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Anterior cruciate ligament tibial insertion site is elliptical or triangular shaped in healthy young adults: high-resolution 3-T MRI analysis

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Abstract
Purpose To clarify the morphology of anterior cruciate ligament (ACL) tibial insertion site in healthy young knees using high-resolution 3-T MRI.
Methods Subjects were 50 ACL-reconstructed patients with a mean age of 21.4 ± 6.8 years. The contralateral healthy knees were scanned using high-resolution 3-T MRI. The tibial insertion sites of the anteromedial (AM) and posterolateral (PL) bundle fibres, and the ACL attachment on the anterior horn of lateral meniscus (AHLM) were segmented from the MR images, and 3D models were reconstructed to evaluate the morphology. The shape of ACL footprint was qualitatively analysed, and the size of AM and PL attachments and AHLM overlapped area was measured digitally.
Results Tibial AM and PL bundles were clearly identified in 42 of 50 knees (84.0%). Morphology of the whole ACL tibial insertion site was elliptical in 23 knees (54.8%) and triangular in 19 knees (45.2%), but not classified as C-shape in any knees. However, the AM bundle attachment was of C-shape in 29 knees (69.0%) and band-like in 13 knees (31.0%). Overlap of ACL on AHLM was found in 26 knees (61.9%), and the size of the overlapped area was 4.8 ± 4.7% of the whole ACL insertion site.
Conclusion 3D morphology of the intact ACL tibial insertion site analysed by high-resolution 3-T MRI was elliptical or triangular in healthy young knees. However, the AM bundle insertion site was of C-shape or band-like. A small lateral portion of the ACL was overlapped with the AHLM. As for clinical relevance, these findings should be considered in order to reproduce the native ACL insertion site sufficiently.
Level of evidence III.

Keywords Anterior cruciate ligament · Morphology · Tibial insertion site · High-resolution · MRI · Young · Footprint

Abbreviations

ACL	Anterior cruciate ligament
AM	Anteromedial
PL	Posterolateral
MRI	Magnetic resonance imaging
ICC	Inter-class correlation coefficients
AHLM	Anterior horn of lateral meniscus

Introduction

Anatomical anterior cruciate ligament (ACL) reconstruction has been reported to be advantageous in restoring normal knee function and kinematics [1, 4, 14]. The principle of anatomical ACL reconstruction is to restore the dimension, collagen orientation and insertion site of the native ACL [6, 7]. Therefore, it is essential to understand the anatomy of the native ACL insertion site.

It has been well known that the anatomy of ACL has double-bundle of anteromedial (AM) and posterolateral (PL) fibres [2, 25, 35, 39]. Some studies have argued that ACL has a ribbon-like appearance of the mid-substance fibres and a "C"-shaped tibial insertion site [23, 30, 31].

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Furthermore, recent cadaveric studies have reported substantial "direct fibres" ACL insertion on the more anterior part of its whole footprint [17, 19, 26], implying the importance of reproducing this localized area. However, most previous studies on ACL anatomy are based on older cadaveric specimens. Because degeneration of the ACL and significant decrease in mechanical properties can occur with the specimen age [38], the anatomical findings of older specimens might be different from younger ones. Focusing only on older specimens with degenerative changes in some part of ACL fibres may lead to an underestimation of ACL area in young individuals.

The geometry relation between the ACL tibial insertion site and the anterior horn of the lateral meniscus (AHLM) has also been focused on recently [3, 9, 10, 32]. It is important to understand the 3D relationship of the insertion site of these structures in order to avoid iatrogenic injuries to the AHLM during reaming of tibial bone tunnels [11]. Damage to the AHLM can cause deviation of the lateral meniscus and decrease of function as a secondary stabilizer of the knee [18, 28].

The purpose of this study was to clarify the morphology of ACL tibial insertion site in healthy young knees using high-resolution 3-T MRI. It was hypothesized that (1) intact ACL tibial insertion site would be of elliptical or triangular shape, (2) AM bundle attachment would be classified as C-shape, and (3) some ACL fibres overlap anterior horn of lateral meniscus. Findings from healthy young subjects would be relevant to the generation who needs ACL reconstruction.

Materials and methods

A total of 50 patients with a mean age of 21.4 ± 6.8 years old underwent bilateral 3-T MRI (Siemens Trio) during their time course after ACL reconstruction in a clinical trial [16]. The contralateral healthy knee data were used for this study. Thirty-three patients were male, and 17 were female. Physical examination showed no evidence of ACL dysfunction such as positive Lachman test or pivot-shift test. The MRI sequence used was three-dimensional double-echo steady state (3D DESS) with a high resolution of 0.365 × 0.365 × 0.70 mm voxels (TR = 16.3 ms, TE = 4.7 ms, slice gap = 0 mm). The ACL tibial insertion was identified, and the attachment of anteromedial (AM) and posterolateral (PL) bundle fibres was distinguished from each other based on its appearance, principally using the sagittal MR images (Fig. 1a) and checked simultaneously with coronal and axial images using 3D processing software (Mimics®, Materialise, Leuven, Belgium). AM and PL bundle insertion sites were segmented on every image with a thickness of 4 pixels, and the 3D models showing the morphology were created from the series of high-resolution 2D slices using the 3D reconstruction algorithm (Fig. 1b). In addition, the lateral meniscus was also segmented and the overlap of ACL fibres with the anterior horn of the lateral meniscus (AHLM) was determined (Fig. 1c).

Evaluation

Patients with intra-ligamentous cyst ($n = 2$), poor MR images due to artefact ($n = 2$) and difficulty in clearly distinguishing AM and PL ($n = 4$) were eliminated from the analysis. The shape of whole ACL tibial insertion site was categorized into elliptical (type I), triangular (type II) and C-shape (type III), according to a classification system, as previously described [12]. The shape of AM bundle tibial insertion was also assessed in axial view and classified as C-shape or band-like. Secondly, the ACL tibial insertion site was projected onto the axial plane of the tibia plateau, and the size of the AM and PL footprint and the AHLM overlapped areas was measured digitally, according to a previously reported method (Fig. 2) [8]. Medial–lateral width and anterior–posterior length of the whole ACL tibial insertion site and AHLM overlapped area were also measured.

The institutional review board (IRB) for human subject research in University of Pittsburgh (3500 Fifth Avenue, Pittsburgh, PA 15213, USA) approved all aspects of this study (ID: PRO09020493), and informed consent was obtained for all patients before enrolment.

Statistical analysis

In order to examine the reliability of MRI analysis, segmentation of the ACL tibial footprint was repeated twice with an interval of 3 months in ten knees by one observer (Y.T.) and repeated twice in ten knees by two independent observers (G.A.L. and Y.T.). The intra-class and the inter-class correlation coefficients (ICCs) were calculated, respectively. For the reliability of footprint shape classification, it was independently categorized by the two observers in all knees and the kappa coefficient value was calculated for the category value [27]. Power analysis was performed from the data reported in a previous study [12] (51, 33 and 16% for each shape type, Cohen's Kappa statistic = 0.73, significant level = 0.05 and power = 0.80) to indicate sample sizes of 35 could address the questions.

Results

Anteromedial (AM) and posterolateral (PL) bundles could be clearly identified in 42 of 50 knees (84.0%).

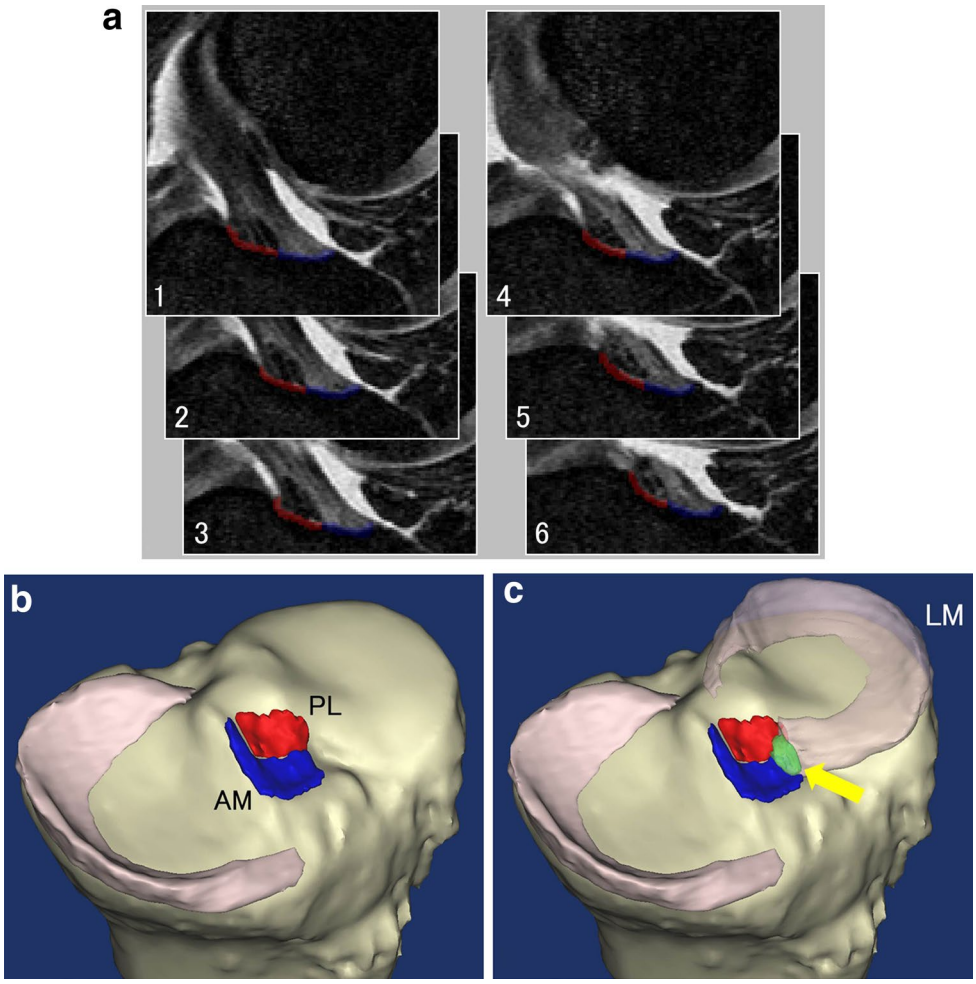

Fig. 1 **a** Anteromedial (AM: blue) and posterolateral (PL: *red*) bundle fibres of the ACL are distinguished from each other at the tibial side, and the attachment is segmented from the sagittal MR images. **b** A 3D model of proximal left tibia with AM and PL insertion sites was created from the MRI slices using the Mimics® software. Medial meniscus is shown in this figure. **c** The lateral meniscus (LM) is segmented and shown in 3D. The overlap of ACL fibres and anterior horn of lateral meniscus (AHLM) is also segmented and reconstructed in 3D (*green* area indicated with *arrow*)

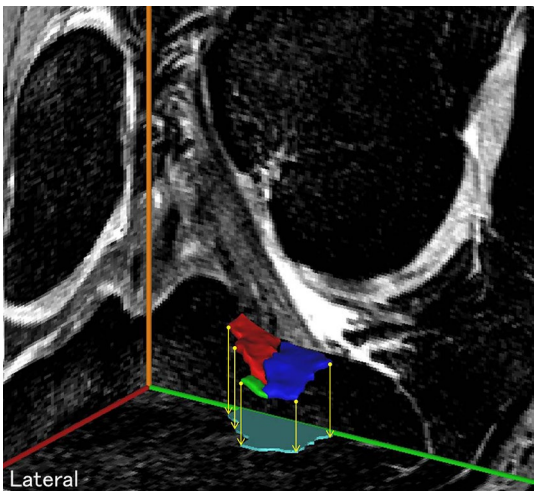

Fig. 2 For the measurement of footprint area (*light blue*), the ACL tibial insertion site was projected onto the axial plane which fits to tibia plateau. Each size of AM (*blue*), PL (*red*) footprint and AHLM overlapped (*green*) areas was measured digitally, according to a previously reported method [8]

Morphology of the whole ACL tibial insertion site was classified as elliptical (Fig. 3a) in 23 knees (54.8%), triangular (Fig. 3b) in 19 knees (45.2%) and C-shape in 0 knees (0.0%), whereas if PL bundle was eliminated and only AM bundle attachment was considered, it was of C-shape (Fig. 4a) in 29 knees (69.0%) and band-like (Fig. 4b) in 13 knees (31.0%). Overlap of ACL and anterior horn of LM (AHLM) was seen in 26 knees (61.9%), but no overlap was seen or just adjacent laterally in 16 knees (38.1%).

The whole ACL area of the ACL tibial insertion site was 182.7 ± 41.1 mm^2 (Table 1). The AM bundle accounted for 53.6 ± 12.5%, the PL bundle for 41.6 ± 13.4%, and the LM overlapped area for 4.8 ± 4.7% of the whole ACL insertion site. Width of the whole ACL tibial insertion site was 14.5 ± 2.2 mm, and length was 15.6 ± 1.8 mm. Width of the LM overlapped area was 2.8 ± 0.9 mm, and length was 4.8 ± 1.7 mm.

The intra-observer reliability of MRI analysis was 0.93, 0.95, 0.94 and 0.90 in ICCs for the segmentation of whole ACL, AM and PL footprints, and overlap of ACL and

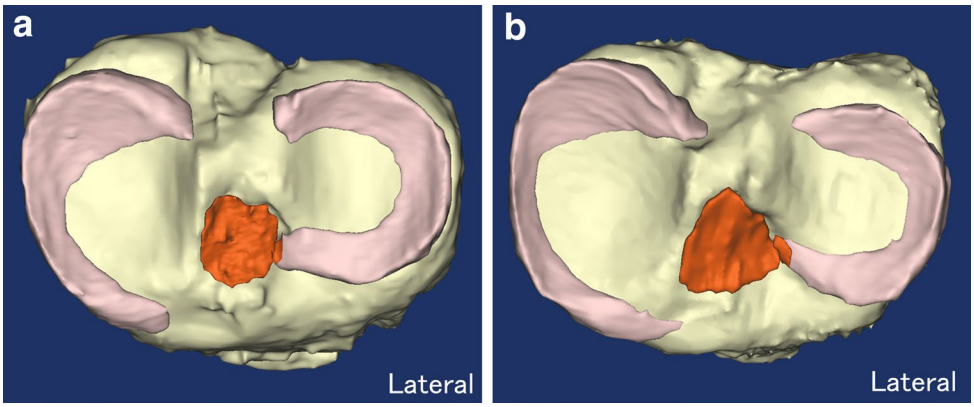

Fig. 3 Morphology of ACL tibial insertion site is shown in axial view. **a** An example of *elliptical* footprint of the whole ACL. **b** An example of *triangular* footprint. It was not classified as C-shape in any knee

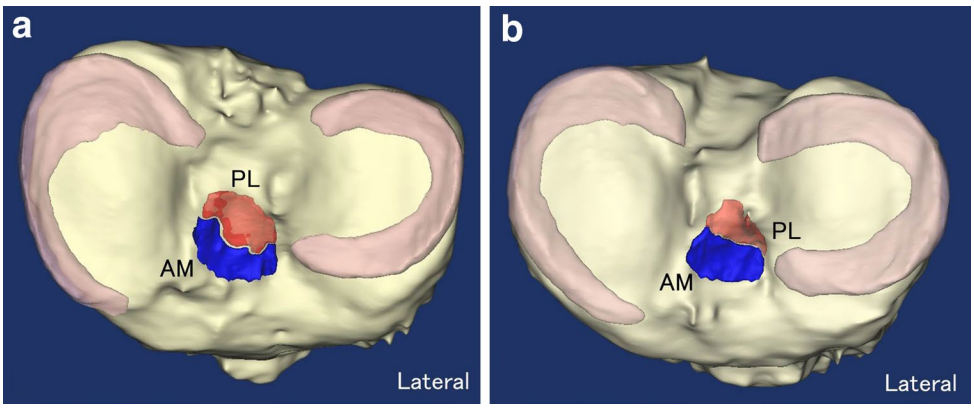

Fig. 4 If PL bundle was eliminated, AM bundle footprint looked C-shape (**a**) in 29 knees (69.0%) and band-like in 13 knees (31.0%) (**b**)

Table 1 Area of the ACL tibial insertion site

	Area (mm^2)	Percentage
AM bundle	98.0 ± 22.8	53.6 ± 12.5
PL bundle	76.0 ± 24.4	41.6 ± 13.4
LM attachment	8.7 ± 8.6	4.8 ± 4.7
Whole ACL	182.7 ± 41.1	100 ± 0.0

The values are presented as the mean ± standard deviation

AM anteromedial, *PL* posterolateral, *LM* lateral meniscus

AHLM, respectively. The inter-observer reliability was 0.87, 0.84, 0.89 and 0.89 in ICCs for whole ACL, AM and PL footprints, and overlap of ACL and AHLM. The reliability of classification for ACL tibial insertion site was 0.81.

Discussion

The most important finding of our study was that the ACL tibial insertion site in healthy young knees was attached to broad area with elliptical or triangular shape. A recent arthroscopic study classified the shape of ACL tibial insertion site in young subjects (mean 26 ± 11 years old) during ACL reconstruction [12]. The rate of ellipse (51%) and triangle (33%) shape was similar to our study, but C-shape was seen in 16% in their study and this was different with our findings. While our MR images were obtained from healthy knees, tissue could be degenerated after ACL injury during the waiting period; thus, the degeneration in their subjects may have been affected by the period from the injury to surgery [20].

Functions and anatomy of double-bundle ACL fibres and elliptical (oval) or triangular shape of its tibial attachment have been reported by many previous studies [2, 13, 22, 24, 25, 35, 39], which was consistent with our study. A recent novel anatomical study on foetus knees has also reported ovoid tibial insertion of the ACL footprint and the presence of two well-distinguished bundles [5]. In contrast, it was reported by a recent cadaveric study that the ACL tibial insertion site was flat and of C-shape, and there were no central or PL inserting fibres in specimens with a mean age of 78 years [30]. This report is seemingly inconsistent with our findings of the whole ACL footprint; however, if the PL bundle was eliminated and only the AM bundle attachment was considered in our young MRI-based models, most of them were of C-shape or band-like, corresponding to the results of the previous cadaveric study. Area of the ACL tibial insertion site in the present study was similar to the

area in previous studies with middle-aged specimens [8], but it was somewhat larger than the area in other studies with older-aged specimens [13, 15, 29]. Because ageing can affect mechanical properties, vascularity, and cell proliferation of the ligament [21, 36, 38], higher age in specimens may affect degeneration of the ACL, especially for PL bundles that may resist rotatory loads [25].

ACL attachment on the anterior horn of lateral meniscus (AHLM) was found in over 60% of our cases. Even in those cases without attachment, ACL insertion on the tibia was found to be closely adjacent to the AHLM. Recent studies using histological analysis or scanning electron microscopy have also reported that a certain lateral portion of ACL tibial insertion overlaps the AHLM in human cadaveric knees [10, 32]. Damage to the AHLM can lead to extrusion of the lateral meniscus and decrease in knee stability after surgery [18, 28]. Surgeons should be careful to avoid damaging the AHLM when creating tibial tunnels.

The intact ACL in healthy young knees was analysed using high-resolution 3-T MRI, and it was considered as the novelty of our study. The use of high-resolution images and strong magnetic field made it possible to visualize anatomical structures precisely [33, 34, 37] and allowed to clearly differentiate AM and PL bundles insertion sites. Computational 3D reconstruction was useful in visualizing the morphology of ACL tibial insertion site, which was uneven and difficult to fully understand only with 2D images.

It is acknowledged that there are some limitations to our study. It was difficult to dissect healthy young knee specimens with intact ACL. Therefore, high-resolution 3-T MRI was used for the analysis and high inter-class reproducibility was shown. Secondly, the femoral side was not described in our study. It was not easy to differentiate AM and PL bundles for the femoral side with high accuracy in our MR images; therefore, only tibial side was analysed.

The finding of our study is of clinical relevance. This may be associated with the creation of tibial tunnels in ACL reconstruction. Considering the ACL tibial insertion site as an anteromedially localized area such as C-shape, based only on the knowledge of high-age cadavers, may lead to reproduction of tibial footprint in extremely localized area. Not only the C-shaped (or band-like) AM area, but also the PL area should be taken into account in order to help restore the anatomical ACL insertion site. In addition, it is important to avoid damaging the anterior horn of lateral meniscus.

Conclusion

3D morphology analysis using high-resolution 3-T MRI showed the intact ACL tibial insertion site was elliptical or triangular, but not of C-shape in healthy young knees. The AM bundle had a C-shape or band-like attachment. A lateral part of ACL was overlapped with the anterior horn of the lateral meniscus (AHLM). It is necessary to consider both AM and PL bundles attachment areas, as well as preserving the AHLM to reproduce the native ACL insertion site sufficiently.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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Ethical approval The institutional review board (IRB) for human subject research in University of Pittsburgh (3500 Fifth Avenue, Pittsburgh, PA 15213, USA) approved all aspects of this study (ID: PRO09020493).

Informed consent Informed consent was obtained for all patients before enrolment.

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