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Finite Element Modeling and Analysis of Prosthetic Knee Joint

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***Abstract*— Degenerative arthritis is a disease that affects the line cartilage of the knee joint. It causes severe pain in the joint and may require a replacement surgery of the affected knee with artificial components. Geometric complexity and non linearity of the materials of the knee make the analytical solutions of the mechanical behaviour of the knee joint difficult. The knee is the most complex joint within the human body. Proper motion of the joint relies significantly on the function of the soft tissue constituents including the four ligaments of the tibiofemoral joint. These ligaments allow primarily flexion/extension and rotation of the joint by enabling the bony constituents (femur and tibia) to translate and rotate relative to each other. In addition to the ligaments, soft cartilage in the joint space permits nearly frictionless contact between the bones. Computational modeling of the knee provides a way for better understanding the interplay between the hard and soft tissue constituents of the knee during normal and pathologic function. Additionally, properly validated models can be used in the design of knee implant systems by understanding the mechanics of the restored knee in order to more closely replicate the healthy knee.**

The objective of this paper was to design a model of prosthetic knee joint from the available literature and study the distribution of contact stresses in the same by assigning it the material properties of polyethylene chopped carbon fibre composite and conventional polyethylene for tibial component and alumina ceramic for femoral component. Commercially available software (ANSYS 11.0) was used for numerical estimation of contact stress. The effects of the sagittal radius, flexion angles on stresses in the joint were investigated.

***Keywords*— Finite Element Analysis, Modeling, Prosthetic Knee Joint, Contact Stress, Flexion angle and Sagittal Radius**

I. INTRODUCTION

Prosthetics are said to have existed from the times of the ancient Egyptians. Prosthetics were used in many applications: function, cosmetic appearance and most important to the ancient Egyptians, psycho-spiritual sense of being whole. It was feared by many that when an amputation was performed the individual would be left un-whole in the afterlife.

Once performed, the amputated limb was buried until the individual passed when it would be placed with the body so as to make them whole for the afterlife. One of the earliest known examples of a cosmetic prosthesis date back to the 18th dynasty of ancient Egypt where a mummy was found with a prosthetic toe made of leather and wood. Greek and Roman civilizations are sometimes credited for creating prostheses for rehabilitation aids. [1]

Modern prostheses are said to have originated from a man known as Ambroise Paré. The French surgeon contributed to the origination and perfection of the amputation procedure itself and among the first to show interest in the design of a functional prosthesis. Paré instructed a Parisian armor maker (Le petit Lorrain) to construct a metal above-knee prosthesis which consisted of a locking knee joint as well as an ankle joint. His prosthesis weighed 7 kg and was only suitable for equestrians. Functional prostheses were not used at that time mainly because the distal end of the residual limb could not be loaded without damage; this limited people to using crutches, peg legs or even crawling as means of locomotion. [2]

After 1816, functional wooden prostheses were built which consisted of a mechanism which synchronized the motion of the knee and ankle joints. This ingenious mechanism was invented by James Potts, who also is credited with the use of the trumpet socket. This Total-Surface-Bearing-type socket along with the joint mechanism was made famous by the Count of Uxbridge, also known as the Marquees of Anglesey who lost his leg in the Battle of Mont St. Jean in 1815. [2]

Over the course of history, large scale wars have directed government interests towards research and development of more efficient and functional prostheses. Following World War I, materials such as aluminum and rubber were being tested as alternative materials which led to the current research on space-age materials and mechanism designed to improve user comfort, mechanical efficiency, and cosmetic symmetry.

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Degenerative arthritis of the knee joint is a disease that affects the line cartilage of the tibia and the femur. It causes severe pain and may require a replacement 1surgery of the affected knee with artificial components [3]. Artificial joints should satisfy certain design requirements, i.e., they should be ergonomical and biocompatible. During activation, stresses are developed at the interface of joint, which in turn dictates the performance of the joint. The intensity of the stresses developed depends on several factors. To ensure the stress intensity, it is important to optimize the design of prosthetic knee joint. In this regard, FEM the most powerful numerical tool can be used to optimize the design.

The main objective of the paper is to develop a three-dimensional solid model of the knee joint and studied the effect of sagittal radius and flexion angles on the performance of knee joint made out of polyethylene and polyethylene chopped carbon fiber composite for tibia and alumina ceramic for femoral component [1].

II. Design Considerations Of Knee Joint

The development of the modern total knee arthroplasty can be dated back to the 1960s. The polycentric knee designed by Frank H. Gunston introduced the use of two cemented polyethylene tibial components articulating on two cemented femoral components. In addition, specialized instrumentation was used to insert the prosthesis. The introduction of a reliable fixation agent, together with a metal on polyethylene articulation, led to a furious development of designs in knee arthroplasties. With the introduction of a multitude of different prostheses with varying degrees of tibiofemoral conformity and different philosophies with regard to the sacrifice of the anterior and posterior cruciate ligaments, different methods of evaluating total knee arthroplasty performance were developed by investigators.

Over time, investigators standardized reporting methods by selecting those they found most useful. The Hospital for Special Surgery Knee Scores and the Knee Society Score are scales most commonly used in the medical literature to report total knee arthroplasty results. Over the last several years, there has been an effort to develop additional ways to measure the results of medical therapeutics. Some of this methodology, commonly known as outcome studies, was developed to evaluate the results of a particular treatment through the patient’s opinion. Outcome studies in total joint arthroplasty are composed of two basic measurements: a health status questionnaire and a pain and function questionnaire. The health status questionnaire attempts to measure the patient’s quality of life.

The Western Ontario and MacMallister Osteoarthritis Index or WOMAC score is currently being used by the Patient Outcome Research Team at the University of Indiana in their evaluation of total knee arthroplasty. The questions asked are as follows:

Pain

How much pain do you have?

Walking on a flat surface, going up or down stairs, at night while in bed, sitting or lying, Standing upright

Stiffness

How severe is your stiffness after first wakening in the morning?

How severe is your stiffness after sitting, lying, or resting, later in the day?

Function

What degrees of difficulty to you have with . . .?

Descending stairs? Ascending stairs? Rising from sitting? Standing? Bending to floor? Walking on flat? Getting in/out of car? Going shopping? Putting on socks/stockings? Rising from bed? Taking off socks/stockings? Lying in bed? Getting in/out of bath? Sitting? Getting on/off toilet? Heavy domestic duties? Light domestic duties?

In this manner, patient variables could be evaluated, as well as different types of prosthesis. Over the last decade there has been increased pressure to decrease the cost of medical treatments. As a result, it has become increasingly important to evaluate the outcomes of different medical treatments. Outcome studies evaluate the change in the patient’s quality of life, as well as the therapeutic result.

III. Solid Modeling And Its Applications In Medicine

A solid model is a three-dimensional mathematical representation of an object. Solid models began development in the 1970s to facilitate the complete automation of the manufacturing of man-made parts [1]. Today, solid modeling is a large field, encompassing virtually all aspects of engineering. When solid modeling is used to represent parts (three-dimensional reconstructions) that are already in existence, rather than to design parts, it is referred to as reverse engineering.

In recent years, solid modeling has been used extensively in medical applications. Creating solid models of hip prosthetics has led to an improved prosthetic hip design [5] and using solid models for visualization purposes has aided people with back pain [6].

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In virtually every field where engineering meets medicine, solid modeling can be found. The benefits of solid modeling to medicine have not yet been fully explored because of the rapid development of solid modeling software. What we do know, however, is that it can be used to accurately produce in vitro results when in vivo (inside the human body) results are not possible. Eventually an ideal solid model of the entire human body will probably be developed including every muscle, bone, and organ in the body. It is even possible that solid modeling could be done at atomic levels to reconstruct the human body. The advantages of this can only be imagined.

IV. Solid Modeling Of Prosthetic Knee Joint

In the paper evaluation version of MIMICS software is used to convert CT images into a 3D model following steps were used. Import images and convert scan data through "Import images" from the "File" menu. Change the orientation as shown in Figure.1 to display the images correctly in MIMICS. Then MIMICS software generates automatically coronal and sagittal images and the results as shown in Figure 2.

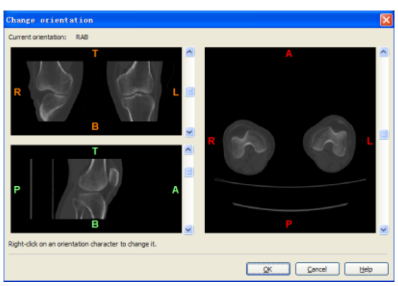

FIGURE.1. ORGANIZE IMAGES OF KNEE JOIN

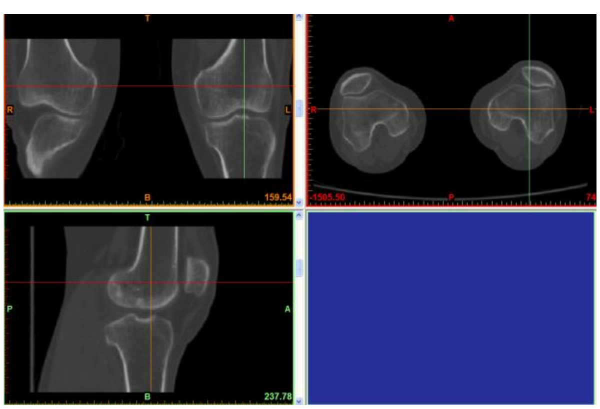

FIGURE. 2. CORONAL AND SAGITTAL PICTURES

From the menu following commands are used to convert CT image into a 3D model Organizing images, Thresholding, Edit Masks, Region Growing, Calculate 3D from the "Segmentation" Menu. The 3D structure of the femur can be visualized clearly. Measure the relevant parameters of the knee including mean, variance, maximum and minimum value and so on, the width of femoral condyle and the anteroposterior diameter of the lateral and medial condyle are the important parameters to design the knee prosthesis. Thus, it is a necessary part of the measured parameters of the knee joint.

From the measurements obtained from CT scan images and available literatures approximate size of the prosthetic knee joint was constructed using CAD software for different sagittal radius and flexion angles.

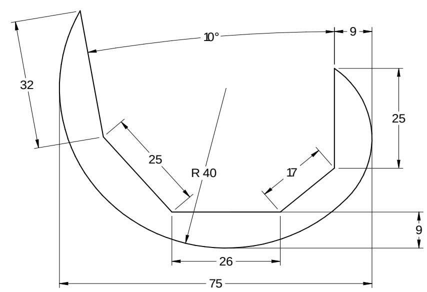

FIGURE.3. 2 D MODEL OF FEMUR

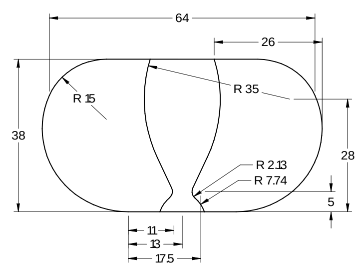

FIGURE.4. 2 D MODEL OF TIBIAL

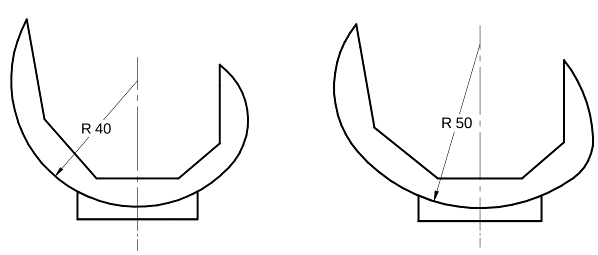

FIGURE.5 PROSTHETIC KNEE ASSEMBLY FOR DIFFERENT SAGITTAL RADII

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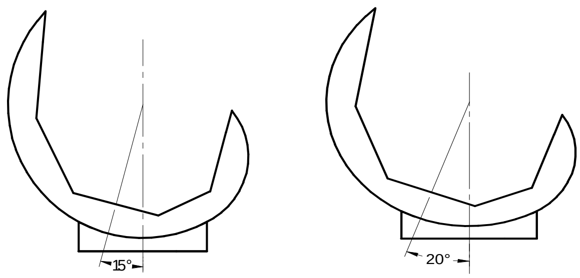

FIGURE.6 PROSTHETIC KNEE ASSEMBLY FOR DIFFERENT FLEXION ANGLES

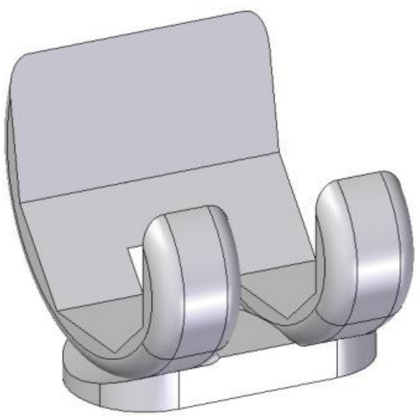

FIGURE.7. 3D MODEL OF PROSTHETIC KNEE JOINT

V. Finite Element Model Of Prosthetic Knee Joint

Finite element analysis (FEA) is a widely used technique to analyze stress-strain states in various biomedical devices and in prosthetic bone joints, in particular. Geometric models of the tibial and femoral components obtained from the CT images and available literatures were constructed using solid edge software and imported to ANSYS software. Three dimensional model of the knee joint with 40 mm, 50 mm and 60 mm sagittal radius and 15^0, 20^0 and 25^0 flexion angels were imported and analyzed [7]. Polyethylene and polyethylene chopped carbon fibre were used to model the tibia part, and alumina ceramic to model the femoral part of the joint.

The finite element model was generated by meshing the solid model with 45 brick elements. The tibial component was constrained in all degrees of freedom at its lower surface. The femoral component was rigidly fixed. A compressive load was applied to the femoral component at the bearing points as shown in Figure.8. Stresses were analyzed for different femoral-tibial alignment positions.

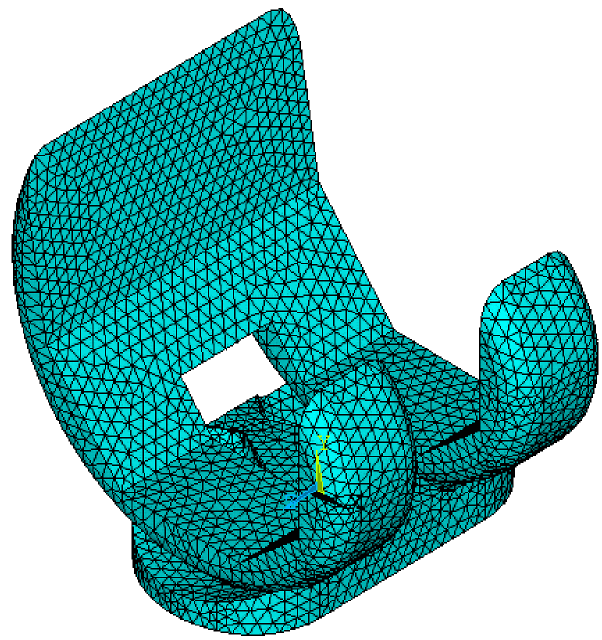

FIGURE.8. FINITE ELEMENT MODEL OF PROSTHETIC KNEE JOINT WITH BOUNDARY CONDITIONS

VI. Results And Discussion

The result mainly consists of stress plots and stress contours Figure. 9 and Figure 10 shows the distribution of shear stress and Vonmoises stress for 40 mm sagittal radius ZERO degree flexion angle

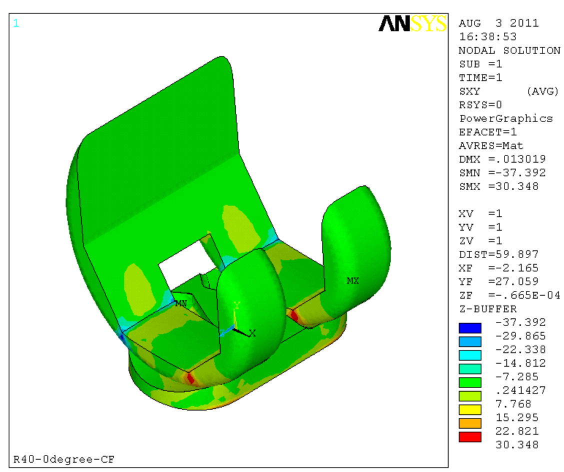

FIGURE.9. SHEAR STRESS DISTRIBUTION FOR 40 MM SAGITTAL RADIUS AND 0^0 FLEXION

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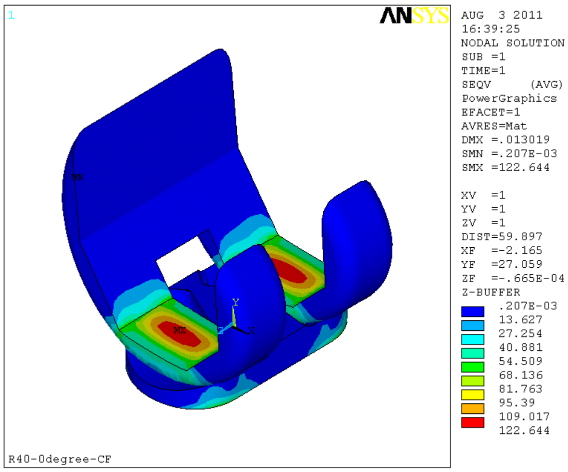

FIGURE.10. VON MISES STRESS DISTRIBUTION FOR 40 MM SAGITTAL RADIUS AND 0^0 FLEXION

A. *Effect of sagittal radius*

An increase in the sagittal radius resulted in increase in the Von Mises stress it did not depend on material properties. This could be attributed to the fact that an increase in the sagittal radius results in increase in the contact area that led to higher bearing pressure and higher stresses (Figure.11). On the contrary shear stress will decrease with increase of sagittal radius this due to fact that increase in the sagittal radius stress concentration at the interface will reduce (Figure.12.)

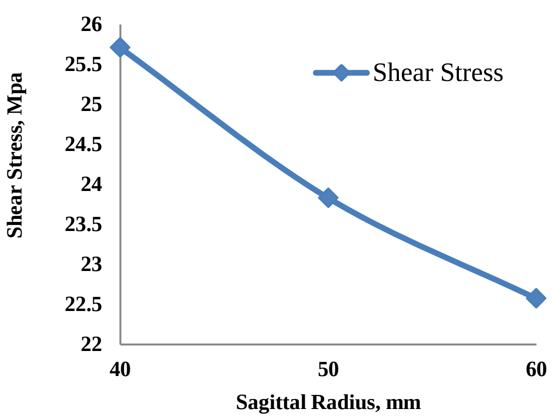

FIGURE.11. SHEAR STRESS FOR DIFFERENT SAGITTAL RADIUS

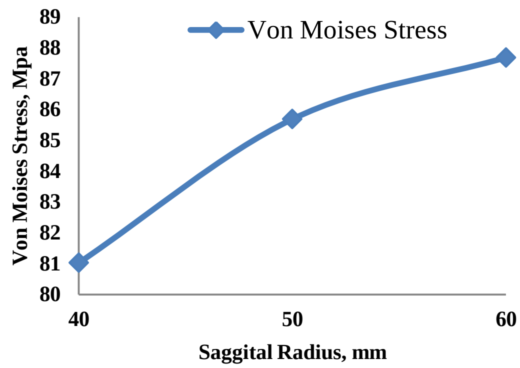

FIGURE.12. VON MOISES FOR DIFFERENT SAGITTAL RADIUS

B. *Effect of Flexion angle*

It is evident from the Figure 13; the von Mises stresses are increased with increase in the flexion angle this is due to increase in the contact area. The shear stress is independent of cross sectional area but shear stress increased with increase in the flexion angle as shown in Figure.14.

C. *Effect of material properties*

An increase in the sagittal radius and flexion angle resulted in increased stress level as shown in Figure.15. It is observed that the polyethylene chopped carbon fiber composite material produced lower stresses in the artificial knee joint for constant loading 8- 10 % of stress level has be reduce only by changing the property of the material and deformation observed will 9-10% less than the polyethylene.

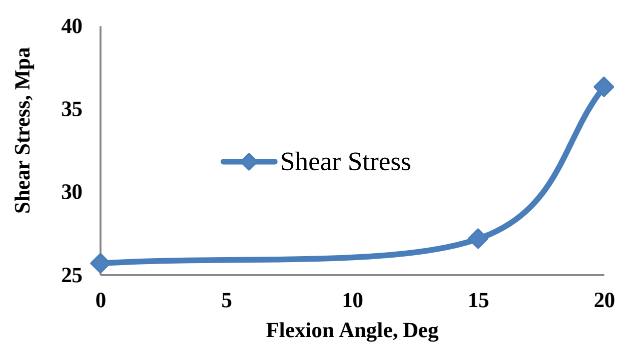

FIGURE.13. SHEAR STRESS FOR DIFFERENT FLEXION ANGLES

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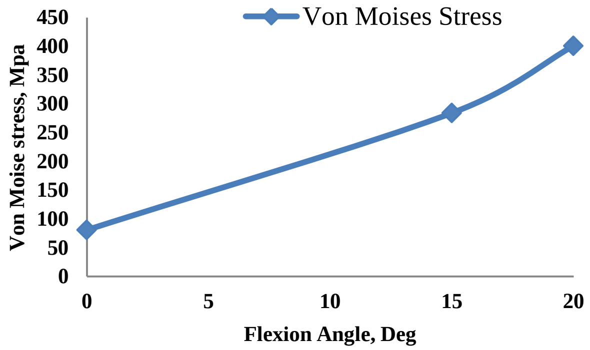

FIGURE.14. VON MOISES FOR DIFFERENT FLEXION ANGLES

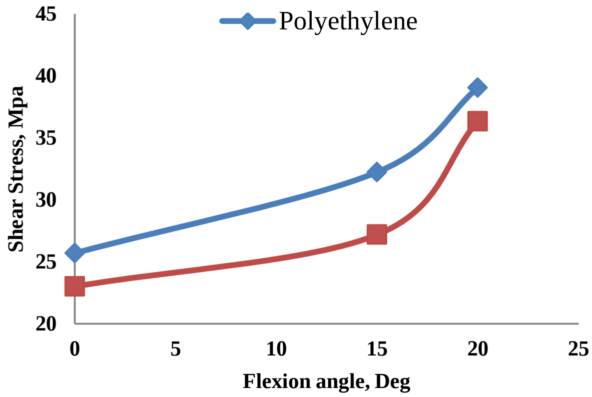

FIGURE.15. SHEAR STRESS FOR DIFFERENT FLEXION ANGLES AND MATERIALS

VII. CONCLUSION

The stress level at the interface of the tibia and femoral component is lower for increased sagittal radius. Shear stress and Von Moises stresses are increased with increase in the flexion angle which is to be optimized. 8-10% of the stress has been reduced for Polyethylene chopped carbon fibre and alumina ceramic combination as compared to polyethylene and alumina ceramic.

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