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Higher strains in the inner region of the meniscus indicate a potential source for degeneration ☆

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ABSTRACT

Complex structural properties of menisci can be characterized in part by their inhomogeneous strain response under compression. This pilot study explored the feasibility to quantify characteristic strain distributions on meniscus cross-sections subjected to static compression using electronic speckle pattern interferometry (ESPI). Cross-sectional specimens of 5-mm thickness were harvested from eight human menisci. After application of 20% pre-strain, strain maps in response to 10 μm compression were captured with ESPI. The 10 μm compression induced an aggregate strain of nominally 0.14% and resulted in highly non-uniform strain distributions. Local compressive strain captured by ESPI ranged from 0.03% to 0.7%. The highest strain was in the central region of meniscus cross-sections, and the lowest magnitude of strain was at the femoral surface of the meniscus. After stratifying for age, peak compressive strain in older menisci (71 ± 6 years, $n=4$) was 0.33% ± 0.09, compared to 0.25% ± 0.06 in younger menisci (34 ± 9 years, $n=4$).

In conclusion, this study captured for the first time continuous strain distribution maps over entire meniscus cross-sections. The non-uniform strain distributions demonstrated inhomogeneous structural properties. Age-related differences in characteristic strain distributions likely represent degenerative changes. As such, ESPI provides a novel strategy of further characterize meniscal function and degeneration.

1. Introduction

The menisci are C-shaped discs interposed between the lateral and medial femoral condyles and the tibial plateau. They support knee joint function by contributing to load transmission and distribution, shock absorption, joint stabilization, nutrition, and lubrication (Beaufils and Verdonk, 2010). Menisci have a unique structure and composition to support this complex functionality, including circumferential and radial fiber bundles that are orthogonally arranged along their c-shaped curvature (Petersen and Tillmann, 1999). The fibrils are surrounded by a highly hydrated extracellular matrix. Differences in density and stiffness between circumferential and radial fibers are responsible for inhomogeneous structural properties within a meniscus (Petersen and Tillmann, 1998). Assessing these characteristic structural differences can uncover links between the functional properties of meniscal tissue and degeneration. Several biomechanical studies have been performed to elucidate the function and structure of menisci. Most of these studies determined material properties on bulk specimens subjected to tensile tests (Anderson et al., 1991; Fithian et al., 1990; Lechner et al., 2000; Proctor et al., 1989; Tissakht and Ahmed, 1995; Zhu et al., 1994). To our knowledge, no prior study has captured continuous strain distributions on meniscus cross-sections to quantify structural inhomogeneities in response to compressive loading.

We used electronic speckle pattern interferometry (ESPI) to capture continuous strain fields on meniscus cross-sections in response to compressive loading. ESPI combines conventional Speckle Interferometry with electronic image processing. One major advantage of the laser-based ESPI-system employed is its non-contacting optical measuring capability which enables a high-resolution, spatial measurement of surface deformation and strain on complex structures such as bone and cartilage (Kessler et al., 2006).

The aim of this pilot study was to demonstrate the feasibility of measuring strain distributions on meniscus cross-sections using

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ESPI. We furthermore hypothesized that characteristic strain distributions differ between healthy menisci and older, degenerative menisci. If true, such differences could provide a better understanding of the degenerative process of the menisci.

2. Materials and methods

2.1. Specimen preparation

After institutional review board approval, eight human medial menisci (four female, four males, 53 ± 21 years old, range 27–80 years) were harvested from fresh-frozen donors (Table 1). One cross-sectional specimen of 5-mm thickness was harvested from the posterior third of each meniscus (Fig. 1). For histologic analysis adjacent meniscus specimens were fixed in formalin and embedded in paraffin.

2.2. Loading conditions

A custom meniscus loading stage was used to subject meniscal cross-sections to incremental semi-confined axial compression (Fig. 2A). Specimens were rigidly supported at their inferior and medial boundary, but the cross-sectional surfaces of the menisci remained unconfined in the circumferential direction.

A cylindrical indenter with a radius of 11 mm was used to indent the femoral surface of the meniscus (Fig. 2B). This radius corresponded to the average coronal plane curvature of the medial condyles of the eight donor femurs. To prevent specimen slippage, the indenter and rigid boundaries were covered with fine (600 grade) sandpaper. This setup simulated the principal compressive loading regime of the meniscus in a well-defined, reproducible manner. The indenter was mounted on a precision linear stage (ULTRAlign™ 461-X-M, Newport, Irvine, CA) and connected to a micrometer with a displacement resolution of 0.25 μm. The indenter was advanced perpendicular to the femoral surface of the meniscus. A nominal pre-strain corresponding to 20% of the midsection height of the meniscus was applied. This considerably large pre-strain was applied to fully seat the meniscal specimen to ensure stable and reproducible loading conditions. After one hour of equilibration, the indenter was advanced a total of 10 μm (40 steps of 0.25 μm). The specimen holder and indenter were enclosed in a 0.9% saline solution reservoir for testing specimens under hydrated conditions.

Table 1
Average age and age range of specimens in test groups.

Group	Specimen	Age (years)		
	n	Average	STDEV	Range
All	8	53	21	27–80
Younger group	4	34	9	27–48
Older group	4	71	6	65–80

2.3. Strain measurements

Tissue strain was measured optically through a glass window adjacent to the cut surface of the meniscus, which created a well-defined and stable fluid-solid interface. Full-field strain distributions over the meniscus cross-sections were acquired with an ESPI system (Q100, Ettemeyer GmbH, Ulm, Germany). This laser-based strain acquisition system computes a 341 × 512 matrix of local strain values, derived from three-directional surface deformation recordings over a 20 × 30 mm measurement area (Petersen and Tillmann, 1999). These local strain components were converted to maps of in-plane principal strain magnitudes superimposed with strain direction vectors. After each incremental displacement step, ESPI strain maps were cumulatively analyzed to obtain the distribution of the relative strain in response to 10 μm compression. ESPI in-plane strain maps were analyzed in terms of minimal principal (compressive) strain ε_C. Additionally, profiles of minimum principal strain along the center line from the femoral surface (A) to the tibial surface (B) were extracted (Fig. 3). The AB line profile was divided in 10 discrete sections and average local strain magnitudes were computed for each section.

2.4. Correlation with donor age

To assess the effect of age on strain distribution, specimens were stratified into a “younger meniscus” group ($n=4$, 34 ± 9 years, range 27–48 years), and an “older meniscus” group ($n=4$, 71 ± 6 years, range 65–80 years) (Fig. 4). For statistical comparison between the younger and older groups, ε_C, shear strain, and von Mises

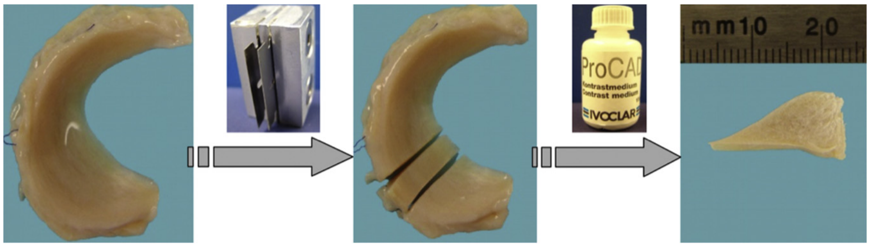

Fig. 1. Photograph of specimen processing. A 5 mm thick specimen was cut from the posterior third of the meniscus and stained with white contrast medium.

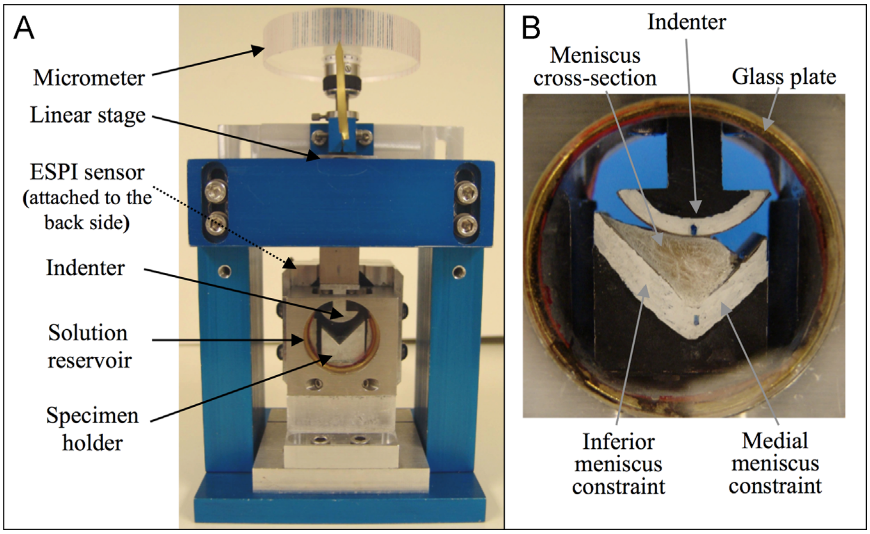

Fig. 2. (A) Photograph of custom apparatus for compressive loading of the semi-confined meniscal specimen. (B) Close up view of the indenter and meniscal specimen.