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Finite Element Analysis of Normal Tibiofemoral Joint and Knee Osteoarthritis: a Comparison Study Validated Through Geometrical Measurements

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Abstract

Objectives: A comparison study of normal tibiofemoral joint and knee osteoarthritis is done to analyse the displacement, stress and strain values. **Statistical Analysis**: Osteoarthritis (OA) is a general type of arthritis in which there is a gradual loss of cartilage from the joints. Global Burden of Disease 2000 estimated that about 10% of the world's population who are greater than 60 years of age have symptomatic issues that can be attributed to OA. The COPCORD investigations in India for the year 2011 concluded that the rough occurrence of clinically diagnosed knee OA was greater in the urban (5.5%) than the rustic group of people (3.3%). **Methods**: Magnetic resonance imaging (MRI) is thought to be an inexorably essential instrument for in vivo investigations of musculoskeletal biomechanics. Magnetic resonance images were obtained for two subjects in the age group of 40-45 years. Three dimensional models of a normal and OA knee joint are obtained using Mimics Research software 17 and FEA is done using ANSYS 14 software to determine displacement, stress and strain values. **Findings:** Finite Element models are powerful tools to foresee the impacts of various parameters required in knee agony and joint degradation and to give data generally hard to acquire from analyses. The 3D model of normal and OA knee joint further helps to design the prosthesis of knee for the treatment of osteoarthritis. Finite Element Analysis (FEA) result includes the stresses and strains induced in the knee articular cartilages and meniscus during single-leg stance. Displacement, stress and strain values for OA knee are higher than the normal knee joint. Hooke's law of modulus of elasticity is verified in this work. Then finite element model (FEM) is validated through geometrical measurements such as Joint space width, cartilage thickness and meniscus thickness. **Improvements:** This data can be combined with other analysis and modeling tools, for example, gait analysis and FE modeling to test hypotheses concerning joint function and the impacts of wounds.

Keywords: Osteoarthritis, Biomechanics, Stresses, Strains, Joint Space Width, Cartilage Thickness

1. Introduction

Osteoarthritis (OA) is a common joint disorder which is most predominant in the knee joint with cartilage defects[1,2]. Global Burden of Disease 2000 estimated that about 10% of the world's populations who are greater than 60 years of age have symptomatic issues that can be attributed to OA. The COPCORD investigations in India for the year 2011 concluded that the rough occurrence of clinically diagnosed knee OA was greater in the urban (5.5%) than the rustic group of people (3.3%). Contact pressure increase or modifications in knee joint structure and contact area are crucial causes of knee pain and osteoarthritis[3]. Appropriate understanding and assessment of knee joint biomechanics are accordingly vital to enhance the anticipation and treatment of related issue and wounds. The solution to the problem is Finite element models (FEM). FEM have been appeared to give knowledge into the mechanical properties of biological tissues and the execution of living organs, diminishing both cost

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and time[4]. FE models are powerful tools to foresee the impacts of various parameters required in knee agony and joint degradation and to give data generally hard to acquire from analyses[5]. Finite element analysis (FEA) has been turned out to be a capable instrument to explore the definite biomechanical conduct of the knee. The dependability of FEA results emphatically relies on upon the exactness and respectability of the 3D knee FEM. In the human knee joint, cartilage deformities because of injury are common among youthful patients. Because of the restricted repair limit cartilage deserts dependably put the knee at hazard for early OA if left untreated[6].

2. Methodology

Three dimensional models of a normal and OA knee joint are obtained using Mimics Research software 17 and FEA is done using ANSYS 14 software to determine displacement, stress and strain values.

2.1 Data Acquisition

Magnetic resonance imaging (MRI) is thought to be an inexorably essential instrument for in vivo investigations of musculoskeletal biomechanics. This research was approved by the Institutional Ethics Committee, SRM Medical College Hospital and Research Centre, Chennai. Magnetic resonance images were acquired for two subjects in the age group of 40-45 years. MRI scan was performed using a 1.5T-MR scanner (Siemens, Germany) around the knee joint under full extension with 4 mm slice thickness and number of slice is 25. The acquisition parameters are 16 cm field of view, 0.7 mm optimal pixel size, and 256 * 256 pixel resolutions.

2.2. 3 D Model and Geometrical Measurements

The MRI data of normal knee (male 41 years) and OA knee (male 44 years) were imported into MIMICS Research software 17(Materialise, Belgium) for the creation of 3D model of the knee joint. Once the 3D models were created, they were imported into 3-Matic Research software 9(Materialise, Belgium) for volumetric meshing. Depending on the type of output file needed, MIMICS has various exporting options including exporting in the STL format. The protocol for obtaining the three-dimensional model of the knee joint is shown in Figure 1. Geometrical measurements such as joint space width for medial and lateral knee joint, articular cartilage thickness for the femoral and tibial region and meniscus thickness for medial and lateral knee joint are obtained.

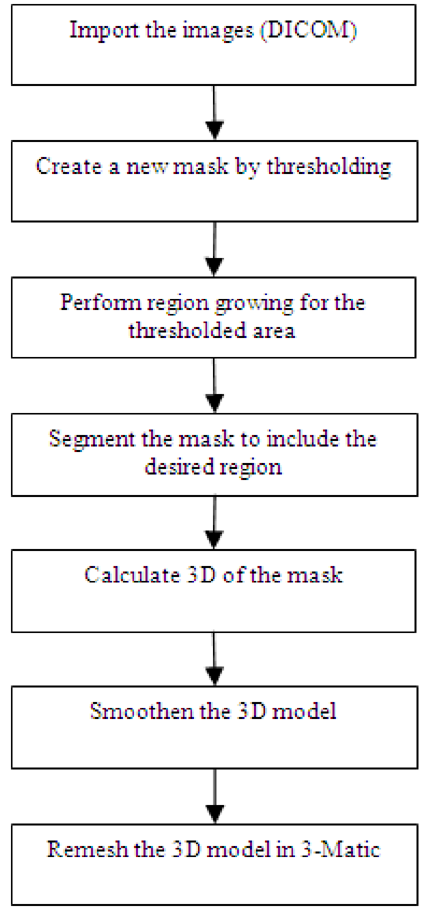


Figure 1. Protocol for obtaining three-dimensional model of knee joint.

2.3 Finite Element Analysis

Once the 3D model was created, it was imported into ANSYS 14.0 software for finite element analysis of knee joint. Steps involved in finite element analysis are pre-processing, solution and post-processing. The material properties of the normal and OA knee joint for bones were assumed to be linear, elastic and isotropic material with Young's modulus of E = 17000MPa and a Poisson proportion of $\upsilon = 0.3$[7,8]. Cartilage was considered to act as a solitary stage versatile and isotropic material with Young's modulus of E = 5MPa and Poisson's proportion of $\upsilon = 0.46$ and in addition the meniscus with the accompanying properties: E = 59MPa and $\upsilon = 0.49$[7,8]. Anatomically suitable boundary condition was applied to tibiofemoral joints. This empowered the body weight to be applied at realistic locations and generate an external adduction moment. Using the assumption of single-leg stance under full extension, a vertical load equivalent to five-sixths of the body weight was applied on the symmetric surfaces of the femur bone[8]. Also, the nodes on the distal surfaces of the tibia and fibula were altered to anticipate interpretation and revolution[9]. The contact surfaces were characterized amongst menisci and femoral articular cartilage and amongst menisci and tibial articular cartilage[10]. Then the stress and strain values were determined for loading conditions of actual body weight and assumed constant body weight. Comparison of normal and OA knee is done to study the biomechanical behaviour of the knee joint.

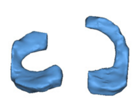
3. Results

Geometrically accurate three-dimensional solid model of the normal knee joint and OA knee joint with special attention given to the meniscus and articular cartilage was developed which is shown in Figure 2 and Figure 3.

a) Entire knee joint

b) Femoral cartilage

c) Tibial cartilage



d) Meniscus

Figure 2. 3D model of normal knee joint.

a) Entire knee joint

b) Femoral cartilage

c) Tibial cartilage

d) Meniscus

Figure 3. 3D model of OA knee joint.

Volume mesh of normal knee joint and osteoarthritis knee joint was obtained as shown in Figure 4 and Figure 5 respectively.

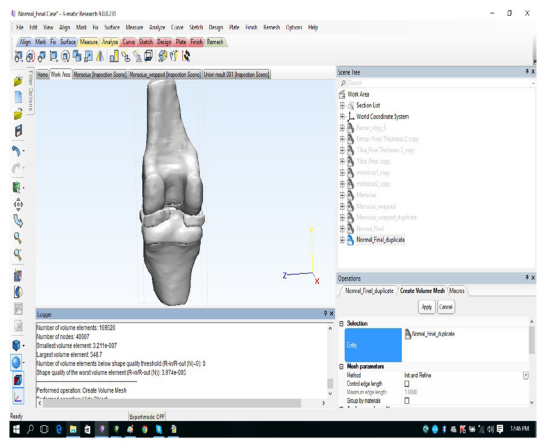


Figure 4. Volume mesh of normal knee joint.

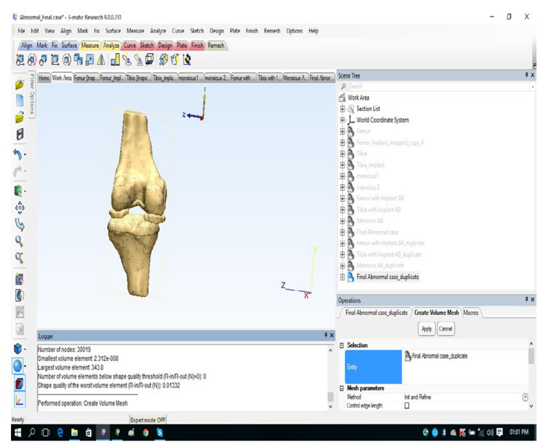
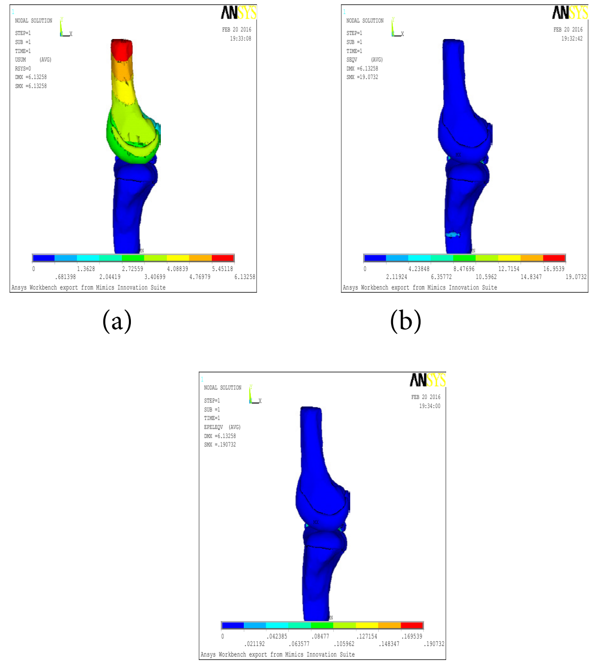


Figure 5. Volume mesh of OA knee joint.

FEA of the knee joint during single-leg stance under full extension, a vertical load of 580N and 530N corresponding to five-sixths of the body weight was applied. The actual body weight of normal and abnormal subject is 71 Kg and 65 Kg respectively. Force is calculated according to Newton's law F=ma where, 'm' is the mass (Kg) and 'a' is the acceleration due to gravity (9.8m/s^2). A force of 555N (F=5/6*68*9.8) is assumed to be constant with a weight of 68 Kg, which is the average weight of normal and abnormal subject.

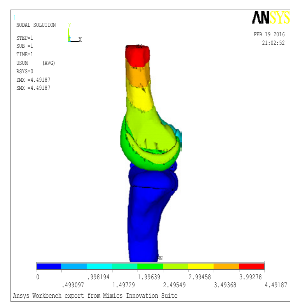
Applying a loading force equal to 580N for the entire biomechanical system of the healthy knee a maximum total displacement equal to 6.13258 mm and a maximum Von Mises stress equal to 19.0732 Mpa are obtained and shown in Figure 6. Von Mises strain obtained for healthy knee corresponding to a loading force equal to 580 N in cartilage and meniscus is 0.190732 Mpa. Applying a loading force equal to 530N for the entire biomechanical system of OA knee a maximum total displacement equal to 100.03 mm and a maximum von Mises stress equal to 22.7476 Mpa as shown in Figure 8. Von Mises strain obtained for OA knee corresponding to a loading force equal to 530 N in cartilage and meniscus is 3.6366 Mpa. Applying a constant force equal to 555N for the entire biomechanical system of healthy and OA knee a maximum total displacement equal to 4.49187 mm and 122.89 mm respectively. When the force of 555N is assumed to be constant, the maximum stress value for normal is 13.9681 Mpa and for OA is 27.9248 Mpa as shown in Figure 7 and Figure 9. The displacements, von Mises stress and strain values are presented in Table 1. We can see an increase of displacement, stress and strain for OA knee joint versus the case of the healthy knee joint.

Geometrical measurements such as joint space width for medial and lateral knee joint, articular cartilage thickness for the femoral and tibial region and meniscus thickness for medial and lateral knee joint are obtained using Mimics tool as shown in Figure 10.



(a) (b) (c)

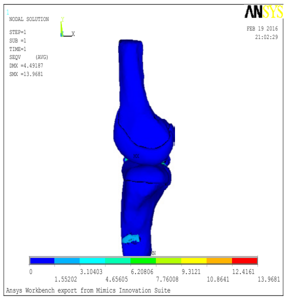
Figure 6. a) Displacement, b) maximum Von Mises stress and c) maximum Von Mises strain of normal knee (F=580 N).



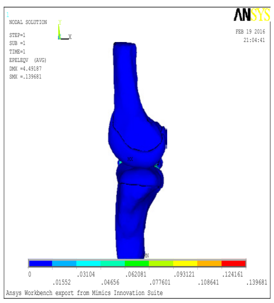
(a)

Table 1. Finite element analysis of knee joint

Normal / OA knee	**Maximum Displacement (mm)**		**Maximum Von Mises stress (Mpa)**		**Maximum Von Mises strain (Mpa)**	
Normal F=580, OA F=530N and Constant F=555N	**Actual body weight**	**Assumed constant weight**	**Actual body weight**	**Assumed constant weight**	**Actual body weight**	**Assumed constant weight**
Normal left knee (Male 41 years, 71 Kg)	6.13258	4.49187	19.0732	13.9681	0.190732	0.139681
OA left knee (Male 44 years, 65 Kg)	100.03	122.89	22.7476	27.9248	3.6366	4.47297

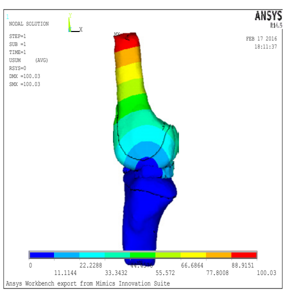


(b)

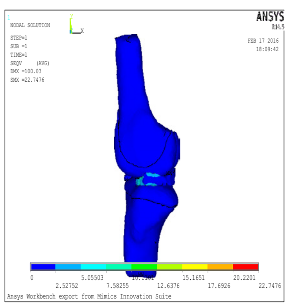


(c)

Figure 7. a) Displacement, b) maximum Von Mises stress and c) maximum Von Mises strain of normal knee (F=555 N).



(a)



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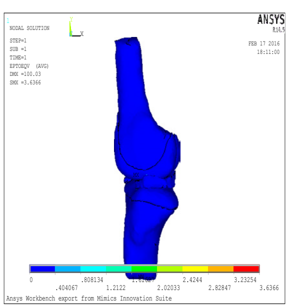
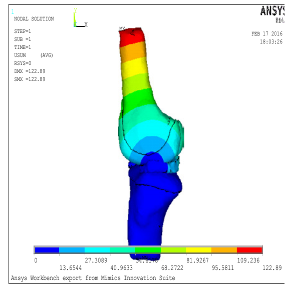
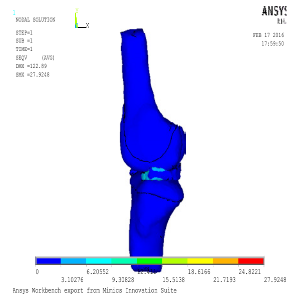


(c)

Figure 8. a) Displacement, b) maximum Von Mises stress and c) maximum Von Mises strain of OA knee (F=530 N).



(a)



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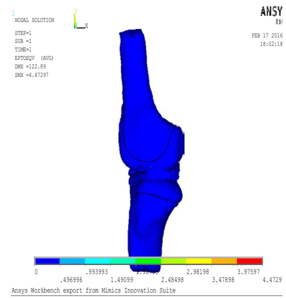
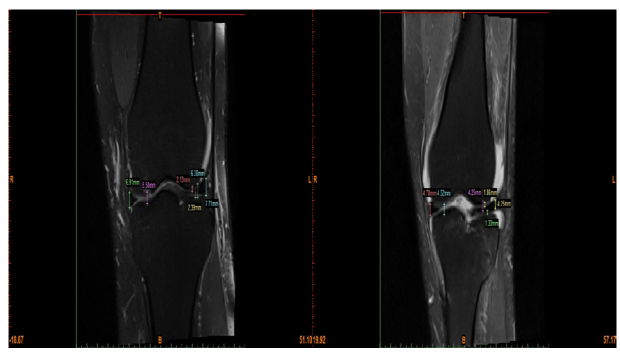


(c)

Figure 9. a) Displacement, b) maximum Von Mises stress and c) maximum Von Mises strain of OA knee (F=555 N).



a) Normal knee joint **b)** OA knee joint

Figure 10. Geometrical measurements.

Parameters such as Joint space width, cartilage thickness and meniscus thickness play a vital role for classification of the subject into normal knee and osteoarthritis of the knee by comparing with the standard values. FEA is verified through geometrical measurements which are shown in Table 2. The standard medial and lateral joint space width of the normal knee joint are 4.63 mm to 6.2 mm and 5.33 mm to 6.22 mm respectively. The standard value of medial and lateral joint space width of OA knee joint is 2.54 mm to 4.62 mm and 4.03 mm to 5.32 mm respectively[11].

Table 2. Diagnosis based on geometrical measurements

Joint Space Width		Articular cartilage thickness		Meniscus thickness		Diagnosis
Medial (mm)	Lateral (mm)	Femoral (mm)	Tibial (mm)	Medial (mm)	Lateral (mm)	
5.58	6.38	2.13	2.39	6.91	7.71	Normal
4.52	4.25	1.86	1.33	4.78	4.25	OA

The estimation of articular cartilage thickness of knee plays a significant role for detection of OA. From the data obtained through research, it was found that the total articular cartilage thickness in OA case should be 0.73 mm (minimum) to 1.825 mm (maximum). Similarly, for normal case the total thickness of articular cartilage is assumed to be above 3.5 mm. Thus, the particular case is classified based on the obtained articular cartilage thickness. If the range is 2.8 mm to 3.5 mm it can be diagnosed as stage 1 or doubtful[12-14].

The average medial and lateral meniscus thickness of normal knee joint are found to be in the range 5.2 mm to 6.9 mm and 4.8 mm to 7.0 mm respectively. Below this range, it is considered to be abnormal. Thus, the subject is classified as normal or abnormal[15].

4. Discussion and Future Work

A comparison study of normal tibiofemoral joint and knee osteoarthritis is done to analyse the displacement, stress and strain values. When the load applied on knee joint is increased there is an increase in maximum displacement, maximum Von Mises stress and maximum Von Mises strain and vice versa. Thus, the load applied on knee joint is directly proportional to maximum displacement, maximum Von Mises stress and maximum Von Mises strain values. Where the stress applied is proportional to strain according to Hooke's law of modulus of elasticity. Advances in the field of medical imaging and its reconstruction have expanded the possibility to incorporate specific tissue morphology and boundary conditions into in vivo subject-specific models. The unwavering quality of FE models firmly depends on the suitable representation of the geometry and assigned material properties, realistic simulation of interactions, constraints and boundary conditions, and lastly through validation against experimental data[16]. This data can be combined with other analysis and modeling tools, for example, gait analysis and FE modeling to test hypotheses concerning joint function and the impacts of wounds[17].

5. Conclusion

Thus, the 3D model of normal and OA knee joint and their geometrical measurements are obtained. Displacement, stress and strain values for OA knee are higher than the normal knee joint. The biomechanical behaviour of the normal knee and the biomechanical response of the OA knee were studied. Deformation, maximum Von Mises stress and maximum Von Mises strain values of the healthy and OA knees are compared. Each of the three variables, in both the lateral and medial compartments, was greater for the OA knee when compared to the healthy knee. Finite element model is validated using experimental data through geometrical measurements such as joint space width, cartilage thickness and meniscus thickness which shows a significant difference between normal and OA. The total articular cartilage thickness of OA case is found to be 3.19 mm which can be diagnosed as an early stage of OA. It can be concluded from the literature survey conducted that MRI is the most appropriate non-invasive imaging modality to diagnose OA at an early stage. Thus, the estimation of articular cartilage thickness of knee plays a significant role in early detection of OA.

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