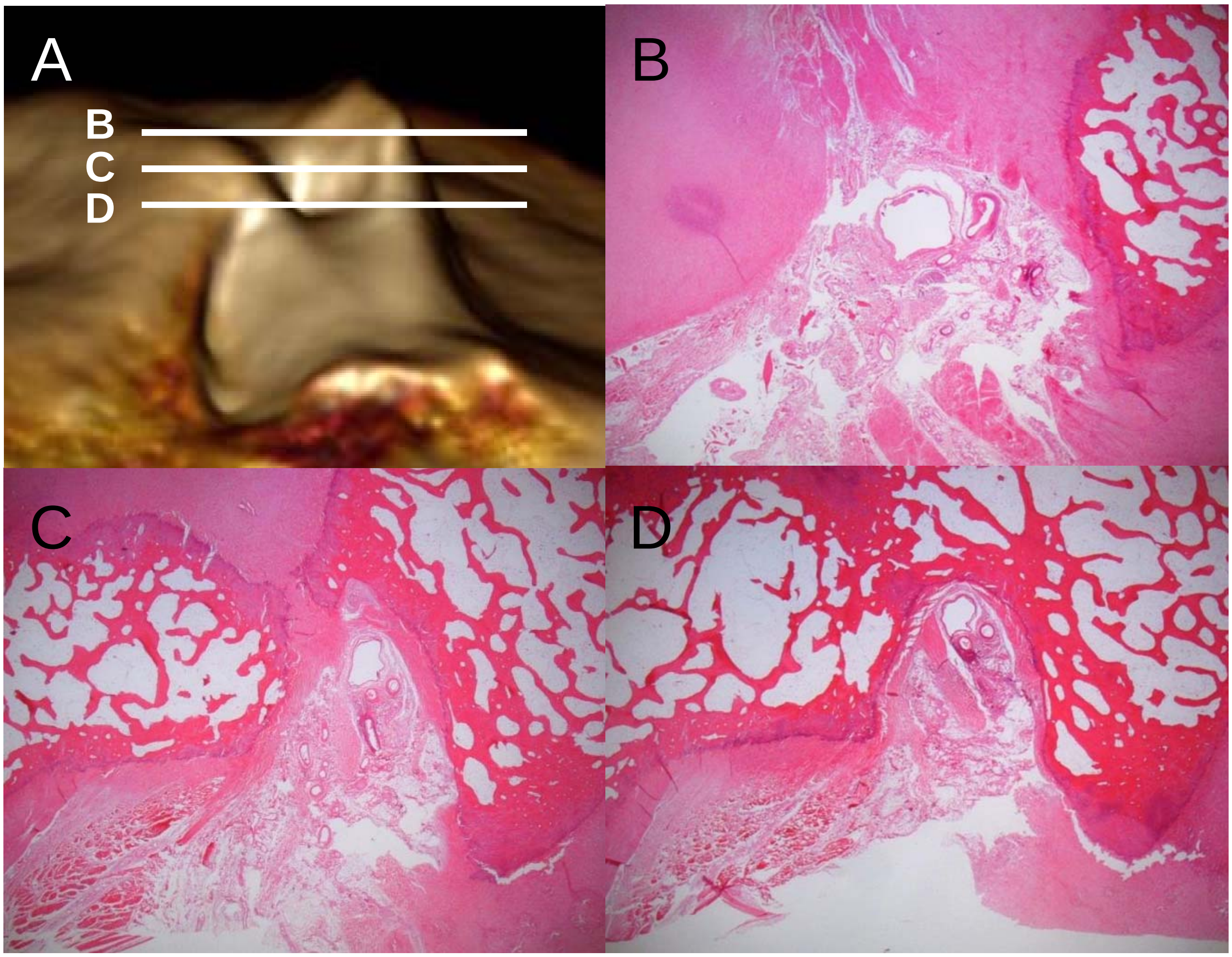

Figure 5