ACTA
ORTHOPAEDICA
et
TRAUMATOLOGICA
TURCICA

Acta Orthop Traumatol Turc 2010;44(1):54-62
doi:10.3944/AOTT.2010.2246

Evaluation of the two bundles of the anterior cruciate ligament with 1.5 tesla magnetic resonance imaging

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Objectives: Studies on the anatomy of the anterior cruciate ligament (ACL) have shown that the normal ACL consists of two functional bundles named as anteromedial (AM) and posterolateral (PL) bundles. In this study, we evaluated the AM and PL bundles of the ACL using 1.5 tesla magnetic resonance imaging (MRI), which is routinely used in clinical practice.

Methods: The study included 150 patients (96 females, 54 males; mean age 33.4±11.6 years; range 18 to 59 years) who did not have any signs of ACL insufficiency and whose knees were examined by MRI for other reasons. Standard magnetic resonance images (77 right, 73 left) were evaluated independently by an orthopedist and a radiologist in terms of distinguishable ACL bundles. The angle between the ACL (and each bundle) and the tibial plateau was measured on sagittal and coronal sections. Arthroscopic surgery was performed in 64 patients (42.7%) for primary diagnoses and arthroscopic and MRI findings were compared.

Results: Magnetic resonance imaging showed an intact ACL in all the patients. The ACL was assessed as a single bundle in the axial, coronal, and sagittal planes in 93 patients (62%). A double-bundle appearance was noted in 57 patients (38%), involving all three planes in 14 patients (9.3%), axial and coronal planes in 41 patients (27.3%), coronal and sagittal planes in one patient (0.7%), and only coronal plane in one patient (0.7%). On MRI sections showing a single bundle ACL, the mean angle between the ACL and the tibial plateau was found as 55.3° in the sagittal plane, and 70.3° in the coronal plane. On sections with a double-bundle appearance, the mean angles between the AM bundle and the tibial plateau were 70.1° and 55.1° in the coronal and sagittal planes, respectively. The corresponding angles for the PL bundle were 81° and 53.5°. The incidence of double bundle ACL appearance in coronal, sagittal, and axial MRI sections was not influenced by sex and side ($p>0.05$). The number of bundles identified in each plane did not show a significant difference between the two observers ($p>0.05$). During arthroscopic surgery, both bundles were identified with normal integrity and function of the ACL in all the patients. Of these, MRI could depict a double-bundle appearance in one or more planes in only 42.2% of the patients.

Conclusion: Even though standard 1.5 tesla MRI, routinely used in clinical practice, has a very high success rate in demonstrating the ACL, it can visualize the two-bundle structure only in about one-third of the patients.

Key words: Anterior cruciate ligament/radiology; knee injuries/diagnosis; magnetic resonance imaging.

The anterior cruciate ligament (ACL) is a ligamentous structure contributing to joint stability through limiting tibial translation in relation to the femur and is one of the most frequently injured knee ligaments.[1-4] The incidence of ACL injuries is higher in athletes practicing high-risk sports.[5-7]

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Submitted: March 17, 2009 **Accepted:** October 1, 2009

Anatomic and embryologic studies have shown that human ACL consists of two separate, functional bundles.[8-14] These two bundles are termed based on their tibial insertions.[15] While the anteromedial bundle (AM) lies in the tibial plateau between the medial aspect of the intercondylar eminence of the tibia and the proximal part of the medial surface of the lateral femoral condyle, the posterolateral (PL) bundle lies on the posterolateral side of the AM bundle in the tibia, between the most medial side of the posterior horn of the lateral meniscus and the anterior cartilage edge of the lateral femoral condyle.[10-12] Both bundles contribute to the stability of the knee: the AM bundle limits anteroposterior translation throughout the knee range of movement, especially during flexion, while the PL bundle limits anterior tibial translation and knee rotation, especially during extension.[16-18] The AM and PL bundles are tight during knee flexion and extension, respectively. While both bundles become parallel and approach each other during extension, they become crossed during flexion displaying a broad-base insertion (Fig. 1).

Magnetic resonance imaging (MRI) is a widely used imaging modality providing information about the natural structure and injuries of the ACL. The sensitivity and specificity of MRI in displaying pathologic conditions of the ACL vary from 90% to 94% and from 95% to 100%, respectively, in broad series using arthroscopy as reference standard.[19-24] On MRI, normal ACL is visualized between the femoral insertion at the most posterior aspect of the intercondylar notch at the lateral femoral condyle and tibial insertion at the anterior aspect of the intercondylar eminence of the tibia. The orientation of normal ACL is approximately parallel to the roof of the intercondylar notch.[20,25] As knee MRIs are normally taken in extension, in the sagittal plane, the PL bundle is tight, and both bundles are approximately parallel to each other. While MRI has a high accuracy in the imaging of normal and completely torn ACLs, information on double bundle structure is not adequate.[26-28] On routine MRI, the AM bundle is usually the one that can be evaluated and the PL bundle is less frequently observed.[28]

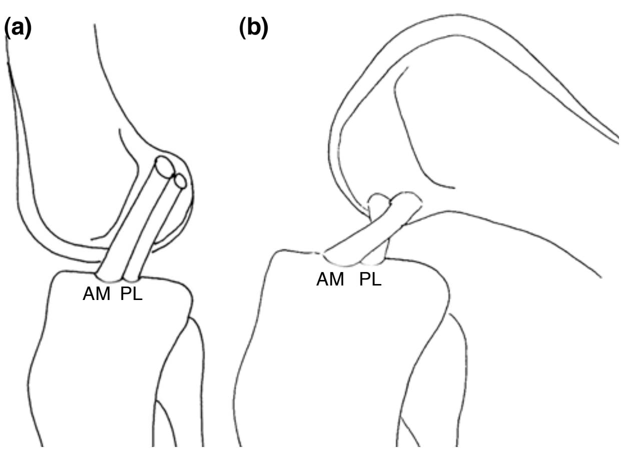


Fig. 1. Schematic drawings of the anteromedial (AM) and posterolateral (PL) bundles of the anterior cruciate ligament in (a) flexion and (b) extension.

The purpose of our study was to obtain information on the double bundle anatomy of normal ACL using 1.5 tesla standard MRI procedure, one of the most frequently used methods in the radiologic imaging of the knee. Based on anatomical studies showing that the human ACL consists of two bundles, we hypothesized that this double-bundle appearance might be visualized on routine knee MRIs. Although there are few studies in the literature using 0.2 and 3 tesla MRI systems,[28,29] the double bundle anatomy of the ACL has not been investigated using 1.5 tesla MRI. We hope that our findings would provide more insight into the normal MRI anatomy of the ACL and serve as a guide for MRI evaluations following double-bundle ACL reconstructions.

Patients and methods

The study included 150 patients (96 females, 54 males; mean age 33.4±11.6 years; range 18 to 59 years) who presented to the Department of Orthopedics and Traumatology with nontraumatic knee complaints between January and October 2008. The patients were evaluated by an orthopedist for primary symptoms and findings, and with the Lachman, pivot shift, and anterior drawer tests. All the patients were below the age of 60 years, had negative results with the Lachman, pivot shift, and anterior drawer tests, did not have any signs by history, complaints, and physical examination findings suggesting ACL insufficiency, and underwent MRI examination for other complaints. Demographic data, study date, and primary preliminary diagnosis were recorded for each patient (Table 1).

Patients with symptoms and physical examination findings (instability, acute trauma, infrapatellar plica, synovial hypertrophy, inflammatory arthritis, effusion, joint laxity) that might disrupt the anatomy and function of the ACL or interfere with the MRI imaging of the ACL were excluded. Preliminary di-

Table 1
Demographic features and primary clinical and MRI diagnoses of the patients

	n	%
Gender		
Male	54	36.0
Female	96	64.0
Side		
Right	77	51.3
Left	73	48.7
Intact ACL on MRI	150	100.0
Clinical and MRI diagnoses		
Medial meniscus tear	21	14.0
Lateral meniscus tear	14	9.3
Chondral lesions	23	15.3
Medial plica	13	8.7
Osteonecrosis	11	7.3
Patellofemoral problems	24	16.0
Combined lesions	23	15.3
Normal clinical and MRI findings	21	14.0

MRI: Magnetic resonance imaging; ACL: Anterior cruciate ligament.

agnoses were chronic medial meniscus tears, chronic lateral meniscus tears, chronic chondral lesions, plica syndromes, patellofemoral problems, osteonecrosis, and combined lesions. Some patients underwent MRI due to unexplained knee pain or failure of the conservative treatment (Table 1).

Each patient underwent standard MRI examination while the knee joint was in extension, including axial T2, proton density, sagittal T1-weighted and T2-weighted inversion recovery, coronal T1- and T2-weighted images. Each scan was taken using a 1.5 tesla closed MRI system (Signa Excite, GE Medical Systems, Waukesha, WI, USA). The MRI protocol contained sagittal spin echo T1-weighted, proton density-weighted and gradient coronal spin echo, T1 proton density-weighted and axial proton density-weighted images. Additional images and planes were not included.

Magnetic resonance images were evaluated independently by an orthopedic surgeon and a radiologist with MRI experience in terms of distinguishable ACL bundles. Each observer assessed identifiable AM and/or PL bundles of the ACL in coronal, sagittal, and axial views and recorded the findings (Fig. 2, 3). Then, the patients were randomly selected by computer and were re-evaluated by the same observers without knowing the initial evaluation results.

During the same period, arthroscopic surgery was performed in 64 patients (42.7%) based on the indications related to their primary diagnoses, during which the intactness of the ACL and the bundles were examined.

The course of the ACL in relation to the tibial plateau was determined by angular measurements on sagittal and coronal sections. The angle between the line parallel to the tibial plateau (perpendicular to the tibial shaft) and the long axis of the ACL (in case of discernible AM and PL bundles, the long axis of the individual bundles) was measured and recorded using a computer-based system (GE Medical Systems, Centricity Enterprise) (Fig. 4).

Statistical analysis

Each observer recorded the number of distinguishable ACL bundles for each patient in three MRI planes at two different times. The mean age of the patients, the number of distinguishable bundles in women and men, and the mean angles made by the AM and PL bundles with the tibial plateau in sagittal and coronal planes were determined. The relationship of single or double bundle imaging with gender and side was examined in each plane by the Pearson chi-square test. Our hypothesis was that double-bundle identification of the ACL should be independent of gender and side. The concordance between the two observers in assessing

Table 2
Details of visible bundles on MRI

	Single bundle	Double bundle	Total
Side			
Right knee	42	35	77
Left knee	51	22	73
Gender			
Female	61	35	96
Male	32	22	54
Total	93	57	150
Planes			
Axial-coronal-sagittal	93	14	
Axial-coronal	–	41	
Coronal-sagittal		1	
Coronal		1	

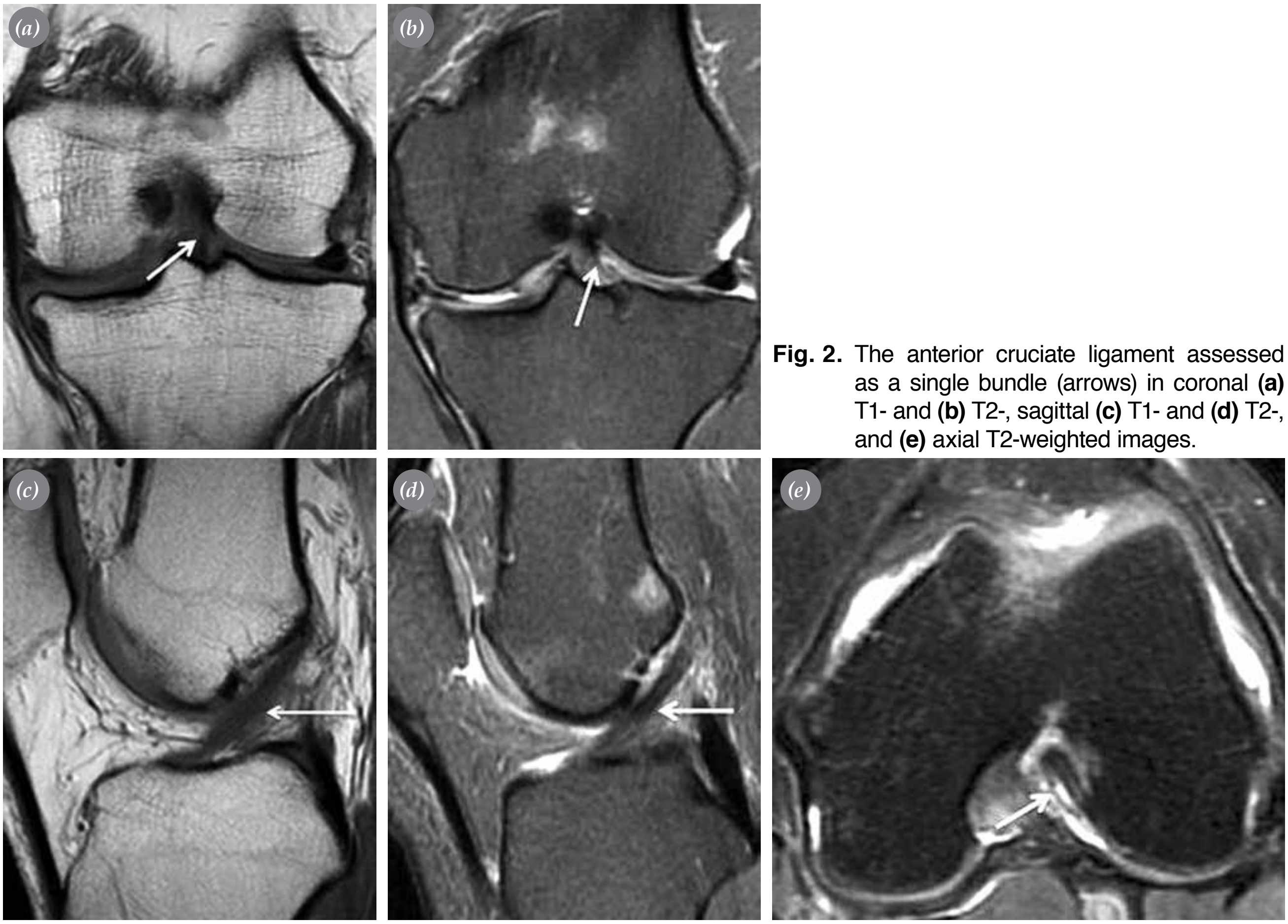


Fig. 2. The anterior cruciate ligament assessed as a single bundle (arrows) in coronal **(a)** T1- and **(b)** T2-, sagittal **(c)** T1- and **(d)** T2-, and **(e)** axial T2-weighted images.

each plane was examined by the descriptive analysis method. All statistical analyses were made using the SPSS statistical software (Windows, version 16.0).

Results

A total of 150 knee MRI scans (77 right, 73 left) were evaluated (Table 2). In all MRI scans and during arthroscopic examination, it was determined that all patients had an intact ACL and that there was not any anatomic variation.

The ACL was assessed as a single bundle in axial, coronal, and sagittal planes in 93 patients (62%). A double-bundle appearance was noted in 57 patients (38%), involving all three planes in 14 patients (9.3%), axial and coronal planes in 41 patients (27.3%), coronal and sagittal planes in one patient (0.7%), and only coronal plane in one patient (0.7%) (Table 2).

Concerning sex distribution, 35 female patients and 22 male patients exhibited a double bundle ACL (Table 2). The rates of single and double bundle ACL were 63.5% and 36.5% in women, and 59.3% and 40.7% in men, respectively. The incidence of double bundle ACL appearance in coronal, sagittal, and axial MRI sections was not influenced by sex and side ($p>0.05$; Table 3).

Table 3

The relationship of gender and side with visible double bundle appearance in axial, coronal, and sagittal MRI planes

	Pearson chi-square *p*	Continuity correction *p*
Gender-		
Coronal plane		0.731
Axial plane		0.805
Sagittal plane		0.955
Side		
Coronal plane	0.829	
Axial plane	0.839	
Sagittal plane		1.00

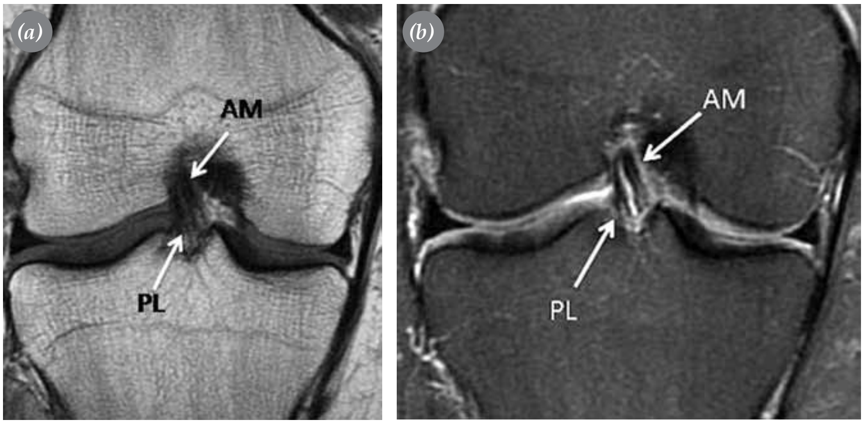
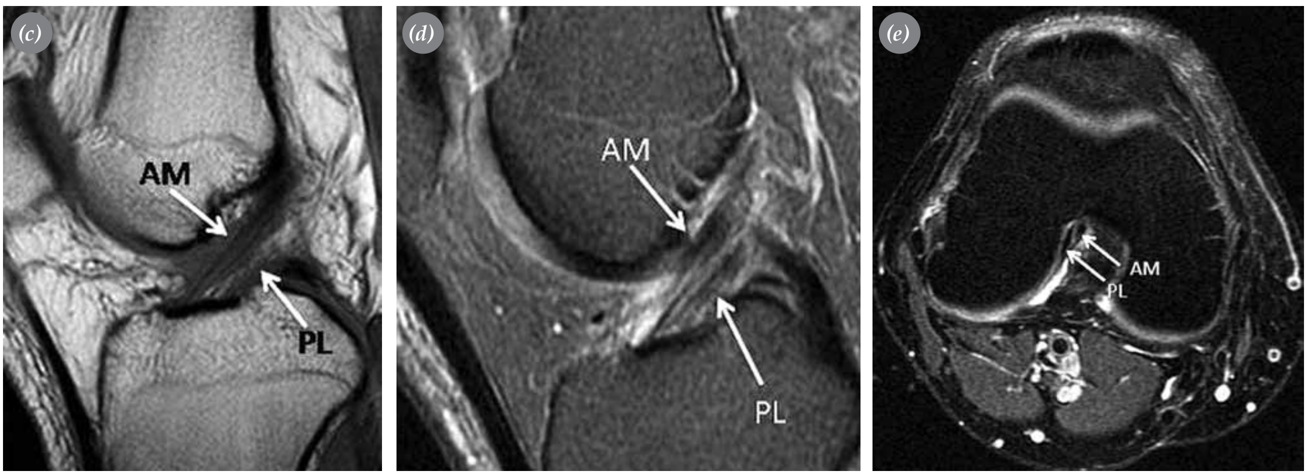


Fig. 3. The anterior cruciate ligament assessed as double bundle (arrows) in coronal **(a)** T1- and **(b)** T2-, sagittal **(c)** T1- and **(d)** T2-, and **(e)** axial T2-weighted images. AM: Anteromedial bundle; PL: Posterolateral bundle.



The ACL was examined in detail in 64 patients (42.7%) who underwent knee arthroscopy for the treatment of primary diagnoses. The AM and PL bundles were examined in knee flexion and in the figure-of-four position, respectively, with the arthroscopy probe with respect to their course, tibial and femoral insertion sites, and integrity (Fig. 5). In all the patients, the ACL was arthroscopically observed with two bundles, having normal integrity and function.

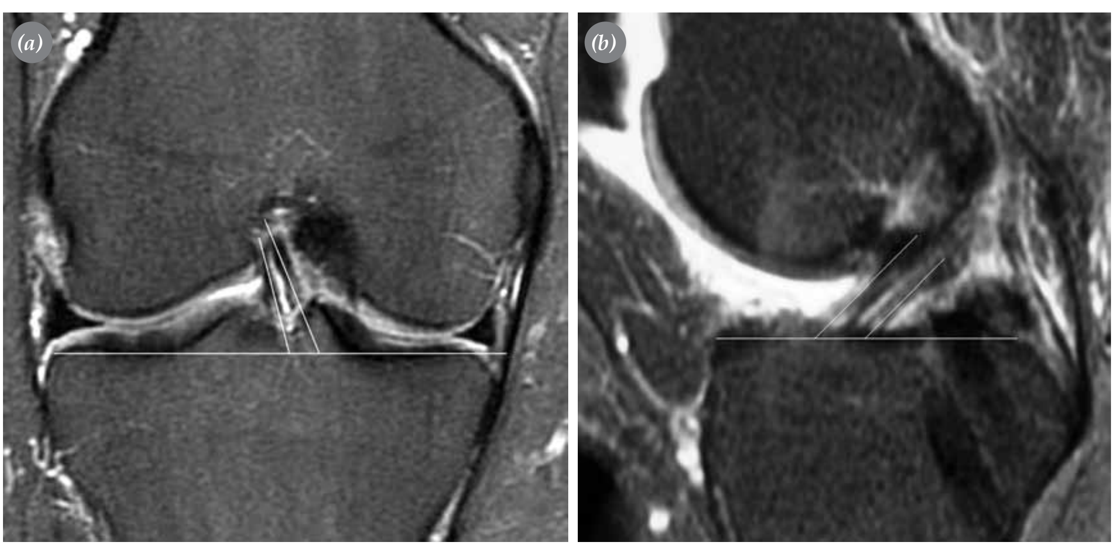


Fig. 4. The angular relationship between the two bundles and the tibial plateau on **(a)** sagittal and **(b)** coronal T2-weighted images.

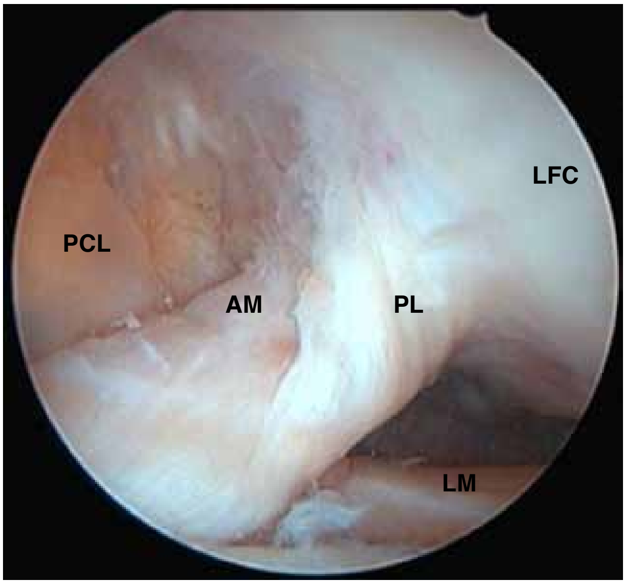


Fig. 5. Imaging of the two bundles of the anterior cruciate ligament in knee arthroscopy. PCL: Posterior cruciate ligament; AM: Anteromedial bundle; PL: Posterolateral bundle; LFC: Lateral femoral condyle; LM: Lateral meniscus.

Taking arthroscopic identification of double bundle ACL in 64 patients as reference, MRI could depict a double-bundle appearance in only 27 patients (42.2%) in one or more planes.

Descriptive analysis of observer agreement for the number of bundles identified in each plane (coronal, sagittal, and axial) did not show a significant variation between the two observers (p=0.48, p=0.31, p=0.49, respectively).

On MRI sections showing a single bundle ACL, the mean angle between the ACL and the tibial plateau was found as 55.3° (range 53.2° to 56.9°) in the sagittal plane, and 70.3° (range 69.3° to 72.5°) in the coronal plane. On sections with a double-bundle appearance, the mean angles between the AM bundle and the tibial plateau were 70.1° (range 68.8° to 72.2°) and 55.1° (range 53.4° to 57.2°) in the coronal and sagittal planes, respectively. The corresponding angles for the PL bundle were 81° (range 78.6° to 83.3°) and 53.5° (range 52° to 56.4°).

Discussion

The anterior cruciate ligament may be evaluated radiologically with plain radiography, arthrography, and MRI. Although plain knee radiographs may well show signs of blurring of Hoffa's fat pad, joint effusion, avulsion fractures of the tibial intercondylar eminence, and impaction of the lateral cavity, they provide limited information on the integrity of the normal ACL and tears without bone involvement.[25] Contrast arthrography, on the other hand, is an invasive procedure performed through injection of an iodinated contrast agent, allowing indirect visualization of the cruciate ligaments. The first reports on the use of MRI in knee pathologies date back to 1980s.[25,30,31] Reicher et al.[30] published the normal MRI findings of the knee in 1985, together with monitoring of the ACL in sagittal sections but with unclear demarcation. Since then, MRI proved to be the best noninvasive auxiliary diagnostic tool in the evaluation of the ACL.

Based on the anatomical, biomechanical, and embryological studies showing that the normal ACL consists of two distinct functional bundles, some authors emphasize the need to identify the type of tears in more detail and recommend to perform anatomic repairs for rotational stability including the repair of both bundles. Double bundle ACL reconstruction is currently performed as a more popular method in some centers with increasing frequency.[10,11,13,14,16,32-35] Proponents of this technique suggest that imitation of the normal anatomy as much as possible would result in better clinical results and decrease problems such as graft insufficiency and impingement in extension. While the MRI features of the normal ACL is known, studies on the imaging of double bundle structure are limited. The normal ACL is observed in the MRI sagittal plane approximately parallel to the Blumensaat line, making a mean angle of 55 degrees with the tibial plateau, and coursing from the posteromedial fossa of the lateral femoral condyle inferomedially, anteromedial to the intercondylar eminence of the tibia.[36,37] Our study was performed to determine the rate of visualization of the two bundles of the normal ACL using 1.5 tesla MRI, commonly used in clinics, in standard planes and without taking additional sections, and to define the MRI characteristics of the two bundles.

Starman et al.[28] examined the normal ACL in 74 knees using 0.2 tesla MRI and reported that it was difficult to reliably detect the AM and PL bundles together using a low-field strength magnet with standard planes of view. Although the AM bundle was detected in most planes of view with high frequency and reliability, detection of the PL bundle was less frequent and none of the three observers (1 radiologist, 2 orthopedic residents) could observe both bundles. Additionally, they examined 10 knees with 1.5

tesla MRI and found that 1.5 tesla MRI facilitated visualization of the individual bundles, but they excluded this examination from their study to conform to the standardization of imaging. The authors concluded that high resolution MRI might enable better visualization of both bundles.

Steckel et al.[29] examined six cadaver knees using 2D and 3D 3 tesla ultra-high-field strength MRI on oblique sagittal and oblique coronal images and found that both sagittal and coronal oblique planes were equally useful in understanding the anatomy. In another study, the authors tried to visualize partial tears in six cadaver knees through 3 tesla MRI and observed that the AM bundle was better seen in all planes compared to the PL bundle, and that the latter could be better distinguished in the paracoronal plane compared to the sagittal plane.[38] Partial ACL tears seem to be more easily distinguished in oblique, sagittal, and coronal images obtained by the 3 tesla MRI technology. On the other hand, Kwon et al.[39] reported that additional oblique planes would be useful in the evaluation of ACL tears; they found no significant difference in terms of sensitivity between the findings of normal sections and oblique coronal and sagittal sections, but specificity and accuracy increased significantly with oblique images. In addition, simultaneous use of normal images with only sagittal oblique, only coronal oblique, or with both sagittal and coronal oblique images did not improve sensitivity, specificity, and accuracy. These findings show that it is still unclear which planes and sections are most appropriate for accurate MRI evaluation of the ACL.

Unlike the above-mentioned studies, we examined normal ACL anatomy with 1.5 tesla MRI and without the use of oblique sections. We observed that the ACL was intact in all the patients and concluded that 1.5 tesla MRI was not sufficient enough in displaying the two bundles for the double-bundle appearance was observed in only 38% of the knees. There was no significant difference between the observers (an experienced radiologist in extremity MRI and an orthopedic surgeon) who assessed the MRI images independently. Our study differs from the two studies cited above[28,29] in that we examined a greater number of patients and used 1.5 tesla MRI which is more common MRI system in clinical practice. In addition, determination of the angles that each bundle of the ACL makes with the tibial plateau in coronal and sagittal planes, which has not been evaluated in previous studies, may be considered a contribution to the literature. We feel that these findings may serve as a reference while planning surgical treatment after ACL injuries and evaluating postoperative MRI scans.

Poellinger et al.[40] examined tunnel diameters, graft orientation, and angular relations of the tibial and femoral tunnels with the tibial shaft and femur axis, respectively, with MRI after double-bundle ACL reconstruction. They measured the mean angles of the AM and PL tunnels with the tibial plateau as 45° and 74° in the coronal plane, and 49° and 55° in the sagittal plane, respectively. In our study, these angles were 70.1° and 55.1° for the AM bundle, and 81° and 53.5° for the PL bundle in the coronal and sagittal planes, respectively. The differences between the values measured in the two studies may arise from the use of tunnel angles in their study,[40] and the use of angles made by the long axes of the bundles with the tibial plateau in our study. The angular difference for the AM tunnel, in particular, may be explained by the fact that the bundles continue their parallel course after the tunnels. Considering the close relationship between anatomical repairs and successful clinical results, recognition of the normal values is of particular importance.

There are some limitations to the results of our study. In particular, the patients included in our study were those having a normal ACL by history, physical examination and MRI findings. Patients who were thought to have partial or complete ACL insufficiency or doubtful physical examination findings were excluded. The intactness of the ACL was verified only in about one-third of the patients undergoing arthroscopic examination. However, there was no significant difference between the overall MRI findings and arthroscopy findings.

In conclusion, as shown by anatomic and biomechanical studies, the human ACL consists of two bundles having distinct anatomical and functional properties, and 1.5 tesla MRI examination can visualize this two-bundle structure only in about one-third of the patients.

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