MENTORS IN ORTHOPEDICS

MEDIAL MENISCUS RAMP LESION INJURY INCREASES EXTRUSION AND MENISCAL MOBILITY

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SUMMARY

Background: Medial meniscus ramp lesions, involving the posterior horn and its meniscocapsular attachments, occur in up to 40% of anterior cruciate ligament (ACL) reconstructions. While these injuries are associated with increased rotatory laxity and anterior tibial translation in ACL-deficient knees, their specific impact on meniscal kinematics and extrusion under axial loading remains insufficiently characterized.

Objective: This cadaveric study aimed to quantify and compare medial meniscal mobility and extrusion between intact knees and those with grade 4 ramp lesions using 7-Tesla MRI and digital volume correlation (DVC) under varying axial loads.

Key Points: Two cadaveric specimens were subjected to axial loads of 0N, 750N, and 1500N in full extension. Following the creation of a grade 4 ramp lesion via a posteromedial arthroscopic approach, DVC analysis of 33,619,968 data points demonstrated significant increases in meniscal displacement. At 1500N, the mean lateromedial displacement (extrusion) increased from 2.11–2.81 voxels in native knees to 4.48–4.71 voxels in injured knees. Similarly, mean anteroposterior displacement increased from 0.48–2.11 voxels to 3.29–7.31 voxels post-injury. These findings indicate that disruption of the meniscotibial and meniscocapsular attachments significantly compromises the stabilizing "hoop" function of the medial meniscus.

Conclusion: Grade 4 medial meniscus ramp lesions significantly increase meniscal extrusion and posterior mobility during axial compression, even in ACL-intact states. Because meniscal extrusion is a known precursor to compartment hyper-pressure and cartilage degeneration, these results suggest that surgical repair of ramp lesions may be necessary to restore joint kinematics and prevent secondary osteoarthritis.

KEYWORDS

Tibial Meniscus, Medial; Knee Joint; Biomechanical Phenomena; Magnetic Resonance Imaging; Cadaver

INTRODUCTION

Medial meniscus ramp lesions and lateral meniscus posterior root lesions are present in more than a third of primary and revision ACL reconstructions [24]. Medial meniscus ramp lesions (RL) are very common traumatic injuries with a prevalence of 21.9% (range, 9.0%-41.7%) at the time of anterior cruciate ligament (ACL) reconstruction [4],[21]. Ramp lesions are defined as a particular type of injury within the posterior horn of the medial meniscus and its menisco-capsular attachments. [38] Among the different types of ramp lesions, meniscocapsular junction tears (type 1) were the most common, followed by type 4 (complete tear in the red zone) [38].

Currently, the understanding of the meniscus biomechanics is certainly at the forefront of orthopaedic discussions [20],[29]. Meniscocapsular and meniscotibial lesions of the posterior horn of the medial meniscus increased knee anterior tibial translation, internal and external rotation, and the pivot shift in ACL-deficient knees.[1],[10],[12],[27],[33],[36] But the available literature discussing the biomechanical consequences of ramp lesions remains limited. It is not clear whether these lesions affect joint kinematics and loading in the medial compartment [3],[4],[6]. Recently, some authors [19],[25] reported that meniscal extrusion is not only due to the root lesions but also relative to meniscotibial ligament (MTL) injuries. Although meniscal extrusion is often the consequence of hyper-pressure in the medial femorotibial compartment, it could be the cause in different cases, such as in the case of a ramp lesion. The objective of this cadaveric study was to compare the medial meniscal mobility between native knees and knees with grade 4 ramp lesions by a digital volume correlation (DVC) method using 7 Tesla MRI images at different loadings. The hypothesis of this study is that medial meniscus ramp lesion increases meniscal mobility and extrusion.

METHODS

Specimen characteristics and preparation

This experimental study was conducted on two cadaveric knees collected at the ABS Lab laboratory of the University of Poitiers (Ministry of Education and Research No. DC-2008-137) and whose morphotype was normo-axed with a meniscal and cartilaginous state judged to be intact during the 7 Tesla MRI examination. The epidemiological data showed a 63-year-old man (73kg) and an 81-year-old woman (79kg) with no osteoarticular history and whose CT scan measurement of HKA angle was 178.9° (leg length: 123.4cm) and 177.8° (leg length: 127.7cm) respectively. These knees were then disarticulated below the hip and above the ankle and dissected, preserving the entire capsule and peripheral ligaments without opening the knee joint. Proximal and distal fixations of rigid polyurethane resin were made in order to facilitate the fixation of the anatomical parts on an MRI-compatible loading bench without ferromagnetic components and designed specifically for this series of experiments (Figure 1). These cadaveric knees initially from fresh and non-formalin fixed specimens were then cryopreserved after the primary dissection phase. Before each experiment, the thawing protocol consisted in placing the cadaveric segments at room temperature for 48h in order to optimize the elasticity-solidity relationship and to get closer to the physiological conditions found in living patients.

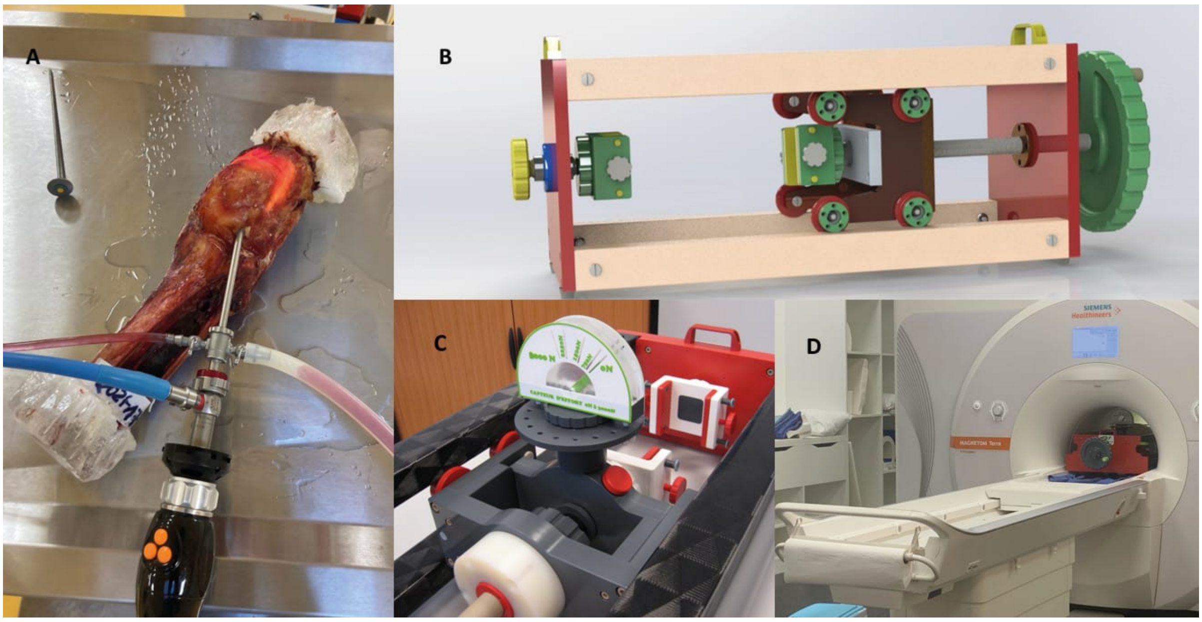

Figure 1: Anatomical view of a knee segment with its proximal and distal fixations of rigid polyurethane resin (A). MRI-compatible loading bench (B) with its pressure sensor (C) without ferromagnetic components to go into the 7T MRI (D).

Experimental protocol

An initial series of 7T MRI imaging was performed on these native knees at progressive loads ranging from 0N to 1500N, equivalent to more than twice the body weight load. A second series of images was then taken on these same knees with the same loads after grade 4 medial meniscus ramp lesions [38] had been made under arthroscopy by a posteromedial instrumental approach (Figure 2).

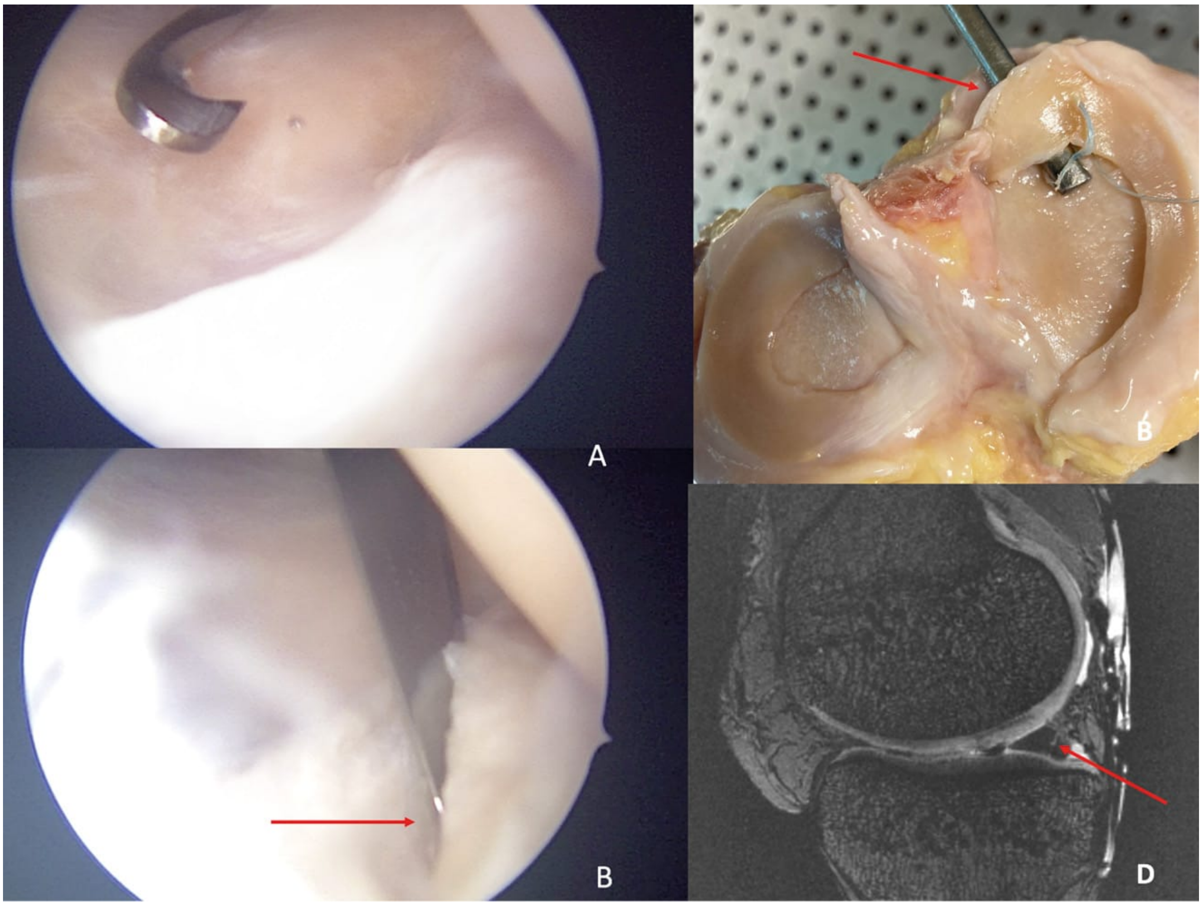

Figure 2: Arthroscopic views (A and B) of subtype 4 medial meniscus ramp lesion realization by a posteromedial approach. Open view of the knee and its meniscal ramp lesion injury after experimentation (C). MRI sagittal view in sequence T2 DESS of the subtype 4 ramp lesion injury.

Digital volume correlation and assessment criteria

Digital volume correlation (DVC) is used to determine the three components of displacement and spatial variations of a material or structure from volumetric images 3,5,11. In the initial image, a sub-volume of voxels (D) is defined in each voxel. Each sub-volume is then searched by measuring the degree of similarity in the distorted image. For this purpose, a correlation sub-volume is represented by the value of the voxels constituting it denoted ($f(\overrightarrow{X})$) at the initial state, with $\overrightarrow{X}$ the position vector of the sub-volume at initial state. The position of the searched sub-volume in the distorted image is denoted $\overrightarrow{x}$ and the gray levels constituting it $g(\overrightarrow{x})$. The level of similarity between a sub-volume of the initial state and a sub-volume of the deformed state is defined by a correlation coefficient 14 based on the optimization of a functional

$f(\overrightarrow{X}) - g(\overrightarrow{\phi} (\overrightarrow{X}))$

and where $\overrightarrow{\phi}$ is the material transformation between the deformation states. This non-contact method allows the measurement of volume displacements in the structure from 1 µm to several tens of millimeters [13],[39] (Figure 3).

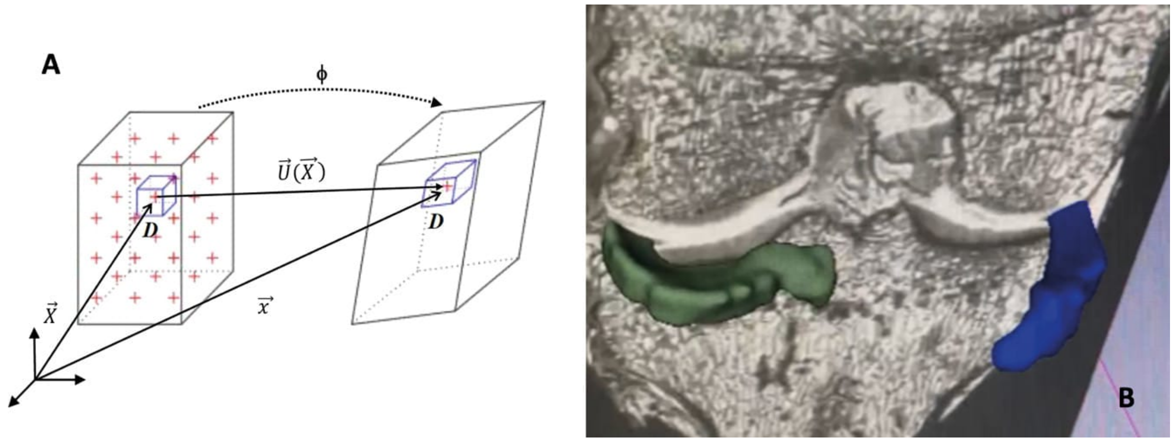

Figure 3: Diagram explaining the principle of the digital volume correlation (DVC) and the measurement of displacement fields between two image sequences (A). View of the manual segmentation of the medial and lateral meniscus to obtain a mask of the region of interest for DVC.

Overlay of the constrained and unconstrained MRI images was performed by semi-automated tibial registration of the image sequences with the 3DSlicer software (Version 4.11, Kitware, France). Manual segmentation of the medial meniscus was performed on the first MRI to obtain a mask of the region of interest to be analyzed to DVC.

The displacement fields were analyzed in all three dimensions, but the observation of the displacements in x and y made it possible to analyze the anteroposterior and/or lateromedial migration of the meniscus after axial compression, with the knee positioned in full extension (Figure 4).

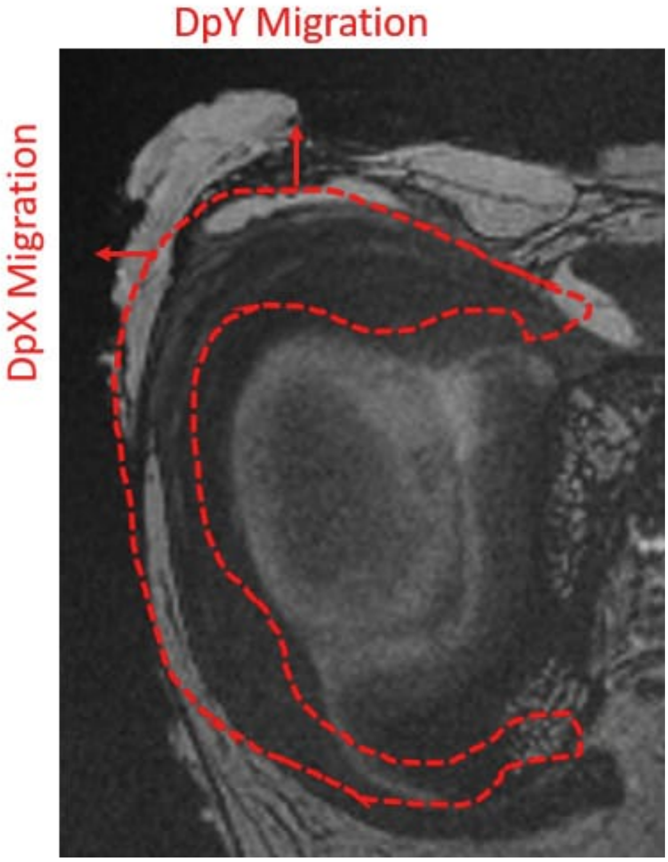

Figure 4: Illustration of the orientation of the displacement fields analyzed in DVC on a coronal MRI slice of a right cadaveric knee.

Statistical analysis

The statistical analysis was performed with IBM SPSS® Statistics software (version 19.0). Wilcoxon paired tests (non-parametric) were used to compare the distribution of each parameter and analyze the variations in the displacement fields in the various experimental conditions. The significance threshold was set at $p < 0.05$.

RESULTS

The directional displacements of the medial meniscus were measured by DVC at 33.619.968 points. Figures 5 through 8 show the directional displacement fields obtained by DVC after application of a 0N, 750N and 1500N axial load.

Mean displacements are expressed in voxels (1voxel=0.35 mm, ± standard deviation) and were measured on the posterior segment of the medial meniscus, anteriorly to the ramp lesion.

In the lateromedial direction (DpX), the mean displacements measured at 1500 N load were -2.809 (±0.778) on the first native knee versus -4.480 (±9.570) on the same knee with ramp lesion injury. For the second knee, the mean displacements measured in X with this same load were 2.108 (±0.380) before and 4.705 (±0.884) after ramp lesion injury. With a grade 4 medial meniscal ramp lesion, the meniscus increases its extrusion in the frontal plane (Figure 5 & 7).

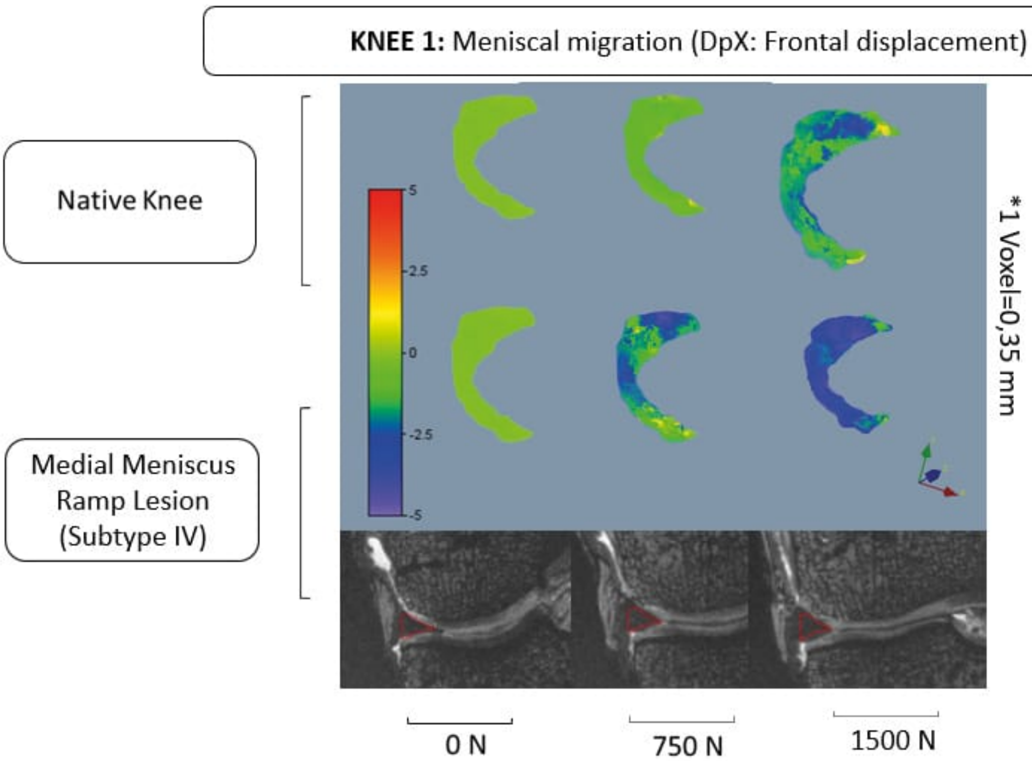

Figure 5: Observation of the displacement fields after DVC assessment for the knee 1 in the lateromedial direction (X).

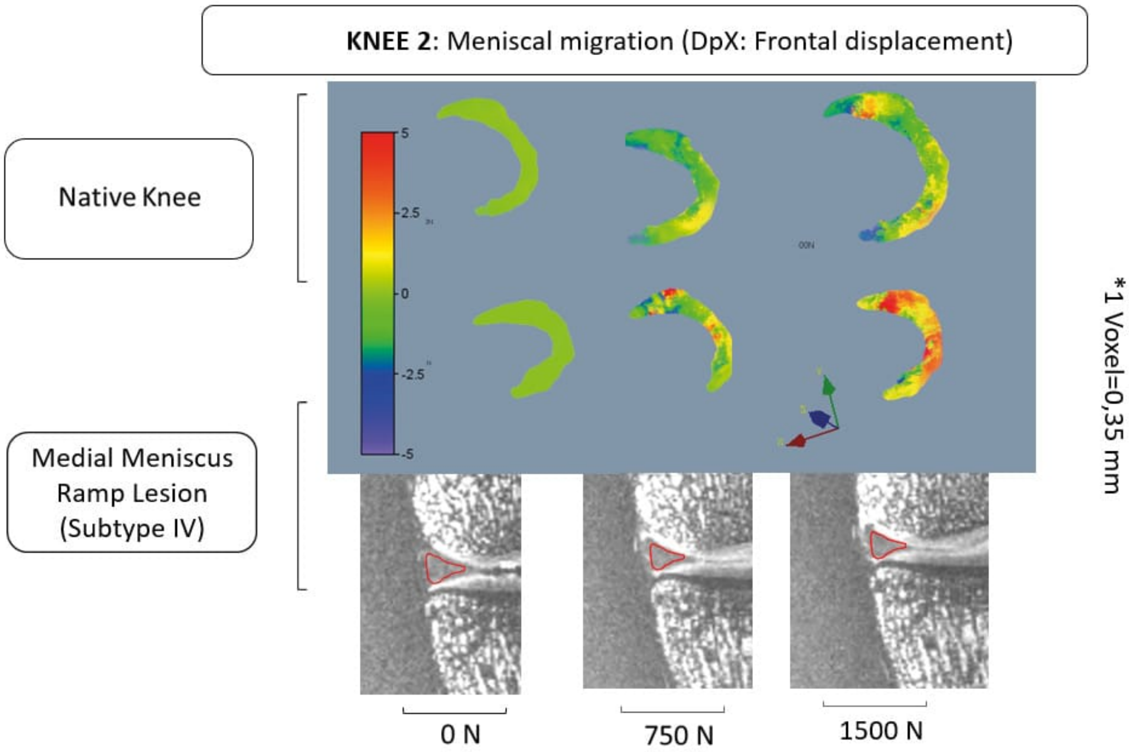

Figure 7. Observation of the displacement fields after DVC assessment for the knee 2 in the lateromedial direction (X).

In the anteroposterior direction (DpY), the mean displacements measured at 1500 N load were 0.476 (±0.552) on the first native knee versus 3.285 (±0.819) on the same knee with ramp lesion injury. For the second knee, the mean displacements measured in Y with this same load were 2.112 (±0.378) before and 7.311 (±1.312) after ramp lesion injury. With a grade 4 ramp lesion, the posterior segment of the medial meniscus increases its posterior extrusion in the sagittal plane (Figure 6 & 8).

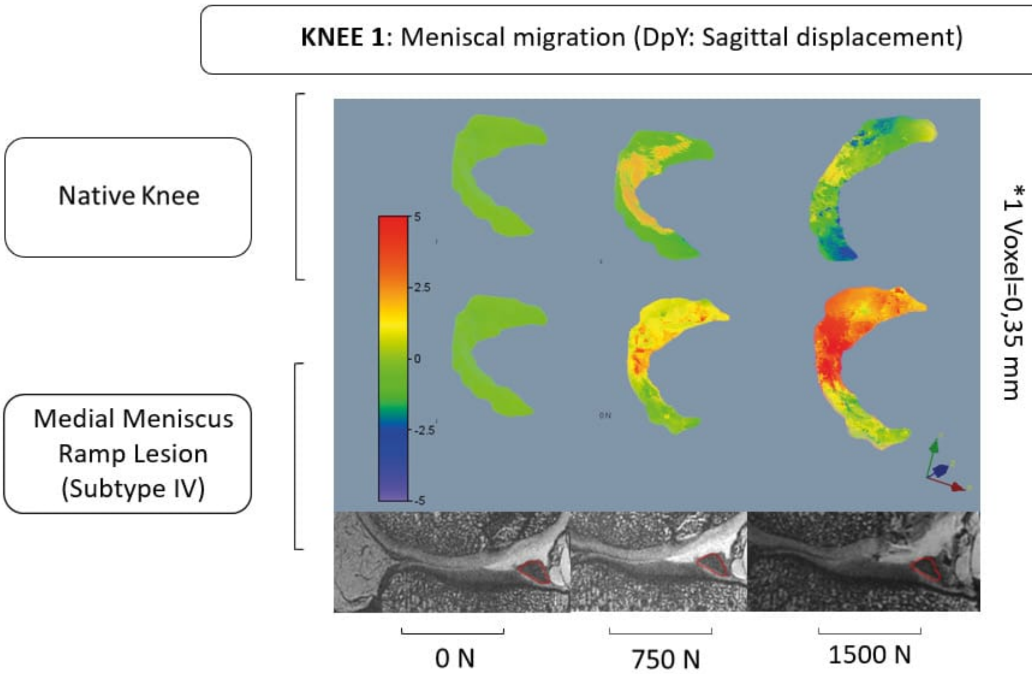

Figure 6: Observation of the displacement fields after DVC assessment for the knee 1 in the anteroposterior direction (Y).

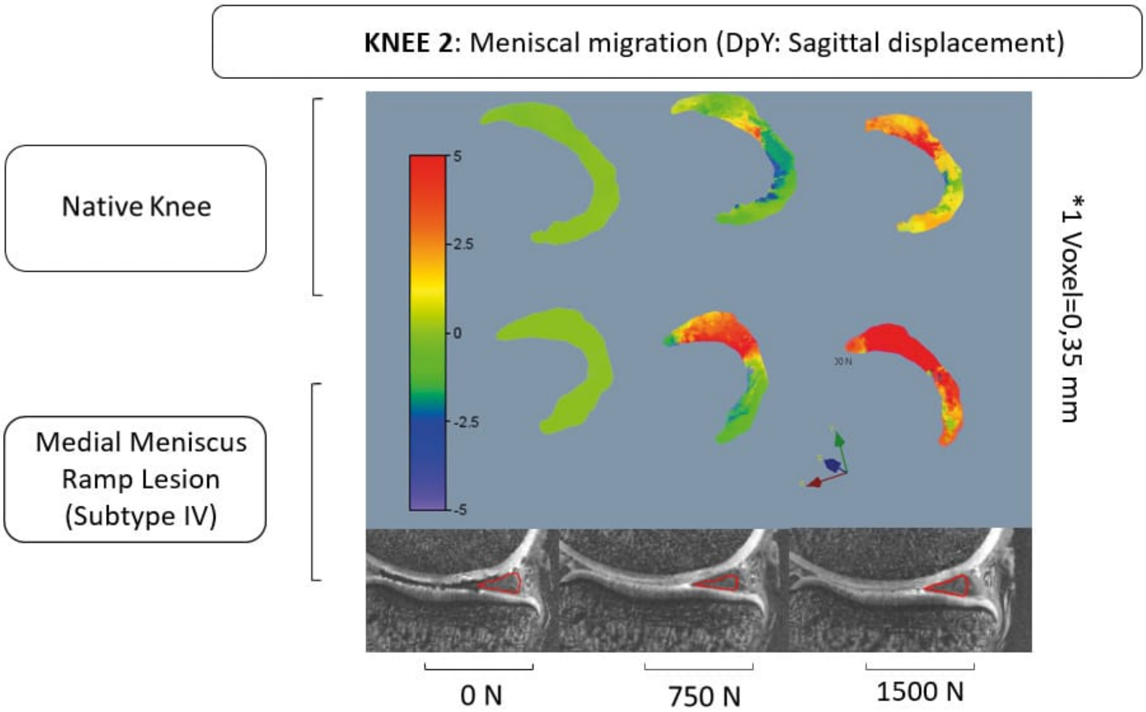

Figure 8: Observation of the displacement fields after DVC assessment for the knee 1 in the anteroposterior direction (Y).

All data on the anteroposterior and/or lateromedial migration of the meniscus after axial compression between native knees and injured knees are summarized in Table 1.

Displacement measurement (DVC)	KNEE 1					
	Native Knee			Medial Meniscus Ramp Lesion		
	0 N	750 N	1 500 N	0 N	750 N	1 500 N
Lateromedial direction (DpX)						
Mean	-0,13	-0,803	-2,809	0,045	-1,952	-4,48
Min-Max	-0,239	-1,51	-4,592	-0,219	-6,693	-35,313
SD	0,042	0,285	0,778	0,055	0,989	9,57
Anteroposterior direction (DpY)						
Mean	-0,213	0,402	0,476	-0,083	0,909	3,285
Min-Max	-0,435	0,134-0,632	-4,872	-0,214	0,296-2,101	3,119-4,949
SD	0,021	0,116	0,522	-0,083	0,3	0,819

Displacement measurement (DVC)	KNEE 2					
	Native Knee			Medial Meniscus Ramp Lesion		
	0 N	750 N	1 500 N	0 N	750 N	1 500 N
Lateromedial direction (DpX)						
Mean	0,052	1,726	2,108	0,04	2,795	4,705
Min-Max	-0,191	1,044-2,768	1,391-2,210	-0,219	0,389-6,873	3,143-7,506
SD	0,039	0,392	0,38	0,056	1,443	0,884
Anteroposterior direction (DpY)						
Mean	-0,084	0,029	2,112	-0,081	4,988	7,311
Min-Max	-0,191	-2,091	1,372-2,803	-0,181	2,346-7,376	4,206-9,046
ET	0,028	0,208	0,378	0,037	1,04	1,312

Table 1: Displacement measurement obtained by DVC after application of a 0N, 750N and 1500N axial load between native knees and injured knees (data are expressed in voxels with 1voxel=0.35 mm).

DISCUSSION

The main finding of this study was that medial meniscus ramp lesion injury increases meniscal extrusion that is defined as the internal displacement of the medial meniscus in relation to the medial margin of the tibial plateau, and meniscal posterior mobility during axial compression. This biomechanical study confirms that ramp lesions could be responsive of meniscal extrusion usually considered as the result of meniscal root lesion or disruption of the coronary ligaments or isolated MTL injury [6],[19],[25],[28],[38].

Meniscal extrusion is known to be an important predictor of accelerated joint degeneration [17],[19]. In most cases, diagnosing meniscal extrusion is critical not only for the acute functional disability it imposes on the patient, but also for its direct relationship with osteoarthritis (OA) and is observed in elderly people [15],[37]. It may seem difficult to know what is the cause or the consequence. However, meniscal extrusion seems to decrease the hoop function of the meniscus and increases the risk of knee OA. 30 In our case, the ramp lesion is a common meniscal injury that principally occur in case of ACL rupture or knee laxity associated with anterior cruciate ligament insufficiency with a higher prevalence for patients younger than 30 years of age and male patients [23]. Nevertheless, the current literature agrees that meniscal extrusion with or without ACL deficiency increased mechanical loading and pathological response of joint tissue to the abnormal mechanical stress can cause degradation of cartilage characteristic of knee OA, especially in the medial compartment knee [8]. In the same principle, a significant relationship was found between the degree of the medial meniscus extrusion and the onset of post-arthroscopic osteonecrosis of the knee [40].

Only one study [28] found contradictory results with a non-significance on the knee medial stress due to ramp lesion injuries, but was performed on ACL-intact knees with a maximum axial compression load of 200N on a freedom robotic testing system. While these same authors think the indications for ramp lesion repair may be limited, there are number of reasons that seem to encourage meniscal repair in addition of the risk of OA degeneration due to RL. Medial menisci with ramp lesions are less stable and could progress toward a bucket-handle tear, especially in case of subtype 4 or 5 lesions [38]. In addition, DePhilippo et al [10] have observed that meniscotibial and meniscocapsular lesions of the posterior segment of the medial meniscus increased knee anterior tibial translation, internal and external rotation, and the pivot shift in ACL-deficient knees. Optimal treatment has been debated in the literature, especially for stable ramp lesions, although good outcomes have been shown with and without repair [4]. Healing rates of ramp lesions were significantly better when lesions are repaired and surgical procedures appear to be reliable. [16] Recently, Park et al [32] have analyzed the joint capsule adjacent to the medial meniscus and found that the perimeniscal joint capsule has collagen fiber orientation similar to that of circumferential meniscal fibers, potentially playing a role in preventing extrusion. They have found that the circumferential rim augmentation suture reduced the degree of meniscal extrusion while restoring meniscal function, potentially preventing progression of arthritis in a rabbit root tear model and porcine knee biomechanical analysis.[32]

Normally, the amount of extrusion is quantified by measuring the distance between the medial edge of the tibial plateau and the most prominent medial point of the medial meniscus [7]. In the literature, a meniscal extrusion greater than 3 or 4 mm seems to have a biomechanical impact on tibiofemoral compartment contact area and pressures [9]. Our results are below these but concern knees without OA and ACL-insufficiency. On the other hand, meniscal mobility was also found in the healthy knees. Kawaguchi et al. demonstrated in an ultrasound-based study that physiologic loading can cause meniscal extrusion to a mild degree [18]. Similarly, another ultrasound study showed that the posterior portion had greater extrusion than the anterior portion and this mainly for the medial meniscus [35]. Other studies have investigated the displacements and 3D morphological changes of the menisci under knee weight-bearing and early flexion conditions in healthy adults using MRI [22]. No data are currently available on injured knees with volume quantification by MRI. Only our work has evaluated meniscal displacement by DVC at different axial compression load. This direct correlation DVC technique is however a reliable, reproducible and already proven technique, provided that the study sub-volumes are optimized [26],[31].

The study has limitations. First, this was a cadaver study. Although we have tried to optimize the elasticity/solidity ratio with our institutional thawing procedure, performing this study on fresh cadaver knees would allow us to come even closer to reproducing the physiological conditions of the meniscal displacement in living patients.

Secondly, this study was realized with the knee in extension because of the 7T RMI device. However, the extrusion of meniscus's medial body seemed to be greater in full extension compared to any other flexing angles. Mechanical loading can significantly deform the menisci in knee extension; however, this effect is limited during knee flexion.[22] In contrast, anteroposterior mobility measures commonly increased with the rising of knee flexion motion [35]. For this reason, the data concerning lateromedial displacement (DpX) appear to be more informative.

It is possible that variability between our results and the findings of other future studies could be due to the characteristics of the created lesions. The definition of ramp lesions is constantly debated, especially in terms of length. A ramp lesion has been commonly defined as a 2.5-cm tear. [2],[6] However, during our experimentation, the length of the ramp lesion we were able to achieve was 20 and 21 mm according with the statement of DePhillipo et al [10] who have clearly etablished that the length of the posteromedial meniscocapsular junction may not exceed 2 cm because otherwise it would be heard at the midportion of the meniscus.

CONCLUSION

Subtype 4 medial meniscus ramp lesion injury increases meniscal extrusion and meniscal posterior mobility during axial compression in ACL-intact knees. Indeed, meniscotibial ligament and meniscocapsular junction seem to behave like the belt and suspenders of the medial meniscus.

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