Biomechanical function analysis of the lateral meniscotibial ligament and its comparison with the capsulodesis technique at the lateral meniscus level

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Its application to lateral allogeneic meniscal transplant.
Biomechanical study in cadaveric knees.

Doctoral Thesis

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PhD Thesis (Rodolfo Morales Avalos)

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"I'm not just going to teach you how to conquer your fears. I'm gonna teach you how to awaken the snake within you. And once you do that, you'll be the one who's feared. You'll build strength. You'll learn discipline. And when the time is right, you'll strike back."

Sensei Johnny Lawrence (Cobra Kai)…

"If a fear cannot be given form, it cannot be defeated."

Stephen King…

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LIST OF ABBREVIATIONS

- **ACL** Anterior cruciate ligament
- **AHLM** Anterior horn of the lateral meniscus
- **APM** Arthroscopic partial meniscectomy
- **BF** Biceps femoris
- **BMI** Body Mass Index
- **CI** Confidence interval
- **ICC** Interclass Correlation Coefficient
- **FBL** Fibular collateral ligament
- **JSW** Joint space width
- **LM** Lateral meniscus
- **LMTL** Lateral menisco-tibial ligament
- **MAT** Meniscal allograft transplant
- **MCID** Minimal clinically important differences
- **MCL** Medial collateral ligament
- **MFL** Meniscofibular ligaments
- **MRI** Magnetic resonance imaging
- **MTPFC** Menisco-tibio-popliteus-fibular complex
- **PASS** Patient acceptable symptom scale.
- **PCL** Posterior cruciate ligament
- **PFL** Popliteofibular ligament
- **PML** Popliteomeniscal ligament
- **SD** Standard deviation
- **STROBE** Strengthening the Reporting of Observational studies in Epidemiology
- **VAS** Visual analog scale

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ABSTRACT

Biomechanical function analysis of the lateral meniscotibial ligament and its comparison with the capsulodesis technique at the lateral meniscus level. Its application to lateral allogeneic meniscal transplant. Biomechanical study in cadaveric knees.

Introduction

The lateral meniscotibial ligament is a fibrous structure that joins the lateral aspect of the meniscus and the lateral tibial condyle. There are few studies on its biomechanical properties, but its relevance for stabilizing the knee in extension with various stresses has been demonstrated. However, it has also been described as a limiting structure in the radial mobility of the lateral meniscus. Techniques that make it possible to imitate its function or a direct reconstruction of the lateral meniscotibial ligament are currently being studied to prevent, limit, or treat the phenomenon of meniscal extrusion.

Justification.

The etiology of the phenomenon of meniscal extrusion has not been determined to date. The techniques for its treatment do not have a follow-up of more than two years. Therefore, they cannot be implemented systematically. In addition, imaging studies have not standardized the visualization of the meniscocapsular and lateral elements. With that, the diagnosis of their injury is complicated with current methods.

Hypothesis.

- The first hypothesis of the current project was that it would be possible to systematically find and measure the structures of the Menisco-Tibio-Popliteus-Fibular complex (MTPFC) of the knee in conventional MRI.
- The second hypothesis was that lateral capsular fixation (capsulodesis) reduces the postoperative degree of allograft extrusion, keeping it stable over time, and does not affect the functional results at the medium-term follow-up.
- The third hypothesis states that the lateral menisco-tibial ligament and the menisco-fibular ligament are limiters to the mobility of the radial movement of the lateral meniscus. Moreover, injury to them increases meniscal extrusion, but both the capsulodesis and centralization techniques restore meniscal extrusion to the preinjury state.

Objectives.

- 1st work. To determine, identify and measure MTPFC structures using MRI in knees without structural abnormalities or a history of knee surgery.
- 2ond work. To evaluate graft survival and report the radiographic and functional outcomes through medium-term follow-up of lateral MAT performed with a soft tissue fixation technique after capsulodesis.
- 3rd work. The purpose of this study was to establish an injury model of the LMTL and the MFL in porcine knees and the results of their reconstruction by using centralization or capsulodesis alternatively.

Methodology.

- 105 knees without previous injury or surgical history were analyzed by means of magnetic resonance imaging. The mean age was 50.1 years ± 14.8. Three observers conducted all measurements. Peripheral structures of the body of the lateral meniscus were identified to determine the location, size, and thickness of the entire MTPFC. The distance to other "key areas" in the lateral compartment was also studied and compared by sex and age.
- 14 patients who had undergone isolated lateral MAT were included. The average follow-up was 7 years. The results were evaluated with the KOOS, Lysholm, Tegner, VAS, MCID and PASS scales. Magnetic resonance imaging with partial weight bearing and a complete radiological protocol were performed to determine the degree of meniscal extrusion and changes in the degree of osteoarthritis and coronal alignment.
- The lateral menisci of 22 porcine knees were evaluated. These were mounted in a test apparatus to apply muscle reaction forces and ground reaction forces. The meniscus was assessed at 30° and 60° of knee flexion using two markers placed on the posterior cruciate ligament and lateral meniscus after applying 200 N axial compression to the knee joint. Measurements were recorded for 5 conditions: the intact lateral meniscus, injury to the LMTL, posterior injury to the MFL, use of the open capsulodesis technique, and reconstruction of the LMTL and MFL with the centralization technique.

Results.

- The lateral meniscotibial ligament (LMTL) was found in 97.1% of the MRIs, the popliteofibular ligament (PFL) in 93.3%, the popliteomeniscal ligament (PML) in 90.4% and the meniscofibular ligament (MFL) in 39%. The anteroposterior distance of the LMTL in an ·axial view was 20.7 mm ± 3.9, the anterior thickness of the LMTL was 1.1 mm ± 0.3, and the posterior thickness of the LMTL was 1.2 mm ± 0. .1 and the height in a coronal view was 10.8 mm ± 1.9. The length of the PFL in the coronal view was 8.7 mm ± 2.5, the thickness was 1.4 mm ± 0.4, and the width in the axial view was 7.8 mm ± 2.2.

- A significant improvement was evident for all scores at the 7-year follow-up when compared to the preoperative values. This improvement remained constant from the first to the second follow-up. A mean absolute extrusion of 2.2 mm ± 1.6 and an extrusion percentage of 28.0% ± 11.43 were found, with no significant differences to the values obtained after 2 years of follow-up. There were no statistically significant differences in terms of the frontal mechanical axis and joint space narrowing between the preoperative value and at the first and second follow-up. A survival rate of 85.7% was found after 6 years of follow-up.
- The distance between two markers was greater in the extrusion group (combined LMTL and MFL injury) than in the intact or reconstruction group (capsulodesis and centralization techniques) (p = < 0.001 all cases). In cases of load application, no significant differences were observed between the control group (intact meniscus) and the groups that underwent reconstruction techniques (p = >0.05). There were also no differences when comparing the results obtained between both reconstruction techniques. In all settings, the distance between the two markers increased with the increasing knee flexion angle.

Conclusions

This set of studies demonstrates the importance and function of the lateral meniscotibial ligament, describing its morphology and prevalence in magnetic resonance studies to distinguish its injury. Subsequently, a porcine biomechanical study was developed where its contribution as a restrictor of meniscal extrusion was observed and confirmed.

Additionally, a comparison was made of two reconstruction techniques that simulate its function and anatomy. Finally, a study was conducted to evaluate the medium-term follow up the allogeneic lateral meniscus transplant associated with the capsulodesis technique. This was done to determine its influence on radiological and functional results. Favorable results were seen at the 7-year postoperative follow-up.

RESUMEN

Análisis de la función biomecánica del ligamento meniscotibial lateral y su comparación con la técnica de capsulodesis a nivel del menisco lateral. Su aplicación al trasplante meniscal alogenico lateral. Estudio biomecánico en rodillas cadavéricas.

Introducción

El ligamento menisco tibial lateral es una estructura fibrosa que une la cara lateral del menisco y de la meseta tibial lateral. Existen pocos estudios acerca de sus propiedades biomecánicas, pero se ha demostrado su relevancia para estabilizar la rodilla en extensión con estrés en varo. Sin embargo, también se ha sugerido que posee una función limitante de la movilidad radial del menisco lateral. Actualmente se estudian técnicas que permitan imitar su función o que directamente reconstruyan el ligamento menisco tibial lateral para prevenir, limitar o tratar el fenómeno de extrusión meniscal.

Justificación.

La etiología última del fenómeno de extrusión meniscal no ha podido ser completamente determinada hasta el momento. Las técnicas propuestas para su tratamiento no tienen un seguimiento superior a los dos años y, por ende, no pueden ser recomendadas de manera sistemática. Los estudios de imagen no han estandarizado la visualización de los elementos meniscocapsulares laterales y, por tanto, el diagnóstico de su lesión resulta complicado con los métodos actuales.

Hipótesis.

- La primera hipótesis establece que es posible encontrar y medir sistemáticamente las estructuras del complejo menisco-tibio-poplíteo-peroneo en resonancia magnética de rodilla convencional.
- La segunda, sostiene que la fijación capsular lateral reduce el grado postoperatorio de extrusión del aloinjerto meniscal, manteniéndolo estable en el tiempo, y sin afectar los resultados funcionales en el seguimiento a medio plazo.
- La tercera, menciona que los ligamentos menisco-tibial lateral y menisco-peroneo son limitadores del movimiento radial del menisco lateral; su lesión aumenta la extrusión meniscal, y las técnicas de capsulodesis y centralización restauran la posición meniscal al estado anterior a la lesión.

Objetivos.

- Determinar, identificar y medir las estructuras del MTPFC mediante resonancia magnética en rodillas sin anomalías estructurales ni antecedentes de cirugía.
- Evaluar la supervivencia a medio plazo del injerto meniscal lateral realizado con una técnica de fijación de tejidos blandos, después de capsulodesis, e informar sobre sus resultados radiográficos y funcionales.
- Determinar un modelo de lesión del LMTL y del LMF y los resultados de su reconstrucción, utilizando alternativamente las técnicas de centralización y capsulodesis, en rodillas porcinas.

Metodología.

- Se analizaron mediante resonancia magnética 105 rodillas sin lesión previa ni antecedentes quirúrgicos. La edad media fue de 50,1 años ± 14,8. Todas las mediciones fueron realizadas por tres observadores. Se identificaron las estructuras periféricas del cuerpo del menisco lateral para determinar la ubicación, el tamaño y el grosor de todo el MTPFC. También se estudió y comparó, por sexo y edad, la distancia a otras "áreas clave" en el compartimento lateral.
- Se incluyeron 14 pacientes a los que se les había realizado MAT lateral de forma aislada. El seguimiento medio fue de 7 años. Los resultados se evaluaron con las escalas KOOS, Lysholm, Tegner, VAS, MCID y PASS. Se realizó resonancia magnética y un protocolo radiológico completo para determinar el grado de extrusión meniscal y los cambios en el grado de artrosis y alineación coronal.
- Se evaluó el menisco lateral de 22 rodillas porcinas, estas fueron montados en un aparato de prueba para aplicar fuerzas de reacción muscular y la ground reaction force. El menisco se evaluó a 30° y 60° de flexión de la rodilla utilizando dos marcadores colocados en el ligamento cruzado posterior y el menisco lateral después de aplicar una compresión axial de 200 N en la articulación de la rodilla. Se registraron mediciones para 5 condiciones: menisco lateral intacto, lesión del LMTL, la lesión posterior del MFL, el uso de la técnica de capsulodesis abierta y la reconstrucción del LMTL y del MFL con la técnica de centralización.

Resultados.

- El ligamento meniscotibial lateral (LMTL) se encontró en el 97,1% de las resonancias

- magnéticas, el ligamento popliteperoneo (PFL) en 93,3%, los ligamentos popliteomeniscal (LMP) en 90,4% y el ligamento meniscoperoneo (MFL) en 39%. La distancia del LMTL, en una vista axial, fue de 20,7 ± 3,9 mm, el espesor anterior del LMTL fue de 1,1 ± 0,3 mm, el espesor posterior del LMTL fue de 1,2 ± 0,1 mm y la altura, en una vista coronal, fue de 10,8 ± 1,9 mm. La duración del PFL en vista coronal fue de 8,7 ± 2,5 mm, el espesor fue de 1,4 ± 0,4 mm y el ancho en vista axial fue de 7,8 ± 2,2 mm.
- Se evidenció una mejora significativa para todas las puntuaciones funcionales en comparación con los valores preoperatorios, en el seguimiento de 7 años. Esta mejora se mantuvo constante desde el primero hasta el segundo seguimiento. Se encontró una extrusión absoluta media de 2,2 ± 1,6 mm y un porcentaje de extrusión de 28,0 ± 11,43%, sin diferencias significativas con los valores obtenidos a los 2 años de seguimiento. No se observaron diferencias estadísticamente significativas en términos del eje mecánico frontal y el pinzamiento del espacio articular entre el valor preoperatorio y los obtenidos en el primer y segundo de seguimiento. La tasa de supervivencia fue del 85,7% tras 6 años de seguimiento.
- La distancia entre dos marcadores fue mayor en el grupo de extrusión (lesión combinada del LMTL y MFL) que en el grupo intacto o de reconstrucción (con técnica de capsulodesis y centralización) (p = <0,001 en todos los casos). En los casos de aplicación de carga, no se observaron diferencias significativas entre el grupo control (menisco intacto) y los grupos a los que se les realizaron las técnicas de reconstrucción (p = >0,05). Tampoco hubo diferencias al comparar directamente los resultados obtenidos entre ambas técnicas de reconstrucción. En todos los entornos, la distancia entre los dos marcadores aumentó con el aumento del ángulo de flexión de la rodilla.

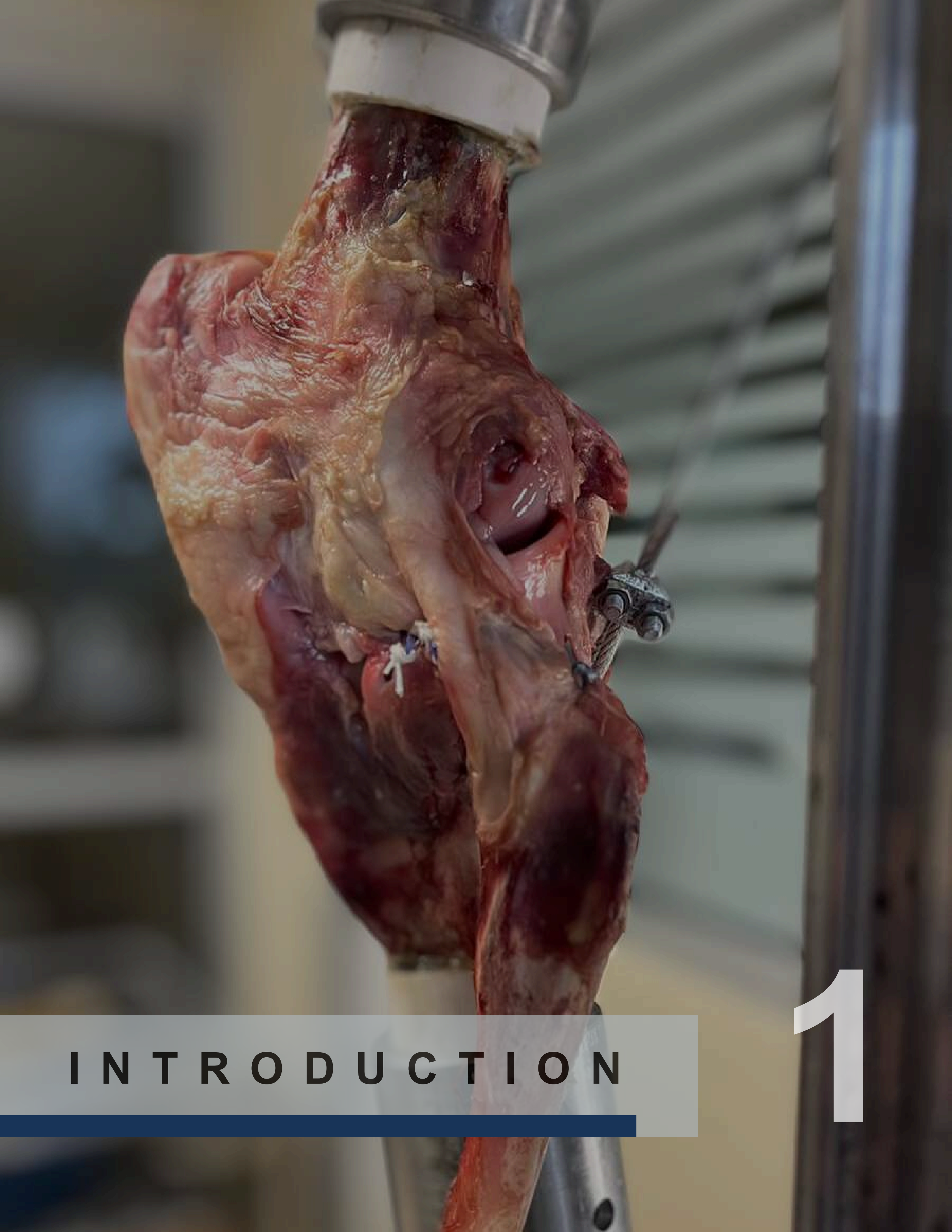
Conclusiones.

Este conjunto de estudios demuestra que:

- El complejo MTPF existe y tiene un patrón morfológico y anatómico constante, en tres de sus cuatro ligamentos, que puede ser identificado y medido por RM. La porción MFL muestra una menor prevalencia y debe considerarse como una estructura difícil de identificar mediante RM de f-identificar mediante RM de 1,5 T.

- La capsulodesis resulta en un bajo grado de extrusión meniscal en casos de MAT lateral aislado y fijado con técnica de sutura a partes blandas. Los resultados clínicos (en términos de escalas funcionales) son satisfactorios y la tasa de supervivencia del injerto es elevada (>85%) tras 7 de seguimiento.

- El estudio biomecánico desarrollado en un modelo porcino demuestra que: los ligamentos meniscotibial lateral y meniscofibular contribuyen a la estabilidad meniscal como restrictores de la movilidad radial del menisco lateral durante la carga axial. Su lesión causa un significativo incremento de la extrusión meniscal y tanto la centralización como la capsulodesis son capaces de reducir dicha extrusión.



1 INTRODUCTION

INTRODUCTION

THEORETICAL FRAMEWORK

1.1 Anatomy and function of the lateral meniscus

The lateral meniscus (LM) is a structure of semilunar morphology that is composed of fibrocartilage that covers the articular surface of the lateral tibial plateau. Its function is to distribute the load on the lateral tibial plateau, reduce the stress that occurs when there is contact between the femur and the tibia, protect the articular cartilage and contribute to knee stability.[1] In conjunction with the medial meniscus, the lateral meniscus provides a concave surface for the femoral condyles to articulate congruently with the tibial plateaus, which are relatively flat.[2] The LM covers 75% to 93% of the lateral tibial plateau compared to the medial meniscus which has a more semicircular shape and covers 51% to 74% of the medial tibial plateau.[3] The role of the medial and lateral menisci as secondary stabilizers of the knee has been demonstrated through biomechanical and clinical research.[4,5]

The anterior and posterior horns of the lateral meniscus insert into the tibia. The anterior horn of the lateral meniscus inserts anterior to the intercondylar eminence next to the insertion site of the anterior cruciate ligament (ACL). On the other hand, the insertion of the posterior horn is located posterior to the lateral tibial spine in a position anterior to the insertion of the posterior horn of the medial meniscus (Figure 1).[6] Although the lateral meniscus is attached to most of the anterolateral and posterolateral capsule of the knee joint, there is a posterolateral area in the region of the popliteus tendon where the lateral meniscus is not attached to the joint capsule, that is what contributes to its greater mobility with respect to the medial meniscus.

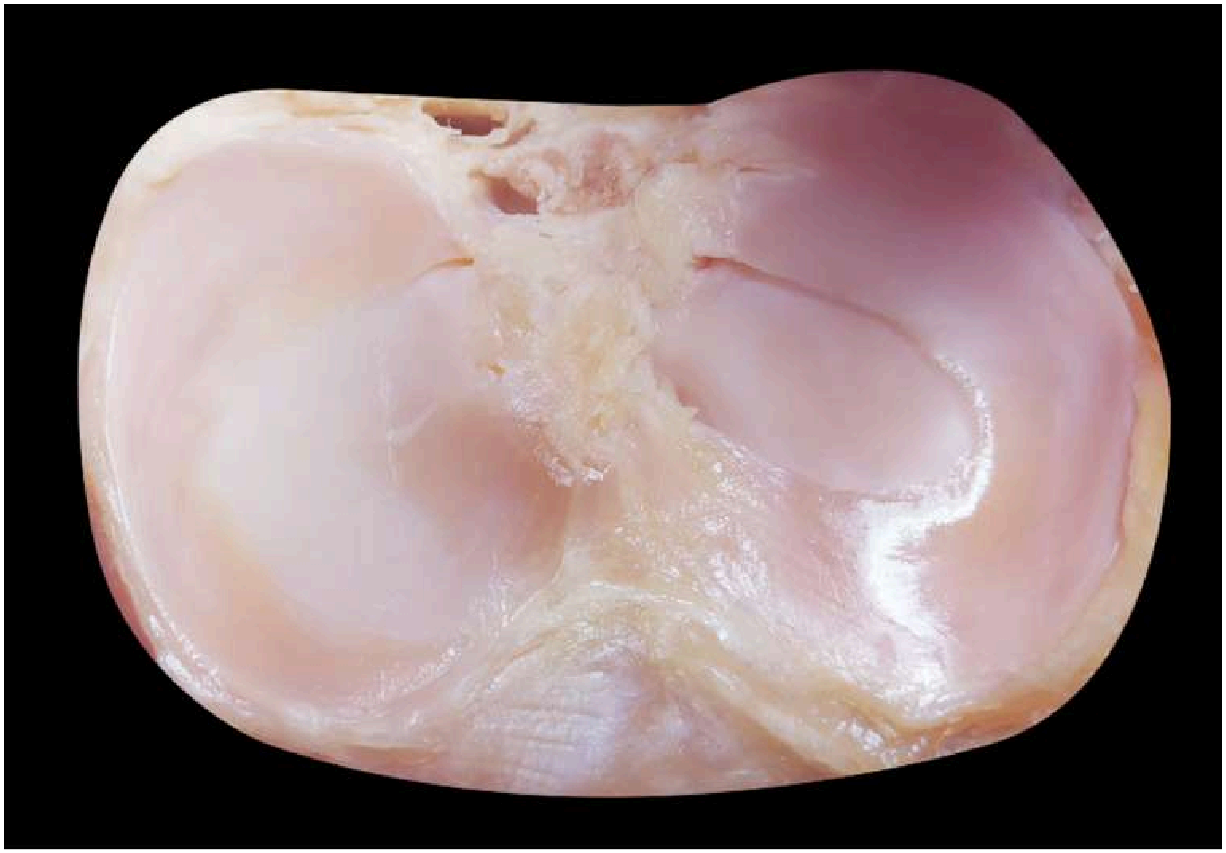


Figure 1. *Superior view of both menisci, where you can see their morphology and the insertion of the roots of both meniscus.*

The function of the meniscus is largely attributed to its unique biomechanical properties. It has a viscoelastic property due to its permeability to fluids depending on whether it is in compression due to loads on the knee. The permeability of the meniscus is lower compared to the articular cartilage, which gives it the ability to maintain its shape during axial loads while tinhibiting compression and maintaining its shape. Its second property is its response to compression. When there is initial compression on the menisci, it is resisted by the elastic characteristics of the collagen bundles and matrix. When a compressive load is applied to the menisci, an axial load causes the phenomenon known as "hoop stresses" in the circumferential fibers of the menisci that extend to their junction at the tibia and femur. As the femur compresses, the menisci are extruded peripherally due to their wedge shape, causing a tangential force. This peripheral extrusion is limited by the meniscus insertions.[7] As a compressive force is applied, a circumferential stress develops that results in the hoop stress phenomenon. These circular stresses allow for stress distribution over a large area of the articular cartilage.[8] When the menisci undergo tensile forces, little is initially needed to lengthen them because the collagen fibers are relaxed. After the initial phase, there is a linear relationship between elongation and applied load. That is followed by a drop in elongation as the fibers begin to fail and tear.[9] The maximum load that the menisci can withstand is called the maximum tensile load. Tensile properties can change depending on the location of the menisci. For the lateral meniscus, the posterior portion has been reported to have the highest tensile modulus.[10] It has been shown that circumferentially, the meniscus is approximately ten times stronger than radially. That may explain why the meniscus is more prone to circumferential rather than radial tears.[11,12]

The biomechanics of the lateral meniscus is different to that of the medial meniscus. The main difference lies in the greater mobility of the lateral meniscus[1], which reduces its tendency to injury compared to the medial meniscus. On the lateral side of the knee, there is a greater variance on the medial side between the femoral condyle and the tibial plateau as both are convex. This is why the mobility of the lateral meniscus allows a greater degree of anterior and posterior translation of the femoral condyle on the tibial plateau.

The meniscus may also help with the nourishing and lubrication of the knee joint. However, the exact mechanics of this are still unknown. The theory is that microchannels within the meniscus communicate with the synovial cavity, allowing fluid to be transported to deeper avascular structures for the nourishing and lubrication of the joints.[6]

The main vascular supply to the menisci is derived from branches of the superior and inferior geniculate arteries. They form a subsynovial and perimeniscal network of capillaries that enter the periphery of the meniscus. Therefore, vascularization is limited to the peripheral parts of the menisci. Next to the blood vessels, there are homonymous nerve fibers. This means that the anterior and posterior horns of the menisci are the most richly innervated and vascularized.

1.2 Embryology and Anatomy of the lateral meniscotibial ligament.

Previous studies reported the formation of both meniscus starting at the 9 weeks of embryonic development, they also described the formation of a ligament that attaches the meniscus to the proximal tibia during weeks nine to thirteen.[13] In data not yet published by our study group, we found that the lateral meniscotibial ligament is formed at 11 weeks of gestation as a constant anatomical structure and acquires its complete morphology at 19 weeks of gestation (unpublished data) (Figure 2).

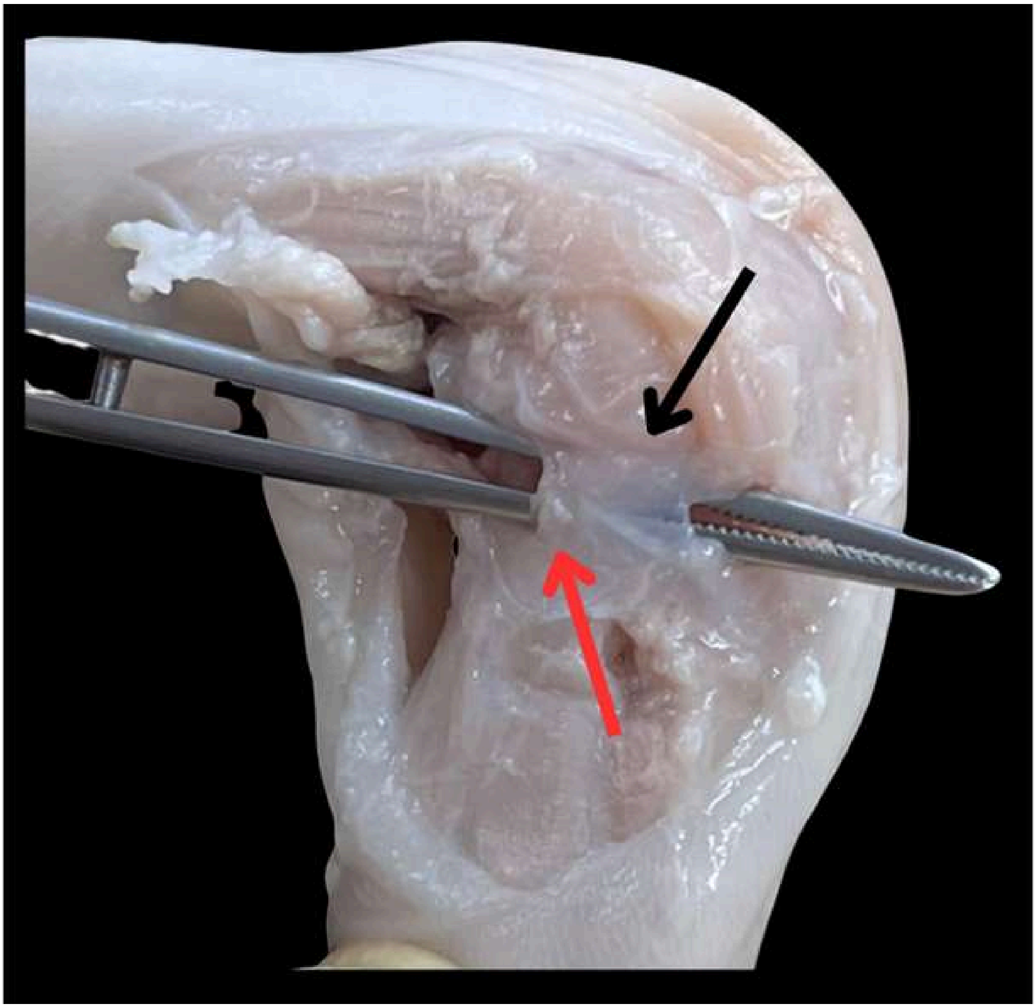


Figure 2. *Lateral view of a nineteen-week embryo knee, where the lateral meniscotibial ligament can be seen (black arrow). The red arrow is pointing the meniscofibular ligament.*

The lateral menisco-tibial ligament (LMTL) is a fibrous structure composed of collagen fibers that joins the lateral surface of the meniscus, runs inferiorly and posteriorly and obliquely until reaching the margin. It is also superolateral to the lateral tibial condyle (Figure 3).[13] There are few studies on its biomechanical properties. Even in their absence, its relevance in stabilizing the knee in extension with varus stress and limiting extrusion with internal rotation with the knee flexed has been observed.[13]

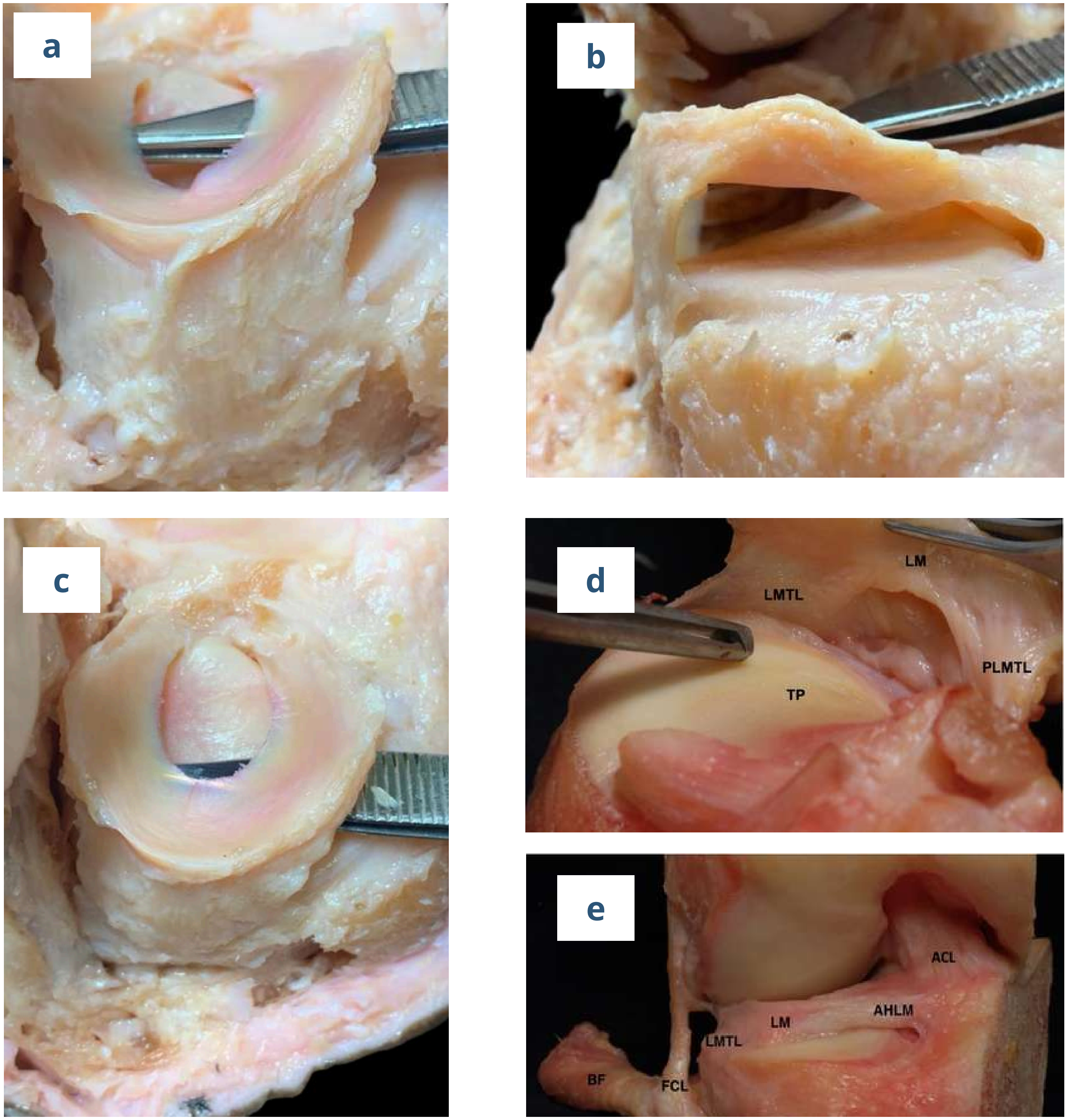


Figure 3. *Lateral meniscotibial ligament.* ***a)*** *Superolateral view.* ***b)*** *Anterolateral view.* ***c)*** *Superior view.* ***d)*** *Internal View.* ***e)*** *Anterior view.*

1.2.1 Arthroscopic Anatomy

From the arthroscopic point of view, the lateral meniscotibial ligament can be observed from the anteromedial portal as a fibrous structure of intermediate thickness, which originates from the posterior edge of the inferior surface of the body of the lateral meniscus, the ligament can be palpated and displaced easily with the help of arthroscopic instruments, the ligament has longitudinal fibers in an inferior direction, with a small virtual space existing between the ligament and the lateral edge of the lateral tibial plateau (Figure 4).

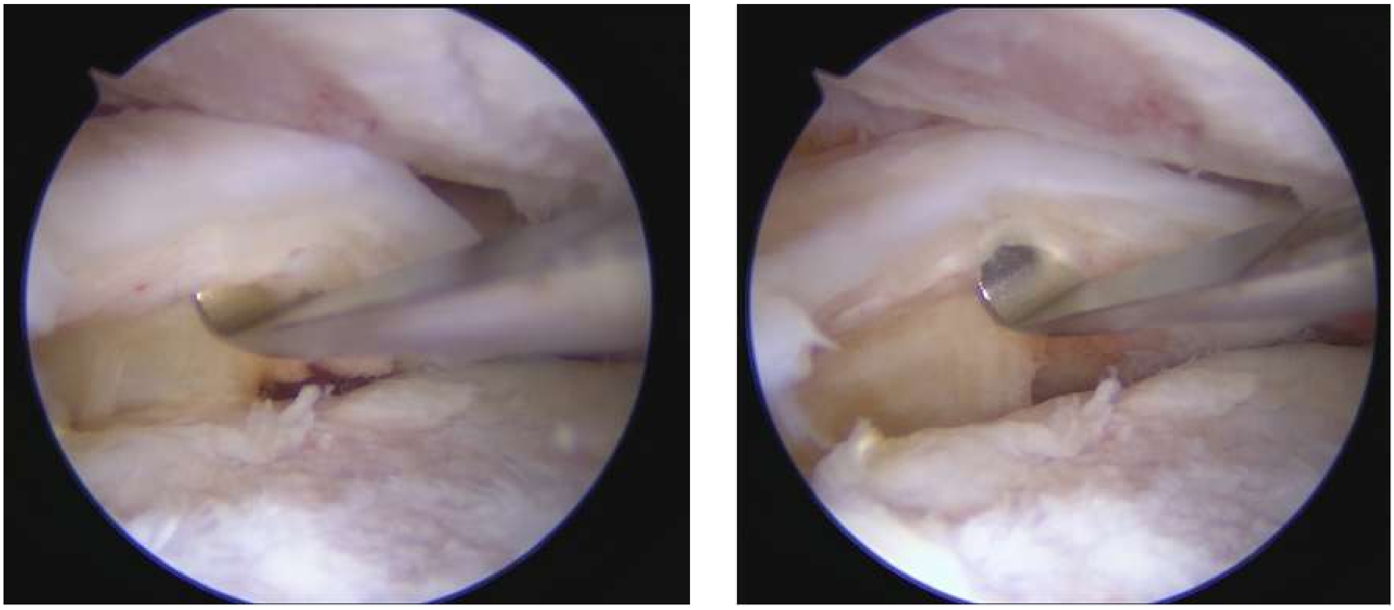


Figure 4. *Arthroscopic view of the lateral meniscotibial ligament from the anteromedial portal.*

1.3 Meniscal injuries

With an incidence of 2/1,000 patients/year, meniscal injury is one of the most common musculoskeletal conditions. Furthermore, the Arthroscopic partial meniscectomy (APM) is the most frequently performed orthopedic procedure in the USA. However, the complete or partial surgical resection of torn or injured menisci significantly increases the risk of the premature onset of osteoarthritis.[5]

A characteristic of the functional alteration of the meniscus that has recently come under study is the concept of meniscal extrusion. It is often defined in Magnetic resonance images as an external displacement of the meniscus in relation to the external central edge of the tibial plateau. It is quantified on the coronal plane in the central region for an unloaded knee as ≥3 mm.[14,15] Costa et al. classified it as minor in dislocations of < 3 mm and greater when extruded by ≥3 mm.[16] Adams et al. grades meniscal extrusion in MRI according to the relationship of the outer margin of the meniscus to the femoral and tibial condyles. Extrusion of less than one-third of the meniscus was graded as mild (grade 1), two-thirds extrusion as moderate (grade 2), and complete as severe extrusion (grade 3). Both can be used for the follow-up of patients after meniscus transplantation.[17]

This anatomical alteration of the meniscus causes the loss of some of its mechanical functions, thereby altering the biomechanical distribution of pressure loads on the articular surface.[18–20]. It predisposes patients to the appearance of early osteoarthrosis of the knee, ruptures of the posterior root of the meniscus and the appearance of Postmeniscectomy syndrome, among others.[20-23] Additionally, this radial displacement of the meniscus has been described as a affecting meniscus allograft transplants and the post-surgical benefits for patients.[24] Given the importance of meniscal extrusion, different studies have been carried out to limit this injury in both native and allogeneic menisci after a meniscal transplant.[25-28]

1.4 Menisco-Tibio-Popliteus-Fibular Complex

From its first description, the lateral compartment of the knee has always been a complex region to describe.[29,30] An example of this is in the naming of the peripheral insertions of the body of the lateral meniscus. It has varied over time as more structures have been identified, causing confusion when trying to achieve a comprehensive anatomical description.[31–35] More recently, these peripheral junctions have been redefined in a cadaveric study by Masferrer-Pino et al. where a consistent pattern of fixation of the lateral meniscus was identified as the Menisco-Tibio-Popliteus-Fibular Complex (MTPFC). It is composed of the lateral meniscotibial ligament (LMTL), popliteofibular ligament (PFL), popliteomeniscal ligaments (PML) and the meniscofibular ligament (MFL) (Figure 5).[25.36] It has been observed that this complex and especially its main component, the lateral menisco-tibial ligament, act as a restrictor of the radial mobility of the lateral meniscus (Figure 6). An injury to it can cause the meniscus to extrude and repair of that ligament significantly reduces extrusion.[37–39]

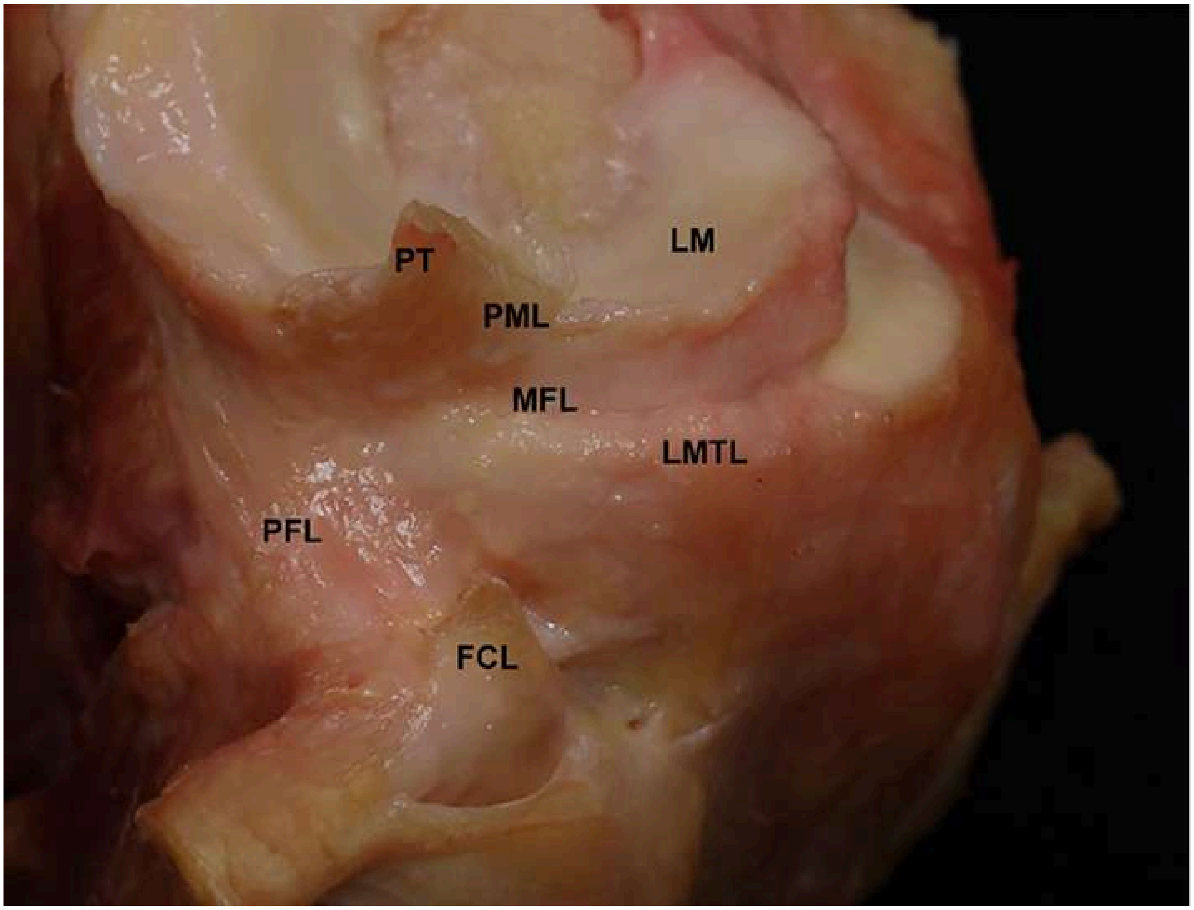


Figure 5. *Photograph of a right knee dissection showing all the elements that are part of the MTPFC. **LMTL:** lateral menisco-tibial ligaments; **PFL:** popliteal-fibular ligament; **PML:** popliteomeniscal ligaments; **MFL**: meniscofibular ligament; **LM:** lateral meniscus; **LCL:** lateral collateral ligament; **PT**: popliteus tendon.*

On the other hand, several radiological studies have been conducted that describe the structures of the lateral compartment of the knee.[40–43] However, those studies have been subject to the same confusion observed in cadaveric studies. That confusion was caused by the lack of uniform naming of the structures, which has relevant implications for the surgical correction of meniscal injuries.

Structures such as the MTPFC have been identified as playing an important role in the development of meniscal extrusion.[25] This highlights the importance of expanding the body of evidence around the radiological anatomy of meniscal injuries of the knee and thereby help in the development of new techniques for the repair and limiting of meniscal extrusion.

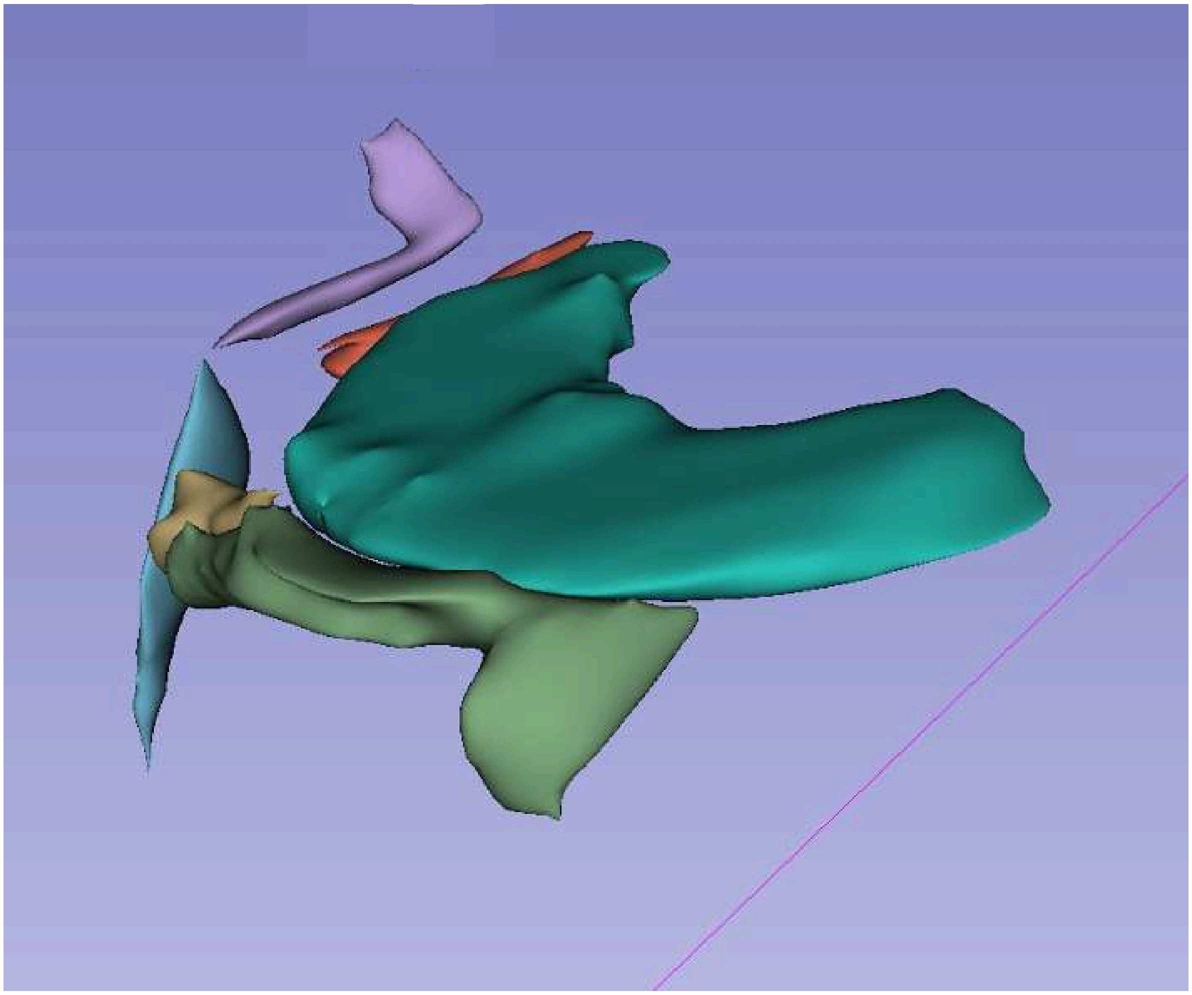


Figure 6. *Three-dimensional model of the MTPFC made by our work group based on the vectorization of magnetic resonance imaging of healthy controls where the different elements that make it up and their topographic relationship can be observed. Light Blue: Lateral meniscus, Green: Lateral meniscotibial ligament, Yellow: Popliteus fibular ligament. Blue: Meniscofibular ligament, Purple: Superior popliteomeniscal ligament, Orange: Inferior popliteomeniscal ligament.*

1.5 Treatment of meniscal extrusion

In recent years, several techniques have been described to repair meniscal extrusion, and especially after meniscal transplantation. These techniques have presented heterogeneity in results with moderate degrees of effectiveness and scarce long-term follow-up data.[15,44] Meniscal extrusion occurs in most cases in the first postoperative year.[18] This is why extrusion can be decreased with the proper surgical technique, the correct choice of procedure and graft size as well as adequate postoperative rehabilitation. Recently, Monllau et al. has described the totally arthroscopic lateral capsulodesis technique without implants (Figure 7).[45] It shows promising results with decreased extrusion when compared to the bone bridge fixation technique and the suture-only fixation technique (Figure 8) without capsulodesis.[46,47] However, long-term data are not available on the effectiveness of these techniques that limit meniscal extrusion. Studies evaluating the long-term effectiveness of this new technique are needed to better understand its role in the repair of meniscal extrusion. These studies should be performed using magnetic resonance imaging and ultrasound under weight bearing conditions.

This technique is performed from the beginning as reinforcement of the LMAT using a suture-only fixation technique, which contributes to its versatility for the fixation points around the graft and facilitates the MAT technique and has obtained good results in previous studies. [45,46] This technique has presented fewer complications, with very similar results in meniscal extrusion. [48]

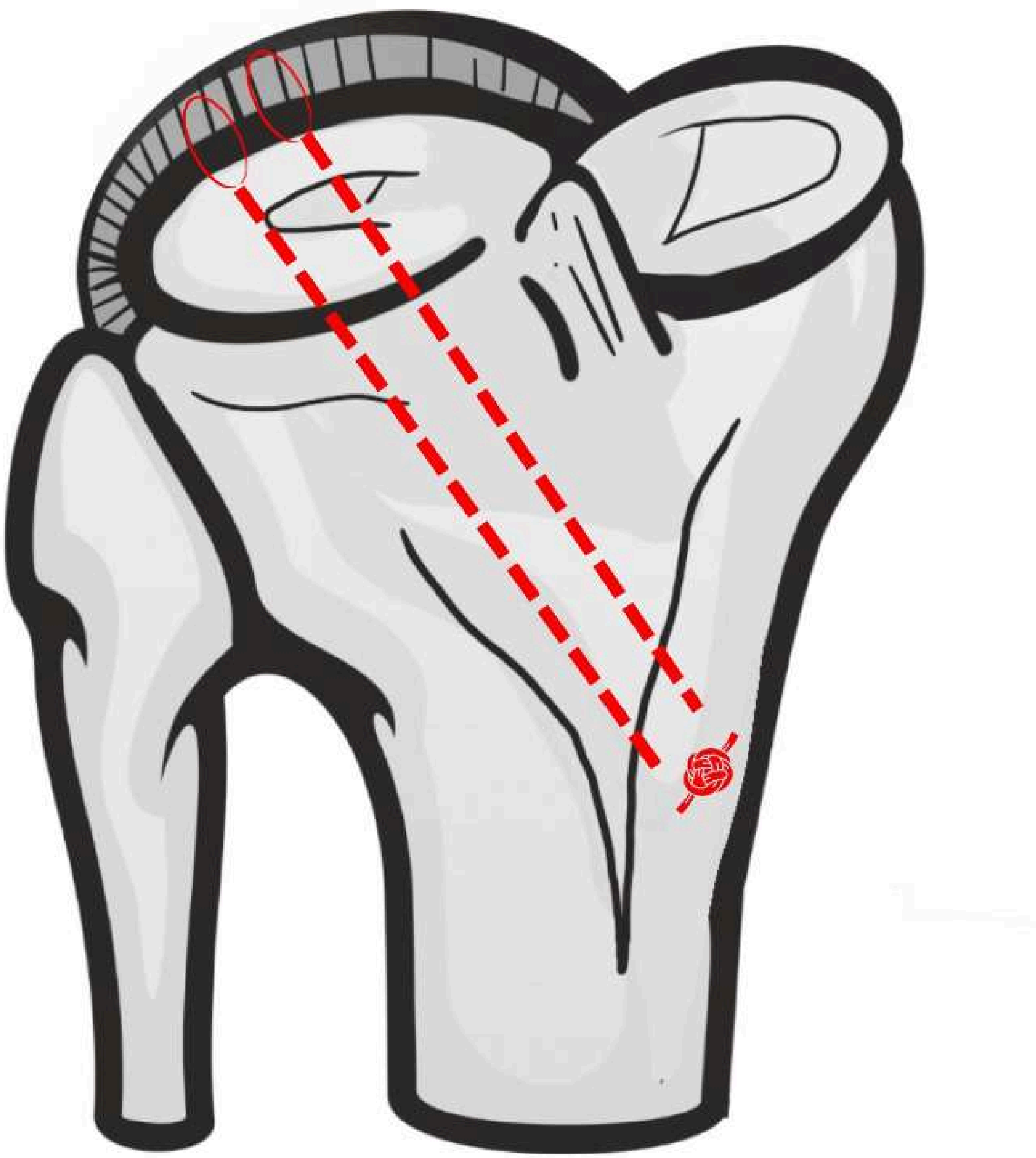


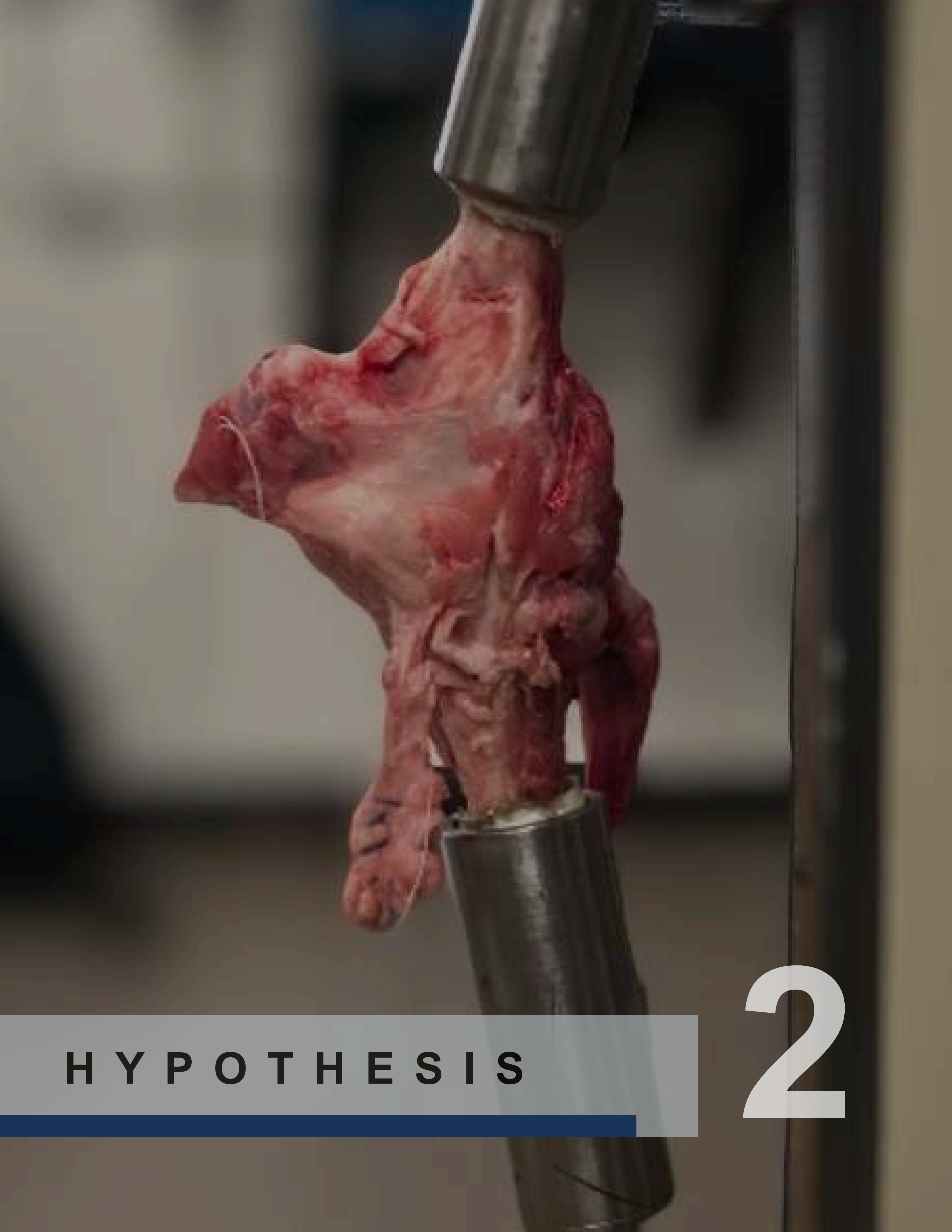
Figure 7. *Schematic representation of the capsulodesis technique proposed by Monllau et al.*

Figure 8. *Meniscal allograft prepared without bone, for a suture-only fixation technique.*

1.6 Prognosis of meniscal extrusion

Previous studies that have used the “soft tissue” technique have shown 75% meniscal extrusion in patients evaluated by means of Magnetic resonance imaging 6 months postoperatively.[49] Choe et al. obtained an incidence of extrusion of 41.6% in 320 cases of lateral MAT using the technique with a bone block that connects the anterior and posterior horns.[50] Abat et al. performed a three-year study where they compared the suture-only fixation technique. With it, extrusion of 38.3% and 30.14% was seen with the bone bar method in allogeneic lateral meniscus transplantation.[51] In longer-term studies, extrusion rates of 70% have been observed using an isolated suture soft tissue fixation technique.[52] On the other hand, Lee et al. evaluated 27 patients who had undergone a lateral MAT with a follow-up time of 10.3 years using the “key hole” technique and found absolute meniscal extrusion of 2.76 mm ± 0.47.[18]

Thus, this thesis compiles three studies that explore the concepts of meniscus extrusion, as a finding after meniscus allograft transplantation, the morphological study of the peripheral insertions of the body of the lateral meniscus in relation to the prevention of meniscal extrusion, and novel techniques to repair meniscal extrusion.



HYPOTHESIS 2

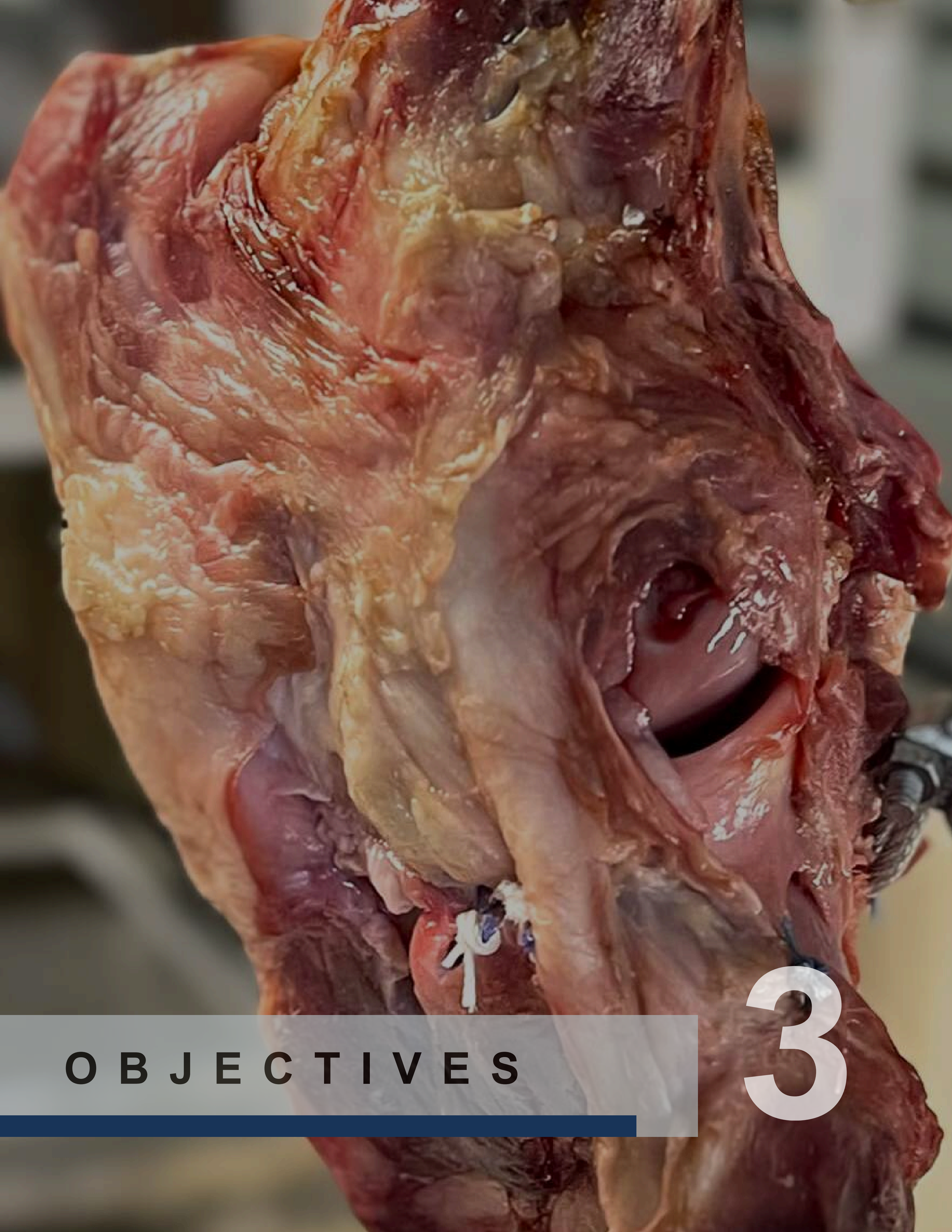
HYPOTHESIS

1) The menisco-tibio-popliteo-fibular complex and its main component, the lateral menisco-tibial ligament, can be consistently identified and its anatomical and topographic characteristics can be described in knee MRI.

2) The lateral menisco-tibial ligament influences the antero-posterior and mediolateral translation biomechanics of the lateral meniscus, thus playing a role in the phenomenon of meniscal extrusion.

3) The arthroscopic capsulodesis technique (lateral capsular fixation) can function biomechanically in a similar way to the lateral menisco-tibial ligament, being able to reduce the phenomenon of extrusion at the level of the external meniscus by limiting and restricting the mobility of the lateral meniscus.

4) Patients with lateral meniscal allografts transplanted in conjunction with performing the arthroscopic capsulodesis technique have a survival rate of over 85% at 7 years of postoperative follow-up, with a low rate of meniscal extrusion and complications.



3 OBJECTIVES

OBJECTIVES

Main objective

To determine the biomechanical function of the lateral menisco-tibial ligament as a limitation of the mobility of the lateral meniscus and to determine if the Capsulodesis technique (lateral capsular fixation) mimics the function of this ligament.

Secondary objectives

1) To evaluate, using knee MRI, the prevalence and morphological characteristics of the ligaments that form the menisco-tibio-popliteo-fibular complex.

2) To determine the graft survival rate, complications and meniscal extrusion rates in patients undergoing lateral meniscal allograft transplantation in a medium-term clinical and radiological follow-up.

3) To determine biomechanically if the section and subsequent reconstruction of the lateral menisco-tibial ligament in addition to the arthroscopic capsulodesis technique restores meniscal extrusion to native values.

COMPENDIUM OF PUBLICATIONS 4

COMPENDIUM OF PUBLICATIONS

The material and methods section of this thesis describes the methodology followed in the three previously published studies. It is important to mention that all three studies were evaluated and approved by the Research Ethics Committee, Research Committee. In the case of the third article, the Institutional Committee for the Care and Use of Laboratory animals of the Faculty of Medicine and University Hospital of the Autonomous University of Nuevo León also evaluated and approved them before the recruitment of patients and/or medical records. It was also the case for the biomechanical experimental study. All studies were performed in accordance with the recommendations of the World Medical Association of 1964 and the Declaration of Helsinki and its revision in 2013.[53] Additionally, all observational studies complied with the Reporting of Observational Studies in Epidemiology (STROBE) guidelines.[54] In the case of the third study, the Official Mexican Standard for the care and use of laboratory animals was also followed.

4.1. Article 1

MRI evaluation of the peripheral attachments of the lateral meniscal body: The Menisco-Tibio-Popliteus-Fibular Complex.

Morales-Avalos R, Masferrer-Pino A, Ruiz-Chapa E, Padilla-Medina JR, Vilchez-Cavazos F, Peña-Martínez VM, Elizondo-Omaña RE, Perelli S, Guzmán-López S, García-Quintanilla JF, Monllau JC. MRI evaluation of the peripheral attachments of the lateral meniscal body: the menisco-tibio-popliteus-fibular complex. **Knee Surg Sports Traumatol Arthrosc.** 2022; 30(4):1461-1470. **DOI**: 10.1007/s00167-021-06633-5. **PMID**: 34142172.

Knee Surgery, Sports Traumatology, Arthroscopy
https://doi.org/10.1007/s00167-021-06633-5

KNEE

MRI evaluation of the peripheral attachments of the lateral meniscal body: the menisco-tibio-popliteus-fibular complex

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Abstract

Purpose To determine, identify and measure the structures of the menisco-tibio-popliteus-fibular complex (MTPFC) with magnetic resonance imaging (MRI) in knees without structural abnormalities or a history of knee surgery.

Methods One-hundred-and-five knees without prior injury or antecedent surgery were analyzed by means of MRI. The average age was 50.1 years ± 14.8. All the measurements were performed by three observers. The peripherical structures of the lateral meniscus body were identified to determine the location, size, and thickness of the entire MTPFC. The distance to other "key areas" in the lateral compartment was also studied and compared by gender and age.

Results The lateral meniscotibial ligament (LMTL) was found in 97.1% of the MRIs, the popliteofibular ligament (PFL) in 93.3%, the popliteomeniscal ligaments (PML) in 90.4% and the meniscofibular ligament (MFL) in 39%. The anteroposterior distance of the LMTL in an axial view was 20.7 mm ± 3.9, the anterior thickness of the LMTL was 1.1 mm ± 0.3, and the posterior thickness of the LMTL 1.2 mm ± 0.1 and the height in a coronal view was 10.8 mm ± 1.9. The length of the PFL in a coronal view was 8.7 mm ± 2.5, the thickness was 1.4 mm ± 0.4 and the width in an axial view was 7.8 mm ± 2.2.

Conclusions The MTPFC has a constant morphological and anatomical pattern for three of its main ligaments and can be easily identified and measured in an MRI; the MFL has a lower prevalence, considering a structure difficult to identify by 1.5 T MRI.

Keywords Lateral meniscus · Lateral menisco-tibial ligament · Popliteo-fibular ligament · Popliteo-meniscal ligaments · Meniscofibular ligament · Menisco-tibio-popliteus-fibular complex

Introduction

Since its first description, the lateral compartment of the knee has always been a complex anatomical region to study [7, 27, 31]. To further confuse the issue, the peripheral attachments of the lateral meniscus body have been denominated in several different ways when referring to the same structures. Initially, the meniscofibular ligament (MFL) [4, 21, 36] was described. Later, the meniscotibial ligament (MTL) [2, 11, 32], which is also known as the coronary ligament, was described. In classic treatises, these structures were omitted and wrongly referred to as a simple capsular reinforcement [26].

Interestingly, the peripheral attachments of the lateral meniscus body were recently redefined in a large cadaveric study. Masferrer-Pino et al. [18] reported on a constant lateral meniscus fixation pattern and defined it as the menisco-tibio-popliteus-fibular complex (MTPFC). As described in their findings, this structure is made up of three interconnected ligaments. They are the lateral meniscotibial ligament (LMTL), the popliteofibular ligament (PFL) and the popliteomeniscal ligaments (PML). All three ligaments have well-defined anatomy in terms of thickness and histology (Fig. 1).

The radiological anatomy of the lateral side of the knee has been thoroughly examined in the literature, making reference to the arcuate ligament, fabellofibular ligament, popliteus tendon, popliteomeniscal fascicles and the popliteofibular ligament [3, 5, 9, 12, 14, 16, 23, 27, 33]. Obaid et al. [22] were the first to perform a magnetic resonance imaging (MRI) study looking specifically at the MFL. The

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The characteristics of the three ligaments of the MTPFC and the MFL were delineated. Prevalence was determined, interest measurements were made and the topographic relationships between them were established. The LMTL was seen in a coronal (Fig. 2a) and axial (Fig. 2b) views lateral to the external meniscus as a hypointense structure. The height of the LMTL and the distance from the articular edge to its tibial insertion were measured on the coronal plane at the points where the anterior region of the fibular head was observed (Fig. 2c). In the axial view, the length of the ligament was measured at the level of the lateral tibial plateau (Fig. 2d). The LMTL was divided into two equal parts at the junction of the anterior third with the middle third and at the junction of the posterior third with the middle third. The thickness was measured at these two points (Fig. 2e). Additionally, measures were taken of the distances from the antero-lateral insertion of LMTL to the middle point of the anterior root and from the postero-lateral insertion to the middle point of the posterior root (Fig. 2f) [29]. Then, the distance from the center of the ligament to the iliotibial band was measured.

The PFL was defined as a hypointense structure between the popliteal tendon and the highest region of the fibular head (Fig. 3a, b, c) [19]. The length and thickness of PFL on the coronal plane were measured at the level of the posterior edge of the lateral meniscus (Fig. 3a). Its sagittal length was measured at the lateral edge of the tibial plateau. It was also possible to observe the popliteal tendon in this view (Fig. 3b). The width was measured in the axial view at the level of the lateral tibial plateau (Fig. 3c). The visualization of the PFL was assessed by using the visual confidence scale. On that scale, there is 2 for more than a half-length of the ligament, 1 for less than a half-length and 0 for no visibility [15].

The two fascicles of the PML were seen in a coronal (Fig. 4a) and sagittal (Fig. 4b) view and its thickness were measured at the level of the highest point of the fibular head (Fig. 4b). The length of the PML was measured on the axial plane at the level of the lateral tibial plateau from the insertion of the lateral meniscus to the popliteal tendon [35]. The length of the inferior fascicle was measured at the level of the body of the lateral meniscus and was traced posteriorly up to the union of the popliteal tendon (Fig. 4c).

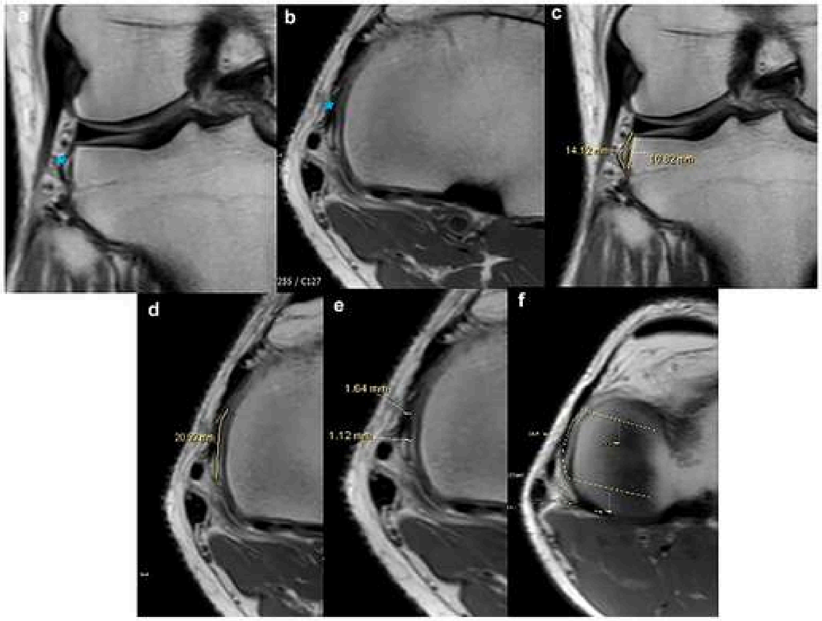

Fig. 2 Lateral menisco-tibial ligament (blue dot). **a** coronal and **b** axial view; **c** height of the LMTL and distance from the articular edge to its tibial insertion; **d** length; **e** anterior and posterior thickness; **f** distances from the antero-lateral insertion of LMTL to the middle point of the anterior meniscal root and from the postero-lateral insertion to the middle point of the posterior meniscal root

the intraclass coefficient correlation test to estimate agreement. To evaluate interobserver error, a random subsample consisting of 25 MRIs was selected and later reviewed by the observers after two weeks. This data was entered into a computer database, and the Intraclass coefficient correlation test was performed to compare the two sets of measurements. For quantitative observations, intra- and interrater reliability were calculated using the intraclass correlation coefficients (ICC) between all pairs. An ICC ≥ 0.8 was considered a good agreement. A p value threshold of 0.05 was used to determine statistical significance. Statistical analysis was performed using the SPSS statistical package version 25 for Mac (IBM, Armonk, NY, USA).

It was determined that 94 patients would provide a confidence level of 95% and a power of 97.5% to find a prevalence of 42% (with 10% precision) for the presence of the 4 ligaments in this anatomical region as per a previous study [10, 35].

Results

Of the two hundred MRI scans that were analyzed in patients over 18 years of age, 95 were excluded due to the inclusion/exclusion criteria (47.5%). Of those 95, 31 had an anterior cruciate ligament injury (32.6%), 10 presented with meniscal extrusion > 3 mm (10.5%), 20 with lateral meniscus tears (21%), 14 with medial meniscus tears (14.7%), 2 with infection (2.1%), 6 had tumors (6.3%) and 12 had artifacts that limited the correct visualization of the images (12.6%). Measurements were taken in 105 resonances, of which 64 (60.9%) were for anterior pain associated with patellofemoral syndrome, 28 due to non-specific chronic knee pain (26.6%) and 16 for repetitive joint effusion (15.2%). All of these MRIs were classified as normal without pathological findings by the radiologist who reviewed the study for diagnostic purposes as well as the musculoskeletal radiologist who analyzed them for the purposes of this study.

In total, 105 patients were included (60% were right knees and 40% were left) with an average age of 50.1 years ± 14.8 (37.7–62.5). There were 58 knees (55.2%) corresponding to male patients and 47 knees (44.7%) to female patients. The totality of the data is shown in Table 1.

Prevalence and anatomical measurements

The LMTL was observed on the coronal and axial planes in DIXON images, with a prevalence of 102 (97.1%). Its average length on the axial plane was 20.7 mm (SD ± 3.9; 95% CI 17.4–24) and the mean height measured in the coronal view was 10.8 mm (SD ± 1.9; 95% CI 9.1–12.5). Its insertion was 6.4 mm (SD ± 1.5; 95% CI 5.1–7.6) from the tibial plateau surface.

The PFL had a prevalence of 98 (93.3%) with partial visualization of 54 (51.4%) in the MRIs, and complete visualization in 44/105 (41.9%). The mean length of the PFL in the coronal view was 8.7 mm (SD ± 2.5; 95% CI 6.6–10.8) and 8.8 mm in the sagittal view (SD ± 2.4; 95% CI: 6.8–10.9).

The PML showed a prevalence of 94 (90.4%) in the sagittal view. The mean length of the inferior PML was 12.9 mm (SD ± 2.2; 95% CI 11–14.7), and the length of the superior fascicle was 16.2 mm (SD ± 3.4; 95% CI 12.4–19.3). The MFL was visualized in 41/105 (39%) in complete extension, with a mean sagittal length of 14.8 mm (SD ± 1.8; 95% CI 13.3–16.3). Complete data is in Table 1.

Gender analysis

There were no differences in age between genders. Similarly, there were no statistically significant differences in terms of prevalence between any of the ligaments. The entire gender analysis is shown in Table 2.

The distance between the articular edge and the tibial insertion of the LMTL was statistically longer in males than in females, 7.3 mm (SD ± 2.2; 95% CI 1.9–12.7) vs. 5.8 mm (SD ± 0.8; 95% CI 4.7–6.8) $p = 0.004$.

The PFL was statistically longer in the sagittal view in males 10.3 mm (SD ± 3.3; 95% CI 1.9–18.6) vs. 8 mm (SD ± 1.5; 95% CI: 6–9.9) $p = 0.026$ for females.

The inferior fascicles of the PML were longer in males at 14.6 mm (SD ± 2.5; 95% CI 8.4–20.9) vs. 11.8 mm (SD ± 1.4; 95% CI 10.1–13.5; $p = 0.041$) in women. The superior fascicles of the PML were also longer at 17.4 mm (SD ± 3.6; 95% CI 12.9–20.4) vs. the 15.1 (SD ± 2.8; 95% CI 10.2–17.3; $p = 0.048$) in women.

Age analysis

The length of the LMTL in the coronal view was statistically significant in the patients over 50 years-old (10.9 SD ± 2.2; 95% CI: 3.9—19.3) when compared to younger patients (9.8 SD ± 2; 95% CI: 8.2—12.9; $p = 0.013$). The rest of the variables were not statistically significant (Table 3).

Morphological results

In the sagittal view, the LMTL was observed as a hypointense linear structure originating at the inferolateral margin of the lateral meniscus, between the mid and posterior third of the meniscus periphery. It was also noted that its insertion extends distally from the tibial plateau (Fig. 2a). On the axial plane, the LMTL was observed as a linear and, in some cases, a curly structure (Fig. 2b).

The PFL was observed in coronal and sagittal views as a thin hypointense linear structure that extends distally from the distal third of the popliteus tendon towards the fibular

Table 2 Comparison of the menisco-tibio-popliteus-fibular complex by sex.

	Males	Females	*p* value
Age, mean ± SD (95% CI)	40 ± 17.4 (32.6–45.8)	56.2 ± 10.6 (43.1–69.3)	*(n.s.)*
Right knee, *n* (%)	27 (46.6)	15 (31.9)	*(n.s.)*
Lateral menisco-tibial ligament			
Prevalence, *n* (%)	57 (98.3)	45 (95.7)	*(n.s.)*
Length (axial), mean ± SD (95% CI)	22.8 ± 4.6 (11.28–34.23)	19.5 ± 3.4 (15.2–23.7)	*(n.s.)*
Anterior root, mean ± SD (95% CI)	24.3 ± 1.1 (21.6–26.9)	21.9 ± 2.6 (18.7–25.1)	*<0.001*
Posterior root, mean ± SD (95% CI)	29 ± 2.8 (22–36.1)	26.2 ± 0.6 (25.3–27)	*<0.001*
Height (coronal), mean ± SD (95% CI)	11 ± 1.2 (7.9–14)	10.7 ± 2.5 (7.6–13.8)	*(n.s.)*
Tibial plateau insertion (coronal), mean ± SD (95% CI)	7.3 ± 2.2 (1.9–12.7)	5.8 ± 0.8 (4.7–6.8)	*0.004*
Thickness 1 anterior third to middle, mean ± SD (95% CI)	1.9 ± 0.2 (1–2)	1.1 ± 0.4 (0.6–1.6)	*0.005*
Thickness 2 middle third to posterior, mean ± SD (95% CI)	1.8 ± 0.1 (0.9–2.5)	1.3 ± 0.2 (1–1.5)	*0.006*
Meniscus to iliotibial band, mean ± SD (95% CI)	1.2 ± 0.6 (0.4–2.8)	1.2 ± 0.5 (0.5–1.9)	*(n.s.)*
Popliteo-fibular ligament			
Prevalence, *n* (%) for partial, *n* (%) for complete	32 (55.2) / 22 (37.9)	22 (46.8) / 22 (46.8)	*(n.s.)*
Coronal length, mean ± SD (95% CI)	9.1 ± 1.4 (5.7–12.5)	8.5 ± 3.1 (4.6–12.4)	*(n.s.)*
Thickness, mean ± SD (95% CI)	1.4 ± 0.4 (0.4–2.3)	1.4 ± 0.6 (0.7–2.1)	*(n.s.)*
Sagittal length, mean ± SD (95% CI)	10.3 ± 3.3 (1.9–18.6)	8 ± 1.5 (6–9.9)	*0.026*
Width (axial), mean ± SD (95% CI)	9.6 ± 3 (2.2–17)	6.8 ± 0.9 (5.7–8)	*(n.s.)*
Popliteo-meniscal ligament			
Prevalence, *n* (%)	52 (91.2)	42 (89.4)	*(n.s.)*
Length inferior popliteo-meniscal ligament, mean ± SD (95% CI)	14.6 ± 2.5 (8.4–20.9)	11.8 ± 1.4 (10.1–13.5)	*0.041*
Length superior popliteo-meniscal ligament, mean ± SD (95% CI)	17.4 ± 3.6 (12.9–20.4)	15.1 ± 2.8 (10.2–17.3)	*0.048*
Thickness inferior popliteo-meniscal ligament, mean ± SD (95% CI)	3.6 ± 0.2 (3.2–4.1)	2.7 ± 0.5 (2.1–3.4)	*0.041*
Thickness superior popliteo-meniscal ligament, mean ± SD (95% CI)	3.8 ± 0.2 (3.2–4.2)	3.1 ± 0.3 (2.7–3.5)	*(n.s.)*
Menisco-fibular ligament			
Prevalence, *n* (%)	22 (37.9)	19 (40.4)	*(n.s.)*
Length MFL sagittal, mean ± SD (95% CI)	15.5 ± 1.2 (12.4–18.5)	14.4 ± 2.1 (11.8–17)	*0.034*

SD standard deviation, *CI* confidence interval

of view. This made it possible to identify it and its connections with the PFL and the PML. Furthermore, it is the first study that characterizes and measures the whole MTPFC by means of MRI.

The soft tissues of the lateral side of the knee represent a diagnostic challenge to musculoskeletal radiologist and knee surgeons. Anatomical variations, inconsistency in nomenclature, and a relative lack of familiarity with several posterolateral structures create an environment at risk for an incomplete or missed diagnosis. As in cadaveric studies, different names have been used to describe similar radiological structures, thereby creating confusion in their study throughout the years. The MFL, that does not distinguish between the PFL and the LMLT, has been analyzed with MRI in previous studies. Obaid et al. found the MFL in 42.5% in a 1.5 T MRI series of 152 patients (results very similar to those obtained in our study). This percentage increased to 63% when there was fluid in the posterolateral corner [22]. The MFL was commonly observed using the fat suppression sequence in the sagittal view with 3 mm slices in which a thickness of 2–6 mm was seen. The conclusion was that this structure should be considered the normal anatomy of a knee in magnetic resonance imaging. Later, Lee et al. [15] observed a prevalence of 89.4% for the MFL even though it was a limited series of 19 magnetic resonance arthrographies and Bozkurt et al. [4] performed a cadaveric study aiming to determine the thickness of the LMTL. They found it to be 3.8 mm with a range of 2.6 to 6.1 mm. These results differ greatly from ours, which are more similar to other cadaveric studies despite not being analyzed by MRI [18, 36]. Among the possible reasons for these differences is that their measurements incorporated part of the lateral capsule, which better differentiates the structures of the MTPFC, unlike the rest of the studies cited. Regarding the MFL, our work team acknowledges its existence. However, this ligament only corresponds to a small number of fibers in a posterior position in continuity with the LMTL. In other words, it is the same ligament. It has a tibial portion of large size (the lateral menisco-tibial ligament) and a small proportion of posterior fibers leading to the head of the fibula work as well as the consistency in its radiological pattern may help both radiologists when searching for and describing lesions at this level and knee surgeons in their effort to better plan surgical management. Biomechanical studies are needed to further analyze the anatomical relationship and functional role of the LMTL, PFL, and PML.

Some of the limitations of the current study might include the power of the magnet, as a 3 Tesla MRI unit might be much more precise. However, most of the published MRI studies used a 1.5 Tesla unit for the resolution for this type of study as it is considered good enough. The high interobserver agreement found in the present work confirms this. The lack of anatomical correlation with the MRI findings is another issue. Ideally, a correlation between MRI and cadaver dissection would have been better. However, all the structures described in this study match the most recent anatomical descriptions found in the literature. Another limitation is that the MRIs used were not taken specifically for study purposes in healthy patients without knee injuries, yet our inclusion and exclusion criteria were strict to select only those MRIs that do not represent a source of bias. Another final limitation may be the fact that only knees of the same ethnicity have been analyzed. Therefore, our findings cannot be generalized with certainty.

Conclusions

The MTPFC, which is made up of its three ligaments (LMTL, PFL, and PML), can be identified by means of MRI as they present a consistent morphological and anatomical pattern. The MFL was found on fewer occasions, considering a structure difficult to identify by 1.5 T MRI which corresponds to the most posterior fibers of the LMTL that reached the head of the fibula.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s00167-021-06633-5.

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Author contributions All authors contributed to the study's conception and design. Material preparation, data collection were performed by RMA, ERC, AMP and JRPM. The methodology was designed by JFGQ. Formal analysis was achieved by SP. Writing—original draft preparation was carried out by FVC: Writing, review and editing was executed by REEO, VMPM and SGL Supervision was carried out by JCM and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Declarations

Conflict of interest Each author certifies that neither he or she, nor any member of his or her immediate family, has funding or commercial associations (consultancies, stock ownership, equity interest, patent/licensing arrangements, etc.) that might pose a conflict of interest in connection with the submitted article. Each author certifies that his or her institution approved the human protocol for this investigation and that all investigations were conducted in conformity with ethical principles of research.

Ethics approval The present protocol was approved by the Institutional Review Board of the School of Medicine and University Hospital "Dr. José Eleuterio Gonzalez" of the Universidad Autonoma de Nuevo Leon with registration number: OR20-00001.

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4.2. Article 2

Mid-term clinical and radiological outcomes of lateral meniscal allograft transplantation with suture-only fixation plus capsulodesis.

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Original Article

Mid-Term Clinical and Radiological Outcomes of Lateral Meniscal Allograft Transplantation with Suture-Only Fixation Plus Capsulodesis

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J Knee Surg

Abstract

Meniscal allograft transplantation (MAT) is an effective reconstructive procedure for treating a symptomatic postmeniscectomy syndrome. It consists of replacing the lost meniscal tissue aiming to improve the clinical outcomes and prevent progressive deterioration of the joint. The aim of this study was to evaluate meniscal graft survivorship and report on the radiographic (in terms of graft extrusion and joint space width and alignment) and the functional results through a midterm follow-up of lateral MAT performed with a soft tissue fixation technique after capsulodesis. In total, 23 patients who underwent lateral MAT as a single procedure were included. The Knee injury and Osteoarthritis Outcome Score, Lysholm, Tegner, and visual analog scale scales were used for patient assessment. Magnetic resonance imaging and a complete radiographic protocol were conducted to determine the degree of meniscal extrusion and the changes in the degree of osteoarthritis and coronal alignment. Assessments were performed after 2 and 7 years of follow-up. A significant improvement in all the scores, relative to preoperative values, was found after 7 years of follow-up. This improvement remained consistent throughout the first and second follow-up periods. A mean absolute extrusion of 2.2 mm ± 1.6 and an extrusion percentage of 28.0% ± 11.43 were found, with no significant differences throughout the follow-up periods. There was no statistically significant difference in terms of the frontal mechanical axis and joint space narrowing between the preoperative value and at

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- lateral meniscus
- meniscal extrusion
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the first and second follow-up periods. A survival rate of 85.7% was found after 7 years of follow-up. Capsulodesis results in a low degree of meniscal extrusion in isolated lateral MAT fixed with a suture-only technique, which is maintained after 7 years of follow-up, with a high graft survival index (>85%) and satisfactory results on the functional scales.

Meniscal allograft transplantation (MAT) is an effective reconstructive procedure to treat symptomatic postmeniscectomy syndrome.[1] It aims to improve clinical outcomes and prevent the progressive deterioration of the joint by replacing the lost meniscal tissue.[2] Although MAT has shown favorable clinical results in terms of pain relief and functional improvement in the mid- and long terms,[3] some magnetic resonance imaging (MRI) studies have reported an extrusion of the allograft, consisting of a radial displacement of the transplanted menisci that exceeded the tibial plateau, which tends to stabilize over time.[4]

Biomechanically, an extruded meniscus could decrease the resistance to hoop stress, especially when the extrusion leads to a subluxation of the transplanted menisci from the tibial margin. Additionally, it decreases the tibial cartilage coverage and increases the incongruity with the femoral condyle,[5] leading to failure in proper weight transfer and shock absorption.[6] Therefore, extrusion of the meniscal allograft might reduce the beneficial effects of MAT and may lead to increased degeneration of the cartilage and graft failure.[7] Although the final clinical impact of allograft extrusion is unknown, the anomalous position of those grafts causes concern among some surgeons and remains a factor influencing postoperative failure.[8]

To limit or prevent lateral meniscal allograft transplantation (LMAT) extrusion, several surgical techniques have been described in the literature over recent years.[9] In 2017, the all-arthroscopic implant-free lateral capsulodesis technique was described. It involves fixing the residual meniscus rim or the lateral capsule to the tibial plateau by means of two 2.4-mm transtibial tunnels using sutures.[10] In 2018, Masferrer-Pino et al found decreased meniscal extrusion using this technique when compared with both the bone bridge fixation technique and the suture-only fixation technique without a capsulodesis.[11] Both studies reported similar functional results at the short-term follow-up.

Currently, there are few studies that analyze the evolution of allograft extrusion after LMAT performed with a soft tissue fixation technique plus capsulodesis at the midterm follow-up. The aim of this study was to evaluate meniscal graft survivorship and report on radiological and functional outcomes of LMAT performed with a soft tissue fixation technique plus lateral capsular fixation (capsulodesis) through a mid-term follow-up. As a secondary aim, this investigation looked to see whether the improvement in the functional scores could be considered clinically relevant. The first hypothesis of this study was that lateral capsular fixation reduces the postoperative degree of allograft extrusion, keeping it stable over time, without compromising functional outcomes at the mid-term follow-up. The second hypothesis was that a graft survival rate greater than 85% would be found after 7 years of follow-up.

Methods

We performed a prospective observational study adhering to the STROBE (Strengthening the Reporting of Observational studies in Epidemiology) guidelines. The study was approved by our local ethics committee, all patients gave their consent to participate before being enrolled. Moreover, we followed the guidelines of the World Medical Association 1964 Declaration of Helsinki and its 2013 revision.[12]

We included 23 patients that had undergone an isolated lateral MAT from January 2014 to February 2021. In all cases, fresh-frozen (−80°C), nonirradiated, nonantigen-matched meniscal allografts, provided by an authorized local tissue bank (Barcelona Blood and Tissue Bank), were transplanted. All the procedures were performed by the same senior author (J.C. M.) who had 30 years of experience in meniscal transplantation. In all cases, the capsulodesis technique was utilized.[13]

We included patients between 18 and 45 years of age, irrespective of sex. All patients were complaining of the lateral postmeniscectomy syndrome, presenting with pain in the lateral knee compartment and joint effusions which did not improve with at least 6 months of nonsurgical therapy. Patients were eligible for MAT if they presented a stable knee, had no previous ligament reconstruction or cartilage repair, and advanced cartilage degeneration in the knee compartment (Ahlback grade greater than II).[14] Patients were excluded from the study if they had concomitant surgeries during meniscal transplantation (ACL reconstruction, osteotomies, articular cartilage surgery, etc.), arthrofibrosis, skeletal immaturity, prior joint infection, synovial disease, or a BMI $\geq 30\,kg/m^2$. A localized grade III or IV defect confined to the area covered by the meniscus was not considered a contraindication for performing the procedure.

Although no relationship between malalignment and meniscal extrusion has been established, malalignment was considered an exclusion criterion to prevent confounding results. We considered genu varus and genu valgum above 5 degrees with respect to the normal axis as malalignment. Patients who were not able to complete the follow-up were excluded from the analysis.

Surgical Technique

Allograft sizing was matched with the donor's morphometric dimensions (weight and size) and double checked with the method described by Pollard et al.[13] The lateral meniscal allograft never exceeded a 5% mismatch in terms of width or length. During the surgical procedure, all allografts were soaked and kept in a vancomycin-saline solution at 36°C.[15] The allograft was prepared outside the knee on a worktable where the meniscus was cleaned of fatty tissue and peripheral ligaments; subsequentially, it was detached from both meniscal roots.

All knees were examined arthroscopically to determine the status of the meniscus, ligaments, and cartilage. The remains of the host menisci were refreshed to promote healing using a combination of rasping, shaving and high-frequency thermocoagulation (Coblation Flow 50 and Werewolf Cobaltion System, Smith & Nephew, Austin, TX), leaving 1 to 2 mm of bleeding peripheral rim. If the presence of a marginal lateral osteophyte was detected, it was removed arthroscopically.[9] No. 2 high-strength sutures (Ultrabrid, Smith & Nephew, Andover, MA) were placed at both horns with a Krackow mattress technique. One additional vertical mattress suture was placed at the junction between the posterior horn and the body of the meniscus. The anterior and posterior horns of all the allografts were fixed to 4.5-mm transtibial tunnels drilled at the anatomic meniscal root attachments (Meniscal Root Repair System, Smith & Nephew, Andover, MA).[16] The posterior-horn suture was used to pull the meniscal allograft into place.

The additional vertical sutures aid in situating the graft because it is first retrieved from the posterolateral or posteromedial corner with an outside-in technique and pulled when the graft is being introduced into the joint.

Once the allograft was placed correctly, final fixation was accomplished with a combination of all-inside (FasT-Fix; Smith & Nephew, Andover, MA) horizontal or vertical sutures in the posterior half of the meniscus, and with outside-in sutures in the anterior half. The sutures were placed alternating between the inferior and superior aspects of the graft every 5 to 10 mm to obtain a better end-position of the MAT.

Whenever possible, we tried not to fix the allograft to the popliteal tendon. However, there were seven cases in which this was not possible. Previous studies have reported that this does not have clinical or biomechanical significance.[17,18] The sutures placed on both horns were tied together over the tibial cortex at the end of the procedure. The capsulodesis technique has been previously described.[10,11,14] With the help of a tibial ACL guide (Pinn-ACL Guide, ConMed, Largo, FL), two 2.4-mm tunnels were drilled from the antero-medial tibial cortex aiming to the edge of the lateral tibial plateau (LTP; ►**Fig. 1a–1c**). A 10-mm bridge was left between them where the capsule was seen more laterally displaced. The capsule, including any meniscal remnant, was pierced with an 18-gauge spinal needle loaded with a #2 PDS suture using an outside-in technique (►**Fig. 1d**). These sutures were replaced by high-strength sutures and pulled down through each tibial tunnel. Finally, the two strands were tied to each other on the tibial cortex. This maneuver brings the capsule over the LTP, reducing any redundancy (►**Fig. 1e and f**).[11] The

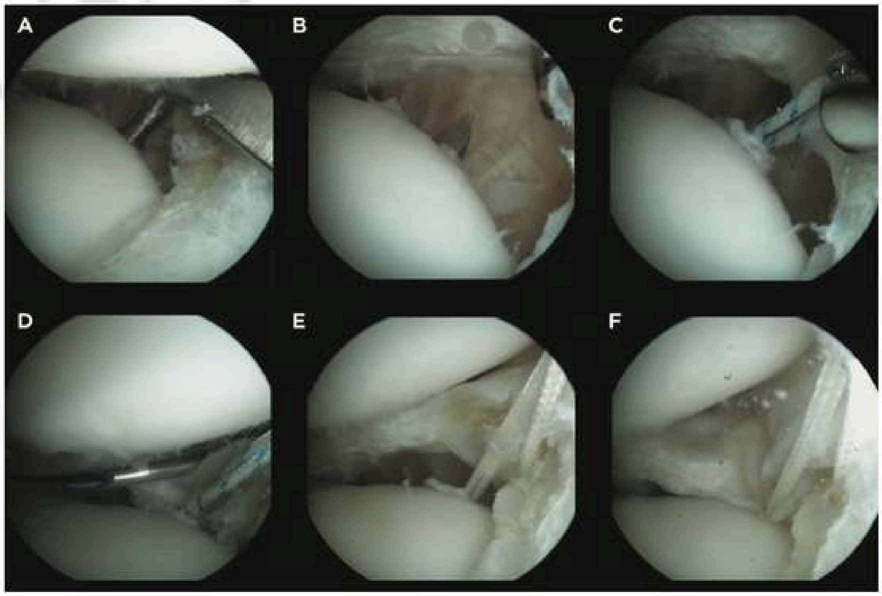

Fig. 1 (A–F) Arthroscopic images of the capsulodesis technique.

whole surgical technique was performed arthroscopically in all the cases. The knee joint was immobilized in full extension immediately after surgery.

Rehabilitation Protocol

All the patients had the same postoperative protocol. On the first postoperative day, quadriceps-setting exercises and straight-leg raises, with a knee brace, were initiated. A progressive range of motion, without exceeding 90 degrees of flexion until the 4th week, was followed with unrestricted progression, per patient tolerance. For the first 2 weeks, only proprioceptive weight-bearing with a knee brace blocked in full extension was allowed. Progressive weight-bearing was subsequently encouraged, depending on the patient's tolerance. Full weight-bearing was regularly obtained by 4 to 6 weeks. Patients were able to return to a normal workload by the 4th month after surgery.

Demographic and Clinical Data

Each patient was subjected to clinical questioning and a thorough clinical examination. Demographic and clinical data were collected from each patient preoperatively and at the final follow-up. To look for radiographic progression of osteoarthritis and changes in the coronal alignment of the lower limb, each patient underwent a standardized radiographic protocol which consisted of lower limb telemetry, a Schuss view, lateral views, a merchant axial view, and an axial weight-bearing view. Information on any complication related to the MAT surgery, the reappearance of symptoms, or the need for further surgery was prospectively collected. A complete physical examination was performed evaluating range of motion, joint leak, presence of pain in the lateral joint line upon palpation or during range-of-motion, palpable meniscus displacement during joint compression, and distraction, rotation, and flexion tests (McMurray). The activity level of the patients was collected preoperatively and during the follow-up.

Magnetic Resonance Imaging and Evaluation

An MRI was performed on each patient before surgery and after 1, 2, and 5 years of follow-up. All MRIs were done with a 1.5-T superconducting magnet (Prestige 2T, Elscint, Haifa, Israel) using a knee-specific circular coil. The imaging protocol consisted of a T2-weighted with fat saturation axial fast spin echo, an intermediate-weighted sagittal spin echo, and a T2-weighted with fat saturation coronal fast spin echo. This imaging protocol has been described previously.[14]

The graft position was evaluated in coronal images at the level of the medial collateral ligament (MCL),[19] where extrusion is maximum. The measuring was conducted drawing two lines: a vertical one intersecting the margin of the LTP at the point of horizontal-to-vertical transition and a perpendicular line from the lateral margin of the meniscus to the first line. The second line was used to measure the absolute meniscal extrusion, as previously described (►Fig. 2).[20] The same measurements were performed on four coronal sections (2 mm thickness) in a posterior to anterior direction, thus covering the region where the MCL was observed. The highest value of extrusion was considered. Given that the patients had different MAT grafts, cartilages, and bone sizes, relative values were calculated for standardization by dividing the quantity of meniscal extrusion by the total width of the meniscus as measured in the same MRI scan (►Fig. 2).[21] This value indicates the relative meniscal extrusion that is the ratio of the subluxated width to the entire meniscus. Minor extrusion was considered when the graft was subluxed by less than 3 mm beyond the LTP. On the contrary, major extrusion was considered when the allograft exhibited more than 3 mm of subluxation or when the meniscus was subluxated by more than 25% of its width.

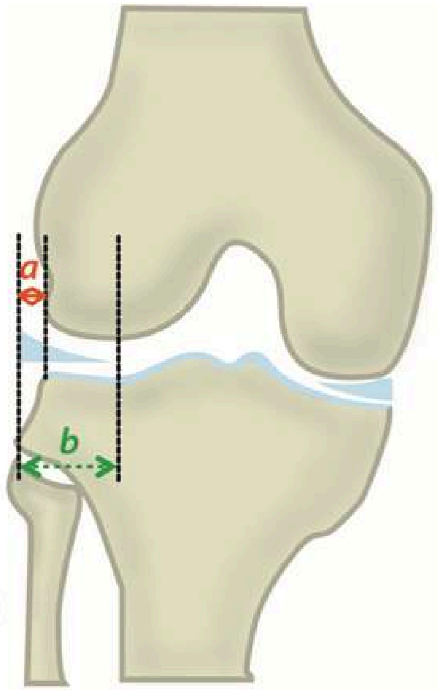

Fig. 2 Schematic view of meniscal extrusion measurements method in an MRI. Absolute meniscal extrusion (a) was defined as the distance between the outer edge of the tibial articular cartilage and the outer edge of the meniscal allograft. The relative value of meniscal extrusion was defined as a relative percentage of extrusion, which was calculated as the absolute extrusion of the meniscus (a) divided by the entire meniscal width (b) and reported as a percentage ($a/b \times 100$). MRI, magnetic resonance imaging.

The tibiofemoral lateral joint space width (JSW) was evaluated with 45 degrees weight-bearing PA radiographs in all knees before surgery and at follow-up to determine if failure of the meniscal allograft was present.[22]

JSW was defined as the joint space opening at its narrow point in the lateral compartment, where the MAT was performed using the digital caliper in the picture archiving and communication system . Limb alignment was measured with full-leg standing radiographs to quantify the degree of deviation in the coronal plane over time. When expressing mechanical axis deviation, valgus mechanical alignment was represented with positive values and varus deviation with negative values.[22]

The images were evaluated twice, with 3 weeks of separation, by three independent observers (three knee surgeons, R.M.A., A.M.P., and J.A.R.). The observers received the same training before evaluation to reduce the possibility of measurement bias. The mean of these three measurements was considered for the statistical analysis. The measurements were only considered relevant if a high interobserver correlation index was present when comparing the results between the three observers.

Functional Evaluation

Each patient filled out questionnaires for the following outcome instruments: Tegner activity score (TAS; 0–10 scale)[23]; Knee injury and Osteoarthritis Outcome Score (KOOS; 0–100 scale, with higher values indicating better patient state); and Lysholm score (scores ranged from 0 to 100, where 95 to 100 points indicated an excellent outcome; 84 to 94 points, a good outcome; 65 to 83 points, a fair outcome; and <65 points, a poor outcome).[24] A 10-point visual analog scale for pain was also used. These scores were compared with their preoperative and short-term follow-up scores (2 years) to evaluate the effects of the lateral MAT and their consistency over time.[11,14] Patient satisfaction was evaluated with a subjective score ranging from very satisfied (4 points), satisfied (3 points), neutral (2 points), somewhat dissatisfied (1 point), and not satisfied at all (0 points). Answers ranging to 3 points or more were considered as a positive result (i.e., satisfied with the postoperative result). The patients were asked whether they would repeat the procedure if needed (yes/no). The scores were measured by an independent orthopedic surgeon who was blinded to the details of the study. The minimal clinically important difference (MCID) and patient acceptable symptom state (PASS) for the Lysholm and the KOOS scales were estimated based on the analysis published by Liu et al.[25] They stated that a difference in the Lysholm scale of 12.3 points was considered clinically significant in patients who had undergone meniscal transplantation. They also concluded that a value of 66.5 is the value beyond which the patients can be considered well. On the contrary, several MCIDs for each of the domains of the KOOS scale (range 9.5–14.6) and PASS values between 22.5 and 74.5 for the KOOS subscales have been described. However, the official web site of the KOOS scale states that the minimal important difference is currently suggested to be 8 to10 points. Thus, we considered this value as our cutoff for MCID.

Definition of Failure Criteria

Surgical failure was defined as a requirement for a revision procedure related to the initial MAT. The requirements included total knee arthroplasty, unicompartmental knee arthroplasty, retransplantation, suture and reattachment of the graft, and complete or partial removal of the allograft.[26] Clinical failure was defined as a poor Lysholm score (<65 points), no improvement in the pain score, and positive clinical signs of a meniscal tear upon clinical examination. Radiologic failure was defined as signs of allograft failure in MRI (grade three signal intensity and more than 50% of meniscal width extrusion or a tear) and loss of joint space in the involved tibiofemoral compartment in 45 degrees weight-bearing posteroanterior radiographs (<2 mm joint space).[27] For patients who experienced surgical failure, clinical scores were not included in the final analysis and the time to revision was noted and used for the survival analysis. For patients who had a poor Lysholm score (<65 points), earlier follow-up evaluations were assessed to detect the exact time when clinical scores declined to not overestimate the length of survival time.

Statistical Analysis

Continuous data were summarized with means and standard deviations or with medians and interquartile ranges and categorical data as frequencies and percentages. Normality was tested by means of the Kolmogorov–Smirnov test. Hypothesis testing was performed with Student's *t*-test, Mann–Whitney U test, or analysis of variance for repeated measurements for continuous data and with the X test for categorical data.[28]

The reliability of meniscal subluxation measurements was assessed using the intraclass correlation coefficient (ICC), which quantifies the proportion of the difference caused by measurement variability (ICC = 1 representing perfect agreement and ICC = 0 representing the opposite). The Kaplan–Meier method was used to estimate the survival function throughout the follow-up period. Finally, a p-value < 0.05 was used as the cut-off for statistical significance. All analyses were performed with the SPSS software (version 21.0, SPSS Inc, Chicago, IL).

Results

All the patients were available for assessment. The study group consisted of 16 men and 7 women (69.5%/30.4%) with a mean age of 40.93 ± 7.03 years at the time of transplantation and 46.29 ± 7.18 years at the time of evaluation. None of them were professional athletes. The mean follow-up of the patients was 84 ± 7 months (7 years). The mean interval period between meniscectomy and the appearance of the painful symptomatology was 11.43 years ± 8.78. The mean interval period between meniscectomy and MAT was 14.29 years ± 5.15. Thirteen (56.5%) MATS were performed on right knees, while nine (39.1%) were performed on left knees. Regarding the medical history, 20 of the patients had undergone a meniscectomy of the lateral meniscus by means of arthroscopy (7 total meniscectomies, 9 subtotal meniscectomies, and 4 partial meniscectomies), 2 patients had an open external meniscectomy, and 1 had an inveterate rupture of the lateral meniscus. In preoperative magnetic resonance images, all patients presented with a severe lateral meniscal deficit.

The average weight of the patients was evaluated before the surgery and upon evaluation was 70.50 kg ± 9.08 and 71.50 kg ± 8.08 ($p = 0.66$). Also, the average BMI at the time of surgery was 25.8 (range, 19–32.4) and 26.2 (range, 18.5–34.5) at the final follow-up ($p = 0.51$). The mean time to full weight-bearing without crutches was 5.7 weeks (range, 4–6 weeks). At the time of the MAT, the presence of grade III–IV of osteoarthrosis was documented in eight of the patients (34.8%) based on the ICRS classification. All cases of osteoarthrosis were confined to the original area covered by the lateral meniscus. In three of those eight patients, lesions were also evident in the lateral femoral condyle (two grade II and one grade III).

Clinical Assessment

The median range of motion of all patients was 131 degrees ± 8.7 (preoperative: 115 degrees ± 4.2, $p = 0.09$) and no patient had a deficit of joint extension or effusion at the time of evaluation. Two patients had pain upon palpation of the lateral joint line and positive meniscal maneuvers. Three patients were subsequently reoperated for a partial meniscectomy of the allograft (clinical and surgical failure). Furthermore, most of the patients were practicing sports activities (20/23, 86.9%), mostly low-impact recreational activities (►**Table 1**). The reasons for stopping sports activities in three out of the 23 patients were knee pain in two patients and fear of reinjury, or graft wearing, in the other one.

Table 1 Comparison of the results obtained in the midterm follow-up with respect to the preoperative state and at the 7-year follow-up in the different variables analyzed in the present study

Variable	Preoperative	2 y	7 y	*p*-Value (Preoperative vs. 2 vs. 7 y/2 vs. 7 y)
Carrying out sports activity, *n* (%)	7 (30.4%)	22 (95.6%)	20 (86.9%)	<0.0001/0.293
Lateral interline pain, *n* (%)	23 (100%)	0 (0%)	2 (8.7%)	<0.0001/0.147
Positive meniscal maneuvers, *n* (%)	23 (100%)	0 (0%)	2 (8.7%)	<0.0001/0.147
KOOS, mean ± SD	52.03 ± 2.95	91.3 ± 7.3	88.07 ± 4.70	<0.0001/0.175
Lysholm, mean ± SD	48.8 ± 13.91	91.4 ± 6.1	87.07 ± 4.16	<0.0001/0.141
Tegner activity score	4 (3–5)	7 (6–8)	7 (6–8)	0.876
Visual analog scale (0–10) score, mean ± SD	8.21 ± 0.97	0.93 ± 1.00	1.24 ± 1.08	<0.0001/0.531
Degree of satisfaction, mean ± SD (0–4)	N/A	3.8 ± 0.42	3.57 ± 0.65	0.276
Patients who said they would repeat surgery, *n* (%)	N/A	23 (100%)	22 (95.6%)	0.313
Meniscal extrusion classification	N/A	Minor extrusion 16 (69.6%) Mayor extrusion 7 (30.4%)	Minor extrusion 15 (65.2%) Mayor extrusion 8 (34.8%)	0.757 minor/0.756 mayor
Graft extrusion percentage (%)	N/A	24.65 ± 15.49	28.80 ± 11.43	0.427
Meniscal extrusion (mm)	N/A	1.94 ± 1.22	2.14 ± 1.58	0.710
Degree of osteoarthritis (Ahlback), *n* (%)	1.5 ± 0.41 I (12/52.2%) II (11/47.8%)	1.64 ± 0.45 I (8/34.8%) II (15/65.2%)	1.85 ± 0.54 I (5/21.7%) II (16/69.6%) III (2/8.6%)	Numerical data: 0.397/0.273 Categorical data: I = 0.430/0.433 II = 0.462/0.697 III = –/0.322
Joint space width (mm)	3.00 ± 1.20	2.84 ± 1.11	2.69 ± 0.27	0.717/0.083
Mechanical axis deviation, (°)	−1.53 ± 1.16 (varus)	-0.75 ± 1.14	0.11 ± 1.17	0.084/0.152
Patients with surgical, clinical or radiologic failure (for any of the reasons considered as a failure criterion)	N/A	0 (0%)	3 (13.04%)	0.073
Reoperations	NA	0	3 (13.04%)	0.075
Complications	NA	0	2 (1 arthrofibrosis and 1 superficial wound infection)	0.154

Abbreviations: KOOS, Knee Injury and Osteoarthritis Outcome Score; SD, standard deviations.

Radiographic Evaluation

►Table 1 shows that how there was a decrease in the measurement of lateral JSW with the passage of time; however, this difference did not reach statistical significance. Also, there was no statistically significant difference in the frontal mechanical axis between the preoperative value and the values at the 2 and 7-year follow-up periods. Additionally, three of the included patients developed an increase in the degree of osteoarthritis, according to the Ahlback classification after 2 years of follow-up. Regarding meniscal extrusion at the end of the follow-up, a mean absolute extrusion of 2.2 mm ± 1.6 and an extrusion percentage of 28.8% ± 11.4 were found, with no significant differences from the values obtained at the 2-year follow-up period. Regarding the classification of meniscal extrusion, only one patient had a greater extrusion compared with the previous assessment (►Table 1).

Functional and Satisfaction Scales

All scores showed a significant improvement after 2 years of follow-up, compared with the preoperative results (►Table 1). This improvement remained consistent after 7 years of follow-up.

There was no statistically significant difference between the scores obtained at the 2- and 7-year periods. The mean preoperative Lysholm score was graded as "good" in the 2-year evaluation and was maintained after 7 years. A high rate of satisfaction and a willingness to repeat the surgery if needed were reported at the final follow-up (►Table 1). No case was considered a clinical failure due to a low score on the Lysholm scale. In accordance with the MCID established by Liu et al,[25] our cohort of patients reported a clinically meaningful difference when comparing their preoperative Lysholm scores with the scores obtained after 2 years (48.8 ± 13.91 vs. 91.4 ± 6.1, respectively; MCID = 12.3). Importantly, this difference was maintained when we compared the scores after 2 and 7 years (91.4 ± 6.1 vs. 87.07 ± 4.16, respectively; MD = 12.3). In all cases, the patients obtained values above the upper range of the previously established PASS.[25] Moreover, regarding the KOOS score, we also found a clinically meaningful difference when comparing preoperative scores with those at the 2-years follow-up (52.03 ± 2.95 vs. 91.3 ± 7.3, respectively; MD = 8–10). This difference was maintained after 7 years of follow-up (91.3 ± 7.3 vs. 88.07 ± 4.70, respectively; MCID = 8–10). All patients obtained values above the upper range of the previously established PASS for the KOOS score.

Reoperations, Surgical Failures, and Clinical Failures

Two patients (8.7%) returned to the operating room after the primary procedure for three different surgeries. One of the patients returned for an arthroscopic arthrolysis due to late arthrofibrosis. It was classified as a complication but did not meet the failure criterion. The patient was subsequently reoperated for reinsertion of the anterior horn of the transplanted graft due to a traumatic rupture caused by falling down the stairs. The other patient returned for a partial graft meniscectomy due to early graft degeneration, which did meet graft failure criteria. The mean time to subsequent surgery was 25 ± 3.75 months. At the last follow-up period, none of the patients were candidates for TKR, UKR, or retransplantation. A survival rate of 85.7% was found after 7 years of follow-up (►Fig. 3) and the mean time to graft failure was 38.7 ± 4.12 months postoperatively.

Fig. 3 Survival plot calculated through the Kaplan–Meier method. Two patients developed graft failure at 37.4 and 40 months each. Nine patients were censored because they completed their follow-up time or were lost-to-follow-up without developing graft failure. The survival probability in the entire follow-up time was estimated at 85.7%.

Interobserver agreement ranged from 0.87 to 0.91, and interobserver agreement ranged from 0.89 to 0.95, for all measured values.

Discussion

Our main finding was that capsulodesis results in low meniscal extrusion degree in lateral MAT fixed with a suture-only technique, which is maintained after 7 years of follow-up. The second finding was that MAT in combination with capsulodesis has a high graft survival rate and produces satisfactory results on the functional scales, reaching adequate MCID and PASS. The cause of graft extrusion after MAT has yet to be completely understood. In recent studies, the presence of preexisting osteophytes in the tibial plateau,[9] a size mismatch between the affected articular surface and the meniscal allograft, bony obliquity of the MAT graft,[29] the position of the bone bridge,[30] an inappropriate fixation technique or peripheral suture tension,[31] and nonanatomic positioning of the meniscal allograft are known factors that influence graft extrusion after MAT.[7] Recently, an anatomic[32] and a radiologic study was performed to describe the structures that could avoid lateral meniscal extrusion (the Menisco-Tibio-Popliteus-Fibular Complex). It is likely that lateral capsulodesis mimics the function of a part of this complex (the lateral menisco-tibial ligament), whose injury has been related to the extrusion phenomenon.[6] It has been previously suggested that the absolute value of meniscal extrusion is conditioned by preoperative and intraoperative factors[6] and that the phenomenon of meniscal extrusion usually presents early during the first postoperative year and stabilizes after that.[6] Therefore, the extrusion can be minimized if the surgical indication is correct, the allograft is properly selected and prepared, as well as placed with an adequate surgical technique.

Capsulodesis allows for versatility in terms of the number of fixation points and locations, without significant bone loss in the tibial plateau. It does not interfere with subsequent magnetic resonances.[10] The capsulodesis technique was initially developed in combination with the MAT with both horns secured (suture-only fixation) because soft tissue fixation of the graft is easier, obtaining good results in previous studies.[33] The clinical studies comparing it with the other techniques that involved bone fixation did not show any beneficial effect regarding clinical, functional, and radiographic outcomes. However, they have shown an improvement in the degree of meniscal extrusion and a reduction of complications,[16] which has been attributed to greater graft stability when bone fixation is used.[34]

Roumazeille et al studied MAT without bone plugs and found that meniscal extrusion was present in 75% of patients evaluated via MRI at 6 months postoperatively.[35] Abat et al found a degree of extrusion of 38.3% ± 14.4 with the suture-only fixation technique and 30.14% ± 13.5 with the bone plug method in a series of lateral MAT with a minimum follow-up of 3 years.[16] Choe et al reported a result of 3.4 mm ± 2.2 for the absolute value of meniscal extrusion and an incidence of extrusion of 41.6% for 320 cases of lateral TMA using the keyhole technique with a bone block connecting the anterior and posterior horns in a retrospective MRI evaluation performed at least 1 year after surgery. There was also a significant decrease in meniscal extrusion as the learning curve increased, obtaining a mean of 2.5 mm ± 2.1 for the total extrusion value and an extrusion percentage of 27.5% for the last 40 operated cases.[22] Verdonk et al reported that the mean degree of subluxation for 17 patients who underwent LMAT between 2004 (follow-up of 23.45 months) and 2006 (minimum follow-up of 10 years) was 5.8 mm ± 2.8. They also reported that partial extrusion occurred in 12 of the 17 patients who received LMAT (70%) using a soft tissue fixation technique with sutures.[36] Ahn et al reported that the extrusion incidence of 72 LMAT using the keyhole technique was 52.8% and the mean subluxation of the extrusion group was 4.4 mm ± 2.8.[28] Lee et al reported an incidence of extrusion after LMAT of 32.2% after 2 years of follow-up, with a mean subluxation of 3.2 mm ± 1.5 in the standard rehabilitation group and 1.8 ± 1.6 mm in the delayed rehabilitation group. Even though no differences in clinical outcomes between the groups were observed.[37] Kim et al evaluated 46 patients who received an LMAT using the keyhole technique with a mean follow-up of 51.1 ± 7.1 months, and they reported a mean absolute meniscal extrusion of 2.8 mm ± 0.89 with an associated extrusion percentage of 27.8 ± 9.7%.[38] They concluded that the extrusion of the meniscal allograft did not significantly increase on the coronal view after LMAT in a midterm follow-up period and reported a score of 90.5 ± 10.1 in the Lysholm score. Jeon et al retrospectively evaluated 88 patients with a peripheral osteophyte in their tibial plateau who underwent a MAT with the modified keyhole technique at 12 months after surgery and compared it with osteophyte excision on their effect on meniscal extrusion, and they found a mean absolute extrusion of 3.5 mm ± 1.5 and 5.5 mm ± 1.6, respectively, with a mean relative percentage of extrusion of 34.1 ± 15.9% and 54.7 ± 20.7%.[9] Lee et al evaluated 27 patients that had undergone an LMAT with a follow-up time of 10.3 years using the keyhole technique and found an absolute meniscal extrusion of 2.76 mm ± 0.47 extrusion and a Lysholm score of 91.1 ± 4.6.[6] The results of our study showed the lowest reported meniscal extrusion values in the literature using only soft tissue fixation Lee et al observed an extrusion of 1.8 ± 1.6 mm in a 2-year follow-up using a bone plug technique, versus the 2.14 ± 1.58 mm obtained in our study in a longer follow-up. Additionally, there was a postoperative immobilization time compared with our study.[37]

There was no significant progression of osteoarthritic changes and JSW throughout the midterm follow-up period after LMAT with suture-only fixation technique and capsulodesis. These results coincide with those obtained by other authors relative to the progression of the degree of osteoarthritis and JSW.[4,6,38]

However, they differ with respect to the total values, being lower in our study. This is easily explained because our patients started the study with lower values than those reported by other studies.[6,38]

Regarding functional improvement, most of the studies report values ranging from good to excellent on the functional scales analyzed in the short and midterms,[39] similar to our study but with an additional decrease in terms of the scales in longer-term studies.[4]

Finally, we found a survival rate of 85.7% after 7 years of follow-up, our study did not have a control group, but previously published studies where the same surgeon realized the MAT without capsulodesis reported similar survival rates, 92.4% at 5 years in one study and 87.8% at 6.5 years in the other.

Furthermore, the current study showed that capsulodesis decreases meniscal extrusion without affecting functionality and the meniscal survival rate.

Limitations

This study had several limitations. The most important is the small number of patients in the cohort (23 cases). Another limitation is the lack of a control group with bone fixation without capsulodesis to be able to establish superiority of the technique. Nonetheless, we performed an exhaustive literature review to be able to compare our results with historical data published in the literature. Another limitation is that the evaluation of meniscal extrusion was performed on static images in the supine position instead of weight-bearing ultrasound or MRI in which the highest degree of apparent meniscal extrusion has been reported.[40] We believe the latter represents future research prospects.

Nevertheless, this is a common limitation present in most of the studies performed to date. Another limitation is that the degree of extrusion of the anterior and posterior horns of the lateral meniscus on the sagittal plane was not calculated. As discussed in the two previous articles on this technique, the learning curve of this technique in the first four cases can negatively influence the final results. Excluding those four cases, the graft survival rate is 100% and the meniscal extrusion rate is significantly reduced.

Conclusions

Capsulodesis seems to lessen meniscal extrusion in lateral MAT fixed with a suture-only technique and maintain a lower degree extrusion over 7 years of follow-up when compared with the results at 2 years. It also showed a high graft survival index, low complication rate, and satisfactory results in the functional and patient satisfaction scales, with no differences in the frontal mechanical axis and joint space narrowing between the preoperative value and the first and second follow-up periods. Thus, our results suggest that this surgical technique improves functional scores and that this improvement is clinically meaningful for patients. Future long-term clinical studies with 10 to 15 years of follow-up will be necessary to confirm the results of the present technique and lead to its potential incorporation as a standardized technique in combination with the lateral MAT.

Ethical Approval
The present protocol was approved by the Institutional Review Board and the Research Ethics Committee of the Hospital Universitari Dexeus of the Universitat Autonoma de Barcelona with registration number: ExtMen 2016-01.

Informed Consent
Informed consent was obtained from all individual participants included in the study.

Consent to Publish
The authors affirm that human research participants provided informed consent for the publication of the images in ►**Fig. 1**.

Availability of Data and Materials
All data are available for review.

Author Contributions
1. R.M.-A.: was responsible for the conception of the research idea, protocol design and drafting, obtaining, analyzing and interpreting the data, drafting the manuscript and approval of its final version, as well as the agreement with the other authors that all doubts or aspects of the manuscript were meticulously reviewed before being sent to publication.
2. A.M.-P.: was responsible for the conception of the research idea, protocol design and drafting, obtaining, analyzing and interpreting the data, drafting the manuscript, approval of the final version, search for current and ancient literature, as well as an agreement that all of the manuscript's minors were reviewed and it has validity and integrity.
3. J.R.P.-M: was responsible for the conception of the research question, acquisition and analysis of the data, writing of a part of the manuscript, and approval of its final version.
4. J.A.-R: was responsible for the conception of the research question, acquisition and analysis of the data, writing of a part of the manuscript, and approval of its final version.
5. M.I.: was responsible for the conception of the research question, acquisition and analysis of the data, contribution of knowledge in the area of statistics, writing of a part of the manuscript, and approval of its final version.
6. S.P.: was responsible for the design and conception of the study, realization of the translation and the statistical analysis, writing of part of the manuscript, search of the literature, analysis of the data and interpretation of them, and support of the final version of the manuscript.
7. C.A.-A.: was responsible for the design and conception of the study, realization of the translation and the statistical analysis, writing of part of the manuscript, search of the literature, analysis of the data and interpretation of them, and support of the final version of the manuscript.
8. J.E.-M.: made a substantial contribution to the manuscript from the orthopaedic point of view and was responsible for the proposal of the research idea, approval of the final version of the manuscript interpretation of the data, and supervision of the study.
9. J.C.M.: was one of the two main investigators of the study and an orthopaedic adviser and was responsible for the editing of the manuscript before its final version, proposal of the idea and clinical relevance of the study, implementation of the protocol methodology, interpretation of results, approval of the final version, and writing of part of the manuscript.

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Conflict of Interests
None declared.

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4.3. Article 3

Effect of Injury to the Lateral Meniscotibial Ligament and Meniscofibular Ligament on Meniscal Extrusion: Biomechanical Evaluation of the Capsulodesis and Centralization Techniques in a Porcine Knee Model.

Morales-Avalos R, José Manuel Diabb-Zavala JM, Mohammed-Noriega N, Vilchez-Cavazos F, Perelli S, Padilla-Medina JR, Torres-Gaytán AG, Huesca-Pérez HA, Erosa-Villarreal RA, Monllau JC. Effect of Injury to the Lateral Meniscotibial Ligament and Meniscofibular Ligament on Meniscal Extrusion: Biomechanical Evaluation of the Capsulodesis and Centralization Techniques in a Porcine Knee Model. **Orthop J Sports Med.** 2023; **DOI**: 10.1177/23259671231212856.

Original Research

Effect of Injury to the Lateral Meniscotibial Ligament and Meniscofibular Ligament on Meniscal Extrusion

Biomechanical Evaluation of the Capsulodesis and Centralization Techniques in a Porcine Knee Model

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Background: Previous biomechanical studies of the meniscotibial ligament have determined that it contributes to meniscal stability. An injury to it can cause the meniscus to extrude, and reconstruction of that ligament significantly reduces extrusion.

Purpose: To assess the biomechanical effects of sectioning the lateral meniscotibial ligament (LMTL) and the meniscofibular ligament (MFL) with respect to the radial mobility of the lateral meniscus and to evaluate the biomechanical effects of the capsulodesis and centralization techniques.

Study Design: Controlled laboratory study.

Methods: The lateral meniscus of 22 porcine knees was evaluated. They were mounted on a testing apparatus to apply muscle and ground-reaction forces. The meniscus was evaluated at 30° and 60° of knee flexion using 2 markers placed on the posterior cruciate ligament and the lateral meniscus after applying an axial compression of 200 N to the knee joint. Measurements were recorded under 5 conditions: intact lateral meniscus, injury of the LMTL, subsequent injury of the MFL, the use of the open capsulodesis technique, and the reconstruction of the LMTL and the MFL with the centralization technique.

Results: The distance between the 2 markers was significantly greater in the extrusion group (combined lesion of the LMTL and MFL) than in the intact or reconstruction groups (capsulodesis and centralization techniques; $P < .001$ in all cases). In the cases of load application, no significant differences were observed between the control group (intact meniscus) and the groups on which the reconstruction techniques were performed. There were also no differences when comparing the results obtained between both reconstruction techniques. In all settings, the distance between the 2 markers increased with the increase in the knee flexion angle.

Conclusion: In a porcine model, the LMTL and the MFL participated as restrictors of the radial mobility of the lateral meniscus during loading. Their injury caused a significant increase in lateral meniscal extrusion, and the centralization and the capsulodesis procedures were able to reduce extrusion.

Clinical Relevance: This study demonstrates the capacity of the LMTL and the MFL to restrict the radial mobility of the lateral meniscus during loading and how it is affected when they are injured.

Keywords: biomechanics; capsulodesis; centralization; extrusion; kinematics; lateral meniscus; meniscofibular ligament; meniscotibial ligament; meniscal mobility; menisco-tibio-popliteus-fibular complex

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Meniscal extrusion is characterized by the meniscus extending and drifting away from the tibial margin of the knee joint. The meniscus displaces from its native position between the tibiofemoral joint and extends into the gutter,[26,29] thereby losing some of its mechanical function. It induces dysfunction of load distribution caused by the disruption of the meniscus hoop function.[12] Previous studies have hypothesized that the recently described meniscocapsular attachments of the lateral meniscus, the so-called menisco-tibio-popliteus-fibular complex, and its main component, the lateral meniscotibial ligament (LMTL), act as restrictors of the radial mobility of the lateral meniscus.[17,27]

Meniscal extrusion is associated with various pathologies (eg, early knee osteoarthrosis, meniscus posterior root tears, radial tears) after anterior cruciate ligament reconstruction[28] and after meniscectomy for symptomatic discoid lateral meniscus.[3,14,23] It is frequently accompanied by rapid progression of the degenerative process of the knee as well as by substantial morbidity and pain.[14] Restoring the lost function caused by meniscal extrusion can delay osteoarthrosis progression[25] and/or lead to improvement of articular cartilage after a meniscal allograft transplantation.[13] After meniscal extrusion, the tibial cartilage receives all the load with the knee in extension.[10]

Previous biomechanical studies on the medial meniscotibial ligament have determined that it contributes to meniscal stability.[4] An injury to it can cause the meniscus to extrude and the repair of that ligament significantly reduces extrusion.[4,6,26] There are no similar studies involving the lateral meniscocapsular junctions, especially the important structures that are part of the lateral knee complex, which are the LMTL, the meniscofibular ligament (MFL), the popliteofibular ligament (PFL), and the popliteomeniscal ligament (PML).[17]

The capsulodesis technique was described by Monllau et al[19] in 2017 as a quick and inexpensive solution to reduce meniscal extrusion after lateral meniscal allograft transplantation, with satisfactory results after 2 and 7 years of follow-up.[15,16,20] The arthroscopic centralization technique consists of suturing the capsule attached to the meniscus to the edge of the tibial plateau using suture anchors. A decrease in lateral extrusion rates in the clinical follow-up at 2 years has been seen through the evaluation with functional scales and magnetic resonance imaging.[9]

The purpose of this study was to determine the normal function and establish an injury and reconstruction model of the LMTL and the MFL in porcine knees in a biomechanical model with simulated weightbearing and knee flexion. We hypothesized that the injury to these ligaments would increase meniscal extrusion. We also hypothesized that the capsulodesis and centralization techniques would restore their biomechanical function to a preinjury state.

METHODS

A total of 22 fresh-frozen left hind legs from 6-month-old commercial pork pigs weighing approximately 100 to 120 kg were used in the present investigation. The specimens used for the experiments were purchased within 24 hours of slaughter and were stored temporarily at 9°C (the sacrifice of the animals was for commercial purposes and was not related to the performance of this study). There was no evidence of previous injury and the joint capsules were perfectly sealed. The current study was approved by the Research Ethics Committee, Research Committee and Institutional Committee for the Care and Use of Laboratory Animals of our institution, following the current official Mexican standard (NOM-062-ZOO-1999).

Before testing, all the knees were evaluated with anteroposterior and lateral radiographs to rule out bone abnormalities, previous surgeries, or evidence of previous fractures. Before testing, a lateral parapatellar arthrotomy was performed on each specimen to check for any intraarticular defect, including lateral meniscal damage. No significant macroscopic osteoarthritic changes of the tibial plateau and femoral condyles were found.

Surgical Techniques

The knees were divided equally into 2 groups (n = 11 per group). In the first group, a modification of the capsulodesis technique described by Monllau et al[19] was realized. In the second group, an LMTL reconstruction was performed following the method described by Condron et al,[4] with modifications for working in the knee lateral compartment and adding a reconstruction of the MFL with the help of a third anchor.

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Ethical approval for this study was obtained from Universidad Autonoma de Nuevo Leon (ref No. PI23-00044).

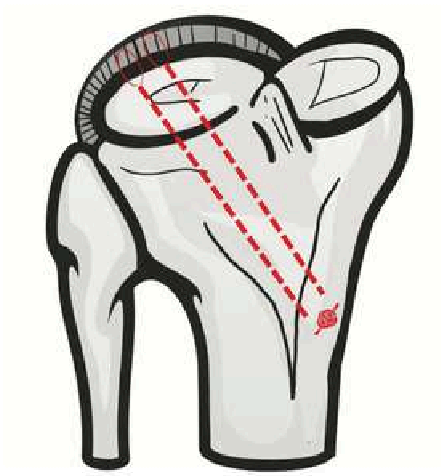

Figure 1. Representative diagram of the capsulodesis technique showing the transtibial tunnels (dashed lines) from the anteromedial cortex of the tibia (red ovals) to the joint capsule attached to the lateral tibial plateau.

Figure 2. Representative scheme of the centralization procedure using 3 anchors (circles), which moved the inner margin of the meniscus to the original position of the intact meniscus (red lines). Posterolateral view.

A board-certified knee surgeon with experience in the field of orthopaedic sports medicine (R.M.-A.) performed all surgical steps. The knees were resected 15 cm from the joint line proximally and distally and stripped of skin and fat tissue. The deep fascia and medial and lateral retinacula were preserved in each specimen. As a first step, the 2 ligaments of interest were intentionally sought in each pig knee, following the classical anatomic description in humans,[17,21,22] and were found in 100% of the specimens with an anatomy very similar to that of humans.

Capsulodesis Technique. Modifications of the capsulodesis technique here consisted of performing it openly. Through a minimal anteromedial and anterolateral capsulotomy (approximately 3 cm due to the great thickness of porcine tissues) and under direct vision, 2 tibial tunnels of 2.4-mm diameter were made. The tunnels were drilled from the anteromedial aspect of the tibia using a low-profile meniscus root tibial guide (Arthrex) with a distance of 0.5 cm between them (Figure 1). Then, two 18-gauge spinal needles loaded with a No. 2 PDS (polydioxanone) suture (ETHICON) were used to pierce the peripheral rim of the meniscus and the capsule with an outside-in technique. This shuttle suture was substituted by a high-strength suture (No. 2 Orthocord; DePuy Synthes) and retrieved through each tibial tunnel. They were then tied to each other on the anteromedial tibial cortex, bringing the capsule together with the tibial plateau (Figure 1). After this, the joint capsule was closed using No. 3 Vicryl suture (Ethicon).

Centralization Technique. First, a complete circumferential tear at the midbody of the lateral meniscus was performed, equidistant from the posterior and anterior horns, at the level of the tibial insertion of the LMTL. The technique of cutting the MFL consisted of making a circumferential cut of the ligament at the level of its fibular insertion under direct vision using a No. 22 blade scalpel. A complete tear was chosen in both cases to ensure that only the repair construct was tested. For this study, other stabilizing structures such as the PFL, the superior and inferior PMLs, and the meniscofemoral ligaments were not used.

Briefly, the LMTL reconstruction consisted of placing 2 high-strength sutures (No. 2 Orthocord) in a horizontal mattress formation through the LMTL and the border between the meniscus, and the remaining capsule was attached to the meniscus using an inside-out technique (Figure 2). One suture was placed at the transition point of the anterior horn and mid-body while the other was placed at the transition point of the posterior horn and midbody. The last suture was placed through the MFL using an inside-out technique. After retrieval from the posterolateral capsule incision, these sutures were threaded through two 3.0-mm anchors (Gryphon; Depuy Synthes), which were inserted into the lateral cortex of the proximal tibia under suitable tension for the LMTL (Figure 2). The first anchor was inserted 1 cm anterior to the popliteal hiatus, the second was inserted 1.0 to 1.5 cm anterior to the first anchor, and the third was inserted in the vertex of the fibula for the MFL. Macroscopically, it resulted in an extruded meniscus that was reduced to its original position. The incisions were closed, and specimens were ready for final testing and measurements.

Testing Procedure

The femur and tibia were fixed by means of fiberglass resin (resin pp250; Poliformas Plasticas) and polyvinyl chloride piping (10-cm length and 10-cm diameter) in a custom-made universal tester. One 4.5-mm cortical screw was placed through the polyvinyl chloride tubing, fiberglass resin and shaft of each long bone to provide further stability to withstand loads during testing procedures. All muscle groups, the 2 cruciate ligaments, the lateral and medial collateral ligaments, and the knee extensor apparatus were preserved.

A custom-made testing apparatus capable of loading muscle groups and delivering ground-reaction forces independently during a simulated squatting maneuver and under a direct axial compression load was constructed (Figure 3). This device was based on a model previously published by McCulloch et al,[18] with the difference that the one used in this study allowed for angulation of 10° in the coronal plane, maintaining the other axes of mobility (flexion and extension from 0° to 150°, internal and external tibial rotation of 10°, and mediolateral translation of 1 cm in the axial plane). When mounted, the tibial axis was perpendicular to the floor and was attached to a loading head that allowed rotational freedom and the femur was attached to a loading head that permitted translational and varus-valgus movement. Isolated muscle leads from the hamstrings and quadriceps were attached individually using suture tape and were reinforced with multiple mediolateral rip-stop passes of No. 2 sutures (Orthocord) to pneumatic actuators, with a tibial pneumatic actuator delivering a ground-reaction force.

Before testing, the specimen tissue was preconditioned. To that end, 100 full flexion-extension cycles were performed to minimize hysteresis. Starting from a base load of 1 N, a repetitive load with a magnitude of 10 N was then applied 100 times (frequency, 1 Hz). A ground-reaction force of 200 N was applied to the distal tibia,[5,8] and scaled loads of 50 N and 20 N were applied to the quadriceps and hamstrings, respectively, at 30° and 60° of flexion (each angle of flexion was confirmed using a goniometer and defined as the angle formed between the anatomic axes of the femur and the tibia at their lateral aspects). The porcine knee cannot extend to 0°, beginning its range of motion at 30° of flexion. The change in marker translation was then averaged and compared for each specimen state at each flexion angle.

Measurement of Meniscal Extrusion

The classic measurement method of meniscal extrusion is performed by measuring the distance from the lateral edge of the tibial plateau to the free edge of the meniscus; however, for this morphometric study in a cadaveric animal specimen, we used the method presented in a previous study.[24]

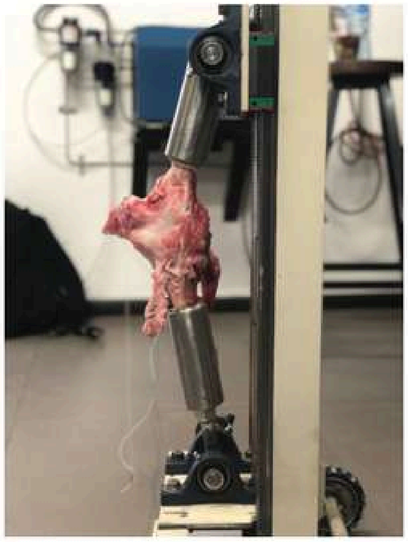

Figure 3. Custom-made testing apparatus. Medial view of a porcine right knee showing the preparation of the muscle groups.

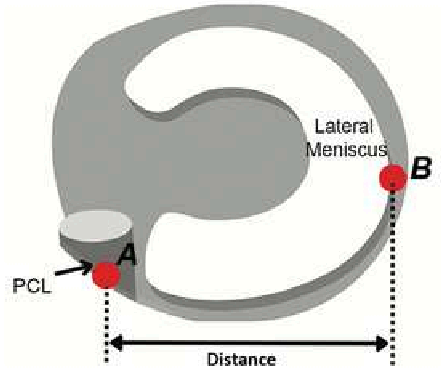

Figure 4. Distance between the marker attached to the PCL attachment, *A*, and lateral side of the lateral meniscus, *B*, measured as the medial-lateral extrusion. PCL, posterior cruciate ligament.

The measurement of meniscal extrusion was performed in accordance with the method described by Ozeki et al,[24] in which spherical plastic color markers (long pins that

Figure 5. Lateral view of a porcine left knee showing the 4 different study conditions. (A) Isolated LMTL injury, (B) combined LMTL and MFL injury, (C) reconstruction of the LMTL with the open capsulodesis technique, (D) reconstruction of the LMTL and MFL with the centralization technique. LMTL, lateral meniscotibial ligament; MFL, meniscofibular ligament.

pierced to the soft tissue 2 cm deep and 4 mm in diameter) were attached to the center of the tibial attachment of the posterior cruciate ligament and the lateral edge of the lateral meniscus in the posterior view (Figure 4). The placement of the spherical markers was agreed among 2 experienced surgeons and 1 anatomist (J.R.P.-M., A.G.T.-G., and H.A.H.-P.), who did not participate in the subsequent measurements. To carry out the measurements, a digital vernier with a precision of 0.01 mm was used (IP67; Skysummr). The markers were put in place before the cut for the meniscal extrusion model (during the preconditioning phase, trial pins were placed in the same locations to ensure that their position did not change during manipulation). Before and after application of the loading forces, the distance between the marker on the posterior cruciate ligament and the marker of the meniscus was measured to evaluate the extrusion. The measurement was made from the medial edge of the lateral marker to the lateral edge of the medial marker. A comparison was not made between the preload and postload conditions in the 2 ligament injury groups as it was considered that the meniscus was extruded before applying the load.

The measurement of the medial-lateral extrusion was carried out in 6 different conditions: intact lateral meniscus (control group) without the application of the loading force (n = 22), control group after applying the 200-N loading force (n = 22), isolated injury of the LMTL (after applying the loading force; n = 22) (Figure 5A), the subsequent injury of the MFL (after applying the loading force; n = 22) (Figure 5B), reconstruction of the LMTL with the open capsulodesis technique (before and after applying the loading force; n = 11) (Figure 5C), and reconstruction of the LMTL and the MFL with the centralization technique (before and after applying the loading force; n = 11) (Figure 5D). Measurements were made at both 30° and 60° of flexion.

Statistical Analysis

Before performing the analysis, all numerical sets of data were tested for normal distribution using the Shapiro-Wilk test. Numerical variables are described as means and standard deviations, while categorical variables are described as frequencies and percentages.

Each measurement was performed by 3 independent observers (R.M.-A., R.A.E.-V., and S.P.). The observers made 2 alternating sets of measurements 50 minutes apart from one another and the difference between each set of measurements was used to calculate the relative intraobserver reliability. The significance of the absolute difference between measurements was also tested using the paired Student *t* test. If no significant difference was detected and the relative intraobserver reliability was <0.2%, the first measurement of the observer was used for further analyses. If this criterion was not met, the measurement was repeated after revising the technique of the observer. Regarding interobserver reliability, the difference between each set of measurements was used to compute the average interobserver difference, and the significance of the difference between each set of measurements was also tested using a 1-way analysis of variance test. If no significant difference was detected and the average interobserver difference was <0.01, any of the measurements was considered acceptable. If this criterion was not met, a consensus was reached by the 3 observers on the final measurement used for the rest of the analysis.

The difference in the degree of meniscal extrusion at baseline and after the axial load was applied, and at 30° and 60° of flexion, was compared in each group using the paired Student *t* test. Regarding the differences between the groups, comparisons were made based on the type of injury and type of reconstruction technique, with the knee at 30° and 60° of flexion, with the Student *t* test.

An a priori sample size calculation was performed using the model described by Kubota et al,[12] considering an expected effect size of 0.7 derived from the difference in degree of meniscal extrusion after the use of either reconstruction technique. With a precision of 0.05 and power of 80%, a sample size of 16 was enough for the determination of our outcome of interest. A decision was taken to increase the sample to 22 due to the availability of samples and the lack of previous models examining the biomechanical effects of the capsulodesis technique.

A P value threshold of <.05 was considered indicative of statistical significance for all the tests. All tests were performed using the IBM SPSS statistical package (Version 26) for Windows 11. The sample size calculation was performed using the G*Power statistical tool package for Windows 11 (Version 3.1.9.7; Heinrich-Heine-Universität Düsseldorf, Düsseldorf, Germany).

RESULTS

The percentage of interobserver variability for all meniscal extrusion measurements was <0.2%, which indicates a difference of <0.01 mm between each measurement. Therefore, no relevant interobserver error was considered. As for the interobserver reliability, the average difference between measurements was <0.01, indicating no impactful errors of measurements were detected. No significant difference was detected between the intra- or interobserver measurements.

The greatest meniscal extrusion occurred in the combined LMTL and MFL lesion group with the application of 200 N at 60° of flexion (25.11 ± 2.19 mm) (Figure 6 and Table 1). The lowest extrusion index occurred in the group in which the centralization technique was applied at 30° of flexion without the application of load (13.02 ± 0.54 mm) (Figure 6 and Table 1).

The application of loading force significantly increased meniscal extrusion compared with the intact meniscus ($P < .05$) (Table 1). However, this increase did not occur with the application of both techniques. On the other hand, it was not compared with the state before the application of load in the situations of ligamentous rupture as it was considered that the meniscus had already been extruded previously with the application of the load to the original meniscus.

Regarding the differences in meniscal extrusion in the cases of load application, no significant differences were observed between the control group (intact meniscus) and the groups in which the reconstruction techniques had been performed. There were also no differences when comparing the results obtained between both reconstruction techniques. There were differences between the groups with ligament injuries and in the groups in which the reconstruction was performed when compared with the control group ($P < .05$ for both); this was also the case when comparing the state of injury of 1 ligament versus the injury of 2 ligaments with each other ($P < .05$) (Table 2).

TABLE 1
Meniscal Extrusion Measurements in the Different Groups by Flexion Angle and Load[a]

Group and Flexion Angle	Extrusion, mm	P
Control group		
30° of flexion		**<.001**
0 N load	13.25 ± 0.44	
200 N load	16.55 ± 0.65	
60° of flexion		**<.001**
0 N load	13.39 ± 0.52	
200 N load	16.91 ± 0.69	
Isolated LMTL injury		**<.001**
30° of flexion, 200 N load	21.12 ± 1.56	
60° of flexion, 200 N load	24.27 ± 1.67	
Combined LMTL + MFL injury		**<.001**
30° of flexion, 200 N load	23.14 ± 1.88	
60° of flexion, 200 N load	25.11 ± 2.19	
Capsulodesis technique		
30° of flexion		.12
0 N load	13.13 ± 0.51	
200 N load	14.25 ± 0.66	
60° of flexion		.09
0 N load	13.29 ± 0.59	
200 N load	14.99 ± 0.92	
Centralization technique		
30° of flexion		.21
0 N load	13.02 ± 0.54	
200 N load	14.18 ± 1.01	
60° of flexion		.19
0 N load	13.18 ± 0.44	
200 N load	14.72 ± 0.49	

[a]Data are shown as mean ± SD. Boldface P values indicate statistically significant difference between comparisons ($P < .05$). LMTL, lateral meniscotibial ligament; MFL, meniscofibular ligament.

In all settings, the distance between the 2 markers increased with the knee flexion angle in the cases in which no load was administered. Conversely, there were no differences in the results between the 2 flexion angles when the 200 N load was applied (Figure 6). Finally, there were no significant differences in the results between the 2 flexion angles analyzed in this study in most cases. However, there were differences in the ligament injury groups ($P < .05$) (see Table 1).

DISCUSSION

The present study demonstrated that the LMTL and the MFL act as restrictors of the radial mobility of the lateral meniscus during loading and that injury to them produces a significant increase in meniscal extrusion. Therefore, our first hypothesis was confirmed. Furthermore, this meniscal extrusion can be restored to its preinjury state by means of the open capsulodesis technique or the centralization technique, without significant differences between the 2 procedures. Using either the centralization or

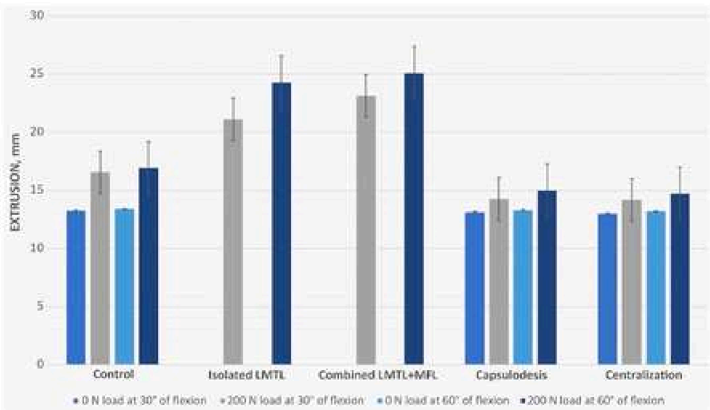

Figure 6. Bar graph showing mean meniscal extrusion measurements according to study and loading conditions and flexion angle. Error bars indicate standard deviations. LMTL, lateral meniscotibial ligament; MFL, meniscofibular ligament.

TABLE 2
Comparison of the Results Obtained Between the Different Study Groups During Load Application[a]

Comparison	*P*
Control 30° vs capsulodesis 30°	.11
Control 60° vs capsulodesis 60°	.13
Control 30° vs centralization 30°	.20
Control 60° vs centralization 60°	.24
Control 30° vs LMTL injury 30°	**<.001**
Control 60° vs LMTL injury 60°	**<.001**
Control 30° vs combined LMTL + MFL injury 30°	**<.001**
Control 60° vs combined LMTL + MFL injury 60°	**<.001**
Capsulodesis 30° vs centralization 30°	.67
Capsulodesis 60° vs centralization 60°	.71
Capsulodesis 30° vs LMTL injury 30°	**<.001**
Capsulodesis 60° vs LMTL injury 60°	**<.001**
Capsulodesis 30° vs combined LMTL + MFL injury 30°	**<.001**
Capsulodesis 60° vs combined LMTL + MFL injury 60°	**<.001**
Centralization 30° vs LMTL injury 30°	**<.001**
Centralization 60° vs LMTL injury 60°	**<.001**
Centralization 30° vs combined LMTL + MFL injury 30°	**<.001**
Centralization 60° vs combined LMTL + MFL injury 60°	**<.001**
LMTL injury 30° vs combined LMTL + MFL injury 30°	**.04**
LMTL injury 60° vs combined LMTL + MFL injury 60°	**.03**

[a]Boldface *P* values indicate statistically significant difference between comparisons ($P < .05$). LMTL, lateral meniscotibial ligament; MFL, meniscofibular ligament.

capsulodesis technique, the lateral meniscus was no longer displaced laterally. Therefore, our second hypothesis was confirmed.

As far as we know, this is the first study to analyze the biomechanical effects of an isolated and combined lesion as well as their reconstruction. Although there were no significant differences between the 2 reconstruction techniques, a somewhat greater decrease in extrusion was observed with the centralization technique. The fact that some modification in the capsulodesis technique was introduced may help explain this subtle difference. In addition, a modification was made in the centralization technique in this study to also perform a reconstruction of the MFL.

Previous studies have determined that isolated LMTL abnormalities lead to severe meniscal extrusion, even in the absence of other knee pathologies.[7,11] A meniscotibial ligament injury leads to the dislodgment of meniscus from the tibial plateau, thereby losing its normal attachment sites and causing meniscal extrusion.[1] Previous studies in porcine models have been carried out under other pathological conditions that also led to meniscal extrusion. They include injury to the posterolateral meniscus root. Ozeki et al[24] found the greatest extrusion with the application of 200 N was 21.9 mm (range, 17.8-25.6 mm) and 15.3 mm (range, 12.9-18.0 mm) in the group that underwent posterior root injury and the centralization technique respectively, which represent values like those of the current investigation in which extrusion was greater after injury and lower following the reconstruction techniques. These differences could be explained because the injured structures in our experiment are different from theirs; however, both led to the appearance of meniscal extrusion. In addition, the differences in the way the centralization procedures were done in both studies might also have contributed to the slight biomechanical differences found. Like Kubota et al[12] in a study on porcine knees, very similar results confirming the fact that the meniscal extrusion increases with the degrees of knee flexion were seen in this study.

The MFL was found in all specimens studied. Therefore, we consider it an anatomically constant structure in humans and pigs.[22] The MFL connects the inferolateral portion of the body of the lateral meniscus, anteriorly and laterally, to the popliteus tendon with the head of the fibula. In its anterior portion, its fibers interconnect and are in continuity with the more posterior fibers of the LMTL. This observation had already been evidenced in a previous study.[21] Previous studies have hypothesized that the function of the MFL is to stabilize the lateral meniscus in external rotation and varus movements. This is due to the fact that, during dorsiflexion of the ankle, the fibula tends to rotate externally, causing a displacement of the external meniscus in that direction.[2] However, to our knowledge, this is the first study to analyze the biomechanical characteristics of the MFL. In addition, we believe that its true function is to reinforce the function of the LMTL and prevent anterolateral displacement of the lateral meniscus. This has been proposed previously in another study.[30] In that study, they also considered rebuilding this ligament during lateral allogeneic meniscal transplantation.

Limitations

The present study has several limitations. First, this was an in vitro bench test study using a porcine rather than a human model. Second, the meniscal extrusion was evaluated only on the mediolateral plane, leaving out evaluations in the anteroposterior plane. Third, only 2 flexion angles were considered, leaving aside greater angulations than 60°. Fourth, the number of samples was limited, although the current sample size was greater than that used in most biomechanical studies. Fifth, the surgical techniques evaluated were originally assisted arthroscopically and were adapted to be performed as open surgery for the purpose of the current work. Sixth, no determinations of the variability in pressure and load on the lateral meniscus were made.

CONCLUSION

The LMTL and MFL participate as restrictors of radial mobility of the lateral meniscus. Injury to these structures causes a significant increase in lateral meniscal extrusion and the centralization and the capsulodesis procedures reduce extrusion in a porcine model.

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5 OVERALL SUMMARY OF RESULTS

OVERALL SUMMARY OF RESULTS

Of the two hundred MRI scans analyzed of patients over 18 years of age, 95 (47.5%) were excluded. Of the excluded knees, 20 had an injury with lateral meniscus tears (21%), 14 with medial meniscus tears (14.7%), 2 with infection (2.1%), 6 had tumors (6.3%) and 12 had artifacts that limited the correct visualization of the images (12.6%). Measurements and morphometries were taken in 105 MRIs, of which 64 (60.9%) were for anterior pain associated with patellofemoral syndrome, 28 MRIs for chronic nonspecific knee pain (26.6%) and 16 MRIs for recurrent joint effusion (15.2%). All these MRIs were classified as normal with no pathological findings by the radiologist who reviewed the study for diagnostic purposes. It was also the case with the musculoskeletal radiologist who analyzed them for the purposes of this study. In total, 105 patients with a mean age of 50.1 years ± 14.8 (37.7-62.5) were included (60% right knee and 40% left knee). There were 58 knees (55.2%) corresponding to male patients and 47 knees (44.7%) corresponding to female patients. All data is shown in Table 1

Table 1. *Baseline characteristics of the included participants*

General characteristics	
Age, mean ± SD (95% CI)	50.1 ± 14.9 (37.7 – 62.5)
Males, n (%)	58 (55.2)
Right knee, n (%)	63 (60)
Body mass index, mean ± SD (95% CI)	27.1 ± 3.2 (24.1 – 29.4)
Lateral menisco-tibial ligament	
Prevalence	102 (97.1)
Length (axial), mean ± SD (95% CI)	20.7 ± 3.9 (17.4 – 24)
Anterior root, mean ± SD (95% CI)	22.8 ± 2.4 (20.8 – 24.8)
Posterior root, mean ± SD (95% CI)	27.2 ± 2.2 (25.4 – 29.1)
Height (coronal), mean ± SD (95% CI)	10.8 ± 2 (9.1 – 12.5)
Tibial plateau insertion (coronal), mean ± SD (95% CI)	6.4 ± 1.5 (5.1 – 7.6)
Thickness 1 anterior third to middle, mean ± SD (95% CI)	1.1 ± 0.3 (0.9 – 1.4)
Thickness 2 middle third to posterior, mean ± SD (95% CI)	1.3 ± 0.2 (1.1 – 1.4)
Meniscus to iliotibial band, mean ± SD (95% CI)	1.2 ± 0.5 (0.7 – 1.6)
Popliteofibular ligament	
Prevalence, n (%) for partial, n (%) for complete	54 (51.4) / 44 (41.9)
Coronal length, mean ± SD (95% CI)	8.7 ± 2.5 (6.6 – 10.8)
Thickness, mean ± SD (95% CI)	1.4 ± 0.5 (1 – 1.8)
Sagittal length, mean ± SD (95% CI)	8.8 ± 2.4 (6.8 – 10.9)
Width (axial), mean ± SD (95% CI)	7.9 ± 2.2 (6 – 9.7)

Popliteomeniscal ligament	
Prevalence, n (%)	94 (90.4)
Length inferior popliteomeniscal ligament, mean ± SD (95% CI)	12.9 ± 2.2 (11 – 14.7)
Length superior popliteomeniscal ligament, mean ± SD (95% CI)	16.2 ± 3.4 (12.4 – 19.3)
Length inferior popliteomeniscal ligament, mean ± SD (95% CI)	3.1 ± 0.6 (2.5 – 3.6)
Length superior popliteomeniscal ligament, mean ± SD (95% CI)	3.2 ± 0.3 (2.8 – 4.1)
Meniscofibular ligament	
Prevalence, n (%)	41 (39)
Length MFL sagittal, mean ± SD (95% CI)	14.8 ± 1.8 (13.3 – 16.3)
SD: standard deviation, ***CI:*** Confidence interval, **ns:** non-significant.	

Prevalence and anatomical measurements.

The LMTL was observed on the coronal and axial planes in DIXON images, with a prevalence of 102 (97.1%). Its average length on the axial plane was 20.7 mm (SD ± 3.9; 95% CI 17.4-24) and the average height measured in the coronal view was 10.8 mm (SD ± 1.9 ; 95% CI 9.1-12.5). The distance to its insertion was 6.4 mm (SD ± 1.5; 95% CI 5.1-7.6) from the surface of the tibial plateau.

The PFL had a prevalence of 98 (93.3%) with partial visualization in 54 (51.4%) in magnetic resonance images and complete visualization in 44/105 (41.9%). The mean length of the PFL in the coronal view was 8.7 mm (SD ± 2.5; 95% CI: 6.6-10.8) and 8.8 mm in the sagittal view (SD ± 2.4 ; 95% CI: 6.8-10.9). The PML showed a prevalence of 94 (90.4%) in the sagittal view. The mean length of the inferior PML was 12.9 mm (SD ± 2.2, 95% CI 11 to 14.7) and the length of the superior fascicle was 16.2 mm (SD ± 3.4, CI 95%: 12.4 to 19.3). The PML was visualized in 41/105 (39%) in full extension, with a mean sagittal length of 14.8 mm (SD ± 1.8; 95% CI 13.3-16.3) Table 1.

Analysis by gender

There were no age differences between genders. Likewise, there were no statistically significant differences in prevalence between any of the ligaments. All gender analysis is shown in Table 2.
The distance between the articular edge and the tibial insertion of the LMTL was statistically greater in men than in women, 7.3 mm (SD ± 2.2; 95% CI 1.9–12.7) vs. 5.8 mm (SD ± 0.8; 95% CI 4.7– 6.8) p = 0.004. The PFL was statistically longer in the sagittal view in men 10.3 mm (SD ± 3.3; 95% CI 1.9–18.6) versus 8 mm (SD ± 1.5; 95% CI: 6 –9.9 p = 0.026) for women. The inferior fascicles of the PML were longer in men, 14.6 mm (SD ± 2.5; 95% CI 8.4–20.9) vs. 11.8 mm (SD ± 1.4; 95% CI % 10.1–13.5; p = 0.041) in women. The superior PML fascicles were also longer at 17.4 mm (SD ± 3.6; 95% CI 12.9–20.4) versus 15.1 (SD ± 2.8; 95% CI 10.2 –17.3; p = 0.048) in women.

Table 2. *Comparison of the Menisco-Tibio-Popliteus-Fibular Complex by gender.*

	Males	**Females**	***p* value**
Age, mean ± SD (95% CI)	40 ± 17.4 (32.6–45.8)	56.2 ± 10.6 (43.1–69.3)	*(n.s.)*
Right knee, *n* (%)	27 (46.6)	15 (31.9)	*(n.s.)*
Lateral menisco-tibial ligament			
Prevalence, n (%)	57 (98.3)	45 (95.7)	*(n.s.)*
Length (axial), mean ± SD (95% CI)	22.8 ± 4.6 (11.28–34.23)	19.5 ± 3.4 (15.2–23.7)	*(n.s.)*
Anterior root, mean ± SD (95% CI)	24.3 ± 1.1 (21.6–26.9)	21.9 ± 2.6 (18.7–25.1)	< *0.001*
Posterior root, mean ± SD (95% CI)	29 ± 2.8 (22–36.1)	26.2 ± 0.6 (25.3–27)	< *0.001*
Height (coronal), mean ± SD (95% CI)	11 ± 1.2 (7.9–14)	10.7 ± 2.5 (7.6–13.8)	*(n.s.)*
Tibial plateau insertion (coronal), mean ± SD (95% CI)	7.3 ± 2.2 (1.9–12.7)	5.8 ± 0.8 (4.7–6.8)	*0.004*
Thickness 1 anterior third to middle, mean ± SD (95% CI)	1.9 ± 0.2 (1–2)	1.1 ± 0.4 (0.6–1.6)	*0.005*
Thickness 2 middle third to posterior, mean ± SD (95% CI)	1.8 ± 0.1 (0.9–2.5)	1.3 ± 0.2 (1–1.5)	*0.006*
Meniscus to iliotibial band, mean ± SD (95% CI)	1.2 ± 0.6 (0.4–2.8)	1.2 ± 0.5 (0.5–1.9)	*(n.s.)*

Popliteofibular ligament			
Prevalence, *n* (%) for partial, *n* (%) for complete	32 (55.2) / 22 (37.9)	22 (46.8) / 22 (46.8)	*(n.s.)*
Coronal length, mean ± SD (95% CI)	9.1 ± 1.4 (5.7–12.5)	8.5 ± 3.1 (4.6–12.4)	*(n.s.)*
Thickness, mean ± SD (95% CI)	1.4 ± 0.4 (0.4–2.3)	1.4 ± 0.6 (0.7–2.1)	*(n.s.)*
Sagittal length, mean ± SD (95% CI)	10.3 ± 3.3 (1.9–18.6)	8 ± 1.5 (6–9.9)	*0.026*
Width (axial), mean ± SD (95% CI)	9.6 ± 3 (2.2–17)	6.8 ± 0.9 (5.7–8)	*(n.s.)*
Popliteomeniscal ligament			
Prevalence, n (%)	52 (91.2)	42 (89.4)	*(n.s.)*
Length inferior popliteomeniscal ligament, mean ± SD (95% CI)	14.6 ± 2.5 (8.4–20.9)	11.8 ± 1.4 (10.1–13.5)	*0.041*
Length superior popliteomeniscal ligament, mean ± SD (95% CI)	17.4 ± 3.6 (12.9–20.4)	15.1 ± 2.8 (10.2–17.3)	*0.048*
Thickness inferior popliteomeniscal ligament, mean ± SD (95% CI)	3.6 ± 0.2 (3.2–4.1)	2.7 ± 0.5 (2.1–3.4)	*0.041*
Thickness superior popliteomeniscal ligament, mean ± SD (95% CI)	3.8 ± 0.2 (3.2–4.2)	3.1 ± 0.3 (2.7–3.5)	*(n.s.)*
Meniscofibular ligament			
Prevalence, n (%)	22 (37.9)	19 (40.4)	*(n.s.)*
Length MFL sagittal, mean ± SD (95% CI)	15.5 ± 1.2 (12.4–18.5)	14.4 ± 2.1 (11.8–17)	*0.034*
***SD**: Standard deviation, **CI:** Confidence interval, **n.s:** non-significant*			

Analysis by age

The length of the LMTL in the coronal view was statistically significant in patients older than 50 years (10.9 SD ± 2.2; 95% CI: 3.9—19.3) when compared to younger patients (9. 8 SD ± 2; 95% CI: 8.2). —12.9; p = 0.013). The rest of the variables were not statistically significant (Table 3).

Table 3. *Comparison of the Menisco-tibio-popliteus-fibular complex by age*

	< 50 years	≥ 50 years	*p* value
Right knee, *n* (%)	33 (57.9)	30 (63.8)	*(n.s.)*
Lateral menisco-tibial ligament			
Prevalence, n (%)	55 (96.5)	46 (97.9)	*(n.s.)*
Length (axial), mean ± SD (95% CI)	18.5 ± 2.9 (15.8–22.4)	19.4 ± 2.5 (17.7–33.1)	*(n.s.)*
Anterior root, mean ± SD (95% CI)	22.4 ± 3.9 (19.6–24.6)	22.3 ± 2.8 (24.8–25)	*(n.s.)*
Posterior root, mean ± SD (95% CI)	26.7 ± 3.1 (25.4–27.5)	26.7 ± 2.9 (14.5–64.1)	*(n.s.)*
Height (coronal), mean ± SD (95% CI)	9.8 ± 2 (8.2–12.9)	10.9 ± 2.2 (3.9–19.3)	*0.013*
Tibial plateau insertion (coronal), mean ± SD (95% CI)	6.2 ± 1.7 (5–6.5)	6.6 ± 1.6 (2.4–28.5)	*(n.s.)*
Thickness 1 anterior third to middle, mean ± SD (95% CI)	1.2 ± .25 (0.7–1.5)	1.2 ± 0.3 (0.1–2.3)	*(n.s.)*

Thickness 2 middle third to posterior, mean ± SD (95% CI)	1.3 ± .3 (1.1–1.5)	1.3 ± 0.3 (0.2–2.1)	*(n.s.)*
Meniscus to iliotibial band, mean ± SD (95% CI)	1.5 ± .8 (0.7–1.8)	1.4 ± 0.9 (1.1–6.4)	*(n.s.)*
Popliteofibular ligament			
Coronal length, mean ± SD (95% CI)	9.4 ± 2.6 (5.7–11.7)	8.9 ± 2 (0–25.7)	*(n.s.)*
Thickness, mean ± SD (95% CI)	1.3 ± 0.3 (0.9–2)	1.5 ± 0.3 (0–6.2)	*(n.s.)*
Sagittal length, mean ± SD (95% CI)	8.9 ± 2 (6.2–11.4)	8.6 ± 2.9 (0–37.6)	*(n.s.)*
Width (axial), mean ± SD (95% CI)	7.1 ± 2 (6–8.3)	6.2 ± 3.3 (0–46.6)	*(n.s.)*
Popliteomeniscal ligament			
Prevalence, n (%)	50 (87.7)	43 (91.49)	*(n.s.)*
Length inferior popliteomeniscal ligament, mean ± SD (95% CI)	12.6 ± 3.7 (10.3–14.6)	12.6 ± 5.4 (0–43)	*(n.s.)*
Length superior popliteomeniscal ligament, mean ± SD (95% CI)	16.5 ± 3.9 (13–18.8)	16.8 ± 3.7 (13.8–19.2)	*(n.s.)*
Thickness inferior popliteomeniscal ligament, mean ± SD (95% CI)	2.8 ± 0.7 (2.27–3.44)	2.9 ± 0.8 (3.3–4.2)	*(n.s.)*
Thickness superior popliteomeniscal ligament, mean ± SD (95% CI)	3.2 ± 0.5 (2.4–3.6)	3.3 ± 0.5 (0–4.1)	*(n.s.)*
Meniscofibular ligament			
Prevalence, n (%)	23 (40.3)	18 (38.3)	*(n.s.)*
Length MFL sagittal, mean ± SD (95% CI)	14.7 ± 2.3 (12.5–16.6)	14.1 ± 1.7 (4–30.8)	*(n.s.)*

SD: Standard deviation; ***CI***: Confidence interval, **n.s**: non-significant

Morphological results

In the sagittal view, the LMTL was observed as a hypointense linear structure originating from the inferolateral margin of the lateral meniscus between the middle and posterior third of the periphery of the meniscus. Its insertion was also noted to extend distally from the tibial plateau. (Figure 5a). On the axial plane, the LMTL was observed as a linear and, in some cases, spring-like structure (Figure 5b).

The PFL was observed in coronal and sagittal views as a thin hypointense linear structure extending distally from the distal third of the popliteus tendon toward the apex of the fibular head. It was also in a situation posterior to the LMLT. In all cases in which both ligaments were observed, a union between the LMTL and the PFL was observed at the posterior corner of the meniscus, following the previously described path towards the insertion into the head of the fibula (Figure 6c).

The two fascicles of the PML were observed as two thin hypointense curvilinear structures. The anteroinferior originated in the body of the lateral meniscus and runs posteroinferiorly toward the popliteus tendon. The posterosuperior fasciculus rises from the edge of the posterior horn of the lateral meniscus in the middle of the popliteus tendon (Figure 6a and 6b). The PML was observed in a sagittal view as a thin, linear, and oblique hypointense structure that originates in the inferolateral and posterior portion of the meniscus and runs posteriorly towards the head of the fibula, anterior and deep to the popliteus tendon. In some patients, this ligament was observed on the sagittal plane, allowing a complete view of the ligament. The results of the intra- and interobserver analyzes resulted in good agreement (ICC > 0.8) for all sets.

Regarding the results of the clinical follow-up of patients 7 years after surgery of lateral allogeneic meniscal transplantation associated with capsulodesis. The study group consisted of 16 men and 7 women (69.5%/30.4%) with a mean age of 40.93 ± 7.03 years at the time of transplantation and 46.29 ± 7.18 years at the time of evaluation. None of them were professional athletes. The mean follow-up of the patients was 84 ± 7 months (seven years). The mean interval between meniscectomy and the appearance of painful symptoms was 11.43 ± 8.78 years. The mean interval between meniscectomy and MAT was 14.29 ± 5.15 years. Thirteen (56.5%) MATs were performed on the right knee while nine (39.1%) were performed on the left knee. Regarding the medical history, 20 of the patients had undergone a meniscectomy of the lateral meniscus by means of arthroscopy (7 total meniscectomies, 9 subtotal meniscectomies and 4 partial meniscectomies), two patients had had a complete meniscectomy and one had had an inveterate rupture-dislocation of the lateral meniscus. In preoperative MRI, all patients had a severe lateral meniscal deficit.

The average weight of the patients was evaluated before surgery and at the time of evaluation. It was 70.50 ± 9.08 kg and 71.50 ± 8.09, respectively (p = 0.66). Furthermore, the average BMI at the time of surgery was 25.8 (range 19 – 32.4) and 26.2 (range 18.5 – 34.5) at final follow-up (p = 0.51) . The mean time to full weightbearing without crutches was 5.7 weeks (range 4 to 6 weeks).

At the time of the MAT, the presence of grade III – IV osteoarthrosis was documented in eight of the patients (34.8%), in accordance with the ICRS classification. All cases of osteoarthritis were limited to the original area covered by the lateral meniscus. In three of those eight patients, the injuries were also evident in the lateral femoral condyle (two grade II and one grade III).

Clinical evaluation

The median range-of-motion for all patients was 131° ± 8.7 (preoperative: 115° ± 4.2, $p = 0.9$) and no patient had extension deficits or joint effusion at the time of evaluation. Two patients presented pain on palpation of the lateral joint line and positive meniscal maneuvers. Subsequently, two patients underwent reoperation with partial allograft meniscectomy (due to 1 clinical failure and 1 surgical failure). Furthermore, many of the patients practiced sports activities (20/23, 86.9%), mostly low-impact recreational activities (Table 4). The reasons for stopping sports activities in three of the 23 patients were knee pain in two patients and fear of reinjury in one patient.

Radiographic evaluation

Table 4 shows how there was a decrease in the measurement of lateral JSW over time. However, this difference was not statistically significant. Furthermore, there were no significant differences between the preoperative value and the values at the two- and seven-year follow-up periods in terms of the frontal mechanical axis. Additionally, three of the included patients showed an increase in the grade of osteoarthritis in the Allhbäck classification, after two years of follow-up. Regarding meniscal extrusion at the end of follow-up, a mean absolute extrusion value of 2.2 ± 1.6 mm and a percentage of extrusion of 28.8 ± 11.4% were found. There were no significant differences with the values obtained at the two years follow-up. Regarding the classification of meniscal extrusion, only one patient had greater extrusion when compared to previous evaluations (Table 4).

Table 4. *Comparison of the results obtained in the midterm follow up with respect to the preoperative state and at the 7 year follow up in the different variables analyzed in the 2nd study.*

Variable	Pre-operative	2-years	5-years	*p* value (preoperative vs. 2 vs. 5 years/ 2 years vs. 5 years)
Carrying out sports activity, n (%)	4 (28.57%)	13 (92.86%)	12 (85.71%)	.0006/.548
Lateral interline pain, n (%)	14 (100%)	0 (0%)	1 (7.14%)	< .0001/.322
Positive meniscal maneuvers, n (%)	14 (100%)	0 (0%)	1 (7.14%)	< .0001/.322
KOOS, mean ± SD	52.03 ±2.95	91.3 ±7.3	88.07 ±4.70	< .0001/.175
Lysholm, mean ± SD	48.8 ±13.91	91.4 ±6.1	87.07 ±4.16	< .0001/.141
Tegner activity score	4 (3–5)	7 (6–8)	7 (6–8)	.876
Visual analog scale (0-10) score, mean ± SD	8.21 ±0.97	0.93 ±1.00	1.24± 1.08	< .0001/.531
Degree of satisfaction, mean ± SD (0-4)	N/A	3.8 ±0.42	3.57 ±0.65	.276
Patients who said they would repeat surgery, n (%)	N/A	14 (100%)	13 (92.86%)	.289
Meniscal extrusion classification	N/A	Minor extrusion 10 (71.4%) Greater	Minor extrusion 9 (64.29%) Greatest	.703 minor/.700 major

		extrusion 4 (28.6%)	extrusion 5 (35.71%)	
Graft extrusion percentage (%)	N/A	24.65 ±15.49	28.80 ±11.43	.427
Meniscal extrusion (mm)	N/A	1.94 ±1.22	2.14 ±1.58	.710
Degree of osteoarthritis (Allhbäck), n (%)	1.5 ±0.41 I (7/50%) II (7/50%)	1.64 ±0.45 I (5/35.71%) II (9/64.29%)	1.85 ±0.54 I (3/21.43%) II (10/71.43%) III (1/7.14%)	Numerical data: .397/.273 Categorical data: I= .430/.433 II= .462/.697 III= -/.322
Joint space width (mm)	3.00 ±1.20	2.84 ±1.11	2.69±0.27	.717/.083
Mechanical axis deviation, (°)	-1.53 ± 1.16 (varus)	-0.75±1.14	0.11±1.17	.084/.152
Patients with surgical, clinical, or radiological failure (for any of the reasons considered as a failure criterion)	N/A	0 (0%)	2 (14.29%)	.154
Reoperations	N/A	0	3	.075

Complications	N/A	0	2 (1 arthrofibrosis and 1 superficial wound infection)	.154

Functional and satisfaction scales

All scores showed significant improvement after two years of follow-up when compared to the preoperative results. (Table 4). This improvement remained constant after seven years of follow-up. There were no statistically significant differences between the scores obtained in the two- and seven-year periods. The mean preoperative Lysholm score was rated "good" at the two-year evaluation and was maintained after seven years. At final follow-up, a high rate of satisfaction and willingness to repeat surgery if necessary was reported (Table 4). No case was considered a clinical failure due to a low Lysholm score. In accordance with the previously established MCID, our cohort of patients reported a clinically significant difference when comparing their preoperative Lysholm scores with those obtained after 2 years (48.8 ± 13.91 vs 91.4 ± 6.1, respectively; MCID = 12.3). Importantly, this difference was maintained when comparing the preoperative scores with those of the 2-year follow-up (52.03 ± 2.95 vs. 91.3 ± 7.3, respectively; MCID = 8.10). This difference was maintained after seven years of follow-up (91.3 ± 7.3 vs. 88.07 ± 4.70, respectively; MCID = 8.10). All patients obtained values above the upper PASS range previously established for the KOOS score.

Reoperation, Surgical Failures, Clinical Failures

Two patients (8.7%) returned to the operating room after the primary procedure for three different surgeries. One of the patients returned for arthroscopic arthrolysis due to late arthrofibrosis. It was classified as a complication but did not meet the failure criterion. Subsequently, the patient underwent reoperation for reinsertion of the anterior horn of the transplanted graft due to a traumatic break caused by a fall downstairs. The other patient returned for a partial graft meniscectomy due to early graft degeneration, which met the criteria for graft failure. The mean time to subsequent surgery was 25 ± 3.75 months. In the last follow-up period, none of the patients were candidates for total knee prosthesis, unicompartmental knee prosthesis or retransplantation. A survival rate of 85.7% was found after seven years of follow-up (Figure 21) and the mean time to graft failure was 38.7 ± 4.12 months postoperatively. Interobserver agreement ranged from 0.87 to 0.91, and intraobserver agreement ranged from 0.89 to 0.95, for all measured values.

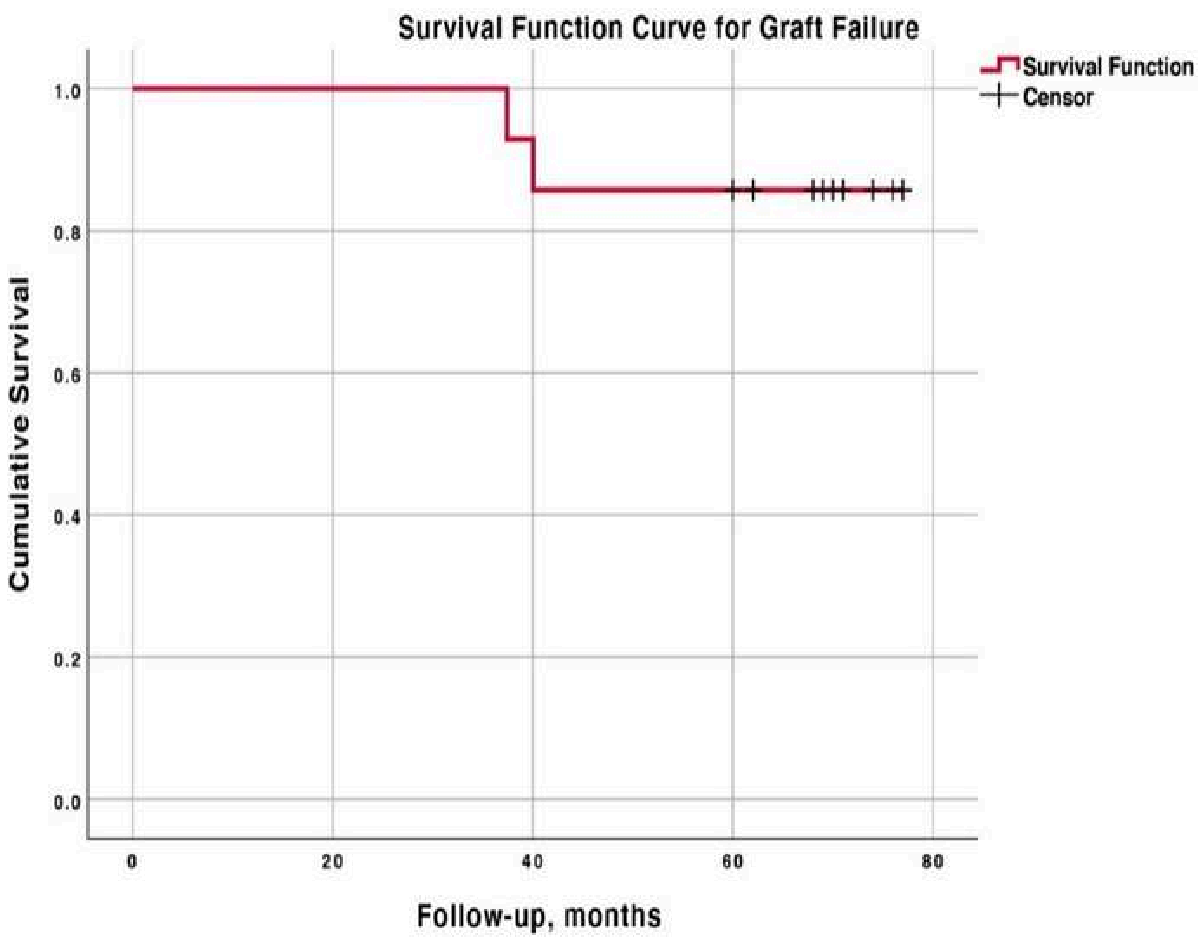


Figure 9. *Survival graph calculated using the Kaplan Meier method. Two patients developed graft failure at 37.4 and 40 months each. Nine patients were dropped because they completed their follow up time or were lost to follow up without developing graft failure. The probability of survival throughout the follow up time was estimated at 85.7%.*

Regarding the results of the biomechanical study in cadaveric pig knees. The greatest meniscus extrusion occurred in the group with combined meniscotibial and meniscofibular ligament injury with the application of 200 N at 60 degrees of flexion (25.11 mm ± 2.19). The lowest extrusion index occurred in the group in which the centralization technique was applied at 30° of flexion without the application of load (13.02 mm ± 0.54).

Loading force application significantly increased meniscus extrusion when compared to the intact meniscus (p = < 0.05). However, this increase did not occur with the application of both techniques (p = >0.05). On the other hand, it was not compared with the state prior to the application of the load in situations of ligamentous rupture since it was considered that the meniscus had already been extruded previously with the application of the load on the original meniscus (Table 5).

Table 5. *Results of meniscal extrusion in the different groups at different angles of flexion.*

	Flexion Angle (°)	Load (N)	Extrusion (mm)	*p* value
	30°	0 N	13.25 ± 0.44	< 0.001

Control Group	30º	200N	16.55 ± 0.65	
	60º	0 N	13.39 ± 0.52	< 0.001
	60º	200 N	16.91 ± 0.74	
Isolated injury of the LMTL	30º	200N	21.12 ± 1.56	< 0.001
	60º	200 N	24.27 ± 1.67	
Combined injury LMTL + MFL	30º	200 N	23.14 ± 1.88	< 0.001
	60º	200 N	25.11 ± 2.19	
Capsulodesis technique	30º	0 N	13.13±0.51	0.12
	30º	200N	14.25±0.66	
	60º	0 N	13.29±0.59	0.09
	60º	200 N	14.99±0.92	
Centralization technique	30º	0 N	13.02 ± 0.54	0.21
	30º	200N	14.18 ± 1.01	
	60º	0 N	13.18 ± 0.44	0.19
	60º	200 N	14.72 ± 0.49	

Regarding the differences in meniscal extrusion when loading was applied, no significant differences were observed between the control group (intact meniscus) and the groups that had undergone reconstruction techniques (p = > 0.05). Neither were there any differences when comparing the results obtained between both reconstruction techniques (p = > 0.05). There were differences between the groups with ligament injuries when compared to the control group (p = < 0.05 and in the groups in which reconstruction was performed vs. the control group (p = > 0.05). This was also the case when comparing the injury status of 1 ligament versus the injury of the 2 ligaments, with significant differences (p = < 0.05, Table 6) (Figure 22)

Table 6. *Comparison of the results obtained between the different study groups during load application.*

Comparison	*p*-value
Control group 30º vs. Capsulodesis technique 30º	0.11
Control group 60º vs. Capsulodesis technique 60º	0.13
Control group 30º vs. Centralization technique 30º	0.20
Control group 60º vs. Centralization technique 60º	0.24
Control group 30º vs. Injury of the LMTL 30º	< 0.001
Control group 60º vs. Injury of the LMTL 60º	< 0.001
Control group 30º vs. Combined injury LMTL + MFL 30º	< 0.001
Control group 60º vs. Combined injury LMTL + MFL 60º	< 0.001
Capsulodesis 30º vs. Centralization technique 30º	0.67
Capsulodesis 60º vs. Centralization technique 60º	0.71

Capsulodesis 30º vs. Injury of the LMTL 30º	< 0.001
Capsulodesis 60º vs. Injury of the LMTL 60º	< 0.001
Capsulodesis 30º vs. Combined injury LMTL + MFL 30º	< 0.001
Capsulodesis 60º vs. Combined injury LMTL + MFL 60º	< 0.001
Centralization 30º vs. Injury of the LMTL 30º	< 0.001
Centralization 60º vs. Injury of the LMTL 60º	< 0.001
Centralization 30º vs. Combined injury LMTL + MFL 30º	< 0.001
Centralization 60º vs. Combined injury LMTL + MFL 60º	< 0.001
Injury of the LMTL 30º Combined injury LMTL + MFL 30º	0.04
Injury of the LMTL 60º Combined injury LMTL + MFL 60º	0.03

In all tests, the distance between the two markers increased with the knee flexion angle in cases where no load was administered. On the contrary, there were no differences in the results between the two flexion angles when the 200 N load was applied. Finally, there were no significant differences in the results between the two degrees of flexion analyzed in the majority of cases in this study. However, there were significant differences in the groups where an injury to any of the ligaments was performed ($p = < 0.05$, Table 5).

The percentage of interobserver variability for all measurements was < 0.2%, indicating a difference of < 0.01 mm between each measurement. Therefore, no relevant interobserver error was considered. Relative to interobserver reliability, the average difference between measurements was < 0.01, indicating that no striking errors were detected in the measurements. No significant differences were detected between intra- or interobserver measurements.

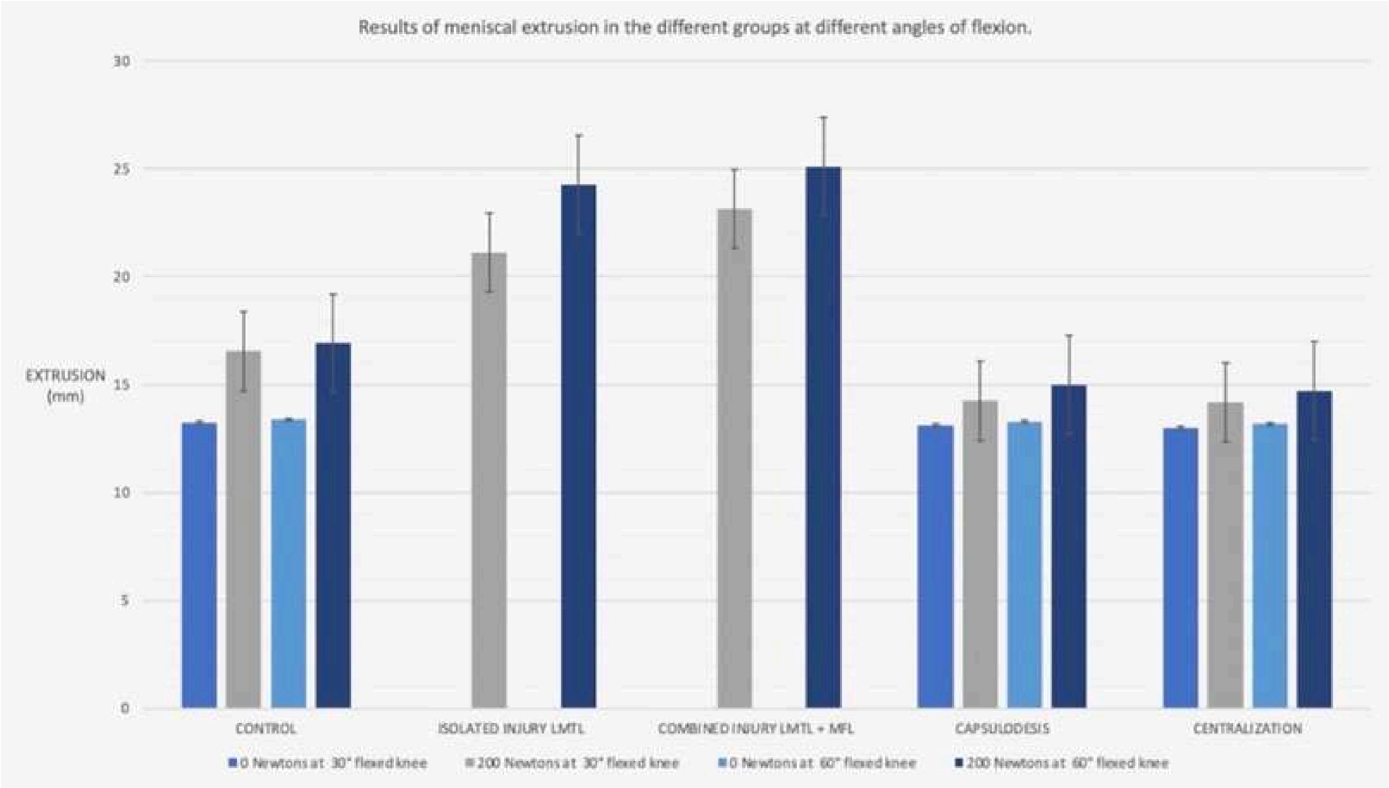
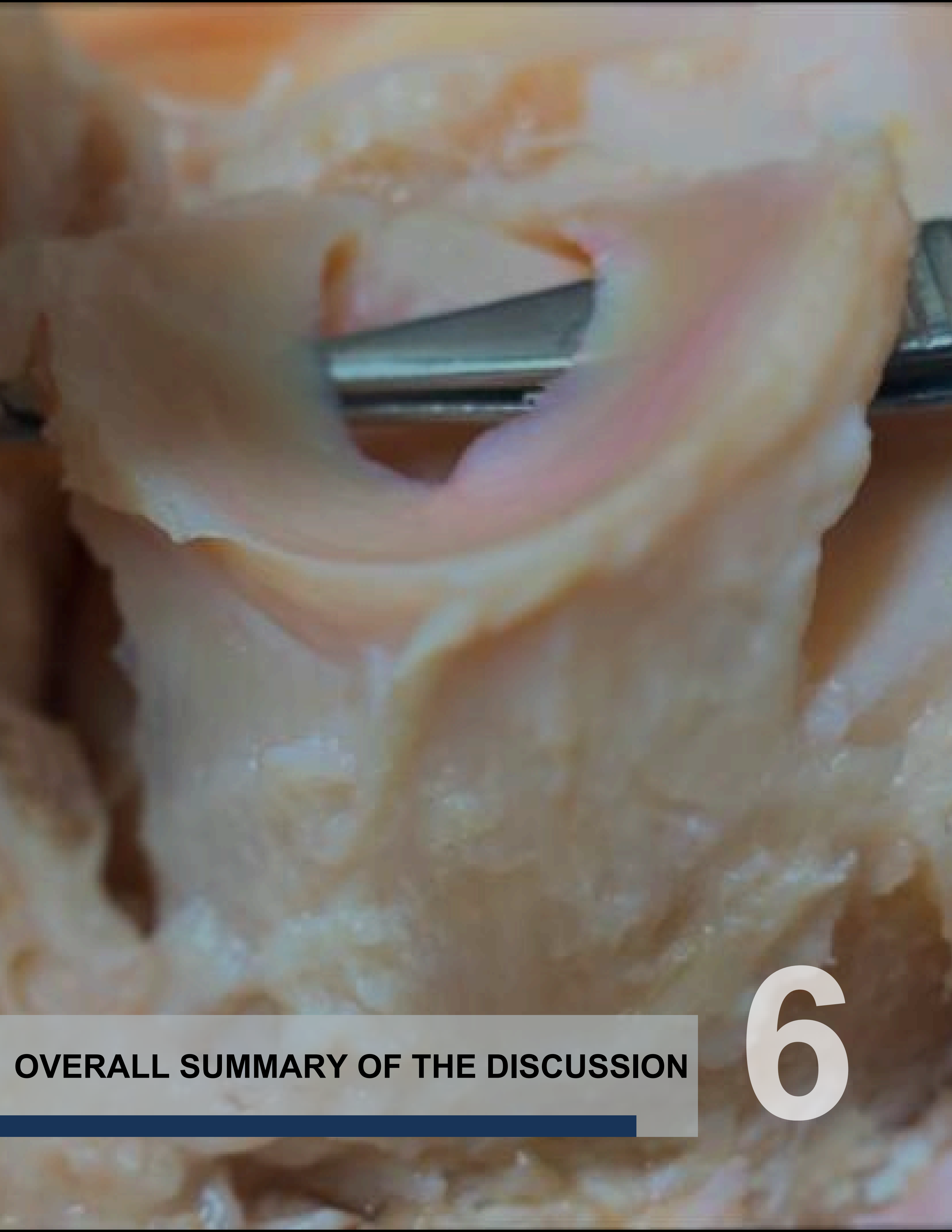


Figure 10. *Bar graph representation of the means and standard deviations obtained by the different study groups.*



6

OVERALL SUMMARY OF THE DISCUSSION

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The most important finding of this study was that the MTPFC could be easily identified and measured on the MRIs studied with a high prevalence. Furthermore, a constant anatomical and radiological pattern was observed in its 3 main structures, the LMTL, the LPP and the LPLM. The PML was observed with a lower prevalence. These findings corroborate our hypotheses.

The structures of the MTPFC play an important role in attaching the body of the lateral meniscus to the circumdate joint capsule and proximal tibia. This complex has been recently studied in cadavers.[25] Nonetheless, to our knowledge, this is the first time that LMLT has been studied from a radiological point of view. This has made it possible to identify it and its connections with the PFL and the PML. Additionally, it is the first study to fully characterize and measure the MTPFC using MRI.

The soft tissues of the lateral aspect of the knee represent a diagnostic challenge for musculoskeletal radiologists and knee surgeons. Anatomical variations, inconsistency in nomenclature, and relative unfamiliarity with various posterolateral structures create a risk environment for an incomplete or erroneous diagnosis. As in cadaveric studies, different names have been used to describe similar radiological structures, thus creating confusion in studying them over the years Similarly, Bozkurt et al. [31] performed a cadaveric study with the objective of determining the thickness of the LMTL. On that study, a measurement of 3.8 mm was described with a range of 2.6 to 6.1 mm. These results differ greatly from ours, which are more similar to other cadaveric studies despite not being analyzed by means of MRI.[25,76] One of the possible reasons for these differences is that their measurements incorporated part of the lateral capsule, thereby obtaining greater results unlike the rest of the studies cited.

Regarding the PML, its existence has been demonstrated in this study. However, this ligament only corresponds to a small number of fibers in a posterior position in continuity with the LMTL. In other words, it is the continuation of the same ligament. It has a large tibial portion (the lateral menisco-tibial ligament) and a small proportion of posterior fibers that lead to the head of the fibula (the meniscofibular ligament). Previous anatomical studies have reported a prevalence of between 80 and 100% for PML.[31,32,61] The PML has been analyzed with MRI in previous studies. Obaid et al. found the PML in 42.5% in a series of 1.5T MRI of 152 patients (results very similar to those obtained in our study). The percentage increased to 63% when there was joint effusion associated with the posterolateral corner. 41 Similarly, Lee et al.[59] observed a prevalence of 89.4% for the PML despite it being a limited series of 19 magnetic resonance arthrograms. Like previous results with the 1.5T MRI, the PML was observed in our study using the fat suppression sequence in the sagittal view with 3 mm slices presenting a length of 2 to 6 mm in 39%.

The PPL, located posterior to the fibular collateral ligament, is also a component of the MTPFC that attaches the popliteus tendon to the fibular head. Its function is to restrict external rotation, varus rotation, and posterior tibial translation from 0° to 120° of the posterolateral structures.[77]

Other studies have reported that the popliteofibular ligament and the arcuate ligament with overlapping definitions are inconsistently observed on MRI examinations, which is in contrast to the high prevalence observed in this study.[40] Yu et al.[78] recommended an oblique coronal projection to increase the visibility of the posterolateral structures. In their study, routine coronal imaging revealed the presence of the popliteofibular ligament in only 8% of the knees studied in contrast to our study in which it was observed 93.3% of the time.

The PML connects the lateral meniscus with the popliteus muscle, anatomically forms the floor and roof of the popliteal hiatus, provides stability to the lateral meniscus at the level of the popliteus muscle, thus limiting the extrusion and lateral movement of the meniscus.[43] Sakai et al.[42] found a prevalence of 94.1% for the anteroinferior LPM and 88.2% for the posterosuperior LPM. That is similar to the results presented here. In contrast, Peduto et al.[79] stated that the LPM with its two fascicles is always present when 1.5 Tesla magnetic resonance arthrography was used.

When comparing the measurements obtained according to sex, it was observed that there is no clinical or radiological relevance despite differences being found in some cases. The differences are minimal and may be due to differences in height and/or weight between the male and female groups.

It has been suggested that these meniscocapsular and meniscotibial attachments and attachments help keep the lateral menisci in place and thus prevent extrusion.[25] This highlights the importance of being able to associate their injuries or alterations with the phenomenon of meniscal extrusion in subsequent clinical studies. The high prevalence of the MTPFC observed in the MRIs of the present work as well as the consistency in its radiological pattern can help both radiologists in the search and description of lesions at this level and knee surgeons in their effort to plan better surgical management. More biomechanical studies are needed to further analyze the anatomical relationship and functional role of the LMTL, PFL, and PML.

Some of the limitations of this current study are the power of the MRI magnet with which the morphometries were performed as a 3 Tesla MRI unit could be much more accurate. However, most published MRI studies used a 1.5 Tesla unit for the resolution of this type of study as it is considered good enough; The high correlation between observers found in the present work confirms this. The lack of anatomical correlation with MRI findings is another problem. Ideally, a correlation between MRI and cadaver dissection would have been better. However, all the structures described in this study coincide with the most recent anatomical descriptions found in the literature. Another limitation is that the MRIs used were not taken specifically for study purposes in healthy patients without knee injuries; however, our inclusion and exclusion criteria were strict so as to select only those MRIs that do not represent a source of bias. Another last limitation may be the fact that only knees of the same ethnicity have been analyzed. Therefore, our findings cannot be generalized to the general population with certainty.

The main finding of this study was that the capsulodesis technique produces a low degree of meniscal extrusion in the lateral MAT fixed with a suture-only technique, which is maintained after seven years of follow up. The second finding was that this procedure has a high graft survival rate and produces satisfactory results on functional scales, achieving an adequate MCID and PASS.

The cause of graft extrusion after MAT is not yet fully understood. In recent studies, the presence of preexisting osteophytes on the lateral tibial plateau,[44] a size discrepancy between the affected articular surface and the chosen meniscus allograft, the position of the bone bridge, an inadequate fixation technique or inadequate tension of the peripheral sutures, as well as non-anatomical positioning of the meniscus allografts are known factors. that influence graft extrusion after MAT.[19,80–82]

It has previously been suggested that the absolute value of meniscal extrusion is conditioned by preoperative and intraoperative factors and that the phenomenon of meniscal extrusion usually occurs early during the first postoperative year with stabilization in subsequent years.[18] Therefore, extrusion can be minimized if the surgical procedure and technique are correct, the allograft is properly selected, and it is transplanted correctly.

The capsulodesis technique offers versatility in terms of the location and number of sutures for fixation with no significant bone loss in the tibial plateau, in addition to not interfering with subsequent magnetic resonance imaging.[45] The capsulodesis technique was initially developed in combination with MAT with both horns secured (suture-only fixation technique) because it is easier to fix the graft to the soft tissues, obtaining good results in previous studies.[45-46] Clinical studies that compared it with other techniques involving bone fixation showed no difference in clinical, functional and radiographic results. However, they have demonstrated a lower degree of meniscal extrusion and a reduction in complications,[48] which has been attributed to greater graft stability when bone fixation is used.[83] Roumazeille et al. studied MAT without bone plugs and found that meniscal extrusion was present in 75% of patients evaluated by MRI at six months postoperatively.[49] Abat et al. found an extrusion degree of 38.3% ± 14.4 with the suture-only fixation technique and 30.14% ± 13.5 with the bone bar method in a series of lateral MAT with a minimum follow-up of three years.[51] Choe et al., in a retrospective MRI evaluation performed at least one year after surgery, reported a result of 3.4 ± 2.2 for the absolute value of meniscus extrusion and an extrusion incidence of 41.6% for 320 cases of lateral TAM using the “Key hole” technique with a bone block that connects the anterior and posterior horns. There was also a significant decrease in meniscal extrusion as the learning curve increased, obtaining a mean of 2.5 mm ± 2.1 for the total extrusion value and an extrusion percentage of 27.5% for the last 40 operated cases.[50] Verdonk et al. reported that the mean degree of extrusion for 17 patients undergoing LMAT between 2004 (23.45-month follow-up) and 2006 (minimum 10-year follow-up) was 5.8 mm ± 2.8. They also reported that partial extrusion occurred in 12 of the 17 patients who received LMAT (70%) using a suture soft tissue fixation technique.[52] Ahn et al. reported that the incidence of lateral TAM extrusion using the “key hole” technique was 52.8% and the mean extrusion of the extrusion group was 4.4 mm ±2.8.2.84 Lee et al. reported an incidence of extrusion after lateral MAT of 32.2% after two years of follow-up, with a mean extrusion of

3.2 mm ± 1.5 in the standard rehabilitation group and 1.8 ± 1.6 mm in the late rehabilitation group.

Although no differences in clinical outcomes were observed between the groups.85 Kim et al. evaluated 46 patients who received a lateral TAM using the “key hole” technique with an average follow-up of 51.1 ± 7.1 months and reported an average absolute meniscal extrusion of 2.8 mm ± 0.89 with a percentage of associated extrusion of 27.8 ± 9.7%. They concluded that meniscus allograft extrusion did not significantly increase in the coronal view after lateral TAM in a medium-term follow up period and reported a Lysholm score of 90.5 ± 10.1.[86] Jeon et al. retrospectively evaluated 88 patients with a peripheral osteophyte on their tibial plateau who underwent MAT with the modified keyhole technique and compared it with osteophyte excision in its effect on meniscal extrusion. They found a mean absolute extrusion of 3.5 mm ±1.5. and 5.5 mm ±1.6, respectively. There was an average relative percentage of extrusion of 34.1 ± 15.9% and 54.7 ± 20.7%.[44] Lee et al. evaluated 27 patients who had undergone a lateral TAM with a follow up time of 10.3 years using the “key hole” technique and found an absolute meniscal extrusion value of 2.76 mm ± 0.47 and a Lysholm score of 91.1 ± 4.6.[18]

It should be noted that the results of the study showed the lowest meniscal extrusion values reported in the literature using only soft tissue fixation. On the other hand, Lee et al. observed an extrusion value of 1.8 ± 1.6 mm in a 2-year follow-up using the bone plug technique. It was 2.14 ± 1.58 mm in our study in a longer follow-up. Additionally, there was more postoperative immobilization time when compared to our study.

Our study showed no significant progression of osteoarthritic changes and JSW during the mid-term follow-up period after LMAT with the suture-only fixation technique and capsulodesis. These results coincide with those obtained by other authors regarding the progression of the degree of osteoarthritis and JSW.[18,87,88] However, they differ with respect to the total values, them being lower in our study. This is easily explained because our patients began the study with lower values than those reported in other studies.[18,88] Regarding functional improvement, most studies report values ranging from good to excellent in the functional scales analyzed in the short and medium term.[89] They are similar to our study but with an additional decrease in long-term studies.[87] Finally, a survival rate of 85.7% was observed after seven years of follow-up. There was no control group, but previous published studies where the same surgeon performed MAT without capsulodesis reported similar survival rates, 92.4% at 5 years in one study and 87.8% at 6.5 years in another. Furthermore, the current study demonstrated that capsulodesis decreases meniscal extrusion without affecting meniscal functionality or the survival rate.

This study had several limitations. The most important is the small number of patients in the cohort (23 cases). Another limitation was the lack of a control group with bone fixation without capsulodesis to establish the superiority of the technique. However, an exhaustive literature review was conducted to compare our results with historical data published in the literature. Another limitation is the that an assessment of meniscal extrusion was performed on static supine images rather than weight bearing ultrasound or magnetic resonance imaging under weight bearing conditions in which the highest degree of apparent meniscal extrusion has been reported.[90] The latter represents perspectives for future research. However, this is a common limitation present in most studies conducted to date. Another limitation is that the degree of extrusion of the anterior and posterior horns of the lateral meniscus on the sagittal plane was not calculated. As discussed in the two previous articles about this technique, the learning curve of this technique in the first four cases can negatively influence the results. Excluding those four cases, the graft survival rate is 100% and the meniscal extrusion rate is significantly reduced.

The biomechanical study demonstrated that the meniscotibial and meniscofibular ligaments function as restrictors of the radial mobility of the lateral meniscus and that their injury produces a significant increase in meniscal extrusion. Therefore, our first hypothesis is confirmed. Furthermore, this meniscal extrusion can be restored to pre-injury state using the open capsulodesis technique or the centralization technique with no significant differences between the two procedures. Using the centralization or capsulodesis techniques, the lateral meniscus was no longer displaced laterally. Therefore, the second hypothesis was confirmed.

To our knowledge, this is the first study that analyzes the biomechanical effects of an isolated and combined injury, as well as its reconstruction. Although there were no significant differences between the two reconstruction techniques, a greater decrease in meniscal extrusion was observed with the centralization technique. The fact that some modification was introduced in the capsulodesis technique may help explain this subtle difference. It is attributed to the fact thata modification was made in the centralization technique in this study to also perform a reconstruction of the meniscofibular ligament. Previous studies have determined that isolated LMTL injuries lead to severe meniscal extrusion, even in the absence of other knee pathologies.[91] An injury to the meniscotibial ligament causes the meniscus to detach from the tibial plateau, thus losing its normal insertion sites and causing extrusion of the meniscus.[92]

Ozeki et al. have carried out previous studies in porcine models where they demonstrated greater meniscal extrusion in patients with posterior radial meniscal lesions and its subsequent improvement when performing the centralization technique. In that study, 200 N of axial load were applied in which a result of 21.9 mm (17.8-25.6) and 15.3 mm (12.9-18.0) for meniscal extrusion was seen. They represent values very similar to those of the present investigation in which there was greater extrusion after the injury and a return to native values after carrying out the reconstruction techniques.[28]

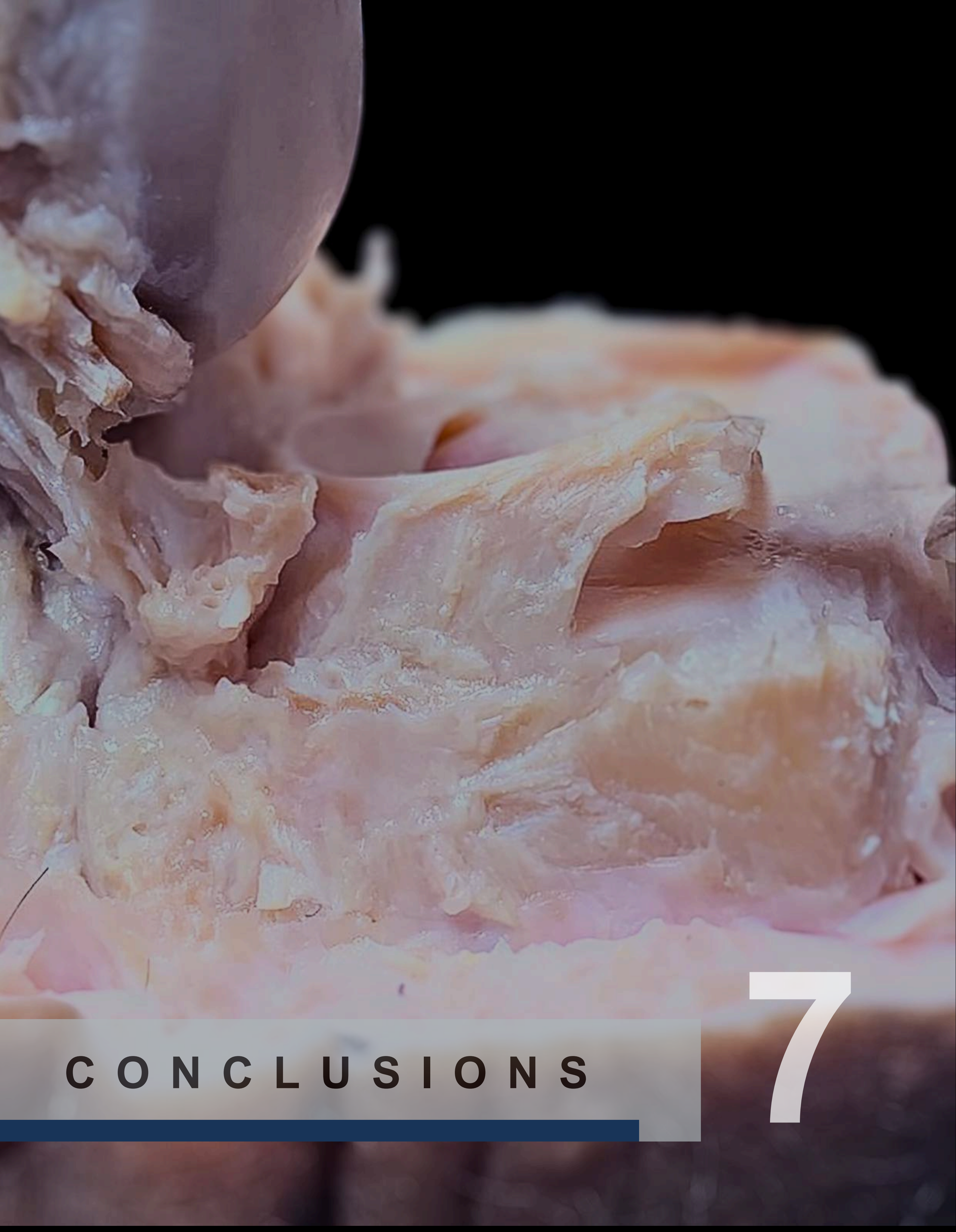
We attribute these differences to injuries to the meniscotibial and meniscofibular ligaments. With that, we conclude that they can cause the extrusion of the meniscus seen in the present work as the authors believe in the primary relevance of these structures in limiting the lateral mobility of the lateral meniscus. Furthermore, differences in the way centralization procedures were performed in both studies could also contribute to the slight biomechanical differences found. In the same way, Kubota et al. described similar results in a study on porcine knees, confirming that meniscal extrusion increases with degrees of knee flexion.[27]

The meniscofibular ligament was found in all the specimens studied, with results similar to studies carried out on humans.[32] This ligament connects the inferolateral portion of the body of the lateral meniscus, posteriorly and laterally, with the head of the fibula. In its anterior portion, its fibers interconnect and are in continuity with the most posterior fibers of the lateral meniscotibial ligament. This observation had already been evidenced in previous studies.[93] Previous studies have hypothesized that the function of the MFL is to stabilize the lateral meniscus in external rotation and varus movements. This is because, the fibula tends to externally rotate during ankle dorsiflexion and causes a displacement of the lateral meniscus in that direction.[31]

However, to the best of our knowledge, this is the first study that analyzes the biomechanical characteristics of the meniscofibular ligament. Furthermore, it is believed that its true function is to strengthen the function of the lateral meniscotibial ligament and prevent anterolateral displacement of the lateral meniscus.[76] In those previous studies, they also considered reconstruction of this ligament during allogeneic lateral meniscus transplantation.

The present study has several limitations. First, it was a trial study, in vitro, using a porcine model instead of a human. Second, meniscal extrusion was only evaluated on the mediolateral plane, leaving aside evaluations in the anteroposterior plane. Thirdly, only two flexion angles were considered, leaving aside larger angulations. Fourth, the number of samples is limited even though the current sample size is larger than that used in most biomechanical studies. Fifth, the evaluated surgical techniques that were originally performed arthroscopically have been adapted to be performed as an open surgery for the purpose of the present work. Finally, determinations of the variability of pressure and load on the lateral meniscus were not made as would have been convenient.

Among the strengths are the triplicate evaluations of the measurements, which provide much more reliability to the data obtained. One strength is the accurate simulation of the biomechanical environment in which the forces of the major muscle groups (i.e., quadriceps and hamstrings) were reproduced. Another is the inclusion of the meniscofibular ligament, whose relationship with the phenomenon of meniscal extrusion had not been previously considered, in the analysis, finally, there is the strict methodology followed with a defined protocol for injury and reconstruction of the ligaments of interest.



7 CONCLUSIONS

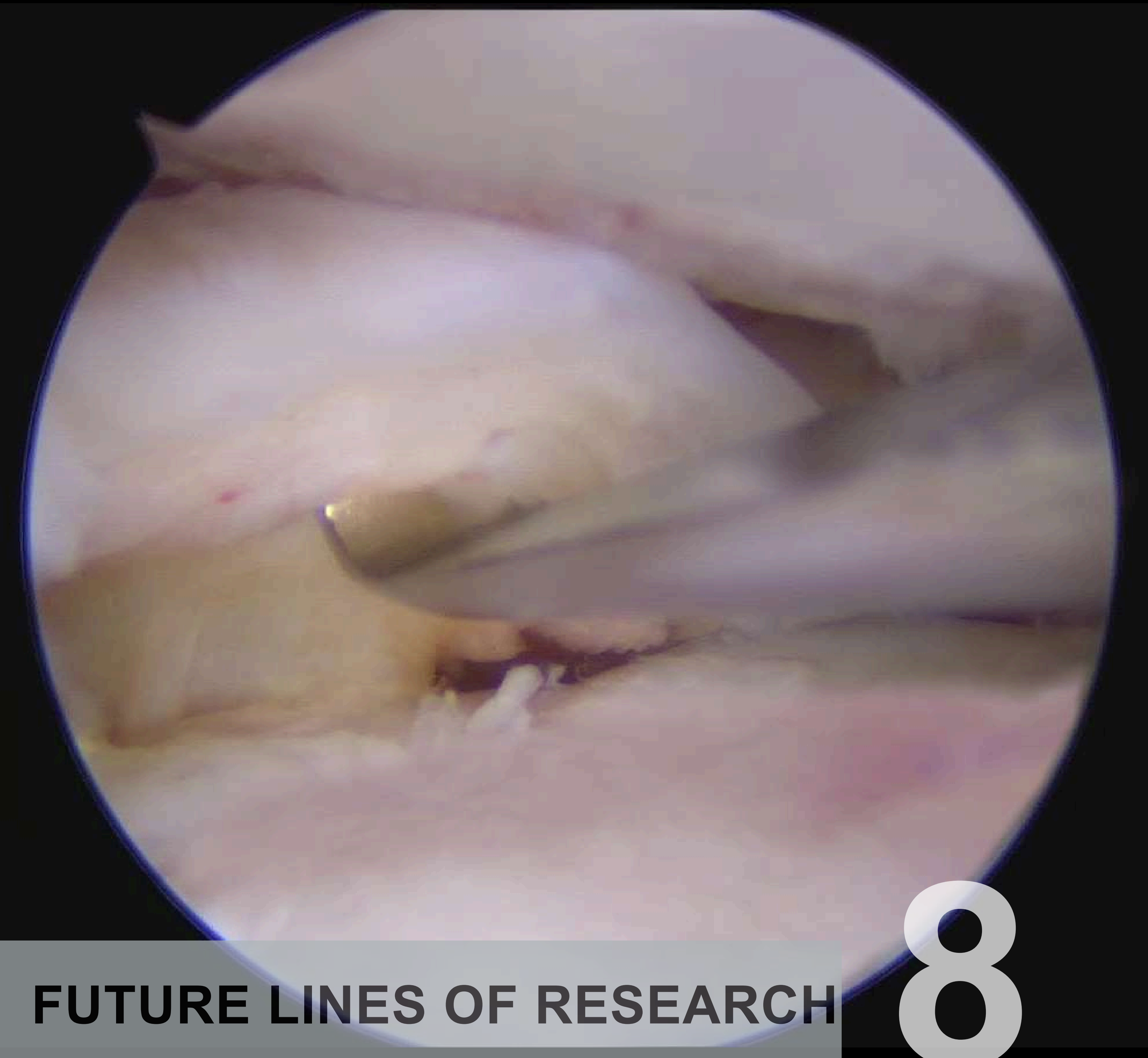
CONCLUSIONS

The MTPFC, which is formed by its three ligaments (LMTL, PFL and PML), can be identified by means of MRI since they present a consistent morphological and anatomical pattern. The MFL was found on fewer occasions, being considered a structure difficult to identify using 1.5T MRI, corresponding to the most posterior fibers of the LMTL that reached the head of the fibula.

The Capsulodesis decreases meniscal extrusion in allogeneic lateral meniscus transplantation fixed with a suture-only technique. Afterwards, there is a subsequent limitation in the degree of clinical and functional progression during seven years of follow-up when compared to the results of the first two years. It also showed a high graft survival rate, a low complication rate and satisfactory results on the functional and patient satisfaction scales. Additionally, There were no significant alterations in the alignment of the lower limbs on the coronal plane and but a decrease in the lateral joint space between the preoperative evaluation and at two and seven years was seen.

Therefore, our results suggest that this surgical technique improves functional scores, and that this improvement is clinically significant for patients. Future long-term clinical studies with ten to fifteen years of follow-up will be necessary to confirm the results of the present technique and lead to its potential incorporation as a standardized technique in combination with lateral MAT.

The lateral meniscotibial ligament and the meniscofibular ligament actively participate as restrictors of the radial mobility of the lateral meniscus. Injury to them causes a significant increase in extrusion rates of the lateral meniscus. The centralization and capsulodesis procedures reduce extrusion in a porcine model.

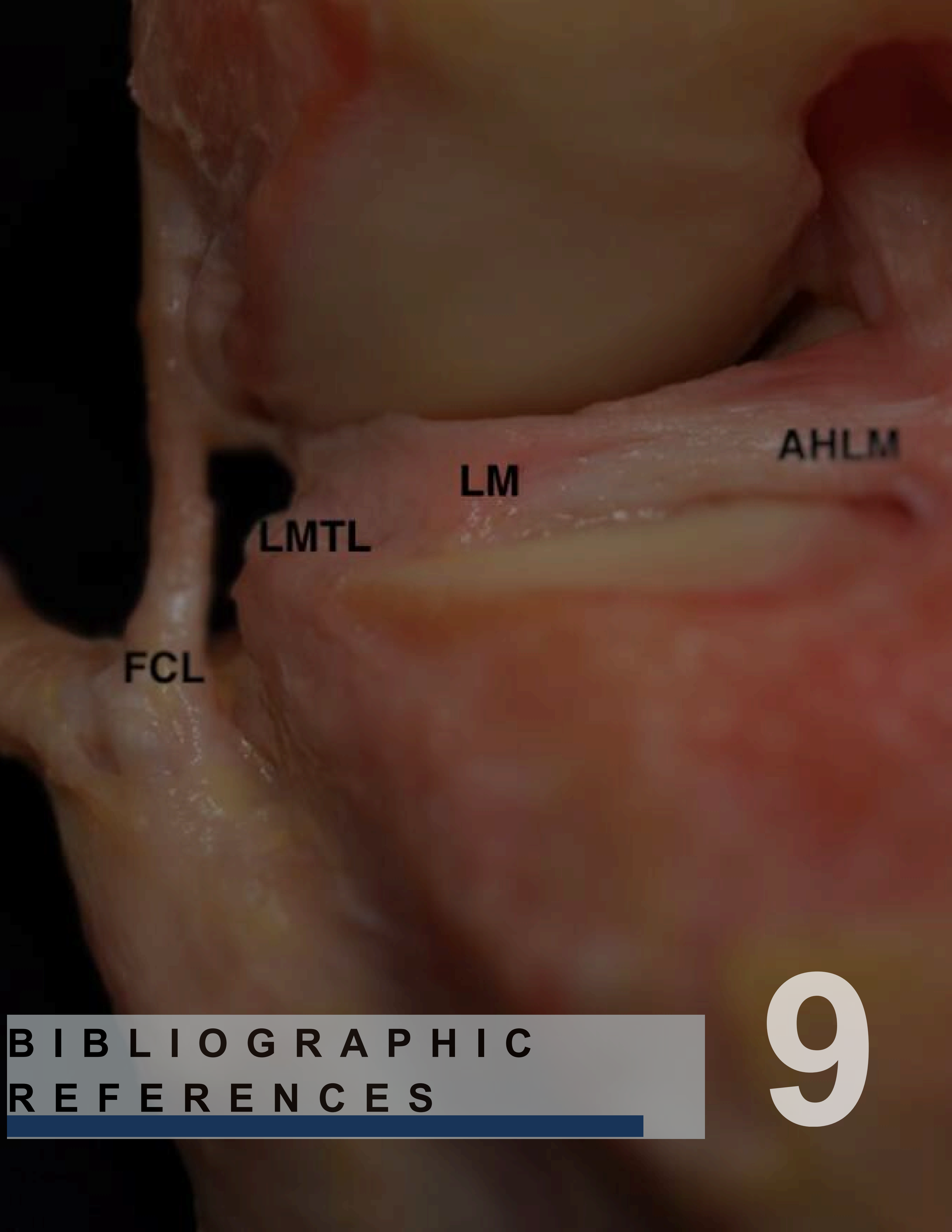


FUTURE LINES OF RESEARCH 8

FUTURE LINES OF RESEARCH

In the same way, it might be worth considering adding the reconstruction of some of those ligaments associated with the allogeneic lateral meniscus transplant and thereby reduce meniscal extrusion and improve the functionality and quality of life of patients who receive this treatment. Likewise, the animal model studied in this thesis is currently being transferred to a human cadaveric model. Moreover, the follow-up of capsulodesis patients is being kept up and increased for the subsequent publication of the results at 10- and 15-year follow-ups.

Our research group is beginning to conduct studies on magnetic resonance and ultrasound imaging under weight bearing conditions to elucidate the exact degree of meniscal extrusion in patients with medial and lateral meniscal transplants, as well as implementing modifications to capsulodesis and centralization techniques.



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ANNEXES 10

10.1. Annex 1. *Letters of Authorization from the Ethics Committee.*

UANL
UNIVERSIDAD AUTÓNOMA DE NUEVO LEÓN

FACULTAD DE MEDICINA Y HOSPITAL UNIVERSITARIO

DR. med. JOSE FELIX VILCHEZ CAVAZOS
Investigador principal
Servicio de Ortopedia y Traumatología
Presente.-

Estimado Dr. Vilchez Cavazos:

Le informo que nuestro Comité de Ética en Investigación del Hospital Universitario "Dr. José Eleuterio González", ha **evaluado y aprobado** el protocolo de investigación titulado: **"Análisis de la función biomécánica del ligamento meniscotibial lateral y su comparación con la técnica de Capsulodesis a nivel del menisco lateral. Su aplicación al trasplante meniscal alogenico lateral. Estudio biomecánico en rodillas cadavéricas"** participando además el Dr. C. Rodrigo E. Elizondo Omaña, Dr. med. Santos Guzmán López, Dr. med. Juan Carlos Monllau García, Dr. Rodolfo Morales Avalos, Dr. med. Víctor Manuel Peña Martínez, Dr. C. Guillermo Elizondo Riojas, Dr. Adrián Antonio Negreros Osuna, Dr. C. Nasser Mohamed Noriega, Dr. José Manual Diabb Zavala, Dr. C. Mario Alberto Bello Gómez, Dr. C. Juan Francisco Luna Martínez, Dr. C. Jesús Gabino Puente Córdova y la Est. Alejandra Johanna Pozos Garza como Co-investigadores, el cual quedó registrado con la clave **OR20-00001.**

- **Protocolo en extenso, versión 2.0 de fecha 17 de Febrero del 2020.**

Cada vez que el Protocolo sufra modificaciones, éstas deberán someterse nuevamente para solicitar su autorización.

Le reitero que es su obligación presentar a este Comité de Ética en Investigación un informe técnico parcial a más tardar el día en que se cumpla el año de emisión de este oficio, así como notificar la conclusión del estudio.

Será nuestra obligación realizar visitas de seguimiento a su sitio de investigación para que todo lo anterior esté debidamente consignado, en caso de no apegarse, este Comité tiene la autoridad de suspender temporal o definitivamente la investigación en curso, todo esto con la finalidad de resguardar el beneficio y seguridad de todo el personal y sujetos en investigación.

Atentamente.-
"Alere Flammam Veritatis"
Monterrey, Nuevo León 17 de Marzo del 2020

COMITÉ DE ÉTICA EN INVESTIGACIÓN
COMITÉ DE INVESTIGACIÓN

DR. med. JOSE GERARDO GARZA LEAL
Presidente de Comité de Ética en Investigación

Comité de Ética en Investigación
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Teléfonos: 81 8329 4050, Ext. 2870 a 2874. Correo Electrónico: investigacionclinica@meduanl.com

Full Accreditation
Septiembre 16, 2017

Annex 1. *Letters of Authorization from the Ethics Committee.*

UANL
UNIVERSIDAD AUTÓNOMA DE NUEVO LEÓN

FACULTAD DE MEDICINA Y HOSPITAL UNIVERSITARIO

DR. MED. JOSE FELIX VILCHEZ CAVAZOS
Investigador principal
Servicio de Ortopedia y Traumatología
Presente.-

Estimado Dr. Vilchez Cavazos:

En respuesta a su solicitud con número de Ingreso **PI20-00076** con fecha del **17 de Enero del 2020**, recibida en las Oficinas de la Secretaría de Investigación Clínica de la Subdirección de Investigación, se extiende el siguiente **DICTAMEN FAVORABLE** con fundamento en los artículos 4° párrafo cuarto y 16 de la Constitución Política de los Estados Unidos Mexicanos; así como los artículos 14-16, 99 párrafo tercero, 102, 106 del Reglamento de la Ley General de Salud en Materia de Investigación para la salud; así como de los artículos 111,112 y 119 del Decreto que modifica a la Ley General de Salud en Materia de Investigación para la salud publicado el día 2 de abril del 2014; Además Punto 4.4, 4.7, 6.2, 8 de la Norma Oficial Mexicana NOM-012-SSA3-2012, que establece los criterios para la ejecución de proyectos de investigación para la salud en seres humanos; así como por el Reglamento interno de Investigación de Nuestra Institución.

Se informa que el Comité de Investigación ha determinado que el Protocolo de Investigación clínica abajo mencionado cuenta con la calidad técnica, aspectos metodológicos y mérito científico requeridos.

"Análisis de la función biomécanica del ligamento meniscotibial lateral y su comparación con la técnica de Capsulodesis a nivel del menisco lateral. Su aplicación al trasplante meniscal alogenico lateral. Estudio biomecánico en rodillas cadavéricas", registrado con la clave **OR20-00001.**

De igual forma los siguientes documentos:

- **Protocolo en extenso, versión 2.0 de fecha 17 de Febrero del 2020.**

Le reitero que es su obligación presentar a este Comité de Investigación un informe técnico parcial a más tardar el día en que se cumpla el año de emisión de este oficio, así como notificar la conclusión del estudio.

Será nuestra obligación realizar visitas de seguimiento a su sitio de investigación para que todo lo anterior esté debidamente consignado, en caso de no apegarse, este Comité tiene la autoridad de suspender temporal o definitivamente la investigación en curso, todo esto con la finalidad de resguardar el beneficio y seguridad de todo el personal y sujetos en investigación.

Atentamente.-
"Alere Flammam Veritatis"
Monterrey, Nuevo León 17 de Marzo del 2020

COMITÉ DE ÉTICA EN INVESTIGACIÓN
COMITÉ DE INVESTIGACIÓN

DR. OMAR KAWAS VALLE
Secretario del Comité de Investigación

Comité de Investigación
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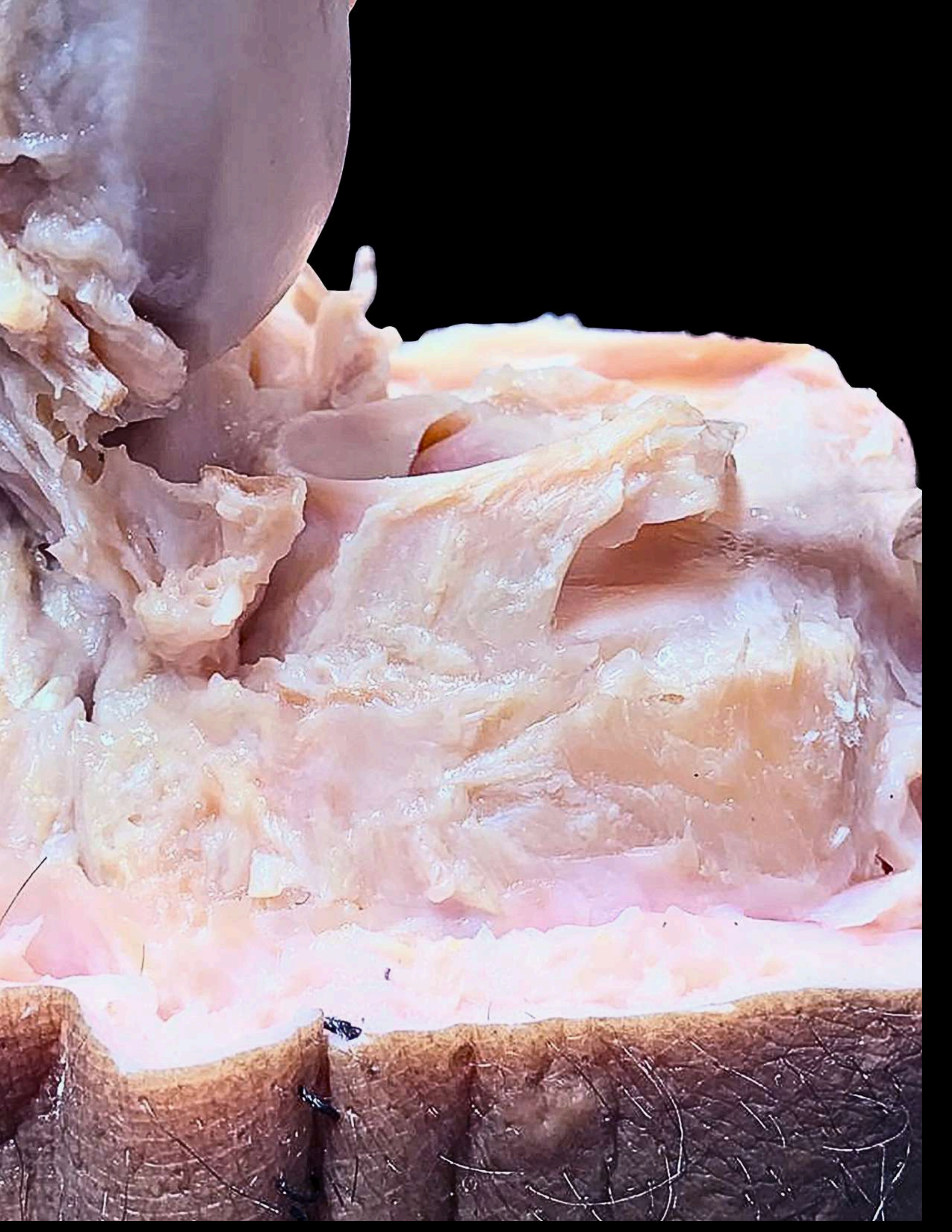
Full Accreditation
Septiembre 16, 2017



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