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High-Speed Strain Mapping of Human Meniscus During Tensile Loading

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Abstract

The knee meniscus is a fibrous soft tissue that is frequently torn. Prevention and treatment requires an understanding of failure mechanisms. Important failure properties are currently unknown, including the magnitude and orientation of principal strains at failure. This information is needed to inform predictive failure theories.

8 human meniscal samples were failed in tension, and surface strains were tracked using a previously validated high-speed digital image correlation system.

Results suggest that failures occur at 44°, along the maximum shearing plane when testing along the reinforcing fibers, and at 6° along the maximum tensile plane when testing normal to reinforcing fibers.

HIGH-SPEED STRAIN MAPPING OF HUMAN MENISCUS DURING TENSILE LOADING

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Introduction

Background

- Meniscus tears are highly prevalent, with over 500,000 occurring each year.[1] These tears cause joint instability and can increase the risk of osteoarthritis.[2]
- The meniscus is anisotropic, with fibers embedded in a ground substance.[5] Common failure patterns, like radial and horizontal tears, are related to the preferred circumferential fiber orientation (**Fig.1**).

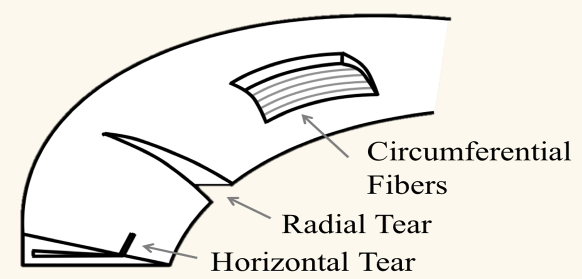

Figure 1: *Illustration of common meniscal tears and the fiber network.*

- Conventional materials use failure criteria to model and prevent fracture. These criteria can be based on the plane that failures follow, as well as physical limits of the material such as yield stress and ultimate tensile stress.

Challenge

- The magnitude and orientation of the principal strains in the tear region at yield and ultimate tensile strength (UTS) have not been quantified for human meniscal tissue. The plane these failures follow have also not been identified for human tissue.

Objective: Measure the strains in the tear region and the orientation of the failure plane of human meniscus when applying tensile loads longitudinal or transverse to the principal fiber direction.

Methods

Sample Preparation

- 8 dog-bone specimens were acquired from 2 unpaired human meniscus allografts following previous methods.[5] Two groups were tested: The principal fiber direction was either *longitudinal* or *transverse* to the loading axis (n=4 for longitudinal, n=4 for transverse).

Testing

- Samples were failed in tension at 1% strain/s using a mechanical test system (**Fig. 2**).
- Tests were filmed using a Photron UX50 high speed camera at a rate of 500 frames/second.

Data Analysis

- Full field strains were found using digital image correlation (DIC) with NCORR software.
- The angle of the failure plane was measured using ImageJ.
- The DIC program provided strain information along the loading direction (ε_{yy}), normal to the loading direction (ε_{xx}), and in shear (ε_{xy}). The 2D principal strains (ε_{max}, ε_{min}) were calculated using strain transformation equations.[3]
- Ultimate tensile strength (UTS) and DIC data were matched by aligning the high speed video and load data from the mechanical test system to within ± 8 milliseconds. The principal strains were determined by selecting a 10 pixel (0.2 mm) region around the failure plane.

Imaging Verification

- The accuracy of the DIC setup was validated by analyzing strain fields in rubber. The strains found by the DIC setup were within 2% of the values found using conventional optical methods and by the known displacement of the clamps (**Fig. 3**).

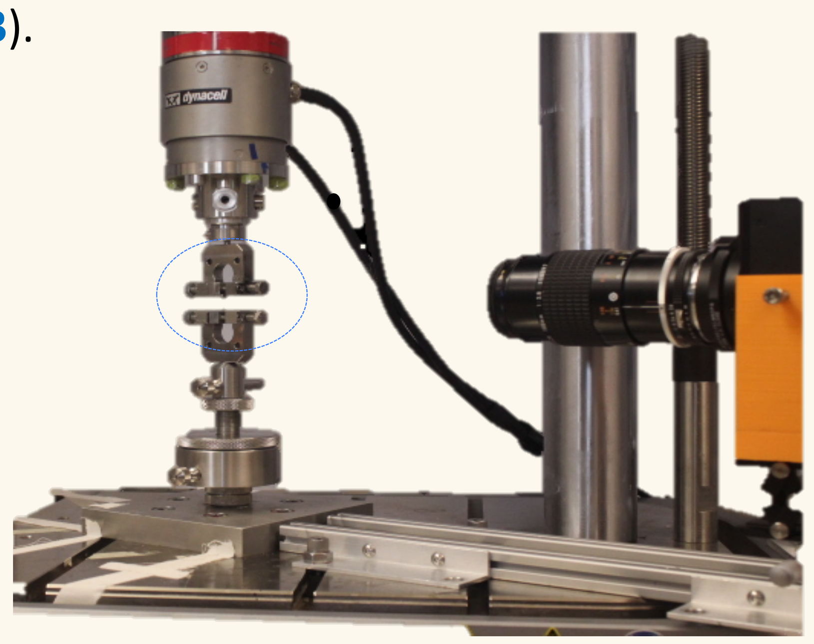

Figure 2: *Instron Mechanical Testing System and high speed camera setup with a speckled meniscus sample (inside dashed circle)*

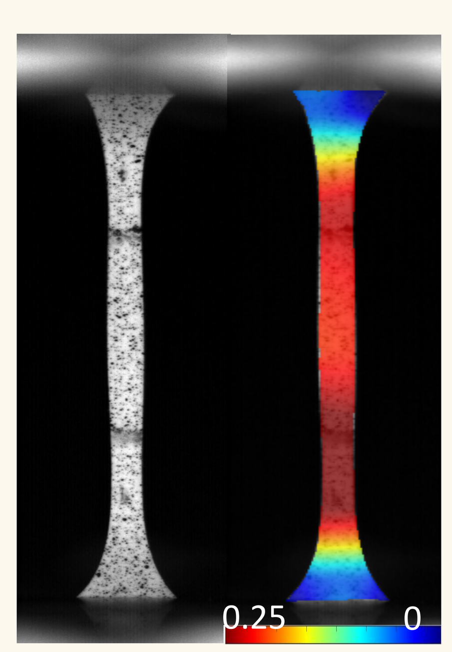

Figure 3: *Rubber sample strained in tension to 30%.*

Results

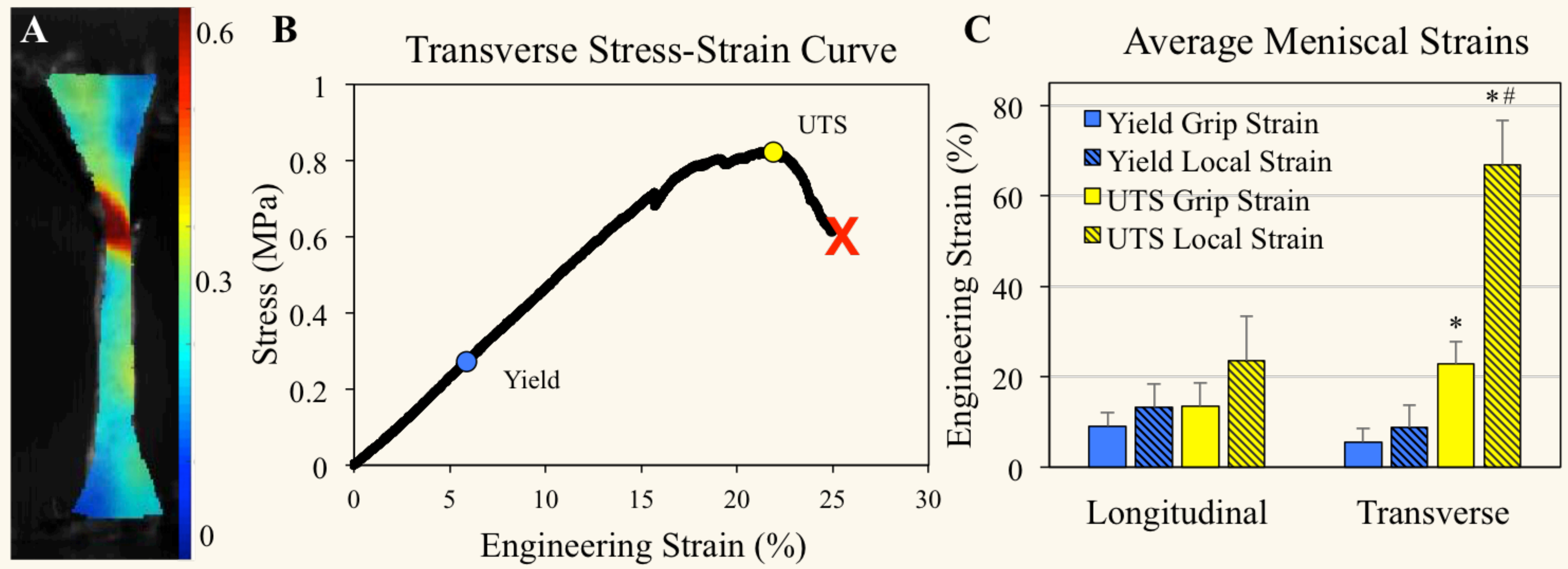

*Figure 4: Results. A) DIC strain map of a transverse sample with its B) stress-strain curve. C) Comparison of different strains in the failure region. *Significantly greater than longitudinal (p < 0.05). #Significantly greater within group (p < 0.05).*

- Local strains in transverse specimens were 2.5 times greater than the grip strains, and 3 times greater than longitudinal local strains (**Fig. 4, C**).
- Longitudinal specimens had an oblique failure angle of 44°, which was significantly greater ($p < 0.05$) than the nearly horizontal failure angle of 6° in transverse specimens .

Discussion

- First study to map the full-field strains of human meniscus at distinct points along the stress-strain curve.
- Failures in the longitudinal specimens most closely followed the plane of maximum shear strain, while failures in the transverse specimens more closely followed the plane of maximum normal strain. These failure patterns corroborate prior studies with bovine menisicus[6].
- These results suggest that fracture is regulated by the ground substance. If fracture was regulated by collagen fibers, the failure plane for the longitudinal specimens would likely have occurred on a surface normal to the loading axis.
- Distortion energy theory may be appropriate for modeling ground substance failure, where the failure threshold of the ground substance governs the failure response of the fiber composite.
- The local strain magnitudes were greater than grip strain at all points of interest, but were only significantly greater at UTS for transverse specimens.

Clinical Relevance: These experimental findings may help inform computational models that predict meniscus failure and therefore can identify clinical guidelines to prevent and treat these injuries.

Acknowledgements

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[1] Kim, S et al, *J Bone Joint Surg Am*. 93 [2] White, L et al., *Radiology*, 222(2):421-429. 2002 [3] Shigley, J et al., *McGraw Hill*. 230-264. 2015[4] Callister, W et al., *Wiley*. 253-289. 2012 [5]Creechley, J et al., *J Mech Behav Biomed Mater*, 69:185-192, 2017.[6] Nesbitt et al., 2017, SB[3]C2017-P24.