INTRODUCTION:
The meniscal ultra-structure is complex, being comprised of a highly oriented and non-homogeneous collagen fiber matrix which dominates its anisotropic behavior. [1] Structural failure of the meniscus can have detrimental consequences for the knee joint and is caused by traumatic events or degenerative processes. To develop effective prevention and repair strategies, understanding of the structural properties of the meniscus is of foremost importance. Although structure-function correlations can be characterized by measuring the strain distribution across the meniscus, such measurements remain rare. The present study employed a laser-based strain measurement system to characterize strain distributions on cross-sections of human menisci under axial compression. Results of this study describe strain distributions on meniscus cross-sections under axial compression, as well as age-dependent changes thereof.

METHODS:
Eight human medial menisci were harvested from donors with an average age of 52 years, range 27 - 80 year. One cross-sectional specimen of 5 mm thickness was excised from the posterior-medial aspect of each meniscus (Fig 1a). The specimen cross-section was stained with white contrast medium to ensure adequate surface reflective properties for strain measurement. A meniscus loading stage was custom designed to subject meniscal cross-sections to incremental unconfined axial compression. Specimens were rigidly supported at their inferior and medial boundary, simulating physiological constraints at the tibial plateau and the capsule attachment (Fig 1b). An indenter with 11 mm radius was advanced perpendicular to the meniscus surface. To prevent slippage, the indenter and rigid boundaries were covered with fine (600 grade) sandpaper. This setup induced a well-defined, reproducible compression which resembled a principal loading regime of the meniscus. The indenter was mounted to a precision linear stage (ULTRAlign 461-X-M, Newport, Irvine, CA) and connected to a micrometer (Patent, Newport Cooperation, Irvine, CA, USA) with a displacement resolution of 0.25 µm. The specimen holder and indenter were enclosed in an 0.9% saline solution reservoir for testing of submerged specimens. A glass window next to the meniscus specimen allowed for optical strain assessment through a defined and stable fluid-solid interface. Full-field strain distributions over the meniscus cross-section were acquired with an Electronic Speckle Pattern Interferometer (ESPI) system (Q100, Ettemeyer GmbH, Neu-Ulm, Germany). This laser-based strain acquisition system delivers 512 x 512 individual strain reports, derived from three-directional surface deformation recordings over a 20 x 30 mm measurement area. [2] Nominal pre-strain of 20% was applied, based on the midsection height l0 of the meniscus. After one hour equilibration, the indenter was advanced by 10 µm in 40 steps of 0.25 µm. After each incremental displacement step, ESPI strain measurements were acquired and accumulatively analyzed to obtain the strain distribution at 20% pre-strain in response to 10 µm compression. ESPI in-plane strain reports were analyzed in terms of minimal principal strain distribution at 20% pre-strain in response to 10 µm compression. Indenter displacement induced an aggregate strain of 0.14%. Meniscus loading by 10 µm generated highly non-uniform strain distributions. Based on a nominal meniscus height of l0 = 7 mm, the indenter displacement induced an aggregate strain of 0.14%. However, ESPI strain distributions yielded εc values ranging from 0.03% to 0.7% in a representative specimen (Fig 2a). Along line lAB, the principal orientation of εc vectors was parallel to l0. Reproducibility of strain gradients along line lAB is depicted in Fig 2b, based on three repeat mountings and measurements of one specimen.

RESULTS:
Meniscus compression by 10 µm generated highly non-uniform strain distributions. Based on a nominal meniscus height of l0 = 7 mm, the indenter displacement induced an aggregate strain of 0.14%. However, ESPI strain distributions yielded εc values ranging from 0.03% to 0.7% in a representative specimen (Fig 2a). Along line lAB, the principal orientation of εc vectors was parallel to l0. Reproducibility of strain gradients along line lAB is depicted in Fig 2b, based on three repeat mountings and measurements of one specimen.

DISCUSSION:
ESPI strain measurements quantified for the first time continuous, inhomogeneous strain distributions on meniscus cross-sections. Prior biomechanical studies were confined to aggregate testing on tissue samples harvested from distinctive meniscus layers to explore constitutive differences in meniscal tissue. Our finding of higher compressive strain in the meniscus mid-region suggests that this section has a lower compressive modulus as compared to the surface region. This correlates to previous studies which divided menisci into femoral, central and tibial layers and reported the lowest Young’s modulus for the central layer [3,4]. We furthermore found that for older specimens, the strain elevation in the mid-region was more pronounced. This correlates with reports that aging is an etiological factor in degeneration of the meniscus, whereby menisci of subjects older than 50 years exhibit a higher modulus profile.

REFERENCES:

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