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# Meniscal injuries associated to anterior cruciate ligament rupture

Cumulative Dissertation

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Submitted by

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# Begleitverletzungen der Menisken bei Ruptur des vorderen Kreuzbandes

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# Contents

# Preliminaries

# Declaration on included original publications

This thesis is presented in the format of a cumulative dissertation. All included articles were published in peer-reviewed journals. All co-authors of the included publications have provided their consent for the original articles to be used in the context of this thesis. A description of the contribution of all co-authors to the scientific work and the corresponding original publications is listed separately for every publication below.

For all publications, the authors declared that they have no conflict of interest. Further, no funding was provided for any of the studies.

The author of the thesis has obtained permission from the publishers to reprint the publications.

In order to ensure a coherent and consistent style throughout this thesis, the summaries and contextual descriptions of the included articles have been harmonized in terms of wording and the use of abbreviations. The original publications themselves remain unchanged. The author confirms that the scientific content, results, and interpretations of the papers have not been altered.

Artificial intelligence, namely *ChatGPT*, was utilized to refine the wording and consistency of the thesis text and to provide limited support during the literature search. The original publications included in this work were written entirely without any artificial intelligence assistance.

The scientific work from the publication entitled “Medial meniscus ramp and lateral meniscus posterior root lesions are present in more than a third of primary and revision ACL reconstructions” was honored with the second place of the “GOTS Young Investigator Award” by *Bauerfeind*, awarded by the German-speaking Society for Orthopedics, Traumatology and Sports Medicine *(Gesellschaft für Orthopädisch-Traumatologische Sportmedizin, GOTS)* at the annual congress 2020.

The scientific work from the publication entitled “Grade III pivot shift as an early sign of knee decompensation in chronic ACL-injured knees with bimeniscal tears” was honored with the first place of the “ReFORM Young Researcher Award”, awarded by the French-speaking Olympic Sports Medicine Research Network (*Réseau Francophone Olympique de Recherche en Médecine du Sport, ReFORM*) at the young researcher day 2021.

1. Mouton C, **Magosch A**, Pape D, Hoffmann A, Nührenbörger C, Seil R (2020) Ramp lesions of the medial meniscus are associated with a higher grade of dynamic rotatory laxity in ACL-injured patients in comparison to patients with an isolated injury. Knee Surgery, Sports Traumatology, Arthroscopy (KSSTA) 28:1023-1028. DOI: 10.1007/s00167-019-05579-z.

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5. Jacquet C, Mouton C, **Magosch A**, Komnos GA, Menetrey J, Ollivier M, Seil R (2022) The aspiration test reveals an instability of the posterior horn of the lateral meniscus in almost one-third of ACL-injured patients. Knee Surgery, Sports Traumatology, Arthroscopy (KSSTA) 30:2329-2335. DOI: 10.1007/s00167-021-06806-2.

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# Abstract (English)

Anterior cruciate ligament (ACL) ruptures are among the most frequent knee injuries and are often accompanied by concomitant soft-tissue damage, particularly involving the menisci. This cumulative dissertation investigates ACL-associated meniscal injuries with a specific focus on the posterior horns of the menisci, including the medial meniscus ramp lesion (MMRL), the posterolateral meniscus root tear (PLMRT), and the lateral meniscus posterior horn instability (LMPHI). Through a series of clinical studies based on prospectively collected data and partly derived from a hospital-based ACL injury registry, this thesis aims to advance the understanding of intra-articular soft tissue damage, its biomechanical relevance, and diagnostic strategies that support comprehensive anatomical restoration in ACL-injured knees.

The first study demonstrates that the presence of a MMRL in ACL-injured patients is significantly associated with increased dynamic rotatory laxity, as expressed by the pivot shift test, confirming the medial meniscus ramp's role as a secondary stabilizer in the ACL-deficient knee. The second study analyzes meniscus tear patterns in a large cohort of patients undergoing primary or revision ACL reconstruction, showing that over two-thirds of patients present concomitant meniscal injuries, and more than half of these involve MMRLs and/or PLMRTs. The third study reveals that a high-grade pivot shift is predominantly found in chronic ACL injuries with extensive intra-articular soft tissue damage, leading to the hypothesis of progressive knee decompensation. The fourth and fifth studies introduce and validate the "aspiration test" as a novel diagnostic tool for detecting LMPHI during knee arthroscopy. This technique shows superior sensitivity to conventional probing and identified a LMPHI in nearly one-third of ACL-injured knees, emphasizing its clinical relevance for complete arthroscopic assessment.

The synthesis of these findings underscores that ACL injuries rarely occur in isolation but rather represent a complex spectrum of soft tissue damage that compromises joint stability and possibly promotes progressive degeneration. This thesis highlights the crucial importance of systematic arthroscopic exploration, including targeted evaluation of the meniscal posterior horns, to ensure complete anatomic and functional restoration of the knee joint. Furthermore, it advocates for early ACL reconstruction with concomitant meniscus repair to prevent chronic instability and premature degenerative changes.

# Abstract (German)

Rupturen des vorderen Kreuzbandes (VKB) gehören zu den häufigsten Verletzungen des Kniegelenks und gehen oft mit begleitenden Weichteilschäden insbesondere der Menisken, einher. Diese kumulative Dissertation untersucht VKB-assoziierte Meniskusverletzungen mit spezifischem Fokus auf die Hinterhörner der Menisken, einschließlich der medialen Meniskusrampenläsion, des posterolateralen Meniskuswurzelrisses und der Instabilität des lateralen Meniskushinterhorns. Diese Arbeit basiert auf einer Reihe klinischer Studien mit prospektiv erhobenen Daten, teilweise aus einem klinik-internen VKB-Verletzungsregister. Ziel ist es, das Verständnis von intraartikulären Weichteilschäden, ihre biomechanische Bedeutung und die diagnostische Strategie zu verbessern, um eine möglichst anatomische Wiederherstellung des VKB-verletzen Kniegelenkes zu ermöglichen.

Die erste Studie zeigt, dass das Vorliegen einer medialen Meniskusrampenläsion bei VKB-verletzten Patienten signifikant mit einer erhöhten dynamischen Rotationslaxität, ausgedrückt durch den Pivot-Shift-Test, assoziiert ist. Dies bestätigt die Rolle der medialen Meniskusrampe als sekundärer Stabilisator im VKB-defizienten Knie. Die zweite Studie analysiert das Verletzungsmuster in einer großen Kohorte von Patienten, die sich einer primären oder erneuten VKB-Rekonstruktion unterzogen, und zeigt, dass über zwei Drittel der Patienten begleitende Meniskusverletzungen aufweisen, wobei mehr als die Hälfte eine mediale Meniskusrampenläsion und/oder einen posterolateralen Meniskuswurzelriss aufweisen. Die dritte Studie zeigt, dass ein stark ausgeprägter Pivot-Shift-Test überwiegend bei chronischen VKB-Verletzungen mit umfangreichen intraartikulären Weichteilschäden vorliegt, was zur Hypothese der progressiven Dekompensation des Kniegelenkes führt. Die vierte und fünfte Studie führen den „Aspirationstest“ als neues arthroskopisches Verfahren zur Diagnose einer Instabilität des lateralen Meniskushinterhorns ein und überprüften seine Validität. Die Methode zeigt eine höhere Sensitivität als die konventionelle Prüfung mit dem Tasthaken und deckt bei nahezu einem Drittel der VKB-verletzten Knie eine Instabilität des lateralen Meniskushinterhornes auf, was ihre klinische Bedeutung für eine vollständige arthroskopische Beurteilung hervorhebt.

Die Zusammenfassung dieser Ergebnisse zeigt, dass VKB-Verletzungen selten isoliert auftreten, sondern ein komplexes Spektrum von Weichteilschäden darstellen, welche die Gelenkstabilität beeinträchtigen und eine fortschreitende Degeneration fördern können. Die Arbeit betont die Bedeutung einer systematischen arthroskopischen Exploration, einschließlich der gezielten Beurteilung der Meniskushinterhörner, um eine vollständige anatomische und funktionelle Wiederherstellung des Kniegelenks sicherzustellen. Darüber hinaus spricht sie für eine frühzeitige VKB-Rekonstruktion mit begleitender Reparation der Menisken, um chronische Instabilität und vorzeitige degenerative Veränderungen zu verhindern.

# Abbreviations

| | |
|---|---|
| ACL | Anterior cruciate ligament |
| ACLISS | Anterior Cruciate Ligament Injury Severity Scale |
| BMI | Body mass index |
| LCL | Lateral collateral ligament |
| LMPHI | Lateral meniscus posterior horn instability |
| MCL | Medial collateral ligament |
| MMRL | Medial meniscus ramp lesion |
| MRI | Magnetic resonance imaging |
| OA | Osteoarthritis |
| PCA | Posterior femoral cortex angle |
| PCL | Posterior cruciate ligament |
| PLMRT | Posterolateral meniscus root tear |
| vs | Versus |

# Main body

# 1. Introduction

## 1.1. Knee joint

From an anatomical, kinematic, and mechanical perspective, the knee joint is one of the largest and the most complex joint in the human body. It is composed of the femorotibial joint, formed between the femoral condyles and the tibial plateau, and the femoropatellar joint, formed between the femoral trochlea and the posterior surface of the patella. It primarily functions as a hinge joint, allowing generally for flexion in the range of 120 to 150 degrees and extension from five to ten degrees [70]. Additionally, the knee permits rotational movement. Passive axial knee rotation shows approximately 45 degrees of external and 25 degrees of internal motion between 30 and 90 degrees of flexion, decreasing toward extension [225]. The knee joint must provide stability in the upright position and concurrently its mobility is crucial for balance on uneven surfaces and for locomotion. Therefore, the knee joint is subjected to significant biomechanical demands, which are managed by a complex system of static and dynamic stabilization mechanisms, including multiple ligaments, the menisci, the joint capsule, and dynamic muscular forces. These structures must withstand substantial forces across multiple planes of movement while maintaining both mobility and alignment [70, 118, 228]. Due to this complex interaction, the knee joint is highly susceptible to injury, with conditions such as ligament tears, meniscal damage, and osteoarthritis (OA) being prevalent in both athletes and the general population [3, 34, 47].

### 1.1.1. Knee joint capsule

The joint capsule consists of an outer fibrous layer and an inner synovial layer. The outer layer is composed of dense, circularly arranged collagen fibers, which contribute to the support and stabilization of the joint. The thickness of the capsule varies, being greatest at the bony attachment sites and thinnest in the central region, where it must stretch and accommodate movement. The synovial membrane is a thin, delicate tissue layer that lines the inner surface of the capsule. It produces the synovial fluid, which nourishes the joint structures and reduces wear, and contains blood vessels, lymphatics, and nerve endings that supply and innervate the joint [70, 168].

### 1.1.2. Medial collateral ligament

The medial collateral ligament (MCL) is a reinforced fibrous bundle of the medial joint capsule, connecting the medial femoral epicondyle to the medial tibial plateau. It has a superficial layer, that is taut during knee extension and resists valgus stress, and a deep layer, that becomes taut during tibial internal rotation constraining internal tibial rotation during extension and early flexion. The posterior portion of the MCL, along with the semimembranosus tendon, forms an additional posteromedial

reinforcement of the joint capsule, referred to as the **posterior oblique ligament**. It is most taut in extension and early flexion and reinforces valgus and rotational stability together with the semimembranosus expansions, which also anchor the capsule, the medial meniscus, and the tibia stabilizing the knee in the posteromedial direction [48, 116, 124].

### 1.1.3. Lateral collateral ligament

The lateral collateral ligament (LCL) connects the lateral femoral epicondyle to the fibular head. Unlike the MCL, the LCL does not attach to the joint capsule or the meniscus. It lies free and extra-articular, running deep to the tendon of the long head of the biceps femoris and superficial to the popliteus tendon. The LCL contributes to lateral stability of the knee in the extended position and is taut in full knee extension and during tibial internal rotation stabilizing the knee against varus stress and restraining external tibial rotation especially in extension and early flexion of the knee [136, 223]. Although the LCL functions independently of the joint capsule, it works in conjunction with other structures, including the popliteus tendon, the popliteofibular ligament, the tendon of the biceps femoris, and the iliotibial band, to reinforce the posterolateral aspect of the joint capsule. This complex is referred to as posterolateral corner [164].

### 1.1.4. Anterior and posterior cruciate ligament

The anterior cruciate ligament (ACL) and the posterior cruciate ligament (PCL) are the principal intra-articular stabilizers of the knee joint. Both reside within the joint cavity, interposed between the fibrous and synovial membranes, and are therefore intra-articular (intra-capsular) but extra-synovial [81]. The ACL originates from the anteromedial aspect of the tibial intercondylar area and inserts on the medial surface of the lateral femoral condyle within the intercondylar fossa. The fibers are organized into an anteromedial bundle, tensioned in internal tibial rotation, and a posterolateral bundle, tensioned in external rotation. Histologically, the ACL consists of dense bundles of predominantly type I collagen, interspersed with fibroblasts and enclosed by a synovial sheath [57]. Mechanoreceptors, such as Ruffini endings, Pacinian corpuscles, and free nerve endings, are concentrated particularly near the bony attachments, thus contributing to afferent proprioceptive feedback and dynamic joint stability [35, 107]. The ACL is primarily vascularized by branches of the middle genicular artery, which establish a periligamentous and endoligamentous vascular network. However, this supply does not exhibit a homogeneous distribution throughout the ligament substance [57]. Its primary mechanical role is to resist anterior tibial translation, with a secondary contribution to rotational stability [93, 140]. The PCL arises from the posterior intercondylar area of the tibial plateau and attaches to the central intercondylar fossa of the medial femoral condyle. Shorter and steeper than the ACL, the PCL resists posterior tibial translation. Similar to the ACL, the PCL consists of two collagen fiber bundles: the anterolateral bundle

is most taut in mid-range flexion, whereas the posteromedial bundle is tensioned in full extension and deep flexion [8, 122, 213].

### 1.1.5. Medial and lateral meniscus

The convex femoral condyles articulate medially with a concave tibial plateau and laterally with a flat or slightly convex tibial plateau. In the sagittal plane, the menisci are wedge-shaped and compensate this incongruity. The surface of the menisci facing the femur is concave, and the surface facing the tibia is flat. In the transversal plane, the menisci are C-shaped, with the medial meniscus displaying a more crescent-like configuration, whereas the lateral meniscus forms an almost complete ring (Figure 1a). In anatomical studies the medial meniscus covers between 51 and 74% of the medial tibial plateau and the lateral meniscus covers between 75 and 93% of the lateral tibial plateau [133]. A congenital anatomical variant is the discoid meniscus whereby the meniscus covers a larger proportion of the medial or lateral tibial plateau. A discoid meniscus occurs more frequently on the lateral side than on the medial side [212]. Both menisci are anchored to the tibial plateau through the anterior and posterior roots, where the fibers of the menisci extend into the tibial osseous structure. Further, they are interconnected by the anterior intermeniscal ligament (transverse ligament), the posterior intermeniscal ligament, and the medial and lateral oblique intermeniscal ligaments [133].

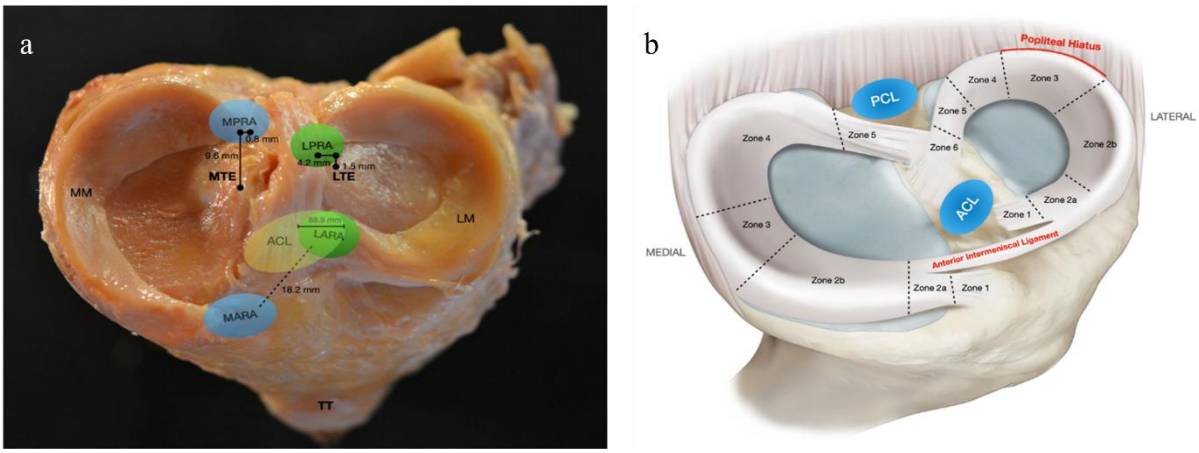


**Figure 1: Superior view of the medial and lateral meniscal (a) and meniscal zones with anatomical relations (b) (from Mameri et al. [133]; https://link.springer.com/article/10.1007/s12178-022-09768-1, published under Creative Commons CC BY Attribution 4.0 International License, https://creativecommons.org/licenses/by/4.0/).**

Abbreviations: ACL, anterior cruciate ligament; LARA, lateral anterior root attachment; LM, lateral meniscus; LPRA, lateral posterior root attachment; LTE, lateral tibial eminence; MARA, medial anterior root attachment; MM, medial meniscus; MPRA, medial posterior root attachment; MTE, medial tibial eminence; PCL, posterior cruciate ligament; TT, tibial tuberosity.

Both menisci increase the load-bearing contact area between the femur and the tibia and reduce tibiofemoral pressure, bearing approximately 80% of knee joint load. The roots and the various ligamentous connections prevent meniscal extrusion and create circumferential tension, while also

contributing to joint stability. Both menisci translate posteriorly during flexion to prevent femoral condyle overriding. The medial meniscus is less mobile than the lateral due to wider roots and further stronger attachments. The posterior horns are generally less mobile than anterior horns [160, 217].

Meniscal vascularization is provided by the superior and inferior medial and lateral genicular branches of the popliteal artery, forming a perimeniscal ring with radial branches penetrating the tissue. Only the peripheral third of the meniscus tissue is vascularized directly. The remaining tissue is supplied by perfusion which gradually decreases towards the inner margin. Vascularity of the peripheral meniscus diminishes with age, while the anterior and posterior horns remain relatively well supplied and are covered by a vascular synovial layer. The lateral meniscus exhibits a relatively avascular zone near the popliteal tendon. Innervation parallels vascularity: nerves accompany the vessels, decreasing from the periphery toward the center, with the horns more densely innervated than the pars intermedia [21, 50, 133].

#### 1.1.5.1. Medial meniscus

The medial meniscus can be divided into five zones (Figure 1b) based on anatomical characteristics [190]. The anteromedial root (zone 1) is located proximal and medial to the center of the superior edge of the tibial tuberosity, typically within the shallow intercondylar area of the tibial plateau. The anteromedial zone (zone 2) comprises the anterior horn of the medial meniscus and extends to the anterior margin of the MCL. At its peripheral edge, the meniscus is connected to the tibia via the narrow meniscotibial ligament. The anterior part of this zone (zone 2a, from the anterior root to the transverse ligament) has no additional attachments to surrounding tissue. The posterior part of this zone (zone 2b, from the transverse ligament to the anterior margin of the MCL) has a narrow attachment to the synovial tissue along its superior edge. In the medial zone (zone 3) the medial meniscus is connected to the joint capsule and the deep layer of the MCL. The meniscotibial ligament continues through the medial and posterior zones. In the posterior zone (zone 4), the ligament inserts approximately seven to ten millimeters below the articular cartilage, forming the posterior recess. This structure, known as the meniscal ramp, represents a continuation of the circumferential collagen fibers of the posterior horn of the medial meniscus, inserting into the subchondral bone of the posterior tibial plateau close to the joint surface. Arthroscopically, the meniscal ramp is covered by the joint capsule and the synovial membrane. The posterior root (zone 5) inserts posterior and lateral to the medial apex of the tibial eminence and anterior to the tibial attachment of the posterior cruciate ligament. No further connections to surrounding tissue are present in this zone [190, 226]. Due to its many connections to the surrounding tissue, the medial meniscus is an important secondary stabilizer of the knee joint.

#### 1.1.5.2. Lateral meniscus

The lateral meniscus can be divided into six zones (Figure 1b) based on anatomical characteristics. The anterior root of the lateral meniscus (zone 1) is located anteromedial to the lateral tibial eminence, beneath the tibial attachment of the ACL. The anterolateral zone (zone 2) comprises the anterior horn (zone 2a) and the pars intermedia (zone 2b) of the lateral meniscus until up to the border of the popliteal hiatus. Part of the lateral meniscus borders the popliteal hiatus (zone 3). Together with the popliteomeniscal fascicles, the meniscotibial ligaments, and the popliteus tendon, which crosses the region obliquely from distal-posterior to proximal-anterior, it defines the margins of the popliteal hiatus. The popliteomeniscal fascicles (zone 4) are meniscocapsular extensions that continue inferiorly into the musculotendinous portion of the popliteus, allowing the tendon to transition from intra- to extra-articular. The popliteofibular ligament extends from the medial popliteus tendon to the medial fibular styloid, forming, together with the lateral meniscotibial and popliteomeniscal ligaments, the recently described menisco-tibio-popliteo-fibular complex. A fiber band connecting the inferior edge of the posterior lateral meniscus to the fibular head, often referred to as the meniscofibular ligament (zone 5), is variably considered a reinforcement of the posterolateral portion of the lateral meniscotibial ligament. The posterior root (zone 6) of the lateral meniscus lies anterior to the posterior root of the medial meniscus and medial to the articular cartilage of the lateral tibial plateau. The posterior horn of the lateral meniscus is also linked to the lateral aspect of the medial femoral condyle and partially to the posterior cruciate ligament via two meniscofemoral ligaments. The anterior meniscofemoral ligament (Humphrey ligament) passes anterior to the PCL, while the posterior meniscofemoral ligament (Wrisberg ligament) runs posterior to it. Additionally, a lateral meniscotibial band, anterior to the anterior popliteomeniscal fascicle, and a posterior meniscotibial band, lateral to the posterolateral meniscus root, are distinguished. The posterior meniscotibial band connects the inferior edge of the posterolateral meniscus to the tibia and is reinforced by aponeurotic attachments of the popliteus muscle [133, 134, 161, 226].

The lateral meniscus posterior horn is part of the **posterolateral corner**, a densely interconnected anatomical and functional complex on the posterolateral side of the knee joint. It comprises several static and dynamic stabilizers that collectively resist varus opening, external tibial rotation, and posterior tibial translation. Its primary static stabilizers include the LCL, the popliteus tendon, and the popliteofibular ligament, which together form the structural core of the complex. Secondary stabilizing components, such as the arcuate ligament complex, the posterolateral joint capsule, and the fascial expansions from the biceps femoris tendon, the iliotibial band, and the lateral gastrocnemius, reinforce this architecture. The posterior horn of the lateral meniscus is intimately related to these structures through the popliteomeniscal fascicles and the popliteus tendon, providing an important biomechanical bridge between the meniscus and the posterolateral corner. This connection stabilizes the lateral meniscus

during knee flexion and rotation, contributing to the control of posterolateral rotatory stability [31, 40, 65, 114, 164].

## 1.2. Knee joint laxity

Laxity is an important clinical construct to assess ligamentous integrity and functional stability of the knee joint. Physiological laxity refers to the knee's natural range of movement [146]. Demographic and anatomical variables, including sex, limb alignment, body mass index (BMI), and neuromuscular control, modulate both static and dynamic laxity profiles [145, 154, 163, 171, 216]. Increased generalized ligamentous laxity predisposes individuals to knee joint injuries, particularly it increases the risk of an ACL rupture and can also affect postoperative outcomes following ACL reconstruction [204]. Among the most frequently used clinical tests for the evaluation of knee laxity in suspected ACL injury are the Lachman and pivot shift tests, which provide information regarding both static and dynamic knee stability. The **Lachman test** quantifies anterior tibial translation relative to the femur. The procedure is performed with the knee flexed to 20 to 30 degrees, maintaining the tibia in neutral rotation. The examiner stabilizes the distal femur with the non-dominant hand while applying an anteriorly directed force to the proximal tibia with the dominant hand. Anterior displacement is measured in millimeters, and the endpoint is classified as firm, delayed, or soft. Translation of less than five millimeters is classified as grade I, five to ten millimeters as grade II, and greater than ten millimeters as grade III. A missing translation is referred to as grade 0. Asymmetry relative to the contralateral knee, particularly when associated with a soft endpoint, is indicative of ACL injury [211]. The **pivot shift test** assesses dynamic rotational laxity of the knee. With the knee in extension, the examiner applies a valgus force to the tibia while maintaining the foot in forced internal rotation, followed by gradual knee flexion. In cases of ACL rupture, the tibia subluxates anteriorly and spontaneously reduces posteriorly between 20 and 30 degrees of flexion. This reduction is frequently accompanied by a palpable “clunk” or shift. Based on observation, instability is categorized into four grades: grade 0 corresponds to no subluxation, grade I to a slight slip or trace, grade II to distinct subluxation with reduction, and grade III to pronounced subluxation with reduction [77, 97, 189].

The Lachman test exhibits the highest sensitivity for the detection of an acute ACL ruptures, with a sensitivity and specificity of both 81% in awake patients. When performed under anesthesia, sensitivity increases to approximately 91%, with specificity of 78%. In contrast, the pivot shift test demonstrates lower sensitivity, detecting only approximately 28% of ruptures in awake individuals, but exhibits high specificity of 81%. Under anesthesia, its sensitivity increases to approximately 73%, while specificity rises to 98% [214]. However, further literature indicates that the diagnostic accuracy of the Lachman test may be overestimated [193]. Therefore, a comprehensive assessment incorporating multiple clinical examinations is recommended. In addition to manual testing, contemporary practice includes the use of instrumented laxity measurement devices, such as arthrometers, which provide objective and quantitative data to complement clinical evaluation. The combined use of instrumented and manual assessments affords a more robust and comprehensive evaluation of knee laxity [145, 146].

Laxity measurements, particularly the pivot shift phenomenon, are influenced by factors beyond ACL insufficiency. Although the precise origin and progression of a high-grade pivot shift test are not yet fully elucidated, current evidence points toward a multifactorial basis involving several anatomical structures. Among these, the menisci have been identified as potential secondary stabilizers contributing to the pivot shift response in ACL-deficient knees [17, 76, 128, 151, 194, 206].

## 1.3. Anterior cruciate ligament injury

ACL tears are common musculoskeletal injuries and are among the highest-studied in orthopaedic research. In recent decades, many countries established ACL injury registries to evaluate epidemiology, injury characteristics and treatment strategies to improve treatment standards and establish prevention programs. Further, there are numerous hospital-based registries and multi-centre study groups with specific reseach questions such as the *Multicenter Orthopedic Outcomes Network (MOON)*, the *Multicenter ACL Revision Study (MARS)* or the *Paediatric Anterior Cruciate Ligament Initiative (PAMI)* [59, 148, 149]. The annual incidence of ACL tears in the United States has been reported to be approximately 69 per 100,000 persons-years [172]. Similarly, an analysis of German inpatient data on ACL reconstruction procedures estimated an incidence of 46 per 100,000 person-years [56]. However, reported incidence rates of ACL injuries vary notably depending on the study population and associated risk factors. Consequently, it is not appropriate to generalize a single incidence estimate to the overall population. Of particular concern is the increasing incidence of ACL injuries and reconstructions among children and adolescents, a trend observed globally over the past decades [153, 180, 219]. Young patients, especially those returning to sport, also face a substantially high risk of sustaining either ipsilateral graft rupture or contralateral ACL injury [53, 158, 220]. In general, ACL injuries carry substantial long-term morbidity and represent a considerable individual and socioeconomic burden [9, 68, 92, 111]. The prevalence of knee OA after an ACL injury is up to 13% in isolated injuries and ranges from 21 to 43% in combined ACL and meniscal injuries more than ten years post-injury with meniscectomy as a major risk factor for the development of OA in this context [121, 135, 218].

Important risk-factors for an ACL injury include a combination of non-modifiable and modifiable factors. Recent evidence suggests a potential genetic predisposition [26]. Further, female sex as well as some anatomical factors, including a narrow intercondylar notch, a steep posterior tibial slope, and a reduced depth of the lateral femoral condyle, have been identified as non-modifiable risk factors. Partly modifiable risk factors include type of sport, particularly contact and pivoting sports, and level of competition [22, 29, 45, 85, 142, 143]. With regard to the underlying injury mechanisms of ACL rupture in sports, current evidence identifies four primary movement patterns: change of direction, landing, direct contact, and gear-related mechanisms. In team sports such as soccer, basketball, and handball, injuries predominantly occur during cutting or rapid changes of direction. Landing mechanisms are most common in jumping sports such as volleyball and badminton, whereas direct contact injuries are prevalent in combat and collision sports. Gear-related injuries, particularly in skiing, are often associated with equipment factors such as binding release failures [203]. The typical bone bruise in magnetic resonance imaging (MRI) of ACL injured knees is located posterior on the tibia and central on the femur

indicating that the tibia moved anteriorly relative to the femur, contacting the posterior tibia against the anterior femoral condyle at the moment of injury. The most common bone bruise pattern is located on the lateral side of both the femur and tibia, suggesting that lateral compression and valgus loading contribute as well. Consequently, a multiplanar loading mechanism involving knee abduction, anterior shear, and rotation causes high shear and tension in the ACL, producing rupture [182, 227]. Direct contact injuries result from external impacts, such as tackles or collisions, producing more variable and unpredictable loading patterns [49].

ACL rupture should be suspected in patients experiencing an adequate trauma, report a “pop” at the time of injury, and/or early hemarthrosis. Clinical diagnosis is mainly based on a combination of laxity tests including the Lachman test, the anterior drawer test, and the pivot shift test. Pain and swelling may complicate clinical assessment. The gold standard to verify an ACL injury is an MRI of the knee, even though it has inherent limitations in diagnostic sensitivity. It is further useful to detect associated meniscal or cartilage injuries [69, 193].

## 1.4. Meniscus injuries

Meniscus injuries represent structural damages of the meniscal tissue that compromise the functional integrity of the menisci to varying degrees. They can be isolated or occur in association with other injuries to the soft tissue of the knee joint, primary ligament ruptures [60, 61, 64, 169, 173]. Isolated meniscus tears are usually caused by indirect trauma. Mostly, this involves a rotational movement with a flexed knee under load, often during sporting activities. In the case of degenerative changes in the meniscal tissue also physiological movements, such as a simple knee bend, can cause a tear [18, 106]. In chronic ACL insufficiency, the medial meniscus is an important secondary stabilizer of the knee joint and therefore exposed to increased continuous stress, which can lead to secondary meniscus injuries [135, 169]. Injuries as well as complete or partial removal of the menisci significantly accelerates the degeneration of the knee joint cartilage and leads to earlier OA of the knee [108, 137]. Meniscus injuries can be classified according to their etiology, anatomical location, morphological type, and stability. These classifications are useful clinically, when deciding on the appropriate treatment procedure, and scientifically, to evaluate studies. Two consensus papers published by the *European Society of Sports Traumatology, Knee Surgery and Arthroscopy (ESSKA)* can be considered the current reference standard for classification, offering a comprehensive synthesis of these aspects [18, 106]. Based on etiology, the term “meniscal tear” should be used for a traumatic injury of the meniscal tissue associated with a sudden onset of pain. The term “meniscal lesion” refers to degenerative changes of the meniscal tissue which are characterized by a slow onset of pain and no history of acute trauma [18, 106]. In terms of anatomical location, the originally by Cooper et al. introduced classification into circumferential and radial zones is the most common one [39]. A modified version of this classification is also included in the *European Society of Sports Traumatology, Knee Surgery and Arthroscopy (ESSKA)* consensus on traumatic meniscus tears. In addition to the aforementioned zones, it considers the meniscal roots and the medial meniscus ramp as specific localizations (Figure 2) [106].

Morphological types are distinguished as radial, vertical or horizontal flap and bucket handle tears. When a meniscus injury comprises several of these morphological types it is often referred to as complex tear. Due to the specific anatomy, injuries to the medial meniscus ramp and the meniscal roots should be considered separately, even though they may contain components of the classic tear types. For these injuries specific classifications have been published [72, 112, 209, 210]. A stable tear does not extend into the joint and cannot be displaced under palpation, or at most only to the inner edge of an intact meniscus. In the case of an unstable tear, the central portion of the torn meniscus can be displaced into the joint. This can lead to impingement between other structures of the knee joint. Radial tears and bucket-handle tears are generally considered unstable [106].

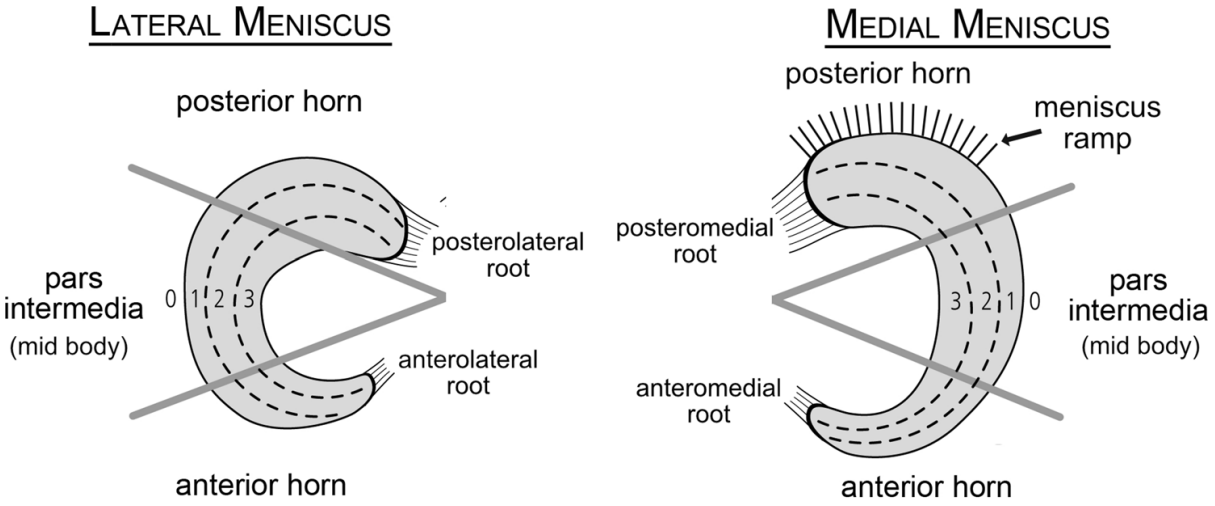


**Figure 2: Classification of meniscus injuries according to location proposed by the consensus of the *European Society of Sports Traumatology, Knee Surgery and Arthroscopy (ESSKA)* (from Kopf et al. [106]; https://link.springer.com/article/10.1007/s00167-020-05847-3, published under Creative Commons CC BY Attribution 4.0 International License, https://creativecommons.org/licenses/by/4.0/).**

The reported incidence of meniscal injuries varies substantially depending on the study population under consideration. Therefore, providing a single incidence value for the general population is not appropriate. Numerous studies have assessed meniscal injury rates stratified by tear location and morphology, their association with concomitant injuries, particularly ACL rupture, and within specific cohorts [85, 100, 166]. Similarly, risk factors for meniscal injuries have been examined from multiple perspectives. Inter alia, patient characteristics such as age, sex and BMI, sporting activity, and anatomical characteristics such as limb alignment, tibial plateau morphology and general laxity have all been identified as relevant contributors [2].

Meniscus surgery has undergone a profound paradigm shift over the past decades. For many years, meniscectomies were considered the standard treatment for meniscal injuries. Nowadays, the guiding principle has become “save the meniscus”, emphasizing the preservation of as much functional meniscal tissue as possible [1, 156, 175]. In recent decades, scientific and clinical attention has increasingly focused on acute injuries of the posterior compartment. Injuries of the medial meniscus ramp and the posterolateral meniscus root have become a particular focus in patients with ACL insufficiency [28, 63]. In contrast to a posterolateral meniscus root tear (PLMRT), a posteromedial root tear is likely to have a degenerative origin, occurring more frequently in patients over 50 years of age and associated with obesity and varus leg axis [14, 106].

### 1.4.1. Medial meniscus ramp lesion

As described before, the medial meniscus ramp is the fan-shaped meniscocapsular attachment of the medial meniscus posterior horn to the posterior tibial plateau, located just below the joint line. It is covered by the joint capsule and synovial membrane, making arthroscopic visualization difficult [190].

Therefore, a medial meniscus ramp lesion (MMRL) is also often referred to as “hidden lesion” [197]. Since their first description by Hamberg in 1984 [88], MMRLs have received increasing attention. Their prevalence in ACL-injured knees has been evaluated between eight and 42% [12, 28]. MMRLs are strongly associated with younger age and complete ACL tears. Male sex and concomitant lateral meniscal tears confer a moderate increase in risk, whereas chronicity of ACL injury shows only a weak association [110]. The mechanisms behind these injuries are not well understood, but they have been associated with the intensity of knee trauma [178]. Given diagnostic limitations and the ongoing evolution in understanding and classification of a MMRL, the true incidence has likely been underestimated [177]. MRI, although a standard imaging tool, has limited sensitivity for detecting these specific meniscal lesions [105]. Direct MRI signs for a MMRL include high-signal irregularities along the capsular margin or disruption of the meniscocapsular junction of the posterior horn of the medial meniscus in sagittal views [89]. Indirect signs include bone marrow edema of the posteromedial tibial rim and the presence of a Segond fracture, a characteristic avulsion injury of the lateral proximal tibia strongly associated with ACL tears [20, 42]. Therefore, arthroscopy remains the gold standard for diagnosis. Especially in ACL-deficient knees, the posteromedial compartment must be inspected thoroughly. Visualization begins through an anterior arthroscopy portal. If the medial meniscus posterior horn can be luxated beyond the equator of the tibial plateau under probing, a ramp lesion should be suspected. The Gillquist maneuver allows partial posterior visualization [106], but complete inspection often requires creation of a posteromedial arthroscopy portal [177]. Thaunat et al. proposed an arthroscopic classification of MMRLs based on their anatomical location and structural stability, providing a structured approach for different treatment strategies [209, 210]. The meniscal ramp is well vascularized and thus demonstrates a favorable healing potential [190]. The objective of treatment is to restore the meniscocapsular continuity and fixation of the meniscus to the posterior tibial plateau. Arthroscopic repair is technically demanding and typically performed through a posterior approach, possibly using a double-portal technique. In cases where the lesion extends to the pars intermedia of the meniscus, combined repair using “all-inside” or “outside-in” sutures may be necessary [41, 177, 185]. Although some authors have discussed possible spontaneous healing in very peripheral lesions, biomechanical and cadaveric studies generally support surgical repair for improved outcomes [7, 13, 90, 119]. A MMRL contributes significantly to knee instability in the context of ACL injury. In vitro studies have demonstrated their effect on increased anteroposterior laxity [6, 55, 159, 201].

### 1.4.2. Posterolateral meniscus root tear

Root tears generally involve injuries of the meniscotibial insertion or radial tears within one centimeter of the meniscotibial insertion site [157]. PLMRTs were first described by Ahn et al. in 2006 [4]. The reported prevalence of PLMRTs in ACL-injured knees ranges from seven to 15% [62, 165]. In contrast to posteromedial meniscus root tears, PLMRTs are usually acute and frequently associated with ACL

ruptures [14, 106]. They are more likely to occur in younger patients, males, those with higher BMI, increased lateral posterior tibial slope, or in presence of concomitant medial meniscal tears. Additionally, injury mechanisms involving contact sports further elevate the risk of these tears [165, 222]. During the anterior tibial subluxation that occurs in an ACL injury, the lateral meniscus and its posterior root are compressed between the femoral and tibial condyles, placing considerable strain on the meniscal tissue and root fibers. The resulting shear forces can lead to a PLMRT [72]. MRI diagnosis of PLMRTs can be challenging. Direct and indirect MRI signs described for posteromedial meniscus root tears, such as the "ghost sign" (absence of the posterior horn in the sagittal plane), the "truncation sign" (vertical defect line in the coronal plane), radial defect lines in the axial plane, meniscal extrusion, and the presence of osteonecrosis, are often less evident in the lateral compartment [14]. Therefore, during arthroscopy, the posterolateral compartment must be thoroughly inspected. Posterior horn stability should be assessed irrespective of the presence of an obvious lesion. Given the potential for additional posterolateral corner injuries, direct visualization through a posterior arthroscopic portal should be considered, particularly in case of a PLMRT [4]. Forkel et al. proposed an arthroscopic classification system for PLMRTs, from which different repair techniques can be derived [71, 72]. The meniscal roots are well vascularized across their entire width, conferring favorable healing potential [226]. In avulsion injuries, the meniscal root is arthroscopically reattached to restore its anatomical position. This is most commonly achieved using transosseous sutures passed through bone tunnels and secured over the tibial cortex, while fixation with a bone anchor represents another viable option. Radial tears close to the insertion area may also be repaired using "all-inside" suture devices [14, 71]. Repair of PLMRTs in ACL-injured knees leads to improved clinical and functional outcomes [5, 4, 63]. Further, it reduces the risk of OA and yields high patient satisfaction compared with meniscectomy or conservative treatment [15]. Posterolateral meniscus root repair or refixation is almost always indicated due to the significant biomechanical impact of its injuries. They compromise the biomechanical function of the meniscus, producing effects comparable to those observed after a complete meniscectomy [157]. Biomechanical cadaver studies in ACL-deficient knees have demonstrated that PLMRTs cause an increased tibial translation and internal rotation at various degrees of knee flexion [58, 73, 74, 123, 138, 184].

### 1.4.3. Lateral meniscus posterior horn instability

Lateral meniscus posterior horn instability (LMPHI) is defined as abnormal mobility of the lateral meniscus posterior horn, typically assessed arthroscopically with a probe. It is considered hypermobile respectively unstable when the lateral meniscus posterior horn can be displaced over the equator of the lateral femoral condyle or up to half its width anteriorly [183]. The hypermobile lateral meniscus posterior horn was first described by Simonian et al. in 1997, who reported arthroscopic evidence of lateral meniscal subluxation associated with disruption of the popliteomeniscal fascicles [188]. The

condition was further defined by George and Wall in 2003, who demonstrated MRI and arthroscopic confirmation of posterior horn hypermobility in a non-discoid lateral meniscus [78]. LMPHI may result from an insufficiency of the posterolateral suspensory complex of the lateral meniscus posterior horn, including the popliteomeniscal fascicles, the posterolateral meniscus root, and the meniscofemoral ligaments (Humphrey and Wrisberg), which contribute to the active and passive stability of the knee [74, 101, 102, 115, 183, 184, 199, 215]. Injury mechanisms may be traumatic, involving rotational or hyperflexion forces, or atraumatic due to congenital absence of stabilizing structures [82, 144]. It can be isolated or occur in association with an ACL or a posterolateral corner injury [19, 63, 83, 196, 199]. Preoperative assessment of injuries to the posterolateral suspensory complex is challenging due to the intricate anatomy difficult to assess on MRI and the lack of consistent clinical findings [109, 113, 187]. It may manifest clinically as lateral knee pain, recurrent locking sensations, or subtle rotational instability [63, 123, 131, 184, 196, 199]. The diagnosis of a LMPHI relies primarily on arthroscopic evaluation. There is currently no evidence guiding treatment for LMPHI. Posterolateral meniscus root tears should be arthroscopically refixed as described before. Repair techniques for popliteomeniscal complex lesions have been described using suture anchors or “outside-in” sutures through an anterolateral portal with visualization from an anteromedial portal [117].

## 1.5. Aim of the thesis

This thesis provides a compilation of studies on ACL-associated meniscus injuries diagnosed prior to ACL reconstruction. The general purpose of this thesis is to increase the knowledge about intra-articular soft tissue damage in ACL-injured patients with specific focus on meniscal injuries and their association with knee joint laxity expressed by the Lachman or pivot shift tests. In particular, this work includes more recently described injuries of the meniscus posterior horns, such as a MMRL and a PLMRT, as well as the LMPHI as manifestation of complex injuries to the suspensory mechanism of the lateral meniscus posterior horn. The aim of this work is to show the importance of a standardized and comprehensive arthroscopic diagnosis of meniscus injuries in ACL-injured patients, including injuries to the meniscal posterior horns, in order to allow complete restoration of the anatomical knee structure and prevent re-injury or premature degenerative changes in the knee joint.

The specific research questions and hypothesis in the respective studies were as follows:

1. Is the presence of a MMRL in an ACL-injured patient associated with increased knee laxity, as measured by the Lachman and pivot shift tests? MMRLs are expected to be more frequently associated with grade III laxity in clinical testing compared to knees without a MMRL.

2. What are the meniscus tear patterns in ACL-injured patients undergoing primary and revision ACL reconstruction, taking into account injuries of the medial meniscus ramp and the posterolateral meniscus root, and are these patterns associated with patient and injury characteristics? It was expected that a substantial proportion of patients would present with a MMRL and/or PLMRT, and that these lesions would be associated with specific patient and injury characteristics.

3. Is the preoperative degree of pivot shift test associated with patient- and injury-related characteristics in primary ACL-injured patients, specifically investigating the presence of a MMRL or a PLMRT as well as a LMPHI during diagnostic arthroscopy? It was expected that a preoperative grade III pivot shift would be linked to the extent of intra-articular soft tissue damage, as reflected by the type of ACL tear and meniscal injuries, and by the chronicity of the ACL rupture.

4. How can aspiration during knee arthroscopy help in diagnosing a LMPHI? This study aimed to enhance the arthroscopic detection of a LMPHI by introducing a novel screening method, called the “aspiration test”.

5. Can the arthroscopic “aspiration test” improve the diagnosis of a LMPHI in patients undergoing primary ACL reconstruction compared to conventional arthroscopic probing? LMPHIs were expected to occur frequently in ACL-injured patients and to be underestimated by current arthroscopic techniques.

The discussion of this thesis situates the preceding individual studies within a broader context and explores future perspectives on ACL-associated injuries.

# 2. Exposition of original publications

## 2.1. Ramp lesions of the medial meniscus are associated with a higher grade of dynamic rotatory laxity in ACL-injured patients in comparison to patients with an isolated injury

Despite the high prevalence of MMRLs in knees with an ACL injury, their clinical significance has not yet been fully established. Cadaver studies show that simulating a MMRL in ACL-deficient knees increases anterior tibial translation as well as rotational laxity during pivot shift testing [55, 200]. In a small clinical series, MMRLs were also linked to mild anteromedial rotatory subluxation [25], but these findings have not been validated in larger patient cohorts, leaving their effect on knee laxity uncertain.

The purpose of this study was to determine whether the presence of a MMRL in patients with ACL injury was associated with a higher grade of knee laxity at the Lachman and pivot shift tests. The hypothesis was that MMRLs were more often associated with a grade III laxity in the Lachman and the pivot shift tests compared to patients with no ramp lesion.

Data from 275 cases of primary ACL reconstruction surgeries performed by a single experienced surgeon were extracted from a center-based ACL injury registry. Patients were asked to fill in a standardized questionnaire, providing personal data (date of birth, sex, height and weight), previous ipsilateral ACL reconstruction surgery and the circumstances of the ACL injury (date of injury, sport at injury and contact with another person during injury). Before surgery Lachman and pivot shift tests were performed under anaesthesia. Arthroscopy was performed systematically including a thorough examination for MMRLs and PLMRTs. Starting with visualization through an anterior portal, the medial meniscus ramp was further assessed via percutaneous palpation using a 21-gauge needle through a posteromedial approach. In cases where a MMRL was suspected, direct arthroscopic inspection was performed through a posteromedial portal [80, 197]. A standardized report of surgery was completed by the operating team. The primary outcome of this study was the presence or absence of a ramp lesion of the medial meniscus at the time of ACL reconstruction. Additional medial or lateral meniscus tears and concomitant ligament injuries were also documented and only cases without meniscal or other ligament involvement were classified as isolated ACL injuries. For analysis, the Lachman and pivot shift tests were considered, with grade III compared to grades 0 to II. Statistical analysis were performed with two groups in three different steps as shown in Figure 3. For the first step, sex distribution was analyzed using chi-square tests, while age at surgery, BMI, and time from injury to surgery were compared with either Student’s t-tests or Mann–Whitney tests, depending on normality of data. For all three steps, chi-square tests were further used to compare Lachman and pivot shift grades between groups.

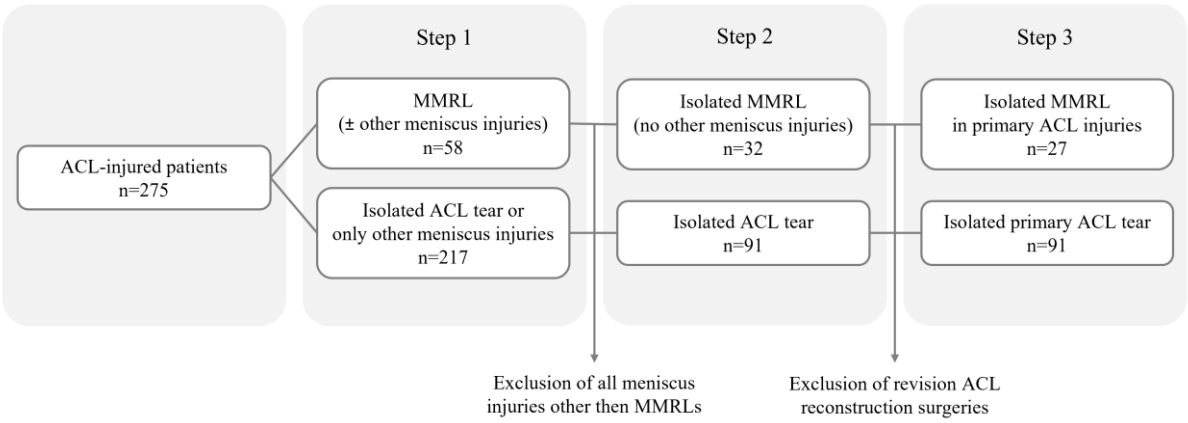


**Figure 3: Overview of the steps for statistical analysis in "Ramp lesions of the medial meniscus are associated with a higher grade of dynamic rotatory laxity in ACL-injured patients in comparison to patients with an isolated injury".**

Abbreviations: ACL, anterior cruciate ligament; MMRL, medial meniscus ramp lesion.

In terms of patient and injury characteristics, the only significant difference between groups was a higher proportion of men with a MMRL than females (25% versus (vs) 15%; $p<0.05$). Overall, no differences were observed between groups for the Lachman test in all three steps. In step 2, a grade III pivot shift was more frequently observed in the group with a MMRL compared to the control group (47% vs 24%; $p<0.05$). In step 3, the difference in the proportion of patients with a grade III pivot shift between the two groups remained significant (44% vs 25%; $p=0.05$).

The findings of this study suggest that a MMRL has an impact on dynamic rotational knee joint laxity as expressed by the pivot shift test and support the assumption that the medial meniscus ramp acts as an important secondary restraint in ACL-injured patients. However, the pivot shift is affected by various factors, including the presence of medial meniscal injury regardless of tear type, as well as age, sex, generalized ligamentous laxity, time from injury to surgery, and anatomical variables such as bony morphology, soft tissue structures, and cartilage degeneration or OA [37, 128, 150, 195, 206]. Although nearly half of patients with a MMRL exhibited a grade III pivot shift, the pivot shift test alone is insufficiently reliable for diagnosis, and the low sensitivity and positive predictive value of MRI further restrict pre-arthroscopic identification [54, 89, 132]. Still, the results indicate how important the repair of a MMRL during ACL reconstruction surgery may be to help avoid residual laxity.

## 2.2. Medial meniscus ramp and lateral meniscus posterior root lesions are present in more than a third of primary and revision ACL reconstructions

Reporting meniscus tear patterns in ACL-injured patients remains challenging, as there is no standardized approach for diagnosing meniscus injuries, especially those located on the meniscal posterior horns [4, 197]. Prentice et al. compared six ACL injury registries and demonstrated that the reported prevalence of meniscal injuries in primary ACL reconstructions varied widely across countries [166]. The sensitivity for diagnosing a MMRL or a PLMRT on preoperative imaging is not fully reliable [86, 109]. Therefore, identifying potential risk factors for those injuries is crucial to guide the surgeon's attention to the posterior horns during arthroscopy. Meniscus tear types in ACL-injured patients, especially MMRL and PLMRT, are frequently evaluated separately, thereby restricting the possibility to comprehensively characterize meniscal pathologies in a more general cohort.

The purpose of this study was to identify the meniscus tear pattern in a series of ACL-injured knees during primary and revision ACL reconstruction, with a special focus on MMRLs and PLMRTs and to determine whether patient and injury characteristics were associated with meniscus tear patterns. The main hypotheses were that a significant number of patients would display a MMRL and/or a PLMRT, and that these meniscal lesions would be associated with specific patient and injury characteristics.

Data from 358 cases of primary and revision ACL reconstruction surgeries performed by a single experienced surgeon were extracted from a center-based ACL injury registry. As described above for the previous study, data collection included a standardized patient questionnaire and systematic arthroscopic evaluation including MMRLs and PLMRTs, with all findings documented in a standardized surgical report. Sport at injury was classified into three levels according to Grindem et al., pursuant to the proportion of jumping, pivoting and hard cutting [87]. For this study, posteromedial or anterolateral bundle conservations and elongations of the ACL were classified as partial tears. Graft ruptures were always assigned as complete tears. ACL injuries were classified as isolated when no associated meniscal injury was described. Other associated injuries such as additional ligament injuries or cartilage damage were not considered in the present study. Statistical analysis were performed in two steps as shown in Figure 4. The first step considered the location of any type of meniscal tear on the medial meniscus, the lateral meniscus or both menisci. In the second step, a distinction was made according to the type of injury, whereby the presence of a MMRL and/or a PLMRT were decisive for the allocation, independent of other concomitant meniscus injuries. Chi-square tests with Bonferroni correction were used to determine whether the groups in both steps differed with respect to various patient and injury characteristics, including sex, previous ipsilateral ACL injury, the injury's relation to sport, person

contact during injury and the type of ACL tear. Age at surgery and BMI as continuous variables were compared between groups using the Kruskal-Wallis test.

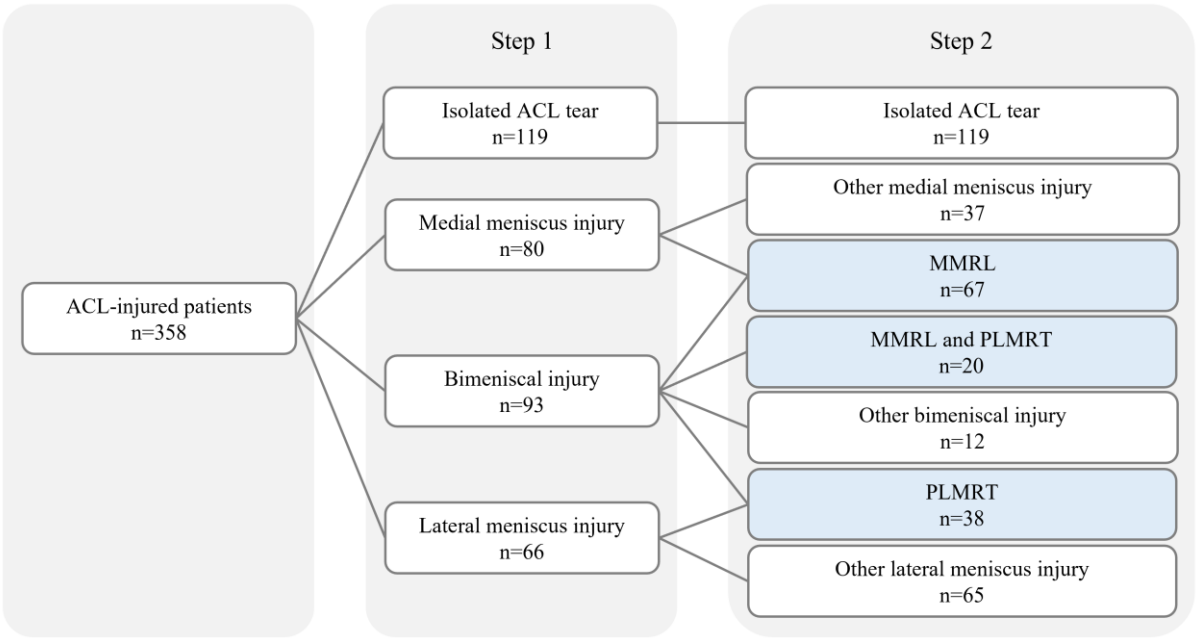


**Figure 4: Overview of the steps for statistical analysis in "Medial meniscus ramp and lateral meniscus posterior root lesions are present in more than a third of primary and revision ACL reconstructions". In step 2, the decisive injury types (MMRL and PLMRT) are highlighted in light blue.**

Abbreviations: ACL, anterior cruciate ligament; MMRL, medial meniscus ramp lesion; PLMRT, posterolateral meniscus root tear.

Two hundred and thirty-nine knees (67%) revealed ACL-associated meniscal injuries and 119 cases (33%) showed an isolated ACL injury. Thirty-three percent (n=80) of meniscus injuries involved the medial meniscus, while 39% (n=93) involved the lateral meniscus and 28% (n=66) of patients had a bimeniscal injuries. Sex, age at surgery, BMI, sport at injury and type of ACL tear significantly differed between these meniscal patterns. Of all ACL-injured patients with concomitant meniscus injury, 125 patients (52%) displayed a MMRL and/or a PLMRT. Twenty-eight percent (n=67) of patients with ACL-associated injury involved the medial meniscus ramp, 16% (n=38) involved the posterolateral meniscus root and in eight percent (n=20) both structures were injured. Sex, age at surgery, mechanism of injury and type of ACL tear significantly differed between groups. Although no characteristic was found to be associated with a PLMRT, a MMRL was especially frequent in male patients (23% vs 12% in females; $p<0.01$), injuries during contact with another person (28% vs 16% in non-contact; $p<0.05$) and in complete ACL tears (21% vs 5% in partial; $p<0.05$). Injuries affecting both the medial meniscus ramp and the posterolateral meniscus root showed a higher percentage of contact injuries compared to non-contact injuries (10% vs 4%; $p<0.05$).

Approximately two thirds of all ACL injuries were associated with concomitant meniscus injury confirming the frequent association of ACL injuries with meniscal tears [27, 36, 127, 197] and half of the cases with ACL-associated meniscus injury involved the biomechanically relevant injuries of the medial meniscus ramp and the posterolateral meniscus root [138, 147]. This indicates that when not looking specifically for these posterior horn injuries a relevant number of meniscus injuries remains unrecognized. A systematic repair to properly restore knee anatomy should be considered. MMRL were more prevalent in male patients, contact injuries, and complete ACL ruptures, underscoring the need for systematic evaluation and improved understanding of their pathomechanisms due to their potential impact on knee biomechanics and ACL reconstruction outcomes.

## 2.3. Grade III pivot shift as an early sign of knee decompensation in chronic ACL-injured knees with bimeniscal tears

The pivot shift test is a common clinical sign indicating rotational knee instability in ACL-injured patients. High-grade pivot shift, both pre- and postoperatively, has been linked to poor functional outcomes and risk of revision surgery [10, 129, 216]. Identifying the causes of a high-grade pivot shift is therefore critical for the therapeutic process. The origin is discussed to be multifactorial, with MMRLs and PLMRTs being among the ACL-associated injuries identified as relevant contributors [76, 128, 141, 147, 151, 191, 196, 206]. As described above, these injuries occur frequently in ACL-injured patients [130]. However, the overall impact of meniscal injuries, including these more recently described injury types, on the pivot shift test remains unclear. Likewise, little is known about the evolution of the pivot shift over time, although the amount of medial meniscus injuries is known to increase with time from injury to ACL reconstruction surgery, potentially aggravating rotational laxity [33, 135].

The purpose of this study was to evaluate the relationship between the preoperative pivot shift test as well as patient and injury characteristics in a series of ACL-injured patients, considering specifically more recently described injuries of the meniscal posterior horns. The hypothesis was that a preoperative grade III pivot shift test was associated with the magnitude of intra-articular soft tissue damage, expressed by the type of ACL injury and meniscus damage, and with chronicity of the ACL injury.

Data from 376 cases of primary ACL reconstruction surgeries performed by a single experienced surgeon were extracted from a center-based ACL injury registry. As in the two preceding studies, data collection included a standardized patient questionnaire and systematic arthroscopic evaluation including specific assessment for a MMRL, a PLMRT and further also a LMPHI, with all findings documented in a standardized surgical report. The time from injury to surgery was categorized as six months or less for acute ACL injuries and more than six months for chronic ACL injuries. The pivot shift test was performed under anesthesia before ACL reconstruction surgery and for analysis a grade III pivot shift test was rated as high-grade, while the grades 0-II were referred to as low-grade. Intra-articular soft tissue damage was classified in four groups with an increasing amount of damaged structures:

1. Partial ACL tear (isolated anteromedial or posterolateral bundle injury or ACL elongation),
2. Complete isolated ACL tear (no meniscus tears),
3. Complete ACL tear with one meniscus injury (either a medial or a lateral meniscus tear), and
4. Complete ACL tear with bimeniscal injury.

Other associated injuries such as additional ligament injuries or cartilage damage were not considered in the present study. Chi-square tests with Bonferroni correction were used to determine whether the pivot shift grading was associated with sex, sport at injury, mechanism of injury, time from injury to surgery or intra-articular soft tissue damage. Age at surgery and BMI were used as continuous variables and the Mann-Whitney-U test was performed to compare pivot shift grading. Given the suggested importance of time from injury to surgery for ACL-associated injuries, additional analyses were performed in two subgroups: patients with acute injuries treated within six months and those with chronic injuries treated after more than six months. Chi-square tests with Bonferroni correction were applied to assess differences in the extent of intra-articular soft tissue damage between the two groups, and the association between the pivot shift grading and intra-articular damage within each subgroup.

There were 44 cases of partial ACL tear (11%), 89 cases of complete isolated ACL tear (24%), 154 cases of complete ACL tear with one meniscus injury (41%), and 89 cases of complete ACL tear with bimeniscal injury (24%). A high-grade pivot shift was observed in 98 patients (26%). A significant association with pivot shift grading was shown for age, time from injury to surgery and intra-articular soft tissue damage ($p<0.05$; Figure 5a). Further analyses showed that high-grade pivot shift was associated with intra-articular soft tissue damage in chronic injuries only ($p<0.01$; Figure 5b). Patients with a chronic complete ACL tear with bimeniscal injury were 3.3 times more likely (95% confidence interval 1.3-8.2) to have a high-grade pivot shift in preoperative testing than patients with acute complete ACL tear with bimeniscal injury.

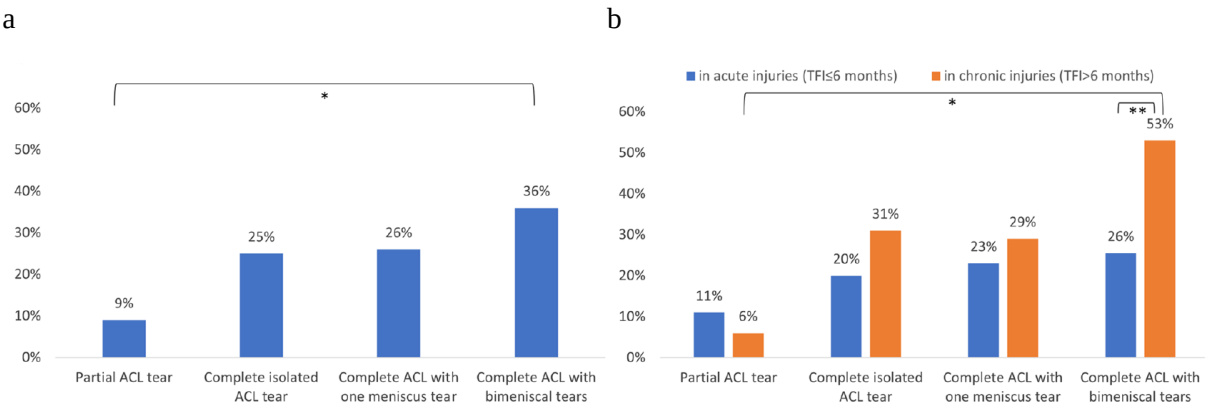


**Figure 5: Percentage of preoperative grade III pivot shift test for classification of intra-articular soft tissue damage in the total cohort (a) and the sub-groups of acute and chronic ACL injuries (b) (from Magosch et al. [131]).**

Abbreviations: *p<0.05; **p<0.01; ACL, anterior cruciate ligament; TFI, time from injury.

In primary ACL-injured patients, a preoperative high-grade pivot shift test was mainly associated with a higher amount of intra-articular soft tissue damage and chronicity of the injury. The classification of structural soft tissue damage, ranging from partial ACL tears to complete ruptures with bimeniscal involvement, was based on the assumption that its extent reflects the energy of the initial trauma, thus

representing a trauma cascade [162]. Complete ACL ruptures are known to require higher injury forces than partial tears [38, 51, 52], and similar associations have been described for meniscal tears [32]. In the acute phase of ACL injury, dynamic rotational laxity as expressed by the pivot shift test may be limited but can progressively develop over time, particularly in chronic cases [75, 167]. Its manifestation may represent an early sign of knee decompensation, potentially reflecting irreversible damage to secondary stabilizers. This highlights the importance of considering both intra-articular soft tissue damage and the chronicity of an ACL injury in the decision-making process and supporting the need for timely diagnosis and treatment.

## 2.4. The aspiration test: an arthroscopic sign of lateral meniscus posterior horn instability

Under arthroscopy, a hypermobility of the lateral meniscus posterior horn was described as an extrusion of more than half of the lateral meniscus beyond the equator of the lateral femoral condyle when traction was applied with a probe [183]. It has been reported that no abnormal preoperative MRI findings could be identified in patients with surgically confirmed LMPHI, likely because MRI, as a static assessment, cannot capture instability that appears only during knee motion [187]. Recent studies have shown that LMPHI may contribute to rotational instability of the knee, highlighting the need for a reliable diagnostic method to enable complete anatomical repair when indicated [123, 184, 196].

The purpose of this report was to further improve the arthroscopic diagnostic reliability of a LMPHI introducing a new arthroscopic screening test called the “aspiration test”.

Currently two arthroscopic techniques are used to assess the stability of the posterior horn of the lateral meniscus, each offering complementary information. The lateral drive-through sign involves advancing the arthroscope through the lateral gutter to visualize the popliteus hiatus, the posterior tibia, and the associated ligamentous structures, but it is technically challenging, highly dependent on surgical skill, and lacks standardized reproducibility. The anterior arthroscopic inspection with probing, performed with the knee in a figure-of-four position, allows direct visualization of the lateral meniscus posterior root and the meniscofemoral ligaments, but has limitations in assessing the popliteomeniscal fascicles and quantifying LMPHI, particularly in narrow knees or incomplete root tears with elongation of the fibers. The “aspiration test” is an additional method to evaluate LMPHI. It is performed with the knee in a figure-of-four position, flexed slightly beyond 90 degrees, using an arthroscope placed through the anterolateral or anteromedial portal directed toward the lateral tibiofemoral compartment. A shaver is positioned at the center of the compartment, and when full aspiration is turned on an anterior translation of the lateral meniscus posterior horn indicates instability. The exact position of the shaver and the specific region of the posterior horn exhibiting excessive translation can be used to infer the underlying structural injuries. Care must be taken not to restrict movement with the shaver or the arthroscope to ensure accurate assessment. Following stabilization of the lateral meniscus posterior horn, the “aspiration test” can be repeated to confirm restoration.

The “aspiration test” provides a new method for identifying a LMPHI. Compared to probing, it exerts a standardized, surgeon-independent traction force evenly across the lateral meniscus posterior horn. In the context of an ACL injury, combined anterior tibial translation and external rotation drive the posterolateral tibial plateau against the lateral femoral condyle, resulting in typical bone bruise or

impression [72, 91]. This mechanism also causes distinct shear forces on the suspensory complex of the lateral meniscus posterior horn, which may result in further injuries thereof. The comparatively high prevalence of tibial (69%) and femoral (31%) bone bruises in ACL-injured knees, relative to the lower prevalence of PLMRT (17%), suggests that a substantial number of these injuries of the suspensory complex of the posterior horn of the lateral meniscus remain undetected [130, 227]. The LMPHI may result from these injuries. The posterolateral meniscus root as well as the different structures of the suspensory complex of the lateral meniscus posterior horn have a biomechanical influence on knee stability that remains incompletely understood to date. While root tears alone may cause limited displacement, combined injuries involving the meniscofemoral ligament can substantially increase meniscal mobility under load [16, 187, 202].

## 2.5. The aspiration test reveals an instability of the posterior horn of the lateral meniscus in almost one-third of ACL-injured patients

Given the recognized contribution of the lateral meniscus posterior horn and its suspensory complex to knee stability, it is important to further investigate this entity [83, 123, 184, 196]. Injuries of this complex may result in a LMPHI. While some meniscal injuries can be diagnosed on MRI or during arthroscopy, the diagnosis of a LMPHI itself remains challenging due to the lack of validated clinical examination techniques and specific imaging criteria [187]. Consequently, LMPHI may frequently be underdiagnosed. As outlined before, the "aspiration test" has been proposed as an alternative to the conventional probing to improve intraoperative detection of a LMPHI [95]. However, its diagnostic utility has not yet been confirmed by clinical evidence.

The purpose of this study was to compare the ability of the conventional probing and the "aspiration test" to identify LMPHI between patients undergoing ACL reconstruction. The hypotheses were that LMPHI was frequently associated with ACL injuries and underestimated with current arthroscopic methods.

This multi-center case-control study included two groups: an ACL group consisting of 103 patients undergoing primary ACL reconstruction, and a control group with 29 patients undergoing knee arthroscopy for other reasons than ACL injury. An important exclusion criterion was any kind of lateral meniscus injury in the control group and a lateral meniscus injury other than a PLMRT in the ACL group. Arthroscopic evaluation was standardized and performed by three experienced surgeons. In case of a PLMRT, the injury was classified in type I to III according to Forkel et al., with an addendum being an elongation of the posterolateral meniscus root fibers and defined as type IV [72]. This type corresponds to an elongation of the root fibers. Both, the probing test and the previously described "aspiration test", were performed to assess LMPHI, defining a translation over 50% beyond the equator of the lateral femoral condyle as positive result. The McNemar test was applied to compare the outcomes of the probing test and the "aspiration test", and the kappa coefficient was reported to assess the level of agreement between them. Chi-square tests with Bonferroni correction were conducted to evaluate whether a positive result in the aspiration or probing test was associated with the arthroscopically determined status of the lateral meniscus (no visible tear, PLMRT type I to IV).

In the control group probing and the "aspiration test" were negative and the lateral meniscus appeared normal in all patients. In the ACL-injured group, the "aspiration test" was positive in 31% (n=32) and the probing test in 13% (n=13) of cases, a significant difference ($p<0.01$). Overall agreement between both tests was moderate ($\kappa=0.46$), with discordant results in 21 patients. The "aspiration test" showed a

significant association with the type of PLMRT ($p<0.01$), while the probing test did not. In type IV root injuries, the probing test was positive in one out of 15 patients (7%) and the "aspiration test" in 13 out of 15 patients (87%). In ACL-injured patients without a visible lateral meniscus injury, the "aspiration test" was still positive in ten out of 76 patients (13%) and the probing test in eight out of 76 patients (11%) (Figure 6).

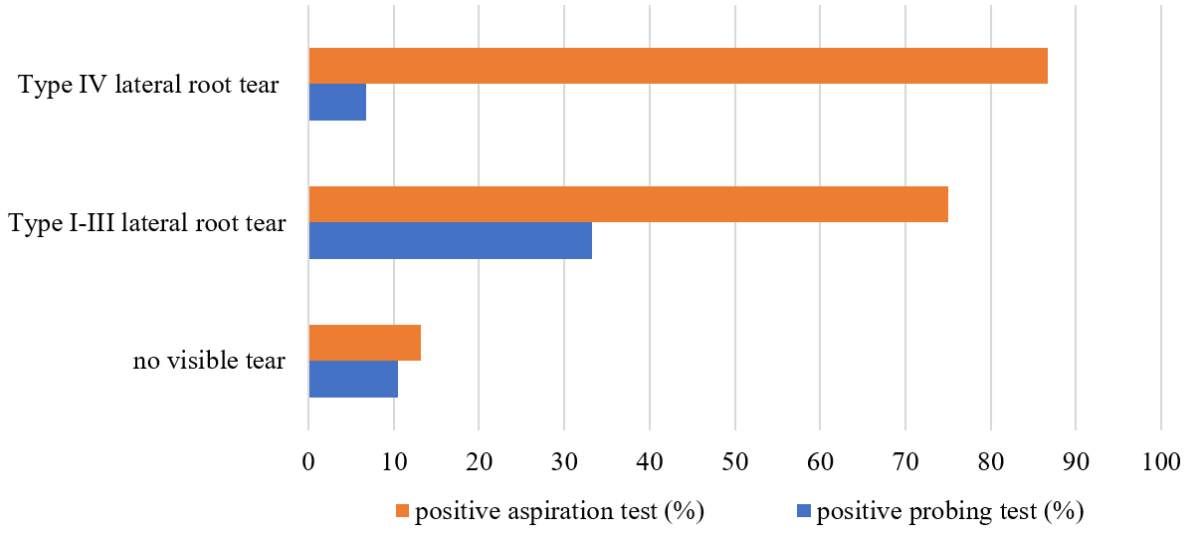


**Figure 6: Distribution of positive probing test and "aspiration test" according to the status of the lateral meniscus in the anterior cruciate ligament group (from Jacquet et al. [96]; classification of posterolateral meniscus root tears type I to III according to Forkel et al. [72]).**

The "aspiration test" demonstrated a high prevalence of LMPHIs in ACL-injured patients, affecting nearly one-third of the cohort. Further, the "aspiration test" proved superior to the probing test in detecting LMPHI especially in ACL-injured patients with an elongation of the posterolateral meniscus root. As outlined before, the recorded prevalences reinforce the notion that based on the ACL-injury mechanism a substantial number of lateral meniscus posterior horn injuries remain undiagnosed. This is indicated by the notably lower prevalence of PLMRT compared to typical bone bruises described by other authors, as well as the high proportion of ACL-injured patients displaying a LMPHI despite the absence of a visible meniscal tear [227]. Thus, a more subtle structural damage to the suspensory complex of the PHLM may occur in a significant amount of ACL-injured knees. Elongations of the posterolateral meniscus root being introduced as type IV PLMRT, involve incomplete root tears with severe distraction and partial healing at injury. This injury type has not been previously described and is an important extension of the classification by Forkel et al. [72].

# 3. Discussion

The most important findings of this thesis are that ACL injuries are frequently associated to complex meniscus injury patterns, involving specifically the meniscal posterior horns, such as MMRLs, PLMRTs, or a LMPHI [96, 130]. These injuries contribute substantially to dynamic knee laxity as expressed by an explosive pivot shift sign [147, 194]. Furthermore, the data suggest a temporal evolution of the pivot shift in chronic ACL injuries associated to the amount of meniscus damage [131]. These results underscore the necessity of a thorough and standardized arthroscopic assessment of intra-articular soft tissue damage and support early ACL reconstruction with repair of concomitant meniscal injuries to achieve complete anatomical and functional restoration.

The present work addressed five specific research questions, each of which can be answered as follows:

1. The presence of a MMRL was found to be associated with increased dynamic rotational laxity, as expressed by grade III pivot shift test. This confirms the hypothesis and supports the biomechanical significance of the medial meniscus ramp as secondary stabilizer in the ACL-deficient knee.

2. Only approximately one-third of ACL-injured patients presented without a concomitant meniscal injury, whereas more than half of ACL-associated meniscal tears involved the posterior horns, specifically a MMRL and/or a PLMRT. This finding confirms the hypothesis, highlighting both the high prevalence and clinical relevance of these injuries. MMRLs were observed more frequently in male patients, following contact injuries, and in cases of complete ACL tears.

3. Preoperative high-grade pivot shift was predominantly observed in patients with chronic ACL injuries and extensive intra-articular soft tissue damage, being especially frequent in cases with complete ACL tears and bimeniscal involvement. These results confirm the hypothesis that preoperative grade III pivot shift is linked to the severity of intra-articular soft tissue injury and the chronicity of the ACL rupture.

4. During diagnostic knee arthroscopy, aspiration with the shaver placed in the lateral compartment can be used to detect LMPHI in adjunction to conventional probing. This finding supports the purpose of the study, demonstrating the utility of the novel “aspiration test” for enhancing arthroscopic diagnosis.

5. The arthroscopic “aspiration test” demonstrated superior sensitivity compared with conventional probing, revealing a LMPHI in about one-third of ACL-injured knees. This confirms the hypothesis that LMPHIs are frequently associated with ACL injuries and are underrecognized by standard arthroscopic techniques, establishing the test as a reliable, standardized method for assessment in this context.

## 3.1. Importance of ACL-associated injuries

In recent years, ACL injury management has undergone a paradigm shift. Patient- and injury-specific characteristics are gaining importance, alongside evolving approaches in surgical treatment [176]. While ACL ruptures were historically regarded as mostly isolated injuries, current understanding increasingly recognizes the importance of concomitant soft tissue damage [166, 174]. This growing awareness of ACL-associated meniscus injuries is mirrored by an increasing proportion of surgeons performing meniscus repair procedures in both paediatric and adult population [23, 30]. Such developments reflect the high prevalence of concomitant meniscal pathology in ACL-injured patients [85, 166]. Given the complex mechanism of an ACL injury and the specific anatomy of the meniscal posterior horns, particular attention should be directed to MMRLs and PLMRTs [72, 190]. At the moment of tibial subluxation both structures are exposed to substantial shear and compressive forces. Approximately one-third of ACL-injured patients displayed at least one of those injuries. Considering the medial meniscus, ramp lesions were diagnosed in 25% of patients, whereas other medial meniscal injuries accounted for only 13%. Consequently, more than 65% of medial meniscus injuries would be overlooked without specific evaluation of the ramp region. Similarly, on the lateral meniscus, root tears occurred in 17% of patients compared to 21% of other lateral meniscus injuries. This indicates that failure to assess root tears would result in overlooking more than 40% of lateral meniscus injuries [130]. Both MMRL and PLMRT exert a significant impact on knee stability and were shown to contribute to an increased preoperative pivot shift grade [123, 147, 184, 196]. Further, their repair has been shown to markedly improve postoperative laxity following ACL reconstruction [90, 181, 200, 207]. To the best of the authors' knowledge, the combined prevalence of MMRLs and PLMRTs (6%) had not been described before [130]. A comparably comprehensive approach was followed in a more recent study by Garcia et al. where only 24% of patients had an isolated ACL tear, whereas 23% had a MMRL, 13% showed a PLMRT, and 67% displayed an additional ALL injury. The combined prevalence of a MMRL and a PLMRT was four percent and the presence of a PLMRT increased the odds of additionally finding a MMRL or an ALL injury [84]. In a study evaluating the reoperation rate after MMRL repair, eleven percent required secondary partial medial meniscectomy at a minimum of a two years follow-up. The addition of ALL reconstruction at the time of ACL reconstruction was associated with a substantially lower risk of subsequent meniscectomy [198]. Consequently, there is a potential biomechanical relationship between the ALL and the medial meniscus ramp.

However, a discrepancy exists between the described prevalence of a LMPRT and the occurrence of concomitant bone bruises, affecting the lateral femoral condyle in 31% and the lateral tibial plateau in 69% of ACL-injured knees according to Zhang et al. [227]. This is consistent with the presence of additional, insufficiently recognized injuries affecting the suspensory complex of the lateral meniscus posterior horn, as indicated by the "aspiration test" when positive without any obvious injury being

detected during knee arthroscopy (31%) [96]. Given the recent description of a type IV PLMRT in addition to the classification introduced by Forkel et al., the reported prevalence of PLMRT in the literature should be questioned and reviewed, especially in other ACL registries [72, 96].

Overall, the spectrum of meniscal pathology in ACL-injured knees is considerably more complex than previously assumed. Comprehensive evaluation of all associated soft tissue injuries is essential to accurately assess the injury severity and guide treatment. Expanding current knowledge, particularly regarding specific meniscus posterior horn injuries in the context of an ACL rupture, and performing meniscal repair whenever feasible are critical steps toward improving postoperative knee laxity and long-term functional outcomes.

In addition to ACL-associated meniscus injuries, recent MRI-based work shows that injuries to the MCL complex are common in patients with acute ACL tears [44, 221]. Posterior oblique ligament injuries are less frequent and were only found in association with an MCL injury. Certain injury patterns on MRI, such as lateral meniscus injury, lateral femoral condyle impaction, or medial femoral condyle bone bruising, were associated with a higher likelihood of MCL complex involvement. Interestingly, medial meniscus injuries were linked to a lower risk of medial ligament injury, likely reflecting different injury mechanisms and force patterns that do not simultaneously stress the two structures [44]. In patients with combined ACL and MCL injuries, non-surgical treatment of the MCL is linked to worse outcomes, including higher ACL revision rates, and chronic valgus laxity, whereas surgical reconstruction of both ligaments improves knee stability and function [46, 94, 205]. Likewise, bone-bruise patterns are very common in ACL injury, recent systematic review data suggest prevalence rates above 70 to 80% in acute ACL ruptures, frequently localized at the lateral femoral condyle and the lateral tibial plateau [192]. These contusions not only reflect the injury mechanism but are also associated with greater early pain, potentially heightened inflammation, and an increased risk of future degenerative changes [67, 99]. Cartilage lesions themselves are increasingly detected on MRI in ACL-injured patients, with about 15% showing cartilage damage on the post-injury MRI [43]. Cartilage lesions diagnosed at the time of ACL reconstruction are common and have been consistently linked to worse outcomes. Systematic reviews show that full-thickness cartilage damage identified during arthroscopy is associated with poorer short- to mid-term patient-reported outcomes, and delays in ACL reconstruction increase the likelihood of detecting these lesions [66, 98, 135]. Thus, concomitant injuries should be systematically assessed and, when present, addressed during ACL reconstruction.

## 3.2. Concept of knee decompensation in ACL-injured patients

It is well-established that secondary meniscal injuries, particularly to the medial meniscus, occur frequently following an ACL rupture, and their prevalence increases with delayed ACL reconstruction [135]. In contrast, the longitudinal progression of rotational knee instability after ACL injury has been less investigated [120]. There is still a lack of prospective data on how rotatory knee laxity changes over time and how it affects clinical outcomes and joint degeneration. Understanding the origin of a high-grade pivot shift is crucial, as preoperative high-grade pivot shift has been associated with an increased risk of graft rupture following ACL reconstruction [129]. Further, ACL reconstructed patients may present with an altered dynamic rotational laxity after primary ACL reconstruction which has been shown to be associated with poor subjective results [103, 104, 170, 208]. Several studies have demonstrated the multifactorial etiology of the pivot shift phenomenon, including associated meniscal injuries. Both medial meniscus ramp lesions and lateral meniscus posterior root tears have been specifically linked to an increased pivot shift [147, 194]. High-grade pivot shift was shown to be associated with younger age, longer time to surgery, and a greater extent of intra-articular soft tissue injury. The frequency of grade III pivot shift increased with the number of concomitant structural injuries. It was most pronounced in patients with chronic complete ACL ruptures associated with bimeniscal tears, where every second patient displayed a grade III pivot shift [131]. These findings suggest that the degree of pivot shift and consequently rotational instability may progress over time. This led to the hypothesis of a time-dependent decompensation of the knee joint following ACL injury. As a consequence of this decompensation the menisci as secondary stabilizers in an ACL-deficient knee may fail progressively, resulting in subsequent injuries that may, in turn, exacerbate the pivot shift phenomenon, creating a self-perpetuating cycle of instability. Although it has been demonstrated that combined ACL reconstruction and meniscal repair can restore the pivot shift phenomenon to normal levels, further studies are needed to determine whether such interventions can truly prevent long-term decompensation of the joint [11, 119, 207]. Other techniques can also help optimize postoperative laxity. Incorporating a lateral extra-articular tenodesis alongside a hamstring autograft has been shown to provide a complementary approach, addressing rotational instability and protecting the graft at two years postoperatively [79]. However, prospective longitudinal data are still lacking to confirm whether these combined surgical procedures can effectively halt the progression of joint degeneration or functional decline. Therefore, additional studies with adequate follow-up and outcome measures are needed.

Further studies have been performed since to support the concept of time-dependent knee decompensation following an ACL injury. Macchiarola et al. investigated the influence of time from injury and meniscal integrity on anterior tibial translation on monopodal weight-bearing radiographs in ACL-injured patients. The ACL-deficient knees demonstrated significantly increased side-to-side difference in anterior tibial translation when compared to the contralateral knees, which further increased

with longer time from injury and in the presence of meniscal tears. Secondary ACL-injuries exhibited the highest side-to side difference in anterior tibial translation, while in primary deficiencies, both prolonged injury duration and meniscal damage were required to produce significant increases. The authors concluded that anterior tibial translation under load increases progressively with chronicity and the loss of secondary stabilizers, supporting the concept of gradual sagittal knee decompensation in ACL-deficient knees. In consequence, monopodal weightbearing radiographs may be used as a tool for early detection of functional instability associated with this decompensatory process [125]. Although the concept of decompensation was not yet established, time-dependent MRI changes in ACL-deficient knees had already been described earlier. Yoon et al. demonstrated that parameters such as PCL curvature, joint effusion, bone bruise signal, and ACL morphology show characteristic alterations over time, allowing estimation of the chronicity of ACL deficiency on MRI [224]. In ACL-deficient knees, the LCL assumes a more vertical orientation, allowing its full length to be visualized on a single coronal MRI slice, a finding described as the coronal LCL sign [139]. Another indirect MRI sign for ACL deficiency is the buckling phenomenon of the PCL, which can be measured reliable and accurate with the recently described angle measured between the PCL and the posterior femoral cortex on the sagittal MRI (posterior cruciate ligament-posterior femoral cortex angle, PCL-PCA) [24, 186]. Oronowicz et al. investigated whether these specific MRI parameters reflect the knee decompensation process. The study demonstrated a significant reduction of the PCL-PCA in chronic compared to acute ACL-deficient knees, indicating progressive posterior bowing of the PCL over time. A positive LCL sign was also associated with a lower angle between the PCL and the posterior femoral cortex, suggesting that both parameters reflect concurrent soft-tissue realignment as the knee loses static and dynamic stability. In consequence, monopodal weightbearing radiographs as well as the PCL-PCA and the LCL sign in MRI may be used as a tool for early detection of functional instability associated with the decompensatory process in an ACL-injured knee [125, 155]. Still, the degree of decompensation visible on MRI should not be equated with clinically assessed or subjectively perceived laxity.

Investigations on the relationship between clinically measured anterior and rotational knee laxity and functional outcomes following ACL injury and reconstruction are ambiguous. A multicenter analysis of the *Multicenter Orthopedic Outcomes Network (MOON) knee group* reported that neither residual anterior translation nor measured rotational laxity at two years post-reconstruction was significantly associated with worse patient-reported outcomes, suggesting that moderate objective laxity may not necessarily translate into functional impairment [126]. In contrast, the *PIVOT Study Group*, an international research group with the aim of validating the pivot shift test as a measure of ACL stability, found that high-grade rotatory instability can be predictable based on injury patterns and may have clinical relevance, as it is often associated with more complex injury features and may necessitate targeted surgical management [152]. The precise impact of clinically examined laxity measures on long-term functional outcomes remains unclear. While minor residual laxity may not immediately affect

subjective function, high-grade rotatory instability, particularly with further soft tissue injuries, may trigger progressive knee decompensation, leading to worsening instability and a self-perpetuating cycle of structural deterioration. The precise thresholds at which laxity becomes clinically significant, and its long-term impact on joint degeneration, remain unknown. Prospective longitudinal studies are needed to better understand how gradual decompensation of the knee influence the follow-up of an ACL injury respectively ACL reconstruction.

## 3.3. Limitations and strengths

Several limitations of this cumulative dissertation must be acknowledged. As most data were derived from a single center and surgeries were performed by a single experienced surgeon, the high methodological uniformity may come at the expense of external generalizability. The cumulative design entails partially overlapping patient cohorts, and the retrospective use of registry data limits control over certain confounding variables such as activity level, generalized ligamentous laxity, or injury mechanism. Clinical laxity assessments (Lachman and pivot shift tests), although performed systematically under anesthesia, remain partly examiner-dependent and were not supplemented by instrumented measurements. Finally, heterogeneity in study design and outcome parameters among the included studies precludes direct meta-analytical comparison. Future multicenter, prospective, and biomechanically oriented research should aim to confirm these findings, clarify the role of the menisci as secondary stabilizers, define the influence of posterior horn lesions on instability in ACL-deficient knees, and assess the long-term outcomes of patients with a positive “aspiration test”.

Nevertheless, the dissertation has several notable strengths. The first three included studies were based on prospectively collected data from a hospital-based ACL registry, ensuring a high degree of methodological consistency and data completeness. The use of a single-surgeon cohort minimized interobserver variability in arthroscopic assessment and surgical technique, providing a uniform diagnostic and therapeutic standard across the investigations. As in the previous studies, data for the second publication about the “aspiration test” was prospectively collected, but here within a multicenter rather than a single-center setting, involving institutions with substantial expertise in ACL injury treatment. This multicenter design provides stronger evidence for the reproducibility and generalizability of a novel test. The large and clinically representative patient populations of all studies allowed detailed analysis of specific meniscal injury patterns, including the more recently described MMRLs, PLMRTs, and LMPHIs. The integration of these studies within a coherent research framework permitted a comprehensive examination of ACL-associated meniscal injuries from both diagnostic and biomechanical perspectives.

## 3.4. Future perspective

The present work highlights the necessity for a systematic and comprehensive assessment of soft-tissue damage in patients with an ACL injury. ACL injuries represent a heterogeneous entity with a broad spectrum of concomitant soft-tissue damage, each potentially exerting a distinct influence on postoperative recovery, long-term joint stability, and the development of post-traumatic OA. In response to this need, Seil et al. developed a documentation tool to standardize the evaluation and quantification of soft-tissue damage in patients undergoing primary ACL reconstruction: the Anterior Cruciate Ligament Injury Severity Scale (ACLISS). This scoring system integrates findings from both MRI and arthroscopy to describe the severity of injury in three grades. In an initial cohort study including 100 patients, the number of associated injuries increased proportionally with the ACLISS grade. Although lateral compartment damage was most frequently observed, the involvement of the medial compartment and the presence of ramp lesions were indicative of more severe injury patterns [179]. However, the ACLISS currently applies exclusively to acute ACL injuries and requires further clinical validation to confirm its reproducibility, prognostic relevance, and applicability in diverse patient populations. Future research should aim to refine this tool, establish standardized imaging and arthroscopic assessment protocols, and evaluate its predictive value for long-term outcomes such as secondary instability, graft failure, and OA. Moreover, prospective studies are needed to better identify patients at risk of progressive knee decompensation and secondary restraint failure, thereby enabling timely and targeted therapeutic interventions to prevent chronic instability and joint degeneration.

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# Appendix

# Figures

# Reprint of original publications

## Ramp lesions of the medial meniscus are associated with a higher grade of dynamic rotatory laxity in ACL-injured patients in comparison to patients with an isolated injury

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# Ramp lesions of the medial meniscus are associated with a higher grade of dynamic rotatory laxity in ACL-injured patients in comparison to patients with an isolated injury

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## Abstract

**Purpose** The purpose of this study was to compare preoperative knee laxity between two groups of patients with primary or revision ACL reconstruction with or without an associated ramp lesion of the medial meniscus.

**Methods** Two-hundred and seventy-five patients with an ACL reconstruction (243 primaries; 32 revisions) were prospectively screened using direct arthroscopic visualisation and divided into a ramp lesion group (RLG) and a control group (CG) regardless of the presence of other associated meniscal tears. All patients were clinically examined under anaesthesia before surgery by grading the Lachman and pivot shift tests.

**Results** Fifty-eight patients were included in the RLG. The CG included 217 patients. With all meniscus lesions included, there were no significant differences between the two groups. After excluding all other meniscus lesions in both groups except for ramp lesions in the RLG, the prevalence of a grade III pivot shift was higher in the RLG (32 remaining patients; 47% grade III) compared to the CG (91 remaining patients; 24% grade III, $p = 0.02$). The difference of patients with a grade III pivot shift between the CG and RLG remained significant after removal of revision ACL reconstructions (CG, 85 remaining patients; 25% grade III—RLG, 27 remaining patients; 44% grade III, $p = 0.05$).

**Conclusion** Patients with an isolated ramp lesion of the medial meniscus in association with an ACL injury displayed a higher amount of dynamic rotational laxity as expressed by the pivot shift test in comparison to patients with isolated ACL injury and no ramp lesion. The association between ramp lesions of the medial meniscus and increased pivot shift grading suggests that it is important to diagnose and repair them during ACL reconstruction surgery.

**Level of evidence** III.

**Keywords** Knee · Meniscus · Ramp lesion · Anterior cruciate ligament · Laxity

## Introduction

Lesions of the posterior part of the medial meniscus in the meniscosynovial area (ramp or "hidden" lesions) have been reported in 15–24% of patients undergoing an ACL reconstruction [13, 17, 20, 23]. Although these lesions have been first described more than 30 years ago [9], little is known about their clinical relevance.

Recent cadaver studies found a significant increase of anterior and rotational knee laxity after sectioning the posteromedial meniscocapsular junction to simulate a ramp lesion in ACL-deficient knees [25]. De Philippo et al. [7] confirmed these findings on 12 matched pair cadaver knees and identified an increase not only in anterior tibial translation, but also in internal and external rotation of the pivot shift. ACL reconstruction and ramp repair restored the pivot shift to normal. In vivo, Bollen noted in a series of 17 ramp lesions that such injuries may be associated with a mild anteromedial rotatory subluxation [4]. So far, these results have never been confirmed in vivo in a larger

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number of patients and the influence of ramp lesions on knee laxity remains unclear.

The purpose of this study was to determine whether the presence of a ramp lesion of the medial meniscus in ACL injuries was associated with a higher grade of knee laxity at the Lachman and pivot shift tests. It was hypothesised that ramp lesions in ACL-injured patients were more often associated with a grade III laxity compared to ACL-injured patients with no ramp lesion.

## Materials and methods

Two-hundred and seventy-five ACL-reconstructed patients (109 women and 166 men) operated by a single surgeon were selected from a prospective cohort. This group of patients included 109 women (age at surgery: 28 ± 12 years, 167 ± 7 cm, 65 ± 11 kg) and 166 men (age at surgery: 27 ± 8 years, 179 ± 7 cm, 79 ± 12 kg). They displayed various types of ACL tears (complete, partial) as well as various associated injuries on cartilage or the menisci. Patients presenting with a paediatric ACL injury, a multiligament injury or a combined osteotomy procedure during ACL reconstruction were not included in the study.

### Surgical procedure

The surgical procedure was described previously [20]. A routine inspection of the knee with a 30° arthroscope through the anterolateral portal was performed to report any lesion to the medial and lateral meniscal bodies as well as to the posterior cruciate ligament and medial/lateral collateral ligaments. The arthroscope was then advanced through the intercondylar notch to inspect the posteromedial compartment [9, 10]. Most of the ramp lesions were identified through direct trans-notch visualisation. In every patient, the medial part of the ramp—which cannot be visualised with the 30° arthroscope—was palpated with a 21 G needle through a posteromedial approach. If a ramp lesion was suspected, direct arthroscopic visualisation was performed through a posteromedial portal. Repair was performed through the posteromedial portal with a curved needle (Spectrum, Conmed, Largo, FL, USA). After debridement of the meniscocapsular junction with a shaver, PDS stitches were knotted every 5 mm and the stability of the repair was tested with a probe. Finally, an anatomic single bundle ACL reconstruction was performed using either an ipsilateral bone patellar tendon bone or a semitendinosus/gracilis graft and bio-interference screws for graft fixation (Arthrex, Naples, FL, USA).

### Data collection

Patients were asked to fill in a standardised questionnaire indicating personal data (sex, height, and weight), previous lower leg injuries and circumstances of the ACL injury (contact with another person or non-contact injury). For surgical data, a standardised report was filled in by the operating team. The presence or absence of a ramp lesion to the medial meniscus at the time of the ACL reconstruction was considered as the main outcome for the present study. Other types of medial and/or lateral meniscus lesion and associated ligament injuries were also reported. The patient was considered as having an isolated ACL injury if no meniscus or ligament lesion was reported. Furthermore, whether the ACL surgery was a primary or a revision reconstruction was indicated.

### Clinical examination

The Lachman test [28] and the pivot shift test [8, 21] were performed under anaesthesia on both knees before the surgical procedure. Both tests were documented in 4 grades: grade 0, I, II and III [12].

All patients gave their written informed consent to participate in the study. The study protocol had previously been approved by the National Ethics Committee for Research (N°201101/05). Data acquisition and storage were notified to the National Data Protection Committee.

### Statistical analyses

As the first step, patients were separated into two groups: the ramp lesion group (RLG) which included patients with a ramp lesion to the medial meniscus and the control group (CG) which included patients with various types of ACL tears (isolated or not) as well as various associated injuries to the menisci but no ramp lesion. In the second step, patients with meniscal injuries other than ramp lesions were excluded from both groups, leaving only isolated ACL injuries in the CG and isolated ramp lesions associated to ACL injuries in the RLG. In the last step, patients with revision ACL reconstructions were excluded leaving only patients with isolated, primary ACL reconstructions in the CG and patients with isolated ramp lesions associated to primary ACL reconstructions in the RLG.

Gender distribution between the RLG and the CG was investigated using Chi square tests. Age at surgery, body mass index (BMI expressed in kg/m$^2$) and time between injury and surgery (expressed in days) were compared between both groups using Student's *t* tests or Mann–Whitney test depending on the normality of the data as verified with the Kolmogorov–Smirnov test. In the CG, Chi square

tests were used to compare Lachman and pivot shift grades between patients with and without an associated meniscus injury. Then, Chi square tests were used to compare Lachman and pivot shift grades between RLG and CG. The analysis was repeated after removing all associated lesions other than ramp lesions to the medial meniscus (second step) and reiterated after removing revision surgeries from both groups (third step). Each expected cell count was checked to be superior to five to verify the test validity. Statistical analyses were performed using version 23.0 of the SPSS software. Significance was set at $p < 0.05$ for all analyses.

## Results

Overall, 58 patients (21%) had a ramp lesion (RLG) and 217 showed no ramp lesion of the medial meniscus (CG) at the time of the ACL reconstruction. There was a higher proportion of men with a ramp lesion (25%) than females (15%; $p = 0.035$). Neither BMI (CG: median 23.6 kg/m$^2$, interquartile range 21.5–25.7, RLG: median 23.7 kg/m$^2$ interquartile range 22.1–25.9), nor age at surgery (CG: median 26 interquartile range 20–35, RLG: median 25 interquartile range 21–33) or time between injury and surgery (CG: median 120 days, interquartile range 69–246, RLG: median 142 days, interquartile range 72–402) differed between both groups.

In the CG, patients with a grade III at the Lachman test were more likely to have any type of associated meniscus injury (68%) compared to patients with a lower grade (52%, $p = 0.02$). In addition, patients with a grade III pivot shift were more likely to have any type of associated injury (68%) compared to patients with a lower grade pivot shift (54%, $p = 0.05$).

Comparisons between the CG and RLG are presented in Table 1 for the Lachman test and Table 2 for the pivot shift test. Overall, no difference could be observed between groups for the Lachman test. After removal of all other meniscal injuries except for ramp lesions (step 2), the pivot shift was more frequently graded as III in the RLG compared to the CG [$p = 0.02$; OR = 2.75 (1.19–6.44)]. After consideration of primary ACL reconstructions only (step 3), the difference of patients with a grade III pivot shift between the CG and RLG remained significant ($p = 0.05$).

## Discussion

The most important finding of this study was that patients with an ACL injury and a ramp lesion of the medial meniscus displayed more frequently a grade III pivot shift than patients with an isolated ACL injury. After exclusion of other types of meniscus lesions, 47% of patients in the RLG displayed a grade III pivot shift whereas only 24% of the CG had a grade III pivot shift. To the best of our knowledge, similar data have not been presented in the literature so far. These findings suggest that ramp lesions have an impact on dynamic rotational knee joint laxity. As the pivot shift grade also positively correlates with the outcome of an ACL reconstruction [3], it is, therefore, important to diagnose and repair ramp lesion to the medial meniscus during surgery.

The impact of ramp lesions on dynamic rotational knee laxity suggests that the ramp of the medial meniscus acts as a secondary restraint in ACL-injured patients. The findings of this study support previous in vitro studies [1, 7, 17, 25] showing an increased anterior tibial translation, internal and external rotation and magnitude of the pivot shift after sectioning the ACL and the posteromedial meniscocapsular junction in cadaver knees. Another study

**Table 1** Comparison of Lachman test grades under anaesthesia in ACL-injured patients with and without a ramp lesion of the medial meniscus

| Description | Group | *N* | Lachman grade | | Absolute difference (%) | Standard deviation of the difference (%) | 95% confidence interval | *p* value | Effect size Cohen's d |
|---|---|---|---|---|---|---|---|---|---|
| | | | 0–I–II | III | | | | | |
| All ACL injuries | CG | 217 | 136 63% [56–69] | 81 37% [31–44] | −1 | 7.1 | [−15.1; 12.8] | n.s. | 0.02 [−013;0.17] |
| | RLG | 58 | 37 64% [51–76] | 21 36% [24–49] | | | | | |
| Exclusion of other types of meniscus lesions | CG | 91 | 65 71% [62–81] | 26 29% [19–38] | 12 | 9.9 | [−7.3; 31.4] | n.s. | 0.23 [0.02;0.44] |
| | RLG | 32 | 19 59% [42–76] | 13 41% [24–58] | | | | | |
| Exclusion of revision ACL reconstructions | CG | 85 | 61 72% [62–81] | 24 28% [19–38] | 13 | 10.6 | [−8.3; 33.4] | n.s. | 0.23 [0.01;0.45] |
| | RLG | 27 | 16 59% [41–78] | 11 41% [22–59] | | | | | |

*CG* control group, *RLG* ramp lesion group

**Table 2** Comparison of pivot shift grades under anaesthesia in ACL-injured patients with and without a ramp lesion of the medial meniscus

| Description | Group | *N* | Pivot shift grade | | Absolute difference (%) | Standard deviation of the difference (%) | 95% confidence interval | *p* value | Effect size Cohen's d |
|---|---|---|---|---|---|---|---|---|---|
| | | | 0–I–II | III | | | | | |
| All ACL injuries | CG | 217 | 149 69% [62–75] | 68 31% [25–38] | 9 | 7.1 | [− 5.7; 22.3] | n.s. | 0.15 [0.00;0.30] |
| | RLG | 58 | 35 60% [48–73] | 23 40% [27–52] | | | | | |
| Exclusion of other types of meniscus lesions | CG | 91 | 69 76% [67–85] | 22 24% [15–33] | 23 | 9.9 | [3.3; 42.1] | 0.016 | 0.45 [0.24;0.66] |
| | RLG | 32 | 17 53% [36–70] | 15 47% [30–64] | | | | | |
| Exclusion of ACL revision reconstructions | CG | 85 | 64 75% [66–84] | 21 25% [16–34] | 19 | 10.7 | [− 1.1; 40.6] | 0.05 | 0.38 [0.16;0.60] |
| | RLG | 27 | 15 56% [37–74] | 12 44% [26–63] | | | | | |

*CG* control group, *RLG* ramp lesion group

confirmed that reconstructing the ACL and repairing the ramp lesion restored the pivot shift to normal [7].

Although nearly 1 out of 2 patients of the RLG displayed a grade III pivot shift, the pivot shift test may not be a reliable procedure to diagnose ramp lesions of the medial meniscus (91 grade III observed: 23 in RLG and 68 in CG). As the sensitivity and positive predictive values of MRI to diagnose ramp lesions are low [6, 11, 15], preathroscopic diagnosis of ramp lesions is rather limited.

In a large series of 2318 ACL-injured patients, Magnussen et al. [14] found a grade III pivot shift in 614 individuals (26.5%). Ramp lesions were not diagnosed but this rate was similar to the 31% of grade III pivot shift in the CG in the present study. The authors [14] also found that the presence of a medial meniscus tear had a significant influence on the magnitude of the pivot shift and that the pivot shift grade III was impacted by several factors such as age below 20 years, female sex, generalised ligamentous laxity and a longer time between injury and surgery. Similarly, other studies reported that anatomical variables such as bony morphology and soft tissue structures [16, 22, 26], as well as cartilage degeneration or osteoarthritis [5], influence pivot shift grading. In addition, other injuries, be it of the menisci or other intra- or extra-articular structures such as the anterolateral ligament, a lateral femoral notch impression fracture or a posterolateral tibial plateau fracture, may have also been responsible for a high-grade pivot shift. For the anterolateral ligament complex, a recent study [24] found a protective effect of anterolateral ligament (ALL) reconstructions in association with ACL reconstructions on posteromedial meniscal repairs, indicating a possible relation between ALL and ramp lesions. All above cited factors may influence and influence the percentage of grade III pivot shift both in the CG and RLG.

Previous cadaver studies [1, 17, 25] pointed out that lesions to the posterior horn of the medial meniscus influenced anterior–posterior tibial translation at different levels of knee flexion. Magnussen et al. [14] were able to show an influence of meniscal tears in general on the Lachman test grade in a large cohort of patients in vivo. Although the present study did not show any relation between the Lachman test and the presence of a ramp lesion, the exploration should be replicated with instrumented sagittal knee laxity measurements and a higher number of patients to further evaluate this question.

Approximately, one-fifth of the patient cohort (21%) had a ramp lesion of the medial meniscus in addition to an ACL injury. This is similar with the prevalence of ramp lesions reported in the literature (17–24%) [13, 15, 17, 20, 22–24]. All patients underwent a systematic arthroscopic evaluation with a posteromedial view to identify ramp lesions. This is of primary importance as the diagnostic potential through an anterolateral portal inspection is very limited (1.8% compared to 23.2% through an intercondylar view or posteromedial portal) [15, 18]. In agreement with Sonnery-Cottet et al. [24], ramp lesions were significantly more frequent in male patients (25 vs. 15% in females). Other previously described associations with BMI, age at surgery and time to surgery [13, 24] could not be found in this study.

The limitations in the present study are as follows. Both Lachman and pivot shift tests were evaluated manually. The quantification of the Lachman and pivot shift tests remains subjective and examiner dependent although laxity was assessed under anaesthesia, which is supposed to improve the conditions of clinical examination by better standardisation and patient relaxation [26]. Although not scientifically ideal, these data still reflect the daily clinical practice of a majority of surgeons, with the test results serving as a basis for treatment decision making [14]. The

role of meniscus lesions and their influence on rotational laxity in ACL-injured patients would help clinicians in better decision making but has not been fully evaluated yet. The current analysis attempts to solve part of the question by a focused evaluation on medial ramp lesions. However, a detailed analysis of other specific injury types like posterior horn root tears of the lateral meniscus was not considered. Many other factors such as bony morphology and injuries to the ALL, a lateral femoral notch impression fracture or a posterolateral tibial plateau fracture were not controlled in this study although they were previously reported to influence the pivot shift grade. Furthermore, neither the type, nor the size of the ramp lesions have been considered [1, 2] which is related to the fact that the classification of ramp lesions in the literature is still in the process of development and evolving continuously during the study period [19, 27]. Analysing these factors would, however, have required a much higher number of patients. The authors believe that overcoming these limitations would result in a comprehensive understanding of the relationship between ramp lesions in ACL injuries and higher knee laxity. Current results, however, already indicate how important that repairing ramp lesion during ACL surgery may help to avoid residual laxity.

## Conclusion

Patients with an ACL injury and a ramp lesion of the medial meniscus displayed higher dynamic rotational laxity as compared to the patients with isolated ACL injury without ramp lesion.

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### Compliance with ethical standards

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

**Ethical approval** All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

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

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# Medial meniscus ramp and lateral meniscus posterior root lesions are present in more than a third of primary and revision ACL reconstructions

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# Medial meniscus ramp and lateral meniscus posterior root lesions are present in more than a third of primary and revision ACL reconstructions

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## Abstract

**Purpose** The purpose of this study was (1) to describe the meniscus tear pattern in anterior cruciate ligament (ACL)-injured patients, with a special focus on medial meniscus (MM) ramp lesions and lateral meniscus (LM) root tears and (2) to determine whether patient and injury characteristics were associated with meniscus tear patterns.

**Methods** Data from 358 cases of ACL primary and revision reconstruction surgeries were extracted from a center-based registry. During arthroscopy, the presence of associated meniscus lesions was documented by systematically inspecting the anterior and posterior tibiofemoral compartments. With a special focus on MM ramp lesions and LM root tears, groups of different injury tear patterns were formed. Chi-square tests were used to determine whether these groups differed with respect to various patient and injury characteristics, including gender, previous ipsilateral ACL injuries, the injury's relation to sport, person contact during injury and the type of ACL tear. Median age at surgery and body mass index were compared between groups using the Kruskal–Wallis test. Significance was set at $p < 0.05$.

**Results** Two hundred and thirty-nine ACL injuries (67%) showed additional meniscal injuries, of which 125 (52%) involved the MM ramp and/or the LM root. Ramp lesions were more frequent in males (23% vs 12% in females, $p < 0.01$), in contact injuries (28% vs 16% in non-contact, $p < 0.05$) and in complete ACL tears (21% vs 5% in partial, $p < 0.05$). Combined injuries of the MM ramp and the LM root showed a higher percentage of contact injuries compared to non-contact injuries (10% vs 4%, $p < 0.05$).

**Conclusion** Two-thirds of all ACL injuries showed a concomitant meniscus injury, of which half involved the biomechanically relevant, but previously often undiagnosed RLMM or the PRLM. These findings provide evidence that until recently about half of ACL-associated meniscus injuries were not properly identified. Ramp lesions were more frequent in males, contact injuries and in complete ACL tears. These findings stress the need for a systematic assessment and a better understanding of the pathomechanism of these specific injuries which may have an important impact on knee biomechanics and the outcome of ACL reconstruction.

**Level of evidence** III.

**Keywords** Anterior cruciate ligament · Meniscal tear · Root tear · Ramp lesion · Prevalence

## Introduction

Ramp lesions of the medial meniscus (RLMM) and posterior root tears of the lateral meniscus (PRLM) are frequently described in anterior cruciate ligament (ACL) insufficient knees [8, 15]. Recent findings identified their impact on knee laxity and rotational control after ACL injuries [28, 30–32]. This is of importance since ACL-reconstructed patients may present with an altered dynamic rotational laxity after primary ACL reconstruction (ACLR), which is associated with poor subjective results [24, 25, 36, 44]. Few studies exist

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with respect to the prevalence of these two specific tear entities in well-defined series of ACL-injured patients. Although they deliver significant epidemiological information on ACL and associated injuries, registry data are not precise enough when it comes to the description of specific meniscus tear patterns. In a comparison of six ACL registries, Prentice et al. showed that the reported prevalence of meniscal injuries in primary ACLRs varied widely across countries [35]. A more systematic detection of these lesions should thus become the gold standard.

After their initial description by Hamberg in 1984 [23], increased attention has been given to RLMM in recent years. Their prevalence has been evaluated between 8 and 42% of ACL-injured knees [5, 8]. Little is known about their injury mechanism. Previous studies have emphasized the energy of knee trauma as being related to their appearance [38]. Several classification attempts describing their various types of appearance have been reported [37, 45]. Their diagnosis is difficult and repair is technically challenging and controversial [6, 27, 37, 41, 45]. Their biomechanical impact on anteroposterior knee laxity has been demonstrated in vitro [1, 13, 33, 43]. In vivo, their presence is related to a higher amount of explosive pivot shift tests in comparison to knees with isolated ACL injuries [31].

PRLM have been described by Ahn et al. in [3]. Previous reports showed that they are less frequent than RLMM. Forkel et al. identified their presence in 14% of patients in a series of 228 ACL injuries [16]. As for the RLMM, little is known about their injury mechanism. Biomechanical cadaver studies examined the effect of a sectioned LMPR on tibial translation and internal rotational at different degrees of flexion [17, 18, 28, 39]. They suggested that LMPR tears further increased rotational knee laxity in comparison with isolated ACL injuries and that it may be restored by root fixation. Like the RLMM, their repair is challenging and controversial. Several repair techniques as well as cases of healing after repair have been described [2, 3, 15].

Preoperative imaging is not sufficiently sensitive to diagnose RLMM and PRLM [21, 26]. Therefore, knowledge of epidemiological characteristics and possible risk factors may be of importance in diagnosing them. These specific meniscal tears have usually been studied independently and it remains unclear whether some characteristics are more likely to be associated with RLMM, PRLM or a combination of both. This lack of overview thus currently prevents proper use of this information in daily practice, although it may be of considerable value in ACL-injured patients as both RLMM and PRLM were previously underdiagnosed despite their impact on knee biomechanics.

The purpose of this study was to (1) identify the meniscus tear pattern in a series of ACL-injured knees during primary and revision ACLR, with a special focus on RLMM and PRLM and (2) to determine whether patient and injury characteristics were associated with meniscus tear patterns. The main hypotheses were that a significant number of patients would display an RLMM and/or a PRLM, and that these meniscal lesions would be associated with specific patient and injury characteristics.

## Materials and methods

Institutional Review Board (IRB) approval for the study protocol was given by the National Ethics Committee for Research in Luxemburg (Comité National d'Ethique de Recherche, notification number 201101/05). All patients gave their written informed consent to participate in the study.

Primary and revision ACLRs performed by a single surgeon were retrospectively extracted from an ongoing hospital-based registry. The registry includes data from a systematic and standardized follow-up conducted with all patients with a confirmed ACL injury, using magnetic resonance imaging (MRI). After the exclusion of five cases of ACL agenesis, 385 ACL-reconstructed patients were included. Table 1 shows the composition of the cohort with regard to gender, age at surgery, body mass index (BMI), previous ACLR and various injury-related characteristics.

**Table 1** Cohort and injury characteristics at the time of ACL reconstruction

| | | |
|---|---|---|
| Gender | | |
| Male | 227 | 63% |
| Female | 131 | 37% |
| Age at surgery (years)[a] | 26 (20–34) | |
| BMI (kg/m$^2$)[a] | 24 (22–26) | |
| Previous ipsilateral ACL reconstruction | | |
| No | 307 | 86% |
| Yes | 51 | 14% |
| Sport at injury | | |
| Level I | 214 | 60% |
| Level II | 78 | 22% |
| Level III/non-sport related | 66 | 18% |
| Mechanism of injury | | |
| Non-contact | 279 | 78% |
| Contact | 78 | 22% |
| Missing value | 1 | 0% |
| Type of ACL tear | | |
| Partial | 43 | 12% |
| Complete | 315 | 88% |

*ACL* anterior cruciate ligament, *BMI* body mass index, *IQR* interquartile range

[a]Values are expressed as median (IQR)

## Surgical procedure

The surgical procedure has been previously described [31, 38]. A systematic evaluation of the knee was performed through the anterolateral portal to report any lesions affecting the medial and lateral meniscal bodies, the cartilage and the posterior cruciate ligament and medial/lateral collateral ligaments. The type of ACL rupture (complete or partial) was also evaluated. To assess the menisci in their entirety, an anterior visual inspection of both menisci was completed, along with examination of their stability using a probe. Then, the arthroscope was advanced through the intercondylar notch to the posteromedial and posterolateral compartment to detect injuries to the posterior horns, in particular RLMM and PRLM [19]. The MM ramp was also palpated percutaneously with a 21-G needle using a posteromedial approach. If a ramp lesion or a root tear was suspected, direct arthroscopic visualization was performed through a posteromedial portal [3, 41]. Meniscal tears were repaired whenever possible, according to clinical standards, and ACLR was performed [38].

## Data collection

Patients were asked to fill in a standardized questionnaire, providing personal data (date of birth, gender, height and weight), previous ipsilateral ACLR and the circumstances of the ACL injury (date of injury, sport at injury and contact with another person during injury). Sport at injury was classified into three levels according to Grindem et al. pursuant to the proportion of jumping, pivoting and hard cutting [22]. Accordingly, sports such as football, basketball and handball were assigned to level I, while sports like volleyball, gymnastics and tennis were allocated to level II. As few patients ($n = 10$) injured themselves in level III sports such as swimming, running and cycling, they were grouped with non-sport-related injuries ($n = 56$) to avoid a small sample size.

A standardized report of surgery was completed by the operating team. Posteromedial or anterolateral bundle conservations of the ACL, as well as elongations, were classified as partial tears. Graft ruptures were always assigned as complete tears. ACL injuries were classified as isolated if no lesions to the menisci were found. Meniscus lesions were documented according to their location on the MM, the LM or both menisci. Types of lesions were recorded as described by ISAKOS [4] with additional inclusion of RLMM and PRLM. Other injuries such as additional ligament injuries or cartilage damage were not considered in the present study. These included: 1 case of associated posterior cruciate ligament reconstruction, 4 cases of associated medial collateral ligament reconstruction and 83 cases with cartilage damage (grade 2 or superior) in at least one compartment of the knee.

## Statistical analyses

Analyses were performed in two steps as presented in Fig. 1. The first step (A) considered the location of any type of meniscal tear on the MM, the LM or both menisci. In the second step (B), a distinction was made according to the type of lesion, whereby RLMM and PRLM were decisive for the allocation, independent of other concomitant meniscus injuries. Statistical analyses were performed using version 25.0 of the SPSS software. Gender, previous ipsilateral ACLR, sport at injury, mechanism of injury and type of ACL tear (partial/complete) were computed as categorical variables. Between-group comparisons (A and B) were performed using the Chi-square test with Bonferroni correction. Each cell count was checked to ensure it was greater than 5, and Cramer's V was reported as an effect size measurement [47]. Age at surgery and BMI were handled as continuous variables. Normality of data was checked using the Kolmogorov–Smirnov test. Between-group comparisons relied on the Kruskal–Wallis test. The epsilon-squared ($\varepsilon^2$) estimate

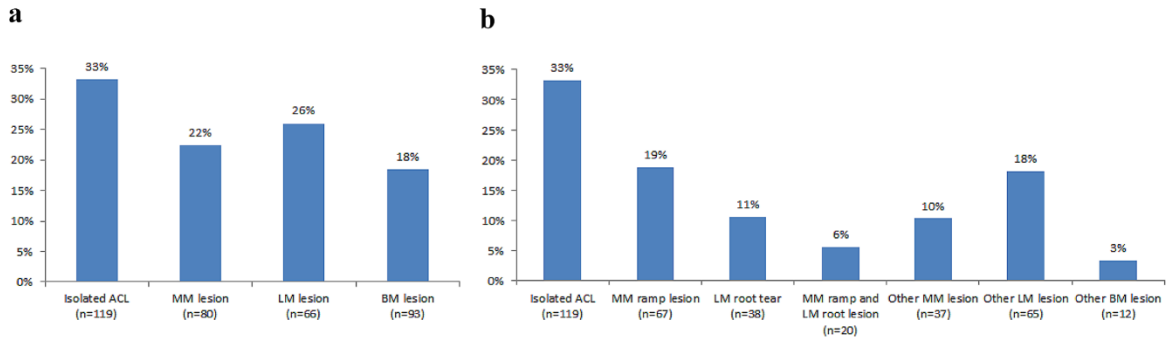


**Fig. 1** Division of the total cohort into subgroups according to the localization of associated meniscus injuries (**a**) and specific type of lesion (**b**). *ACL* anterior cruciate ligament, *MM* medial meniscus, *LM* lateral meniscus, *BM* bimeniscal

of effect size was calculated [47]. Significance was set at $p < 0.05$ for all analyses.

## Results

Two hundred and thirty-nine knees (67%) revealed ACL-associated meniscal injuries and 119 cases (33%) showed an isolated ACL injury.

Thirty-three percent ($n = 80$) of meniscus injuries involved the MM, while 39% ($n = 93$) involved the LM and 28% ($n = 66$) were bimeniscal (BM) injuries (Fig. 1a). Gender, age at surgery, BMI, sport at injury and type of ACL tear significantly differed between these meniscal patterns (Table 2). Female gender, level II sport at injury and partial tears were more likely to be associated with an isolated ACL injury. MM lesions were more frequent in males (26%) than females. Lesions of the LM occurred less frequently in level II (17%) sports than in level I (27%) or level III sports/non-sport-related injuries (35%, $p < 0.05$). They were also observed in younger patients (median 23 years) compared to isolated ACL injuries (28 years, $p < 0.05$) or MM injuries (26 years, $p < 0.05$) and showed a lower BMI (23 kg/m$^2$ in LM; 24 kg/m$^2$ in isolated/MM/BM, $p < 0.05$). Bimeniscal lesions were more frequent in males, as well as in contact injuries and in complete ACL tears.

Of all ACL-injured patients with concomitant meniscal lesions, 125 patients (52%) displayed an RLMM and/or a PRLM. Twenty-eight percent ($n = 67$) involved the MM ramp, 16% ($n = 38$) involved the LM root and in 8% ($n = 20$) both structures were injured (Fig. 1b). Gender, age at surgery, mechanism of injury and type of ACL tear significantly differed between groups (Table 3). RLMM were more common in males (23% vs 12% in females), in contact injuries (28% vs 16% in non-contact) and in complete tears of the ACL (21% vs 5% in partial). There were no significant differences within the group of PRLM. Injuries affecting both the MM ramp and the LM root showed a higher percentage of contact injuries compared to non-contact injuries.

Other MM lesions were more frequent in non-contact injuries. Patients with other LM lesions were more frequent in females and this group was significantly younger than patients with isolated ACL injuries ($p < 0.01$), patients with LM root tears ($p = 0.05$) or patients with other MM lesions ($p < 0.01$).

## Discussion

The most important findings of this study were that two-thirds of the ACL-reconstructed patients showed additional meniscal injuries and that 36% of ACL-injured patients presented with an RLMM and/or a PRLM. This shows that approximately half of ACL-associated meniscus injuries involved the MM ramp and/or the LM root, two specific and biomechanically relevant tear types which have only been recently discussed in the literature and may still be overlooked by many surgeons. To the best of the authors' knowledge, their combined prevalence has not yet been defined in previous publications.

Although no characteristic was found to be associated with PRLM root tears, RLMM were especially frequent in male patients (23%), injuries during contact with another person (28%) and in complete ACL tears (21%). RLMM were more frequent than injuries of the body of the posterior horn of the medial meniscus, indicating that a high number of structural lesions of the medial meniscus complex, which includes both the meniscus body and the meniscotibial attachment, were not identified in the previous ACL literature. The frequent occurrence of these lesions in the context of ACL injuries emphasizes the importance of a systematic and standardized identification of these tears, with the goals of improving the understanding of their pathomechanism and ultimately restoring knee anatomy and kinematics.

This study confirms the frequent association of ACL injuries with meniscal tears [7, 9, 29, 41]. Of all 358 ACLRs the MM was affected in 22%, the LM in 26% and BM in 19%. These numbers are consistent with the prevalence shown in ACL registers from Denmark, Luxembourg, Norway, Sweden, the UK and the USA, varying from 15 to 34% for the MM, 11 to 42% for the LM and 5 to 16% for BM injuries [35]. In this study, almost one patient out of four had an RLMM associated with their ACL injury. A comparable prevalence (24%) was found by Sonnery-Cottet et al. in a cohort of more than 3200 ACL-injured patients [42]. In recent years, there has been a trend toward increasing frequency, with other authors reporting a prevalence of RLMM of up to 42% [5, 8]. These results must be interpreted carefully as the knowledge about ramp lesions is constantly growing and their definition and classification continues to evolve [37]. A prevalence of 17% for PRLM is in accordance with previously reported numbers, ranging from 7 to 15% [14, 34].

As preoperative MRI showed insufficient sensitivity to detect RLMM and PRLM [21, 26], arthroscopy currently remains the most efficient tool to identify them. Their high prevalence should encourage surgeons to systematically look for these injuries during ACLR. Furthermore, as recent biomechanical studies showed that both RLMM and PRLM are associated with a higher degree of pivot shift [30, 31], these findings should encourage systematic repair to properly restore knee anatomy.

In agreement with previous literature, MM lesions, and more specifically RLMM, were more frequent in males than in females [27, 42] as well as in different types of sports [20]. Previous findings concerning the association of contact

**Table 2** Patient characteristics, injury information for each group and results of between-group comparison divided according to the localization of associated meniscus injuries (A)

| Characteristics | Isolated ACL | | | MM lesion | | | LM lesion | | | BM lesion | | | *p* value | Cramer V/$\varepsilon^2$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Gender[b] | | | | | | | | | | | | | | |
| Male | 67 | 29% [23–35] | ]* | 59 | 26% [20–32] | ]* | 52 | 23% [18–28] | | 49 | 22% [17–27] | ]* | < 0.01 | 0.18 |
| Female | 52 | 40% [32–48] | | 21 | 16% [10–22] | | 41 | 31% [23–39] | | 17 | 13% [7–19] | | | |
| Age at surgery (years)[a] | 28 (20–38) | | | 26 (21–35) | | | 23 (18–32) | | | 25 (21–31) | | | < 0.05 | 0.02 |
| BMI (kg/m$^2$)[a] | 24 (22–26) | | | 24 (22–26) | | | 23 (21–25) | | | 24 (22–26) | | | < 0.05 | 0.02 |
| Previous ipsilateral ACL reconstruction[b] | | | | | | | | | | | | | | |
| No | 107 | 35% [30–40] | | 65 | 21% [16–26] | | 80 | 26% [21–31] | | 55 | 18% [14–22] | | n.s | 0.01 |
| Yes | 12 | 24% [12–36] | | 15 | 29% [17–41] | | 13 | 25% [13–37] | | 11 | 22% [11–33] | | | |
| Sport at injury[b] | | | | | | | | | | | | | | |
| Level I | 62 | 29% [23–35] | ]* | 48 | 22% [16–28] | | 57 | 27% [21–33] | | 47 | 22% [16–28] | | < 0.05 | 0.14 |
| Level II | 37 | 47% [36–58] | | 18 | 23% [14–32] | | 13 | 17% [9–25] | ]* | 10 | 13% [6–20] | | | |
| Level III/no sport | 20 | 30% [19–41] | | 14 | 21% [11–31] | | 23 | 35% [23–47] | | 9 | 14% [6–22] | | | |
| Mechanism of injury[b,†] | | | | | | | | | | | | | | |
| Non-contact | 98 | 35% [29–41] | | 64 | 23% [18–28] | | 73 | 26% [21–31] | | 44 | 16% [12–20] | ]* | n.s | 0.13 |
| Contact | 21 | 27% [17–37] | | 16 | 21% [12–30] | | 19 | 24% [15–33] | | 22 | 28% [18–38] | | | |
| Type of ACL tear[b] | | | | | | | | | | | | | | |
| Partial | 24 | 56% [41–71] | ]* | 5 | 12% [2–22] | | 11 | 25% [12–38] | | 3 | 7% [0–15] | ]* | < 0.01 | 0.19 |
| Complete | 95 | 30% [25–35] | | 75 | 24% [19–29] | | 82 | 26% [21–31] | | 63 | 20% [16–24] | | | |

*ACL* anterior cruciate ligament, *MM* medial meniscus, *LM* lateral meniscus, *BM* bimeniscal, *BMI* body mass index, *IQR* interquartile range

*Marks proportions that differ significantly from each other at the 0.05 level

†Missing value, $n = 1$

[a]Values are expressed as median (IQR)

[b]Values are given as absolute numbers and percentages [95% confidence interval of percentages]

**Table 3** Patient characteristics, injury information for each group and results of between-group comparison divided according to the specific type of meniscal lesion (B)

| Characteristic | Isolated ACL | | MM ramp lesion | | LM root tear | | MM ramp and LM root lesion | | Other MM lesion | | Other LM lesion | | Other BM lesion | | *p* value | $V/\varepsilon^2$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Gender[b] | | | | | | | | | | | | | | | | |
| Male | 67 | 29% [23–35] ]* | 51 | 23% [18–28] ]* | 29 | 13% [9–17] | 16 | 7% [4–10] | 25 | 11% [7–15] | 32 | 14% [9–19] ]* | 7 | 3% [1–5] | < 0.01 | 0.23 |
| Female | 52 | 40% [32–48] | 16 | 12% [6–18] | 9 | 7% [3–11] | 4 | 3% [0–6] | 12 | 9% [4–14] | 33 | 25% [18–32] | 5 | 4% [1–7] | | |
| Age at surgery (years)[a] | 28 (20–38) | | 24 (20–32) | | 28 (18–37) | | 26 (21–30) | | 27 (21–45) | | 22 (18–30) | | 26 (22–35) | | < 0.05 | 0.04 |
| BMI (kg/m$^2$)[a] | 24 (22–26) | | 24 (22–26) | | 24 (22–26) | | 25 (23–26) | | 24 (22–27) | | 23 (22–25) | | 25 (21–26) | | n.s | 0.04 |
| Previous ipsilateral ACL reconstruction[b] | | | | | | | | | | | | | | | | |
| No | 107 | 35% [30–40] | 60 | 20% [16–24] | 31 | 10% [7–13] | 15 | 5% [3–7] | 28 | 9% [6–12] | 56 | 18% [14–22] | 10 | 3% [1–5] | n.s | 0.15 |
| Yes | 12 | 24% [12–36] | 7 | 14% [4–24] | 7 | 14% [4–24] | 5 | 10% [2–18] | 9 | 17% [7–27] | 9 | 17% [7–27] | 2 | 4% [0–9] | | |
| Sport at injury[b] | | | | | | | | | | | | | | | | |
| Level I | 62 | 29% [23–35] ]* | 48 | 22% [16–28] | 24 | 11% [7–15] | 12 | 6% [3–9] | 18 | 8% [4–12] | 40 | 19% [14–24] | 10 | 5% [2–8] | n.s | 0.17 |
| Level II | 37 | 47% [36–58] | 12 | 16% [8–24] | 4 | 5% [0–10] | 3 | 4% [0–8] | 10 | 13% [6–20] | 11 | 14% [6–22] | 1 | 1% [0–3] | | |
| Level III/no sport | 20 | 30% [19–41] | 7 | 11% [3–19] | 10 | 15% [6–24] | 5 | 8% [1–15] | 9 | 14% [6–22] | 14 | 21% [11–31] | 1 | 1% [0–3] | | |
| Mechanism of injury[b,‡] | | | | | | | | | | | | | | | | |
| Non-contact | 98 | 35% [29–41] | 45 | 16% [12–20] ]* | 32 | 12% [8–16] | 12 | 4% [2–6] ]* | 34 | 12% [8–16] ]* | 48 | 17% [13–21] | 10 | 4% [2–6] | < 0.05 | 0.21 |
| Contact | 21 | 27% [17–37] | 22 | 28% [18–38] | 6 | 8% [2–14] | 8 | 10% [3–17] | 3 | 4% [0–8] | 16 | 20% [11–29] | 2 | 3% [0–7] | | |
| Type of ACL tear[b] | | | | | | | | | | | | | | | | |
| Partial | 24 | 56% [41–71] ]* | 2 | 5% [− 2 to 12] ]* | 4 | 9% [0–18] | 0 | 0% [0–0] | 4 | 9% [0–18] | 7 | 16% [5–27] | 2 | 5% [0–12] | < 0.05 | 0.21 |
| Complete | 95 | 30% [25–35] | 65 | 21% [17–25] | 34 | 11% [8–14] | 20 | 6% [3–9] | 33 | 11% [8–14] | 58 | 18% [14–22] | 10 | 3% [1–5] | | |

*ACL* anterior cruciate ligament, *MM* medial meniscus, *LM* lateral meniscus, *BM* bimeniscal, *BMI* body mass index, *IQR* interquartile range

*Marks proportions that differ significantly from each other at the 0.05 level

‡Missing value, $n = 1$

[a]Values are expressed as median (IQR)

[b]Values are given as absolute numbers and percentages [95% confidence interval of percentages]

injuries and complete ACL ruptures with ramp lesions could also be confirmed [38]. This is in agreement with other studies showing an association between contact ACL injuries and meniscus pathologies [5]. Level I sport, contact injuries and complete ACL tears suggest a high-energy trauma mechanism. As the MM is less mobile than the LM and the MM posterior horn is the least mobile part [46, 48], the ramp may be particularly vulnerable in this context. Contact injuries involve a forceful external impact, and complete ACL ruptures were shown to require higher forces than partial ruptures [10–12].

Other factors may influence the ACL-associated meniscal injury pattern, although these were not significant in the present study. Unlike previous authors, who found an association of RLMM with age under 30 years [27, 42], no relationship between age at surgery and meniscal lesions could be identified in this study. Age was, however, considered as a continuous variable and the present cohort included and compared all types of meniscal tears. The previously mentioned association of RLMM with revision ACLR, as found by Sonnery-Cottet et al. [42], could not be confirmed either. Finally, no significant association could be highlighted with the occurrence of PRLM, although previous authors found an association with male gender and contact mechanism [14, 34].

The current study is not without limitations. Since only statistical relationships were shown, causality cannot be concluded. The aim of this study was to focus on RLMM and PRLM. Further associated injuries like chondral lesions, other ligament ruptures or lesions of the anterolateral complex were not considered and other types of meniscus lesions (i.e., longitudinal and horizontal tears) were cumulated. This study also presents a limited selection of possible associated factors. Further contributing factors, such as preoperative differential knee laxity, meniscal slope or bone marrow edema [5, 40, 42], may be of interest for further studies. Finally, future studies will need to show if the outcome of ACLR and meniscus repair in the presence of RLMM and PRLM will be superior to ACLR alone. To the authors' knowledge, this may be the first time that a study reported on the high prevalence of RLMM and PRLM in ACL-deficient knees. A reliable diagnosis and a better understanding of the pathomechanism of these specific injuries is of high clinical relevance, since they may have an important impact on knee biomechanics. In daily practice, a thorough and systematic investigation of the menisci should thus always be performed during ACLR.

## Conclusion

Two-thirds of all ACL injuries showed a concomitant meniscus injury, of which half involved the biomechanically relevant, but previously often undiagnosed RLMM or the PRLM. These findings provide evidence that until recently about half of ACL associated meniscus injuries were not properly identified. Ramp lesions were more frequent in males, contact injuries and in complete ACL tears. These findings stress the need for a systematic assessment and a better understanding of the pathomechanism of these specific injuries which may have an important impact on knee biomechanics and the outcome of ACLR.

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**Author contributions** All authors contributed equally to the study.

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## Compliance with ethical standards

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

**Ethical approval** Ethical approval was provided by National Ethics Committee for Research (No. 201101/05).

**Informed consent** All patients signed an informed consent to participate in the study.

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# Grade III pivot shift as an early sign of knee decompensation in chronic ACL-injured knees with bimeniscal tears

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# Grade III pivot shift as an early sign of knee decompensation in chronic ACL-injured knees with bimeniscal tears

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## Abstract

**Purpose** To analyse possible associations between the preoperative pivot shift (PS) test and both patient and injury characteristics in anterior cruciate ligament (ACL)-injured knees, considering previously neglected meniscal injuries such as ramp and root tears. The hypothesis was that a preoperative grade III PS was associated with the amount of intra-articular soft-tissue damage and chronicity of the injury.

**Methods** The cohort involved 376 patients who underwent primary ACL reconstruction (239 males/137 females; median age 26). Patients were examined under anesthesia before surgery, using the PS test. During arthroscopy, intra-articular soft-tissue damage of the injured knee was classified as: (1) partial ACL tear; (2) complete isolated ACL tear; (3) complete ACL tear with one meniscus tear; and (4) complete ACL and bimeniscal tears. Chi-square and Mann–Whitney *U* tests were used to evaluate whether sex, age, body mass index, sport at injury, mechanism of injury, time from injury and intra-articular damage (structural damage of ACL and menisci) were associated with a grade III PS. Intra-articular damage was further analyzed for two sub-cohorts: acute (time from injury $\leq 6$ months) and chronic injuries ($> 6$ months).

**Results** A grade III PS test was observed in 26% of patients. A significant association with PS grading was shown for age, time from injury and intra-articular soft-tissue damage ($p < 0.05$). Further analyses showed that grade III PS was associated with intra-articular damage in chronic injuries only ($p < 0.01$). In complete ACL and bimeniscal tears, grade III PS was more frequent in chronic (53%) than in acute knee injuries (26%; $p < 0.01$). Patients with chronic complete ACL and bimeniscal tears had a grade III PS 3.3 [1.3–8.2] times more often than patients in the acute sub-cohort.

**Conclusion** In ACL-injured patients, a preoperative grade III PS was mainly associated with a higher amount of intra-articular soft-tissue damage and chronicity of the injury. Patients with complete chronic ACL injuries and bimeniscal tears were more likely to have a preoperative grade III PS than their acute counterparts. This suggests that grade III PS may be an early sign of knee decompensation of dynamic rotational knee laxity in chronic ACL-injured knees with bimeniscal lesions.

**Level of evidence** Level III.

**Keywords** Pivot shift test · Rotatory laxity · Anterior cruciate ligament · Meniscus · Intra-articular soft-tissue damage · Knee decompensation

## Abbreviations

| | |
|---|---|
| ACL | Anterior cruciate ligament |
| BMI | Body mass index |
| CI | Confidence interval |
| IRB | Institutional Review Board |

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| | |
|---|---|
| IQR | Inter quartile range |
| LM | Lateral meniscus |
| MM | Medial meniscus |
| MRI | Magnetic Resonance Imaging |
| ns | Not significant |
| PS | Pivot shift |
| TFI | Time from injury |

## Introduction

The pivot shift (PS) test is a common clinical sign used to assess the rotational laxity occurring in anterior cruciate ligament (ACL)-injured patients. It is known to be the most specific test for diagnosing ACL ruptures, especially under anesthesia [44]. Despite the recent development of objective and standardized evaluation methods, manual evaluation of the PS in four grades remains the gold standard [16, 17]. A preoperative grade III PS is associated with increased odds of ACL revision surgery [25]. Furthermore, the persistence or recurrence of a high-grade PS after ACL reconstruction is correlated with poor functional outcomes [3, 45]. Identifying and understanding the reason behind a preoperative high-grade PS is thus essential to the therapeutic decision-making process.

The exact origin and the evolution over time of a preoperative high-grade PS is still controversial and incompletely understood [14]. Recently, a multifactorial background, involving different anatomical structures, has been discussed [29, 37, 42]. The influence of the menisci as secondary stabilizers of the PS in ACL-deficient knees has specifically been investigated [24, 32]. Several studies have described the impact of posteromedial and posterolateral lesions of the menisci, such as ramp lesions and root tears, on rotational knee laxity [30, 38]. These types of tears are observed in a relevant number of ACL-injured patients [26], with a frequency of 8–42% for ramp lesions of the medial meniscus (MM) [4, 5] and 7–15% for posterolateral root tears [12, 35]. However, the influence of the total amount of meniscus injuries, including their more recently described variations like ramp or root tears, on the PS has never been investigated. Likewise, little is known about the evolution of the PS over time although it is well known that MM lesions increase with time from injury [7, 28], thus potentially leading to increased knee laxity.

The purpose of this study was to evaluate the relationship between the preoperative PS test and patient and injury characteristics in a series of ACL-injured patients, considering previously neglected meniscal injuries such as ramp and root tears. The hypothesis was that a preoperative grade III PS was associated with the magnitude of intra-articular soft-tissue damage (type of ACL injury and meniscus damage) and with chronicity of the ACL injury.

## Materials and methods

Institutional Review Board (IRB) approval for the study protocol was given by the National Ethics Committee for Research in Luxembourg (Comité National d'Ethique de Recherche, notification number 201101/05). All patients gave their written informed consent to participate in the study.

Data were retrospectively extracted from an ongoing hospital-based register. This register collects data from a systematic and standardized follow-up set up for all patients with an ACL injury confirmed on Magnetic Resonance Imaging (MRI). Initially, 430 patients with primary ACL reconstruction performed by a single surgeon were extracted (Fig. 1). Patients were excluded if they had additional medial or lateral collateral ligament injuries requiring repair or reconstruction (2 patients), additional injury of the posterior cruciate ligament (2 patients), an ACL agenesis (6 patients), a mucoid degeneration of the ACL (1 patient), or an associated tibial fracture (1 patient). Furthermore, patients for whom the preoperative PS testing under anesthesia was not documented (42 patients) were excluded. The final study cohort involved 376 patients (239 males/137 females).

### Patient and injury characteristics

Patient and injury characteristics included sex, age, and body mass index (BMI) as well as sports practice at injury, mechanism of injury, and time from injury (TFI) to surgery. Sports practice at injury was classified according to Grindem et al. [15] into: (1) Level I sport (football, basketball and handball), (2) Level II sport (skiing, volleyball, gymnastics, tennis), (3) Level III sport (swimming, running and cycling). Level III sports were grouped with non-sport-related injuries to avoid a small sample size. With regard to the mechanism of injury, a distinction was made between injuries involving contact with another person and non-contact injuries. TFI was divided into two categories in accordance with Magnussen et al. [24]: $\leq 6$ months to define an acute ACL injury and $> 6$ months to define a chronic ACL injury. Table 1 shows the distribution of patient and injury characteristics in the final cohort.

### Clinical examination and surgical procedure

For both knees, the PS test was performed under anesthesia before ACL reconstruction surgery [44, 45]. The test results were documented into four grades distinguishing between no subluxation (grade 0), slight slip or trace

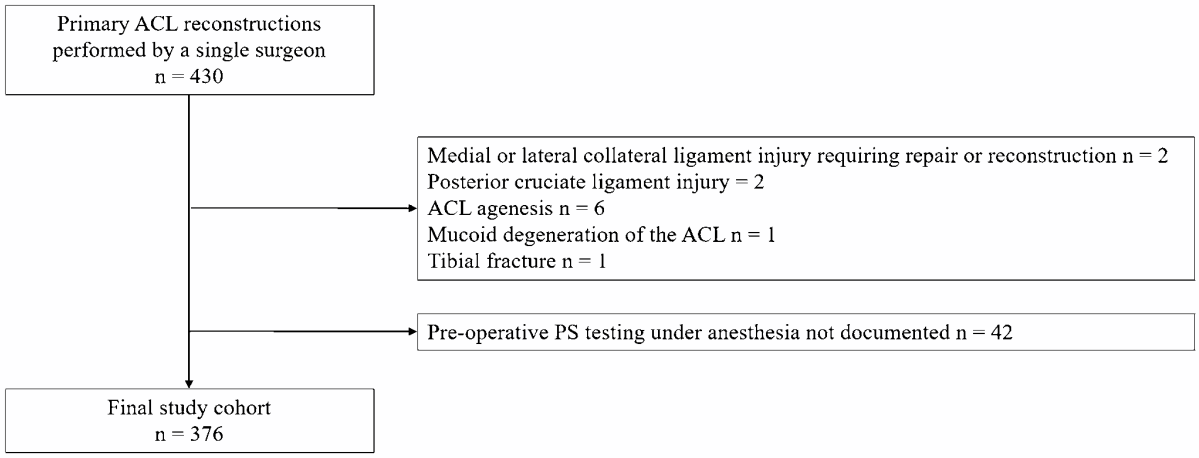


**Fig. 1** Patient selection from the hospital-based register. *ACL* anterior cruciate ligament, *PS* pivot shift

**Table 1** Patient and injury characteristics

| | | |
|---|---|---|
| Sex | | |
| Male | 239 | 64% |
| Female | 137 | 36% |
| Age at surgery (years)[a] | 26 (19–34) | |
| BMI (kg/m$^2$)[a] | 24 (22–26) | |
| Sport at injury | | |
| Level I | 234 | 62% |
| Level II | 99 | 26% |
| Level III/non-sport related | 43 | 11% |
| Mechanism of injury | | |
| Non-contact | 283 | 75% |
| Contact | 91 | 24% |
| Missing value | 2 | 1% |
| Time between injury and surgery (days)[a] | 145 (72–356) | |

*ACL* anterior cruciate ligament, *BMI* body mass index, *IQR* interquartile range

[a]Values are expressed as median (IQR)

(grade I), distinct subluxation and reduction (grade II) and pronounced subluxation and reduction (grade III) [16].

The surgical procedure was performed as previously described [26]. Before ACL reconstruction, a systematic inspection of the different structures of the knee was performed by the senior author through both an anterolateral and a posteromedial portal. The type of ACL rupture (partial or complete), and concomitant pathologies were documented. All types of meniscal tears including MM ramp lesions and posterolateral root tears [1, 19] and their locations (anterior horn, pars intermedia, posterior horn) were systematically investigated. An instability of the lateral meniscus (LM) posterior horn, as evaluated with a probe, was also considered to be a lesion, as the cause is presumed to be a complex injury of anatomic compounds of the LM with surrounding structures [20, 40].

## Classification of intra-articular soft-tissue damage

A primary distinction was made between partial and complete tears of the ACL. Anteromedial or posterolateral bundle conservations, as well as elongations of the ACL, were classified as partial ruptures [8]. All other types of ACL injuries were rated as complete ruptures and further divided according to the presence of additional meniscal tears. Isolated ACL injuries, in which both menisci appeared intact, were distinguished from injuries involving one meniscus (either medial or lateral) or both menisci. This resulted in four groups with an increasing level of intra-articular soft-tissue damage: (1) partial ACL tear; (2) complete isolated ACL tear; (3) complete ACL with one meniscus tear; and (4) complete ACL with bimeniscal tears.

Ninety-seven patients included in the final cohort displayed cartilage damage (grade 2 or higher according to the Outerbridge Classification of Chondral Lesions [35]) in at least one compartment of the knee. Overall additional surgical procedures to address the cartilage damage was limited to 13 patients (3.5%). For these reasons, these injuries were not further considered in the present study.

## Statistical analyses

Statistical analyses were performed using version 26.0 of the SPSS software. A grade III PS test of the injured knee was rated as high-grade PS, while grades 0–II were aggregated as low-grade PS. To be able to detect a difference of 10% in the percentage of high-grade PS, with a statistical power of

80% and an alpha value of 5%, knowing that according to Magnussen et al. [24], the proportion of high-grade PS in a series of ACL-injured patients is 26.4%, a minimum sample size of 262 patients was required.

First, chi-squared tests with Bonferroni correction were used to determine whether the PS, distinguished as low-grade and high-grade, was associated with sex, sport at injury, mechanism of injury, TFI or intra-articular soft-tissue damage. Each expected cell count was checked to ensure it was greater than five. To estimate the effect size, phi was reported for 2 × 2 tables, while for larger tables Cramer's $V$ was used [43]. Age at surgery and BMI were used as continuous variables. Normality of data was checked using the Kolmogorov–Smirnov test. As normality of data was not assumed, the Mann–Whitney $U$ test was used to compare low-grade and high-grade PS for these variables. The correlation coefficient $r^2$ was calculated to estimate the effect size [43].

Since TFI is considered an important factor in the appearance of associated lesions in ACL-deficient knees [7, 24, 28], intra-articular damage was further analyzed for two sub-cohorts: patients with acute injury being operated on within 6 months of injury and patients with chronic injuries with greater than 6 months. Chi-square tests with Bonferroni correction were used to determine whether (1) the amount of intra-articular soft-tissue damage differed between the two sub-cohorts, and (2) the PS was associated with intra-articular damage in each sub-cohort. Odds ratio was computed for significant comparisons and reported with 95% CI (Confidence Interval). Significance was set at $p < 0.05$ for all analyses.

## Results

Preoperative PS grades and arthroscopic findings are listed in Table 2. Intra-articular soft-tissue damage was distributed as follows: 44 partial ACL tears (11%); 89 complete isolated ACL tears (24%); 154 complete ACL tears with one meniscus tear (41%); and 89 complete ACL with bimeniscal tears (24%). Twenty-three out of 44 patients with partial ACL tears had an additional meniscus tear (5 with MM tear, 14 with LM tear, 4 with bimeniscal tear).

A preoperative grade III PS was observed in 26% ($n = 98$ out of 376 patients) of patients, while grades 0, I and II were documented for 74% ($n = 278$ out of 376 patients). A significant association was observed between grade III PS and younger age, chronic ACL injuries (TFI > 6 months) and intra-articular soft-tissue damage (Table 3). There was more preoperative grade III PS in complete ACL and bimeniscal tears (36%) compared to partial ACL tears (9%; $p < 0.05$; Fig. 2a).

**Table 2** Preoperative pivot shift grades and intraoperative findings

| | | |
|---|---|---|
| Pivot shift grading | | |
| Grade 0 | 28 | 7% |
| Grade I | 103 | 27% |
| Grade II | 147 | 39% |
| Grade III | 98 | 26% |
| Intra-articular soft-tissue damage | | |
| Partial ACL tear | 44 | 11% |
| Complete isolated ACL tear | 89 | 24% |
| Complete ACL with one meniscus tear | 154 | 41% |
| Complete ACL and bimeniscal tears | 89 | 24% |
| Additional meniscal injury | | |
| None | 110 | 29% |
| MM tear | 69 | 18% |
| LM tear | 104 | 28% |
| Bimeniscal tears | 93 | 25% |
| Location of meniscus tear[a] | | |
| MM posterior horn | 150 | 40% |
| MM pars intermedia | 62 | 16% |
| MM anterior horn | 17 | 5% |
| MM unknown | 9 | 2% |
| LM posterior horn | 176 | 47% |
| LM pars intermedia | 49 | 13% |
| LM anterior horn | 11 | 3% |
| LM unknown | 10 | 3% |
| Type of meniscal tear[a] | | |
| MM ramp lesion | 91 | 24% |
| LM root tear | 70 | 19% |
| LM posterior horn instability | 31 | 8% |
| Other types | 177 | 47% |

*ACL* anterior cruciate ligament, *MM* medial meniscus, *LM* lateral meniscus

[a]Percentages are given per row as a proportion of the total cohort ($n = 376$)

Chronic ACL injuries displayed more MM tears (28%) than acute ACL injuries (11%) but fewer LM tears (22% in chronic and 32% in acute; $p < 0.01$). The overall distribution of intra-articular soft-tissue damage as classified in this study did not differ significantly between acute and chronic injuries (Table 4). The association between preoperative grade III PS and the magnitude of intra-articular damage was only confirmed in the sub-cohort of chronic ACL injuries ($p < 0.01$, Cramer $V = 0.277$; Fig. 2b). In complete ACL and bimeniscal tears, the presence of a grade III preoperative PS was significantly greater in chronic ACL injuries (53%) than in acute ACL injuries (26%, $p < 0.01$, Phi = 0.278; Fig. 2b). Patients with a chronic ACL injury associated with bimeniscal tears were 3.3 [95% CI 1.3–8.2] times more likely to have a preoperative grade III PS than patients with acute ACL injuries and comparable meniscus damage.

**Table 3** Patient and injury characteristics according to preoperative pivot shift low- and high-grade

| Characteristic | Low-grade (0–II) $n=278$ | | High-grade (III) $n=98$ | | $p$ value | Effect size |
|---|---|---|---|---|---|---|
| Sex | | | | | | |
| Male | 177 | 74% | 62 | 26% | n.s | − 0.004 |
| Female | 101 | 74% | 36 | 26% | | |
| Age at surgery (years)[a] | 26 (21–34) | | 24 (18–30) | | 0.028 | 0.013 |
| BMI (kg/m$^2$)[a] | 24 (22–26) | | 24 (21–26) | | n.s | < 0.001 |
| Sport at injury | | | | | | |
| Level I | 170 | 73% | 64 | 27% | n.s | 0.088 |
| Level II | 79 | 80% | 20 | 20% | | |
| Level III/non-sport related | 29 | 67% | 14 | 33% | | |
| Mechanism of injury[b] | | | | | | |
| Non-contact | 213 | 75% | 70 | 25% | n.s | 0.048 |
| Contact | 64 | 70% | 27 | 30% | | |
| Time between injury and surgery | | | | | | |
| ≤ 6 months | 168 | 79% | 46 | 21% | 0.020 | 0.120 |
| > 6 months | 110 | 68% | 52 | 32% | | |
| Intra-articular soft-tissue damage | | | | | | |
| Partial ACL tear | 40 | 91% | 4 | 9% | 0.011 | 0.172 |
| Complete isolated ACL tear | 67 | 75% | 22 | 25% | | |
| Complete ACL with one meniscus tear | 114 | 74% | 40 | 26% | | |
| Complete ACL and bimeniscal tears | 57 | 64% | 32 | 36% | | |

*ACL* anterior cruciate ligament, *n.s.* not significant, *IQR* inter quartile range

[a]Values are expressed as median (IQR)

[b]Missing value ($n=2$) excluded

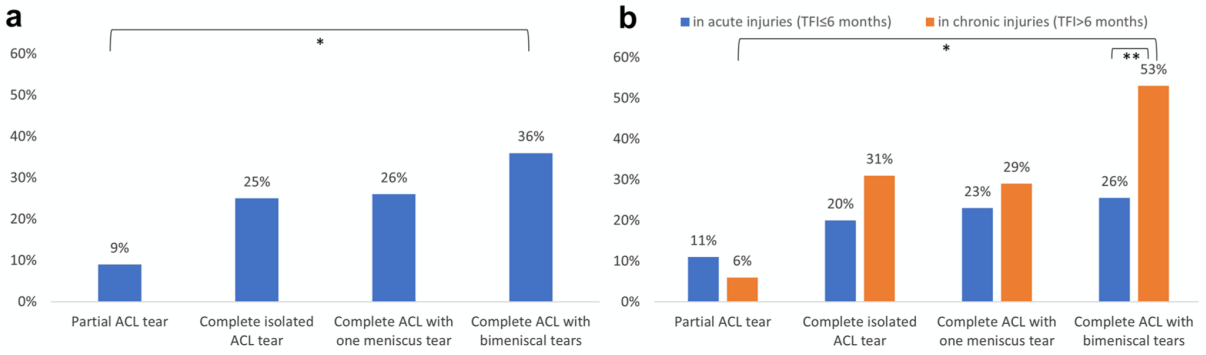


**Fig. 2** Percentage of preoperative grade III pivot shift tests for classification of intra-articular soft-tissue damage in the total cohort (**a**) and the sub-cohorts of acute and chronic ACL injuries (**b**). *$p<0.05$; **$p<0.01$. *ACL* anterior cruciate ligament, *TFI* time from injury

**Table 4** Number and proportion of patients in each group of intra-articular soft-tissue damage in two sub-groups according to TFI

| | Acute injury (TFI ≤ 6 months) $n=214$ | | Chronic injury (TFI > 6 months) $n=162$ | | $p$ value | Effect size |
|---|---|---|---|---|---|---|
| Intra-articular damages | | | | | | |
| Partial ACL tear | 27 | 13% | 17 | 10% | n.s | 0.074 |
| Complete isolated ACL tear | 50 | 23% | 39 | 24% | | |
| Complete ACL with one meniscus tear | 82 | 38% | 72 | 44% | | |
| Complete ACL with bimeniscal tears | 55 | 26% | 34 | 21% | | |

*ACL* anterior cruciate ligament, *TFI* time from injury, *n.s.* not significant

## Discussion

The most important finding of this study was that a preoperative grade III PS was associated with a higher amount of intra-articular soft-tissue damage and chronicity of the injury. Preoperative grade III PS was more frequent in patients with chronic ACL injuries displaying complete ACL and bimeniscal tears. This group of patients was 3.3 times more likely to have a preoperative grade III PS than their acute counterparts. This highlights the importance of considering both the intra-articular soft-tissue damage and the chronicity of an ACL injury in the therapeutic decision-making process. The findings suggest that a grade III pivot shift may be an early sign of knee decompensation of dynamic rotational knee laxity in chronic ACL-injured knees with bimeniscal lesions. To prevent this, early identification and close follow-up of injuries with important structural damage thus seems to be a key factor in patients in which an early ACL reconstruction and associated meniscal repair cannot be considered.

So far only few studies with large patient cohorts evaluated patient and injury characteristics in relation with the preoperative PS. Magnussen et al. [24] described increased odds for a preoperative high-grade PS in female patients and those aged under 20 in a series of more than 2300 patients. These findings could not be confirmed by Song et al., who could identify involvement in a pivoting sport at the time of injury as an independent risk factor for a preoperative high-grade PS [39]. While the results of the present study could not confirm an association of preoperative grade III PS with sex and sport at injury, a younger age was observed in patients with preoperative grade III PS. However, the small effect size ($r^2 = 0.01$) questions the clinical significance of this finding. One major reason for the observed discrepancies between studies may be related to patient selection. Song et al. [39] limited their analysis to acute ACL injuries (TFI to surgery was less than 3 weeks) while Magnussen et al. [24] and the present study included patients with both acute and chronic injuries. Magnussen et al. reported, that chronic ACL tears (TFI > 6 months) were three times as likely to have preoperative high-grade PS in comparison to acute ACL tears (TFI < 3 months) [24]. This was confirmed by the present study and is also in accordance with Nishida et al., who used a quantitative measurement for PS and described an increase in tibial acceleration in patients operated on more than 12 months after injury [33]. A similar association between excessive static anterior tibial translation on MRI and chronicity of the ACL tear has been previously demonstrated [27]. The increase in knee laxity over time may thus be an indicator of a progressive soft-tissue decompensation phenomenon in the knee joint after ACL injury.

Dynamic rotational laxity as expressed by the PS may not be present early after knee injury and develop over the following months [13, 36] but little is known about the spontaneous evolution of the PS over time in non-operated patients. This may be an early sign of knee decompensation, reflecting irreversible structural damage of the secondary stabilizers. It is well established that the occurrence of MM tears increases with time from injury to surgery [7, 28]. This was confirmed in the present study with 11% of MM tears in acute versus 28% in chronic injuries. Still, the overall distribution of intra-articular soft-tissue damage did not differ significantly between acute and chronic ACL injuries which may be related to the fact that the laterality of meniscal damage was not considered but only its total amount (one vs bimeniscal injury). While medial [24] and lateral meniscus tears [18, 24, 33, 39] have been shown to be associated with preoperative high-grade PS, previous authors did not investigate the total amount of structural soft-tissue damage; nor did they explicitly mention how meniscus tears were documented. It is therefore unclear whether they considered the full range of meniscus tears, including the frequently undiagnosed MM ramp lesions and posterolateral root tears. These should be systematically considered as they may play an important role in the presence or progressive appearance of a preoperative grade III PS.

In the present study, the proportion of preoperative grade III PS increased significantly with the amount of intra-articular soft-tissue damage; from 9% in partial ACL tears to 36% in complete ACL tears with bimeniscal tears. The present classification of structural soft-tissue damage was based on the hypothesis that the amount of injured intra-articular soft-tissue structures is related to the initial trauma energy, inducing a spectrum of injuries ranging from partial ACL to complete ACL tears and major bimeniscal damage, thus reflecting a real trauma cascade [34]. Complete ACL ruptures are indeed recognized to require higher forces at injury than partial ruptures [8–10]. Such correlations with the amount of energy at the initial impact have also previously been described for meniscus tears [6]. In partial ACL tears, although 23 out of 44 patients displayed an associated meniscus tear, the low percentage of preoperative grade III PS (9%) is likely to be due to the remaining fibers of the ACL, which provide residual stability to the knee [2, 21], rather than the menisci themselves. The higher percentage of grade III PS observed when bimeniscal tears were combined with complete ACL tears supports the hypothesis that meniscus tears were involved in the development of the PS [24, 30, 32, 38].

An important finding of the present study was the fact that the association between preoperative grade III PS and the magnitude of intra-articular damage mainly resulted from the sub-cohort of chronically ACL-injured patients. Patients with chronic complete ACL injuries combined

with bimeniscal tears, who represented a non-negligible proportion of our cohort (24%), displayed a preoperative grade III PS 3.3 times more often than patients with acute injuries and similar intra-articular damage. These results indicate that patients with acute complete ACL tears and bimeniscal tears should receive particular attention within the first months after the injury. They may indeed be at higher risk of undergoing later decompensation of rotational knee joint laxity once the injury becomes chronic, and for later failure of ACL reconstruction [23, 25]. A proper evaluation of intra-articular soft-tissue damage is thus critical to identify those patients who may benefit from an early ACL reconstruction as well as extensive meniscal repair, with the ultimate goal of achieving a complete anatomical restoration of the injured intra-articular soft tissues.

This study is not without limitations. Since only statistical relationships were shown, causality cannot be concluded. The PS test was evaluated manually and the quantification remains subjective and examiner-dependent. However, despite the recent development of objective and standardized evaluation methods, clinical examination of the PS remains the gold standard [17]. The main strength of this study was the combination of ACL injury and concomitant single or bimeniscal tears with a thorough diagnostic examination. The majority of meniscal tears involved posterior horns so that analyzing in depth the location and size of tears would have led to underpowered analyses, although the authors recognize that these parameters may also have an influence on the presence of a preoperative high-grade PS. Injuries to the anterolateral capsular structures and Kaplan fibers were not considered, although there is evidence that they play a role in rotational laxity [22]. Anatomical factors such as bone morphology and generalized ligamentous laxity, for which a relationship with the PS has previously been described [11, 24, 31, 41], were also not evaluated. However, this series of 376 primary ACL reconstructions considered all types of known meniscal tears, including the often undiagnosed or underestimated MM ramp lesions and posterolateral root tears. The thorough determination of meniscus status provides additional evidence to the impact of meniscus injuries on the etiology of the PS, especially in chronic ACL injuries. Further studies are needed to evaluate the influence of specific types of meniscal tears and other extra- (anterolateral capsular structures, Kaplan fibers) or intra-articular injuries (posterolateral tibial plateau or lateral condylar impression fractures) as well as many other factors, including constitutional laxity and bony morphology to better understand the precise determinants of the PS and the possible later decompensation phenomenon that may occur in ACL-injured knee joints.

## Conclusion

A preoperative grade III PS was mainly associated with a higher amount of intra-articular soft-tissue damage within the knee and the chronicity of the ACL injury. Patients with chronic ACL injuries displaying complete ACL and bimeniscal tears were more likely to have a preoperative grade III PS than their acute counterparts. The findings suggest that grade III PS may be an early sign of knee decompensation of dynamic rotational knee laxity in chronic ACL-injured knees with bimeniscal lesions. To prevent this, early identification and close follow-up of injuries with important structural soft-tissue damage thus may be a key factor in patients in which an early ACL reconstruction and associated meniscal repair cannot be considered.

**Author contributions** All authors contributed equally to the study.

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## Declarations

**Conflict of interest** None.

**Ethical approval** National Ethics Committee for Research (No. 201101/05).

**Informed consent** All patients signed an informed consent to participate in the study.

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# The aspiration test: an arthroscopic sign of lateral meniscus posterior horn instability

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# The aspiration test: an arthroscopic sign of lateral meniscus posterior horn instability

Christophe Jacquet[1,2], Amanda Magosch[1], Caroline Mouton[1,3] and Romain Seil[1,3,4*]

**Abstract**

The suspensory mechanism of the posterior horn of the lateral meniscus (PHLM) is an anatomically complex structure including the popliteomeniscal fascicles, the meniscotibial posterior root attachment and the meniscofemoral ligaments. Damage to one or several of these structures – either through knee trauma or congenital abnormalities—can result in an instability of the PHLM that may lead to lateral knee pain, locking sensations or lack of rotational control of the knee (e.g. after anterior cruciate ligament injuries). The diagnosis of PHLM instability is complex due to the lack of reliable clinical tests and imaging signs. Direct visual dynamic inspection via arthroscopy thus remains the gold standard. However, arthroscopic probing of the PHLM is not always reliable and the precise quantification of the amount of subluxation of the PHLM can be difficult. Therefore, the main objective of this report was to describe a quick and easy arthroscopic screening test called "the aspiration test" in order to help surgeons to detect PHLM instability. During the exploration of the lateral tibiofemoral compartment with the knee kept in the figure of 4 position, the arthroscope is placed in the antero-lateral portal and directed towards the lateral tibiofemoral compartment. The aspiration test is then performed by activating the aspiration of the 4-mm shaver when located in the intercondylar notch. In case of a PHLM instability, an excessive displacement of the PHLM is observed. After repair, a second aspiration test allows to verify that the PHLM has been stabilized.

**Keywords:** Popliteo-meniscal complex, Popliteo-meniscal fascicles, Hypermobile lateral meniscus, Aspiration test, Posterior horn lateral meniscus instability

## Introduction

Identifying an instability of the posterior horn of the lateral meniscus (PHLM) can be challenging due to the lack of an appropriate, dynamic method to confirm the diagnosis. Instability of the PHLM can result from a traumatic or an atraumatic insufficiency of the posterolateral suspensory complex which includes the popliteomeniscal fascicles [24], the meniscotibial posterior root attachment and the meniscofemoral ligaments [9]. It may induce locking sensations during deep knee flexion and can be isolated or observed in association with anterior cruciate ligament (ACL) or posterolateral corner injuries [3, 6, 27, 28]. Recently, it has been shown that instability of the PHLM may impact knee rotational instability [17, 25, 27]. It is therefore crucial to further investigate this entity to improve its diagnosis and to allow for complete anatomical repair when indicated.

Several structures of the posterolateral suspensory complex contribute to the active and passive stability of the knee: the popliteus tendon and the popliteo-meniscal fascicles (PMF) [12, 16, 32], the meniscofemoral ligaments (Humphrey and Wrisberg) [9, 13, 28] and the posterior root of the lateral meniscus [9, 25]. Injuries to the posterolateral suspensory complex of the LMPH are commonly under-recognized due to the lack of consistent clinical or MRI findings [14, 15, 26]. In a study by Simonian et al. [26], none of the patients with a instability of the PHLM at the time of surgery presented abnormal preoperative MRI findings. As MRI assesses the knee in

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static conditions, it may indeed not allow diagnosing the instability of the PHLM that occurs during knee motion.

An arthroscopic confirmation of the instability of the PHLM remains the diagnostic gold standard. Shin et al. [24] suggested that the instability was confirmed when more than half of the lateral meniscus could be extruded during arthroscopic probing. This led to define the lateral meniscus as being hypermobile. But arthroscopic probing may not always be a reliable test to diagnose the instability of the PHLM. There is thus a need to improve the detection of this condition during arthroscopic exploration. The main objective of this report was to describe an arthroscopic screening test called "the aspiration test" to help surgeons to better detect the instability of the PHLM.

## Techniques for arthroscopic evaluation of the PHLM

The diagnosis of the instability of the PHLM cannot be made by a single test. It is the sum of several individual clinical signs (patient history, clinical examination, imaging, arthroscopic findings). A reliable diagnosis of PHLM instability would ideally require a systematic visual dynamic inspection of the lateral meniscus under arthroscopy, currently considered as the gold standard. Direct arthroscopic inspection of the posterolateral suspensory complex of the PHLM including popliteus tendon, meniscofemoral ligaments and the PMF's as well as the interpretation of the arthroscopic findings is however challenging. Currently, there are 2 arthroscopic methods to evaluate the stability of the PHLM. Both offer complementary information.

### The lateral drive through sign

The lateral drive through sign is performed in the extended knee. The arthroscope is advanced distally and caudally in the lateral gutter until visualization of the popliteus hiatus and the popliteus tendon. Knee flexion is then increased to 90° to 'plunge' the arthroscope in the popliteal space. This technique allows the visualization of the posterior tibia, the menisco-tibial capsular attachments, the popliteo-fibular ligament, the postero-superior PMF (PS-PMF) (Fig. 1b), the posterior lateral femoral condyle and the posterior aspect of the lateral meniscus. The antero-inferior PMF (AI-PMF) may sometimes be visible as well (Fig. 1a). The popliteus tendon is visible at its midportion only, as the femoral attachment site and its musculotendinous junction are difficult to visualize [7].

This visualization technique is challenging and may not be easy to perform for beginners. Beneath the technical difficulties related to the direct visualization of the posterolateral complex, interpreting the findings is highly related to the surgeon's skills and has limited reproducibility because of a lack of standardization and scientific evaluation.

### Anterior arthroscopic inspection of the PHLM

The second arthroscopic method to evaluate the stability of the PHLM is the classic anterior view with the knee held in a figure-of-4 position [16] This method has several disadvantages like the impossibility or difficulty to directly assess the PMF's and the limited joint line opening of the lateral tiobiofemoral compartment in narrow knees. But it however does allow for a direct visualization of the posterior root of the lateral meniscus (PRLM) and of the meniscofemoral ligaments. The diagnosis of PLRM injuries is commonly based on direct visualization of the tear or by the avulsion of the root during probing [4, 6]. In case of an incomplete root tear with an elongation of its meniscotibial attachment fibers (Video 1 and Fig. 2), the probing test is sometimes insufficient to unmask the instability of the PHLM. In case of an excessive mobility of the lateral meniscus during probing, the diagnosis of the PHLM instability can be made. However, this method is not always reliable and does not allow to precisely quantify the amount of subluxation of the PHLM.

### The aspiration test

The authors noticed a frequent discrepancy between instability of the PHLM at probing and with aspiration (Video 1). We therefore propose a quick and easy screening test to evaluate the instability of the PHLM: the aspiration test. At the time of the exploration of the lateral tibiofemoral compartment with the knee held in the figure of 4 position [16] and flexed to slightly more than 90°. The arthroscope is placed in the antero-lateral or antero-medial portal and directed towards the lateral tibiofemoral compartment. The aspiration test is easily performed by completely activating the aspiration of a 4,5 mm shaver placed at the center of the lateral tibiofemoral compartment (arthroscopy pump with standard knee configuration: DualWawe, Arthrex, Naples, FL, USA). The test can be repeated to allow for an ideal placement of the arthroscope or the shaver. As aspiration can trigger bleeding, it should then be performed during a shorter amount of time. Despite bleeding, this test has no known risk of structural meniscus injuries. In the absence of a pathological instability of the PHLM, no anterior translation is observed. Conversely, the diagnosis of instability of the PHLM can be confirmed in the presence of an excessive translation of the most unstable part of the posterior portion of the lateral meniscus to, or close to, the center of the lateral tibial plateau with fluid aspiration (Video 2). The location of the displaced portion of the PHLM may

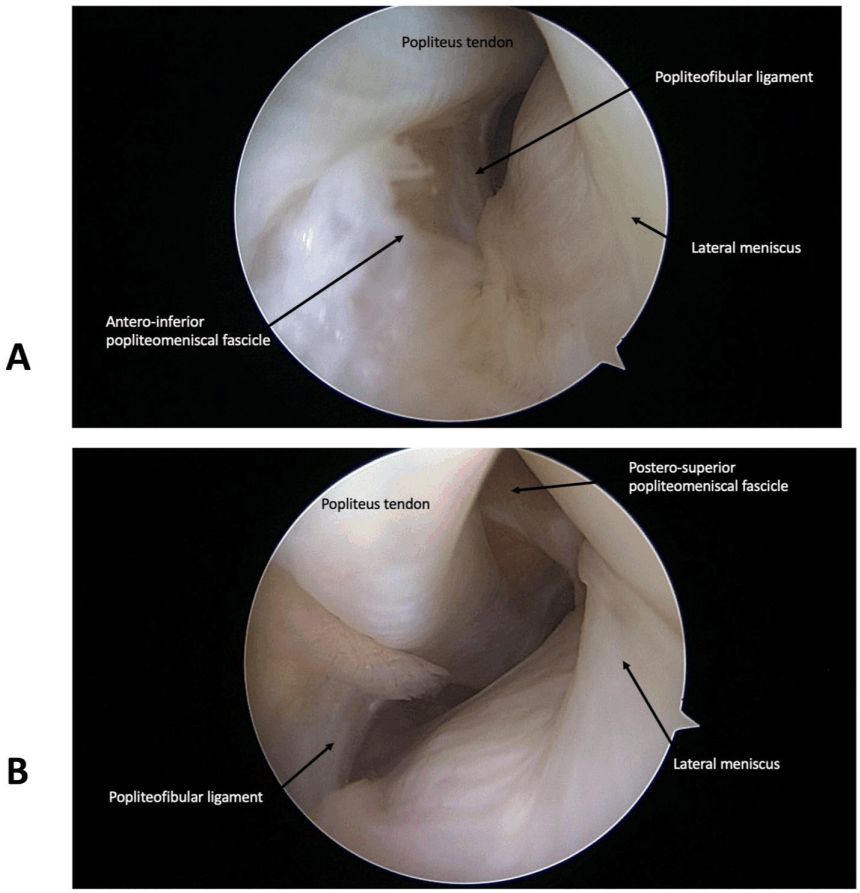


**Fig. 1** The lateral drive through sign showing the popliteus tendon, the antero-inferior popliteomeniscal fascile (**a**) and the postero-inferior popliteomeniscal fascicle (**b**)

indicate whether the instability is merely caused by an insufficiency of the AI-PMF, the PS-PMF (Video 2 and Video 3), the root attachment area or by a combination of insufficiencies in these structures. To obtain a reliable information during the aspiration test, care should be taken not to immobilize one of these areas with the shaver or the camera.

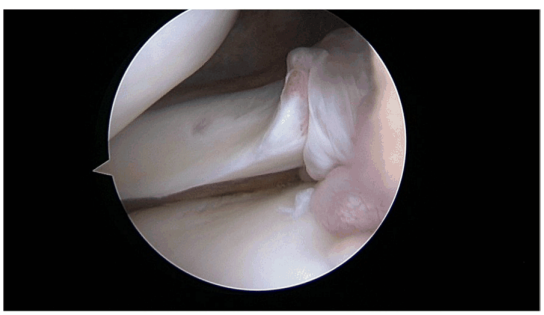

**Fig. 2** Incomplete root tears with an elongation of its meniscotibial attachment fibers

In case of an excessive anterior translation of the PHLM during the aspiration test, an additional evaluation by probing the PHLM and attempting to actively displace it into the joint can be performed. According to Shin et al., a translation of the lateral meniscus by more than 50% or 'beyond the equator' of the lateral femoral condyle, is considered as hypermobility [24]. This mobility may be influenced by the force exerted with the probe as well as the degree of opening of the lateral femorotibial compartment. It thus appears to be poorly reproducible. After repair of the PHLM and its suspensory mechanism, a second aspiration test allows to verify that the PHLM has been stabilized. (Video 1 and Video 4).

## Discussion

The most important information of this report was the description of the aspiration test, an easy and quick arthroscopic test to detect an instability of the PHLM.

The description of this test is important because the diagnosis of PHLM instability is often delayed or missed due to unclear and inconsistent clinical and imaging findings with no evident meniscal or articular cartilage abnormalities. Likewise, structural damage of the suspensory mechanism of the PHLM consisting of the popliteomeniscal fascicles, the meniscotibial posterior root attachment and the meniscofemoral ligaments is rarely obvious, even under direct arthroscopic visualization. The aspiration test is therefore useful to firmly identify the instability of the PHLM as well as to verify its stabilization after arthroscopic repair.

The anatomy of the suspensory mechanism of the PHLM is complex and its structural tissue damage difficult to evaluate arthroscopically. The PMF's are posterolateral menisco-capsular extensions that blend inferiorly into the musculotendinous portion of the popliteus. They allow the tendon to pass from an intraarticular to an extraarticular location while maintaining the compartmental integrity of the knee joint. At the height of the popliteal hiatus, the popliteus tendon attaches to the PHLM via at least two PMF: an anteroinferior (AI)-PMF and a posterosuperior (PS)-PMF [22]. Altogether, these fascicles form the hoop-like appearance of the popliteal hiatus. The PHLM has also two variable fibrous attachments from the femur running in front of and behind the PCL, the anterior meniscofemoral ligament (Humphrey), and the posterior meniscofemoral ligament (Wrisberg) [28]. Finally, the meniscus root which has been defined by Brody et al. [5] "as the last few millimeters of meniscal tissue angling down to the tibial plateau attachment in the intercondylar notch".

The pathophysiology of PHLM instability remains controversial. A frequent origin is a congenital deficiency of the peripheral attachments, like the Wrisberg-variant type of the discoid meniscus [10, 19] where the meniscotibial ligament or root attachment is absent, but the PHLM presenting an otherwise near normal shape [21, 33]. Another cause is that PHLM instability may occur in traumatic conditions, such as in ACL injuries. In these, the instability may be caused by a subtle and often invisible structural damage to the suspensory mechanism of the PHLM. ACL injuries typically occur during a combined anterior translation and external rotation of the tibia against the femur [8] causing a blow of the posterolateral tibial plateau against the lateral femoral condyle typically resulting in a bone bruise or an impression [11]. At the moment of anterior subluxation, the posterolateral suspensory complex of the PHLM is squeezed and massively strained between the femur and the tibia. The exerted shear forces may lead to a lateral meniscus tear or a structural damage to the suspensory mechanism of the PHLM. The incidence of these lesions however currently remains unknown. The high prevalence of lateral meniscus root tears (17% [18]) and lateral femoral and tibial bone bruises/impression fractures in association with ACL tears however suggests that a significant number of tears of the suspensory mechanism of the PHLM remains undiagnosed and untreated.

Several studies attempted to evaluate the structure and functions of the PMFs and its relations to the lateral meniscus and knee stability. In a cadaveric study, Simonian et al. [26] demonstrated an 78% average increase in anterior knee displacement at 90° of knee flexion with a 10-N load after cutting both the AI and PS-PMF. In their recent investigation comparing MRI and arthroscopic findings, Suganuma et al. [30] demonstrated the clinical importance of these structures by analyzing their presence or absence in recurrent subluxations of the lateral meniscus (RSLM) in stable knees. Abnormal PS-PMFs and AI-PMFs were found in 40 and 26%, respectively, in a control group of 215 healthy knees. An abnormal PS-PMF was identified in 100% of the knees with RSLM ($n=16$) and 100% of the contralateral knees of patients with RSLM ($n=7$). Abnormal AI-PMF was found in 100% of knees with RSLM compared to only 29% in the contralateral knees of patients with RSLM. An abnormal AI-PMF therefore seems to be the source of symptomatic instability of the lateral meniscus.

The biomechanical consequences of a PHLM root avulsion or elongation and meniscofemoral ligament injuries on PHLM stability have received little attention so far. The simulation of a complete radial root tear of the PHLM in a finite element model could however show that the lateral meniscus was only slightly displaced in a radial pattern by a compressive load. Additional insufficiency of the posterior meniscofemoral ligament, however, markedly increased the amount of the meniscal displacement [2]. Another study by Simonian et al. [26] confirmed that the section of PFMs increased significantly meniscal motion but did not determined meniscal displacement in the notch.

Despite the fact that the instability of the PHLM is directly associated with the lateral meniscus, distinct symptoms consistent with lateral meniscus pathology are uncommon. Knee locking in deep flexion however seems to be one of the repeating complaints in isolated PHLM instabilities [32]. In the absence of clear meniscal symptoms and imaging findings, mechanical symptoms should thus raise suspicion of a PHLM instability as part of the differential diagnosis [1].

The knowledge about the MRI appearance of the suspensory complex of the PHLM is still insufficient.

It is known from dissection study that the anatomy may vary from one subject to another. The presence or absence of PMF has been recorded with some variance [23]. Furthermore, Tria et al. [31] reported that 18 of 40 cadaveric knees had an isolated insertion of the popliteus tendon to the lateral femoral condyle with no connection to the lateral meniscus. Munshi et al. [20] reported seven of seven cadaveric knees with two fasciculi, also detectable in corresponding MRI images. Suganuma et al. [30], also recently reported on the use of magnetic resonance imaging (MRI) in the diagnosis of PMF tears. MRI however assesses the knee in static conditions and may not allow diagnosing the instability of the LMPH that occurs during knee motion as confirmed by Simonian et al. [26] who highlighted that patients with an unstable PMF tears at the time of surgery had normal MRI results. Similarly, Krych et al. [14] observed that on 45 patients with arthroscopically confirmed PHLM tears, only 15 (33%) were initially diagnosed on preoperative MRI. Arthroscopy and visual dynamic inspection of the lateral meniscus thus remains the gold standard in the diagnosis of PHLM instability.

The aspiration test has some advantages compared to the probing test. The traction force exerted during the aspiration test is standardized and operator-independent. Likewise, the aspiration force is equally applied to the entire structure of the PHLM and not only to the extremity of the arthroscopy probe. An alternative to the aspiration test has been described in the study by Steinbacher et al. [29] and was called the Tom's test in which an aspiration force is generated through the arthroscope and not the shaver. It has the disadvantage to negatively influence the visibility of the PHLM.

There are several limitations to the present report. The goal was not to evaluate the sensitivity or specificity of this test in the absence of a diagnostic gold standard. In the authors' current surgical practice, the presence of clinical symptoms suggestive of PHLM instability associated with a positive aspiration test systematically lead to a repair to stabilize the PHLM by using an all-inside repair technique. Another limitation is that this study did not look into the correlation with MRI, but it seems unsuitable for the diagnosis of this pathology. Further investigations are needed to evaluate the presence of a positive aspiration test in normal knees without PHLM instability symptoms as well as in patients with ACL injury.

## Conclusion

The aspiration test is a quick and easy arthroscopic test which can be performed in daily practice to evaluate the instability of the PHLM.

## Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s40634-021-00327-0.

**Additional file 1: Video 1**. Right knee with the 30° arthroscope in the antero-lateral portal. Incomplete root tears with an elongation of its meniscotibial attachment fibers with a discrepancy between instability at probing and with aspiration and a negative aspiration test after reparation.

**Additional file 2: Video 2**. Left knee with the 30° arthroscope in the antero-lateral portal. Positive aspiration test with displacement of the posterior part of the PHLM reflecting an insufficiency of the PS-PMF.

**Additional file 3: Video 3**. Left knee with the 30° arthroscope in the antero-medial portal. Positive aspiration test with displacement of the posterior and the anterior part of the PHLM reflecting an insufficiency of the PS-PMF and AI-PMF.

**Additional file 4: Video 4**. Left knee with the 30° arthroscope in the antero-medial portal. Negative aspiration test after reparation of the case presented in the video 2.

### Authors' contributions

CJ, RS have made substantial contributions to the conception and design of this report. All authors have made substantial contributions to the acquisition of data, or analysis and interpretation of data and have been involved in drafting the manuscript or revising it critically. All authors have given final approval of the version to be published and agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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### Ethics approval and consent to participate

Not applicable.

### Consent for publication

Not applicable.

### Competing interests

The authors declare that they have no competing interests.

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## Publisher's Note

# The aspiration test reveals an instability of the posterior horn of the lateral meniscus in almost one-third of ACL-injured patients

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# The aspiration test reveals an instability of the posterior horn of the lateral meniscus in almost one-third of ACL-injured patients

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## Abstract

**Purpose** Anterior cruciate ligament (ACL) injuries often lead to associated injuries of the posterior horn of the lateral meniscus (PHLM). Arthroscopic, assessment of PHLM instability may be difficult in the absence of a visible meniscus damage. The main objective of this prospective multi-center study was to compare the ability of the probing and aspiration tests to identify PHLM instability in a population of patients undergoing ACL reconstruction (ACLR) and a control group of patients with an intact ACL undergoing knee arthroscopy.

**Methods** A prospective case–control analysis was performed in three sports medicine centers. One-hundred and three consecutive patients operated for a primary isolated ACLR without structural lateral meniscus damage other than a root tear were included. They were compared to a control group of 29 consecutive patients who had a knee arthroscopy with an intact ACL and no structural lateral meniscus lesion. The probing and aspiration tests were consecutively executed according to previously published methods.

**Results** In the control group, no lateral meniscus lesions were visualized during arthroscopy, and both probing and aspiration tests were negative in all patients. In the group of ACL-injured patients, a Forkel type I–III posterolateral meniscus root tear (PLMRT) was found in 12 patients (12%). In this subgroup, the probing test was positive in 4/12 patients (33%) and the aspiration test in 5 additional patients (75%). In 15 patients (15%), an elongation of the posterior root of the lateral meniscus (defined as type IV PLMRT as an addendum to the Forkel classification) could be observed during arthroscopy. In this subgroup, only 1 patient displayed a PHLM instability with the probing test (7%), whereas the aspiration test was positive in 13/15 patients (87%). In the remaining 76 patients (74%), no structural lesion of the PHLM could be identified. Nevertheless, an instability of the PHLM could be identified in 8 of them (11%) with the probing test, and the aspiration test was positive in 2 additional knees (13%) of this apparently normal subgroup. Altogether, in the entire ACL injury cohort, a positive probing test was observed in 13/103 patients (13%) and a positive aspiration test in 32/103 knees (31%) ($p < 0.01$).

**Conclusion** Careful observation and examination of the PHLM with the aspiration test revealed a substantial amount of previously undiagnosed lateral meniscus instabilities in ACL-injured knees. The prevalence of PHLM instability as evaluated by the aspiration test was high (31%). The aspiration test was superior to the probing test in detecting an instability of the PHLM in a population of ACL-injured patients.

**Level of evidence** II.

**Keywords** ACL · Lateral root tear · Hypermobile meniscus · Instability · Aspiration test · Probing test

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## Introduction

The anatomy of the lateral meniscus is more complex than on the medial side [11]. This is due to complex posterior suspensory structures including the popliteomeniscal fascicles (PMF) and the posterior meniscotibial ligament (MTL) [2, 7, 19], as well as the posterior root and the meniscofemoral ligament which is made of a meniscotibial and a meniscofemoral fixation [3]. Damage to one or several of these structures can result in an instability of the posterior horn of the lateral meniscus (PHLM) which may occur either in isolation or in association with an anterior cruciate ligament (ACL) injury. Whereas the latter may cause a lack of rotational control of the knee, the former usually leads to lateral knee pain or locking sensations [5, 14, 15, 20, 22, 23].

The subluxation occurring in the lateral tibiofemoral compartment during the ACL injury mechanism may cause injuries to the area of the PHLM [12, 16]. Previous publications describing PHLM root tears estimated their prevalence to around 15% [6, 16]. Other injuries to the PHLM without arthroscopically visible structural damage such as posttraumatic instability have been described recently [10], but their prevalence is currently unknown. Since the structures of the PHLM play a role in rotational knee stability [8, 14, 20, 22], it seems crucial to further investigate this new entity. While major structural meniscus damage is easy to identify on MRI or during arthroscopy, assessment of PHLM instability may be difficult due to the lack of reliable clinical tests and imaging signs [21]. Therefore, PHLM instability may currently be easily overlooked. Direct visual dynamic inspection via arthroscopy remains the gold standard. Shin et al. [19] defined a PHLM instability as a displacement of more than half of the lateral meniscus underneath the 'equator' of the lateral femoral condyle during arthroscopic probing. In cases of limited joint line opening, probing as well as the precise quantification of the amount of subluxation can be difficult. This method is therefore not always reliable to diagnose PHLM instability. Recently, a new arthroscopic test called "the aspiration test" [10] has been proposed as an alternative to the probing test to improve the diagnosis of PHLM instability, but to date, no data are available to confirm this hypothesis.

Therefore, the main objective of this prospective multicenter study was to compare the ability of the probing and aspiration tests to identify PHLM instability between patients undergoing ACL reconstruction (ACLR) and a control group of patients with an intact ACL who underwent knee arthroscopy for other reasons. The hypotheses were that PHLM instability was frequently associated with ACL injuries and underestimated with current arthroscopic methods.

## Materials and methods

A prospective case–control analysis was performed in three sports medicine centers (France, Luxembourg, and Switzerland) between December 2020 and May 2021. The study was performed in accordance with ethical standards. All data were gathered anonymously by the team of clinicians who took care of the patients, so that it did not require prior approval according to our respective law and national ethical guidelines.

The first group of patients (ACL group) consisted of consecutive patients between 18 and 50 years of age who were operated for a primary ACLR. Patients were excluded if they had structural lesions (bucket-handle, vertical, horizontal, or radial tears) of the lateral meniscus other than a posterolateral meniscus root tear (PLMRT) according to the Forkel et al.'s classification [6] as observed during arthroscopic exploration, ACL agenesis, previous knee surgery in the ACL-deficient knee, concomitant collateral (> MRI grade 2) or posterior cruciate ligament injury, associated bone or cartilage procedure, and lateral discoid meniscus. Finally, 103 patients met inclusion and exclusion criteria, and were included.

The control group consisted of consecutive patients between 18 and 50 years of age who underwent knee arthroscopy with an intact ACL as confirmed by MRI. Control patients did not have clinical symptoms of the lateral tibiofemoral compartment and more specifically no clinical suspicion of the rare condition of an isolated PHLM instability. Exclusion criteria included structural lesions (bucket-handle, vertical, horizontal, or radial tears) of the lateral meniscus as observed during arthroscopic exploration, lateral femoral or tibial chondral defects ICRS > 1 [4], previous knee surgery, and lateral discoid meniscus. Finally, 29 patients met inclusion and exclusion criteria, and were included in this group. Indications for knee arthroscopy were collected and distributed as follows: 15 medial meniscus repairs (52%), 6 medial meniscectomies (21%), 5 isolated medial tibiofemoral or patellofemoral chondral defects (17%), and 3 diagnostic arthroscopies (10%).

### Arthroscopic evaluation

All arthroscopies were performed by three senior surgeons (one in each center). For both the ACL and the control group, a systematic arthroscopic exploration was performed at the beginning of the procedure to confirm the diagnosis and to identify the inclusion and exclusion criteria. The standardized surgical sequence was as follows:

1. Direct visualization of the lateral tibiofemoral compartment

A classic anterior view with an antero-medial portal with the knee held in a figure-of-4 position was performed. It allowed direct visualization of the chondral status for both the lateral tibial plateau and the lateral femoral condyle using the ICRS classification [4], the lateral meniscus, its posterior root, and the meniscofemoral ligaments. The "lateral gutter drive-through" sign [18] which theoretically allows for the visualization of the posterior tibial plateau, the meniscotibial capsular attachments, and the PMF was not routinely performed in this study. In case of a PLMRT associated or not with a meniscofemoral ligament tear, the Forkel classification [6] was used to categorize the tear. A new type IV lesion called "elongation" was added to this classification (Fig. 1). This type of lesion corresponds to an elongation of the root occurring at the time of the trauma without an identifiable disruption of the meniscotibial fibers, but with fibers that were distended after injury.

2. Probing test

   The arthroscope was placed in the same antero-medial portal with the knee held in a figure-of-4 position. A new antero-lateral portal was created to introduce the probe in the lateral tibiofemoral compartment to reach the PHLM. According to Shin et al. [19], a translation of the lateral meniscus by more than 50% or 'beyond the equator' of the lateral femoral condyle was considered as a positive probing test.

3. Aspiration test

   The test was performed as previously described [10]. With the knee held in the figure-of-4 position and flexed to slightly more than 90°, the arthroscope was placed in the antero-lateral or antero-medial portal and directed towards the lateral tibiofemoral compartment. The aspiration test was performed by activating the aspiration of a 4.5 mm shaver (arthroscopy pump: DualWawe, Arthrex, Naples, FL, USA, with standard knee configuration, aspiration shaver: 300 ml/min), and placed at the center of the lateral tibiofemoral compartment. As for the probing test, a translation of the lateral meniscus by more than 50% or 'beyond the equator' of the lateral femoral condyle was considered as a positive aspiration test.

## Statistical analysis

The analyses were performed using SPSS software v.25 for Windows.

The Mc Nemar test was used to compare the result (positive or negative) of the probing and the aspirations tests and the kappa coefficient (Kappa Test for Agreement) was reported to indicate the extent of agreement between both tests. Chi-square tests with Bonferroni correction were used to determine whether positive aspiration test, respectively, and positive probing test were associated with the status of the lateral meniscus (no visualized tear, type I–III root tear, and type IV root tear) under arthroscopy. Each expected cell count was checked to ensure that it was greater than five. If more than 20% of cells had an expected cell count inferior to five, the $p$ value of likelihood-ratio Chi-square test was considered. To estimate the effect size, Cramer's $V$ was used [15]. Significance was set at $p < 0.05$ for all analyses.

A priori sample size was calculated to obtain a statistical power of 80% and an alpha value of 5% using unpublished pilot data on the probing and aspiration test results of 60 patients. Based on the proportion of negative probing test/positive aspiration test (no event–event) of 10% and the proportion of positive probing test/negative aspiration test (event–no event) of 1%, a minimum sample size of 104 patients was required.

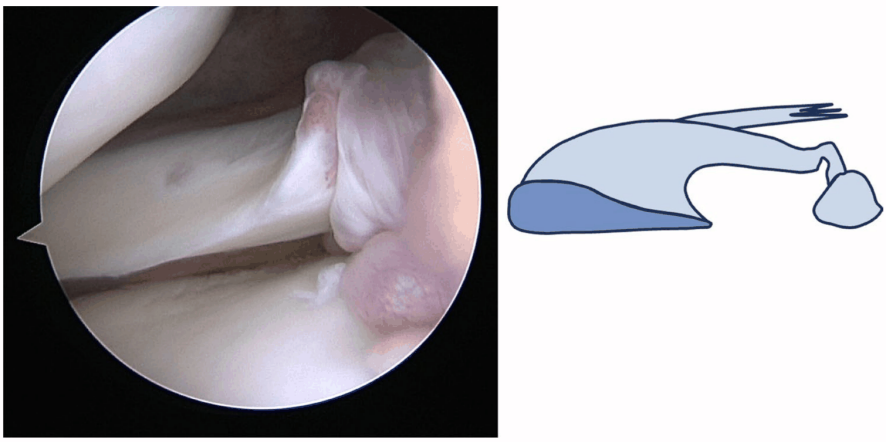

**Fig. 1** Arthroscopic view and representation of the new type IV posterolateral meniscus root tear

**Table 1** Lateral meniscus status in both the ACL and the control group

| Type of lateral meniscus tears | ACL group ($n=103$) | Control group ($n=29$) |
|---|---|---|
| No visible tear | 76 (74%) | 0 |
| Root tear type I | 3 (3%) | 0 |
| Root tear type II | 2 (2%) | 0 |
| Root tear type III | 7 (7%) | 0 |
| Root tear type IV | 15 (15%) | 0 |

## Results

The status of the lateral meniscus under arthroscopy is presented in Table 1, both for the control and the ACL groups. In the control group the probing and aspiration tests were negative and the lateral meniscus appeared normal under arthroscopy in all patients. In the group of ACL-injured patients, the probing and aspiration tests were positive in 13% ($n=13/103$) and 31% ($n=32/103$) of the cases, respectively (Table 2). The difference between the probing and the aspiration test was significant ($p<0.01$). Both tests showed agreement in 111 out of 132 patients (Kappa agreement = 0.46). In 20 ACL-injured patients (17% of all studied cases), the probing test was negative, while the aspiration was positive. The reverse was true in only one ACL-injured patient.

The percentage of positive aspiration tests varied according to the status of the lateral meniscus (no visible tear, type I–III root tear, type IV root tear; $p<0.01$; Cramer's $V=0.65$). The same association could not be confirmed with a positive probing test (n.s). In the presence of a type I–III root tear, the probing test was positive in 4/12 patients (33%) and the aspiration test in 9/12 patients (75%; Kappa agreement between both tests = 0.29). In the presence of a type IV root tear, the probing test was positive in 1/15 patients (7%) and the aspiration test in 13/15 patients (87%; Kappa agreement between both tests = 0.02). In the absence of a visible tear, the probing test was positive in 8/76 patients (10.5%) and the aspiration test in 10/76 patients (13%; Kappa agreement = 0.748) *(Fig. 2)*.

**Table 2** Results of the probing and the aspiration tests in both the ACL and the control group

| Group | Type of lateral meniscus tear | *n* | Aspiration test | | Probing test | |
|---|---|---|---|---|---|---|
| | | | Positive | Negative | Positive | Negative |
| ACL | | 103 | 32 (31%) | 71 | 13 (13%) | 90 |
| | Root tear types I–III | 12 | 9 (75%) | 3 | 4 (33%) | 8 |
| | Root tear type IV | 15 | 13 (87%) | 2 | 1 (7%) | 14 |
| | No visible tear | 76 | 10 (13%) | 66 | 8 (11%) | 68 |
| Control | | 29 | 0 | 0 | 0 | 0 |
| | No visible tear | 29 | 0 | 0 | 0 | 0 |

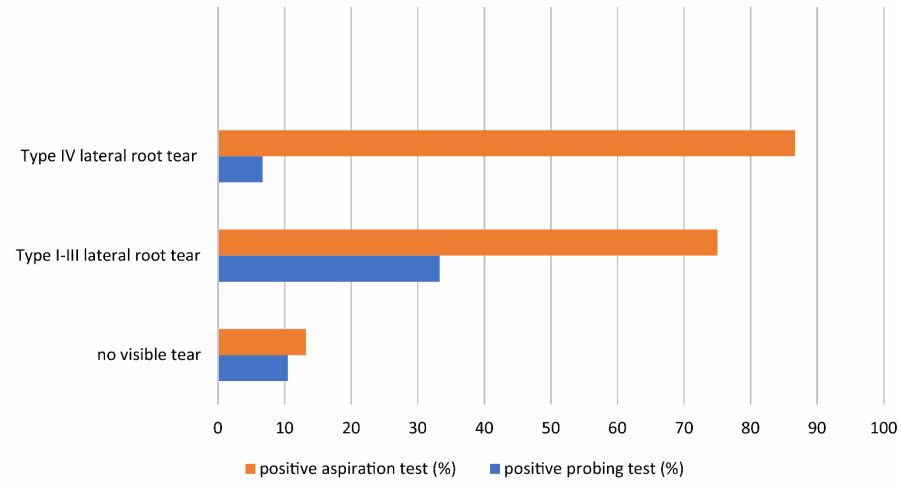


**Fig. 2** Distribution of positive probing and aspiration tests according to the status of the lateral meniscus in the ACL group

## Discussion

The main finding of this study was that the aspiration test allowed to identify a prevalence of PHLM instabilities in 31% of ACL-injured patients versus 0 in the control group. Of the 32 patients with a positive aspiration test, 9 had an easily identifiable I–III tear of the PLMR and 13 displayed the newly presented elongation of the PLMR (named type IV as an addendum to the Forkel classification). Finally, 10 ACL-injured patients with a positive aspiration test displayed a PHLM instability despite an arthroscopically intact lateral meniscus. In comparison to the probing test, the aspiration test allowed to better identify instabilities of the PHLM. The superiority of the aspiration test became especially obvious for type IV PLMRT, where more than 85% of the cases could be detected (versus less than 10% with the probing test). The hypothesis that the prevalence of PHLM instability was high in ACL-injured patients (31%) and that PHLM instability was underestimated by the probing test is thus confirmed.

In a recent study, Jacquet et al. [10] described the aspiration test, a method supposed to allow for a better discrimination of PHLM instability as compared to the probing test. The latter was until today the gold standard procedure during routine arthroscopic surgery to identify this condition. According to Shin et al. [19], a translation of the lateral meniscus during the probing test by more than 50% or 'beyond the equator' of the lateral femoral condyle is considered to reflect an instability. However, probing may not necessarily be the best method to evaluate PHLM instability, since mobility of the PHLM may be influenced by the force exerted with the probe as well as the degree of opening of the lateral tibiofemoral compartment [10]. The aspiration test allows to apply a standardized and evenly distributed traction force to the PHLM and thus reflects a reliable visual dynamic inspection of the lateral meniscus. The results of this study showed its superiority compared to the probing test and confirmed the improved detection of PHLM instability which was identified in 31% of ACL-injured patients. In the absence of the rare condition of an isolated PHLM instability (excluded in this study in the control group), the fact that none of the patients of the control group had a positive aspiration test allowed to literally rule out the possibility of false-positive evaluations and confirmed that the aspiration test is an effective method to evaluate PHLM instability in ACL-injured patients.

The pathophysiology of PHLM instability in ACL-injured knees remains insufficiently understood and its prevalence remains unknown. ACL injuries typically occur during a combined anterior translation and external rotation of the tibia against the femur [6] causing a blow of the posterolateral tibial plateau against the lateral femoral condyle typically resulting in a bone bruise or an impression fracture [9]. At the moment of anterior subluxation, both the posterolateral suspensory complex and the posterior root of the lateral meniscus are squeezed and massively strained between the femur and the tibia. The exerted shear forces may thus lead to the currently well-classified [6, 13] and easily identifiable PLMRT. The variability in the reported prevalence of type I–III PLMRT (7–17%) [5, 16, 17] and the high prevalence of lateral femoral and tibial bone bruises/impression fractures [24] in the area of the suspensory complex of the PHLM may suggest that a significant number of lesions to the PHLM are undiagnosed. Thus, a more subtle structural damage to the suspensory complex of the PHLM may occur in a significant amount of ACL-injured knees. These pathologic tissue alterations are either not macroscopically visible or they present with an elongation of the PLMRT, here classified as type IV lesions, the suggested extension of the Forkel classification. To the best of the authors' knowledge, type 4 PLMRT or elongations of the posterior root of the lateral meniscus have not been described previously. This type of lesion corresponds to an incomplete tear of the root occurring at the time of injury where the meniscus tissue undergoes a severe distraction with an incomplete subsequent healing process (Fig. 1). In their respective PLMRT classifications, neither Laprade et al. [13] nor Forkel et al. [6] described this entity. In this study, this type of PLMRT was observed in 15 ACL-injured patients. Likewise, in ten additional patients, a PHLM instability without visible structural damage to the lateral meniscus could be identified and could represent an isolated damage to the suspensory complex of the PHLM.

The prevalence of type I, II, and III PLMRTs was 12% in the current series. This is in accordance with the previous publications where it was reported to be between 7 and 17% [5, 16, 17]. Adding the type IV to the other three types of PLMRT leads to a prevalence of 27% of PLMRT. In all but two patients (13/15; 87%) presenting with this specific type IV lesion, the aspiration test revealed a PHLM instability, whereas the probing test allowed to identify it in only 7% of patients. The poor agreement between the tests for this subpopulation supports the fact that the aspiration test is superior to the probing test in differentiating stable from unstable PHLM lesions that may need to be repaired. Further studies are needed to specifically investigate the biomechanical and clinical consequences of this type of lesion, such as their impact on dynamic rotatory laxity and the residual pivot-shift phenomenon after ACLR.

There are several limitations to the present study. Due to the multi-centric and international design of the study, and in order to be in accordance with ethical approval, no epidemiological data concerning the patients such as age, gender, and

mechanism of injury could be analyzed. Following sample size calculation, the size of the ACL group cohort was limited to 103 patients. Larger cohorts or registries are needed to confirm the prevalence of PHLM instability in ACL-injured patients. Another limitation is that this study did not look into the correlation with MRI, which—at the current state of knowledge—seems unsuitable for the diagnosis of this pathology [1, 21]. It is also important to note that one of the main strengths of this study is the presence of a control group in which no instability of the PHLM could be demonstrated during both the probing and the aspiration tests. Further studies are needed to investigate the natural history, the biomechanical consequences and the surgical management of PHLM instabilities. Despite these limitations, the results of this study confirmed the superiority of the aspiration test over the probing test in the diagnostic of PHLM instability but also the high prevalence of this pathology in ACL-injured patients. The aspiration test should be used in routine clinical practice during systematic arthroscopic exploration of ACL-injured patients.

## Conclusion

Careful observation and examination of the PHLM with the aspiration test revealed a substantial amount of previously undiagnosed lateral meniscus instabilities in ACL-injured knees. The prevalence of PHLM instability as evaluated by the aspiration test was high (31%). The aspiration test was superior to the probing test in detecting an instability of the PHLM in a population of ACL-injured patients.

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## Declarations

**Conflict of interest** The authors declare no conflict of interest in relation to the subject of work.

**Ethical approval** All data were gathered anonymously by the team of clinicians who take care of the patients and therefore have a right to access to their medical records. As the study was performed in accordance with ethical standards of the institutional and national research committee, it did not require prior approval.

**Informed consent** None.



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# List of further publications

## Original articles

Schröter S, Lohmann B, **Magosch A**, Heiss R, Grim C, Freiwald J, Engelhardt M, Hoppe MW, Hotfiel T. Effects of foam rolling on vastus intermedius and lateralis microvascular blood flow. *Journal of bodywork and movement therapies*. 2023;36:228-234. DOI: 10.1016/j.jbmt.2023.07.011.

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**Magosch A**, Nührenbörger C, Hoffmann F, Mouton C, Seil R. VKB-Verletzungen im Kindes- und Jugendalter [Paediatric and Adolescent ACL Injuries]. *Sportverletzung Sportschaden: Organ der Gesellschaft für Orthopädisch-Traumatologische Sportmedizin*. 2025;39(4). Epub ahead of print. DOI: 10.1055/a-2537-6205.

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Hoffmann A, **Magosch A**, Pape D, Seil R. Wachstum und Entwicklung des Kindes [Growth and development of the child]. In: Schmitt H (editor). *Sportorthopädie und -traumatologie im Kindes- und Jugendalter: Sporttauglichkeitsprüfung und Sport bei Verletzungen und Erkrankungen, 2nd edition*. Springer, Berlin/Heidelberg. 2023. p. 3-15. DOI: 10.1007/978-3-662-63737-1_1. ISBN: 978-3-662-63736-4.

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# Curriculum Vitae

For data protection reasons, the curriculum vitae is not included in the electronic version of this dissertation.