A Novel Technique for Quantifying Three-Dimensional Meniscal Strain

Introduction

The knee is a large and complex diarthrodial joint, for which the mechanical function and strain behavior is not fully understood. More comprehensive understanding of joint mechanics may contribute to improved treatments options for patients affected by osteoarthritis. Accurate assessment of joint mechanics is complex due to composite material anisotropy, viscoelasticity, contact, and the intricate muscle-actuated loading mechanisms.

Assessment of soft tissue strain in previous work has been primarily limited to ex vivo applications, involving video extensometry [1] or microscopy [2]. Recent efforts have been made to quantify 2D strain of soft tissue via texture correlation of magnetic resonance images [3] but this approach has not been successful in quantifying 3D strain. Previous work has also demonstrated that copper microspheres exhibit excellent x-ray attenuation properties with minimal artifact detected in 3D micro computed tomography (μCT) [4].

In vitro 3D strain of the intact meniscus has not yet been reported in the literature. Medical imaging modalities, such as μCT, may be useful in contributing to an improved knowledge-base of knee joint mechanics. The objective of this work was to use μCT in concert with copper microsphere markers to quantify three-dimensional strain of the meniscus under physiologic loading.

Methods

Two healthy fresh frozen ovine knee specimens were harvested for this study (51kg & 57kg). Copper microspheres (0.5mm) were injected into tetrahedral clusters into the medial meniscus using depth-marked 20-gauge hypodermic needles and music wire as driving pins. Multiple tetrahedral elements (anterior & posterior) were injected into one specimen (51kg) to investigate location effects. Needle cavities were sealed with ovine tendon tissue to restrict localized microsphere motion. The microspheres were injected in respective anterior and posterior tetrahedral arrangements to facilitate accurate strain measures.

The joints were potted in a 5 DOF CT compatible device capable of applying physiologic loads at varying flexion angles [5]. Micro-CT images were acquired with the joint unloaded, then 1, 3 and 5 minutes following static load application; and 1, 3 and 5 minutes at a reduced load. The two specimens were loaded to 100% ± 20% body weight (BW) at 62°±1° of flexion. The 51kg specimen was also loaded to 50% ± 10% BW at 68° & 98°. The reduced load for all images was 25% ± 12% BW. Images were reconstructed and microsphere coordinates were digitized with commercial software (MicroView 2.1.2, GE Healthcare). Joint flexion angles [6] were measured using joint coordinate systems for both the tibial [7] and femur [8] established from bony anatomy. Microsphere displacements were converted to 3D strain tensors using the finite element strain matrix for tetrahedral elements (Figure 1).

![Figure 1: 3D spherical marker deformation field in the meniscus following loading to 50% body weight at 68° flexion](image)

A General Electric Health Care (GEHC) eXplore Locus Ultra μCT scanner was used. The anatomical scan protocol was set with an acquisition time of 16 seconds and x-ray exposure energies of 120kVp, 20mA. The reconstruction matrix size was 512 x 512 x 680 with voxel dimensions of 0.154mm x 0.154mm x 0.154mm. Load data was collected using Labview 8.6 software (National Instruments, TX, USA).

Results

The average maximum principle strains in the anterior element of the two specimens at 62° of flexion increased by 21% during loading and decreased by 13% during unloading (Table 1).

| Table 1: Average maximum principle strains and standard deviation (SD) of two sheep knees at 62° ± 1° flexion angle with 100% BW load for the anterior microsphere tetrahedrons |
|-----------------|--------|--------|--------|--------|--------|--------|--------|--------|
|                  | 1      | 3      | 5      | 1      | 3      | 5      | 1      | 3      | 5      |
| Avg strain (SD)  | 0.41   | 0.59   | 0.62   | 0.74   | 0.56   | 0.61   | 0.07   | 0.18   | 0.31   |

For the 51kg multi-element specimen, the maximum principle meniscal strains for the meniscus at 68° and 98° with 50% BW applied load (Table 2). The maximum principle strains were larger in the anterior element than the posterior. The strains in the anterior element decreased with time following load application, and then decreased after the load was removed. In the anterior increased strains were exhibited at the larger flexion angle. The posterior element did not exhibit differences in strain with respect to angle.

| Table 2: Maximum principle strains of a 51kg sheep knees at 68° and 98° flexion angle with 50% BW load for the anterior and posterior microsphere tetrahedrons |
|-----------------|--------|--------|--------|--------|--------|--------|
|                 | 1      | 3      | 5      | 1      | 3      | 5      |
| Ant. element    | 0.38   | 0.38   | 0.38   | 0.35   | 0.33   | 0.23   |
| Post. element   | 0.44   | 0.42   | 0.32   | 0.44   | 0.24   | 0.22   |

Discussion

The objective of this work was to develop a reliable method for quantifying 3D strains in the meniscus. Results support the notion that μCT imaging with copper microspheres in the meniscus may be a viable technique for 3D strain analysis. The relatively low residual strains measured in this study indicate that copper microspheres are stable markers. Results also indicate that tendon tissue acts as a serviceable sealant, likely due to the similar mechanical properties to meniscus.

Limited work has been previously conducted to quantify 3D strain of the meniscus. Gilchrist et al [3] conducted a 2D strain analysis ex vivo and reported 6-10% axial strain and 0-1% transverse strain with an applied axial strain of 7.5% ex vivo. No previous findings have been reported on 3D strains of the meniscus under physiologic loading.

This technique may be useful in directing future studies aimed at understanding impact of specific meniscal pathologies and the success of repair techniques. Future work will be aimed at applying this technique to healthy and pathologic cadaveric specimens. Further, soft tissue 3D strain data would be effective in validating computational biomechanical models.

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References

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