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Original article

The relationship between medial meniscal subluxation and stress distribution pattern of the knee joint: Finite element analysis

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ABSTRACT

Background: Degenerative changes of the knee joint and clinical follow-up after meniscal subluxation are well documented. In the current study three-dimensional (3D) finite element analysis (FEA) of human lower limb was used to investigate the effect medial meniscal subluxation on the loadings of the knee structures.

Methods: Apart from the reference model, a total of ten 3D models were created, according to amount of medial meniscal subluxation. ANSYS® 14 was used to analyze the stress/load distribution, that is to say the maximum equivalent stress (MES) (von Mises stress) on bones, cartilages, ligaments and menisci. MES was expressed as Newton/mm^2 = Megapascal (MPa).

Results: In a static and standing upright position the MES on all knee structures were evaluated in the reference model. Although MES increased in all structures with the increase of medial meniscal subluxation degree, tibia cartilage was found to be the most affected structure with an increase of 22.73-fold in the10 mm subluxation model when compared with references values.

Conclusion: This study showed that medial meniscus subluxation is associated with increased loadings on all knee structures especially the tibia cartilage. Also the degree of the medial meniscal subluxation correlates with distribution and the amount of loadings on tibia cartilage which may be a prominent feature of knee osteoarthritis.

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1. Introduction

The menisci are one of the important biomechanical components in human knee joint, playing a multifunctional role in shock absorption, enhancement of the knee stability and lubrication, proprioception and load transmission [1]. The wedge-shaped menisci, located between the convex femur and the relatively flat tibia increase contact areas and protect cartilages from excessive axial stresses [2,3]. The role of the menisci in load transmission has been discussed by many authors, and it has been shown to depend heavily on the meniscus integrity [4–6].

Despite the association between meniscal subluxation and cartilage degeneration being reported by previous studies, there is still controversy over which comes first [7–10]. Previous reports have documented some association of meniscal subluxation with radiographic findings in osteoarthritis such as, cartilage degeneration, osteophyte formation, anterior cruciate ligament tear, joint space narrowing, and joint effusion [7,9–12]. However these studies have not evaluated the relationship between the amount of subluxation and stress distribution at the main structures of the knee (femoral and tibial cartilages, menisci, collateral ligaments and cruciate ligaments.)

When hoop tension is not efficient to optimally distribute load within the knee, it was found to be associated with increased cartilage degeneration in the same compartment [7,13]. Based on these predictions, we hypothesized that, depending on the amount of the medial meniscal subluxation, loading on the knee structures might be altered. Finite element analysis (FEA) gave us opportunity to study how meniscal subluxation affects the stress distribution at

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main structures of the knee. The purpose of this study was to demonstrate the relationship between medial meniscal subluxation and stress distribution pattern of the knee joint.

2. Materials and methods

Three-dimensional (3D) FEA of human lower limb was used to investigate the effect of medial meniscal subluxation on the loadings of the knee structures. In the current study 3D model was constructed based on computed tomography (CT) and magnetic resonance imaging (MRI) images of one healthy volunteer subject. The subject was a thirty-four year old man with 100 kg weight and 185 cm height. He has no evidence of previous knee pathologies.The models were created with the help of MIMICS® (Materialise's Interactive Medical Image Control System, Materialise-Belgium) software by using 3D CT images. The images were acquired with Toshiba® Aquilion Multislice CT scanner as the subject was in supine position, with the hip and knee joints at complete extension, and the patellae facing upwards. Longitudinal CT scans of the lower extremity consist of parallel layers at the neutral position and a pixel resolution, the image matrix was 512 9512. An 1841-layer shooting was carried out to develop the model used as reference, it was obtained with a slice thickness of 0.5 mm with the hip joint in internal rotation and perpendicular to the mechanical axis of the lower extremity on the axial plane. Also, MRI scans of the lower extremity of the subject were obtained with a slice thickness of 0.2 mm for menisci and cartilage data was gathered by using a Philips Achieva 3 T MR Scanner (Rel.10.4) (Philips Healthcare, Best, the Netherlands), using a knee coil with eight channels. Institutional Review Board approval was obtained for experiments along with signed consent from the subject.

2.1. Three-dimensional finite element models

The CT images were used to generate 3D solid biomodels with the help of visualization and segmentation software. All DICOM (The Digital Imaging and Communications in Medicine) formatted images were transferred to another computer workstation and 3D solid formats of femur, tibia and fibula were created by using MIMICS® 12.11. Soft tissue construction was another detailed modeling process. Medial and lateral menisci (MM an LM respectively), femur and tibia cartilage, anterior cruciate ligament (ACL), posterior cruciate ligament (PCL), medial collateral ligament (MCL), lateral collateral ligament (LCL) were modeled via SolidWorks® (Dassault Systems, USA) software. MRI images were used for verification of structures with respect to size, shape, origin and insertion.

3D biomodels were exported in MIMICS® and were transferred to reverse engineering software GEOMAGIC® (Raindrop Inc., USA) for preparing anatomical original geometry. The surface failure fixing and smoothing of the biomodels were performed in GEOMAGIC®. The 3D models were transferred by stereolithography (STL) format from GEOMAGIC® to MIMICS® and assembled as a non-manifold assembly using MIMICS® FEA module for volumetric mesh generation. Also, GEOMAGIC® and MIMICS® were used to geometrical shape comparisons of all models to the original CT or MRI scans.

2.2. Mesh and material properties

A total of 12 bodies (bones, ligaments, menisci and cartilages) were constructed with MIMICS FEA interface. Ten-node tetrahedral elements were used to form the mesh of the finite elements models. An average of 487,549 nodes and 320,354 elements were used for each model. Element types were accepted as 'quad element size' and the sizes were 3 mm for bones, 2 mm for cartilages and menisci, and 1 mm for ligaments, respectively (Fig. 1). The model was initially assigned material properties reported in the literature and all bodies were allocated with a linear elastic isotropic material [4,14–17]. Cartilages and menisci are tissues that have viscoelastic material properties. However, in our case, considering that the loading time corresponded to that of a single leg stance situation, the time constant of the viscoelasticity of cartilage approached 1500 s [15,18]. That is the reason why cartilages were considered to behave in a single-phase linear elastic isotropic and homogeneous material. For the same reason, menisci were also assumed to be a single-phase linear elastic and isotropic material; also the under stress or creep relaxation material properties of the solid matrix where determined from equivalent conditions after fluid flow.

2.3. Boundary and loading conditions

ANSYS® software (Version 14, Ansys Inc., USA) was used to analyze the stress/load distribution, that is to say maximum equivalent stress (MES) (von Mises stress), on bones, cartilages, ligaments and menisci. All connections between the structures were defined by using '*contacts*' tool in ANSYS® software. 'Bonded' contact type was defined for connections between cartilages and bones, ligaments and bones, anterior and posterior horns of menisci and bones respectively. 'No separation' contact type was used for connections between menisci and cartilages. 'Displacement tool' was used to determine motions of menisci on X, Y and Z axis respectively. Meniscal attachments to the tibia at the anterior/

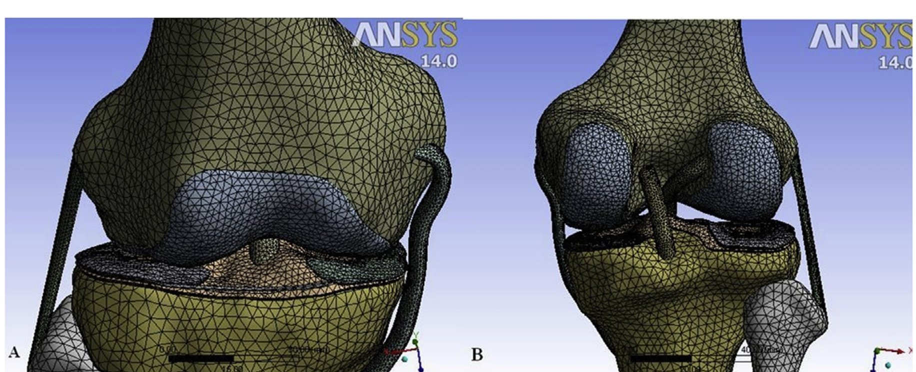

Fig. 1. A) Anterior **B)** Posterior view of three dimensional (3D) solid knee model showing mesh type and intra-extra articular bones and soft tissues that were used for reference model.

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