TOWARD AN MRI-BASED METHOD TO DETERMINE THREE-DIMENSIONAL DEFORMATIONS IN ARTICULAR CARTILAGE

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INTRODUCTION

The experimental study of the non-uniform deformation of articular cartilage throughout the volume of the tissue (hereafter termed three-dimensional (3D) deformation) in response to compressive loading is important to provide a comprehensive understanding of the properties of the normal and diseased tissue. Such 3D deformation of cartilage is expected due to the anisotropic and inhomogeneous properties of cartilage [1]. Investigations of 3D deformation may provide an increased understanding of the process of mechanical signal transduction, where the 3D deformation of the extracellular cartilage matrix influences the deformation experienced by individual chondrocytes [2]. Moreover investigations of 3D deformation may allow for the detection of possible disease sites in the tissue by identifying localized areas where the stiffness of the tissue has changed from normal [1].

Methodologies that make use of magnetic resonance imaging (MRI) have the ability to measure cartilage deformation in vivo [3]. Such methodologies have been used to measure surface deformations (i.e. depth and volume changes). However, to our knowledge no MRI-based methodology has been developed to measure 3D cartilage deformation throughout the volume of the tissue.

The realization of an MRI-based method to measure 3D cartilage deformation requires the fulfillment of several objectives. One objective is the design of a unique MRI pulse sequence to apply features throughout the volume of the articular cartilage. A second objective is the design of an apparatus to load the tissue within the MRI scanner. A third and final objective is the development of image processing software to mathematically compute deformation from MR images. This paper describes how these objectives were satisfied.

MATERIALS AND METHODS

A phantom material (Sylgard 527 Silicone Dielectric Gel, Dow Corning, Midland, Michigan) was used to demonstrate the new MRI-based method. This material has T_1 and T_2 properties similar to articular cartilage [4]. A phantom material rather than articular cartilage was used because the phantom material can also be used to verify the 3D strain calculations ultimately of interest. The thickness of the phantom was approximately 6 mm (representing the maximum thickness expected in human cartilage on the tibial plateau).

MRI. The MRI pulse sequence was designed to visualize the phantom material when imaged in both undeformed and deformed states. Determining deformations in the phantom material required imaging in both states to directly observe changes in geometry. Importantly, conventional MRI of the phantom material only identifies surface shape and volume changes and not internal features required for 3D deformation throughout the volume of the tissue. Thus, prior to imaging features were superimposed onto the material using MRI to allow for tracking of individual tissue points.

The DANTE pulse sequence was used to generate a grid of features (i.e. *tag lines*) in the phantom [5] using a Biospec 70/30 MRI system with microgradients (7.05 Tesla (T), Bruker Medical GMBH, Ettlingen, Germany). The grid of tag lines allowed individual tissue points to be tracked during a deformation because the grid was directly observed to move and change shape in images captured before and after loading. The DANTE pulse sequence was implemented by applying a series of radiofrequency (RF) pulses in two orthogonal directions in the presence of magnetic field gradients to generate a rectilinear grid of tag lines. In each orthogonal direction 20 RF pulses were applied (duration of 4 *m*s, inter-pulse duration = 100 *m*s) during the application of a 20 Gauss/cm magnetic field gradient.

Subsequent to the DANTE pulse sequence, the fast spin echo pulse sequence was used to image the phantom material in both the undeformed and deformed states. Fast spin echo imaging parameters were: TR = 5000.0 ms; TE = 6.8 ms; number of echoes per TR = 8; field of view = $2.00 \times 2.00 \times 0.05$ cm^3; image matrix size = 256×256 pixels^2; number of excitations = 1; slice thickness = 1 mm.

The time available for image acquisition was limited by the time duration of the tag lines superimposed by the DANTE technique. The contrast between the tag lines and the phantom decays according to the T_1 of the material (approximately 1.5 s), which is much less than the 80 s total acquisition time for two images (i.e. one slice) representing the undeformed and deformed phantom. The stringent time limits on image acquisitions motivated the need for a custom apparatus with loading cycles synchronized to the MRI pulse sequence thus providing a method for observing changes in deformation by acquiring image data over many loading cycles. Image data was acquired for all regions of a particular slice to assemble a complete image of the phantom.

Cyclic loading apparatus. An apparatus composed of electronic and pneumatic components was constructed to load a tissue sample within the bore of an MRI scanner. The apparatus regulated pressure to a loading mechanism that included a double-acting pneumatic cylinder to apply load-controlled compression cycles to material samples. All mechanism components were constructed from nonferromagnetic materials. In addition, the apparatus allowed gating for MR image acquisition (Figure 1). During a typical cycle, the tag lines were applied and the image data was acquired prior to loading for the undeformed material. A load was then applied to the material (in approximately 200 ms) and held constant while image data was acquired for the deformed material. For the phantom material, the cyclic loading apparatus was configured for a 20 N cyclic load magnitude (for the soft gel) with a 5-second total cycle duration.

Image processing. An automated image processing algorithm was used to calculate deformations of specific cartilage material regions from the MR volume images. This algorithm mathematically and automatically determined the transformation needed to "morph" undeformed images into deformed images. More specifically, deformations were determined using a free-form deformation-based formulation such that squared differences in volume image intensities between the undeformed and deformed images were minimized [6].

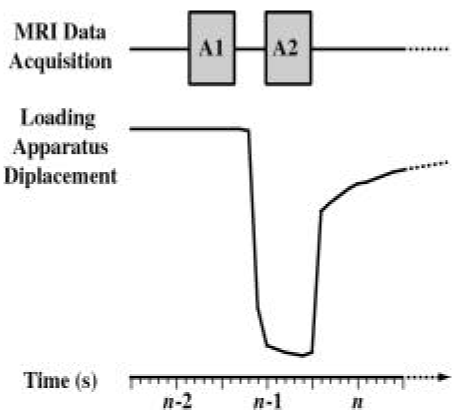


Figure 1. A timing diagram indicates the synchronous actions of the MRI pulse sequence and cyclic loading apparatus. The MRI pulse sequence acquires images in two acquisitions: *A1* applies the DANTE pulse sequence and images the undeformed phantom, and *A2* images the deformed phantom.

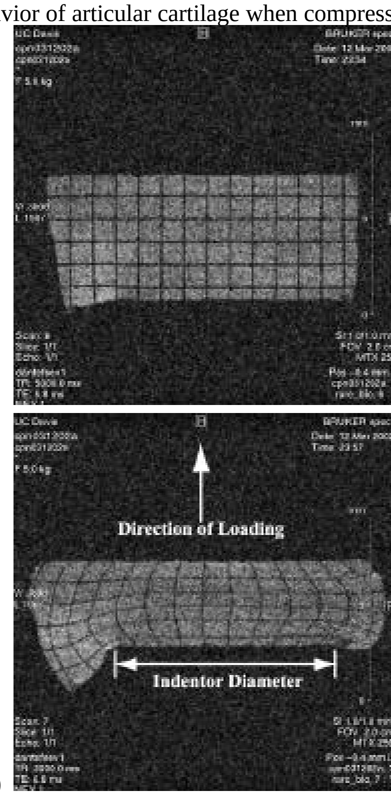
RESULTS

Images of a phantom material were successfully captured by integrating the cyclic loading apparatus and MRI pulse sequences (Figure 2). The DANTE parameters in conjunction with the fast spin echo technique produced a grid pattern of tag lines initially spaced approximately 1 mm apart. The fast spin echo parameters resulted in voxel dimensions of $78 \times 78 \times 500$ microns^3 which were sufficient to demonstrate deformation of the phantom material. The timing of the apparatus and MRI scanner allowed for the acquisition, assembly, and visualization of images depicting the material in undeformed and deformed states. From these images, the 3D deformations were computed using the image processing algorithm.

DISCUSSION

This study was motivated by the need for detailed 3D articular cartilage deformation under compressive loading. The key results were that 1) a phantom material was imaged in undeformed and deformed states and 2) the 3D deformation was determined from these images, thus demonstrating the potential of this unique method to measure 3D deformation in cartilage. To realize this potential, the phantom used for demonstration can now be replaced by cartilage. The foundation is now laid to acquire images of cartilage in the undeformed and deformed states and mathematically determine the corresponding 3D deformations. This will represent a major advance in our ability to analyze the behavior of articular cartilage when compressively loaded.

(A)



(B)

Figure 2. A set of phantom material images in undeformed (A) and deformed (B) states. DANTE tag lines are seen to deform with the tissue, thus permitting the calculation of deformation on the material surface and throughout the interior.

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