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Design And Analysis of Different Artificial Human Hip Stems Based on Fenestrations Using PEEK Material

Mr. Rohith. N[1], Dr. H. C. Chittappa[2]

[1]M. Tech Student, Department of Mechanical Engineering,
University Visvesvaraya College of Engineering, Bangalore, Karnataka, India.
[2]Professor, Department of Mechanical Engineering,
University Visvesvaraya College of Engineering, Bangalore, Karnataka, India.

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Abstract - *The Hip joint is a primary joint which provides stability to the human body. These joints will be replaced by the implants during hip replacement procedures due to wear and strain brought on by ageing and other factors. Hip joint prostheses are structural parts that still struggle with complex issues including the interaction of the hip stem's physical and biological characteristics with the human femur bone. On the commercial market, there are numerous varieties of artificial hip joints. The needs of the patients can be accommodated by choosing from a variety of materials and designs. One of them is the hip stem design with fenestrations. Titanium and stainless steel are the materials that are frequently utilised in hip joint replacement. The design and analysis of complete joint replacements and other orthopaedic devices have benefited from the use of the finite element approach in orthopaedic biomechanics.*

In this work, three different types of hip stems were considered viz., hip stem with out fenestration, hip stem with bigloop fenestration and hip stem with slot fenestration were modeled using SOLIDWORKS 2018 by Dassault Systems and these hip stems were analyzed for the stress–strain distribution and deformation over the hip stem prosthesis under different loading conditions like, standing, walking, jumping and running for this we used two different materials Polyether-ether-ketone (PEEK) and Ti-6Al-4V using renowned tool ANSYS Workbench 2022 R2 version to produce the hip stem with the best design and material available.

Key Words: **Finite Element Method, Biomaterials, Hip implant, Artificial hip joint, PEEK.**

1. INTRODUCTION

A biomaterial is a material that have been produced to interact with living systems for therapaeutic (treating, improving, fixing, or changing a tissue function of the body) either diagnostic purpose. Bio-materials has been a field of study for nearly 50 years. Bio-implants, which include porous bone implants, dental implants, prostheses, wearable biosensors, and drug delivery devices, are all implants used in medical or clinical therapy. Typically, they are placed within the body of a person for more than 30 days. They integrate with the human body, the qualities of materials, and the intactness of bio-implants to fix, sustain, recreate, either to improve the function of the human tissues.

1.1 Total Hip Replacement

Hip joint replacement using artificial replacement surgery needs to be performed for patients with permanent hip joint damage due to, aging, necrosis, osteoarthritis, osteoporosis or accidents. Many patients with hip joint disease have difficulties carrying out for daily activities; thus, hip replacement surgery has become a standard method. THR is called as “Operation of Century” because it has revolutionised the treatment of a patient with advanced hip disorders. THR involves exchange of the morbid hip with a hip implant referred to as prosthesis, that is employed to transferring the load from socket to the leg bone by implanting a hip stem into the latter. Ideally, the stem area of a hip implant thought to be fully contact with the surrounding femure cortical bone to attain stable fixation during a THR. The hip implant is additionally responsible for getting the physiological load from the hip stem and transfers some amount of it to the surrounding tissues. These are the major surgical procedures, that are solely undertaken once the disease has proceeded to the stage where no different treatment is possible the aim is to alleviate pain and improve mobility [1].

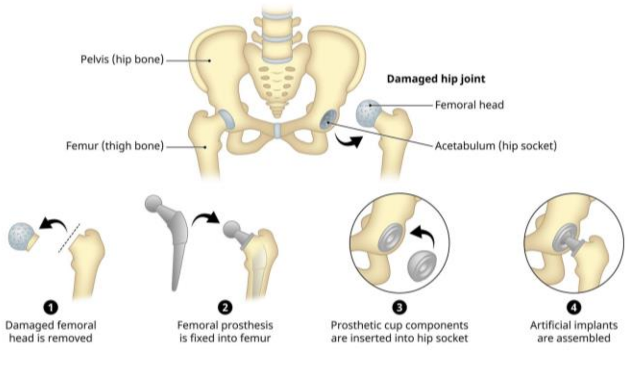


Fig. 1 Steps of Total Hip Replacement surgery

2. LITERATURE REVIEW

Solehuddin bin Shuib et al. Hip implants are prosthetic joints made of metals like titanium alloy or stainless steel. They are carried in place by lengthy stems that protrude deep into the femur canal. When a human hip joint withstands a biological injury, it is typically used. Analysis also reveals a yearly rise in the number of people who get this type of surgery, especially those who are older and fall into the 65+ age group. The objective of this study is to research hip implant advancements and to suggest a design that fully satisfies the requirements for designing a hip implant. Hip implants must take into consideration a variety of factors, including stiffness, implant characteristics, and implant size. Materials are among the most essential design considerations for a hip implant since they have a direct impact on the implant's stiffness. Titanium and stainless steel are the commonly used materials [2].

Kelechukwu Onuoha et al. The process of THR is eminent. By reducing pain and functional impairment, THR enhances the quality of life for persons with moderate to serious hip arthritis. In this analysis, only hip osteoarthritis patients were included. It was simple to identify osteoarthritis as an indication for the surgery because research also shown that arthritis was a common reason for THR. 71.4 % of the patients in this work were found to be older than 50 years [3].

Manuel Guzman et al. The femoral head and the hip stem are the two primary parts of the prosthesis utilized in THR. SS 316L, Ti alloys (Ti-6Al-4V and TMZF), and Co-Cr alloys are the most commonly utilized metal alloys for these components, despite the fact that they are prone to loose particles. These materials after implanted, plays a crucial role in the distribution of stress and strain because their high elasticity modulus which is greater than that of human bone. The requirements for a hip implant's design are complicated because there are so many factors to be taken into an account, including the patient's age, the geometry of the implant, the bone structure, and the biocompatibility of the material. All of these factors have an impact on how much stress and strain the implant will experience. One way to avoid future complications, including aseptic loosening or implant fracture, is to modify the shape of an existing prosthesis or use an ideal biomaterial [4].

Anthony L. Sabatini et al. This article reevaluated a number of hip stems. For all the stems, FE Analysis was carried out using different cross-sections. In addition to recording the displacement, von-Misses stress comparisons were performed for each of the stems at the predetermined places. The analysis was conducted using three materials: Ti-6Al-4V, SS316L, and Cr-Co-Mo. Ti-6Al-4V showed less stress than the other two materials. The circular and eliptical cross-sections shaped even distribution of stresses throughout the length of the hip stem than the other cross-sections viz.; trapezoid and oval. This analysis could clarify the scenarios that should be avoided for hip implants that need stress shielding. For total hip replacements, additional anatomical designs are required [5].

M. Paglia et al. PEEK is a polyaromatic semi-crystalline thermoplastic polymer which was first developed for engineering applications by Victrex PLC in the early 1980s. It was initially made available for industrial use in the production of bearings, compressor plate valves, cable insulation, turbine blades, piston parts, and aircraft. PEEK is a polymer that is organic and colourless that is a member of the PAEK (polyaryl-ether-ketone) family. A single monomer makes it a homopolymer. This thermoplastic semi-crystalline polymer retains its outstanding chemical and mechanical characteristics even at elevated temperature. PEEK is stable at high temperatures due to its chemical compositions and structure, which facilitates simple manufacturing of PEEK implant components. When subjected to heat sterilising processes, PEEK is resistant to degradation. Due to its excellent thermal characteristics, superior wear resistance, great processability, inertness, corrosion resistance, high strength, and elastic modulus, PEEK is widely employed in both medical and engineering fields. In fact, it has an elastic modulus that is identical to human bone, indicating uniform stress distribution to the tissues around it. PEEK is a non-toxic, non-mutagenic substance that is extremely compatible with the tissues in its surrounding environment. As a result, it may be the perfect replacement for those who are allergic to titanium and other metals. PEEK has a more aesthetically pleasing appearance and doesn't have a metallic tone it seems beige with a hint of grey [6].

Jiaqi Zhang et al. Skull deformities are treated through cranioplasty, which involves raising the scalp and reshaping the skull with the original piece, titanium mesh, or solid biomaterial. Medical practitioners are increasingly using additive manufacturing technology, often known as 3D printing, to create specialized, replicas of tissues, organs, and bones, providing a viable solution with ideal anatomic fitting in the individual and skeletal reconstruction. Here, we analyze a patient from 15 years ago that had titanium mesh cranioplasty. The left eyebrow arch was weakened by the titanium mesh's unsightly appearance, which also caused a sinus tract to develop. An additively produced polyether ether ketone (PEEK) skull implant was used during cranioplasty. PEEK skull implants have been inserted successfully without any issues. To our information, this is the 1st reported case of direct use of fused filament fabrication (FFF) fabricated PEEK implant for cranial repair. The FFF-printed PEEK customized skull implant can possess simultaneously with adjustable material thickness and more complex structure, tunable mechanical properties, and low processing cost compared to traditional manufacturing processes [7].

3. PROBLEM IDENTIFICATION

At present in medical field Titanium alloys, Stainless steel and Co-Cr alloy materials are been used for the artificial human hip stems. These materials have good mechanical and physical properties, they are very strong in nature. But the stiffness / elastic modulus of these materials are too much high when compared with the bone properties, due to this when the load applied on the hip joint the maximum load will be on the implant. When hip implant carries more load than the femur bone then there will be a wear between bone and the implant this effect is called as shield stressing, by this it gets loosen very quickly before its life span. Also, weight of the implant is more. Increases in bone porosity. Decrease in bone mass. There will be a magnetism effect and anode-cathode reactions.

4. OBJECTIVES

- To design for development of an artificial human hip stems based on fenestration using CAD modelling software i.e., SOLIDWORKS 2018.
- To perform FEA for all different types of fenestrated artificial human hip stems for Polyether–ether–ketone (PEEK) and Ti-6Al-4V materials under different conditions such as standing, walking, jumping and running using ANSYS Workbench 2022 R2.
- Results of the three different hip stems with PEEK and Ti-6Al-4V materials will be compared and one of the best will be suggested.
- To reduce the weight of human hip implant by using PEEK material instead of Titanium alloys, Stainless steel and Co-Cr alloy.
- To improve the strength, corrosion resistance and wear resistance of the hip stem by this stress shielding can be prevented.

5. METHODOLOGY

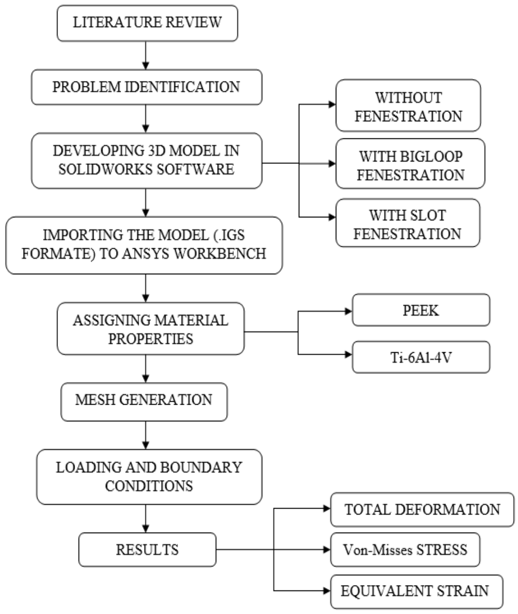


Fig. 2 Methodology flow chart

6. DESIGN AND ANALYSIS OF HIP STEMS

The CAD models have to be created in the computer environment. Here we designed a Hip Replacement of each different parts, the dimensions of each part is collected from previous record. SOLIDWORKS 2018 have been used in the modeling process.

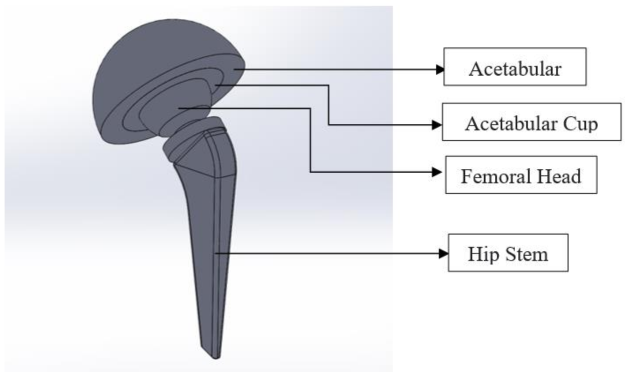


Fig. 3 Isometric view of hip implant

6.1 Different types of fenestration designs

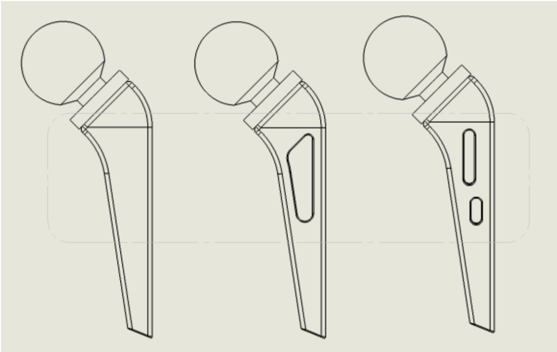


Fig. 4 Types of fenestration

For hip replacement, artificial hip joints come in a variety of designs and shapes. Three different hip joint designs were used in this study, as shown in Fig. 4: a hip stem without fenestration, a hip stem with a big loop fenestration, and a hip stem with a slot fenestration [8]. The only difference in dimensions was fenestration. PEEK and Ti-6Al-4V were both employed as the materials. Materials were chosen for their high biocompatibility, durability, resistance to wear and corrosion, and strength. The material was thought to be uniform, isotropic, and linearly elastic.

7. RESULTS AND DISCUSSION

The final model was assembled in SOLIDWORKS and imported to ANSYS Workbench software in .IGS format and the analysis is carried out in Static structural. So in this project we are going to consider three different types of hip stem designs namely, hip stem without fenestration, hip stem with big loop fenestration and hip stem with slot fenestration. Further these hip stems should be analyzed for different loading conditions like, standing, walking, jumping and running. Then comparing the results of PEEK material with commonly used Titanium based alloy Ti-6Al-4V for all these hip stems. The mechanical property of these materials is given below Table 1.

Sl.No	Materials	Young's Modulus (GPa)	Density (kg/m³)	Poisson's ratio	Yield strength (MPa)
1	PEEK	3.95	1320	0.3931	170
2	Ti-6Al-4V	120	4430	0.34	900

Table 1 Mechanical properties of the materials used for hip stems [9]

We are going to use some different activities like standing, walking, etc. So the stress analysis on a hip prosthesis during various patient activities, such as standing, walking, jumping as well as in running. These loads are considered according to Aftab S et al. [10] on a patient who weighs 75 Kg, with an age group of around 35 years. Due to the symmetry of the human body, when a person is standing, their weight will be distributed evenly between their two legs. For this reason, the weight was divided in half and boundary conditions were applied to the finite element model. The analysis was performed under the assumption that the subject was standing normally, with a load of 370 N applied to the head of the femur at the hip joint and the hip stem fixed when in contact with the femoral bone. Similar to this, the hip stem was examined under a variety of situations derived from various human everyday activities, such as jumping, where a force of 750 N acting on one leg was applied, for walking an additional 800 N was applied, and running, where a load of 1463 N was applied. Also shown in the Table 2.

Table 2 Loading conditions of hip joint for different daily activities [10]

Activity	Maximum Load (N)
Standing	370
Walking	800
Jumping	750
Running	1463

The following Fig. 5 shows the meshing process which chosen to be 1mm element size.

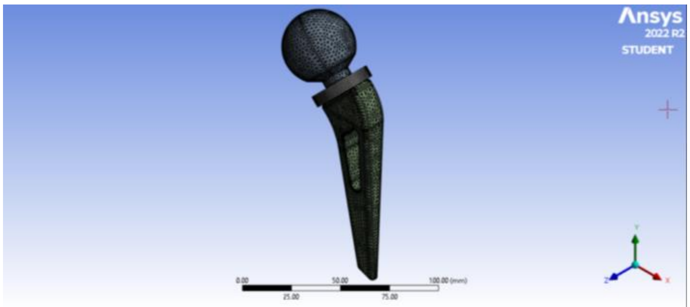


Fig. 5 Meshing process

Table 3 Number of Elements used in analysis

Element size: 1mm

Types of hip stem	Nodes	Elements
Without fenestration	77915	32325
With big loop fenestration	86111	36782
With slot fenestration	89874	39068

The below Fig. 6 indicates the fixed/support condition to the hip implant.

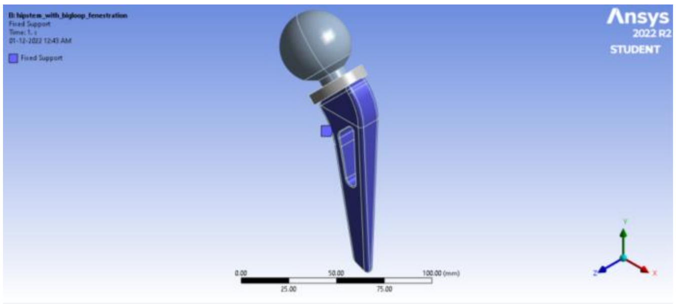


Fig. 6 Support condition

The Fig. 7 shows the applying of loading conditions which are mentioned in the Table 2. The force of 370 N magnitude is applied along the -y direction as shown in the following figure.

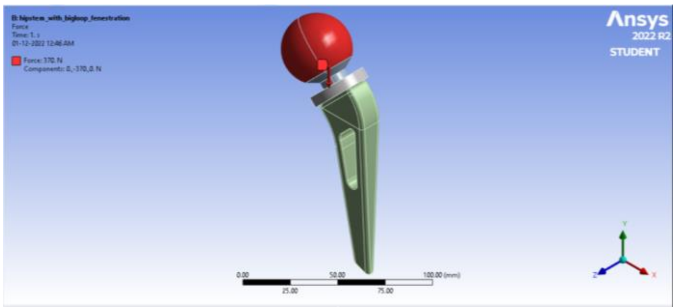


Fig. 7 Applying the load

7.1 Computational Results

7.1.1 Masses of the different types of fenestrated hip stems

These below mentioned masses are taken from the SOLIDWORKS software by applying the material properties of the PEEK and Ti-6Al-4V for the different hip stem designs.

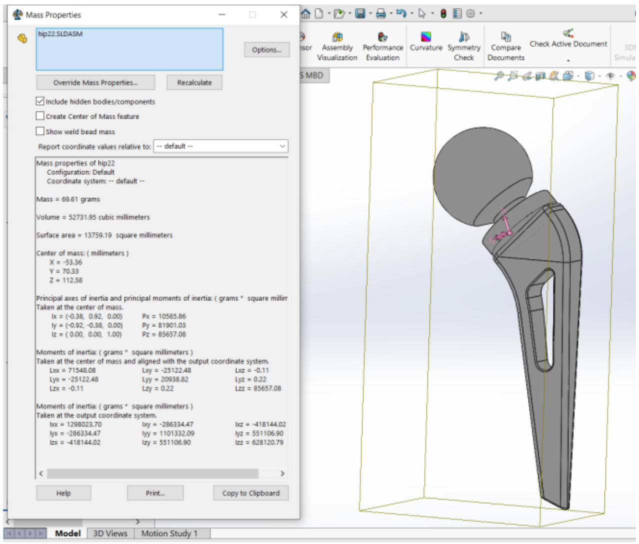


Fig. 8 Mass of the hip stem **with big loop fenestration** for **PEEK** material

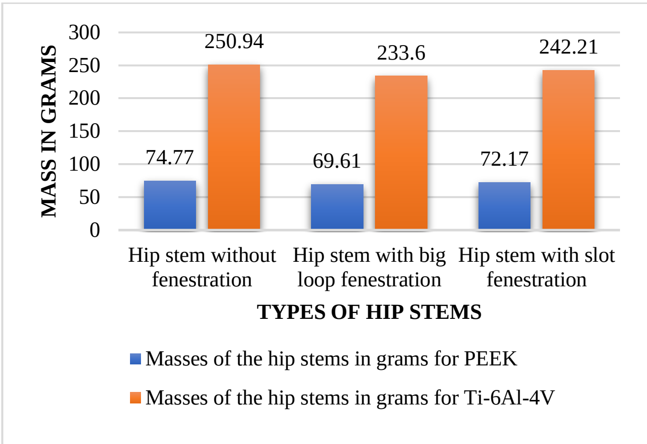
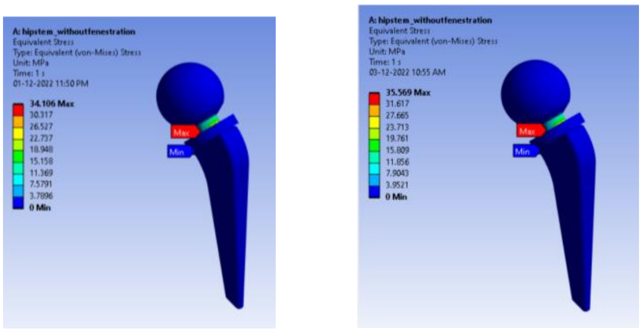


Fig. 9 Comparison of masses for different types of hip stem

7.1.2 Standing condition (370 N)

The Fig. 10(a) refers to Von-misess stress produced in the hip stem without fenestration under standing condition when PEEK material is applied to the hip stem which is 34.106 MPa, which is similar for the remaining fenestrations.

The Fig. 10(b) refers to Von-misess stress produced in the hip stem without fenestration under standing condition when Ti-6Al-4V material is applied to the hip stem which is 35.569 MPa, which is similar for the remaining fenestrations.



(a) (b)

Fig. 10 Hip stem without fenestration under standing condition for **PEEK** and **Ti-6Al-4V** material

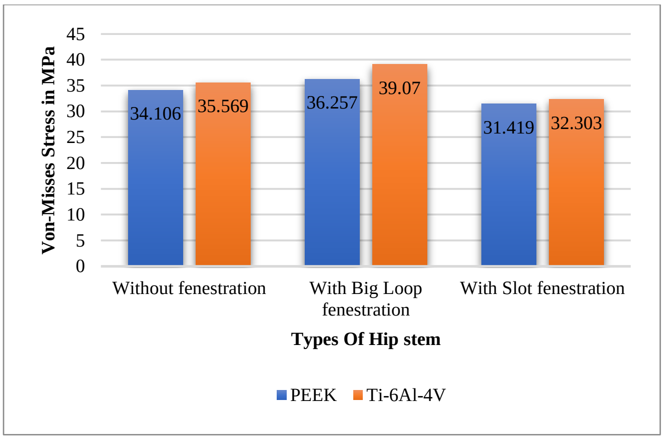


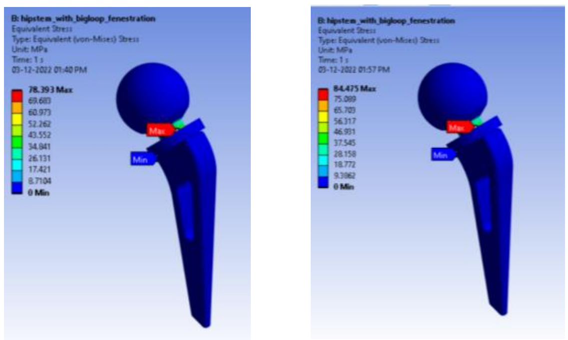
Fig. 11 Comparison of Von-Misses stress under Standing condition

From Fig. 11 the von-misses stress of hip stem with slot fenestration for PEEK material is least when compared to others in standing condition.

7.1.3 Walking condition (800 N)

The Fig. 12(a) refers to Von-misess stress produced in the with bigloop fenestration under walking condition when PEEK material is applied to the hip stem which is **78.393 MPa** which is similar for the remaining fenestrations.

The Fig. 12(b) refers to Von-misess stress produced in the hip stem with bigloop fenestration under walking condition when Ti-6Al-4V material is applied to the hip stem which is **84.475 MPa** which is similar for the remaining fenestrations.



(a) (b)

Fig. 12 Hip stem with big loop fenestration under walking condition for **PEEK** and **Ti-6Al-4V** material

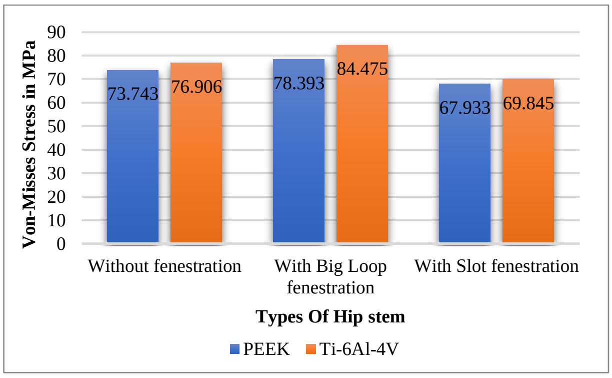


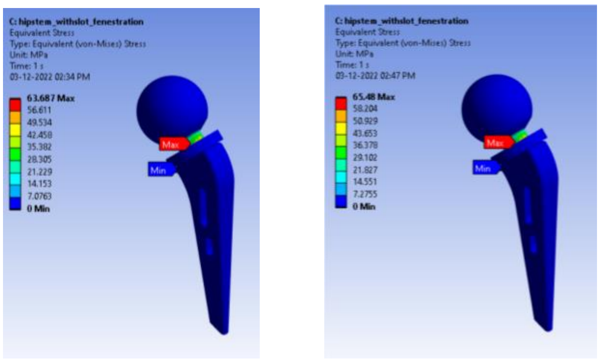
Fig. 13 Comparison of Von-Misses stress under Walking condition

From Fig. 13 the von-misses stress of hip stem with slot fenestration for PEEK material is least, when compared to others in walking condition.

7.1.4 Jumping condition (750 N)

During jumping with the both legs 750 N load will be applied on one leg. The Fig 14(a) refers to Von-misess stress produced in the hip stem with slot fenestratation when PEEK material is applied to the hip stem which is **63.687 MPa,** which is similar for the remaining fenestrations.

The Fig. 14(b) refers to Von-misess stress produced in the hip stem with slot fenestratation when Ti-6Al-4V material is applied to the hip stem which is **65.48 MPa,** which is similar for the remaining fenestrations.



(a) (b)

Fig. 14 Hip stem with slot fenestration under jumping condition for **PEEK** and **Ti-6Al-4V** material

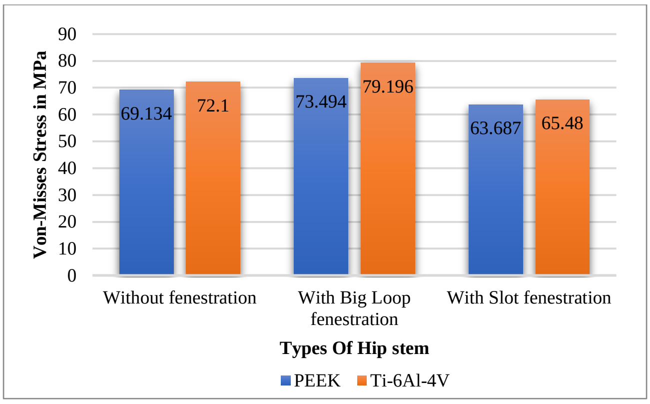


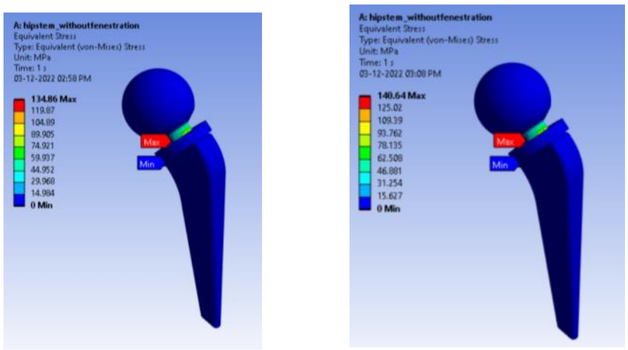
Fig. 15 Comparison of Von-Misses stress under Jumping condition

From Fig. 15 the von-misses stress of hip stem with slot fenestration for PEEK material is least, when compared to others jumping condition.

7.1.5 Running condition (1463 N)

The Fig. 16(a) refers to Von-misess stress produced in the hip stem without fenestration under running condition when PEEK material is applied to the hip stem which is **134.86 MPa,** which is similar for the remaining fenestrations.

The Fig. 16(b) refers to Von-misess stress produced in the hip stem without fenestration under jumping condition when Ti-6Al-4V material is applied to the hip stem which is **140.64 MPa,** which is similar for the remaining fenestrations.



(a) (b)

Fig. 16 Hip stem without fenestration under running condition for **PEEK** and **Ti-6Al-4V** material

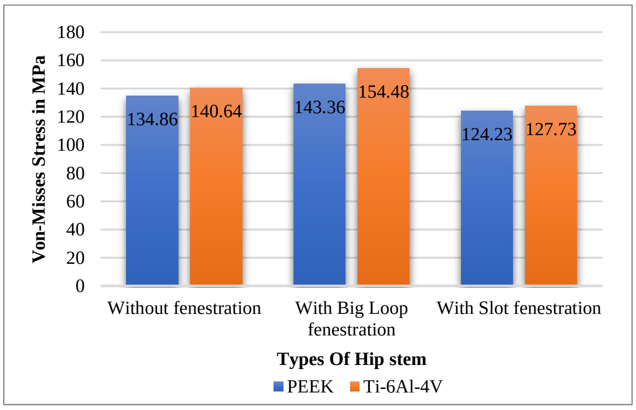


Fig. 17 Comparison of Von-Misses stress under Running condition

From Fig. 17 the von-misses stress of hip stem with slot fenestration for PEEK material is least, when compared to others in running condition.

8. CONCLUSION

In this work, three hip stem designs, namely without fenestration, with bigloop fenestration and with slot fenestration designs were modeled. For all designs, two materials PEEK and Ti-6Al-4V was used. PEEK is used because it as the similar stiffness as human femur bone and it as good wear properties, low moist absorption, low co-efficient of friction etc. All of these designs, which use materials with various physical properties, will be put through the rigours of daily activities like standing, walking, jumping, and running. Static structural analysis was carried out using ANSYS Workbench with the application of the loading boundary condition as per the work by Aftab S. et al. All three designs were found to suggest lower stress levels than the yield strength. Also, in these three designs for PEEK and Ti-6Al-4V materials under different loading conditions, the artificial human hip stem with slot fenestration for PEEK material has lesser Von-Misses stress under all different loading conditions as mentioned above. Ti-6Al-4V has less deformation when compared to PEEK material for all the designs which were modeled in the current work. It is observed that for all the designs under different loading conditions the von-misses stress is almost similar for PEEK and Ti-6Al-4V material. Also, weight of the PEEK material is lesser than the Ti-6Al-4V. So, PEEK material with slot fenestration can be suggested.

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