INTRODUCTION: In articular cartilage, collagen network architecture is depth-dependent [1]. Cartilage surfaces also exhibit specific fibril orientations, i.e. split-lines, which are thought to be a result of joint loading [2, 3, 4]. In osteoarthritis (OA), superficial fibrils lose their organization and the functional properties of cartilage are altered. The effect of predominant collagen orientations on cartilage mechanics has been shown in in vitro simulations [5].

Combination of patient-specific magnetic resonance imaging (MRI) with sophisticated biomechanical modelling, i.e. functional imaging, may provide a future tool for the diagnostics of OA [6]. Recently, a 2D biomechanical model with the geometry obtained from MRI showed the effect of the collagen fibril orientations in normal and diseased cartilage on strains and stresses within a joint [6]. The aim of this study, combining MRI and finite element (FE) modeling, was to create a 3D joint model, including the collagen split-lines and structural changes present in OA, and to assess the effect of the collagen architecture and OA on the joint function.

MATERIALS AND METHODS: 3D geometry of a knee joint was obtained from clinical MR-images of a left knee of a healthy volunteer (male, age: 61 years, weight: 100 kg) (Fig. 1). MR-imaging (GE Signa Twin-Speed 1.5T clinical scanner, GE Healthcare, Milwaukee, WI) was performed with Fast spoiled gradient echo sequence using the following imaging parameters: TR=26.7 ms, TE=6.7 ms, flip angle=20°, slice thickness=1.5 mm, matrix=512x512, in-plane resolution=0.27 mm. FE geometry of the knee joint was meshed with 4637 hexahedral elements.

- Depth-dependent fibril orientations with split-line patterns were implemented for the femoral and tibial cartilage of the models. Three different models were constructed:
  1) A model with arcade-like collagen orientations and split-line patterns in the cartilage surfaces [1, 2, 3] (Fig. 2a)
  2) A model with arcade-like collagen orientations and without split-line patterns (Fig. 2b)
  3) A model with typical structural OA changes in medial femoral condyle (Fig. 2c).

In the OA model, the superficial and middle zones had unorganized collagen fibrils (Fig. 2c). Elsewhere cartilage had arcade-like collagen orientations and split-line patterns as in the model 1.

Fibril reinforced poroviscoelastic (FRPVE) material properties were implemented in the models [6, 7]. In the OA model, in addition to the changes in the collagen structure, both fibril network stiffness and proteoglycan matrix modulus were reduced [6]. Simulations were completed by applying 500 N axial loading on the femoral cartilage with 0° flexion angle. Interface between bone and tibial cartilage was fixed. Simulations were performed using ABAQUS (Dassault Systèmes, Providence, RI).

RESULTS: In the surface of femoral cartilage, local deformations in the direction 1 (perpendicular to split-lines) were higher in the model with split-line patterns, as compared to the model without split-lines (Fig. 2a, b). Opposite was shown parallel to the split-lines. In the OA model, significantly increased deformations were observed in the contact area of the medial femoral cartilage surface in all directions (Fig. 2c).

Contact pressures were similar in the reference models with and without split-lines (Fig. 3a). However, the fibril strains were slightly lower in the model with split-lines (Fig. 3b). In the OA model, contact pressures were reduced in the medial femoral condyle (OA site), while they were increased in the lateral condyle (Fig. 3a), and the collagen fibril strains were significantly increased, especially in the diseased area (Fig. 3b).

DISCUSSION: We demonstrated the effect of split-line patterns and changed collagen architecture of femoral cartilage on the knee joint function by combining MRI and FE modeling. Consistent with a recent in vitro simulation study [5], the present results suggest that the superficial collagen orientations, indicated by split-lines, have a major role in controlling local deformations and strains in cartilage. Instead, they were shown to have a minor role in distributing stresses on the cartilage surface. Degenerated area in the joint is suggested to impair the knee joint function by increasing local strains and modulating contact pressures of cartilage both in the lateral and medial site of the femoral condyle. Increase in strains was consistent with a recent a 2D model study [6]. We believe that our new patient-specific approach with a 3D model can have a role in the functional imaging and OA diagnostics in the future.

Figure 1. A sagittal MR-image of a knee joint (a) with segmented three-dimensional geometry (b).

Figure 2. Local deformation distributions in the surface of femoral cartilage in the directions 1 and 3 (see the coordinate system). First column shows split-line patterns in the each model: a) a model with split-lines, b) a model without split-lines, c) a model of OA. Second and third columns show the local deformation distributions in the directions 1 and 3, respectively.

Figure 3. Contact pressure (a) and logarithmic collagen fibril strain (b) distribution in the surface of femoral cartilage with split-lines (first column), without split-lines (second column) and OA (third column).

ACKNOWLEDGEMENTS: Financial support from the Academy of Finland and Kuopio University Hospital, Finland (EVO) is acknowledged.