Journal of Material Science and Mechanical Engineering (JMSME)
p-ISSN: 2393-9095; e-ISSN: 2393-9109; Volume 6, Issue 3; April-June, 2019 pp. 183-188

http://www.krishisanskriti.org/Publication.html

Design and Modelling of Artificial Knee Joint Implants using Computational Techniques

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Abstract—*As the cases of arthroplasty are increasing day by day which results in the total knee replacement surgery or partial knee replacement surgery the need for effective, durable and compatible artificial knee joint implant is increasing. Knee Joint being an important part of the human body has complex anatomy which suffers different load under varying conditions of daily activities. During knee replacement surgeries the success rate of surgeries depends largely on the design and material of knee joint implant. So this paper tries to analyse the three dimensional model of knee joint implant with different biocompatible materials using FEA techniques. Various implant materials used for knee joint prosthesis implants are compared under different load conditions analysing their performance in real time situations.*

In this paper, we have modelled and design artificial knee joint in Solid works by using customized computational techniques to find out various forces and stresses acting between the femoral and tibial joint. We have used computational techniques to model knee joint implant and try to analyse its behaviour under varying body weight.

This research paper focuses on the design and modelling of a knee joint implant under real-time situations by considering CT scan data. We have modelled a three-dimensional FEA model of knee joint implant using CT scan data obtained after segmentation of DICOM (Digital Imaging and Communications in Medicine) images. Three-dimensional models of the knee prosthesis are being modelled using Solid works and then the simulation is done in Ansys 17.1.

Keywords: *Human knee implant, Knee Prosthesis customized, CT scan, Biomechanics, Computational Techniques, FEA*

1. INTRODUCTION

Knee being most important part of human body as it is responsible for motion of the human body. It comprises of upper part known as Femur bone which is subjected to maximum body weight being the longest bone of human body, the middle tissue known as meniscus comprises of ACL (Anterior Cruciate Ligament) and PCL (Posterior Cruciate Ligament) is known as meniscus and third component is Tibial Stem .[1]

It is observed that when a person is subjected to any accident or physical injury then its ligaments or Knee joint get injured. Generally diseases related to knee joint are treated with surgical procedure where procure is diagnosed. Generally damaged ligaments is treated through knee surgeries which include PKR (partial knee replacement) and TKR (total knee replacement).

Total knee replacement (TKR) include removal of damaged tissues with artificial implants of different biomaterials with respect to the customized data obtained through CT scan data. It helps to relieve and reduce pain and increased mobility of knee joint normal as to that of normal knee motion. [2]

The rate of Total Knee Replacement is expected to rise at a rapid pace with increasing population and diversity with respect to different size of the knee, obesity, in balance life style. A native design of knee prosthesis of Total Knee Replacement include a femoral component made up of metal or metal alloy , plastic insert made up of generally of polyethylene and metal tibial component containing stem which is induced in tibial bone during surgical procedure. The optimum purpose of TKR replacement surgeries is to remove the damaged tissues and implant artificial implants in place of it to provide patient a normal motion after post-surgery. [3]

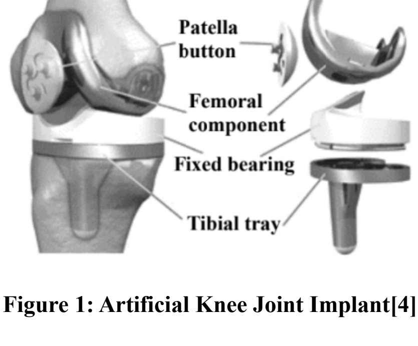

Figure 1: Artificial Knee Joint Implant[4]

The importance of gait analysis of knee prosthesis is important as it not only depicts the failure of total knee replacement but also predict the alignment of failure of knee implant with respect to the flexion angle and sagittal radius. The failure of Total Knee Prosthesis not only impact patient health as well as the functional capability of human body

For example, in this paper we have considered the mechanical axis of knee joint motion normal to the axis of sagittal radius. Many times due to lack of ineffective design of knee prosthesis result in more pain as well as fizziness in joint stiffness, lack of inability in walking. It has been observed that after implant surgeries there is lack of gait analysis related to normal knee motion. With the abnormal kinematics, the TKR can reduce efficiency of the quadriceps and change patella mechanics, and patients would not have the feeling of a normal knee. The demands in a higher range of motion such as squatting and kneeling require the total knee replacement to provide better function. Because size of bones of every individual is different than that of other so design of artificial knee prosthesis is preferred to done customized approach designing individual implants. [4]

If we consider even two knees of different persons differ from each other with approximately allowance of 5% positive as well as negative error.

So, there is need to design a computational technique to design customized knee implant for each patient individually.the concept to design the individual artificial knee joint has arose. To find a customized approach in this regard we have created a step ladder approach of designing a 3D model of knee implant with respect to CT and MRI data with individual dimensions. After the modelling of 3D model of knee prosthesis the CAD model is analysed under varied body weight.And based on that the customized implants were developed with specific procedure and analysed with different kind of biomaterial for medical implants.[5-7]

The main objective of the paper is to develop a three dimensional solid model of prosthetic knee joint and to study the nature of stresses and deformation under different body weight.In this research paper we studied the nature of stresses and contact pressure between the different components of knee implant prosthesis at different flexion angles of the knee. We have studied the nature of different stresses with different biomaterials with the use of finite element analysis and find out the best suited biomaterial for knee joint prosthesis. Solid Work 2017 was used for modeling of 3D FEA model of knee joint implant components. Finite element analysis of knee prosthesis using different biomaterials was carried out in analysis software ANSYS 17.1 by applying the load at various moving conditions.

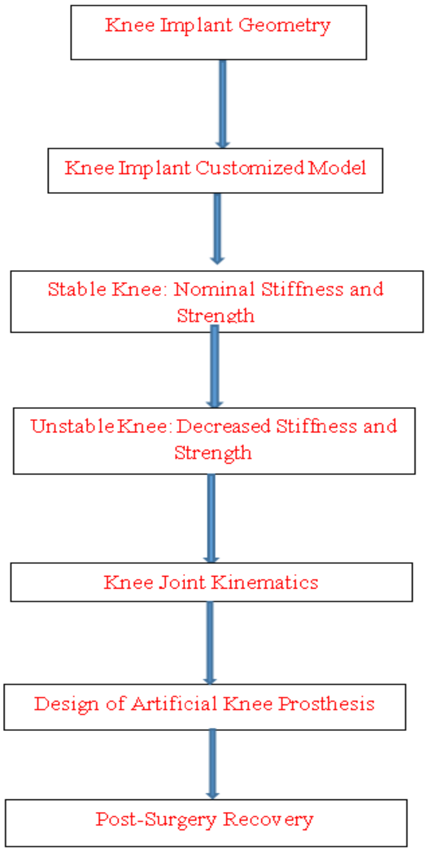

Figure 2 :- Flow Diagram Of Computational Modelling Of Artificial Knee Joint

2. MODELLING OF HUMAN KNEE MODEL:-

We have modelled the 3D CAD model of human knee joint from the CT scan of patient damaged knee so that the artificial implant can be created. For modelling 3Dmodel we have to first convert the MRI/CT scan data into 3D model by segmentation of DICOM images into the software “Mimics 21.0”. In this software, we have converted the CT scan data into a 3D model of human knee model excluding cartilages and ligaments as per the patient data.

Then after creation of 3D model of human knee a artificial knee prosthesis is designed in Solid with the compatibility established amongst Solid Work and user interface of Mimics. And that file was successfully imported to CAD platform and used for further simulation on Ansys for different types of Biomaterials.

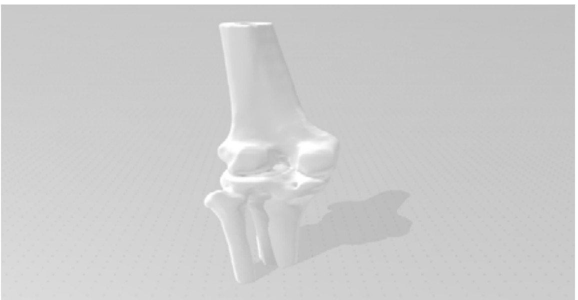

Figure 3: Modelled Human Knee Model

3. MATERIAL AND METHODS

3.1. Artificial Knee Prosthesis Biomaterials:-

The materials that are used for medical include metal alloys, polymers, ceramics and composites and other biocompatible material. The metals commonly used as biomaterials for knee prosthesis include titanium alloys, cobalt-chromium alloys, and stainless steels, and various alloys of aluminum which are new area of research.. In polymers UHMWPE (ultra-high molecular weight polyethylene) is most commonly used as plastic insert in the artificial knee prosthesis.

More recently ceramics has shown capability to use as artificial implant metals in total knee replacement with the extremely their superior wear resistance properties. In this study biomechanical analysis of titanium alloys, cobalt chromium alloys, stainless steels, ZrO_2 and UHMWPE have been carried out using FEM and compare the results. Materials which are generally used for manufacturing the femoral component of implant are Ti6Al4V alloy, Co-Cr-Mo alloy, SS 316L alloy and oxidized zirconium and the commonly used material of polyethylene for manufacturing the linear insert now a days is UHMWPE (ultra-high molecular weight polyethylene).

Table 1: Commonly Used Biomaterials

Material	Density (g/cm^3)	Elastic Modulus(MPa)
Cobalt-Chrome alloy	8.5	730
316L Stainless Steel	8.0	230
CP Titanium	4.51	200
Ti6Al4V	4.40	106
Bone	1.55	10^5

3.2 Material Properties:-

While designing artificial knee prosthesis the design consideration towards the normal anatomy of knee is very important. Being heterogeneous and nonlinear in nature, it is very difficult to assign material properties along each direction of the bone model due to which its analysis become complex. In Biomechanical study of the model we can assign material in two ways either in Mimics or during CAD modelling in solid work. We can solve a small portion of bone for anisotropic solution which become extremely difficult to solve for complete bone.

Property	Cortical Bone	Ti-6AL-4V
Density(kg/m^3)	1750	4520
Elastic Modulus, E (Gpa)	16.7	113.80
Poisson's ratio	0.3	0.342
Elasticity	Linearly Elastic	Linearly Elastic
Isotropy	Isotropic	Isotropic

4. METHODOLOGY

4.1 CAD Modeling of Artificial Knee Joint

The design and its geometry play an important role in the knee replacement surgeries which has significant effect on the working life of knee joint therefore need of adopting the standard procedure to model the prosthesis is required.

The geometrical models were developed by using Solid Work 2017 Software after referring the design standards prescribed by G Mallesh et al 2012.

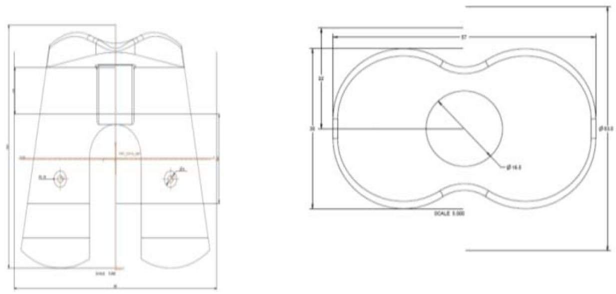

Figure 4:- 2D Model Of Knee Prosthesis

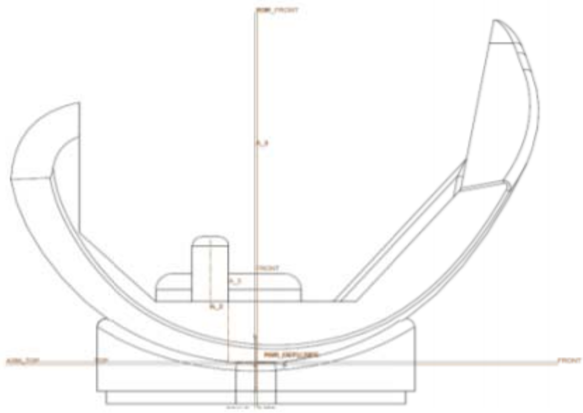

Figure 5 :- 2D Model Of Knee Prosthesis

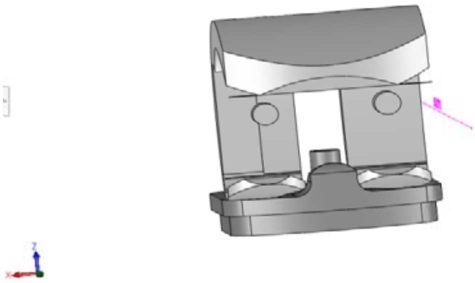

Figure 6: - 3D Modelled FEA Design of Knee Prosthesis

4.2 Mesh Diagram of Artificial Knee Joint Implant:-

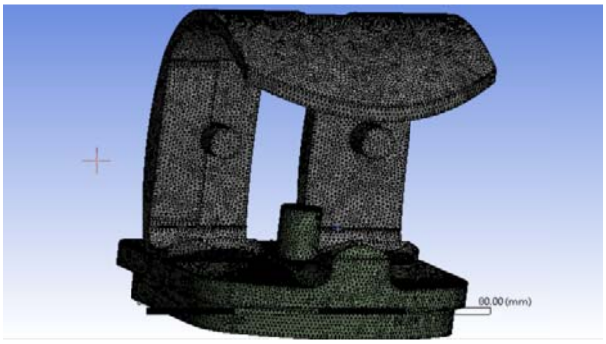

Figure 7: - Mesh Diagram of Artificial Knee Implant

Meshing of Modelled Knee Implant:

After creating model as per the design obtained from CT scan data, for further Finite element analysis (FEA), a tetrahedron surface mesh is generated for femur bone model in ANSYS workbench 17.1. This surface mesh is used to analyse various mesh size with respect to the loading conditions and perform mesh convergence test.. The volumetric mesh can be generated in ANSYS for the model of femur bone. The FEA software ANSYS 17.1 was used for generating tetrahedron surface mesh to find out the highly stressed zone.

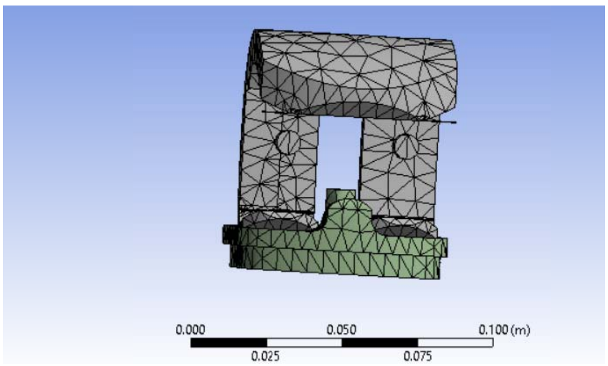

Figure 8 :- Mesh Size Diagram of Posterior View

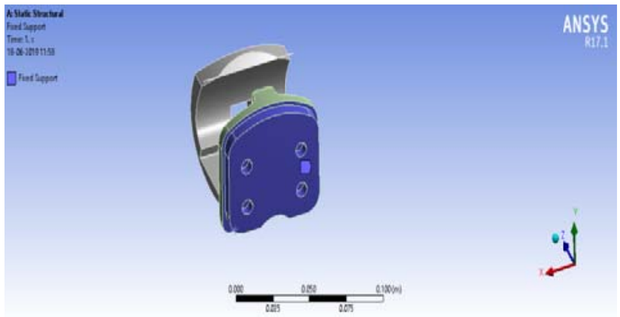

Figure 9 :- Application of Constraints

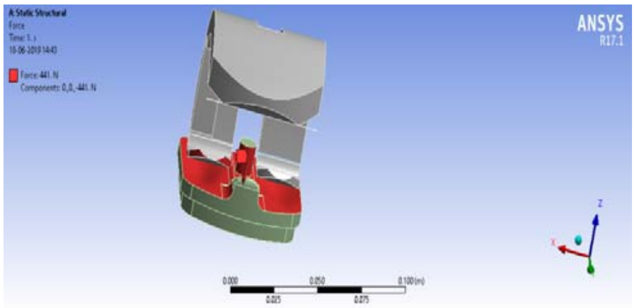

Figure 10 :- Application of Force Constraint

4.3 Mesh Convergence Test

We have considered a tetrahedral element while meshing of 3D model .Mesh Convergence test is done to evaluate the variation of von mises stress to the mesh size .A check point is tested on the assembly by using mesh convergence test in order to simplify and justify the analysis result. In this process the stress level is tested on assembly by taking different size of element during meshing.

Meshing of the model was done after completing the mesh convergence test and defining the material collectors and assigning the materials for each of the component. Tetrahedral elements were used for all the components.. According to the mesh convergence test Size of the tetrahedral element was 4mm for all the components of knee joint implant and a total no. of 7266 nodes and 3595 elements were generated after the meshing.

4.4 Defining Boundary Interfaces:-

Various types of interfaces are available in ANSYS 17.1 but one of them which are used is:

Frictional Contact: we have considered the friction contact between the two meting surfaces and it required some value of coefficient of friction. Frictional contact was considered between femoral component and tibial poly. We have considered values of coefficient of friction in this paper as 0.02-0.05 for $Ti6Al4V$- 0.13, SS 316L- 0.12, Co-Cr-Mo- 0.07, ZrO_2- 0.02-0.07.

5. BOUNDARY CONDITIONS:-

We have applied body weight in the form of load to the model as axial load is applied on the joint during its motion. We have performed stress analysis at standing position. In this paper we have performed test analysis at different body weight from 40 kg, 45 kg,50 kg,55 kg,60 kg, 70 kg considering average weight of an individual to be 60 kg in our study we have performed test with different materials to analyse their performance as implant materials. We have analysed the change in stress, deformation and strain with increasing value of body weight on the knee prosthesis.

6. RESULT AND DISCUSSION:-

The finite element analysis has been carried out in ANSYS 17.1 software and to find out von-misses stresses, total deformation and elastic strain at different body weight with respect to different material.

- For different biomaterials at different loading conditions explained above we performed FEA analysis of the designed knee prosthesis.
- From the result shown in table 2 Ti-6Al-4V shows von mises stress of 2.1026 MPa at body weight of 70 kg which is lower than the other implant materials which shows that the Ti-6AL-4V is best suited for Knee prosthesis.

SS 316L ranks second with maximum stress value of 2.3456 MPa. The variation of stresses with respect to body weight shows that the forces at joint is highest due to which the implant material should possess less stresses at the interface so that there should less wear and tear at the interfaces.

Table 2: Von Mises Stress with respect to Body Weight

Body Weight	Ti-6AL-4V	Co-CrMo	Ss316-L	ZrO_2
40	1.2015	1.36128	1.3912	1.3918
45	1.3508	1.3508	1.3604	1.3802
50	1.5019	1.5119	1.5218	1.5723
55	1.6521	1.6621	1.6728	1.6829
60	1.8022	1.8122	1.8238	1.8345
70	2.1026	2.2235	2.3456	2.35123

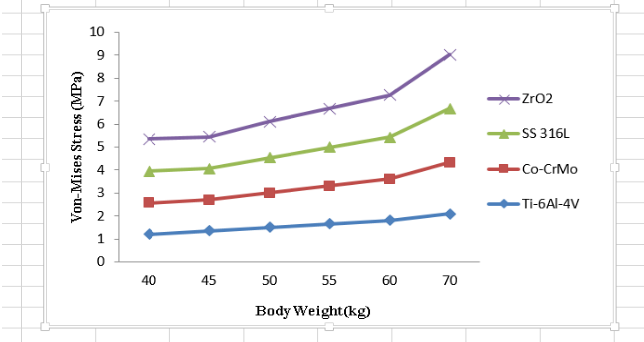

Figure 11: - Stress Variation with respect to Body Weight

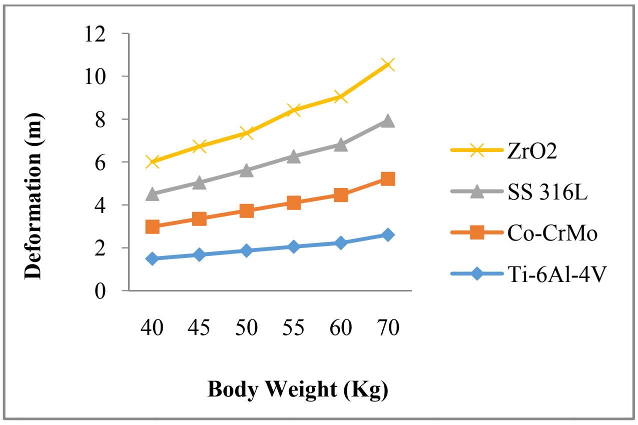

Figure 12: - Deformation with respect to Body Weight

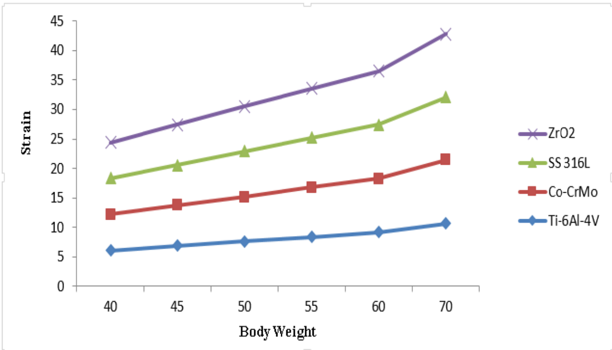

Figure 13: - Strain variation with respect to Body Weight

7. CONCLUSION :-

In the present research paper we have modeled three dimensional model of artificial knee joint and we have analysed at different body weight condition. We observed that at steady state condition the total deformation is higher in ZrO2 and in Co-Cr comparatively less in Ti-6Al-4V and SS 316L.

In order to validate our result from the finite element model of the knee joint, it is important to know the knee's geometry, boundary conditions applied and the constraints. We developed the three dimensional knee prosthesis model our result shows that stress distribution in our design is less in comparison to previous design..

The von misses stress for Ti-6Al-4V is minimum in comparison to all other prosthetic bio-materials and shows less deformation. SS 316L comes second and there is a minor difference in vonmises stress value for Co-Cr and ZrO2.

Finite element analysis of knee prosthesis proved to an efficient technique for predicting failure of prosthesis at different loading conditions.

- From the study of FEA analysis of joint we find that stresses at contact point between femoral implant and plastic insert is lowest for Ti-6AL-4V
- We conclude that our designed knee prosthesis is safe and will not fail under extreme condition It is clear that even under extreme loading conditions the designed knee prosthesis is safe and gives optimum results for biomaterials such as Ti-6Al4V, Co-Cr, SS-316L, UHMWPE and ZrO2.
- Static structural analysis of knee prosthesis shows that mechanical axis of artificial prosthesis should be same as that of normal knee anatomy.
- It is clear from the FEA analysis results that the Titanium Alloys (Ti-6Al-4V) is the best suitable material for knee prosthesis material for knee implant because it shows the minimum Von-mises stress at different body weight so that effective stress can be simulated.
- Analysis of artificial knee prosthesis is very important as it helps to identify the failure of implant under varying loading conditions.

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