Available online at www.sciencedirect.com
SCIENCE DIRECT®
ELSEVIER
Clinical Biomechanics 20 (2005) 498–507
CLINICAL BIOMECHANICS
www.elsevier.com/locate/clinbiomech

Finite element analysis of the effect of meniscal tears and meniscectomies on human knee biomechanics

E. Peña, B. Calvo, M.A. Martínez, D. Palanca, M. Doblaré *

Group of Structural Mechanics and Material Modelling, Aragon Institute for Engineering Research (I3A), University of Zaragoza, María de Luna, 3. E-50018 Zaragoza, Spain

Received 25 March 2004; accepted 7 January 2005

Abstract

Background. Many authors have suggested that the high levels of shear and tensile stresses that appear in the articular cartilage after meniscectomy are partly responsible for cartilage pathologies, such as osteoarthrosis.

Methods. In this paper, we investigate the effect of meniscal tears and meniscectomies on the human knee joint. Solid models of the tibia, femur, menisci and cartilage were generated from MRI images. A three-dimensional finite element model was developed that included the femur, tibia, cartilage layers, menisci and ligaments. The femur and tibia were considered to be rigid, the articular cartilage and menisci to be linearly elastic, isotropic and homogeneous and the ligaments were modelled as hyperelastic. Three different situations were compared: a healthy tibio-femoral joint, a tibio-femoral joint with tears in one meniscus and a tibio-femoral joint after meniscectomy.

Findings. The minimal principal stresses corresponding to a compressive load at 0° flexion were obtained for the posterior zone of the medial meniscus and the corresponding region of the articular cartilage. Under an axial femoral compressive load, the maximal contact stress in the articular cartilage after meniscectomy was about twice that of a healthy joint.

Interpretation. This fact could partially explain the cartilage damage and degeneration that have been observed after meniscectomy.

Keywords: Human knee joint; Finite element method; Meniscal tears; Meniscectomy; Articular cartilage; Arthrosis

1. Introduction

An important multifunctional component of the knee are the menisci. They are a complex biomechanical system in themselves, with a fundamental role in load transmission, shock absorption, proprioception, improvement of stability and lubrication (Vedi et al., 1999). In order to perform these functions efficiently, their behavior is completely dynamic. They effectively distribute contact forces over the articular surfaces by increasing the contact surface of the joint. Load distribution over an incongruent joint surface is redistributed by the menisci by maintaining maximal congruency. The functionality of the menisci and their role in load transmission across the knee have been discussed by many authors (Fithian et al., 1990; Macnicol and Thomas, 2000). This functionality is strongly affected by various lesions. For example, Scheller et al. (2001) found frequent degenerative changes after meniscectomy. Similar degenerative changes were reported by Jackson (1968) and Crevoisier et al. (2001).

Clinical studies have demonstrated that meniscal injuries are painful even before an important degeneration of the joint has occurred. Its propagation throughout the meniscus can lead to joint locking. For example, the longitudinal or bucket handle tear usually extends to more than 50–65% of the meniscal length, and may

* Corresponding author.
E-mail address: mdoblare@unizar.es (M. Doblaré).

0268-0033/$ - see front matter © 2005 Elsevier Ltd. All rights reserved.
doi:10.1016/j.clinbiomech.2005.01.009

result in an unstable fragment that can lock the joint. It may also displace into the intercondylar notch and remain there chronically, becoming fixed and distorted (Fu et al., 1994). Clinically, about 81% of the injuries are parrot beak or longitudinal tears affecting more often the medial meniscus (Greis et al., 2002). This is probably due to its firmer insertions under the tibial plate that makes it more sensitive to tangential stresses. The percentage of cases with deterioration is higher for the lateral femoral cartilage than for the medial.

Most authors agree that total meniscectomy leads to progressive articular wear after a few years. This is mainly due to the fact that the global biomechanics of the knee is altered and the articular instability increases, resulting in a progressive and degenerative arthrosic pathology (Macnicol and Thomas, 2000; McNicholas et al., 2000). Therefore, total meniscectomy is now avoided and only partial meniscectomies are usually performed. In spite of the good results obtained with this latter technique, the knee also suffers a progressive long-term wear. For example, the excellent or good results achieved after surgery decrease to only 91.7% after 4 years, and 78.1% after 12 years. Fauno and Nielsen (1992) found radiologic arthrosic alterations in 53% and 23% of damaged contralateral knees, eight years after medial and lateral total meniscectomies, respectively. Rangger et al. (1995) also found degenerative changes in 38% of the cases, four years after arthrosporic medial partial meniscectomies and 24% after lateral partial meniscectomies. Meniscectomies dramatically alter the pattern of static load transmission of the knee joint (LeRoux and Setton, 2002). Several researchers have reported higher stresses and a decrease in shock-absorbing capability after total meniscectomy (Fithian et al., 1990; Dandy, 1990; Macnicol and Thomas, 2000; Silver and Bradica, 2002).

In addition to extensive statistical campaigns and experimental tests, numerical modelling is progressively becoming an important tool in qualitative assessment of the overall biomechanical behavior and its evolution in many different organs (Fung, 1993; Cowin, 2001; Holzapfel, 2001; Humphrey, 2002). However, even though numerical methods have been substantially improved (especially finite element techniques), we still need to make a strong effort in getting more accurate information regarding the constitutive behavior of some of the most common biological tissues, such as ligaments, tendons and cartilage.

With respect to meniscus biomechanics and its possible degeneration, finite element simulations help to understand the stress distribution in the human knee joint and prevent joint injuries and pathological degeneration of articular joints. Three-dimensional finite element models can also be used to estimate the consequences of surgical treatments such as total or partial meniscectomies.

Several authors suggested that damage in cartilage starts at its surface and extends through the thickness. This can be explained by a maximal shear stress criterion (Donahue et al., 2000; Eberhardt et al., 1991). This corresponds to a damage situation without disruption of the underlaying bone nor calcified cartilage layers.

Some computational models of the human knee have already been constructed to predict the biomechanical behavior of the joint (Eijden et al., 1986; Abdel-Rahman and Hefzy, 1993). Heegard et al. (1995) developed a three-dimensional model to analyze human patella biomechanics during passive knee flexion. Beynnon et al. (1996) developed an analytical sagittal plane model of a knee joint to study how cruciate ligament bundles control joint kinematics. Jalani et al. (1997) and Bendjaballah et al. (1995, 1998) constructed a nonlinear finite element model of the entire human joint to investigate the detailed biomechanics of the passive tibiofemoral joint in full extension under anterior–posterior drawer forces and internal-external torques. Périé and Hobatho (1998) and Li et al. (1999, 2001) considered joint contact stresses and contact areas on the human knee menisci.

To our knowledge, only Wilson et al. (2003) considered the effect of meniscectomies on the human knee joint using the finite element method. They determined the stress and strain distributions and fluid velocities in the articular cartilage before and after meniscectomy, but only used an axisymmetric model. Their study was concentrated on the estimation of the development of osteoarthrosis after total meniscectomy. However, it is well-known that the behavior of the menisci and the articular cartilage is far from being axisymmetric (Fig. 3) (i.e. the behavior of the medial meniscus is completely different from the lateral). Besides, there are no studies in the literature regarding the human tibio-femoral joint with meniscal tears and partial meniscectomy.

The main objective of this study was to develop a three-dimensional finite element model of the human tibio-femoral joint including the femur, tibia, cartilage layers, menisci and main ligaments to estimate the contact areas and pressure distributions between menisci and articular cartilage and the stress distribution in the articular cartilage to investigate the effect of meniscal tears and meniscectomies on these variables. This could help to explain the cartilage degeneration after a total or partial meniscectomy (Andersson-Molina et al., 2002; LeRoux and Setton, 2002).

2. Methods

2.1. Finite element model of the healthy tibio-femoral joint: geometry and mesh

The geometrical data of the model here developed were obtained by CT (computerized tomography) and