



Static structural analysis of different stem designs used in total hip arthroplasty using finite element method



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ABSTRACT

Background: The Hip joint is the primary joint which gives stability to the human body. The wear and tear associated with age and other factors, require these joints to be replaced by implants using hip arthroplasty surgeries. Cobalt chromium alloy (CoCr), titanium alloy, stainless steel are some of the most common hip joint materials used for hip implants. The design requirement for hip joint implants are very stringent to avoid revision joint surgeries due to aseptic loosening. There are various choices in shapes and materials used for stem and acetabular designs. This makes it more difficult to make an informed decision on the type of design and material that can be used for hip implants.

Methods: Circular, Oval, ellipse and trapezoidal designs with three individual cross sections (defined as profile 1, profile 2 and profile 3) are considered for the study. All models are modeled using CATIA V-6. Static structural analysis is performed using ANSYS R-19 to arrive at the best possible design and material combination for stem and acetabular cup.

Results: It was found that, profile 2 of all the four designs has the lowest possible deformation and von Mises stress when compared to profile 1 and profile 3. In general, profile 2 with trapezoidal stem has best outcomes in terms of its mechanical properties. Besides, stem designed with material CoCr and its associated acetabular cup with CoC (ceramic on ceramic) material can produce an implant having better properties and longer durability.

Conclusions: CoCr was found to be the preferred choice of material for stem design. It was also observed that, irrespective of material considered for the analysis profile 2 with trapezoidal stem showcased lesser deformation and von Mises stress over the other eleven models. For analysis involving acetabular cups, CoC implants exhibited better mechanical properties over the conventional CoPE (Ceramic on polyethylene) materials such as Ultra-high molecular weight polyethylene (UHMWPE). It is inferred from the findings of this study that, the profile 2 with trapezoidal stem design made of CoCr material and acetabular cup made of CoC material is best suited for hip joint implants.

1. Introduction

The importance of hip can be summarized by the fact that it facilitates human movement and supports entire body weight without causing any pain [1]. The hip joint consists of femoral head which is attached into the acetabulum [2]. The total hip joint arthroplasty is performed to reduce pain and induce normal movement in cases of wear and tear of the joints [3]. Sir John Charnley was the pioneer in the advancement of total hip replacement in early 1960 and recent advances in hip material has made it a popular alternative [4, 5]. Two types of stems namely modular and non-modular are

frequently used. Both stems are identical except the modular neck stem has a separate neck piece that allows for 60 different options for head center. Whereas the non-modular neck has only 10 options [6, 7]. In addition to design, many types of materials are used to make these implants [8, 9]. The materials used in hip implants such as cobalt chromium alloy, titanium alloy, stainless steel are popular because of their biocompatibility property [10]. The basic requirement of materials is that, it should be biocompatible and produce less wear rate so that chances of revisions are avoided due to aseptic loosening of implants [11]. Aseptic loosening is the major problem leading to the revision of joints post-surgery [12, 13].

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Finite element analysis (FEA) is very popular tool used to analyze the behaviors of the any models which are developed [14]. Anthony et al. [15] re-evaluated the hip joint designs by using FEA. Circle, ellipse, oval, trapezoidal designs were modelled using solid works. Three materials namely Co–Cr–Mo, Stainless Steel SS316L, and titanium alloy (Ti–6Al–4V) were considered. The analysis was carried out for all the stems to determine their von Mises stress and displacement. The load was applied on femoral head. The lateral condyle and some portion of greater trochanter was fixed [16]. Jiang et al. [17] considered four different models of hip implants. UHMWPE, CoCrMo alloy, 316L stainless steel and Ti–6Al–4V alloy were considered in this study. Using finite element method mechanical characterization was carried out under static and dynamic conditions. The strain and stress distribution across the implants and deformation were observed in all the models. In the first model acetabular cup was considered as UHMWPE along with metallic femur head. In the second model a metallic backing cup covers the UHMWPE acetabular cup. In the third model a layer of artificial cartilage covers the femoral head. The fourth model was identical to the third model except the acetabular cup made up of UHMWPE is covered by metallic cup. A 28mm diameter femoral head was considered along with acetabular cup of 8mm thickness. They observed that cartilage layer distributes the load which resulted in reduction of the peak stress and deformation in the implants. Finally, they concluded that mechanical properties of the model with artificial cartilage layer and a Ti–6Al–4V cup are the best among the four models. Zafer et al. [18] investigated the static, dynamic and fatigue behavior of Ti–6Al–4V and cobalt–chromium metal materials and compared the stem shape developed by Charnley. Four different stems with varying surface curvatures straight, notched, notched and curved shapes were considered for the study. They found that all the stems were safe against stress conditions imposed. Notched stem made of Ti–6Al–4V was the best among all remaining models under both static and dynamic conditions.

Yan et al. [19] studied the effect of a porous titanium femoral prosthesis on bone remodeling. In this study implants made of solid titanium and solid cobalt–chrome, porous titanium with different prosthesis were evaluated. The elastic modulus of prosthesis strongly influence the bone loss around the implant. They also inferred that the volume of bone with density will decrease if instead of porous titanium implant, cobalt–chrome implant was used. The numerical study also showed that the increase in the porosity will lead to a linear decrease in both the volume and density of bone. It was also determined that the strength of porous titanium decreased with increase in the porosity. In another study, Bah et al. [20] applied the load on the center of femoral head with the joint reaction force acting on greater trochanter. Horak et al. [21] The hip joint computational model was loaded using force and kinematic conditions, which were implanted into the center of rotation of the femur head. Contact was modelled between the femoral head and the acetabulum as a normal contact with a friction coefficient $f = 0.08$. Mangesh et al. [22] followed the ISO 7206–4 and ASTM F2996–13 static loading boundary conditions. There is clear lack of uniformity in the type of boundary conditions applied and the type of design and/or material that would be best suitable for hip joint prosthesis.

In this work, four shapes namely circular, ellipse, oval and trapezoidal are modelled with three different profiles. Finite element method is used to carry out static analysis is on all the twelve models using ANSYS R-19. Boundary conditions are considered according to the ASTM standards. Ti–6Al–4V and CoCr alloys are the widely used materials in the hip implant stems [23]. Both materials are evaluated along with different designs to find the best suited materials which can be used for hip stems. The first part of the study involves the modeling and analysis of stems which is a basic component in total hip arthroplasty. Next a combination of stem, acetabular cup, femoral head and backing cup are analyzed to find the best suited complete hip implant.

2. Materials and methods

Several types of designs are popularly used in the total hip arthroplasty. The shape and profile are the important parameter in the design of the stem. In this study, circular, oval, ellipse and trapezoidal shapes as shown in Fig. 1 are considered in the analysis. Fig. 1 also shows the changes in the cross sections of the stem and defined as profile 1, profile 2 and profile 3. In profile 1, a straight stem with radius on lateral side near the proximal end is considered. The arc length and diameter of the profile 2 is increased along with the total angle between the medial and lateral faces. In profile 3, a cornered shoulder replaces the radius on the lateral side. The neck and medial side dimensions are constant in all the three designs. In total, twelve designs are modeled using CATIA V-6 as non-modular implant stems. These models are subjected to static structural analysis using ANSYS R-19 to evaluate the von Mises stress, deformation in load acting direction and total deformation. The material properties considered in this study are represented in Table 1.

2.1. Meshing & boundary conditions

The models were meshed using unstructured mesh. The mesh independency study carried out resulted in the selection of optimal mesh size for the analysis. In this work, the circular shaped profile 1 stem was considered for mesh dependency. Several mesh size was developed by varying the mesh size from 5mm to 0.25mm [22]. The result of different mesh size in terms of stresses developed are presented in Fig. (2a). It can be seen that the stresses increase significantly as the mesh size is reduced 1mm from the initial size of 5 mm. Beyond the mesh size lesser than 1mm, there is no major changes in stresses for subsequent mesh size. Thus the mesh size of 1 mm was adopted for the analysis of all the models in this work. The total number of elements and nodes obtained in modeling of various implants were approximately 675, 000 nodes and 495,000 elements.

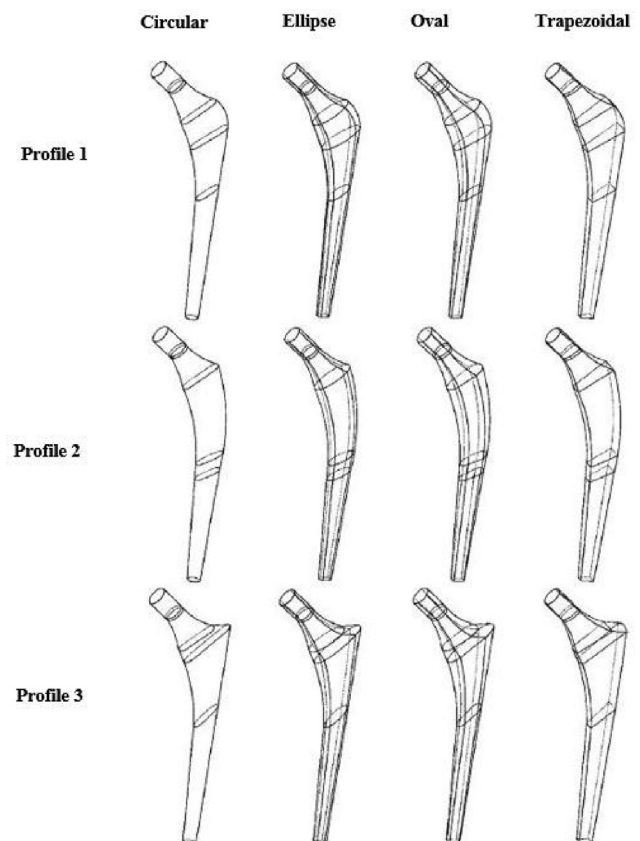


Fig. 1. The different stem designs used for the study.

Table 1
Mechanical properties of the materials used for stems [24].

Sl	Materials	Young's modulus [GPa]	Density [gm/cm ³]	Poisson's ratio	Ultimate Tensile strength [MPa]
1.	Ti-6Al-4V	114	4.5	0.31	930
2.	CoCr Alloy	200	8.5	0.30	1503

The boundary conditions are applied as per the ASTM F2996-13 and loading conditions are considered as per ISO 7206-4:2010(E) [25]. According to the standards, the modelled stems are bisected into three cross sections from the top surface of the stem. The hip stem is sectioned from the center of head as per the ISO 7206-4:2010(E) with the worst-case head/neck offset. This section from the center of head helps represent the stress distribution over the implant. A second section was made 10 mm below the first cut. The hip stem was constrained in all directions on all faces distal to the second cut. Constraining the stem in this manner ensures that excessive erroneous stresses are not generated at the region of interest due to the influence of rigid fixation. The fixation of the stem and the load application is as shown in Fig. 2(b). Static structural analysis is carried out for all the twelve designs by enforcing identical boundary conditions.

3. Results

A preliminary study is carried out on all the models to arrive at the best suitable design for stem implant. The commercially available

implants are made of cobalt chromium (CoCr) or Ti-4Al-6V materials. The 12 designs are analyzed for the implants made of CoCr and Ti-4Al-6V materials at uniform loading of 2300 N. The results for CoCr alloy are compiled in Table 2. It was observed from Table 2 that, profile two exhibited less deformation compared to other two profiles in all the four different shapes. Fig. 3 shows the contour plots of von Mises stress, deformation and strain for stem with oval design.

Similar analysis is performed with the Ti-4Al-6V material and the results are tabulated in Table 3. Table 3 shows that stems with materials Ti-4Al-6V produced higher deformation values in all the models when compared to the deformation obtained when CoCr alloy was used (Table 2). Fig. 4 shows the deformation, von Mises stress and elastic strain for trapezoidal stem with materials properties of Ti-4Al-6V.

From the analysis carried out in Table 2 & Table 3, it was found that the trapezoidal shapes showcased least deformation and lowest von Mises stress irrespective of the material used for stem design. Another important observations was that, the hip stem with CoCr material exhibited lower deformation values when compared to Ti-6Al-4V. Therefore, it can be established that, the stem with CoCr would perform better than Ti-6Al-4V alloy.

The next stage of analysis involved the combination of stem made of CoCr (based on the findings from Tables 2 and 3) along with its acetabular components. The acetabular cup is fitted to the head with a constant thickness of 4mm which is further covered with a metal backing cup having a thickness of 2mm. The material combination is defined as

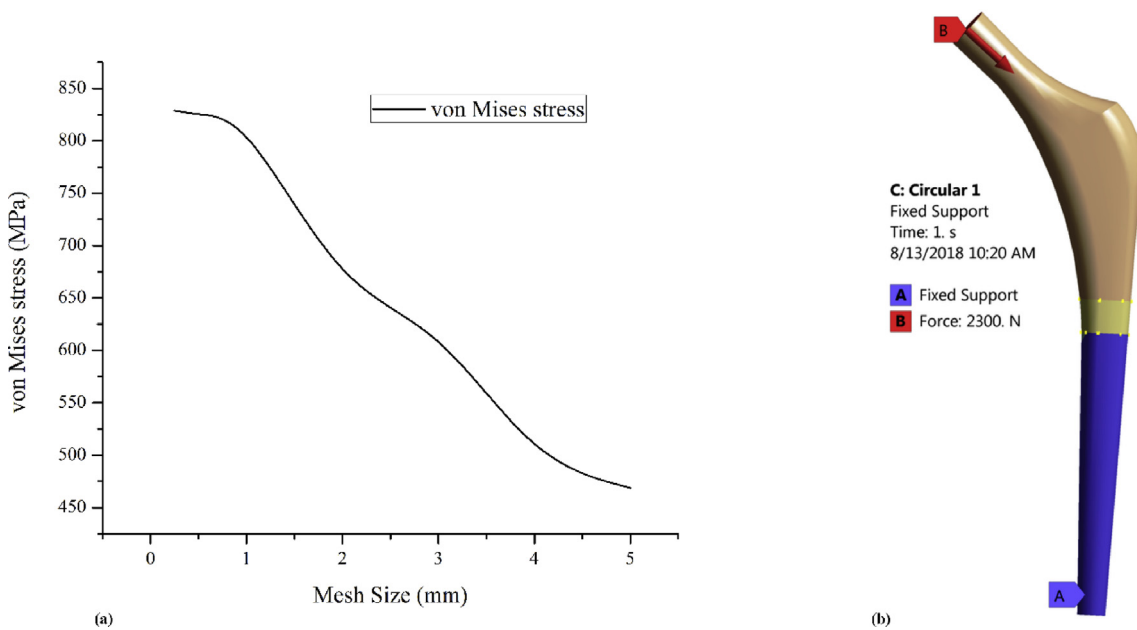


Fig. 2. (a) Variation of the stress values with a change in mesh size; (b) Boundary conditions considered as per ASTM F2996-13 standards.

Table 2
Static analysis of hip stem as per the ASTM F2996-13 standards using CoCr alloy.

Sl.	Stem Material	Shape	Profile	Load in N	Total deformation in mm	Equivalent von Mises stress in MPa	Equivalent strain in mm/mm
1.	CoCr alloy	Circular	Profile 1	2300	0.397	834.18	0.0043
2.	CoCr alloy		Profile 2		0.234	616.98	0.0030
3.	CoCr alloy		Profile 3		0.396	893.4	0.0045
4.	CoCr alloy	Ellipse	Profile 1	2300	0.422	923.73	0.0046
5.	CoCr alloy		Profile 2		0.257	665.35	0.0033
6.	CoCr alloy		Profile 3		0.441	1034.2	0.0051
7.	CoCr alloy	Oval	Profile 1	2300	0.411	816.93	0.0042
8.	CoCr alloy		Profile 2		0.245	540.1	0.0027
9.	CoCr alloy		Profile 3		0.418	868.8	0.0044
10.	CoCr alloy	Trapezoidal	Profile 1	2300	0.275	777.21	0.0038
11.	CoCr alloy		Profile 2		0.171	422.28	0.0021
12.	CoCr alloy		Profile 3		0.280	623.48	0.0031

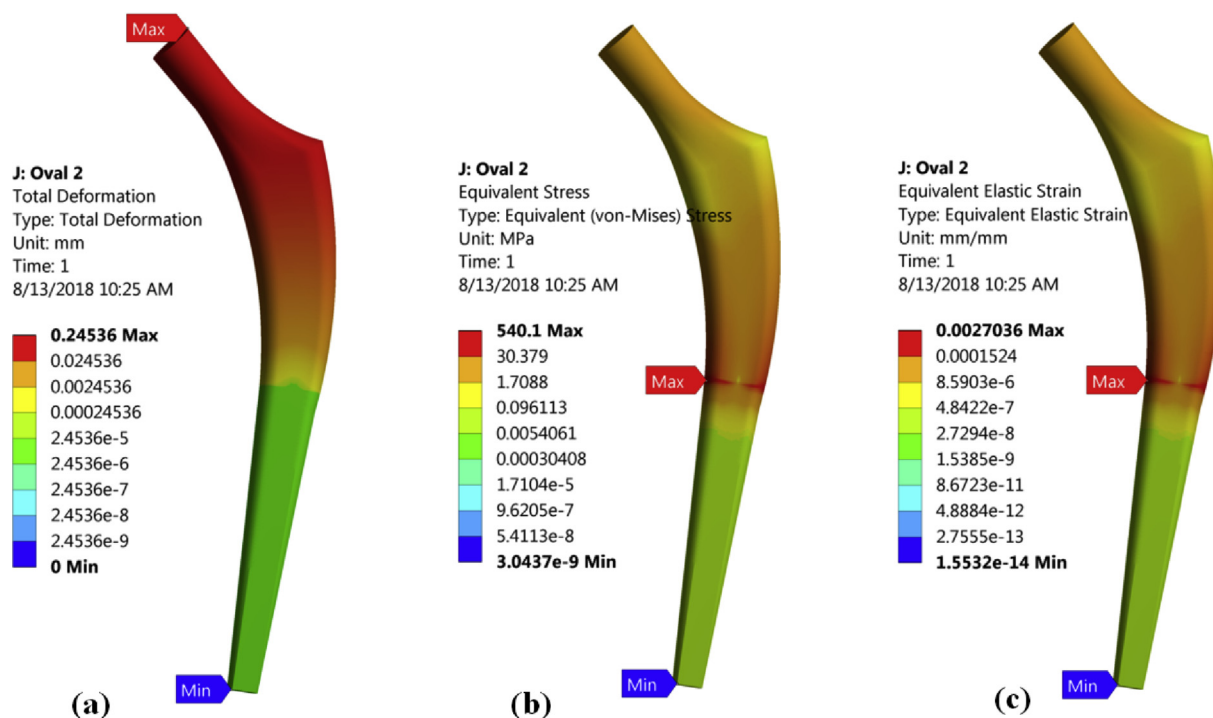


Fig. 3. Oval Profile two: (a) Total Deformation, (b) von Mises Stress, (c) Elastic strain.

CoCr material for hip stem, femoral head, and backing cup (thickness of 2mm). The acetabular liner of thickness 4mm was investigated for 2 materials which are CoCr [CoC implants] and UHMWPE [CoPE implants] [26, 27, 28, 29]. Two different combination of materials are considered for the study namely CoC (ceramic on ceramic) and CoPE (ceramic on polyethylene).

The boundary conditions are taken as per ASTM F2996-13 standards [25]. A load of 2300 N is applied from the metal backing cup and the stem below the 90mm from the center of femoral head is fully constrained as fixed support. Fig. 5 shows the boundary conditions applied on the hip implant. The stem is fitted with femoral head, the size of which varies from patient to patient, and usually in the range from 22mm to 36mm [30, 31]. In the present study, the femoral head size for all the models is considered as constant of size 28mm. Static structural analysis is performed on all the twelve designs with acetabular components to identify the best materials combination suitable for implants.

The results of the static structural analysis carried out for material combination of CoPE as Acetabular liner and Hip stem, Femoral head, backing cup with thickness of 2mm made of CoCr are presented in Table 4.

It can be inferred from Table 4, that the trapezoidal profile 2

Table 3
Static analysis of hip stem as per the ASTM F2996-13 standards using Ti-4Al-6V.

Sl.	Stem Material	Shape	Profile	Load in N	Total deformation in mm	Equivalent von Mises stress in MPa	Equivalent strain in mm/mm
1.	Ti-4Al-6V	Circular	Profile 1	2300	0.696	825.5	0.0075
2.	Ti-4Al-6V		Profile 2		0.410	611.82	0.0053
3.	Ti-4Al-6V		Profile 3		0.694	887.69	0.0079
4.	Ti-4Al-6V	Ellipse	Profile 1	2300	0.739	913.96	0.0080
5.	Ti-4Al-6V		Profile 2		0.451	662.45	0.0058
6.	Ti-4Al-6V		Profile 3		0.773	1022.4	0.0089
7.	Ti-4Al-6V	Oval	Profile 1	2300	0.720	810.22	0.0073
8.	Ti-4Al-6V		Profile 2		0.429	533.62	0.0046
9.	Ti-4Al-6V		Profile 3		0.733	861.61	0.0076
10.	Ti-4Al-6V	Trapezoidal	Profile 1	2300	0.482	774.79	0.0067
11.	Ti-4Al-6V		Profile 2		0.300	422.3	0.0037
12.	Ti-4Al-6V		Profile 3		0.490	622.24	0.0054

produced least deformation and lowest von Mises stresses when compared to other implants. This is further explored in the contours plots for deformation, von Mises stress and elastic strain for trapezoidal shaped implant in Fig. 6.

Table 5 tabulates the results of the static structural analysis carried out for material combination of CoC as Acetabular liner and Hip stem, Femoral head, backing cup with thickness of 2mm made of CoCr under identical boundary conditions.

The results of Table 5 also identify trapezoidal profile 2 showcasing least deformation and lowest von Mises stress for the acetabular liner made of CoC. The Stress distribution, deformation and elastic strain for stem having CoC acetabular liner are shown in Fig. 7.

The Trapezoidal Profile 2 has been proved to be having the lowest values for deformation and von-Mises stresses irrespective of the material used for acetabular liner results from Table 4 and Table 5. It was also determined that, stem having the acetabular liner made of CoC material was better than that made from CoPE material.

4. Discussion

The most common hip joint materials used for hip implants are cobalt

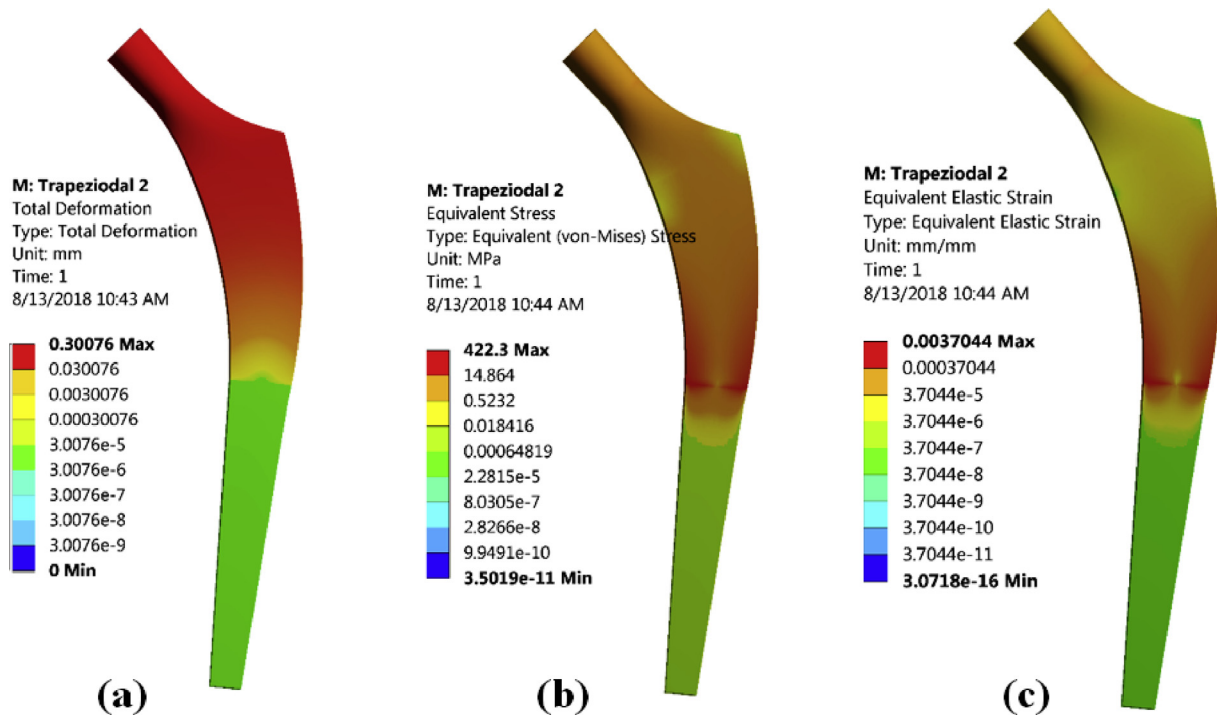


Fig. 4. Trapezoidal Profile 2: (a) Total Deformation, (b) von Mises Stress, (c) Elastic strain.

chromium alloy, titanium alloy, stainless steel [10]. The design requirement for hip joint implants are very stringent to avoid revision

joint surgeries due to aseptic loosening [12]. Most of the earlier studies have considered various shapes and materials for stem and acetabular designs. The best fit design and material choices are difficult to identify based on the earlier findings in the literature. Although, FEA is a popular tool to analyze the stem design, the boundary conditions adopted are devoid of any standards. This makes it difficult to arrive at common grounds for analyzing the results available in open literature. Jiang et al. [17] investigated four different structural models made of ultra-high molecular weight polyethylene (UHMWPE), CoCrMo alloy, 316L stainless steel and Ti-6Al-4V alloy. Their mechanical characteristics under static and dynamic conditions were studied using finite element method (FEM). They found that the deformation of 0.1mm in the implants with a material of Ti-6Al-4V [17]. Chalernpon et al. [12] found that the stress values were lesser than the yield strength for Ti-4Al-6V alloy when the hip implant along with femur bone was considered. Katarina et al. [32] considered the hip implant with the materials property of Ti-6Al-4V alloy. They found the stress was 256MPa in their implant for the applied load of 6000N.

In this study, all the twelve models are evaluated for the total deformation and von Mises stress by considering the ASTM F2996-13 standards. All the models exhibited stresses lesser than the yield strength of the material for the loading of 2300N. Among all the four designs, profile 2 demonstrated the least possible deformation compared to profile 1 and profile 3. Profile 2 exhibited 25% lesser deformation and von Mises stress compared to profile 1 and profile 3.

In the stem design, the CoCr resulted in lesser deformation compared to Ti-4Al-6V alloys. In general, profile 2 with trapezoidal shaped stems produced the best outcome, with a total deformation of 0.171mm, von Mises stress of 422.18MPa and equivalent strain of 0.0021mm for the stem made up of CoCr material.

Similar findings were reported for complete implants with acetabular liner. The implants made of CoCr had their acetabular liners made of either CoC or CoPE. It was found that implant with acetabular made

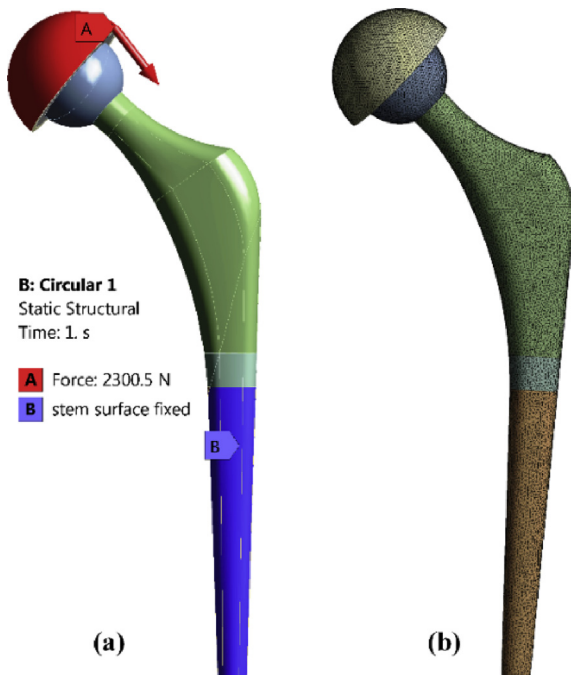


Fig. 5. (a) Boundary condition applied on the implant with acetabular, (b) Discretized model of the implant with acetabular cup and backing cup.

Table 4
Static analysis of hip Implant as per the ASTM F2996-13 standards with Acetabular cup made of CoPE.

Sl.	Material Combination	Shape	Profile	Load in N	Total deformation in mm	Equivalent von Mises stress in MPa	Equivalent strain in mm/mm
1.	CoPE	Circular	Profile 1	2300	0.099	364.59	0.0037
2.	CoPE		Profile 2		0.058	299.69	0.0027
3.	CoPE		Profile 3		0.102	428.57	0.0034
4.	CoPE	Ellipse	Profile 1	2300	0.107	427.6	0.0033
5.	CoPE		Profile 2		0.061	313.89	0.0035
6.	CoPE		Profile 3		0.113	411.84	0.0035
7.	CoPE	Oval	Profile 1	2300	0.104	392.00	0.0035
8.	CoPE		Profile 2		0.060	222.22	0.0033
9.	CoPE		Profile 3		0.107	417.91	0.0035
10.	CoPE	Trapezoidal	Profile 1	2300	0.071	330.69	0.0035
11.	CoPE		Profile 2		0.050	191.72	0.0035
12.	CoPE		Profile 3		0.073	300.58	0.0035

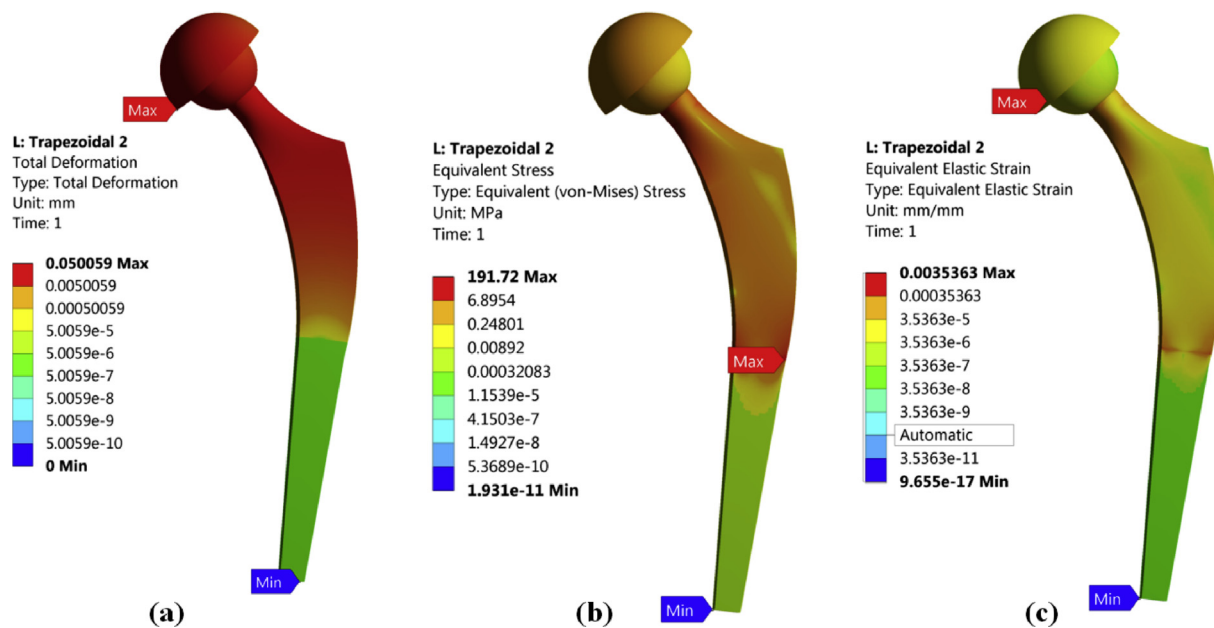


Fig. 6. Trapezoidal Profile 2: (a) Total Deformation, (b) von Mises Stress, (c) Elastic strain.

Table 5
Static analysis of hip Implant as per the ASTM F2996-13 standards with Acetabular cup made of CoC.

Sl.	Material Combination	Shape	Profile	Load in N	Total deformation in mm	Equivalent von Mises stress in MPa	Equivalent strain in mm/mm
1.	CoC	Circular	Profile 1	2300	0.091	364.59	0.0015
2.	CoC		Profile 2		0.047	299.7	0.0014
3.	CoC		Profile 3		0.095	428.57	0.0021
4.	CoC	Ellipse	Profile 1	2300	0.100	427.6	0.0021
5.	CoC		Profile 2		0.051	313.9	0.0015
6.	CoC		Profile 3		0.108	411.84	0.0021
7.	CoC	Oval	Profile 1	2300	0.097	392.01	0.0020
8.	CoC		Profile 2		0.049	222.22	0.0011
9.	CoC		Profile 3		0.100	417.91	0.0021
10.	CoC	Trapezoidal	Profile 1	2300	0.062	330.69	0.0016
11.	CoC		Profile 2		0.038	191.72	0.0009
12.	CoC		Profile 3		0.064	300.58	0.0015

of CoC has lesser deformation compared to CoPE material. Moreover, the profile 2 with trapezoidal shaped implant has a least deformation of 0.038mm and von Mises stress of 191.72MPa when compared to all the other eleven designs. Thus, it can be inferred from the findings of

this study that, profile 2 with trapezoidal stem is well suited for knee implants. The stem should be made of CoCr material and the acetabular liner should be of CoC material for safe and durable usage as implants.

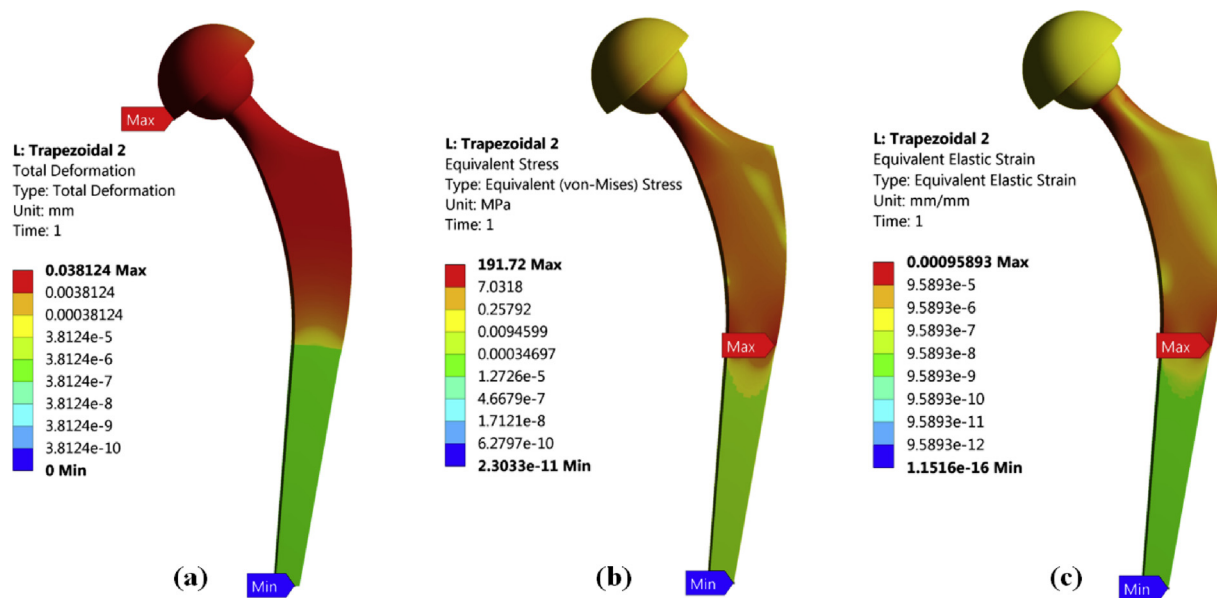


Fig. 7. Trapezoidal Profile 2, (a) Total Deformation, (b) von Mises Stress, (c) Elastic strain.

5. Conclusion

CoCr, Ti–6Al–4V materials are popularly used as stem materials nowadays due to its superior mechanical properties and biocompatibility. In this work, circular, ellipse, oval and trapezoidal stem designs with three different profiles were modelled using CATIA V-6. Loading conditions were applied as per the ASTM F2996-13 standards. CoCr was found to be the preferred choice of material for stem design. It was also observed that, irrespective of material considered for the analysis profile 2 with trapezoidal stem showcased lesser deformation and von Mises stress over the other eleven models. For analysis involving acetabular cups, CoC implants exhibited better mechanical properties over the conventional CoPE materials such as UHMWPE. It is inferred from the findings of this study that, the profile 2 with trapezoidal stem design made of CoCr material and acetabular cup made of CoC material is best suited for hip joint implants.

Declarations

Author contribution statement

Chethan K N & Mohammad Zuber: Conceived and designed the experiments; Performed the experiments; Contributed reagents, materials, analysis tools or data.

Shyamasunder Bhat N, Satish Shenoy B & Chandrakant R Kini: Analyzed and interpreted the data; Wrote the paper.

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Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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