Improving MRI knee protocol to best differentiate the two bundles of Anterior Cruciate Ligament

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Aims and objectives

The knee is a complex joint where convex surfaces (the femoral condyles) and flat surfaces (the tibial plateaus) are related. It is susceptible to injuries, both traumatic and degenerative. (1-3)

The main causes of traumatic knee injuries occur in young or adult age and are often associated with sports, where the ligaments are often involved. (1)

Because of its excellent contrast to soft tissue structures, Magnetic Resonance Imaging (MRI) has proven to be an accurate imaging method in identifying these important structures. (1,4-5)

Anterior Cruciate Ligament (ACL) acts as a stabilizer in knee translation and rotation movements, especially in the anterior tibial translation in relation to the femur. (2) It is a structure that, although it has been the subject of several investigations, to date diverges opinions about its anatomy and its function. (2,6)

Based on anatomical, biomechanical and embryological studies it is stated that the ACL is formed by two bundles (7).

Girgis in his dissections, also proved it, and Reim, Jackson, Arnoczky and Warren, explained the physiology of the ACL based on two distinct bundles, however, there are authors who describe a third bundle and others do not confirm the separation of the ACL in more than a lobed contour bundle, thus explaining their bipartite appearance. (2,8)

A recent study of robotics, whose device senses strength through a sensor, underlined the importance of the posterior-lateral (PL) bundle. This study demonstrated that the in situ forces of the PL bundle, in response to a load of 134 Newton, are superior in the maximum extent and decrease as flexion increases. In addition, the study demonstrated that PL bundle plays a significant role in stabilizing the knee when a combined rotational charge it is applied. This suggests the need of an anatomic carefully reconstructed planning that reliably replicates the function of the two ACL bundles. (9)

The routine of Magnetic Resonance for knee study can only accurately evidence the Anterior-Medial (AM) bundle being the PL observed being less frequently. (7)

The main indication for magnetic resonance imaging of the knee is the evaluation of the internal anatomical structures, also called "central pivot", especially the meniscus and ligaments (10).
The ACL study is usually obtained with thin slices in oblique sagittal orientation (20-30°) in relation to the sagittal plane and Proton Density (PD) weighting with fat signal annulment but, with this technique, it is not possible to accurately individualize the two bundles and classify the degree of injury in each one. (3)

Considering the importance of this anatomical structure in the pathophysiology of knee injuries during surgery and posterior recovery, (11) the objective of this investigation was, based on the work done by us and supported by the literature: Characterize the structure, morphology, biomechanics and magnetic resonance imaging of the PL and AM bundles of the anterior cruciate ligament through:

A) Presentation of a set of images that illustrates the problem;

B) Reference to the "state of the art" of the Magnetic Resonance protocols to study the knee joint with a view to a better radiological approach to this joint;

C) Demonstration the MRI importance in the characterization and representation of ACL bundles to increase the success of surgical and / or conservative treatment.

D) Characterization of the ACL from the point of view of the macro and microstructure of its bundles.

E) Address the available MRI technology for these studies and to suggest the optimization of MR acquisition protocols in order to better characterize the ACL and thus increase the clinical benefits.
Methods and materials

It was an experimental study, resulting from the following methodological approach:

Phase I - Literature review intrinsic to osteoarticular MRI and particularly over the knee joint that corresponds to an exploratory research component

Phase II - Analysis of 114 clinical-radiological reports regarding magnetic resonance imaging of the knee and protocols applied.

Phase III - Analysis of knee MRI protocols through the clinical reports obtained in the previous phase.

Phase IV - Characterization by scanning electron microscopy of the microstructure of both bundles.

Phase V - Optimization of the specific MR protocol for ACL with assessment by two observers to measure their efficacy and propose a complementarity to the standard study.

The analysis of 114 clinical reports of knee MRI had as objective to know the main protocols applied in the study of the knee joint, assess if they meet the suggested in the literature and to confirm if, in the clinical description, the two ACL bundles were individually discriminated or not. The criteria for inclusion of the reports were: i) no signs of prior surgery; ii) belong to adult individuals and iii) are current.

One sheet of classification was done to analyze the contents. The clinical reports were obtained from eight hospitals, six private and two public. The set of reports were done by 20 different doctors. The relative proportion of reports in the sample is according to the geographic distribution of MR equipments in the country.

All of examinations from this reports were made in 1.5T Magnetic field equipments. The objective of the dissection of the knee was to verify and characterize the morphology and the function of the fibers of the AM and PL bundles of the ACL in relation to the movements of rotation and translation of the tibia on the femur.

The dissection was performed on a cadaver of female gender, 79 years old, whose death occurred on 04/18/2012 due to colon cancer.

The optimization of the study protocol of the knee by MRI and its evaluation had as objective to evaluate the contribution of the proposed technique - coronal oblique DP sequence - in the study of the standard ACL in the differentiation of the two bundles.
A 2D TSE sequence in Proton Density (PD) with a thickness of 2.0mm and oblique coronal orientation was added to a standard study of 30 knee MRI patients. The planning of the slices had the sagittal image to reference and was obtained in PD with the slices from the proximal to distal insertion. Were oriented with slope along the long axis of the ACL, with $26 \pm 6$° from the coronal plan and parallel to the Blumensaat line. (11) Fig. 3 on page 8

The structural composition of the ACL is not consensual among authors so we tried to characterize the microstructure of the ACL components and to verify if there are observable differences in the histological composition of the AM and PL bundles that can guide the MR protocol in order to result in structures with different contrasts and thus increase the differentiation between the two bundles. The bundles were observed with particular attention to the size, arrangement and distribution of the collagen fibers.

During the anatomical dissection process, longitudinal ACL fragments from the AM bundle and another from the PL beam were collected for further observation by scanning electron microscopy. Both samples were fixed in 4 containers where two of them contained 10% formaldehyde and the other two, acetone pro-analysis.

In first time the images of the 30 MRI scans were observed by two Radiologists (readers) both with large experience in Osteoarticular MRI (more than 20 years). They evaluated the same images in independence condition (2 blind testers). They were asked to interpret the clinical images of the 30 cases with an evaluation directed at the ACL. Regarding the radiological report made initially, a new second evaluation was then made regarding the ACL by applying the methodology of intra-observer integrity in the evaluation of the data. In this last evaluation the oblique coronal sequence directed to the ACL was presented and the observers were asked to re-evaluate the ACL with reference to the evidence, or not, of distinguishing the ACL bundles. Fig. 2 on page 7

Below is presented the table with MRI protocols. The last row show the protocol values of the technique proposed to increase the evidence of ACL.

<table>
<thead>
<tr>
<th>Weight Orientation</th>
<th>Technique Turbo factor</th>
<th>FOV</th>
<th>TR</th>
<th>TE</th>
<th>FA</th>
<th>TH</th>
<th>NSA</th>
<th>Matrix</th>
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<tr>
<td>PD</td>
<td>lateral FSE 2D</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>2</td>
<td>220mm</td>
<td>1350ms</td>
<td>20ms</td>
<td>90°</td>
<td>4,0mm</td>
<td>2</td>
<td>256x256</td>
</tr>
<tr>
<td>T2W*</td>
<td>lateral GRE 2D and W/F separation</td>
<td>200mm</td>
<td>742ms</td>
<td>17ms</td>
<td>30°</td>
<td>4,0mm</td>
<td>2</td>
<td>256x256</td>
</tr>
<tr>
<td>PD</td>
<td>Coronal oblique</td>
<td>FSE 2D</td>
<td>6</td>
<td>180mm</td>
<td>1168ms/20ms</td>
<td>90°</td>
<td>2.0mm</td>
<td>4</td>
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Fig. 1: Representative diagram of the methodological phases and their interrelationship

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Fig. 2: Reading Scheme.

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Fig. 3: In 4 A) is shown the plans coronal oblique directed to the ACL bundles and in B) is shown the final image resulting.

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Results

It was verified that in the 107 analyzed (seven were rejected) only six of them give reference to the individualization of the two ACL bundles.

The sagital proton density (PD) is, in many institutions, the most applied sequence with 40.19% followed by the DP with fat suppression with 35.5%. This same weighting with thin collimation directed to ACL acquired 33.6% of observations and T2w* with Fat-Sat, 28.0%.

For the specific study of ACL in the analyzed reports we found 37.37%.

Some reports referred acquisitions in 3D GRE for visualization of patellar cartilage or evaluation of position / instability of the patella.

As demonstrated by the movements performed during anatomic dissection of the knee, it was verified that the main function of the ACL is to prevent the anterior tibial translation and acts as a second element in the stability in the medial tibial rotation and/or angulation in valgus. (12)

In the frontal plane, the Antero-internal bundle presented a more vertical orientation (about 70 ° from the knee baseline) and parallel to the roof of the intercondyliar bevel or Blumensaat line (1,7-8), while the Postero-lateral is more horizontal (about 55° from the baseline of the knee). (13)

With the knee in flexion the AM bundle is under tension, while the PL is moderately relaxed. However, with the flexed knee the femoral insertion of the ACL assumes a more horizontal orientation, causing a compression of the AM bundle and loosening the PL. Fig. 4 on page 12

Internal rotation conditioned an ACL distension slightly superior to the lateral rotation acting as a secondary restriction to the maximum extension. (14)

The stress on both the AM and PE beams in the extension and the PE beam relaxation in the flexion was verified as reported by Noronha, 2006 (2).

The bundles of collagen fibbers are arranged in various directions and the microstructural organization is varied and complex. (15)
ACL is composed of fibroblasts and an extracellular matrix where the collagen type I is
the major component and is responsible for resisting to a tensile stresses of the ACL and
tendons. This pattern and the fibers of elastine also visible in horizontal direction may be
observed in Fig. 5 on page 12.

Clinical cases involving 30 knee MR studies were analyzed by two readers. The sample
had a mean age of 42 years.

It was observed that the sagittal projection in PD and thin slices provides a good
visualization of the ACL, but the two bundles are not always easily distinguishable
because they are parallel and very close.

For this reason, as we evaluated from the 107 reports analyzed, in the standard MRI the
clinical report refers the ACL but, in fact, only analyse the fibbers of the AM bundle.

In the observation prior to the application of the proposed sequence the visualization and
individualization of the ACL bundles was 26.7% (8 in 30 reports).

The proposed sequence presented a percentage of discrimination of the two bundles of
73.3%, which mean, in 22 of the 30 cases, the readers referred to the ACL with reference
to the two bundles. In this way there was a substantial increase in the individualization of
the ACL bundles after the application of the proposed sequence. Fig. 6 on page 13

The Kappa index revealed an interobserver agreement of 0.67, 0.4 and 0.78 among the
3 readings respectively.
Fig. 4: Joint plane of the knee in frontal-oblique approach with the knee in flexion and observation of the AM and PL bundles fibers of the ACL (blue arrows).

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Fig. 5: Image of the ACL obtained with a electron microscopy scan of 20 kV and with a magnification of 5000x

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Fig. 6: Image of sequence proposed with the evidence of the two bundles of ACL

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Conclusion

Through this study we can conclude about the double bundle morphology of the ligament and its biomechanical characteristics. It was observed that the knee MRI studies assume a prominent position in the ostreoarticular clinical images.

Many clinical reports of the MR exams do not refer the constitution of the ACL considering its two bundles due to the overlap of the ligament fibbers in the images obtained in the sagital plane. A protocol suitable for knee joint pathology and adapted to MRI equipment may bring additional clinical information to ACL reconstructive surgery. The technical protocols applied follow a heterogeneous orientation among the departments of Radiology and are not in agreement with the suggested in the literature about technical protocols.

The use of open magnets has the advantage of being able to better evaluate the function and kinematics of the knee joint by allowing alternative positions that mimic the most frequent injury mechanisms.

The proposed protocol (2D TSE 2mm coronal oblique) combined with the routine sequences for the study of the ACL, following to the trajectory of the ACL fibbers, increase the evidence of the ligament and allow to individualize the AM and PL bundles. These two approaches may give a more satisfactory response to the radiological diagnosis in pre-surgical planning.
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Fig. 7: Logo_ESTeSL

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Fig. 8: Logo_Remagna

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