INTRODUCTION: Degenerative changes in the structure and composition of articular cartilage in osteoarthritis, such as collagen fibrillation, proteoglycan depletion and increased water fraction, alter the mechanical behavior of cartilage [1, 2]. It has been shown that the collagen fibrils primarily modulate cartilage mechanical response under dynamic and impact loading [3]. This emphasizes the role of the depth-wise collagen fibril network in modulating cartilage function in a knee joint. However, effects of osteoarthritic changes in cartilage on stresses in a knee joint have not been shown. The aim of this study was to combine clinical magnetic resonance imaging (MRI) and finite element (FE) modeling, and to apply a fibril reinforced poroelastic model [4, 5] to examine especially the influence of the collagen network fibrillation of osteoarthritic articular cartilage on the stress distribution in a knee joint.

MATERIALS AND METHODS: Two-dimensional geometry of a knee joint was obtained from a clinical MR-image of a voluntary male subject (age: 29 years, weight: 70 kg, height: 175 cm) (Fig. 1a). From this image, the geometry for the FE model was constructed by manually segmenting cartilage and menisci.

Depth-wise collagen fibril orientations of cartilage and menisci in a healthy joint were implemented into the FE model (Fig. 1b). The superficial zone of cartilage was characterized with horizontally oriented collagen fibrils, in the middle zone the fibrils bended from horizontal to vertical direction, and the deep zone exhibited vertically oriented fibrils [6]. Fibrillation of the collagen network in osteoarthritis was simulated by disorganizing the collagen network either only in the superficial zone (Fig. 1c [7]) or in the superficial and middle zone (Fig. 1d). In the menisci, the fibril orientations were implemented parallel-to-surface in the superficial layers and randomly in the deeper layers [8].

Typical material properties were implemented into the FE models of healthy and fibrillated cartilage [9]; initial and strain-dependent fibril network moduli were 0.47MPa and 673MPa, respectively, non-fibrillar matrix modulus was 0.31MPa, initial permeability was 1.74x10⁻⁹m²Ns and permeability strain-dependency coefficient was 7.1. In addition to the collagen fibrillation (Fig. 1d), increased water content (5% higher), decreased non-fibrillar matrix modulus (75% lower) and reduced fibril network moduli (75% lower) were implemented into the FE model simulating advanced osteoarthritis. In every model, the material parameters of the menisci were kept the same [10].

Axial step-load of 700N was used to simulate impact loading of the knee joint. Cartilage-bone interface in tibia was fixed in all directions and meniscal structures were tied together using a spring (9.21N/mm). All simulations were performed using Abaqus v6.8 (Dassault Systèmes, Providence, RI).

RESULTS: We found that the superficial fibrillation decreased the stresses in the superficial zone of cartilage, while stresses and tensile strains of the deep zone collagen fibrils in some other regions of cartilage were increased (Fig. 2). This effect was further amplified by extending the collagen fibrillation into the middle zone. The same behavior was observed in stresses of tissue with advanced osteoarthritis, however, due to the reduced mechanical parameters of cartilage, menisci experienced dramatically increased stresses (Fig. 2d).

DISCUSSION: In the present study, we have demonstrated the role of degenerative collagen network fibrillation and changed mechanical properties of articular cartilage on the stress distribution experienced by cartilage and menisci. Our results indicated that the superficial fibrillation of articular cartilage in osteoarthritis reduces stresses in the superficial zone, while some other areas experienced peak stresses. When the fibrillation reached the middle zone, this effect was amplified. This phenomenon can be explained by the fact that, under loading, the collagen fibrils in the upper layers of the middle zone of cartilage with the superficial fibrillation (Fig. 1c) bended parallel to the cartilage surface [9], while the fibrils in more degenerated cartilage (Fig. 1d) did not show the same response.

Interestingly, we found that the tensile strains of the deep vertical collagen fibrils under menisci increased as osteoarthritis progressed. This produced greater stresses and may predict future failure areas. In the future, the present technique combining clinical MRI and a sophisticated biomechanical model could potentially be used for patient-specific estimation of cartilage mechanics in osteoarthritis and predicting possible failure areas, thus, having a role in clinical decision making.

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