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Depth and rate dependent mechanical behaviors for articular cartilage: Experiments and theoretical predictions

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ABSTRACT

An optimized digital image correlation (DIC) technique was applied to investigate the depth-dependent mechanical properties of articular cartilage and simultaneously the depth-dependent nonlinear viscoelastic constitutive model of cartilage was proposed and validated. The creep tests were performed with different stress levels and it is found that the initial strain and instantaneous strain increase; however the creep compliance decreases with the increase of compressive stress. The depth-dependent creep strain of cartilage was obtained by analyzing the images acquired using the optimized DIC technique. Moreover the inhomogeneous creep compliance distributions within the tissues were determined at different creep time points. It is noted that both creep strain and creep compliance with different creep times decrease from cartilage surface to deep. The depth-dependent creep compliance increases with creep time and the increasing amplitude of creep compliance decreases along cartilage depth. The depth-dependent and stress rate dependent nonlinear stress and strain curves were obtained for articular cartilage through uniaxial compression tests. It is found that the Young's modulus of cartilage increases obviously along cartilage depth from superficial layer to deep layer and the Young's modulus of different layers for cartilage increases with the increase of stress rate. The Poisson's ratio of cartilage increases along cartilage depth with given compressive strain and the Poisson's ratio of different layers decreases with the increase of compressive strain. The depth-dependent nonlinear viscoelastic constitutive model was proposed and some creep data were applied to determine the parameters of the model. The depth-dependent compressive behaviors of cartilage were predicted by the model and the results show that there are good agreements between the experimental data and predictions.

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1. Introduction

Articular cartilage is the connective tissue covering the surface of subchondral bone in diarthrodial joints, providing a nearly frictionless surface for joint articulation and functioning to transmit loads, absorb shock and sustain daily loading histories. In activities of daily living, the cartilage is exposed to a wide range of loads up to 10 times body weight and is subjected to both static and dynamic load. Microscopically, the composition and structure of cartilage vary through the depth of the tissue [1–5]. In normal articular cartilage, the water content decreases from more than 80% at the surface to 65% in the deep zone. The concentration of proteoglycan (PG) content is relatively low in the superficial zone and increases to a higher value in the middle zone. The collagen fibrils are oriented parallel to the articular surface in the superficial zone and are perpendicular to the articular surface in the deep zone. The unique structure and composition of cartilage hint to the inhomogeneity and anisotropy of the tissue's mechanical properties. So it is significant to investigate inhomogeneous mechanical properties of articular cartilage considering the importance of cartilage in maintaining the mobility and quality of life of individuals.

Classical compression tests, utilizing unconfined compression, indentation, and confined compression on full-thickness cartilage samples were performed to determine mechanical properties of articular cartilage since the compressive load is a kind of important physiological load for cartilage [6,7]. However, test results were limited to bulk properties averaged over the test specimen volume. Recognizing the dramatic differences in composition, structure and mechanical properties of different layers for cartilage, the relations between the mechanical deformation and composition and structure of cartilage were studied under compressive load [8–11]. The compression tests of partial thickness cartilage samples had been conducted [12,13], which yielded to the characteristic differences in mechanical properties between cartilage samples, harvested from surface, middle and deep cartilage layers. The depth-dependent mechanical properties of cartilage were investigated preliminarily [14–16]. Chegini and Ferguson [14] simulated the time and depth dependent Poisson's ratio of cartilage by developing an inhomogeneous orthotropic fiber embedded biphasic model. Bell

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et al. [15] investigated the steady-state deformations of different layers for solid phase of articular cartilage based on the completely homogeneous, layered and isotropic, and layered and anisotropic models. Oliver et al. [16] found that the depth-dependent strain gradients were most pronounced for 5% off-set strain. Recently, an optimized digital image correlation (DIC) technique was applied to achieve the measurement of two-dimensional deformation fields and obtain some depth-dependent properties for cartilage under uniaxial compression [5,17]. Taken together, these experiments have provided the foundation for understanding inhomogeneous cartilage biomechanics and developing computational models. However there is still the need to better understand the depth-dependent properties and their influences on mechanical response.

Frequently, many theoretical models have been proposed to predict the mechanical behaviors of articular cartilage. In these models, the solid phase of cartilage was assumed to be a hyperelastic [18,19], quasi-linear viscoelastic [20] or continuum fiber reinforced medium [21–23]. Nonetheless it is well-known that cartilage macromolecules are polydisperse [24] and likely exhibit complex molecular interactions. Namely the solid phase of cartilage is a nonlinear viscoelastic medium. Additionally, these models were able to explain the average time dependent, but not depth-dependent mechanical behaviors of cartilage. Hence the depth-dependent nonlinear viscoelastic characteristic needs to be incorporated in the constitutive law of cartilage which shows the flow-independent contribution to cartilage viscoelasticity.

In this study, the optimized DIC technique was applied to investigate the depth and loading rate dependent mechanical properties for articular cartilage through creep tests and uniaxial compression tests with different stress rates. The depth-dependent creep compliance of cartilage at different creep time points was obtained under constant compressive stress. The Young's modulus and Poisson's ratio of different layers were determined for articular cartilage with different stress rates. A depth-dependent nonlinear viscoelastic constitutive model was proposed to predict the depth-dependent creep behaviors and uniaxial mechanical behaviors of cartilage under unconfined compression.

2. Experiments

Articular cartilage from about 8-month-old pig knee joint was obtained 4–6 h post-mortem from a local slaughterhouse. The eighteen full-thickness cartilage samples with subchondral bone were harvested from the trochlea sites of three joints by using the steel trephine with the trephine core axis perpendicular to the articular surface since the structured and flat samples, which can be compressed on the entire surface, were easier to be taken from the trochlea site than from the condyle site. These samples were made in a dimension of about 5.5 mm in length, 4 mm in width and 2 mm in thickness. The structure of cartilage can be divided into three distinct zones: superficial zone, middle zone and deep zone by microscopic examination. Before conducting experiment all samples were soaked in saline so as to maintain the humidity of cartilage.

An optimized digital image correlation technique was applied to measure the two-dimensional deformation fields for cartilage samples under unconfined compression by using the microscopic mechanical testing system as shown in Fig. 1. The essence of this technique is to automatically measure displacements by tracking the change in position of points on digitized images of the object's surface. The optimized digital image correlation requires a random pattern on the sample surface that can be readily identified in sequential images. This random pattern enables us to perform digital image correlation of sequential images that record the deformation of the sample. In this study the iron oxide nanoparticles with diameter of 50 nm, which were scattered and embedded in the cartilage sample profile by being pressed very gently under microscope, were used as fiducial markers for cartilage sample and the relative position of these nanoparticles gave rise to a random pattern on the sample surface. Fig. 2 shows the microscopic images of a section of cartilage sample before and after creep under unconfined compression. It is shown that the black particles are the iron oxide nanoparticles. The nanoparticle group, the smallest visible diameter of which is 2–3μm, is considered to be the reference point due to the agglomeration of particles. The deformations of different layers for cartilage can be observed before and after creep under unconfined compression as shown in Fig. 2.

The creep tests were conducted at given stress levels under unconfined compression for cartilage specimens. Prior to any compressive loading the initial thickness of each sample was measured microscopically. The image of the sample in its load-free reference state was first acquired. The constant compressive stress levels of 0.1, 0.5 and 1 MPa were chosen by Ref. [25] and applied on three sets of independent samples at room temperature respectively and the creep time was 60 min. Simultaneously the cross sections of the compressed samples were imaged at a frame per second during the whole creep process and the images were analyzed using the optimized DIC technique to generate the displacement fields and strain fields. For each condition three samples were tested considering random error.

The uniaxial unconfined compression tests were carried out with different stress rates such as 0.0045, 0.045, 0.225 MPa/s at room temperature for three sets of independent cartilage specimens respectively and for each condition three samples were tested considering random error. Prior to any compressive loading the initial thickness of each sample was measured microscopically and the image of the sample was first acquired. The samples were also imaged during the whole compressing process and the images were analyzed using the optimized DIC technique to generate the displacement fields and the strain fields. The depth-dependent Young's modulus was investigated with different stress rates.

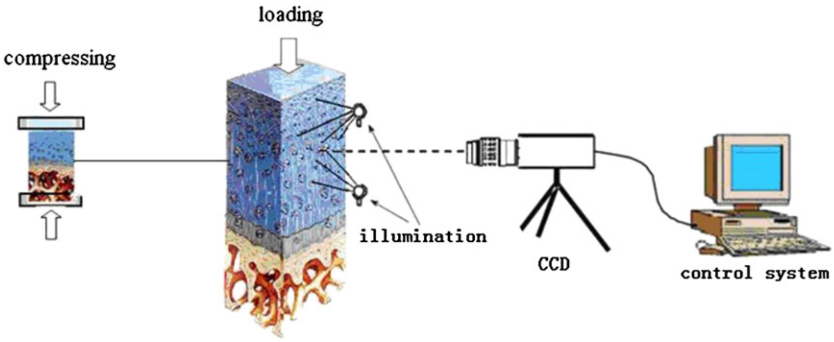

Fig. 1. Schematic diagram of the experimental system for cartilage under unconfined compression.

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