2024-1 | 49th congress of the Société de Biomécanique
29-31 octobre 2024, Compiègne, France

Multidisciplinary Biomechanics Journal

Biomechanical effects of medial meniscus ramp lesions on tibial cartilage, extrusion, and mobility using 7T Magnetic Resonance Imaging and Digital Volume Correlation

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Received date: 07/04/2024
Accepted date: 28/06/2024
Publication date: 31/01/2025

Keywords: medial meniscus, ramp lesion, cartilage, digital volume correlation (DVC), MRI

1. Introduction

The study investigates subtype 4 medial meniscus ramp lesions, a common occurrence in ACL-deficient knees, but one that lacks thorough biomechanical understanding (Ollivier *et al.*, 2022) for adjacent structures under physiological loadings. Ramp lesions, often seen in ACL reconstruction cases, involve the posterior horn of the medial meniscus and its attachments, notably the meniscocapsular junction and meniscotibial ligament (Ahn *et al.*, 2011; Dephilippo *et al.* 2018). While some suggest that these lesions might heal well, their impact on cartilage biomechanics remains uncertain, with limited literature addressing joint kinematics and loading in the medial compartment. Consequently, this study aims to bridge this gap by measuring medial tibial strain variations coupling 7T-Magnetic Resonance Imaging (MRI) and the DVC method in three conditions.

2. Methods

2.1 Experiments

This biomechanical experimental study involved two anatomical specimens with normal knee joint alignment and intact meniscal and cartilaginous structures, obtained with approval of ethical committee of the Anatomy Laboratory of the University of Poitiers (DC-2019-3704 Université de Poitiers). The specimens, comprising a 63-year-old man and an 81-year-old woman without osteoarticular history, underwent dissection while preserving the joint capsule and ligaments. Polyurethane rigid fixations were applied to facilitate attachment to an MRI-compatible loading bench. A customized loading apparatus was developed to be used within the MRI device, enabling compression loading up to 2000N and calibrated using a home-made hydraulic sensor (Figure 1). Sequential 7 Tesla MRI imaging was conducted on native knees according to anatomical axial direction at progressive loads up to 1500N, followed by induction of grade 4 medial meniscus ramp lesions through arthroscopy. Anatomical images were acquired using 3D T2 DESS 0.35 mm isotropic (TR 8ms, TE 2.48 ms, slice 0.35 mm, 464 × 464 matrix size, FA 24°, FOVr 164mm, FOVp 72.4%, 1 Nex, PAT 2) (Severyns *et al.*, 2024). Additional MRI scans were performed post-lesion creation and after arthroscopic suture repair or total meniscectomy. To minimize degradation, experiments were completed within 24 hours with hydration maintenance, except during MRI acquisitions.

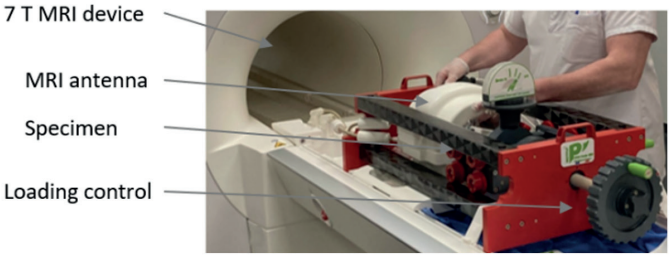

Figure 1. Specific loading device.

To cite this article: Mathieu Severyns, François Zot, Guillaume Herpe, Mathieu Naudin, Jérôme Danion, Tanguy Vendeuvre, Arnaud Germaneau, Biomechanical effects of medial meniscus ramp lesions on tibial cartilage, extrusion, and mobility using 7T Magnetic Resonance Imaging and Digital Volume Correlation, *Multidisciplinary Biomechanics Journal*, 2024, vol. 1, p. 343-345, DOI: 10.46298/mbj.14539.

2.2 Digital Volume Correlation (DVC)

DVC was employed to assess displacement and spatial variations, allowing measurement of volume displacements ranging (Valle *et al.*, 2019). Tibial registration and manual segmentation facilitated analysis of medial tibial cartilage and meniscus areas, respectively. Displacement fields were analyzed in three dimensions, focusing on anteroposterior and lateromedial migration of the meniscus during axial compression with the knee in full extension.

3. Results and discussion

The directional displacements of the medial meniscus and tibial cartilage were observed under axial compression. The meniscus exhibited increased extrusion in the frontal plane and posterior extrusion in the sagittal plane with grade 4 ramp lesions. Specifically, in the lateromedial direction (X), mean displacements at 1500N load increased post-lesion, indicating greater extrusion for both knees. Similarly, in the anteroposterior direction (Y), mean displacements significantly increased after ramp lesion injury, indicating posterior extrusion. These findings are summarized in Table 1, illustrating the meniscus' migration following axial compression.
Conversely, displacement fields of the medial tibial cartilage along the Z axis demonstrated restoration with all-inside arthroscopic suture and increased thickness with meniscectomy. Volume displacement observations revealed quantitative changes in mean displacements with various interventions at 1500N load. Normal loaded knees exhibited specific mean displacements, which were altered post-ramp lesion creation and further modified with repair or meniscectomy. Notably, after total internal meniscectomy, mean displacement increased significantly on one specimen, highlighting the impact of surgical interventions on cartilage displacement under axial compression.
The study's primary findings highlight the impact of medial meniscectomy and all-inside arthroscopic suture on medial tibial cartilage displacement under compression, revealing that meniscectomy increases displacement fields while suture restores conditions similar to pre-injury. These results mark an original quantitative assessment of knee cartilage mechanics under loading, emphasizing the significance of ramp lesions in altering stress patterns and the potential of surgical repair to restore physiological behavior.

Table 1. Migration of meniscus according to axial compression.

	Native knee	Medial Meniscus RL
	1500N	1500N
Lateromedial direction (mm)		
Mean	0.860	1.607
Min/Max	-1.599/0.487	-3.154/1.101
SD	0.272	3.350
Anteroposterior direction (mm)		
Mean	0.286	0.705
Min/Max	-1.014/0.691	1.091/1.732
SD	0.183	0.287

The study underscores the biomechanical implications of ramp lesions, linking them to meniscal extrusion and associated risks of osteoarthritis. While some studies suggest limited influence on knee mechanics, others emphasize the importance of repair due to instability and potential progression to more severe tears.

4. Conclusions

The study highlighted that subtype 4 medial meniscus ramp lesions lead to increased meniscal extrusion and posterior mobility during axial compression in ACL-intact knees, suggesting that meniscotibial ligament and meniscocapsular junction act as crucial stabilizers. While these findings enhance understanding of ramp lesions biomechanics, their clinical implications warrant long-term evaluation before advocating routine arthroscopic repair. Additionally, the study introduces novel experiments conducted in a 7T MRI device to assess displacement fields on knee cartilage surfaces, revealing that ramp lesions exacerbate medial tibial cartilage displacement.

Acknowledgements

Authors would like to thank ABS Lab of the University of Poitiers for all the support for experiments.

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