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Finite element modeling following partial meniscectomy: Effect of various size of resection

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***Abstract*— *Introduction:* Meniscal tears are a common occurrence in the human knee joint. Orthopaedic surgeons routinely perform surgery to remove a portion of the torn meniscus. This surgery is referred to as a partial meniscectomy. It has been shown that individuals who have decreased amount of meniscus are likely to develop knee osteoarthritis. This research presents the analysis of the stresses in the knee joint upon various amounts of partial meniscectomy.**

***Methods:* To analyse the stresses in the knee joint using finite element method an axisymmetric model was developed. Articular cartilage was considered as three layers, which were modelled as a poroelastic transversely isotropic superficial layer, a poroelastic isotropic middle and deep layers and an elastic isotropic calcified cartilage layer. Eight cases were modelled including a knee joint with an intact meniscus, 10%, 20%, 30%, 40%, 50%, 60% and 65% medial meniscotomy.**

***Findings*: Under the axial load of human weight on the femoral articular cartilage with 40% removal of meniscus high contact stresses took place on cartilage surface. Further, with 30%, 40%, 50% of meniscectomy significant amount of contact area noticed between femoral and tibial articular cartilage. After 65% of meniscectomy the maximal shear stress in the cartilage increased up to 225% compared to knee with intact meniscus. It appears that meniscectomies greater than 20% drastically increases the stresses in the knee joint.**

I. BACKGROUND

The partial meniscectomy of knee joint results in significant changes to load carrying attributes of meniscus.

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In addition, partial or whole meniscectomy often leads to osteoarthritis degenerative changes in the articular cartilage of the femur and tibia. Some of these changes include flattening of the ridge formation of the femoral condyle over the site of the removed meniscus and narrowing of joint space.

Kurosawa et al. 1980 [2], determined that after the menisci were removed, the cartilage deflection increases and the size of the contact areas decreased significantly by a third to a half. The results of an energy study indicate that the menisci gave more elastic stability to the joint. After the menisci were removed, more energy was dissipated during cyclic loading. Thus, the menisci provide surface compliance and serve to transmit stresses across the wider areas to the periphery, and, therefore, help to avoid stress concentration both in the articular cartilage and in the subchondral bone, especially under high loads over 1000N.

Baratz et al. 1986 [4], determined that removal of 33% of the meniscus in the knee produced a 65% increase in peak local contact stress. Kleemann et al. 2005 [5], determined an association between meniscal damage and structural, mechanical and histological changes to the articular cartilage.

Various authors have proposed models of the ligaments, meniscus and articular cartilage. A number of models of the meniscus have been used in the previous studies. Initially, axisymmetric models of the meniscus were developed using materials represented by linear isotropic elastic properties [8] or transversely isotropic elastic material properties [10]. But Spilker et al. [11] concluded in their study that the transversely isotropic biphasic properties of the meniscus are essential for proper meniscus simulation. Also, in a recent study by Yao et al. [12] the meniscus was modeled as transversely isotropic elastic material.

For Articular cartilage, Askew and Mow [13] suggested that collagen fibril ultra structure varies with depth from cartilage surface. They modeled the superficial-tangential zone of cartilage consisting of sheets of randomly oriented fibril network lying parallel to the articular surface by a transverse isotropic elastic layer. The middle and deep zone were modeled as isotropic elastic layers. However, they did not consider the biphasic material properties of the articular cartilage, which may affect the result of the stress distribution analysis significantly. Garcia et al. [14] performed a stress analysis on an axisymmetric model of articular cartilage. The model considered cartilage as poroelastic transversely isotropic and as poroelastic isotropic with a poroelastic transversely isotropic superficial layer. Both models were tested under a normal impact load of indenters on an axisymmetric cylindrical disk of cartilage. Recent work by Singh et al. [15] suggests that multilayer poroelastic models are the proper way to model the articular cartilage. Using this model, they were able to simulate type I and type II damage to the articular cartilage.

With respect to meniscus biomechanics and its possible degeneration, Finite Element Analysis (FEA) is particularly well suited to dealing with such complex problems to get accurate results in terms of stress, strains and displacement. Few authors have developed FEA models to examine the load altering behavior of meniscectomies.

Wilson et al., 2003, [9] developed an axisymmetric model to investigate stresses changes in the articular cartilage. Pena et al., 2005, [16] developed and implemented a three-dimensional finite element model that included the femur, tibia, cartilage layers, menisci, and ligaments. Solid models of the tibia, femur, menisci and cartilage were generated from MRI images. The femur and tibia was considered rigid, the articular cartilage and menisci to be linearly elastic, isotropic and homogenous and the ligaments were assumed as hyperelastic. The results of their study concluded that maximal contact stress in the articular cartilage after meniscectomy was about twice that of a healthy knee joint. However, in this research work, he has considered mainly three cases, knee joint with intact meniscus, knee joint with full meniscectomy and knee joint with different types of tears.

Recently, Zielinska B. [17] has studied effect of partial meniscectomy using 3D finite element model to quantify the changes in knee joint contact behavior following various degree of partial medial meniscectomy. However, she did not consider the cartilage as a three layers material. Further more, she has not considered the biphasic material properties of articular cartilage and modeled cartilage as linearly elastic isotropic material.

The purpose of the present study is to determine peak stresses in the cartilages and meniscus, as well as the contact area by following partial meniscectomy, by properly modeling the cartilage and meniscus.

The results of this study may help to provide the medical community with data to understand the impact of meniscectomy on the progression of knee osteoarthritis.

II. METHODS AND MATERIAL

An axisymmetric finite element model of the human knee joint was developed and analyzed in Adina8.2 (ADINA R & D, Inc., 71 Elton Ave, Watertown, MA-02172) on UNIX platform. This model consists of the meniscus, tibio-femoral articular cartilage, and portions of the femur. Wilson et. al. (2003), [9] previously developed the axisymmetric model. However, a new axisymmetric model has been developed more closely resembling actual knee geometry. This new axisymmetric model is shown in Fig. 1. Most notably this model has increased curvature of the femoral condyles. In addition, Wilson's model incorrectly implied that each condyle was completely encircled by meniscus. This modeling change directly impacts stress results, particularly when there is cartilage to cartilage contact.

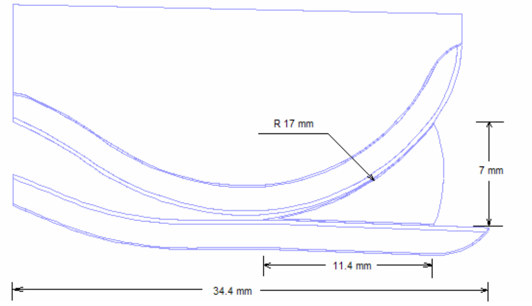

Fig. 1. 2D Axisymmetric model of knee joint consists of meniscus, tibio-femoral articular cartilage and portion of femur

TABLE I
MATERIAL PROPERTIES

	Material Characteristic	Material Property	
Cartilage (Superficial layer)	Transversely Isotropic poroelastic	E_x=E_y=5.8 MPa, E_z=0.46 MPa, ν_{xy}=0.0002, ν_{yz}=0, G_{xz}=0.37 MPa, k=5.1*10^{-15} m^4/Ns, Φ_m=0.25	[1]
Cartilage (Middle and deep zone layers)	Isotropic poroelastic	E=0.69MPa, ν=0.018, k=3*10^{-15} m^4/Ns, Φ_m=0.25	[1]
Calcified Cartilage	Elastic	E=10MPa, ν=0.499	[3]
Meniscus	Transversely Isotropic elastic	E_x=100MPa, E_y=E_z=0.075MPa, ν_{xy}=0.0015, ν_{yz}=0.5, G_{xy}=0.025MPa, k=1.26*10^{-15} m^4/Ns, Φ_m=0.75	[3, 6, 7
Bone	Elastic	E = 400MPa, ν=0.3	[9]

Material properties assigned to cartilage, meniscus, calcified cartilage and bone (E = Elastic modulus, ν = Poisson ratio, k = Permeability, G = Shear modulus and Φ_m = Solid volume fraction)

The cartilage and meniscus are modeled as poroelastic materials. The articular cartilage is modeled with three layers which has been shown to be essential for proper knee joint simulation [15]. The poroelastic representation is equally important since fluid pressure carries a significant portion of the applied load [12]. Table 1 presents the material properties of the meniscus, articular cartilage layers, and bone used in this study.

In this axisymmetric knee joint model (Fig 1), the cartilage consists of three layers, a superficial tangential layer, the middle and deep zones as one layer and the calcified part of the cartilage. The maximum thickness of the cartilage is 2.4 mm [18] in the center of the model. The thickness of the superficial tangential layer varies between 10 and 20 percent of the total thickness of the cartilage [19].

In our model the superficial layer and calcified part of the cartilage accounted respectively for 15% and 5% of the total cartilage thickness [20].

The stress distribution in models was obtained by performing a finite element contact analysis. Three contact pairs have been defined, the femur and meniscus, the tibia and meniscus, and the femur and tibia. Because of large meniscus movement with increasing applied body weight, program was not apparently converging. In order to provide a smooth transition between contacting surface, a thin flexible membrane with thickness 0.1 mm, with a very low stiffness was introduced between the meniscus and cartilages outer layer, fixed to the meniscus [9]. This thin layer dose not have significant effect on the deform geometry. The contact between the articular cartilages and thin flexible membrane were assumed frictionless. A finite element model with eight-node element was tried, but with eight node elements the solution did not converge. Hence, this model was analyzed using four-node element system.

A pressure of 0.17 MPa was applied at the top surface of the femur, which corresponds to half of the body weight of a 60 kg person. Here, we have assumed that the lateral and medial part of the knee joint carry the same amount of load, independent of the knee joint condition in standing posture. This assumption is under investigation by the authors via 3D modeling of the knee joint. The full load was applied linearly in one second and then was kept constant for the next 59 seconds. A similar load history was used by Wilson et al. [9] for evaluating the stress distribution in the human knee joint for standing posture.

To consider the effect of partial meniscotomy on stress distribution, eight different cases have been analyzed. These cases include a knee joint with an intact meniscus and a knee joint with various amount of meniscus removed from medial region (10%, 20%, 30%, 40%, 50%, 60% and 65% of total length of meniscus). These removal percentages approximate common practice in surgical operations.

II. RESULTS AND DISCUSSION

The analysis showed that for a healthy knee joint, the

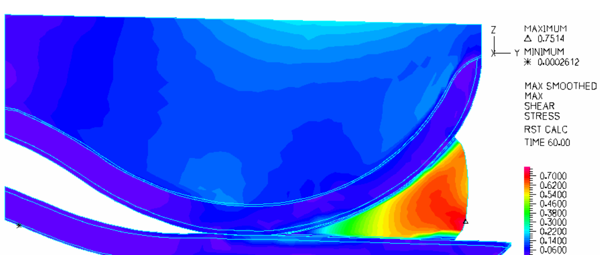

Fig. 2. Maximum shear stress contour of axisymmetric knee joint with full meniscus.

shear stress distribution in the cartilages is fairly uniform (Fig. 2). Furthermore the maximum normal stress (Contact stress) is located at the interface of bone and cartilage. This maximum normal stress increases drastically with the removal of meniscal tissue (Fig. 3). However, there was minor change in the contact stress above 50% meniscectomy.

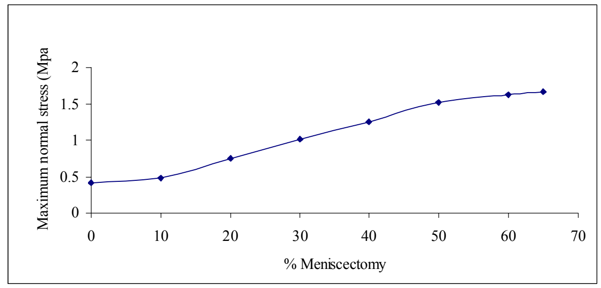

Fig. 3. Maximum normal stress (contact stress) in the articular cartilage with respect to percentage removal of partial medial meniscectomy

As pressure is applied at the femoral bone, the tibial and femoral cartilages come into contact, and apart from axial normal stress, shear stress is also experienced on the surface of tibial and femoral plateau. Our research shows that considering the presence of meniscus, the maximum shear stress always happens in the meniscus because of its soft tissue material property. The location of this maximum shear stress, for the intact meniscus, was seen in the lateral region of the meniscus. With a higher percentage removal of meniscus, a significant amount of shear stress develops in the cartilage. Removing portions of the medial meniscus generally did not alter the location of maximum shear stresses. The results showed that there was little change in shear stress in the cartilage up to 20% partial medial meniscectomy (Fig. 5). However, further removal increased

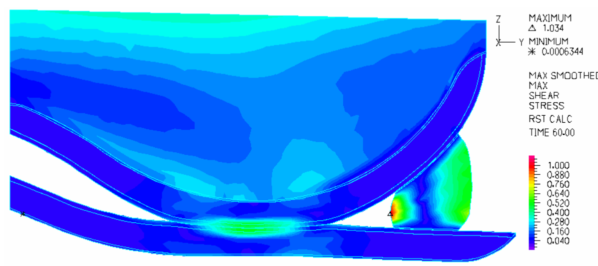

Fig. 4. Maximum shear stress contour of axisymmetric knee joint with 65% meniscectomy.

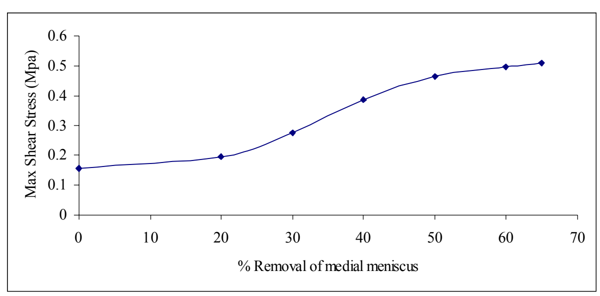

Fig. 5. Maximum shear stress in the articular cartilage with respect to percentage removal of partial medial meniscectomy

shear stresses drastically.

The contact area between femoral and tibial cartilage surface significantly increases up to 40% of the medial meniscus removed (Fig 6). However, minor change was noted in contact area for further meniscectomy. This is expected as increase in the contact area is limited by the curvature and stiffness of the femoral condyle.

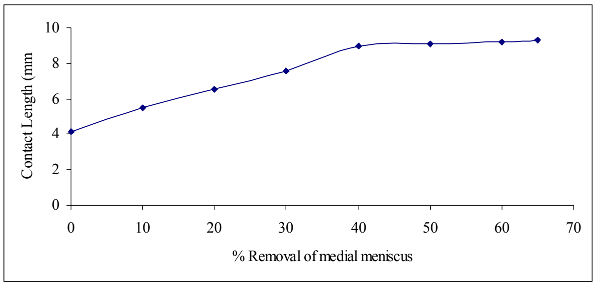

Fig. 6. Contact length of tibio-femoral articular cartilage surface with respect to percentage removal of partial medial meniscectomy

Some biological facts show reason behind increase in shear and normal stresses with respect to partial meniscectomy. Shear properties of cartilage correlated with collagen fibrillar organization measured at superficial surface of cartilage; and compressive properties correlated with glycosaminoglycan content. With the loss of collagen and glycosaminoglycan, significant amount of cartilage function loss found in previous research work. LeRoux et al. [21] concluded that, this is mainly due to decrease of 20-50% compressive and shear modulus, which happens after total meniscectomy.

III. CONCLUSION

Finite element analysis of knee joint was performed to understand the effect of partial meniscectomy on stress distribution, both in cartilage and meniscus. The results showed that shear distribution in the cartilage is little effective up to 20% medial removal of meniscus. However, with further removal, significant normal and shear stress developed in the cartilage, which could lead to its degeneration. Contact area, between tibio-femoral cartilage surfaces, also increased with percentage removed meniscus. This effect is more pronounced with 20% or more meniscus removal. These results could help physicians performing meniscectomy to decide on the percentage of meniscus that could be removed without leaving the patient prone to development of a severe osteoarthritis.

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