Static structural analysis of hip joint with various profiles by finite element method

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Abstract. The hip joint is one of the primary joints which give stability to the body. The hip anthroplasty surgery is performed due to constant wear and tear of the hip due to a person’s age and various factors. Due to this surgery, the joints are replaced by the implants made up of mostly Cobalt Chromium alloy (CoCr), Titanium alloy, Stainless Steel (SS316L). A comparative study will be done amongst these materials so as to choose the better one. Also various shapes with different design profiles will be modeled and analyzed by using finite element method and the best results will be tabulated. The profiles studied are circular, ellipse and rectangular profile. The main aim of this research is to find best material as implant and also best design so that minimum amount of wear takes place during practical situations for the comfort of the person. Based on various results obtained by Finite element analysis (FEA) like Von-Mises stress, Total deformation, Equivalent Elastic Strain, it has been found that the CoCr is the best material to be used as hip implants for static loading conditions.

1. Introduction
The hip is a ball and socket joint surrounded by powerful and well balanced muscles [1]. This enables a wide range of locomotion and also exhibits remarkable stability. The hips carry forces from the ground up and also take forces from the trunk portion, head, neck and upper extremities of the human body [2]. This is the reason why this joint has become an essential part for athletic and physical activities and is mostly exposed to normal axial and torsional forces. Due to damage of hips due to various reasons and also due to old age there is increase in hip replacements in modern days. Due to this, the design for long lasting implant is required for both longevity and functionality point of view. As a result, it is driving the need for an optimized design for hip replacement [3]. This hip joint consists of a femoral head that is attached to the acetabulum. The hip anthroplasty is done to reduce the pain and induce normal movement in case of wear and tear of the joints [4]. The materials such as cobalt chromium alloy, stainless steel and titanium alloy are generally used for hip implants due to their biocompatibility property [5]. The basic necessity of the materials used is such that they should be biocompatible and produce minimal wear rate to avoid revisions due to asceptic loosening. By using the finite element analysis, it is possible to predict the behaviours of the models developed. The investigation of hip joints by Anthony et al. [6] was done by considering various models of circular, ellipse, trapezoidal by using FEA. The materials used are Stainless Steel SS316L, CoCr and Titanium alloy (Ti-6Al-4V). Von-Mises stress and displacement of the stem was determined in all the cases. Zafer et al. [7] studied the static and dynamic behaviour of Ti-6Al-4V and cobalt-chromium alloy and also made a comparison to the stem developed by Charnley [8]. S.J. Hampton et al. [9] performed three dimensional stress analysis of the
femoral stem of total hip prosthesis wherein stress distribution with the implanted femoral stem was studied by using finite element analysis.

In this work, three different profiles were used for hip implants viz. circular, ellipse, rectangular and each profile is investigated for three materials [10] CoCr, Ti-6Al-4V and Stainless Steel (SS316L). Finite element analysis is used to carry static analysis by using ANSYS Workbench. The boundary conditions were applied according to ASTM standards. Titanium alloy and CoCr were used due to their biocompatibility and popularity in bioimplants.

2. Materials and methods

Although several designs were popularly used in total hip anthropotomy, in this paper three profiles of circular, ellipse and rectangular were used. The geometry dimensions were taken from the previous literature Ref. [11]. The profiles were modeled by using Solid Works. The meshed part is analyzed in ANSYS. The materials used in this study are Cobalt chromium CoCr, Ti-6Al-4V and Stainless Steel (SS316L).

2.1. Meshing and boundary conditions
The models were meshed with unstructured mesh. The total number of elements and nodes obtained by modeling various implants were approximately 520000 nodes and 400000 elements. The boundary conditions are applied as per ASTM F2996-13 and loading conditions considered were according to ISO 7206-4:2010. The hip stem was constrained in all degrees of freedom at the bottom face. The fixation and load application is shown in the figure 1.

![Figure 1. Meshed part of circular cross section made of CoCr and boundary conditions for the study](image)

Static structural analysis is carried out for all profiles by giving similar bounding conditions. The mechanical properties of the materials used for the implants are shown in table 1.

| Sr. No. | Materials       | Young’s modulus [GPa] | Density [gm/cm³] | Poisson’s ratio | Ultimate Tensile Strength [MPa] |
|---------|----------------|-----------------------|------------------|----------------|--------------------------------|
| 1.      | CoCr Alloy     | 200                   | 8.5              | 0.30           | 1503                           |
| 2.      | Ti-6Al-4V      | 114                   | 4.5              | 0.31           | 930                            |
| 3.      | SS316L         | 193                   | 8                | 0.25           | 515                            |
3. Results and discussion
The design is carried to preliminarily obtain results and to decide the best possible cross section for hip implant. The implants were made of commercially available materials cobalt chromium (CoCr), Titanium alloy (Ti-6Al-4V) and Stainless Steel (SS316L). The profile models were subjected to uniform loading of 2300 N. The results of CoCr are compiled in table 2 for Von-Mises stress, total deformation and equivalent elastic strain.

Table 2. Static analysis of hip implant by using CoCr

| Material | Shape   | Load in N | Total deformation in mm | Von-Mises stress in MPa | Equivalent elastic strain in mm/mm |
|----------|---------|-----------|-------------------------|------------------------|-----------------------------------|
| CoCr     | Circular| 2300      | 6.0134                  | 3722.2                 | 0.018833                          |
| CoCr     | Ellipse | 2300      | 13.435                  | 4974.9                 | 0.025424                          |
| CoCr     | Rectangular | 2300    | 17.462                  | 4101.7                 | 0.021047                          |

Table 3. Static analysis of hip implant by using Ti-6Al-4V

| Material     | Shape   | Load in N | Total deformation in mm | Von-Mises stress in MPa | Equivalent elastic strain in mm/mm |
|--------------|---------|-----------|-------------------------|------------------------|-----------------------------------|
| Ti-6Al-4V    | Circular| 2300      | 11.073                  | 3897.4                 | 0.034544                          |
| Ti-6Al-4V    | Ellipse | 2300      | 26.027                  | 5478.7                 | 0.048183                          |
| Ti-6Al-4V    | Rectangular | 2300 | 35.175                  | 4610.7                 | 0.041623                          |

Table 4. Static analysis of hip implant by using SS316L

| Material | Shape   | Load in N | Total deformation in mm | Von-Mises stress in MPa | Equivalent elastic strain in mm/mm |
|----------|---------|-----------|-------------------------|------------------------|-----------------------------------|
| SS316L   | Circular| 2300      | 6.2805                  | 3827.4                 | 0.020041                          |
| SS316L   | Ellipse | 2300      | 14.047                  | 4996.5                 | 0.025938                          |
| SS316L   | Rectangular | 2300 | 18.296                  | 4200.4                 | 0.022145                          |

From table 2, it can be seen that CoCr has less deformation when it is in circular cross section as compared to ellipse and rectangular. It is also observed that Von-Mises stress and elastic strain in circular cross section is less in value. From table 3, it can be seen that amongst Ti-6Al-4V material, the circular profile if offering least deformation, least Von-Mises stress and elastic strain. The rectangular cross section has maximum total deformation for SS316L as can be seen from table 4. figure 2 shows the contour plots of Von-Mises stress, deformation and equivalent elastic strain for circular profile for CoCr.
Figure 2. Circular profile for CoCr with Deformation, Von-Mises Stress and Elastic Strain

The contour plots for Ti-6Al-4V with ellipse profile were shown in figure 3. Similarly, contour plots for SS316L made of rectangular profile are shown in figure 4.

Figure 3. Elliptical profile with Ti-6Al-4V with Deformation, Von-Mises Stress and Elastic Strain

Figure 4. Rectangular profile with SS316L with Deformation, Von-Mises Stress and Elastic Strain
4. Conclusion
The present work focuses on the static structural analysis of the hip joint with various cross sections and different materials was analyzed with finite element method. From the above results, it can be seen that CoCr is offering good resistance against deformation and also inducing least Von-Mises stress. Due to this, for this material, the amount of wear taking place is less. Within CoCr, the cross section with circular profile has best possible results. It is inferred from the findings of this study that the circular profile made of CoCr material is the best one for hip joint implants. CoCr is also a popular material due to its superior mechanical properties and biocompatibility.

5. References
[1] Byrne DP, Mulhall KJ, Baker JF. Anatomy & biomechanics of the hip. The open sports medicine Journal. 2010;4(1).
[2] Campbell JD, Higgs R, Wright K, Leaver-Dunn D. Pevis, hip and thigh injuries. In: Schenck RC, Guskiewicz KM, Holmes CF, Eds. Athletic Training and Sports Medicine. Rosemount: American Academy of Orthopaedic Surgeons 2001; p.399.
[3] Sabatini AL, Goswami T. Hip implants VII: Finite element analysis and optimization of cross-sections. Materials & Design. 2008 Jan 1;29(7):1438-46.
[4] Izzo GM. Support for total hip replacement surgery: Structures modeling, Gait Data Analysis and Report system. European Journal of Translational Myology. 2012 Mar 1;22(1-2):69-121.
[5] Chethan KN, Zuber M, Shenoy S, Kini CR. Static structural analysis of different stem designs used in total hip arthroplasty using finite element method. Heliyon. 2019 Jun 1;5(6):e01767.
[6] Sabatini AL, Goswami T. Hip implants VII: Finite element analysis and optimization of cross-sections. Materials & Design. 2008 Jan 1;29(7):1438-46.
[7] Senalp AZ, Kayabasi O, Kurtaran H. Static, dynamic and fatigue behavior of newly designed stem shapes for hip prosthesis using finite element analysis. Materials & design. 2007 Jan 1;28(5):1577-83.
[8] CAMPBELL RE, ROTHMAN RH. Charnley low-friction total hip replacement. American Journal of Roentgenology. 1971 Dec;113(4):634-41.
[9] Hampton SJ, Andriacchi TP, Galante JO. Three dimensional stress analysis of the femoral stem of a total hip prosthesis. Journal of biomechanics. 1980 Jan 1;13(5):443-8.
[10] Colic K, Sedmak A, Grbovic A, Tatic U, Sedmak S, Djordjevic B. Finite element modeling of hip implant static loading. Procedia Engineering. 2016 Jun;149:257-62.
[11] Darwich A, Nazha H, Abbas W. Numerical study of stress shielding evaluation of hip implant stems coated with composite (carbon/PEEK) and polymeric (PEEK) coating materials.