INTRODUCTION: Gait cycle of a knee joint includes 6 different simultaneous movements: 3 rotations (extension-flexion, internal-external, varus-valgus) and 3 translations (posterior-anterior, medial-lateral, distal-proximal) [1]. Implementation of the loading characteristics and gait cycle in a finite element (FE) model can help to evaluate stresses and strains in healthy, diseased, damaged and surgically operated joints. There are some FE models in the literature that simulate joint loading during a gait cycle [2]. However, material characterization in those models is strongly simplified, e.g., usually time-independent. Currently, the most sophisticated 3D FE models of a knee joint with realistic material behavior of articular cartilage consider only axial compression [3, 4]. Therefore, these models fail to predict time-dependent knee joint stresses and strains during realistic human movement, e.g., walking or stair climbing. The aim of this study was to implement characteristic joint loading during a gait cycle into a sophisticated FE model of a knee joint with articular cartilage modeled as a fibril reinforced poroviscoelastic material.

MATERIALS AND METHODS: Three-dimensional geometry of a left knee joint of a healthy 60 year old male patient (weight: 100 kg) was created from magnetic resonance images (MRI). Femoral and tibial cartilages were modeled as a fibril-reinforced poroviscoelastic (FRPVE) material with the non-fibrillar matrix modulus of 0.31MPa and the initial and the strain-dependent fibril network moduli of 0.47MPa and 673MPa, respectively [5, 6]. Depth-dependent collagen fibril orientations as well as split line alignments were implemented in cartilage, in accordance with the literature. Depth-dependent fluid fraction was also included in cartilage layers [5]. Menisci were modeled as transversely isotropic materials with the Young’s modulus of 150MPa in the circumferential direction and 20MPa in the axial and radial directions [7]. Values for the rest of the material parameters of cartilage and meniscus were also obtained from the literature [5, 6, 7].

Realistic information of the gait cycle during walking [1, 8, 9] (Fig. 1) was implemented into the reference point (RF), located in the middle between the lateral and medial epicondyles [10, 11]. Bottom of tibial cartilage was fixed, meniscal horns were attached into tibia using linear springs with the total stiffness of 2000N/mm per horn, and free varus-valgus rotation was allowed. Then, the model was simulated using Abaqus v6.10 (Dassault Systemes, Providence, RI, USA).

RESULTS: Free varus-valgus angles of the FE model were similar to those shown in the experimental study (Fig. 1, bottom right, R=0.89, p<0.0001). Maximum contact pressures were in agreement with previous experimental studies (Fig. 3) [12, 13].

von Mises stresses, contact pressures, pore pressures and maximum principal strains were significantly different in medial and lateral sides of the knee joint during the gait cycle (Figs. 2 and 3). At the first peak force, the highest stresses and strains of cartilage were located at the anterior side of medial tibia and medial femoral condyle (Figs. 2a and 3). von Mises stress values were significantly greater than pore pressure values in the medial tibial cartilage (Fig. 3).

At the second peak force, joint loads were partly transferred from the medial to the lateral side of the knee joint. The highest stresses and strains of cartilage were located at the medial side of lateral tibia and close to the middle point of medial tibia (Figs. 2e and 3). Subsequently, similar stress distributions were observed in the medial and lateral femoral condyles. At this time point of the gait cycle, von mises stress and pore pressure values were not significantly different in tibial cartilage (Fig. 3).

Meniscal stresses were highest in the interior lateral meniscus at the first peak force (Fig. 2b). During the second peak force, stresses decreased in the lateral meniscus and increased significantly in the medial meniscus (Fig. 2e).

DISCUSSION: For the first time, information of a gait cycle was implemented into a sophisticated FE model of a knee joint in which cartilage was modeled as a fibril reinforced poroviscoelastic material. Stresses and strains experienced by cartilage and menisci were evaluated as a function of time. Importance of the lateral menisci during the first peak force of the gait cycle was obvious in distributing stresses and reducing those experienced by cartilage. Supporting effect of the medial meniscus was smaller than that of the lateral meniscus. Primarily due to these reasons, maximum stresses and strains in the medial tibial cartilage were significantly higher than those in the lateral tibial cartilage. These findings suggest that lateral meniscal injury may develop more likely to this specific patient. On the other hand, cartilage injury and osteoarthritis would be more likely to occur at the medial tibial cartilage.

SIGNIFICANCE: Evaluation of stresses and strains in a knee joint can provide information of possible failure sites in joints. However, those can depend on time and locations, and this study provides a novel tool to solve that problem.

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