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FATIGUE LIFE EVALUATION OF DIFFERENT HIP IMPLANT DESIGNS USING FINITE ELEMENT ANALYSIS

John Valerian Corda[1], Chethan K N[1], Satish Shenoy B[1], Sawan Shetty[2]*, Shyamasunder Bhat N[3], Mohammad Zuber[1]

[1] Department of Aeronautical & Automobile Engineering, Manipal Institute of Technology, Manipal Academy of Higher Education, Manipal-576104, Karnataka, India
[2] Department of Mechanical & Industrial Engineering, Manipal Institute of Technology, Manipal Academy of Higher Education, Manipal-576104, Karnataka, India
[3] Department of Orthopaedics, Kasturba Medical College, Manipal, Manipal Academy of Higher Education, Manipal-576104, Karnataka, India

** sawan.shetty@manipal.edu*

Fatigue failure is one of the causes of the failure of hip implants. The main objective of this work is to carry out fatigue failure analysis on different hip profiles and compare the outcomes for various combinations of materials. Three profiles each for circular, oval, elliptical, and trapezoidal stems are utilized for this study with four different material combinations consisting of materials like Ti–6Al–4V, CoCr Alloy and UHMWPE. CATIA V-6 is used for the modelling of these implants and the fatigue analysis using Goodman's mean stress theory is simulated using ANSYS 2022 R1. ISO 7206-4 and ASTM F2996-13 standards are used to define the boundary conditions. A total of 48 combinations were studied across four different shapes, three different profiles and four different material combi-nations to deduce the best possible combination for a hip implant for static and fatigue loading. Comparison of the implants is based on the factors like equivalent von Mises stress, displacement, equivalent elastic strain, fatigue life, safety factor and equivalent alternating stress. Profile 2 of the trapezoidal-shaped hip implant with a Ti–6Al–4V stem exhibited superior results both under static and fatigue loading conditions. Compared to displacements obtained for profiles one and three, profile 2 trapezoidal stem with Ti–6Al–4V and other parts as CoCr Alloy has about 72% lower displacement. Based on the findings, profile 2 with a trapezoidal stem made of Ti–6Al–4V and an acetabular cup made of CoCr shows the enhanced results over the other combinations considered.

Keywords: total hip arthroplasty, fatigue, finite element analysis, implants, displacement

1 INTRODUCTION

The hip joint constitutes a ball and socket joint that articulates between the femoral head and the pelvis acetabulum [1]. The primary purpose of the hip joint is to dynamically support the weight of the body in addition to the transmission of forces and loads from the axial skeleton to the lower extremities thereby facilitating mobility [2–6]. The hip joint facilitates movements in all three axes that are at right angles to each other. The femoral head marks the centre of the axis. The flexion and extension movements are facilitated by the transverse axis, the longitudinal axis assists in internal and external rotation and the sagittal axis facilitate the abduction and adduction [7,8]. Total hip arthroplasty (THA) or total hip replacement as it is most commonly referred to is a common procedure undertaken to reduce disorders in hip joints which include osteoarthritis, arthritis (rheumatoid and infectious), lupus and avascular necrosis. This procedure is executed by the replacement of the acetabular surface and the femoral head with prosthetic implants thereby attaining the functionality of the joint caused by mechanical damage or degenerative disease [9–12]. Typically, hip implants are designed for a life of twenty years. A range of material combinations used in THA includes Titanium alloys (Ti–6Al–4V), CoCr alloys and stainless-steel alloys [13–16]. Reports suggest that 95% of the implants are carried out on people aged over 45 years [17]. In European countries hip implants are increasing at a CAGR of 1.2%, increasing from 1.8 million in 2015 to 2.8 million in 2050 and some countries like Norway, Australia and Ireland are set to witness an increase in hip implants by +95% and +120% from 2015 to 2050 [18]. The demand for primary total hip arthroplasty is anticipated to increase by 174% by 2030 [19,20].

The operational life span of the hip implant is affected by various factors that lead to the failure of the stem and fracture due to fatigue is considered to be a primary cause of failure [21–23]. The fatigue crack initiation and propagation in hip joint prosthesis were studied to find the numerically determined values of the stress intensity factor increase as a result of the numerical simulation of crack growth in the material [24]. A fatigue crack growth from 0.5mm to the failure limit of 18.5mm was investigated on hip implants for different walking conditions like slow walking, normal walking and fast walking loading conditions and was found to be safe for up to 20 years of life [25]. Some studies have pointed out that although medical-grade titanium has excellent fatigue properties, the ISO pre-clinical durability testing standard does not adequately account for the influence of femoral offset or stem size to reflect safe design practice [26]. For static human body weight load, hip joint prostheses were found to be safe and dynamic analysis revealed that the hip joint prosthesis had an infinite fatigue life [27]. A hip joint model made of UHMWPE/ TiO2 Polymer composite used to study fatigue failure was found to be safe in static and fatigue analysis [23]. Senalp et al. [28] conducted static, dynamic and fatigue analyses of four different stem designs with static analysis under body loading conditions and dynamic analysis under walking conditions. Fatigue analysis was done in 109 cycles and the implants were found to be safe for both the Ti–6Al–4V and cobalt-chromium alloy materials.

Studies on hip implants mostly concentrate on static structural analysis [29–31]. One analysis was carried out to identify the effect of varying taper lengths on the stresses induced under static loading conditions. It was concluded that the von Mises stresses decrease as the taper length is decreased. It was also inferred that a reduced taper length results in the dislocation of the implant so an optimization between the taper length and femoral head was suggested [32]. The effect of femoral head size on hip implants was studied by researchers under static loading conditions [33]. A corrugated hip im-plant device analyzed for dynamic gait cycle loading showed maximum stress of 255 MPa at the femoral head. The analyses revealed minimal micro-motions (roughly 7 µm) between the femur and implant, minimal stresses at the implant and bone within elastic ranges, and uniform stress distribu-tion, which, unlike current hip implants [34].

A total of eight different types of stem designs were experimentally and numerically studied for fatigue using materials like 316L, cobalt chrome alloy, and Ti-6Al-4V. Based on safety factor values, mini-mum fatigue cycles, and critical fatigue areas it was concluded that all the stem designs are safe and the lateral side of the implant experienced maximum stresses [35]. The design, analysis and manu-facture of lightweight implants showed a reduction in the weight of implants by 15% and also ensured that the life of the implants was more than 5 million loading cycles [36]. A hip implant was designed and different materials combinations were used for the fatigue analysis along with the femur which is modelled using the CT scan of a 72-year healthy person. They have found titanium is more advan-tageous based on lower stress concentration, resulting in longer life of the designed implant [37].

Fatigue studies in hip implants have been previously studied, however, a detailed study on the dif-ferent shapes and profiles of implants with different material combinations are not carried out and this gap is bridged by this present work that adds uniqueness to this study. This study employs four different types of stem shapes with three profiles each that were employed previously for the static structural simulations of hip implants [38]. Additionally, four different material combinations are used comprising materials like Ti–6Al–4V, CoCr Alloy and UHMWPE. CATIA V-6 is used for the modelling and ANSYS 2022 R1 is used to perform stress analysis. Loading and boundary conditions are applied as per the relevant ISO and ASTM standards respectively [39,40]. The fatigue life of all the implants used for the current study is analyzed for safety factors. This work helps select the most competent profile based on the fatigue life evaluation.

2 MATERIALS AND METHODS

2.1 Stem shapes and material combinations

Different types of stem designs are currently used in THA. Each of them has its merits and draw-backs. The most commonly used stem shapes are circular, elliptical, oval and trapezoidal as shown in Figure 1 [38,41]. A straight stem with a radius on the lateral side close to the proximal end is taken into account in profile 1. Profile 2's arc length and diameter are both increased, as is the overall angle between the medial and lateral faces. The radius on the lateral side is replaced in profile 3 by a cor-nered shoulder. All three designs share the same neck and medial side measurements. Irrespective of the design and profile the stem lengths are considered 180 mm. The size of the femoral head, ace-tabular cup and backing cup considered in this work for all the profiles is 28mm, 4mm and 2mm respectively [42,43].

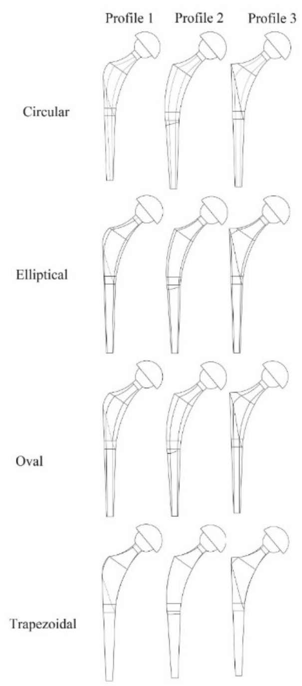

Figure 1: Different implant shapes and profiles [38,41]

The hip implant consists of a stem, femoral head, backing cup and acetabular liner. The materials used for these parts include stainless steel, titanium alloys and cobalt-chromium alloys [44,45]. This study focuses on the fatigue analysis of the entire hip implant with three different materials namely titanium alloys, cobalt-chromium alloys and UHMWPE. The different biomaterials are considered due to their superior mechanical properties. The material properties of these materials are given in Table 1.

Table 1: Material properties of the stem [32,46,47]

Sl No	Material	Young's Modulus (GPa)	Poisson's Ratio	Density (gm/cm^3)	Ultimate tensile strength (MPa)	Yield Strength (MPa)
1	Ti–6Al–4V	114	0.31	4.5	930	880
2	Co Cr Alloy	200	0.30	8.5	1503	612
3	UHMWPE	0.963	0.31	0.949	48	21

The materials used for the implants as indicated in Table 1 are defined for their S-N curves which is a graph of alternating stress versus the number of cycles plotted in logarithmic scale as shown in Figure 2.

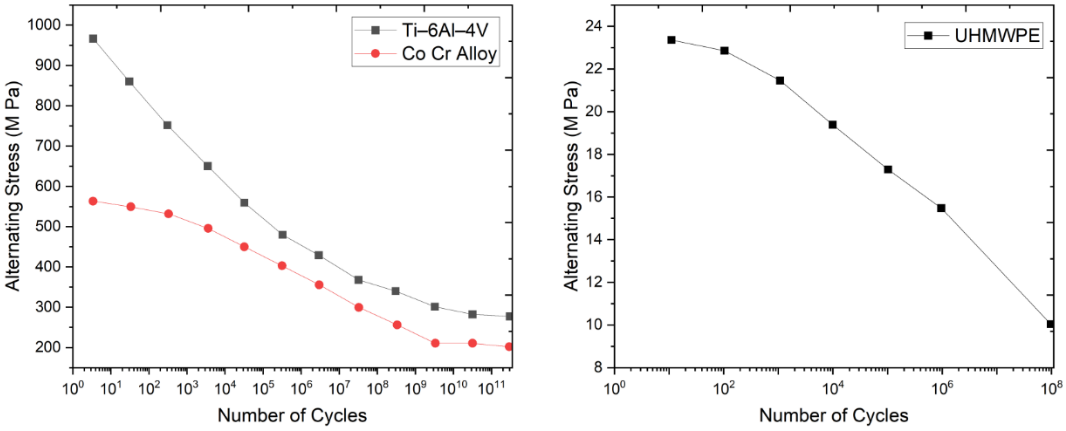

Figure 2: S-N curve for Ti–6Al–4V, CoCr Alloy and UHMWPE [28,47]

Two basic prerequisites to selecting these materials are biocompatibility and mechanical properties. At the beginning of hip replacement surgery, biocompatibility was a major concern, while the me-chanical properties deal with resistance to wear, stress concentration and stability of the implant [48,49]. Human compatibility is the major reason why these materials are used as a replacement for natural hip joints. The combination of materials used in the study is given in Table 2 and the materials considered are linear elastic isotropic in nature. The friction coefficient between CoCr Alloy and UHMWPE is 0.23, between CoCr Alloy and CoCr Alloy is 0.21 and the friction coefficient between CoCr Alloy and Ti-6Al-4V is 0.2. These friction coefficients are chosen based on the values available from the previous literature [50–52].

Table 2: Material Combinations used

Combination Number	Acetabular Cup	Liner	Femoral Head	Stem
C1	CoCr Alloy	UHMWPE	CoCr Alloy	CoCr Alloy
C2	CoCr Alloy	CoCr Alloy	CoCr Alloy	CoCr Alloy
C3	CoCr Alloy	UHMWPE	CoCr Alloy	Ti-6Al-4V
C4	CoCr Alloy	CoCr Alloy	CoCr Alloy	Ti-6Al-4V

A study showed 23% of the patients underwent THA made up of CoCr alloys due to its superior me-chanical properties [53]. However, another study reported that around 11% of the patients who had undergone THA using CoCr alloys complained of an audible squeaking sound during normal day-to-day activities [54]. To avoid these squeaking sounds UHMWPE is used along with CoCr alloy [55].

2.2 Meshing and Boundary Conditions

Unstructured mesh is considered in this work. With reference to our previous work mesh size is finalized to 1mm. The total number of nodes ranged from 675,000 to 742,500 and the total number of elements ranged from 495,000 to 543,500 for all the implants used in this analysis. In the previous work mesh grid independence is carried out to finalize the mesh size [38]. It is imperative to be noted here that the previous studies have used mesh counts ranging from 5 mm to 0.25 mm [56]. Figure 3 represents the meshed model.

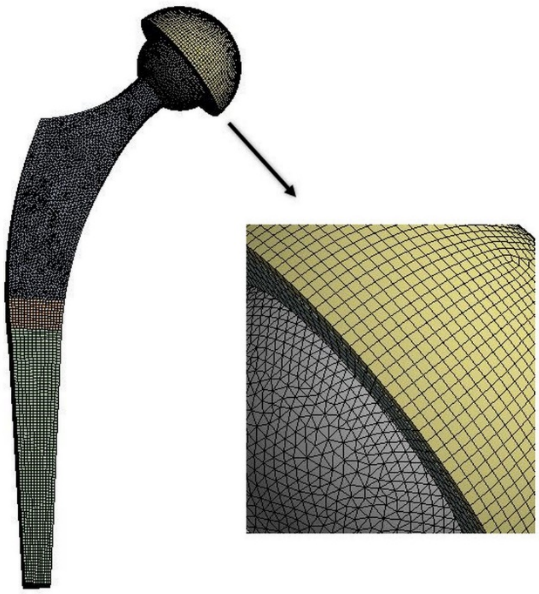

Figure 3: Meshed model

Boundary conditions used in this study are applied as per ASTM F2996-13 and the fatigue loading conditions are set up as per ISO 7206-4:2010 [39,40]. Accordingly, the ASTM standard requires the stem to be segmented into three cross-sections starting from the top. As per the ISO standard, for the first cut, the hip stem is sectioned from the head centre providing the most conservative head or neck offset which facilitates the stress distribution representation over the implant. The second cut on the stem is 10mm below the first cut. The remainder of the stem post this second cut is constrained in all directions thereby assuring that the area is not subjected to excessive or incorrect stresses as a result of the rigid fixing of the stem. These are shown in Figure 4. The stem length considered in this work is 180 mm and the lower 90 mm is constrained in all directions as per ISO 7206-4:2010 [40]. All three sections are considered bonded during the analysis. Typically for the static stress analysis of the hip implants, a load of 2300 N is applied at the centre of the stem [57]. The fatigue analysis of the hip implants that are the focus of this in silico study is carried out as per the fatigue test conditions with maximum and minimum loads of 2300 N and 300 N [36]. Goodman's mean stress theory is utilized for fatigue analysis [28,37]. The safety factor is calculated based on equation (1).

$$\frac{1}{SF}=\left(\frac{\sigma_a}{S_e}\right)+\left(\frac{\sigma_m}{S_u}\right) \quad (1)$$

Where SF represents Safety Factor, σ_a and σ_m represent alternating stress and mean stress respectively, S_e and S_u represent endurance limit stress and ultimate strength respectively. Figure 4 represents the loading and boundary conditions for this study. The von-Mises yield stress criteria were used to calculate the equivalent stress as there was a possibility of multi-axial stresses occurring during the loading conditions.

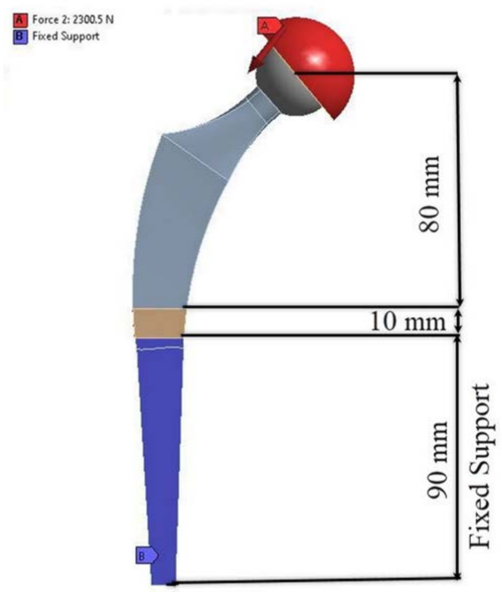

Figure 4: Loads and Boundary Conditions

3 RESULTS

As indicated in the methodology section, four different shapes of stem implants were used in this study and each shape consisted of three different profiles. Previous studies on these profiles con-cluded that the trapezoidal shape was preferable for hip joint implants based on lower displacement and von Mises stress [38]. Also, the wear estimation calculations of the same implants resulted in the circular profiles being preferred over the other shapes [58]. Therefore the fatigue life evaluation re-sults produced henceforth will be for the trapezoidal and circular-shaped hip implants.

3.1 Static Structural Analysis

Static structural analysis is carried out on all four shapes of implants with three profiles each and four material combinations as indicated in Table 2. Our previously published literature on the implants has shown that the circular and trapezoidal-shaped implants exhibit a minimum of 27% lesser von Mises Stresses compared to the elliptical and oval-shaped stem implants and the same pattern of results was observed in the current study [38,58]. The equivalent von Mises stresses induced in the implants and the total displacements obtained from the FEA calculations are reported in Table 3. The location of the maximum values reported in Table 3 can be obtained from Figure 5. The results of elliptical and oval shapes are given in Appendix A.

Table 1: Static structural results

Shape	Profile	Material Combination	Equivalent von Mises Stress (MPa)	Total Displacement (mm)	Equivalent Elastic Strain (mm/mm)
Circular	Profile 1	C1	292.51	0.144	0.0045
		C2	292.51	0.113	0.0015
		C3	290.06	0.224	0.0045
		C4	290.06	0.195	0.0026
	Profile 2	C1	208.3	0.101	0.0044
		C2	208.3	0.057	0.0010
		C3	205.19	0.140	0.0044
		C4	205.18	0.097	0.0018
	Profile 3	C1	350.13	0.140	0.0044
		C2	350.13	0.108	0.0019
		C3	350.42	0.216	0.0044
		C4	350.42	0.187	0.0033
Trapezoidal	Profile 1	C1	157.49	0.083	0.0044
		C2	158.53	0.040	0.0011
		C3	295.21	0.168	0.0044
		C4	295.21	0.137	0.0026
	Profile 2	C1	149.87	0.090	0.0044
		C2	149.87	0.047	0.0008
		C3	147.53	0.122	0.0044
		C4	147.53	0.080	0.0013
	Profile 3	C1	222.91	0.114	0.0044
		C2	222.91	0.081	0.0011
		C3	219.94	0.170	0.0044
		C4	219.94	0.139	0.0019

Table 3 shows that Equivalent von Mises Stresses induced in the implants for profile 2 are lower compared to the stresses induced in profile 1 and profile 3. Also, the total displacement profile 2 is preferable over the other profiles as the displacement values are lower in comparison with other profiles. Table 3 also indicates the stress induced in profile 2 of circular and trapezoidal shapes for the combinations of C4 is less as compared to the other three material combinations C1, C2 and C3. It can be seen that the maximum stress is induced at the mid-region of the implant. Considering the stresses induced, displacement and equivalent elastic strain the material combination of C4 is better than the other three. This is based on the fact that though the stresses induced are almost the same, the displacement and the equivalent elastic strain values in the material combination of C4 are lesser when compared to C3. Figure 5 shows the equivalent von Mises stress, displacement and equivalent elastic strain plots for profile 2 of the trapezoidal cross-section with material combination C4.

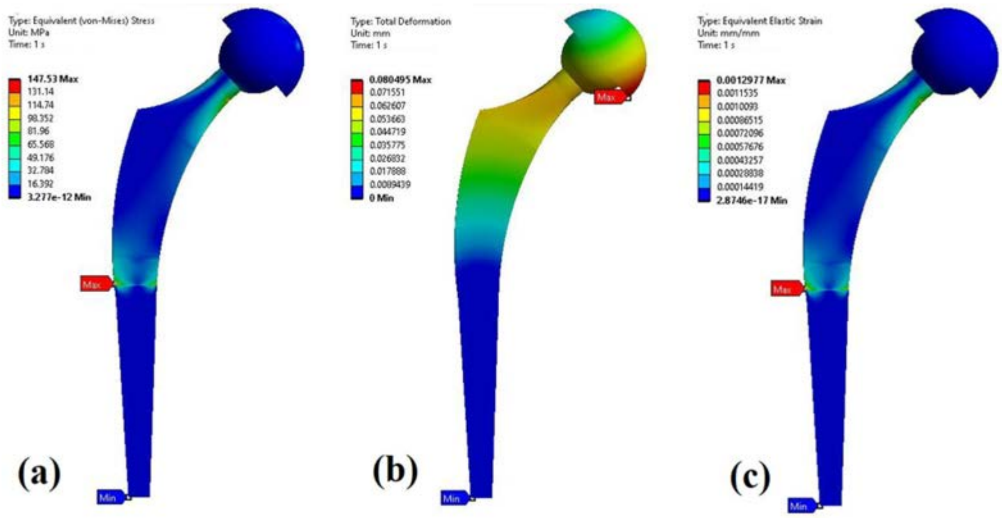

Figure 5: Static Analysis Results for Trapezoidal Cross Section of Profile 2. (a) Equivalent von Mises Stress (b) Displacement (c) Equivalent Elastic Strain

3.2 Fatigue Analysis

In fatigue results, we report the values of the minimum fatigue life of the implant, minimum damage, the safety factor and the equivalent alternating stress as shown in Table 4. In Section 3.1, we have established that profile 2 with material combination C4 is preferred based on static structural analysis by considering the factors of equivalent von Mises Stresses, total displacement and the equivalent elastic strain. Results from Table 4 also indicate a 2.7% and 2.6% higher safety factor for C3 and C4 material combinations when compared to C1 and C2 for trapezoidal and circular profiles respectively. Additionally, though the life of the implants is well within the acceptable limit of 15 million cycles considering 15 years of life with a million cycles each year, the material combination C4 results in higher life compared to C3. The results of elliptical and oval shapes are given in Appendix B.

Table 4:- Fatigue Results

Shape	Profile	Material Combination	Life (Cycles)	Damage	Safety Factor	Equivalent Alternating Stress (M Pa)
Circular	Profile 2	C1	$1.00E^{+08}$	$1.50E^{-01}$	2.759	98.266
		C2	$3.42E^{+11}$	$4.39E^{-05}$	2.759	98.266
		C3	$1.00E^{+08}$	$1.50E^{-01}$	2.8306	101.92
		C4	$3.12E^{+11}$	$4.81E^{-05}$	2.8306	101.92
Trapezoidal	Profile 2	C1	$1.00E^{+08}$	$1.50E^{-01}$	3.8347	69.054
		C2	$3.42E^{+11}$	$4.39E^{-05}$	3.8347	69.054
		C3	$1.00E^{+08}$	$1.50E^{-01}$	3.9369	70.464
		C4	$3.12E^{+11}$	$4.81E^{-05}$	3.9369	70.462

The damage factor is the ratio of the cycles to infinite life to the cycles to failure that are predicted from the simulation [59]. In this work, 15 million cycles are used considering one million cycles per year as the average usage of implant post-surgery [60] Fatigue damage factor values exceeding 1 indicate a failure of the component before the design life has reached [61]. From the fatigue results in Table 4, we can see that the damage factor values are less than 1 concluding that the implants are safe.

The safety factor is evaluated as per equation (1) represented as the factor of safety at a given design life. The maximum value of the safety factor is 15 and any value of less than 1 attributes to failure before the design life has reached. From our results, it can be seen that the safety factor is greater than 1 and the implants used are safe. After taking into account the fatigue loading type, mean stress effects, multiaxial effects, and any other factors in the fatigue analysis, the equivalent alternating stresses are used to review the fatigue S-N curve in Figure 2. Before figuring out the fatigue life, the equivalent alternating stress can be considered as the final parameter to be calculated. This result is useful because it encompasses all fatigue-related calculations generally, irrespective of any material properties [61]. In this study, the equivalent alternate stress distributions were examined to more accurately assess the stem's long-term functionality following total hip replacement.

4 DISCUSSION

This study focused on the fatigue life evaluation of four different shapes of implants, with three dif-ferent profiles each and with four different types of material combinations. Simulations were carried out with boundary conditions and fatigue loading as per ASTM F2996-13 and ISO 7206-4:2010 re-spectively [39,40]. Our results from the static structural analysis were in line with our previously published works conducted which indicated that circular and trapezoidal shapes are preferable when compared to elliptical and oval shapes [38,58]. Among the circular and trapezoidal shapes, profile 2 was chosen based on enhanced results over profile 1 and profile 3. The simulation was carried out using four different material combinations, consisting of materials like Ti–6Al–4V, CoCr alloys and UHMWPE. Chethan et al. [38] have used bonded contacts between the parts of the implants but in this study, we have used friction contacts as indicated in the methodology which gives realistic criteria for the fatigue failure simulations. The equivalent von Mises stresses in the static structural analysis are thus reduced by 43% and 28% respectively for circular and trapezoidal cross sections in profile 2 of this study. For stem and acetabular designs, the majority of earlier studies have taken into account different shapes and materials [35] Aseptic loosening is a major cause for revision of joint surgeries thus requiring strict design requirements for hip implants [62]. Aseptic loosening contributes to around 52% of THA revisions [63,64]. Higher displacements were observed in all of the analyses involving titanium alloys because of the Titanium alloy's lower elastic modulus than CoCr alloys [35]. Also stresses below yield stress were observed when Ti–6Al–4V alloy for hip implants with femur bone was analyzed [62]. Using CoCr Alloy in the results of the implant in a squeaking sound and the reason for this remains undetermined [53]. The majority of investigations deduced that squeaking after THA with CoCr alloys was due to increased wear or impingement induced by prosthesis design, patient char-acteristics, or surgical factors. However, due to differences between the various studies, the primary causes of the squeaking remain unknown [65].

Senalp et al. [28]designed four different stem designs with varying cross sections at the stem me-dullary-region. Static and dynamic analysis was carried out by considering the femur along with the hip implant considering Ti–6Al–4V and cobalt chromium alloy. They found the von Mises stresses between 145.6 MPa and 221.5 MPa along with the safety factors that were reported between 1 and 3.24. They also reported the Ti–6Al–4V material to be superior both in static loading and dynamic loading conditions as compared to cobalt-chromium alloy. Post-surgery recovery when patients return to normal daily activities, the hip implant is subjected to both static and cyclic loading from actions like walking, jumping, climbing, and adopting various body postures. Therefore, it is crucial to investigate the biomechanical characteristics of the hip implant under conditions of repetitive loading that could result in fatigue failure. Hence this study was conducted with different material combinations and the safety factor along with the cycles to failure was evaluated. Both the predicted fatigue life and the stress distribution should be satisfied by a good implant design. Alternating stresses are a significant problem in mechanical design because they result in fatigue in a component, which after many cycles may collapse at a stress lower than its yield stress. A material is subjected to applied stress known as alternating stress when forces change in direction or strength over time. In this study, the equivalent stress distributions were examined to more accurately assess the long-term functionality. In our study, we have found that the implants with titanium alloys used resulted in lower stresses induced in static analysis. Further, the fatigue calculations indicated a higher fatigue life, lower damage and a higher safety factor with titanium alloy used as the stem. Some studies have shown that titanium alloys, despite their high cost, are biocompatible [66] The fatigue life of implants with CoCr is slightly higher when compared to those with titanium alloys by about 9.6% which is in line with previous studies [35]. In a study four stem shapes of varying curvatures were analyzed for static and fatigue behaviour and found that Ti–6Al–4V was a feasible material compared to CoCr alloys, however, it was also found that the safety factor for static and dynamic conditions are different [28]. Another study also pointed towards using Ti–6Al–4V for hip implants based on static and dynamic loading of hip implants [37]. Studies have also shown that the life expectancy of hip implants is about 25 years in 58% of patients [67].

The major highlights obtained from this work can be listed as follows.

- Hip implants with trapezoidal cross-sections of the stem are subjected to lower stresses when compared to circular, oval and elliptical stems.
- For the trapezoidal stem, among the three profiles considered, profile 2 exhibited superior mechanical properties for static and fatigue loading conditions.
- Material combinations consisting of titanium alloy for the stem exhibited higher factors of safety and lower damage values.
- Displacements obtained for the trapezoidal stem of profile 2 for the C4 material combination are about 72% lesser than that obtained for profile 1 and profile 3.

4.1 Limitations of the current work

Different material combinations are considered in this work. However , the joint reaction force and moments acting on the implants are not taken into account in this study. These two factors need to be considered further to understand their effects on the fatigue life of implants. Additionally, different gait cycle loads from stair climbing, walking and running can be used to study fatigue life which is not considered in this work. This study has neglected the presence of the femur bone which provides a future scope of the study using the femur along with hip implant for dynamic loading conditions. The safety factor obtained in this study is on the highly conservative side which provides us with an op-portunity to optimize the stem design. A study applied a lattice structure on implants thereby reducing the weight by 15% as compared to solid implants and providing more flexibility with increased pore diameter. These optimized implants produced an acceptable level of fatigue life [36]. The implants used in this study can be optimized using similar principles and evaluated for fatigue life. Also, opti-mized implants can be further 3D printed to estimate life using hip simulators through experimental studies.

5 CONCLUSIONS

Fatigue analysis studies of four different shapes of hip implants with three different profiles each and three material combinations were carried out which resulted in a total combination of 48 simulations. Previous studies on the same implants were restricted to a few material combinations and by using bonded contacts between the components of the implants which was improvised in this study by using realistic and relevant friction coefficients that adds novelty to the present work. The static structural and fatigue life evaluation results showed that profile 2 of the trapezoidal cross-section with a material combination of Ti-6Al-4V for the stem and CoCr alloy for all the other parts of the implants was most suitable compared to other combinations used in the present work. The current work also shows that the safety factor for the implants for infinite life is much higher than 1 which attributes to an overde-signed implant. This provides a scope for improvisation in the designs where the focus shall be on reducing the weight of the implants without any impact on the static and dynamic properties of the redesigned implant.

ABBREVIATIONS	
ASTM	American Society for Testing and Materials
CAGR	Compound Annual Growth Rate
CATIA	Computer-Aided Three-Dimensional Interactive Application
ISO	International Organization for Standardization
THA	Total hip Arthroplasty
UHMWPE	Ultra-High Molecular Weight Polyethylene
UTS	Ultimate Tensile Strength

6 ACKNOWLEDGMENT

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Appendix A

Shape	Profile	Material Combination	Equivalent von Mises Stress (MPa)	Total Displacement (mm)	Equivalent Elastic Strain (mm/mm)
Elliptical	Profile 1	C1	341.37	0.15495	0.0044
		C2	341.37	0.12514	0.0017
		C3	336.89	0.24418	0.0044
		C4	336.89	0.21709	0.0030
	Profile 2	C1	279.09	0.10095	0.0044
		C2	279.09	6.17E-02	0.0017
		C3	278.07	0.14361	0.0044
		C4	278.06	0.10555	0.0030
	Profile 3	C1	219.35	9.04E-02	0.0044
		C2	219.35	4.81E-02	0.0011
		C3	334.08	0.25216	0.0044
		C4	334.08	0.23304	0.0030
Oval	Profile 1	C1	162.96	8.99E-02	0.0044
		C2	162.96	4.68E-02	0.0008
		C3	311.1	0.23498	0.0044
		C4	311.09	0.20965	0.0028
	Profile 2	C1	243.27	0.10481	0.0045
		C2	243.25	6.10E-02	0.0014
		C3	240.4	0.14696	0.0045

Shape	Profile	Material Combination	Equivalent von Mises Stress (MPa)	Total Displacement (mm)	Equivalent Elastic Strain (mm/mm)
		C4	240.4	0.10409	0.0025
	Profile 3	C1	345.47	0.14969	0.0044
		C2	345.47	0.12239	0.0017
		C3	342.06	0.23716	0.0044
		C4	342.06	0.21199	0.0030

Appendix B

Shape	Profile	Material Combination	Life (Cycles)	Damage	Safety Factor	Equivalent Alternating Stress (MPa)
Elliptical	Profile 2	C1	$1E^{+08}$	0.15	2.0592	135.58
		C2	$3.42E^{+11}$	$4.39E^{-05}$	2.0592	135.58
		C3	$1E^{+08}$	0.15	2.0887	145.49
		C4	$3.12E^{+11}$	$4.81E^{-50}$	2.0887	145.49
Oval	Profile 2	C1	$1E^{+08}$	0.15	2.3623	116.43
		C2	$3.42E^{+11}$	$4.39E^{-05}$	2.3626	116.41
		C3	$1E^{+08}$	0.15	2.4161	122.41
		C4	$3.12E^{+11}$	$4.81E^{-05}$	2.416	122.41

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