Effect of Lateral Meniscus Tears and Partial Meniscectomy on Stress Concentrations in Knee Joint During Walking

INTRODUCTION: Load distribution and shock absorption are the primary functions of menisci in the knee joint [1]. Therefore, maintenance of intact menisci is important for prevention of osteoarthritis. Radial tears are common injury types in menisci [2, 3]. Partial meniscectomy is generally used for treatment of radial tears [4]. In this operation, a small part of the meniscal tissue is removed.

Finite element (FE) method can be used to simulate knee joint stresses and strains, and the effects of meniscal injuries and meniscectomy. Earlier models on meniscal tears or partial meniscectomies, including the whole knee joint geometry, do not consider realistically knee joint movement [5, 6]. Therefore, they exhibit limited prediction accuracy, in terms of location and time dependence. Furthermore, earlier models do not include realistic depth-dependent collagen fibril orientations and split-lines in the models. The aim of this study was to evaluate the influence of different meniscal tears and partial meniscectomy on the cartilage and meniscus stresses by implementing a fibril reinforced poroviscoelastic (FRPVE) material and realistic gait cycle loading into a FE model.

MATERIALS AND METHODS: Three dimensional geometry of an intact knee joint was constructed from magnetic resonance images using Mimics v12.3 (Materialise, Leuven, Belgium). Then, the geometry was imported into the FE analysis package Abaqus v6.10 (Dassault Systèmes, Providence, RI, USA), where the FE mesh and model were created. Femoral and tibial cartilages were modeled as FRPVE materials [7] and menisci were considered as transversely isotropic materials [8]. In cartilage layers, collagen fibrils had realistic depth-dependent arcadeline orientations and cartilage surfaces exhibited typical split-line patterns [9, 10].

Four different models of the knee joint were constructed with different geometries for lateral meniscus: healthy, intact menisci; radial tear in the middle lateral meniscus; radial tear in the posterior lateral meniscus; partial meniscectomy, indicating the surgical operation for the middle lateral tear (Fig 1).

For the boundary conditions of the models, realistic time-dependent gait cycle data including 2 rotations and 2 translations, as well as loading force, were obtained from the literature [11, 12, 13] and implemented into the models.

RESULTS: Highest stresses in the lateral meniscus were detected during the first peak force at the relative time of 0.2 of the full gait cycle (Fig. 2). In the models with radial tears, high stress concentrations in the menisci were predicted especially at the ends of tears (Fig. 2a-c). In the model with partial meniscectomy, high stress concentrations in the menisci were located at the area of the surgical operation (Fig. 2d).

In lateral tibial cartilage (contact area with femoral cartilage), meniscal tears and especially surgical operation altered von mises stresses, contact pressures, and pore pressures during the first 50% time of one gait cycle (Figs. 2 and 3). At the first peak loading force, von mises stresses increased by 20% and 41% in the models with meniscal tears, and 73% in the model with surgically operated meniscus (Figs. 2a-d). At the same time point of the gait cycle and in the corresponding models, contact pressures increased by 13%, 25% and 85% (Fig. 3a), while pore pressures increased by 15%, 30% and 92% (Fig. 3b).

During the last 50% of the gait cycle, medial healthy meniscus supported a large portion of the joint load, thus, von mises stresses, contact pressures and pore pressures were not altered in the lateral cartilage at the second peak loading force (Fig. 3). Furthermore, lateral meniscal tears and surgical operation caused only minor changes in cartilage and meniscus stresses at the medial side of the knee joint.

DISCUSSION: We presented the effect of different lateral meniscus tears and partial meniscectomy, simulating the surgical treatment, on the meniscus and cartilage stresses under realistic knee joint movement by implementing the FRPVE material with realistic collagen fibril orientations of cartilage in the 3D knee joint model. The highest lateral meniscal support and stresses were predicted during the first peak loading force of the gait cycle. Thus, meniscal tears and especially surgical operation increased stresses and fluid pressures in the lateral tibial cartilage. At the second peak loading force of the gait cycle, stresses were distributed more evenly between the unhealthy lateral and healthy medial sides of the joint, showing no possible failure points in cartilage or menisci in any of the models.

The present results suggest that the meniscal tears create a significant risk for total failure of the meniscus. On the other hand, treatment of the radial tear by removing surgically a small part of the meniscus alters the stress distributions and may increase the risk for the onset of osteoarthritis in cartilage.

SIGNIFICANCE: By the presented computational tool, it is possible to evaluate the effect of different meniscal injuries and meniscectomy on knee joint stresses and optimize the area of partial meniscectomy for minimizing overload-induced failure of cartilage and meniscus. Thus, this tool could be used as a clinical aid in a decision making for clinical treatments and operations for patients or athletes with meniscal injuries.

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