# Effect Of Finite Element Analysis On Knee Implant Materials Under Static Conditions

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**Abstract:** Finite Element Analysis (FEA) is a powerful computational tool used to study the behaviour of materials and structures under various conditions. This study specifically focuses on conducting static analysis of knee implant materials to evaluate their mechanical performance and suitability for biomedical applications.The research involves modelling knee implant components using FEA to analysed stress distribution, deformation, and overall structural integrity under static loading conditions. Various materials commonly used in knee implants, such as titanium alloys, cobalt-chromium alloys, and ultra-high-molecular-weight polyethylene (UHMWPE) are evaluated to understand their mechanical properties and interactions. The results obtained from the analysis reveal the results of a finite element analysis (FEA) conducted on the tibial part of a knee implant. It presents a stress distribution plot, highlighting areas of maximum stress at 2.355 MPa and minimum stress at 0.002 MPa. These highlighted regions offer valuable insights into the behaviour of the implant material when subjected to static loading conditions. The image depicts a finite element analysis (FEA) representation, specifically focusing on the tibial part of a knee implant under static loading conditions. The stress distribution is clearly visualized, with distinct indications of maximum stress at 2.361 MPa and minimum stress at $3.053E^{-05}$ MPa. The image suggest the applied loading points, likely simulating forces exerted during normal or specific activities.

**Keywords:** Finite Element Analysis, Knee Implant, Tibial Component, Static Conditions, Stress Analysis, Implant Materials, Biomechanics, Mechanical Properties, Implant Design Optimization, Biomedical Engineering**.**

## 1. Introduction

**1.INTRODUCTION**

The knee is the largest and most complex joint in the body, playing a crucial role in weight-bearing and facilitating movements between the thigh bone (femur), shin bone (tibia), and knee cap (patella). The menisci act as shock absorbers and help distribute load, while ligaments provide stability, and tendons connect muscles to bones, allowing for coordinated movement [1].The knee endures significant compressive forces, which can reach up to ten times body weight during activities such as walking. This remarkable ability to withstand high loads is essential for maintaining stability and mobility during various physical activities [2].The design of the knee joint, along with its supporting structures, allows it to effectively manage these forces while facilitating a wide range of movements, including bending, straightening, and pivoting [3]. The femoral component is designed to replicate the shape and function of the natural femur, while the tibial articulation surface and tray provide a stable platform for weight-bearing and movement. The materials used in these components are chosen for their durability, biocompatibility, and ability to withstand the significant forces experienced in the knee joint during daily activities. [4]. The tibial tray is inserted into the proximal tibia, providing a stable foundation for the knee implant, while the patellar component replaces the posterior surface of the patella. Both the tibial articulating surface and the patellar component are typically made from ultra-high molecular weight polyethylene (UHMWPE) or cross-linked polyethylene [5]. In contrast, the femoral component and the tibial tray are usually constructed from metals such as titanium-based alloys, stainless steel, and cobalt-chromium-molybdenum (Co-Cr-Mo) alloys. These materials provide the necessary strength, durability, and biocompatibility required to withstand the significant forces experienced in the knee joint [6]. In some cases, ceramics like alumina, zirconia, and their composites may also be used for these components, offering advantages such as high wear resistance and reduced friction, although they may have different mechanical properties compared to metals[7]. The choice of materials for knee implants is influenced by a variety of patient-specific factors. The materials used must be compatible with the human body to minimize the risk of adverse reactions. Biocompatible materials ensure that the body does not reject the implant and that inflammatory responses are minimized. The materials must possess adequate strength, stiffness, and fatigue resistance to withstand the significant loads and stresses experienced during daily activities. This includes considerations for wear resistance, as the implant surfaces will experience continuous friction during movement. The age of the patient can influence material choice, as younger patients may require more durable materials that can withstand higher activity levels over a longer period, while older patients may have different needs based on their activity levels and overall health. Patients who lead active lifestyles may benefit from implants made of materials that offer enhanced durability and wear resistance. Conversely, less active patients might not require the same level of material performance, allowing for a wider range of material options [8].Finite Element Analysis (FEA) is a powerful computational tool used to simulate mechanical tests on knee implants, effectively saving time and costs by predicting stress and mechanical behaviour under static conditions. Finite Element Modelling (FEM) plays a crucial role in analysing the interactions between the femoral component of a knee implant and the underlying femur [9]. By simulating how loads and deformations are transferred through these components, FEM provides valuable insights that help optimize implant design. FEM allows engineers to visualize stress distribution across the implant and the femur. By identifying areas of high stress concentration, design modifications can be made to redistribute loads more evenly, which can prevent localized failure or damage to both the implant and the surrounding bone [10].

**Objective**

The main Objective of this research paper is to assess how metallic and non-metallic biomaterials respond to axial loading conditions, simulating physiological loads experienced during standing activities. To investigate the stress distribution patterns around the implant-bone interface and identify potential areas of high stress concentration that could lead to aseptic loosening.

## 2. Methods and 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 [11], [12]. 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-high-molecular-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

**Table 1. Import the CAD model into finite element analysis for Metallic Femur Implant Materials[16].** .

| Components Material | Density g/cc ($\rho$) | 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 |

**Table 2. Import the CAD model into finite element analysis for Non-Metallic Femur Implant Materials[16].**

| Components Material | Density g/cc ($\rho$) | 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 3. Import the CAD model into finite element analysis for Metallic tibia implant Materials[16].**

| Components Material | Density g/cc ($\rho$) | 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 [2]. 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].

**2.2 Model of knee Implant**
It is critical to comprehend how people move and the forces at work on the body when doing tiresome jobs. In training for sporting events, compression pressures can reach up to ten times the body weight. These forces are caused by daily activities, which vary in magnitude from two to four times the human body load [14]. The approximate dimensions of the knee implant model taken into consideration for this investigation. The femoral component of knee prosthesis is developed supported the CAD/CAM system and rapid prototyping. Rapid prototyped model is fabricated from three-dimensional CAD model for concurrent development[15].

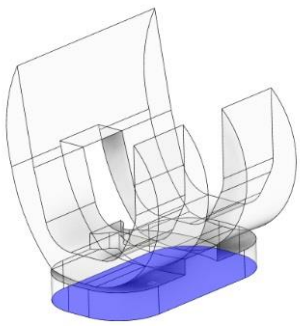


**Fig 2.2 .3-D Model of Prosthetic Knee Joint**

Quantify the knee related parameters of interest like the average, variance, maximum, minimum values and so on. The anteroposterior diameter of the lateral and medial femoral condyle, as well as the width of the femoral neck, is important for the conception of the knee prosthesis. That is why this parameter is so important of the knee joint measured parameters.

**2.3 Meshing and Finite Element Analysis**
In this work, mesh refinement was performed by adjusting the element size from 1.1 mm to 1.5 mm to monitor the equivalent von Mises stress in the tibial cushion and femoral component. The convergence requirement, defined as less than 5% variance in results, was achieved using a 1.5 mm element size and quadratic tetrahedral elements [16].

**Table 3. Shows the number of nodes and Elements**

| Type | Nodes | Elements |
|---|---|---|
| Solids | 2994 | 1388 |

**Fig 2.3.Meshed Model of Prosthetic Knee Joint**

### 3. Results

### 3.1 Stress Results of Different Bio-Materials

Three different sets of material combinations were considered when doing the finite element analysis on the knee implant assembly. Three materials have been subjected to FE analysis: Co-Cr-Mo alloy, titanium alloy ISO-5832-2, and stainless-steel ISO-5832-1. The analysis was conducted for the Femoral, Tibial, and Cushion Pad Components. Ultra-high molecular weight polyethylene (UHMWPE) materials were used for the tibial cushion.

**Case-1 Standing at Flexion angle $0^0$**

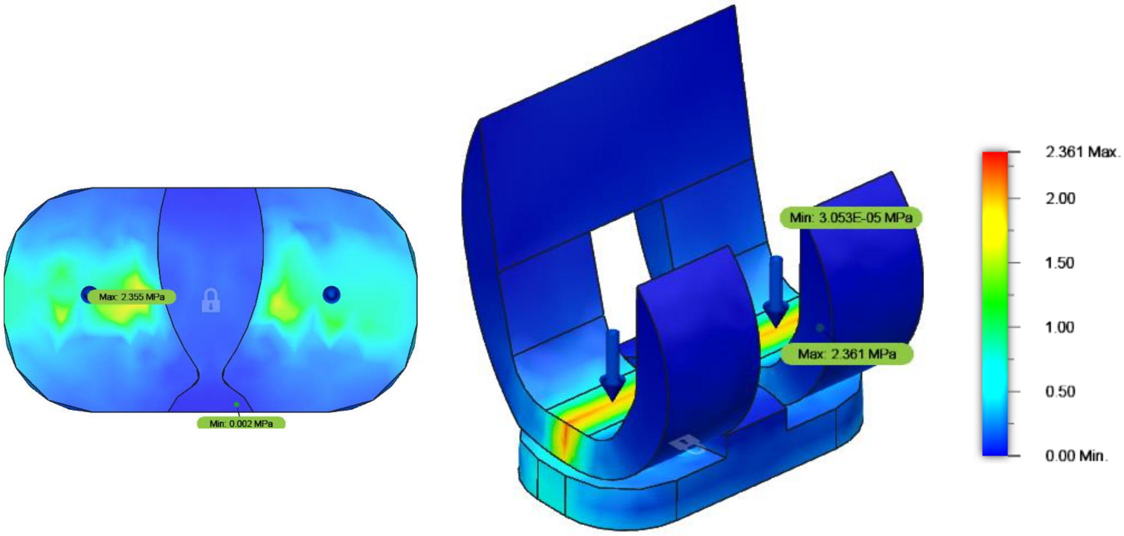



**Fig 3.1 Stress Distribution of Knee model for 60mm diameter, 45mm Sagittal Radius and $0^0$ flexion angle for Epoxy Resin Bio-Materials**

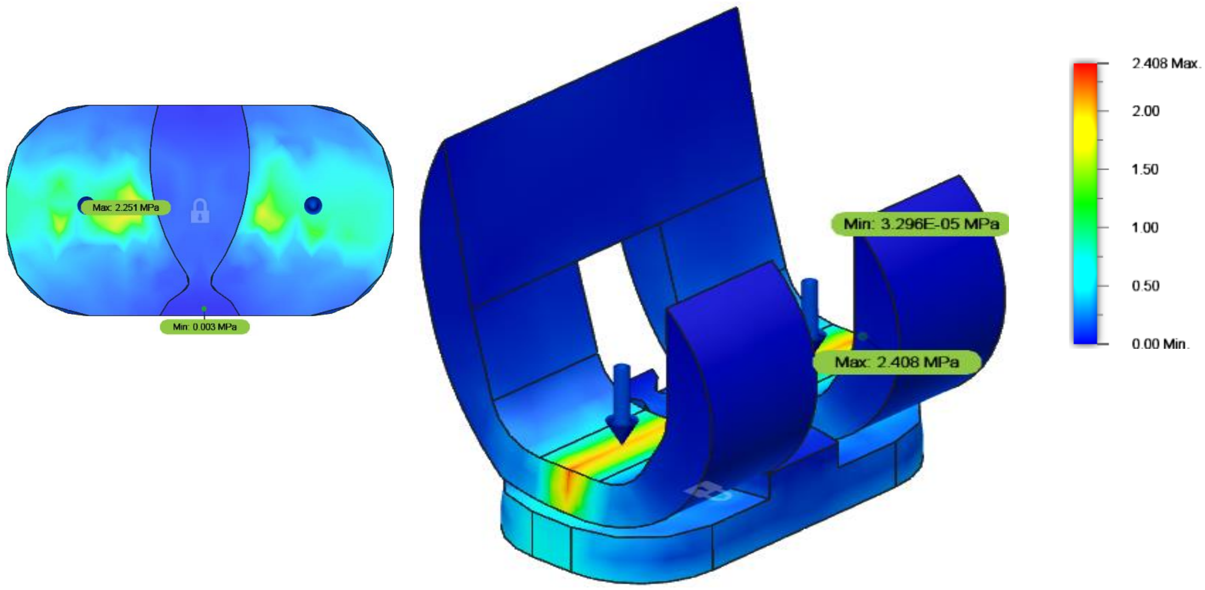



**Fig 3.2. Stress Distribution of Knee model for 60mm diameter, 45mm Sagittal Radius and $0^0$ flexion angle for UHMWPE Bio-Materials**

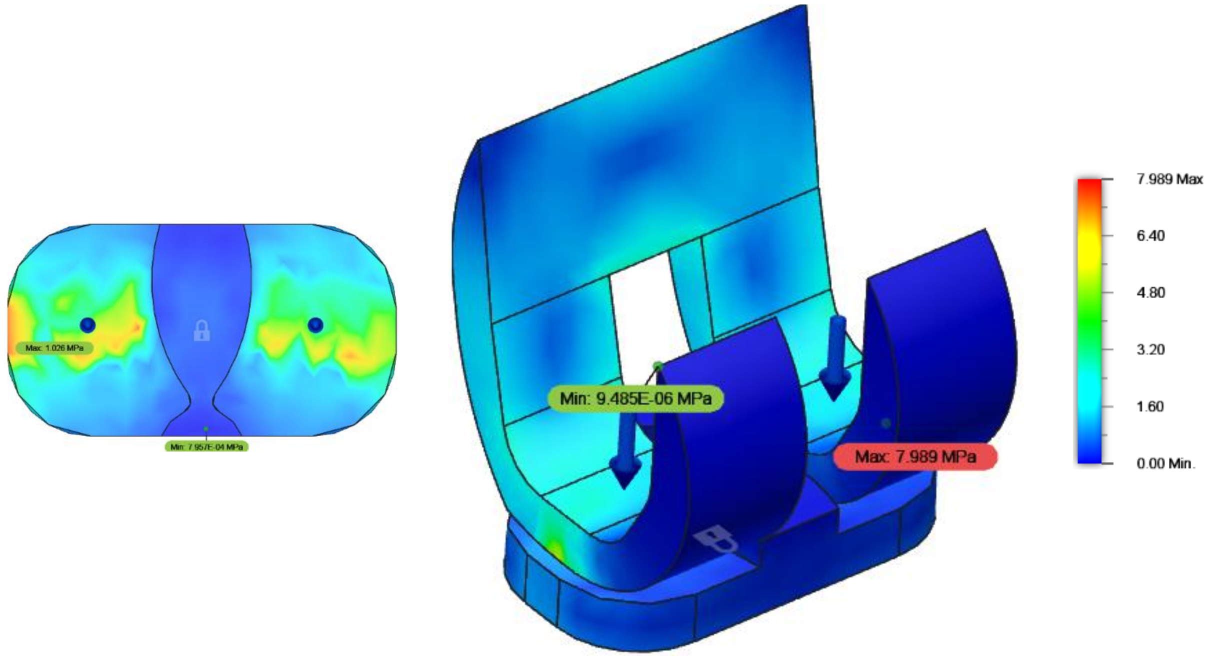



**Fig 3.3 Stress Distribution of Knee model for 60mm diameter, 45mm Sagittal Radius and $0^0$ flexion angle for Alumina Ceramic(femur) Bio-Materials**

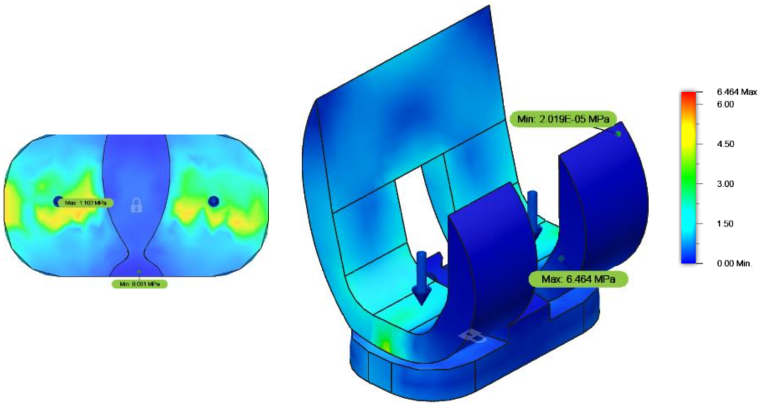



**Fig 3.4 Stress Distribution of Knee model for 60mm diameter, 45mm Sagittal Radius and $0^0$ flexion angle for Grade 5 Titanium (femur) Bio-Materials**

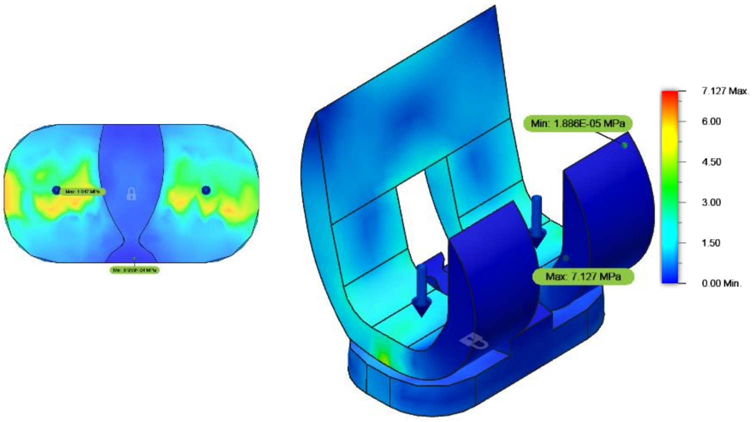



**Fig 3.5 Stress Distribution of Knee model for 60mm diameter, 45mm Sagittal Radius and 00 flexion angle for Cobalt Chromium (femur) Bio-Materials**

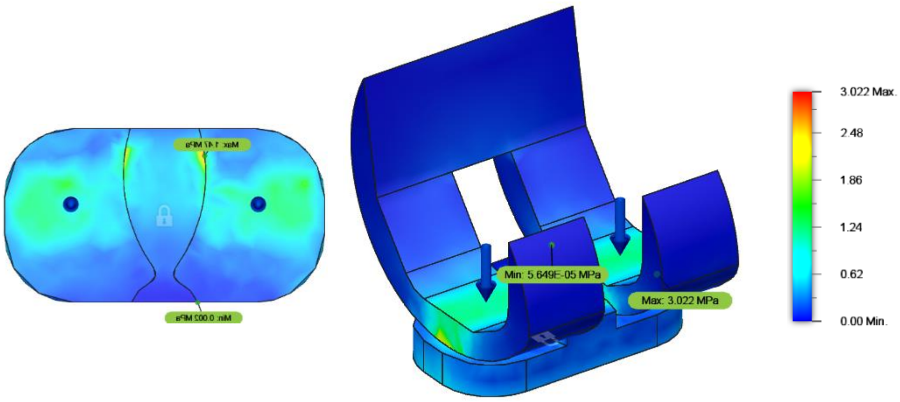



Fig 3.6 Stress Distribution of Knee model for 85mm diameter, 45mm Sagittal Radius and $0^0$ flexion angle for PEEK Bio-Materials

## 4.Results and Discussion

### 4.1. Graph Comparison of Stress Results for Different Bio-Materials at $0^0$ Flexion angle

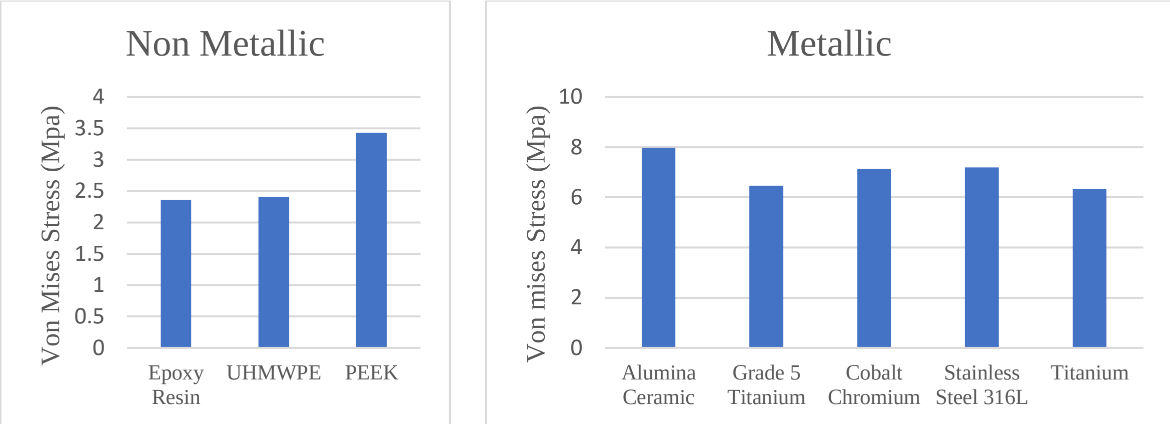
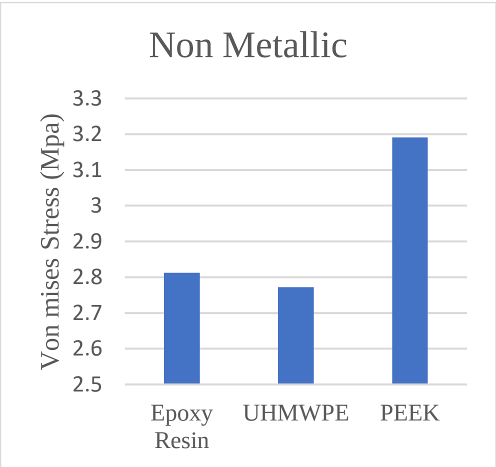



**Fig 4.1 Result comparison of Von mises stress vs Different Bio-material at 60mm diameter 45mm Sagittal Radius and $0^0$ Flexion angle**

It displays moderately high Von Mises stress due to its rigidity. The material's limited ability to deform under load restricts stress redistribution, resulting in localized stress concentrations. The geometry (60 mm diameter, 45 mm sagittal radius) and 0° flexion angle ensure a symmetrical load distribution, simplifying stress patterns. Biomaterials with higher rigidity typically exhibit greater Von Mises stress, while more compliant materials demonstrate lower stress due to their capacity for deformation. UHMWPE displays the lowest stress, high compliance, and wear resistance, making it suitable for articulating surfaces such as tibial inserts. Alumina ceramic presents moderate stress, high rigidity, and wear resistance, making it ideal for femoral components but susceptible to brittle failure. Epoxy resin experiences high stress, is brittle, and prone to failure, rendering it unsuitable for long-term or high-stress orthopaedic applications. UHMWPE is ideal for tibial components because of its capacity to absorb and redistribute stresses. Alumina Ceramic is the preferred choice for femoral components, where wear resistance and high compressive strength are essential, as long as careful design reduces stress concentrations. Epoxy Resin is not appropriate for functional implants but can be used as a prototype material for testing designs in controlled conditions.
The material exhibits a moderate Von Mises stress of approximately 2.5 MPa, which indicates relatively lower deformation and stress absorption compared to other materials. Due to its brittle nature, it is likely limited in its ability to handle stress effectively, making it less ideal for dynamic or high-load applications. In comparison to epoxy resin, it shows slightly higher Von Mises stress at around 2.7 MPa. However, its viscoelastic behaviour suggests that despite the slightly higher stress, it remains highly reliable under cyclic and dynamic loads, ensuring durability and wear resistance in orthopaedic applications. It exhibits the highest Von Mises stress at approximately 3.5 MPa, reflecting its rigid and semi-crystalline structure, which provides strength but limits stress redistribution. PEEK's performance suggests suitability for load-bearing components, though its higher stress levels could raise concerns under extreme conditions. It is suitable for prototype testing or low-load scenarios, but not ideal for functional implants due to potential failure under cyclic or high-load conditions. It is considered the most reliable among the three for articulating components (e.g., tibial inserts) in knee models due to its balance of low stress, high wear resistance, and durability. It is best suited for high-strength applications, such as structural or load-bearing components, but requires careful design to mitigate localized stress concentrations. The material is ideal for applications where stress absorption and durability are critical, being strong and rigid, although higher stress levels may limit its use in certain high-impact conditions. It is considered the least favourable for high-stress applications due to moderate stress levels and brittleness.
Materials with high wear resistance, such as those used for femoral components, are best suited for articulating surfaces. However, their high stress levels and brittleness restrict their use in load-bearing structures without reinforcement. M Materials with high wear resistance, such as those used for femoral components, are best suited for articulating surfaces. However, their high stress levels and brittleness restrict their use in load-bearing structures without reinforcement. Materials with lower stress levels, good fatigue resistance, and biocompatibility, like those used for femoral stems, are excellent for load-bearing components. They are suitable for high-strength applications where wear and corrosion resistance are crucial, although their higher stress levels may lead to localized stress concentrations. For temporary implants, an economical option is available, but it is slightly more susceptible to stress and corrosion, making it less ideal for long-term applications. Implants requiring good biocompatibility and stress absorption are ideal for certain materials, but they may lack the strength required for highly loaded components. Materials with low stress levels and high biocompatibility are ideal for load-bearing implants. Some materials may have moderate stress levels but excellent strength and wear resistance, making them suitable for structural and articulating components. On

the other hand, materials with high stress levels and brittleness are limited to wear-resistant articulating surfaces materials with lower stress levels, good fatigue resistance, and biocompatibility, like those used for femoral stems, are excellent for load-bearing components. They are suitable for high-strength applications where wear and corrosion resistance are crucial, although their higher stress levels may lead to localized stress concentrations. For temporary implants, an economical option is available, but it is slightly more susceptible to stress and corrosion, making it less ideal for long-term applications. Implants requiring good biocompatibility and stress absorption are ideal for certain materials, but they may lack the strength required for highly loaded components. Materials with low stress levels and high biocompatibility are ideal for load-bearing implants. Some materials may have moderate stress levels but excellent strength and wear resistance, making them suitable for structural and articulating components. On the other hand, materials with high stress levels and brittleness are limited to wear-resistant articulating surfaces.



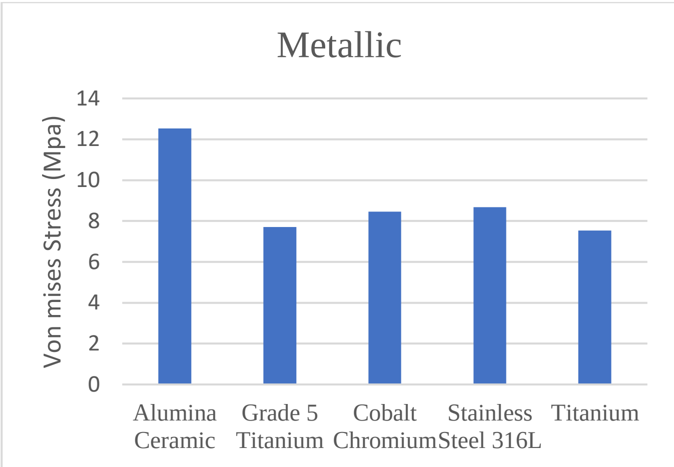




**Fig 4.2 Result comparison of Von mises stress vs Different Bio-material at 60mm diameter 50mm Sagittal Radius and $0^0$ Flexion angle**

When it comes to knee models, UHMWPE and Grade 5 Titanium stand out as the most reliable materials. UHMWPE is particularly superior in articulating components, while Grade 5 Titanium excels in load-bearing roles. For high-strength applications, Cobalt-Chromium and Stainless Steel are viable options, but they may necessitate careful design to address stress concentrations. Alumina Ceramic, on the other hand, is best suited for non-load-bearing, wear-resistant applications due to its high stress levels and brittleness. Ultimately, the choice of material for knee models should be informed by the specific application within the knee joint, taking into account factors such as wear resistance, stress absorption, and long-term durability.
Ultra-high-molecular-weight polyethylene (UHMWPE) is considered the top-performing non-metallic material for knee model applications because of its exceptional stress-handling properties. On the other hand, poly ether ether ketone (PEEK) is stronger and more rigid than UHMWPE, but it is not as effective in reducing stress concentrations, making it more suitable for specific structural applications. In contrast, epoxy resin is considered the least suitable for high-load or stress-sensitive applications due to its brittle nature and higher stress levels.The data shows that Alumina Ceramic endures the highest stress among the listed metallic materials, indicating that it may be less suitable for applications that require lower stress. Metallic materials like Stainless Steel 316L and Cobalt Chromium may be more appropriate for moderate stress conditions, whereas Grade 5 Titanium and Titanium are suitable for applications with lower stress tolerance. This comparison can assist in material selection according to stress-handling requirements.

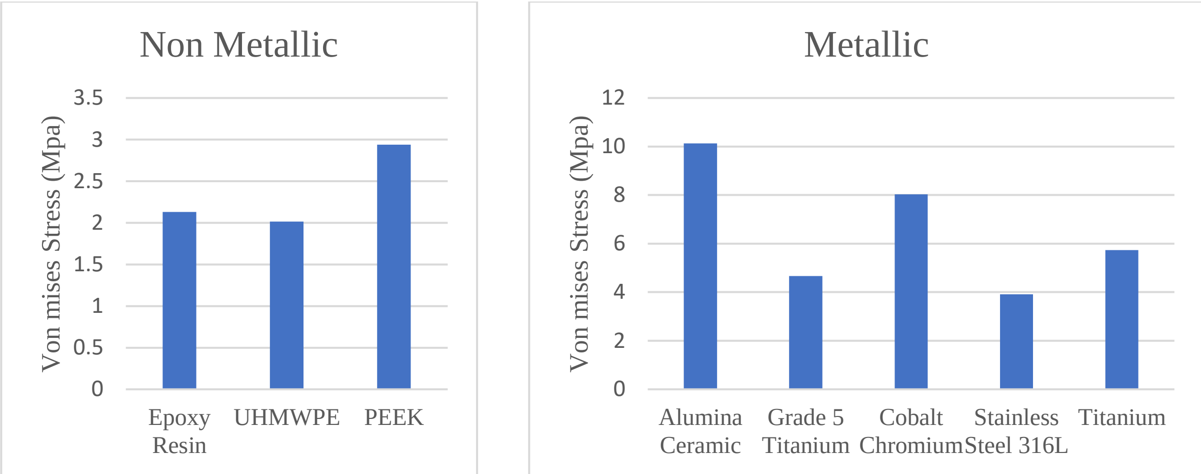



**Fig 4.3 Result comparison of Von mises stress vs Different Bio-material at 65mm diameter 45mm Sagittal Radius and $0^0$ Flexion angle**

Among the non-metallic materials, PEEK demonstrates a higher stress-handling capacity, making it potentially suitable for applications requiring better mechanical strength. In contrast, Epoxy Resin and UHMWPE are more suited for applications where moderate stress levels are acceptable. This comparison highlights PEEK's superiority in strength under stress within the non-metallic category. Alumina Ceramic can withstand the highest stress levels, making it a strong but potentially brittle material for applications requiring high mechanical strength. Cobalt Chromium and Titanium demonstrate good stress-handling capacities, suitable for applications requiring a balance of strength and toughness. Stainless Steel 316L and Grade 5 Titanium are better suited for applications with lower stress demands, where factors like corrosion resistance or biocompatibility may be prioritized over stress performance.

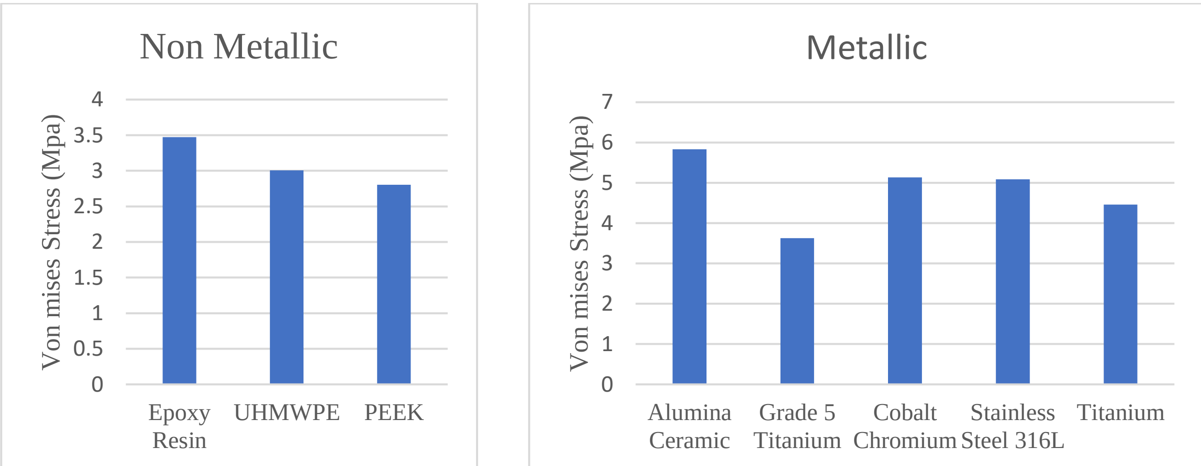



**Fig 4.4 Result comparison of Von mises stress vs Different Bio-material at 65mm diameter 50mm Sagittal Radius and $0^0$ Flexion angle**

Epoxy Resin has the highest Von Mises stress. This indicates that it is experiencing the highest level of stress among the three materials. UHMWPE has the second highest Von Mises stress. PEEK has the lowest Von Mises stress. This suggests that it is experiencing the least amount of stress among the three materials. The Von Mises stress is a measure of the overall stress state in a material. Higher stress values generally indicate that a material is under greater stress, which could potentially lead to failure if the stress exceeds the material's yield strength. Therefore, these results suggest that Epoxy Resin has the lowest strength among the three materials, while PEEK has the highest strength. The choice of material for a particular application often depends on its ability to withstand the stresses it will be subjected to. Based on these results, PEEK might be a better choice for applications where high stress is expected, while Epoxy Resin might be more suitable for applications with lower stress levels .The Von Mises stress is just one factor to consider when selecting a material. Other factors such as cost, weight, environmental resistance, and processing characteristics should also be taken into account. The specific testing conditions under which

these results were obtained should be considered when interpreting the data. For example, the stress levels may be different under different loading conditions or temperatures.
Alumina Ceramic has the highest Von Mises stress. This indicates that it is experiencing the highest level of stress among the five materials. Grade 5 Titanium has the second highest Von Mises stress. Cobalt Chromium has the third highest Von Mises stress. Stainless Steel 316L has the fourth highest Von Mises stress .Titanium has the lowest Von Mises stress. This suggests that it is experiencing the least amount of stress among the five materials .The Von Mises stress is a measure of the overall stress state in a material. Higher stress values generally indicate that a material is under greater stress, which could potentially lead to failure if the stress exceeds the material's yield strength. Therefore, these results suggest that Alumina Ceramic has the lowest strength among the five materials, while Titanium has the highest strength. The choice of material for a particular application often depends on its ability to withstand the stresses it will be subjected to. Based on these results, Titanium might be a better choice for applications where high stress is expected, while Alumina Ceramic might be more suitable for applications with lower stress levels.

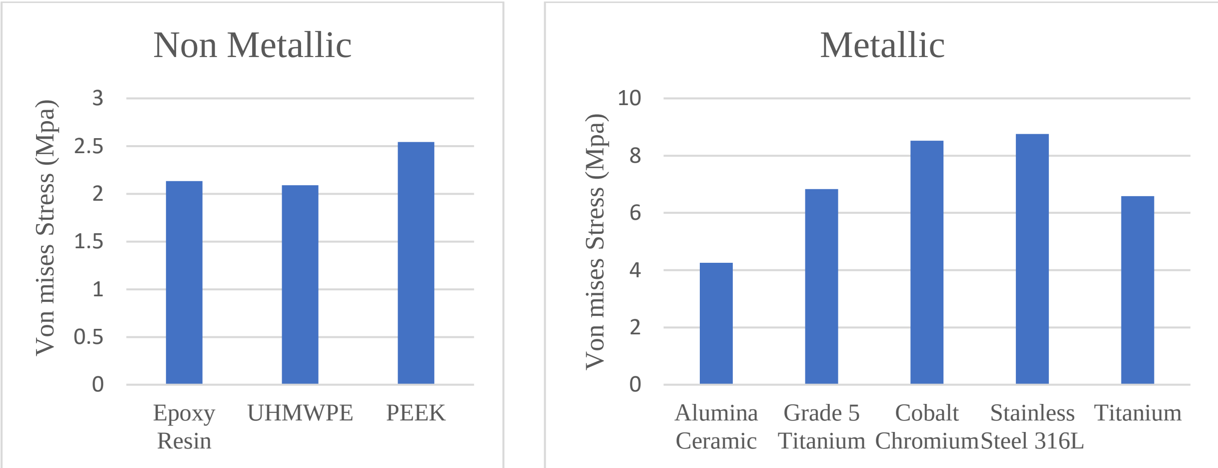



**Fig 4.5 Result comparison of Von mises stress vs Different Bio-material at 70mm diameter 45mm Sagittal Radius and $0^0$ Flexion angle**

PEEK has the highest Von Mises stress. This indicates that it is experiencing the highest level of stress among the three materials. UHMWPE has the second highest Von Mises stress. Epoxy Resin has the lowest Von Mises stress. This suggests that it is experiencing the least amount of stress among the three materials. The Von Mises stress is a measure of the overall stress state in a material. Higher stress values generally indicate that a material is under greater stress, which could potentially lead to failure if the stress exceeds the material's yield strength. Therefore, these results suggest that PEEK has the lowest strength among the three materials, while Epoxy Resin has the highest strength .The choice of material for a particular application often depends on its ability to withstand the stresses it will be subjected to. Based on these results, Epoxy Resin might be a better choice for applications where high stress is expected, while PEEK might be more suitable for applications with lower stress levels.
Alumina Ceramic has the highest Von Mises stress. This indicates that it is experiencing the highest level of stress among the five materials. Grade 5 Titanium has the second highest Von Mises stress. Cobalt Chromium has the third highest Von Mises stress. Stainless Steel 316L has the fourth highest Von Mises stress. Titanium has the lowest Von Mises stress. This suggests that it is experiencing the least amount of stress among the five materials.

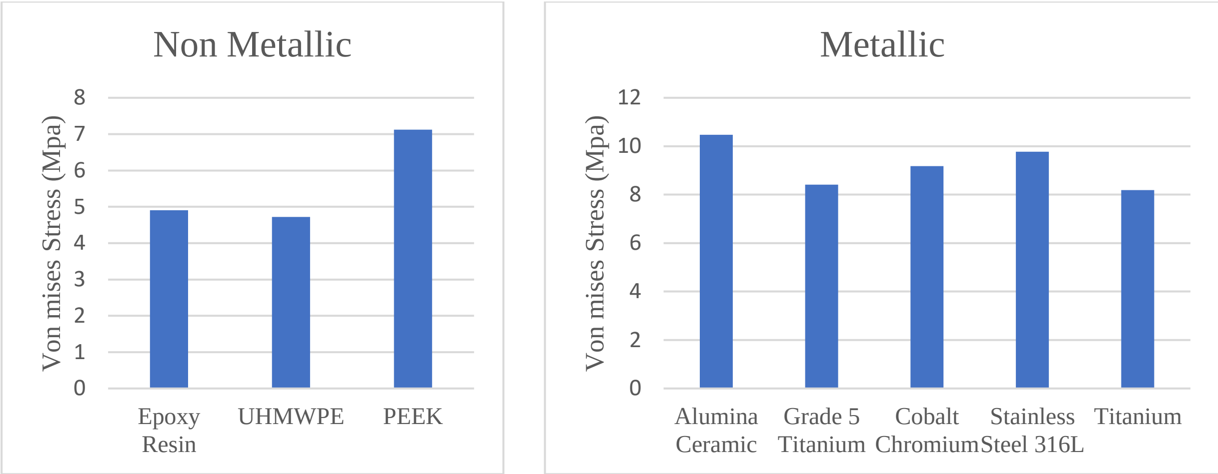



**Fig 4.6 Result comparison of Von mises stress vs Different Bio-material at 75mm diameter 45mm Sagittal Radius and $0^0$ Flexion angle**

PEEK has the highest Von Mises stress. This indicates that it is experiencing the highest level of stress among the three materials. UHMWPE has the second highest Von Mises stress. Epoxy Resin has the lowest Von Mises stress. This suggests that it is experiencing the least amount of stress among the three materials.
Alumina Ceramic has the highest Von Mises stress. This indicates that it is experiencing the highest level of stress among the five materials .Grade 5 Titanium has the second highest Von Mises stress. Cobalt Chromium has the third highest Von Mises stress. Stainless Steel 316L has the fourth highest Von Mises stress.
Titanium has the lowest Von Mises stress. This suggests that it is experiencing the least amount of stress among the five materials.

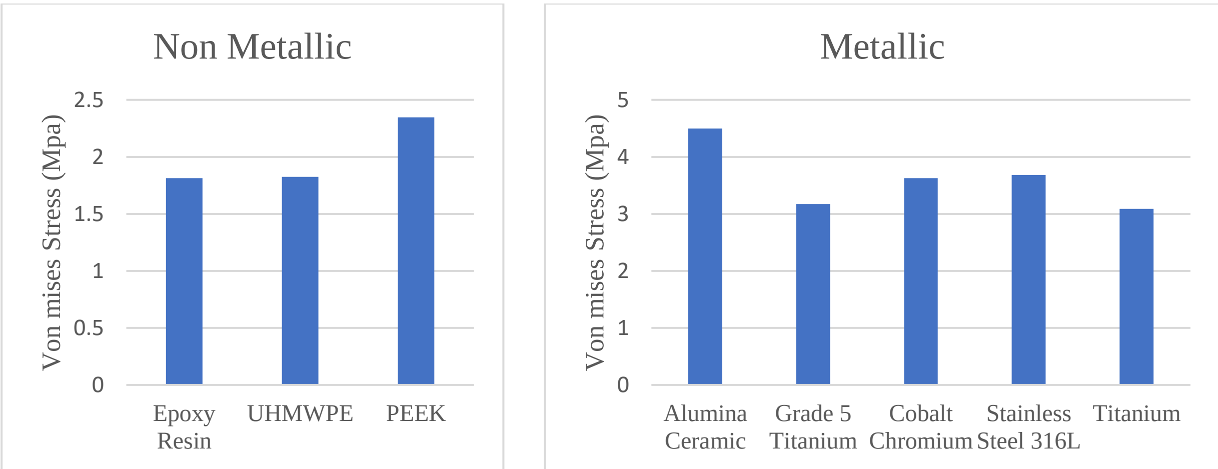



**Fig 4.7 Result comparison of Von mises stress vs Different Bio-material at 75mm diameter 50mm Sagittal Radius and $0^0$ Flexion angle**

PEEK has the highest Von Mises stress. This indicates that it is experiencing the highest level of stress among the three materials. UHMWPE has the second highest Von Mises stress.Epoxy Resin has the lowest Von Mises stress. This suggests that it is experiencing the least amount of stress among the three materials.
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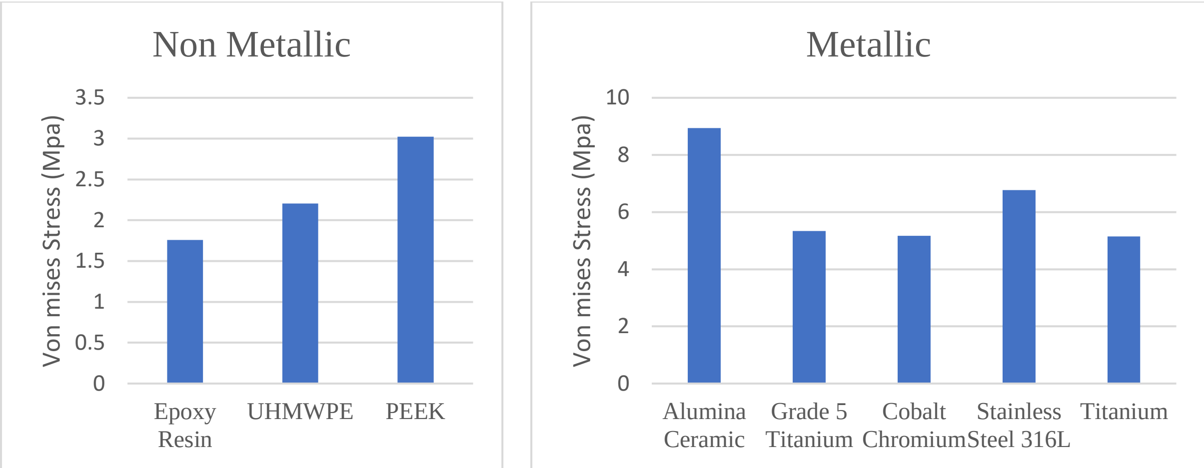


**Fig 4.8 Result comparison of Von mises stress vs Different Bio-material at 80mm diameter 45mm Sagittal Radius and $0^0$ Flexion angle**

PEEK has the highest Von Mises stress, indicating it's experiencing the most stress. UHMWPE has the second highest Von Mises stress. Epoxy Resin has the lowest Von Mises stress, suggesting it's under the least stress. Alumina Ceramic has the highest Von Mises stress. Grade 5 Titanium has the second highest Von Mises stress. Cobalt Chromium has the third highest Von Mises stress .Stainless Steel 316L has the fourth highest Von Mises stress .Titanium has the lowest Von Mises stress. Higher Von Mises stress generally indicates a material is under greater stress, which can lead to failure if it exceeds the material's yield strength. Therefore, Non-Metallic: PEEK likely has the lowest strength, while Epoxy Resin has the highest strength .Metallic: Alumina Ceramic likely has the lowest strength, while Titanium has the highest strength .For analysing the results Non-Metallic Bio-Material have less stress and Metallic Bio-material have more stress compare to non-metallic with respect same load condition

**Conclusion**

- Metallic biomaterials generally exhibit higher mechanical strength and fatigue resistance compared to non-metallic counterparts. This characteristic allows them to sustain greater loads under axial stress, making them suitable for applications requiring high durability.
- Non-metallic biomaterials, while often less strong, tend to exhibit better elasticity and ductility. Under axial loading, they may undergo significant deformation without fracturing, which can be advantageous in applications where flexibility and cushioning are essential, such as in orthopedic implants.
- The response of biomaterials to axial loading affects the stress distribution within the material. Metallic biomaterials can concentrate stresses at certain points, leading to potential failure, while non-metallic materials may distribute stresses more evenly, potentially reducing the risk of localized failure.
- Non-metallic biomaterials often demonstrate superior biocompatibility compared to metallic materials. This quality is crucial for long-term integration with biological tissues under physiological loads, influencing healing and functional outcomes in clinical applications.
- Areas with high stress concentrations in the bone surrounding the implant can lead to stress shielding.
- Identifying areas of high stress concentration allows for targeted design modifications to the implant geometry. This can include optimizing the implant shape, surface texture, and fixation mechanisms to improve stress distribution and reduce the risk of loosening.

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