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Study of Stress Levels in Various Materials in Total Knee Replacement under Static Condition

Ramesh Kandadai [1], Shreyas Harsha [2]
[1,2] *(Dept of Mechanical Engineering, School of Mechanical Engineering, SRM University, Chennai)*

***Abstract**: With the increase in the number of people being affected by Osteroarthritis, Rheumatoid Arthritis, and other knee complication, Total Knee Replacement (TKR) has emerged as one of the better solution for mobility and to reduce the pain, stiffness etc, among people. In TKR the affected portion of the Femur is fitted with a metallic implant while the Tibia is fitted with an implant made of a Polymer. The knee joint is considered to be the most complex joint in the human body. Accordingly, the material utilized for knee implant assumes an exceptionally important part for survival of knee prosthesis. These implant materials must meet the physical, mechanical and biological necessary to serve its purpose and long term use. The materials that are utilized incorporate Metals, Composites, Ceramics and Polymers. Of these materials Co-Cr Alloy, Ti6Al4V, SS 316L, Zirconia and Porous Tantalum are used for Femur and Ultra High Molecular Weight Polyethylene (UHMWPE) for Tibia. The aim of this project is to prepare a 3D model of the Knee prosthesis and calculate the Stress, Contact Pressure and Deformation for the various bio-materials used in the TKR components statically. The 3D Modeling of knee prosthesis was made using SolidWorks, while the pre-processing was done using HYPERMESH and the FEA software ABAQUS CAE was used as a solver for the contact pressure, deformation on the knee. The aim is to find out by FEM analysis results, for the various bio-materials under static condition and find out the best materials for the purpose of the Knee Implant.*

I. Introduction

The knee joint joins the thigh with the leg and consists of two articulations: one between the femur and tibia, and one between the femur and patella. It is the largest joint in the human body. The knee is a pivotal condylar joint, which permits flexion and extension as well as a slight internal and external rotation. The knee is a hinge type synovial joint, which is composed of three functional compartments: the femoro-patellar articulation, consisting of the patella, or "kneecap", and the patellar groove on the front of the femur through which it slides; and the medial and lateral femoro-tibial articulations linking the femur, or thigh bone, with the tibia, the main bone of the lower leg. The joint is bathed in synovial fluid which is contained inside the synovial membrane called the joint capsule. The knee consists of three more or less independent articulations: one between each cylinder-like condyle of the femur and a corresponding but more planar condylar surface of the tibia, with interposed menisci, and a third between the patella and the patellar groove of the femur. None of the pairs of bearing surfaces is exactly congruent, which results in a combination of rolling and gliding motions determined by the restraints of a complex network of ligaments, capsular structures, and the contours of the bones themselves. This intricate arrangement of anatomic interrelationships allows the knee six degrees of freedom of motion: three rotations and three translations. The translations are antero-posterior (5 to 10 mm), compression–distraction (2 to 5 mm), and medio-lateral (1 to 2 mm). These motions are limited by the ligaments, capsule, The rotations are flexion–extension, varus–valgus, and internal–external rotation, and in general they are much more extensive than the translations. Normal flexion and extension of the knee is variable, ranging from 0° to 15° of hyperextension to 130° to 150° of flexion. Internal and external rotation ranges from little or no motion in full extension to 20° to 30° with the knee flexed. [9]

Arthritis is a disorder that results in the inflammation of one or more joints. There are over 100 different types of arthritis. The most common type, osteoarthritis, is due to trauma to the joint, infection of the joint, or age.Joint replacement represents an appealing means to relieve the pain and increase the mobility of arthritic patients. Nearly 200,000 TKR are implanted annually in the United States. Most TKR designs incorporate a polished metallic femoral component, usually made from a Cobalt- Chrome alloy or Titanium Aluminum alloy in contact with a tibial bearing made from Ultra- High Molecular Weight Polyethylene (UHMWPE). Femoral component is also made up of Zirconium Oxide, Stainless Steel, pure Titanium and pure Tantalum in certain cases. The loading conditions in knee joints are cyclic in nature, and they vary with the flexion and extension angle. Owing to inertia forces during the human gait, loads of more than 2-3 times body weight can be supported by the knee during a typical walk cycle and other research has shown that loads can exceed 8 times body weight in many cases. These loads cause high contact pressures in the concentrated contact between the metallic femoral component and the UHMWPE tibial bearing. Therefore, after implantation the non conforming TKR bearings are subjected to many cycles of high contact stress during oscillatory rolling/sliding contact. Although many implanted knee prostheses have withstood 10 or even 20 years of activity without substantial surface damage many other tibial bearings of TKR have shown evidence of significant wear and contact fatigue damage, requiring early replacement (5 years after implantation). The replacement procedures are costly and can sometimes have serious health consequences. [1][2][3][4]

The aim of this project is to find out the Stress, Strain and Deformation for the various materials that are used as femoral implants in TKR using Finite Element Analysis (FEA). Also taking into consideration other factors such as Density and Osseointergration, to find the material that is best suited as a femoral implant, when UHMWPE is taken as the material for Tibia. In order to find the best material for femoral implant, a Multi-Criteria Decision Making procedure known as Analytic Hierarchy Process (AHP) is used.

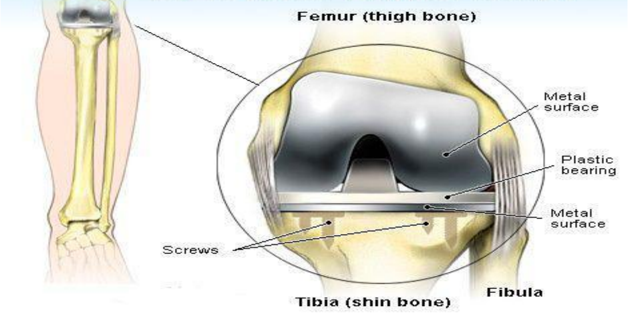

Fig.1- Representation of Total Knee Replacement

II. CAD Model

The geometry of the knee implant has a significant influence in the performance of the implant. Thus it is necessary to model the implant according to the standard procedure. The 2D model of the knee implant can be made using CT scan of the knee and with the help of MIMICS software. For the purpose of this project, the 2D model of the knee implant was referred from the research paper "Finite Element Modeling and Analysis of Prosthetic Knee Joint" by G.Mallesh and Sanjay.S.J.[5] 2D model of the Femur and Tibia implants are shown in Fig.2 and Fig.3

The 3D model of the implant was made using SolidWorks 2014 X 64 Edition. SolidWorks is a solid modeling Computer Aided Design (CAD) that runs on Microsoft Windows. It is a powerful 3D design solution for rapid creation of parts, assembly and 2D drawing. Application specific tools for sheet metals, surfacing, welding, mold tools etc and also available in SolidWorks. The Solid modeling of the Knee Implant is shown in Fig4, Fig.5 and Fig.6

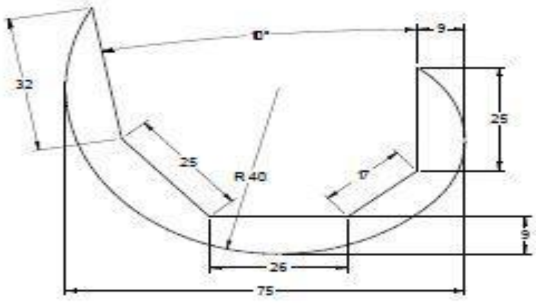

Fig.2- 2D Model of Femur Implant

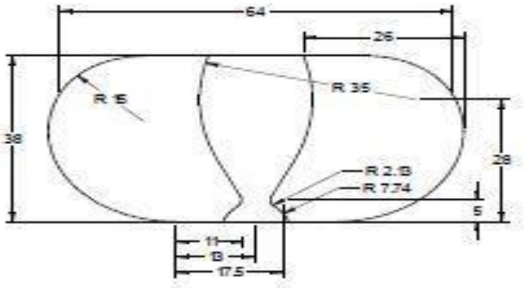

Fig.3- 2D Model of Tibia Implant

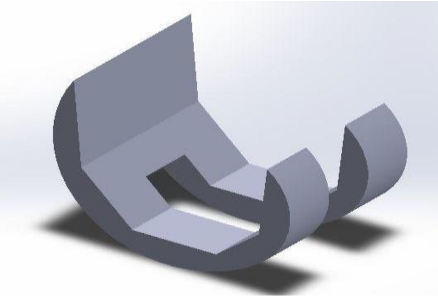

Fig.4- 3D Model of Femur Implant using SolidWorks

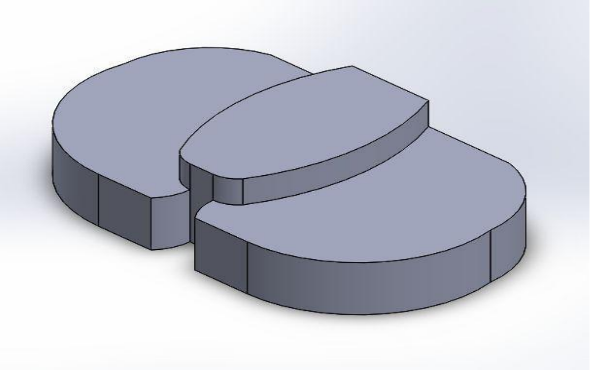

Fig.5- 3D model of Tibial Implant using SolidWorks

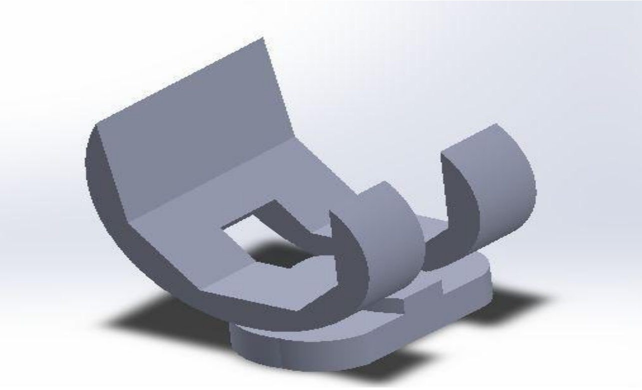

Fig.6- Assembled model of the Knee Implant

TABLE 1. MATERIAL PROPERTIES

MATERIAL	DENSITY (Kg/m3)	YOUNGS MODULUS (MPa)	POISSIONS RATIO
316L SS	8000	1.97E+5	0.3
Co-Cr Alloy	8300	2.3E+5	0.3
Ti6Al4V	4430	1.15E+5	0.342
Porous Tantalum	16700	1.86E+5	0.34
Zirconia	6040	2.1E+5	0.3
UHMWPE	930	6.9E+3	0.29

III. Meshing and Contact Interface

Finite Element Method (FEM) analysis of the prosthetic joint for various bio-materials of the femur was performed partly in HYPERMESH and partly in ABAQUS. The meshing, defining interfaces and boundary conditions of the model was performed on Hypermesh. [6][7][8] The assembled solid model of the knee implant was imported into HYPERMESH in the form of IGES format. ABAQUS user profile was used when working on Hypermesh. Tetrahedral elements were chosen over the brick elements because tetrahedral elements better approximate the shape around the sharp corners, with minimal error. The size of the elements was chosen to be 0.5 mm. Meshed model of the Knee Implant is shown below in Fig. 10. All the elements are then checked for any possible errors such as max length, min length, min and max angles, skew, jacobian etc, in order for the load/pressure/force to be transmitted from one part of the model to another part of the same model, it is necessary for the two parts to have some kind of surface interaction. In this model, Tie Constrain is defined between the contacting surfaces of the Femur and Tibia.

III. Material Properties

Both parts of the solid model were defined by a material. And for each of the material, their respective material properties such as Density, Youngs's Modulus, Poissions Ratio etc were defined. In Total 5 Femoral materials were considered i.e 316L Stainless Steel, Cobalt – Chromium alloy, Titanium Aluminum Alloy, Porous Tantalum and Zirconia. The Tibial material always remained constant, i.e Ultra High Molecular Weight Polyetylene. The material properties of these materials are tabulated below in Table.1[1][9] [10] [11] [12] [13] [14] [15] [16] [17] [18] [19] [20] [21]

Load on the model is applied in the form of force. According to ISO 14243-1, an axial compressive load is one which acts while standing and thus needs to be applied on the model. Also according to ISO 14243-1, maximum load should be applied for testing of the knee implant. In this study, 3 loading case scenario are considered i.e Walking (2.84 X Body weight), Running (5.5 X Body Weight), Jumping (9 X Body Weight). Thus the load being applied on each knee while Walking, Running and Jumping are 994N, 1925N and 3150N respectively considering a person of 70Kg weight. The Tibial part of the prosthesis was constrained of all degrees of freedom (DOF) from the bottom surface. The load is applied on the flat surface of the Femoral implant that is parallel to the Tibial surface.

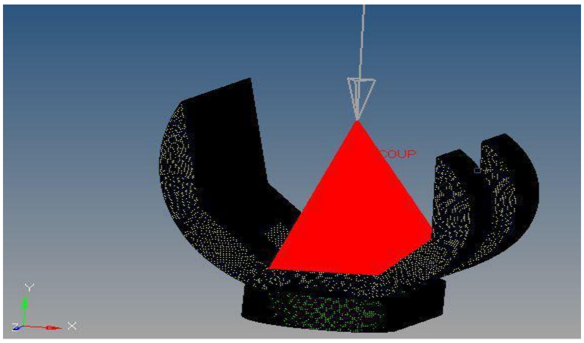

Fig.7 - Meshed Model of the Knee Implant with Boundary Conditions

IV. Finite Element Method Results

Stress is the force per unit area that some particles in a body exert on adjacent particles. In prosthesis such as the knee, lower the value of stress better is the prosthesis. The following 5 figures shows the Contour Plot of Von-Mises Stress for the five different materials that were used as femoral implants. The scenario considered for loading was jumping with a load of 3150N.

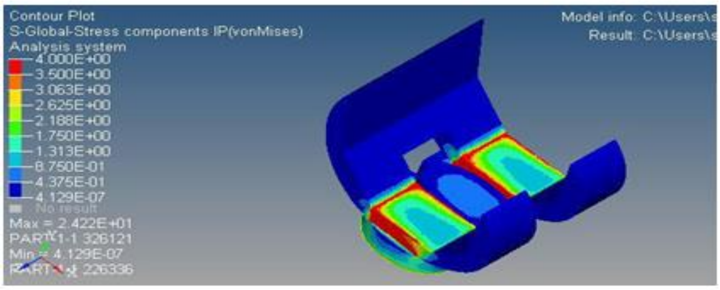

Fig.8 - Contour Plot of Von-Mises for Zirconia (Jumping)

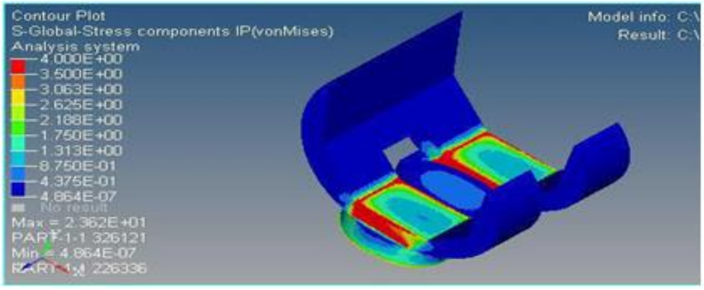

Fig.9 Contour Plot of Von Mises for Ti6Al4V (Jumping)

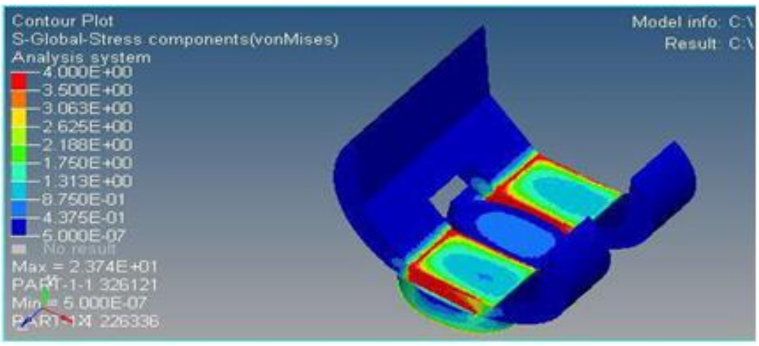

Fig.10 - Contour Plot of Von-Mises for Porous Tantalum (Jumping)

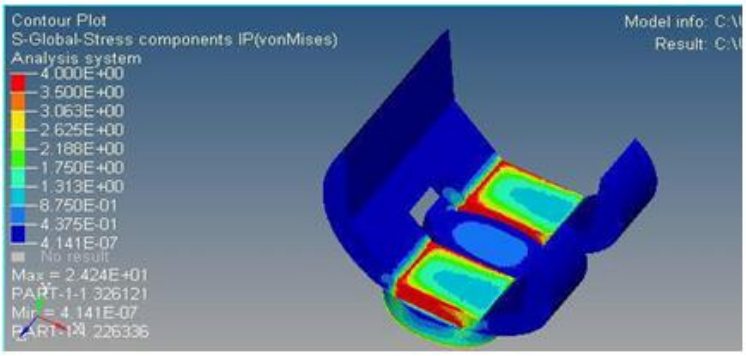

Fig.11 - Contour Plot of Von-Mises for Co-Cr Alloy (Jumping)

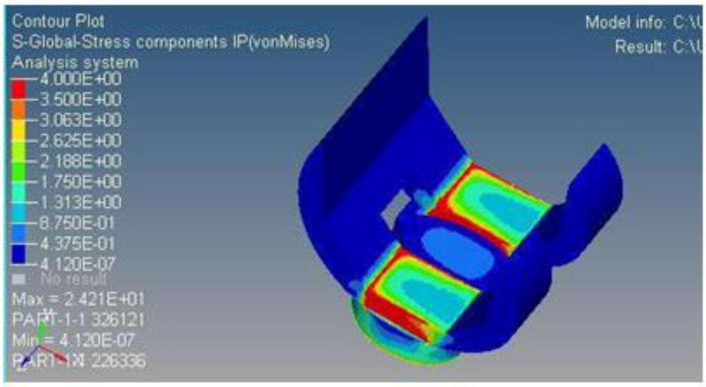

Fig.12 - Contour Plot of Von-Mises for 316L Stainless Steel (Jumping)

Strain/Deformation in continuum mechanics is the transformation of a body from a reference configuration to a current configuration. A Configuration is a set containing the positions of all particles of the body. A Deformation may be caused by external loads, body forces, or change in temperature, moisture, etc. In terms of the prosthesis, lower the value of stress, safer and better is the prosthesis. The following five figures, show the contour plotting of the strain induced in each of the 5 prosthesis. The loading condition is considered to be Jumping where the load applied is 3150 N.

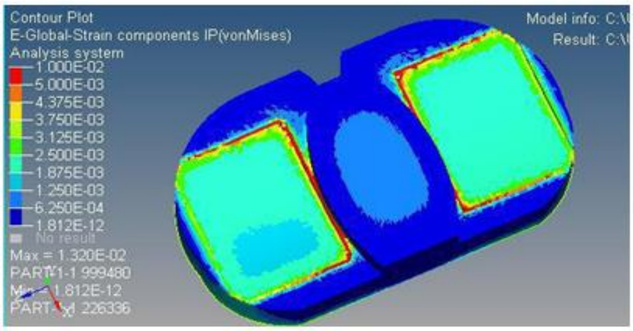

Fig.13 - Contour Plot of Strain for 316L SS (Jumping)

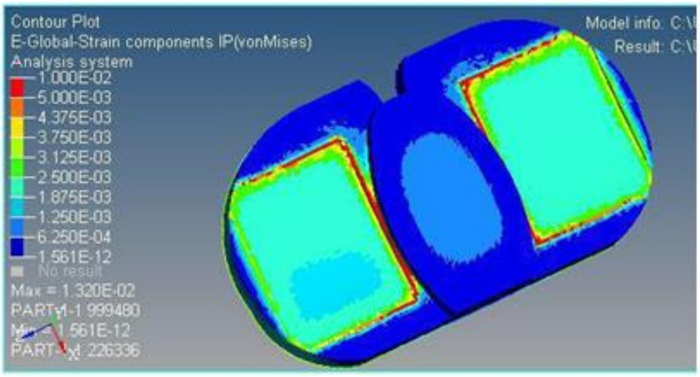

Fig.14 - Contour Plot of Strain for Co-Cr Alloy (Jumping)

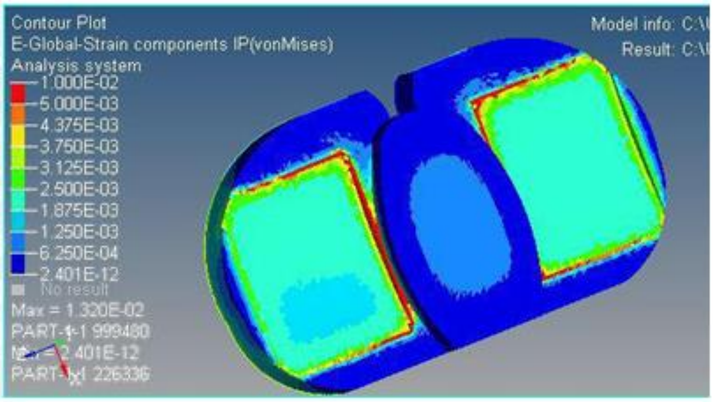

Fig.15 - Contour Plot of Strain for Porous Tantalum (Jumping)

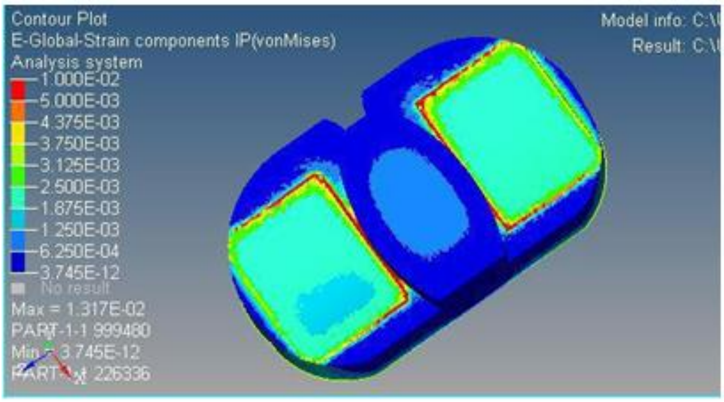

Fig.16 - Contour Plot of Strain for Ti6Al4V (Jumping)

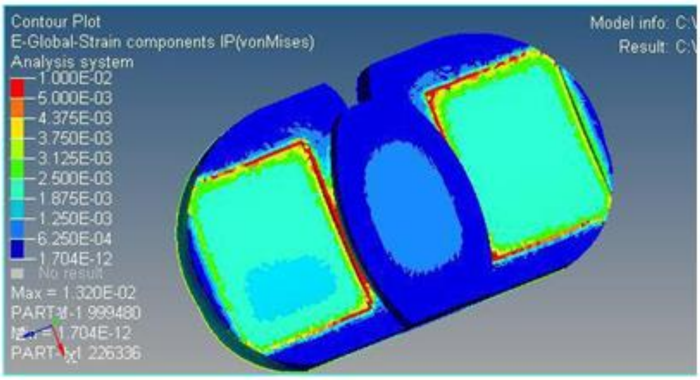

Fig.17- Contour Plot of Strain for Zirconia (Jumping)

V. Results

According to the results obtained for stress using FEM, it suggests that Ti6Al4V > Porous Tantalum > Co-Cr Alloy > 316LSS > Zirconia, however as per the results obtained from the strain analysis, it suggests that Ti6Al4V > Co-Cr Ally > Porous Tantalum > 316L SS > Zirconia. However, while finding out the better/best material, stress and strain are not the only factors that needs to be taken into consideration. Other factors such as Osseointergration, Coefficient of Friction, Density, etc also needs to be considered. While considering multiple factors and multiple alternatives, the task of choosing the best material becomes tedious. To solve such a problem, the use of Multi Criteria Decision Making (MCDM) process is made. Of the available methods under MCDM, Analytic Hierarchy Method (AHP) is used to solve the problem of determining the best material from five options available. Scoring tables for Osseointergration and Coefficient of Friction is given below in Table 2 and Table 4. All the data required to perform AHP is tabulated in Table. 3. The following method is then performed to complete the AHP method.

A) Each of the five criteria are assigned weight-age. The criteria that holds the most importance, is given the highest weight-age, while the least weight-age is given to the criteria that holds the least importance of all the criteria.

B) Each of the alternative are relatively ranked or given a relative score for each of the five criteria. (The ranking/score is given on the basis that the most suitable material in a particular criterion is given the lowest score/value)

C) The AAHP for each of the material is calculated my multiplying the weight-age of each criteria and its respective score/rank.

TABLE.2 SCORING TABLE FOR OSSEOINTERGRATION

OSSEOINTERGRATION	
EXTREMELY HIGH	1.25
VERY HIGH	2.5
HIGH	3.75
ABOVE AVERAGE	5
AVERAGE	6.25
LOW	7.5
VERY LOW	8.75
EXTREMELY LOW	10

A_{AHP} (316L SS) = (5*0.3) + (4*0.15) + (3*0.15) + (2*0.2) + (3*0.2) = 3.55

A_{AHP} (Co-Cr Alloy) = (3.75*0.3) + (1*0.15) + (5*0.15) + (2*0.2) + (2*0.2) = 2.82

A_{AHP}(Ti6Al4V) = (2.5*0.3) + (4*0.15) +(1*0.15) +(1*0.20) +(5*0.2) = 2.7

A_{AHP} (Porous Tantalum) = (2.5*0.3) +(4*0.15) +(2*0.15) + (2*0.2) + (1*0.2) = 2.25

A_{AHP}(Zirconia) = (1.25*0.3) (3*0.15) + (4*0.15) + (2*0.2) + (4*0.2) = 2.58

TABLE.3 – TABLE FOR EVALUATION OF AHP

Criteria/ Material	**Osseointergration**	**Coefficient Friction**	**Stress (MPa)**	**Percentage Elongation**	**Density (N/mm^3)**
316L SS	Above average	0.156	7.6	0.416	8000
Co-Cr Alloy	High	0.012	7.649	0.416	8300
Ti6Al4V	Very High	0.112	7.452	0.4156	4430
Porous Tantalum	Very High	0.14	7.49	0.416	16690
Zirconia	Extremely High	0.082	7.644	0.416	6040

Table. 4 - SCORING TABLE FOR COEFFICIENT OF FRICTION

COEFFICIENT OF FRICATION	
0 - 0.025	1
0.025 – 0.05	2
0.05 – 0.1	3
0.1 - 0.2	4
0.2 - 0.3	5
0.3 - 0.5	6
0.5 - 1	7
>1	8

IV. Conclusion

The completed AHP table is tabulated below in Table.5 By performing the AHP method, considering Osseointergration, Coefficient of Friction, Stress induced, Percentage of Elongation and the Density of the material, it can be concluded that preference of materials for the femoral insert of the Knee Prosthesis is as follows:

Porous Tantalum > Zirconia > Ti6Al4V > Co-Cr Alloy >316L SS

The results indicate that Porous Tantalum is the best suited Femoral Implant, while the least suited material is Stainless Steel (316L grade). Porous Tantalum is a novel porous biomaterial that was developed to overcome the limitations of the other biomaterials that were being used to manufacture knee implants, such as low volumetric porosity, suboptimal frictional characteristics, and higher modulus of elasticity relative to that of bone. Initial laboratory results indicate that porous tantalum has physical, mechanical, and tissue in growth properties that make it a potentially improved biomaterial particularly in complex joint reconstructions. Porous tantalum is a highly porous biomaterial with good biocompatibility, excellent corrosion resistance, and high coefficient of friction. Although clinical testing of Porous Tantalum in reconstructive knee, primary hip and revision hip are encouraging, there is need of further research and studies to determine whether the theoretical advantage of the material can actually provide long term fixation and stability to the bones and tissues around the implant.

Acknowledgement

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TABLE.5 ANALYTIC HYERARCHY PROCESS TABLE

	Criteria	**Osseo-intergration**	**Coff. Of Friction**	**Stress (MPa)**	**Percentage Elongation**	**Density (N/mm^3)**	**AAHP**
Material	**Weight-age**	***30%***	***15%***	***15%***	***20%***	***20%***	***100%***
316L SS	Value/ Data	Above Average	0.156	7.6	0.416	8000	**3.55**
	Rank	5	3	2	3		
Co-Cr Alloy	Value/Data	High	0.012	7.649	0.416	8300	**2.825**
	Rank	3.75	1	5	2	2	
Ti6Al4V	Value/Data	Very High	0.112	7.452	0.4156	4430	**2.7**
	Rank	2.5	4	1	1	5	
Porous Tantalum	Value/ Data	Very High	0.14	7.49	0.416	16690	**2.25**
	Rank	2.5	4	2	2	1	
Zirconia	Value/ Data	Extremely High	0.082	7.644	0.416	6040	**2.587**
	Rank	1.25	3	4	2	4	

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