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Research paper

Mechanical properties of normal and osteoarthritic human articular cartilage

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ABSTRACT

Isotropic hyperelastic models have been used to determine the material properties of normal human cartilage, but there remains an incomplete understanding of how these properties may be altered by osteoarthritis. The aims of this study were to (1) measure the material constants of normal and osteoarthritic human knee cartilage using isotropic hyperelastic models; (2) determine whether the material constants correlate with histological measures of structure and/or cartilage tissue damage; and (3) quantify the abilities of two common isotropic hyperelastic material models, the neo-Hookean and Yeoh models, to describe articular cartilage contact force, area, and pressure. Small osteochondral specimens of normal and osteoarthritic condition were retrieved from human cadaveric knees and from the knees of patients undergoing total knee arthroplasty and tested in unconfined compression at loading rates and large strains representative of weight-bearing activity. Articular surface contact area and lateral deformation were measured concurrently and specimen-specific finite element models then were used to determine the hyperelastic material constants. Structural parameters were measured using histological techniques while the severity of cartilage damage was quantified using the OARSI grading scale. The hyperelastic material constants correlated significantly with OARSI grade, indicating that the mechanical properties of cartilage for large strains change with tissue damage. The measurements of contact area described anisotropy of the tissue constituting the superficial zone. The Yeoh model described contact force and pressure more accurately than the neo-Hookean model, whereas both models under-predicted contact area and poorly described the anisotropy of cartilage within the superficial zone. These results identify the limits by which isotropic hyperelastic material models may be

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used to describe cartilage contact variables. This study provides novel data for the mechanical properties of normal and osteoarthritic human articular cartilage and enhances our ability to model this tissue using simple isotropic hyperelastic materials.

1. Introduction

Articular cartilage is a thin layer of soft tissue that lines the ends of bones in diarthrodial joints. It provides the contact surfaces for load transfer between bones and facilitates near-frictionless joint articulation (Ateshian and Mow, 2005). Cartilage tissue achieves these functions through its complex structure comprised of a depth-dependent collagen fibril network and proteoglycans (PGs) saturated with an interstitial fluid phase. Degeneration of cartilage due to osteoarthritis (OA) alters its internal structure, leading to changes in its mechanical properties (Setton et al., 1999). Accurate knowledge of these mechanical changes could facilitate a better understanding of the initiation and progression of OA and lead to improved treatment therapies.

Cartilage undergoes large finite deformations *in vivo* with compressive strains of up to 30% (Bingham et al., 2008), and its compressive stiffness is characterized by a nonlinear stress–strain curve that varies with strain rate (Oloyede et al., 1992). To simulate physiological loading, cartilage has been loaded at strain rates greater than 15%/s (Henak et al., 2014; Park et al., 2004; Pierce et al., 2009). This produces an 'instantaneous' response of the tissue, where there is negligible interstitial fluid-flow so that the cartilage behaves as an incompressible elastic solid (Ateshian et al., 2007; Pierce et al., 2009). Hyperelastic materials may be used to model cartilage tissue because their strain energy functions not only represent the nonlinear stress–strain relationships of cartilage but also describe its incompressible behavior (Henak et al., 2014). However, few data are available for the hyperelastic material properties of healthy human cartilage (Anderson et al., 2008; Henak et al., 2014; Pierce et al., 2009), and no previous studies to our knowledge have used these models to determine the material constants of osteoarthritic human cartilage.

Previous work has shown that for linear-elastic, biphasic or hyperelastic models of cartilage, the respective material constants vary considerably across joints and between individuals (Armstrong and Mow, 1982; Henak et al., 2014; Pierce et al., 2009; Shepherd and Seedhom, 1999). The variations in the material constants have been found to correlate with tissue composition (Kiviranta et al., 2006; Rieppo et al., 2003) and/or OA severity (Armstrong and Mow, 1982; Kiviranta et al., 2008; Kleemann et al., 2005; Saarakkala et al., 2003). Whilst the material constants in hyperelastic cartilage models are most likely to change due to OA, the extent of these changes and whether they can be predicted by variations in tissue structure or degree of OA severity remain unknown.

Isotropic material models have been used to describe cartilage in finite element models of entire joints because they are readily implementable and have low computational cost (Haut Donahue et al., 2003; Kiapour et al., 2014). The ability of isotropic hyperelastic models to predict contact mechanics for macroscopically undamaged cartilage was recently evaluated by Henak et al. (2014). They found that the neo-Hookean and Veronda Westmann hyperelastic models both yielded an RMS error in predicted contact pressure of approximately 24%, and concluded that contact area and pressure predictions at the whole-joint level are relatively insensitive to the type of constitutive model used. However, these authors also calculated contact pressure using measurements of contact force obtained for small, idealized half cylinders of cartilage and found clear differences between the neo-Hookean and Veronda Westmann models. Direct measurements of contact area and the use of models that incorporate specimen-specific geometry may provide a more accurate means of analyzing hyperelastic model predictions at smaller length scales and help to address the differences in predicted contact mechanics (e.g., contact area and pressure) derived from small- and large-scale geometries.

Therefore, the aims of the present study were to:

(1) Measure the hyperelastic material constants of normal and osteoarthritic human knee cartilage using isotropic hyperelastic models;
(2) Determine whether the hyperelastic material constants correlate with structural parameters and/or severity of cartilage damage; and
(3) Determine the accuracy with which isotropic hyperelastic models that incorporate specimen-specific geometry describe measurements of contact force, contact area, average contact pressure and anisotropy of the superficial zone.

We hypothesized that the hyperelastic material constants change with damage to the tissue and that these changes correlate with the structural parameters of cartilage.

2. Methods

2.1. Specimen preparation

Fifty-one cylindrical osteochondral plugs (each 5 mm in diameter) were harvested from the cartilage and bone removed from the tibiofemoral joints of 10 patients (4 male, 6 female, age 69.7 ± 9.3 years) undergoing total knee arthroplasty (TKA). Femoral specimens were harvested from the medial and lateral femoral condyles. Tibial specimens were harvested from the medial and lateral compartments of the tibial plateau in regions that were covered or uncovered by

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