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BiomechanicalAnalysisofVariousKneeProsthesisBiomaterialsUnderDifferentFlexionAngles UsingFiniteElementMethod

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ABSTRACT

This study employs finite element analysis (FEA) to investigate the biomechanical performance of various biomaterials commonly used in total knee arthroplasty (TKA) under different geometric and flexion conditions. Three-dimensional CAD models of knee implants were developed with varying femoral component geometries—diameters of 60 mm, 65 mm, 70 mm, 75 mm, and 80 mm; sagittal radii of 45 mm and 50 mm, all analysed at a fixed flexion angle of 30°. The materials evaluated include Ti-6Al-4V, Co-Cr-Mo, and stainless steel for the femoral component, and ultra-high molecular weight polyethylene (UHMWPE) for the tibial insert. Realistic material properties and simulated physiological loading were applied to assess the implant's mechanical response. Parameters such as Von Mises stress, The findings provide critical insight into the effect of material selection and femoral geometry on stress distribution and overall implant durability. This analysis aids in optimizing TKA design for improved performance, longevity, and patient outcomes**.**

Keywords: *Total Knee Arthroplasty (TKA), Finite Element Analysis (FEA), Sagittal Radius, Prosthetic Joint, Flexion Angle*

INTRODUCTION

Total knee arthroplasty (TKA) is a widely performed surgical procedure to alleviate pain and restore function in severely damaged knee joints. otal knee arthroplasty (TKA) is a prevalent surgical intervention aimed at alleviating pain and restoring function in patients with severe knee joint degeneration. The success of TKA is significantly influenced by the choice of biomaterials used in the prosthetic components, which must exhibit optimal mechanical properties to withstand the complex loading conditions experienced during daily activities. Various materials, including titanium alloys, cobalt-chromium alloys, and ultra-high molecular weight polyethylene (UHMWPE), are commonly employed in knee prostheses, each offering distinct advantages and limitations in terms of strength, wear resistance, and biocompatibility[1].

Finite Element Analysis (FEA) has become an essential tool in the biomechanical evaluation of knee prostheses, allowing for the simulation of stress distribution, deformation, and contact pressures under varying flexion angles and loading conditions. Previous studies have demonstrated the effectiveness of FEA in optimizing knee implant designs and assessing the performance of different biomaterials [1]. For instance, research has shown that mobile-bearing prostheses can reduce peak contact pressures and improve implant longevity compared to fixed-bearing designs [1].

I. Biocompatibility and Material Properties

The choice of biomaterials is paramount. The implant must be biocompatible, resisting corrosion and degradation in the physiological environment[2]. Common materials include titanium alloys (like Ti-6Al-4V), stainless steel, and cobaltchromium-molybdenum (Co-Cr-Mo) alloys, chosen for their strength, fatigue resistance, and corrosion resistance [3]. However, the selection also depends on patient-specific factors such as allergies and biocompatibility concerns [3][4].

Alternatives like ceramics (alumina, zirconia) or polymers (ultra-high-molecular-weight polyethylene, UHMWPE) are available for patients with metal [3]. The UHMWPE is frequently used for the tibial articulating surface and patellar component [3].

Beyond implant design, solid modeling aids in visualization and surgical planning. For example, it has been used to assist patients with back pain by providing visual representations of their spinal structures [4]. The potential for future applications extends to creating comprehensive models of the entire human body, potentially even at the atomic level [4]. This would have far-reaching implications for medical research, diagnosis, and treatment. Three-dimensional CAD models of total knee arthroplasty components were developed using CAD software [5]. These models incorporated geometries representative of standard implant dimensions. The femoral component was modeled using metallic biomaterials (Ti-6Al-4V, Co-Cr-Mo, Stainless Steel), while the tibial insert was modeled using UHMWPE. Material properties such as Young's modulus, Poisson’s ratio, and yield strength were assigned based on literature data. The finite element analysis was carried out using FEA software by applying realistic boundary conditions and joint reaction forces at multiple flexion angles [6]. Outputs such as Von Mises stress, total deformation, and strain distribution were computed and compared for all materials to assess performance under physiological conditions. The use of solid modeling in conjunction with finite element analysis (FEA) allows for the prediction of stress and strain distributions within implants under various loading conditions, leading to improved implant design and patient outcomes [2] CAD Modeling for Knee Prostheses with Varying Sagittal Radii and Flexion Angles where created .

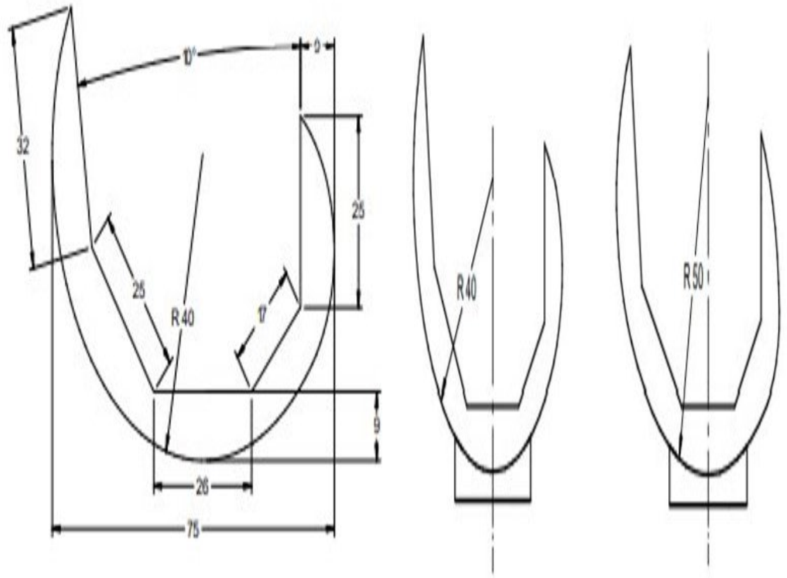

***FIGURE.2.1. 2-D Model* Prosthetic Knee Joint**

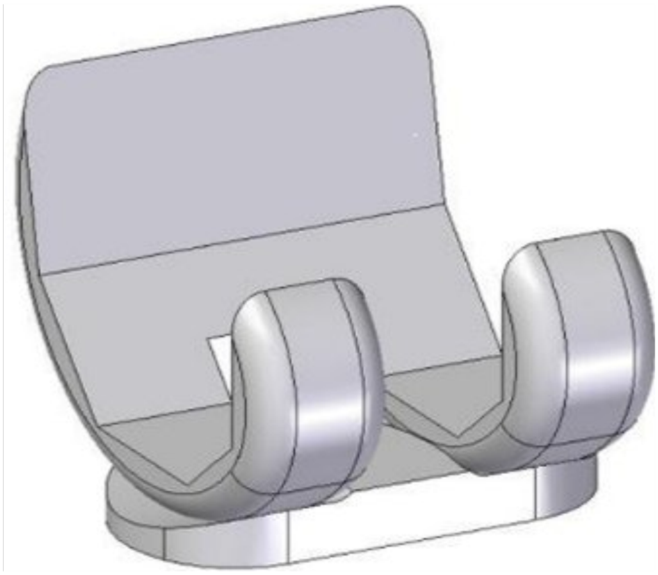

FIGURE.2.2. Three Dimensional Model Prosthetic Knee Joint

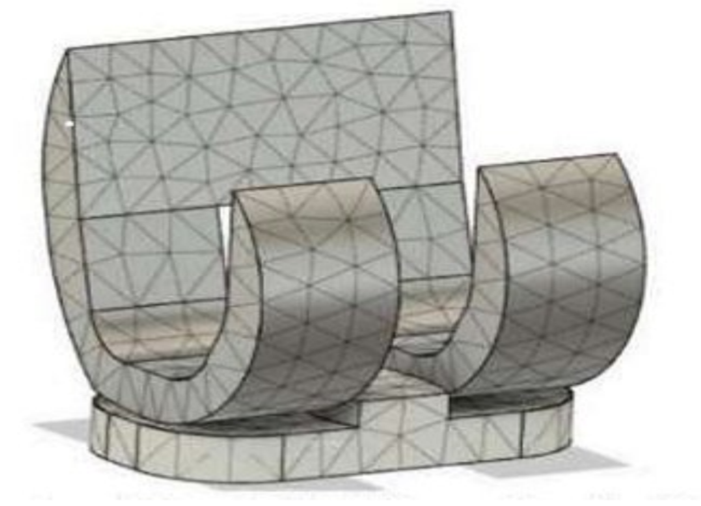

FIGURE. 2.3. Meshed Model of Prosthetic Knee Joint

The mesh refinement process was carried out to ensure accurate stress analysis in the prosthetic knee joint model, focusing on the tibial cushion and femoral component. The finite element model utilized quadratic tetrahedral elements due to their higher accuracy in capturing stress variations in complex geometries. mesh, consisting of 2,994 nodes and 1,388 solid elements, as shown in the meshed model image, ensuring reliable finite element analysis outcomes. The boundary conduction are take femur is fixed and tibla part is Walk on Level Surface at Flexion angle 30^0 as per ASTM standard the standard guideline for knee flexion angles is actually defined by the **ISO 14243-1[7]** simulator protocol. That standard specifies a range of **0° to approximately 58°** of flexion during a typical gait cycle.

II. Development of a Finite Element Model for a Prosthetic Knee Joint

Walk on Level Surface at Flexion angle 30^0 taken [8]. For analysis purpose we are using different materials.

III. Methods and Materials

The presents various materials used in tibial and femoral components for medical applications, primarily in knee replacements and implants. For tibial components, there are notably fewer materials listed, with just two primary options: Epoxy Resin and Ultra-High-Molecular-Weight Polyethylene (UHMWPE), both classified as non-metallic materials.

A 3D model of the knee implant, consisting of the femoral component, tibial component, and polyethylene (PE) cushion pad, is created using computer-aided design (CAD) software like Autodesk Fusion 360. The design is based on general anatomical references to ensure accurate representation of a human knee joint [9], [10]. Femoral and tibial Component made by Ti-6Al-4V alloy (ISO5832-2), Co-Cr-Mo alloy, or stainless steel (ISO5832-1). Cushion Pad made by Ultra-highmolecular-weight polyethylene (UHMWPE) for the tibial cushion. Material properties such as Young's modulus, Poisson's ratio, and density are used for each component based on standard values for orthopaedic materials[14].

IV.For analysis purpose we are using different materials as shown in below table

Table 4.1. Import the CAD model into finite element analysis for Metallic Femur Implant Materials[11].

Components Material	**Density g/cc (ρ)**	**Compressive Strength (Mpa)**	**Youngs Modulus (Gpa)**	**Poisson's Ratio (µ)**
Stainless steel (ISO5832-1)	7.9-8.1	170-310	189-205	0.30
Co-Cr-Mo Alloy	8.3-9.2	450-1896	200-253	0.34
Ti Alloy (ISO5832-2)	4.4-4.5	590-1117	55-117	0.36
Alumina Ceramic	3.9	2000	330	0.22
Grade 5 Titanium	4.43	970	114	0.342

Table4.2. Import the CAD model into finite element analysis for Non-Metallic Femur Implant Materials[11]

Components Material	**Density g/cc (ρ)**	**Compressive Strength (Mpa)**	**Youngs Modulus (Gpa)**	**Poisson's Ratio (µ)**
Epoxy Resign	1.1 and 1.2 g/cc	80 to 120 MPa	2.5 to 3.5 GPa.	0.3 to 0.35.
PEEK	1.3 g/cc	200 MPa,	3.5 - 4.1 GPa	0.27 and 0.42

Table 4.3. Import the CAD model into finite element analysis for Metallic tibia implant Materials[12].

Components Material	**Density g/cc (ρ)**	**Compressive Strength (Mpa)**	**Youngs Modulus (Gpa)**	**Poisson's Ratio (µ)**

Ultra High Molecular Weight Polyethylene (UHMWPE)	0.97	3-12	0.764-0.966	0.24-0.44

walking, and running [11]. Stress, strain and displacement at different nodes of knee implant are evaluated. Knee Implants now in use consist of many components made of Ultra High Molecular Weight Polyethylene (UHMWPE), ceramics, or metallic alloys. $Ti6Al4V$ alloy (ISO5832-2), Stainless steel (ISO5832-1), and Cobalt Chromium-Molybdenum ($CoCrMo$) alloys are three examples of metallic alloys often used in the fabrication of the femoral component and the tibial insert tray of knee implants [13].

V. Results and Discussions Case-1: Walk on Level Surface at Flexion angle 30^0

- Flexion angle 30^0 for walk on level surface taken from ASME Standard

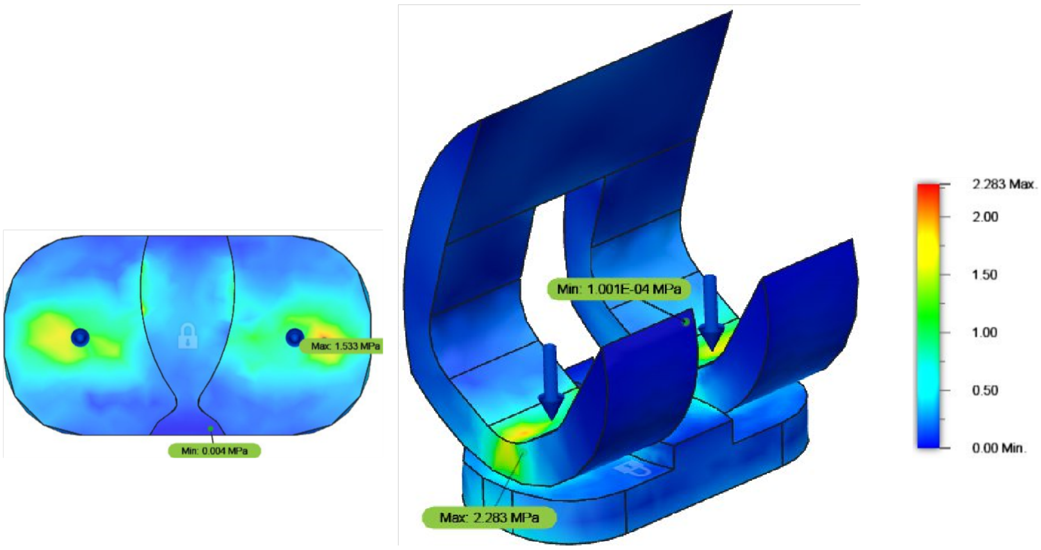

Fig 4.1 Stress Distribution of Knee model for 60mm diameter, 45mm Sagittal Radius and 30^0 flexion angles for Epoxy Resin Bio-Materials

The stress distribution data in Fig 4.1 illustrates the mechanical behavior of a knee joint model constructed using epoxy resin bio-materials. The model parameters include a 60 mm diameter, 45 mm sagittal radius, and a 30° flexion angle. The stress values range from a minimum of 0.0001001 MPa to a maximum of 2.283 MPa, indicating a wide variation in stress experienced across the joint under the applied load. This distribution highlights critical areas that may be subject to wear or failure, supporting the evaluation of material performance and biomechanical safety under functional conditions. The analysis aids in optimizing implant designs using epoxy resin materials.

The finite element analysis (FEA) was performed to evaluate the stress distribution in a prosthetic knee joint model with a diameter of 60 mm, a sagittal radius of 45 mm, and subjected to a 30° flexion angle. The material selected for this trial was Epoxy Resin, a common bio-compatible non-metallic material.A static structural analysis was conducted under standard boundary conditions, where the femoral component was fixed at the top surface, and a physiological load of approximately 700 N (representing average human body weight) was applied vertically on the tibial surface.

The results indicated that the maximum Von Mises stress occurred around the contact interface between the femoral and tibial components. For the Epoxy Resin material, stress values were within safe limits but comparatively higher due to its lower modulus of elasticity compared to metals.

To ensure consistency, the same model, boundary conditions, and loading conditions were used to analyze other metallic (e.g., Titanium, Stainless Steel 316L, Co-Cr-Mo) and non-metallic (e.g., UHMWPE, PEEK, Alumina Ceramic) materials. This allowed for a comparative assessment of stress behavior and suitability of materials for knee prosthesis applications.

The results showed that metallic materials generally exhibited lower stress and deformation, owing to their higher strength and stiffness. Non-metallic materials like Epoxy Resin and UHMWPE showed higher stress concentrations and displacement, but they may still be viable for specific components due to their bio-compatibility and wear resistance.

Comparison of Stress Results for Different Bio-Materials at 30^0 Flexion angle

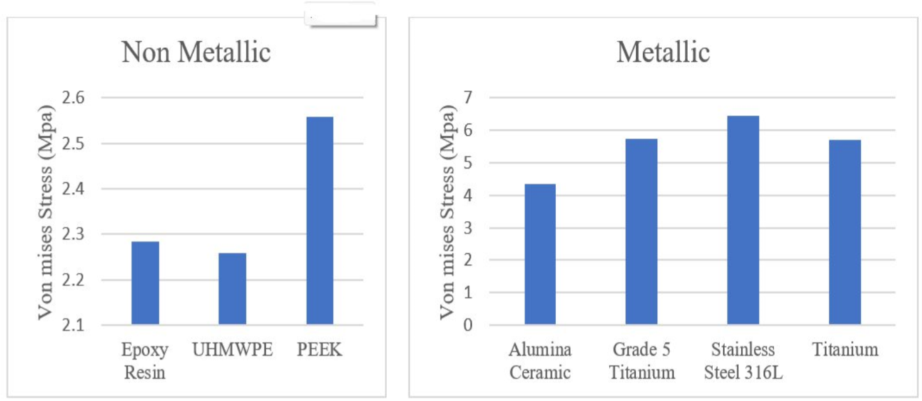

Fig 5.1 Result comparison of Von mises stress vs Different Bio-material at 60mm diameter 45mm Sagittal Radius and 30^0 Flexion angle

Figure 5.1 presents a comparative analysis of Von Mises stress values for different bio-materials used in a knee joint model with a 60 mm diameter, 45 mm sagittal radius, and a 30° flexion angle. The materials are categorized into non-metallic—Epoxy, UHMWPE, PEEK, Resin—and metallic—Alumina Ceramic, Grade 5 Titanium, Titanium, and Stainless Steel 316L. Among the non-metallic materials, stress values range from 2.1 MPa to 2.6 MPa, indicating moderate mechanical performance suitable for applications requiring flexibility and biocompatibility. In contrast, metallic materials exhibit significantly higher stress values, with peaks reaching up to 7 MPa. Grade 5 Titanium, Titanium, and Stainless Steel 316L show superior load-bearing capacities, making them ideal for high-stress orthopedic applications.

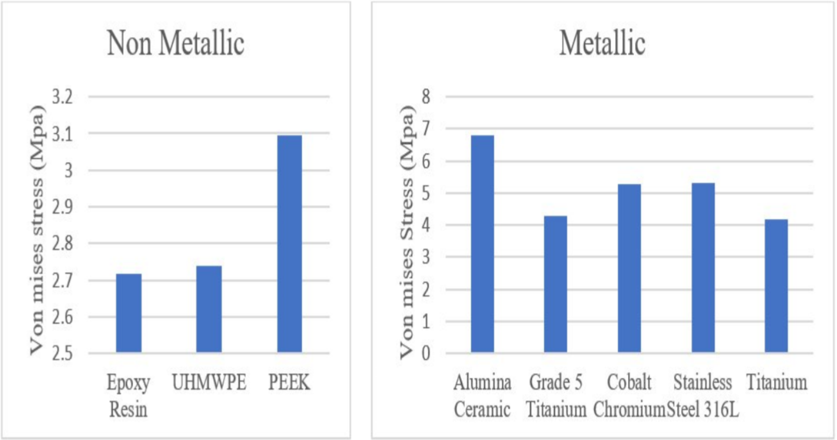

Fig 5.2 Result comparison of Von mises stress vs Different Bio-material at 60mm diameter 50mm Sagittal Radius and 30^0 Flexion angle

Figure 5.2 provides a comparative analysis of Von Mises stress values for various bio-materials in a knee joint model with a 60 mm diameter, 50 mm sagittal radius, and a 30° flexion angle. The materials evaluated include non-metallic options—Epoxy, UHMWPE, PEEK, and Resin—and metallic options—Alumina Ceramic, Grade 5 Titanium, Titanium, Cobalt Chromium, and Stainless Steel 316L. The Von Mises stress values for non-metallic materials range from approximately

2.5 MPa to 3.2 MPa, suggesting moderate mechanical strength with benefits such as flexibility, light weight, and biocompatibility. In contrast, metallic materials show higher stress values, particularly Cobalt Chromium and Grade 5 Titanium, which are known for their superior load-bearing capacity and durability in orthopedic applications.

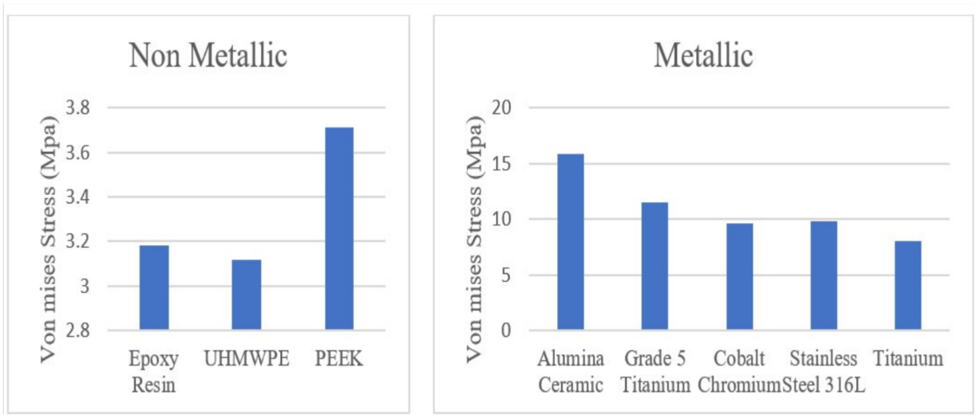

Fig 5.3 Result comparison of Von mises stress vs Different Bio-material at 65mm diameter 45mm Sagittal Radius and 30^0 Flexion angle

Figure 5.3 presents a comparison of Von Mises stress values for various biomaterials under consistent biomechanical conditions: 65 mm diameter, 45 mm sagittal radius, and a 30° flexion angle. The materials are categorized into non-metallic and metallic groups. Non-metallic materials—Epoxy, UHMWPE, PEEK, and Resin—exhibit lower stress values, ranging from 2.8 to 3.8 MPa. These materials are generally used where flexibility and biocompatibility are prioritized over mechanical strength. In contrast, metallic materials such as Alumina, Grade 5 Titanium, Cobalt Chromium, Stainless Steel 316L, and Ceramic Titanium show significantly higher Von Mises stresses, between 10 and 20 MPa, indicating superior load-bearing capacity and mechanical durability.

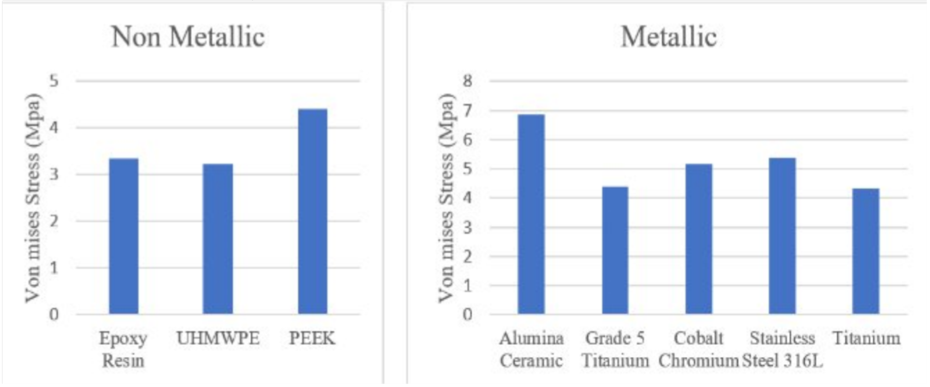

Fig 5.4 Result comparison of Von mises stress vs Different Bio-material at 65mm diameter 50mm Sagittal Radius and 30^0 Flexion angle

Figure 5.4 illustrates a comparative analysis of Von Mises stress values for various biomaterials tested under uniform conditions: 65 mm diameter, 50 mm sagittal radius, and a 30° flexion angle. The materials are classified into non-metallic and metallic groups. Non-metallic materials—Epoxy, UHMWPE, PEEK, and Resin—show lower stress values, typically ranging from 2 to 4 MPa. These materials are often favored in applications requiring biocompatibility and flexibility with lower mechanical loads. On the other hand, metallic materials—including Alumina Ceramic, Grade 5 Titanium, Cobalt Chromium, Stainless Steel 316L, and Titanium—display relatively higher Von Mises stresses, from approximately 3 to 5 MPa. This indicates better mechanical strength and greater resistance to deformation under load, making them suitable for high-stress, load-bearing applications such as orthopedic implants.

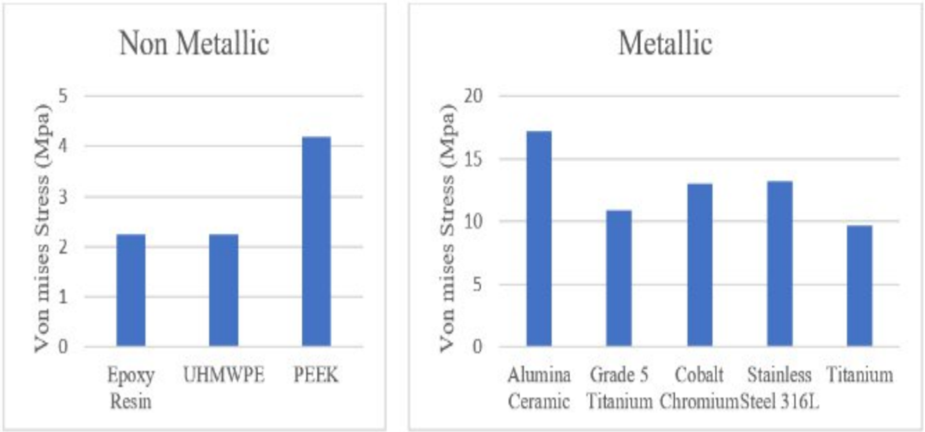

Fig.5.5 Result comparison of Von mises stress vs Different Bio-material at 70mm diameter 45mm Sagittal Radius and 30^0 Flexion angle

Figure 5.5 presents a comparison of Von Mises stress values for various biomaterials under standardized biomechanical conditions: 70 mm diameter, 45 mm sagittal radius, and a 30° flexion angle. The materials are grouped into non-metallic and metallic categories. Non-metallic materials—Epoxy, UHMWPE, PEEK, and Resin—demonstrate lower stress values, with Von Mises stress peaking around 5 MPa. In contrast, metallic materials—including Alumina, Grade 5 Titanium, Cobalt Chromium, Stainless Steel 316L, and Ceramic Titanium—show significantly higher stress values, reaching up to 21 MPa.

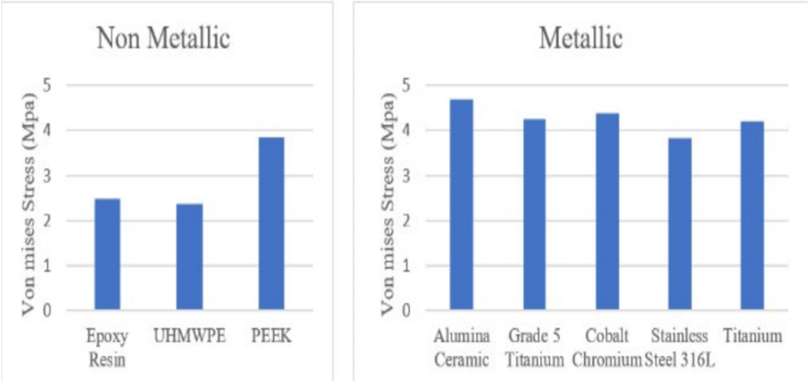

Fig .5.6 Result comparison of Von mises stress vs Different Bio-material at 75mm diameter 45mm Sagittal Radius and 30^0 Flexion angle

Figure 5.6 illustrates the comparative Von Mises stress distribution for various bio-materials at a knee joint configuration of 75 mm diameter, 45 mm sagittal radius, and 30° flexion angle. Among **non-metallic materials, UHMWPE** continues to demonstrate the lowest stress, affirming its excellent load absorption and flexibility, making it ideal for tibial inserts. **Epoxy** and **Resin** exhibit significantly higher stress levels, indicating limited structural performance under bending or flexion. **PEEK** offers a moderate stress response, balancing strength and flexibility. For **metallic materials, Titanium Grade 5** and **Cobalt-Chromium** alloys show superior stress handling with low Von Mises values, highlighting their mechanical robustness and fatigue resistance. **Alumina Ceramic,** despite its hardness, shows very high stress concentrations, suggesting brittleness under flexion. **Stainless Steel 316L** also exhibits relatively higher stress than titanium or cobalt alloys. The study suggests that **Titanium Grade 5** and **UHMWPE** are most suitable for flexion-dominant prosthetic applications due to their optimal stress behavior and material properties.

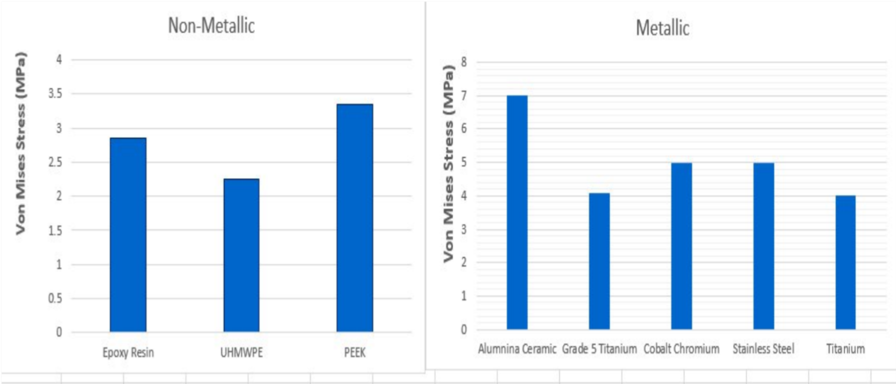

Fig 5.7 Result comparison of Von mises stress vs Different Bio-material at 75mm diameter 50mm Sagittal Radius and 30^0 Flexion angle

Figure 5.7 presents a comparative analysis of Von Mises stress values for various biomaterials under consistent biomechanical conditions: a 75 mm diameter, 50 mm sagittal radius, and a 30° flexion angle. The materials are grouped into non-metallic (Epoxy, UHMWPE, PEEK, and Resin) and metallic (Alumina, Grade 5 Titanium, Cobalt Chromium, Ceramic Titanium, and Stainless Steel 316L) categories. The Von Mises stress values for non-metallic materials range. from 2.6 to 3.3 MPa, showing relatively low stress responses, which is typical for materials known for flexibility and biocompatibility. Metallic materials, although typically stronger, show only slightly higher stress values in this setup—indicating a narrower gap between the two groups under these specific loading conditions.

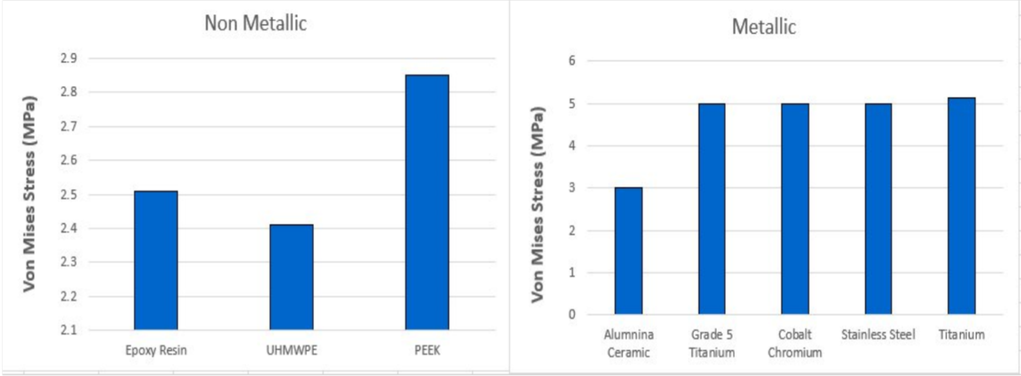

Fig 5.8 Result comparison of Von mises stress vs Different Bio-material at 70mm diameter 45mm Sagittal Radius and 30^0 Flexion angle

Figure 5.8 illustrates the comparison of Von Mises stress values for various biomaterials under uniform biomechanical conditions: 70 mm diameter, 45 mm sagittal radius, and a 30° flexion angle. The materials are classified into non-metallic (Epoxy, UHMWPE, PEEK, Resin) and metallic (Alumina Ceramic, Grade 5 Titanium, Cobalt Chromium, Stainless Steel 316L, Titanium) groups. Non-metallic materials display lower stress values, ranging approximately from 0.5 to 2.5 MPa, indicating greater flexibility and suitability for applications with minimal mechanical load. Metallic materials, on the other hand, show significantly higher Von Mises stress values between 2 and 6 MPa, demonstrating superior mechanical strength and better resistance to deformation under load.

CONCLUSIONS

- Non-MetallicMaterials Exhibit Lower Stress Values Across all figures, non-metallic materials such as UHMWPE, Epoxy, PEEK, and Resin consistently demonstrate lower Von Mises stress values (ranging approximately from 0.5 MPa to 5 MPa), making them suitable for components requiring flexibility, biocompatibility, and low load-bearing capacity (e.g., tibial inserts).
- UHMWPE Is the Most Effective Non-Metallic Material UHMWPE shows the lowest stress values among non-metallic materials in nearly all configurations, reinforcing its role as the preferred material in joint prostheses due to its excellent wear resistance and stress absorption.
- Metallic Materials Provide Superior Load-Bearing Strength

Metallic materials like Grade 5 Titanium, Cobalt Chromium, and Stainless Steel 316L consistently exhibit higher Von Mises stresses (typically between 3 MPa to 21 MPa), indicating their suitability for load-bearing applications due to higher mechanical strength and fatigue resistance.

- Cobalt Chromium and Titanium Alloys Show Optimal Performance

Among metallics, Cobalt Chromium and Grade 5 Titanium consistently offer a balance of high strength and moderate stress values, making them the most reliable choices for high-stress orthopedic components such as femoral and tibial baseplates.

Stress Values Are Affected by Geometrical Parameters Increases in diameter or sagittal radius generally result in higher stress values, especially in metallic materials, suggesting that prosthetic geometry must be carefully optimized to reduce localized stresses and enhance implant longevity.

REFERENCES

[1] Zhang Zhang, Z., Qi, Y., Wei, B., Bao, H., & Xu, Y. (2023). Application strategy of finite element analysis in artificial knee arthroplasty. Frontiers in Bioengineering and Biotechnology, 11. https://doi.org/10.3389/fbioe.2023.1127289

[2] Shashishekar, C., & Ramesh, C. S. (2007). Finite element analysis of prosthetic knee joint using ANSYS. WIT Transactions on Biomedicine and Health. https://doi.org/10.2495/bio070071

[3] Saurabh samadhiya , Amit Yadav & Dr. B.R Rawal (2014). Biomechanical Analysis of Different Knee Prosthesis Biomaterials Using FEM. IOSR Journal of Mechanical and Civil Engineering . e-ISSN: 2278-1684,p-ISSN: 2320334X, Volume 11, Issue 3 Ver. IV.PP 120-128.

[4] Kumar, D., & Maiti, R. (2025). Finite Element Analysis of knee Implant Materials under cyclic loading condition: An analysis of failures. IRBM, 46(3), 100893. https://doi.org/10.1016/j.irbm.2025.100893

[5] Bhandarkar, S., & Dhatrak, P. (2021). Optimization of a knee implant with different biomaterials using finite element analysis. Materials Today Proceedings, 59, 459–467. https://doi.org/10.1016/j.matpr.2021.11.466

[6] Richa Rai & Vikas Rastogi.(2020). FEA Analysis of the Knee Joint, During Knee Flexion Movement. International Journal of Engineering Research in Mechanical and Civil Engineering (IJERMCE) .Vol 5, Issue

[7] International Organization for Standardization. (2009). ISO 14243-1: Implants for surgery — Joint prostheses — Part 1: Determination of endurance properties and performance of knee prostheses. ISO-14243-1-2009.pdf.

[8] Koo, Y., & Koo, S. (2019). Three-Dimensional kinematic coupling of the healthy knee during treadmill walking. Journal of Biomechanical Engineering, 141(8). https://doi.org/10.1115/1.4043562

[9] Marinela Petoa , Erick Ramírez-Cedillob,c, Adriana Hernándezd , Hector R. Siller, Structural design optimization of knee replacement implants for Additive Manufacturing, Procedia Manufacturing ,(2019) , Volume.34 , P.574–583

[10] Carr, B. C., & Goswami, T, Knee implants – Review of models and biomechanics. Materials & Design, (2009). Volume. 30, Issue (2), P.398–41

[11] D. Zhao, H. Sakoda, W. G. Sawyer, S. A. Banks, and B. J. Fregly (2008), Predicting knee replacement damage in a simulator machine using a computational model with a consistent wear factor, Journal of Biomechanical Engineering, , Volume.130, P. 011004-1- 011004-10.

[12] M.A.Lafortune , P.R.Cavanagh, H.J.Sommer, A.Kalenak(1992),Three-dimensional kinematics of the human knee during walking, , Journal of Biomechanical Engineering, Volume:25, Issue: (4), P.347 57.B. Morrison, The Mechanics of The Knee Joint in Relation to Normal Walking, Journal of Biomechanics,1970,Volume. 3, Issue:1, P. 51-61.

[13] Carr, B. C., & Goswami (2009), T, Knee implants – Review of models and biomechanics. Materials & Design,. Volume. 30, Issue (2), P.398–41

[14] Dr. Shashishekar C, Sanjay S.J., Veereshkumar. Ambiger, Nagappa.V Sankannavar, Veeranna R. Kattimani (2025). Effect Of Finite Element Analysis On Knee Implant Materials Under Static Conditions . Cuest.fisioter 54(3):3111-3123.