Experimental characterization of the human meniscal tissue

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***Abstract*— The meniscus plays a critical role in load transmission, stability and energy dissipation in the knee joint. Loss of the meniscus leads to joint degeneration and osteoarthritis. In a number of cases replacement of the resected meniscal tissue by a synthetic implant might avoid the articular cartilage degeneration. None of the available implants presents optimal biomechanics characteristic due to the fact the biomechanics functionality of the meniscus is not yet fully understood. Mimicking the native biomechanical characteristics of the menisci seems to be the key factor in meniscus replacement functioning. This is extremely challenging due to its complex inhomogeneous microstructure, the lack of a full experimental characterization of the material properties and the lack of 3D theoretical, numerical and computational models which can reproduce and validate the experimental results. The objective of this work is to present the experimental characterization of the anisotropic meniscal tissue at the macroscale. Innovative Biaxial tests have been conducted and the results are new to the literature.**

Keywords—meniscal tissue; biaxial tests; fractional viscoelasticity

I. INTRODUCTION

The meniscus is a type of tough fibro cartilage, crescent-shaped soft tissue that conforms to the surfaces of the bones upon which they rest within the knee joint. There are two menisci: lateral and medial meniscus, each rests between the thigh bone (femur) and shin bone (tibia) as shown in Fig.1a [1]. The meniscus plays a critical role in load transmission, stability and energy dissipation in the knee joint by helping to protect the joint from the stresses placed on it from physical activities. Meniscal injuries are the most common injuries of the knee, in 15 % of all knee injuries either one of the menisci is involved. Medial meniscal injuries are generally seen more frequently than injuries of the lateral meniscus. Due to an aging and more active population, the number of meniscus-related operations has notably increased in the last decade [2]. It has been noticed that the loss of the meniscus leads to joint degeneration and osteoarthritis as contact stresses on the tibial plateau increase proportionally with the amount of meniscus tissue removed as schematically shown in Fig. 2a. Hence replacing the resected meniscal tissue by an artificial implant might be necessary in order to avoid the articular cartilage degeneration. Currently the clinical and functional outcomes for these devices are not ideal [2]. Therefore, mimicking the native biomechanical characteristics of the menisci seems to be the key factor in meniscus replacement functioning. The mechanical functionality of the meniscus and its relationship with the tissue's complex material properties and structure is still not fully understood and is currently a key challenge within the field of musculoskeletal biomechanics. The cross-section of both menisci can be divided into three distinct layers as shown in Fig 2b. The different microstructure, fiber orientation and composition of the three layer leads to different stress concentrations hence to site specific biomechanical properties. At the macroscale the meniscal tissue can be considered as a

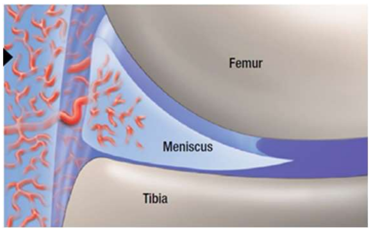


Fig1. (a) Schematic representation of the meniscus [1].

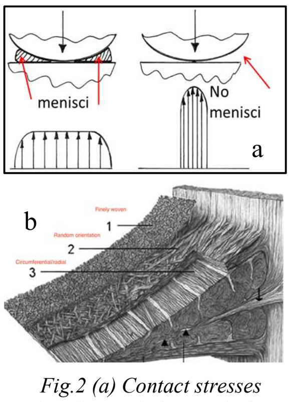


Fig.2 (a) Contact stresses distribution before and after meniscectomy [3]. (b) collagen fiber ultrastructure and orientation within the meniscus[4].

composite material exhibiting a transversely isotropic behavior. Additionally, the presence of material heterogeneity that modifies the mechanical characteristic of the meniscus possess a multiscale nature due to the different arrangements of the fibers in the tissue. Under these circumstances the use of classical mechanics is no more the more appropriate choice and non-local models, with physically justified additional terms in the governing equations may provide more reliable results [5-8]. The question is then: what mechanical properties and which internal structure at micro-macro level an optimal meniscal replacement need to have in order to mimic the native biomechanical characteristics of the menisci? This work aims to start addressing this question by presenting uniaxial tests and biaxial tests on different region of the meniscal tissue. The results show that the meniscal tissue is anisotropic. Uniaxial tests show that the Young moduli in the circumferential direction are significantly higher than in the radial direction [8]. Biaxial tests allowed to determine the material parameters needed for characterizing the transversely isotropic behavior of the meniscal tissue. The results will be used in a subsequent work in order to carry out three dimensional finite element simulations of the meniscal tissue behavior [9-12].

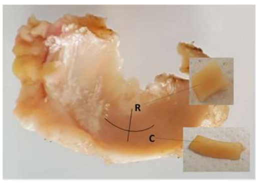


Fig.3 Uniaxial samples in circumferential and radial direction of the meniscal tissue [8].

II MATERIALS AND METHODS

The menisci have been retrieved from meniscectomies which have been performed at the Rizzoli Orthopedics Institute in order to implant a total knee replacement. A scalpel has been used in order to cut specimens in both radial and circumferential directions from lateral and partial medial meniscal tissues. The dimensions of the specimens for the uniaxial tensile tests are: 3mm length and 6mm diameter for the radial specimens; 5mm length and 5mm diameter for the circumferential specimens. For the biaxial tests square specimens with thickness between 2.5 and 5mm have been cut. The specimens have been embedded in a solution of NaCl 0.9% solution during both set of tests.

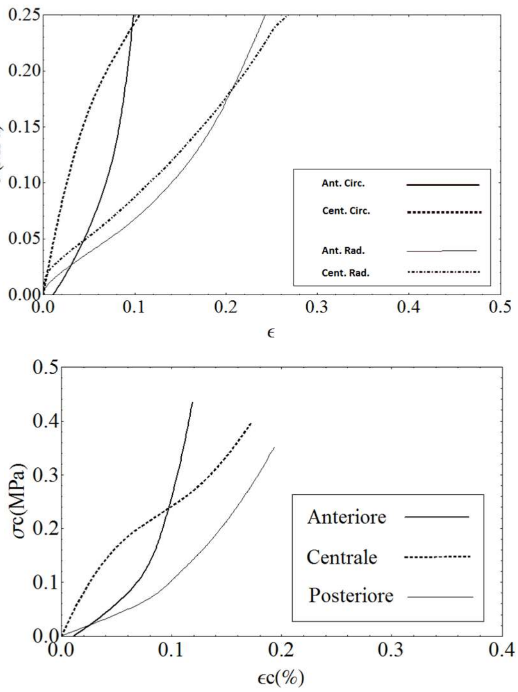


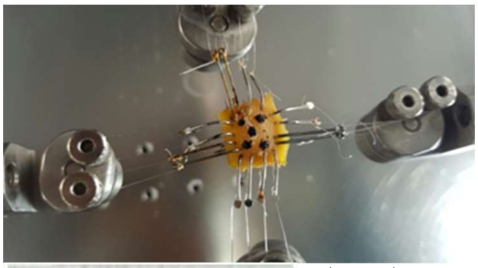
Fig.4 (a) Radial and Circumferential specimens: comparison stress-strain curves, (b) Circumferential specimen: stress-strain curves in anterior, central and posterior region [8].

III RESULTS

Uniaxial tensile tests

Uniaxial tests along the two principal directions (radial and circumferential as shown in Fig.3) have been performed by using the Multi-Specimen Bio Dynamic. A load of 10 N and a loading rate of 0.05 N/s has been applied. The results show a considerably higher stiffness in the circumferential direction as shown in Fig. 4a. It is worth to be noted that the behavior of the meniscal tissue for both radial and circumferential specimens is different in the anterior, central and posterior regions as illustrated in Fig.4b.

Biaxial tensile tests



Biaxial tests of meniscal tissue from the three regions anterior, central and posterior have been performed using the Planar Biaxial Testbench BOSE. Fig.5 shows the experimental set up and the position of the meniscal sample. A series of equi-biaxial tests at three loading levels of 10N, 5N and 2N have been performed in a previous study. Results in Fig.6 a and b show a lateral contraction of the anterior portion of the lateral meniscal tissue in both directions when a load of 10N is applied. Furthermore, Fig.7 a and b show a different behavior for the posterior portion of the lateral meniscal tissue when a loading of 5N is applied. It can be seen that, in this case, in the radial direction an initial lateral elongation is observed followed by a lateral contraction. However, in the circumferential direction an elongation is observed throughout the test. It has been experienced that in order to obtain a more uniform strain field in the specimen, a ratio of about 2:1 of the load in the two directions needs to be considered. Fig.8a and Fig.8b shows the result of biaxial tests of the anterior portion of the lateral meniscus. A load of 5N in the circumferential direction and of 2N in the radial direction has been applied. It can be seen that, the anterior part of the meniscus stretches in both directions. Fig.9a and Fig.9b show

Fig. 5 Experimental set up for biaxial test, including a magnification showing the positioning of the sample [8]

the stress-strain curves of a posterior medial meniscal specimen loaded at 8N in the circumferential fiber direction and 4N in the radial fiber direction. It can be noted an initial lateral extension is observed followed by a lateral contraction in the radial direction. A lateral elongation in the circumferential direction is registered throughout the test.

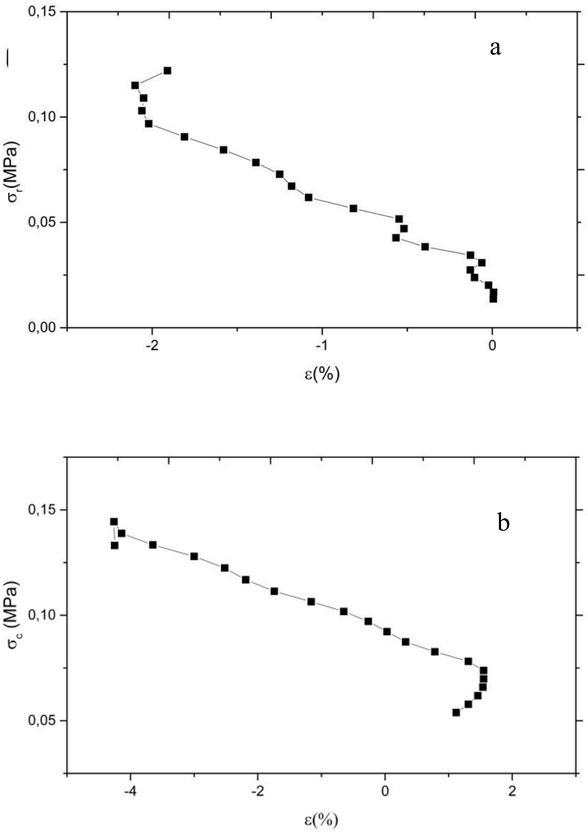


Fig. 6 Tests at 10 N and 10 N for an anterior lateral meniscal tissue. (a) radial direction and (b) circumferential direction.

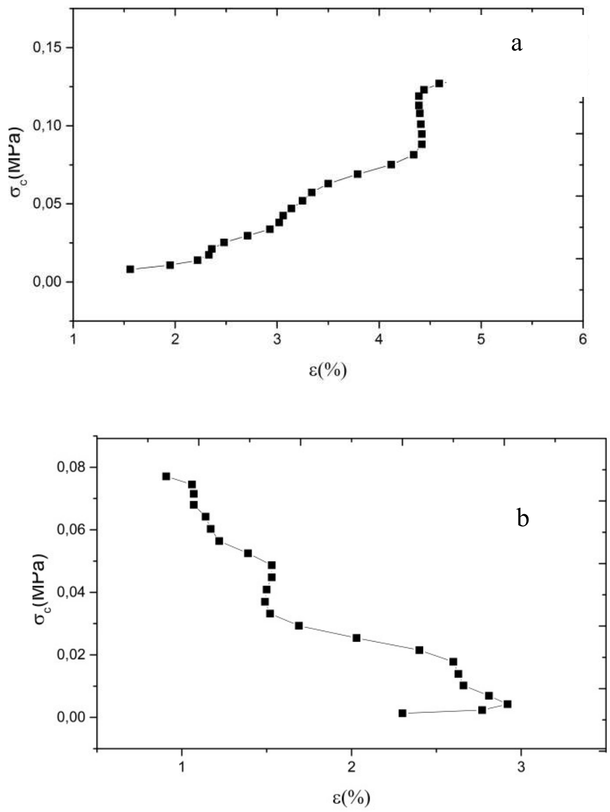


Fig. 7 Tests at 5N and 5 N for a posterior lateral meniscal tissue. (a) radial direction and (b) circumferential direction.

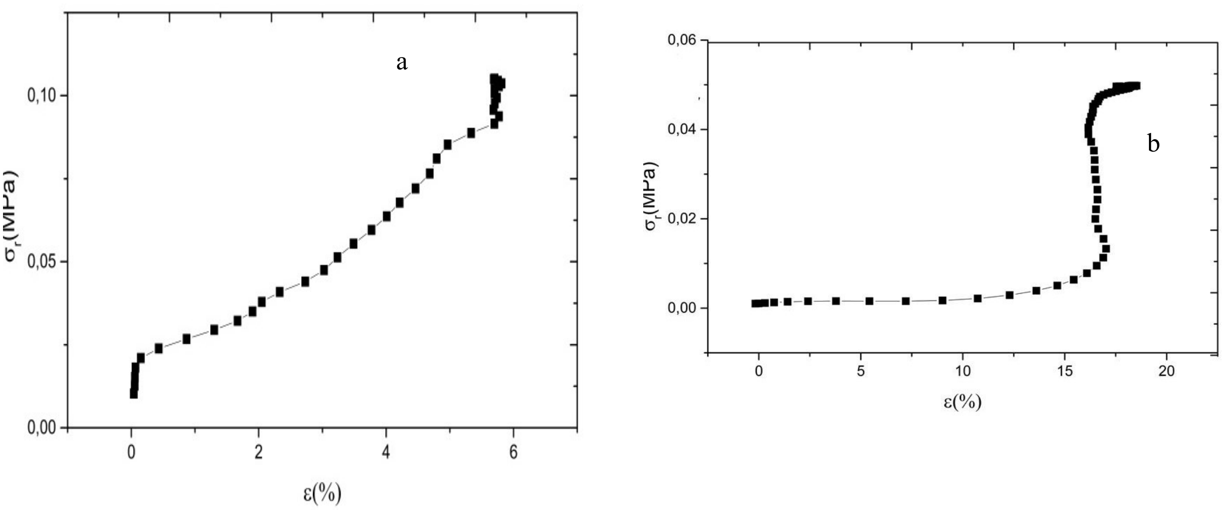


Fig. 8 Tests at 2N and 5N for a anterior lateral meniscal tissue. (a) radial direction and (b) circumferential direction.

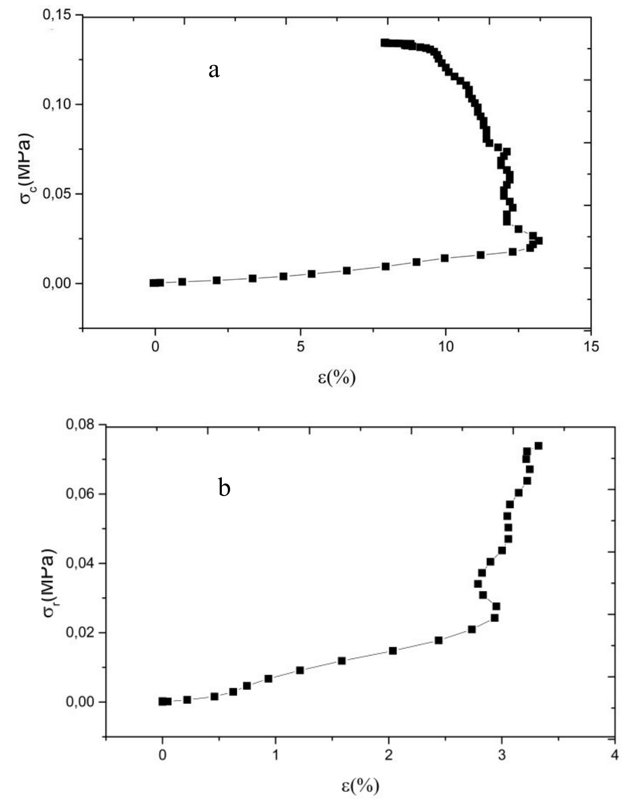


Fig. 9 Tests at 8 N and 4 N for a posterior medial meniscal tissue. (a) radial direction and (b) circumferential direction.

Table 1 summarizes the average values found in the biaxial tests, stress, strains and Young's module for the two directions of interest.

IV CONCLUSIONS

A range of uniaxial biaxial experimental test on anterior and posterior region of lateral meniscal tissue has been presented.

Uniaxial tests highlight a consideraly higher stiffness in the circunferencial directions than the radial direction. This is due to the fact that internally the fibers are alligned with the direction of the load. Biaxial tests results emphasise the strong difference between the behavior of the anterior and the posterior portion of the lateral meniscus. Both equi-biaxial tests and tests in which a 2:1 ratio of the loads in the two directions has been applied, have been performed and show similar results. While the anterior portion exhibits a lateral contraction in both circunferencial and radial direction, the posterior portion shows a different behaviour in the two directions. In particular, in the radial direction, an initial lateral extension is observed followed by a lateral contraction. Instead a lateral elongation in the circumferential direction is observed throughout the test. These results highlight and confirm the highly anisotropy of this tissue. Understanding the

Test	σ_C [MPa]	σ_R [MPa]	ε_C	ε_R	E_C [MPa]	E_R [MPa]
10N -10N Lateral Anterior	0.076±0.038	0.054±0.0413	1.39±1.008	1.8±0.0373	0.147±0.057	0.02±0.0006
5N-2N Lateral Anterior	0.082±0.0473	0.064±0.0327	3.86±1.1	3.56±2.13	0.19±0.088	0.0487±0.007
5N-5N Lateral Posterior	0.027±0.0017	0.03±0.025	1.35±0.99	2.03±1.28	0.021±0.025	0.012±0.006
8N-4N Medial Posterior	0.082±0.059	0.036±0.019	9.15±3.31	1.54±0.48	0.01±0.006	0.08±0.001

Table. 1 Average values of the stress, strain and o the Young module E in MPa±SD for both direction related to each test.

reason behind the difference in the behavior of the anterior/posterior region is extremely important in order to understand the macroscopic behavior of the meniscus and to formulate appropriate constitutive models. In this article there are different differences from what reported in the literature. In particular, the values of elastic modulus observed in the present work are lower than what is found in the literature. This is due to several factors: the age of the patients, the machine used for the tests that in a number of experiments are custom made and the way the specimens are cut among others.

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