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Research Article

Elastic Behavior of Uncemented Hip Prosthesis Made of Composite with Material Property Grading

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Functional graded materials (FGMs) are widely used for hip plant component materials because of their specific properties in a specific design to meet the requirements of the hip joint system. Stem is manufactured with the concept of making new FGM using three different composition of Ti, CrCo, and HA. This has led to the development of a suitable design for functional femoral parts that can be used for a long time. The new FGM design has helped to reduce the protection of the stress and the associated stress that exists on the interface. After changing in composition of FGM, the natural frequency and deformation response exhibited by our model were quite satisfactory. The deflection comes out to be 0.33 mm at the frequency of 15 Hz. The equivalent von Mises stress is found to be 19.5 MPa. These values are closely matching with previous studied. Fatigue study was carried based on “Goodman” theory. This gave promising results. The safety factor found is more than one, which indicates that the part is safe under design. The anticipated life of stem model is 0.3284×10^5 cycle.

1. Introduction

Working on 2D FGM to improve cementless hip stem design, two models were used (using three objects with different E1, E 2, and E3). In model I, there is a gradual shift of E1 and E2 near the upper stem keeping E3 unchanged at the base of the stem and vice versa. It was found that the model I was expecting to reduce stress protection by 91% and 12%, respectively, as compared to model II. Furthermore, new design helps in reduction of maximum interface shear stress by about 50% on the lateral and medial aspects of the femur as compared with titanium stem. Also reduction of 17% and 11% is found on the lateral and medial facets of the femur, respectively, when comparing with model II of FGM [1, 2].

Developing finite element model to predict stresses in all the components of the hip joint using ANSYS, this resulted in the development of geometric nonlinear model of the hip joint.

In order to calculate fatigue life, nine different postures in hip joint (using three different materials such as CrCo, Ti6Al4V, and UHMWPE) are considered. It is concluded that CrCo and titanium alloys can be considered as the most appropriate materials as a substitute of cementless hip. Furthermore, UHMWPE material is a suitable material to be used for stem for stress shielding purpose, but its performance against fatigue loading is not up to the mark. Moreover, most suitable shape of stem considering all loading is conical [3, 4].

Developing a framework for analyzing the cement fixation in acetabular replacements from fatigue integrity point of view, a newly developed hip simulator was utilized for simulating effects of the loading which are generated during walking and stair climbing. Analysis of experimental results reveals that deboning at the cement interface is the main reason of malfunction, and this is consistent when compared with the constant amplitude fatigue test. The number of cycles to failure is observed to be lower as compared with hip simulator. Finite element evaluation of implanted bone samples additionally showed new hip simulator study. This failure mechanism is regular with that of samples tested below consistent amplitude fatigue. Every other prospective is that under physiological loading situations (walking and stair hiking), preliminary defects occurring at the interface point of bone/cement might also subsequently lead towards failure of the interface [4].

Jenan has manufactured four types of materials by adding nanoceramic particles. These materials are polyetheretherketone (PEEK), alumina (Al_2O), titanium dioxide (TiO_2), and reinforced biocomposites. It is concluded that reduction of 26, 09%, and 20% happened for maximum equivalent elastic strain and maximum strain energy, respectively. And also comparison with natural femur bone material reveals that safety factor increases by 5 and 81%, and the biocomposite caused the increased in fatigue life greater than 40 and 43% [5, 6].

Using finite element analysis has determined the optimum coating of cementless hip stem, and horizontal FGM is introduced at the medial proximal region of the femur to relieve stress shielding as well as shear stress lesser in magnitude developed across the bone and coating. The resulting optimal thickness of coating is 500 μm. This coating (rich in hydroxyapatite due to composition variation) is applied to the neighboring region of stem, whereas graded hydroxyapatite is applied near to the femoral bone. The increase in the distribution of von Mises occurred about 60% in a stem made up of titanium and 15% in the stem of titanium (having HAP coating) and the medial proximal region of the femur. Alternatively, a decrease of about 18% and 6% occurred in the maximum lateral shear stress, and also maximum medial shear stress decreased by 35% and 8%, respectively. [7, 8]

Proposed the optimum coating of cementless hip stem with the assistance of FEA and optimization method making use of vertical graded FGM in order to lessen stress shielding at the medial proximal region of the femur and reducing the interface shear stress between the coating and bone. Von Mises stress developed (on the medial proximal location of the femur) experienced increase of 65% and 19% and a reduction of "the maximum lateral shear strain". There is reduction of medial stresses by making the stem with the titanium and titanium coated with HAP. The optimum thickness of the material is found out to be 500 lm. The composition, which results in hydroxyapatite spreading in greater amount in the region, has a parameter of 0.1 [9].

Carried out research for total hip arthroplasty (THA) and hip stem (made up of functionally graded implants) is up to the mark as of Ti alloys with the assistance of six exceptional models. Maximum von Mises strain accelerated in each cortical and cancellous bone using Ti alloys with HA. The use of TNZT-HA stem in cortical and cancellous bones led to the growth of von Mises stress. In comparison to the stem of Ti alloys, better stresses dispensed within the larger vicinity of the central portion of cortical bone. Common pressure electricity improved the use of a femur stem from the second generation of Ti alloys as an FGM with HA in both cortical and cancellous bones. Stem is made up of FGM materials having lower stiffness in axial direction as compared to stems made up of titanium [9–11].

The developed hip joint model using Ansys and static analysis evaluated the distribution of stresses [12]. The fabric used is UHMWPE (having composition by weight about 50%), whereas E-glass have weight composition of fibers about 40% and matrix formulation of TiO_2. On the basis of static analysis, fatigue life of hip joint is estimated. The linear Palmgren damage rule is applied and found that factor of safety is considerably less than 1. This indicates that safety factor is well below the acceptable limits [10].

Bulent Ekici has used optimization techniques along with different material models and combining it with three-dimensional stress analysis model to achieve optimized layout of femoral aspect preserving in view of reduction and smoothness adjoining to the interface. Static and dynamic analysis has been used to estimate the factor of safety considering fatigue life for Ti alloy and chromium/cobalt alloy materials. The fatigue life calculated based on infinite fatigue lifestyles criteria using available fatigue theories in literature such as Goodman, Gerber, and Soderberg. The stem made up of Ti alloy is the best suitable material for fatigue primarily based on static and dynamic loading. It is concluded that stem shape is safe for fatigue considering static loading; however, dynamic loading may cause failure due to repetitive nature [13].

Yunus and Mehmet studied hip implants made up of lightweight material using lattice shape, utilizing it for fatigue design in order to utilize it in total hip arthroplasty (THA). The lattice shape employed resulted in reduction of mass with the aid of 15–17% in comparison to a strong one. Additionally, it is concluded that by increasing pore diameter improvement occurred in bending behavior of implant using lightweight at the same time as preserving the lattice shape geometry constant. [14, 15]

Investigated implants made up of different porous FGMs are designed based on predominant configurations, such as NFGP, IFGPs, and DFGPs, while finite element is employed to analyze the actual femoral bone. It has been discovered that the IFGPs would be best and suitable for strolling situations considering its load bearing capability; however, they do not help in increasing the stress which would actually happen on real bone, whereas DFGP helps in the development of load increment on the bone. The reduction of the elastic modulus of the base cloth of the prosthesis would result in the misalignment across the prosthesis and bone. This would affect the stress shielding, which results in very bad effects on an affected person. There is a very less statistics available on the porous FG prostheses with advanced strain defensive; the outcomes provided may be instrumental towards future design of femoral prostheses under everyday strolling loading situations [13].

Carried out FEA for static and dynamic loading considering four extraordinary (stem 1, directly; stems 2 and 3, notched; and stem 4, curved geometry) stem shapes, the factor of safety is calculated for fatigue life under both loadings (static and dynamic). The finite element analysis reveals that stem shapes are safe under static loading; however, the outcome of fatigue analysis suggested that stem 2 would fail on interface point of cement bone. The best suitable stem shape is 3 (made up of Ti alloy) considering static and dynamic loading as well as for fatigue [14].

Oshkour evolved a three-dimensional finite element model of femur and cement using functionally graded

Table 1: Maximum/minimum von Mises stress and fatigue life based on alternating stress.

σ_{max}	σ_{min}	σ_a	σ_m	$\sigma_f{}'$	N
30.323	0.241e-4	15.161	15.161	23.837	6.9×10^4
40.045	0	20.012	20.012	38.65	7.2×10^3
26.815	0	13.407	13.407	19.805	4.1×10^5

Table 2: Material model implemented.

S.no	Material #	1st phase	2nd phase	3rd phase
1.	Material 1	Ti	—	HA
2.	Material 2	CrCo	—	HA
3.	Material 3	CrCo	Ti	HA

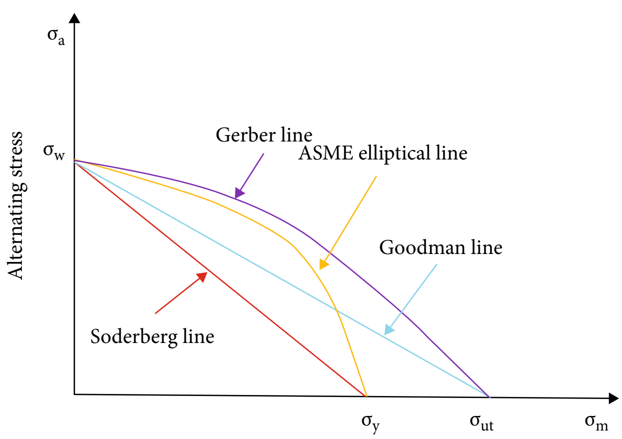

Figure 1: Alternating stress theory.

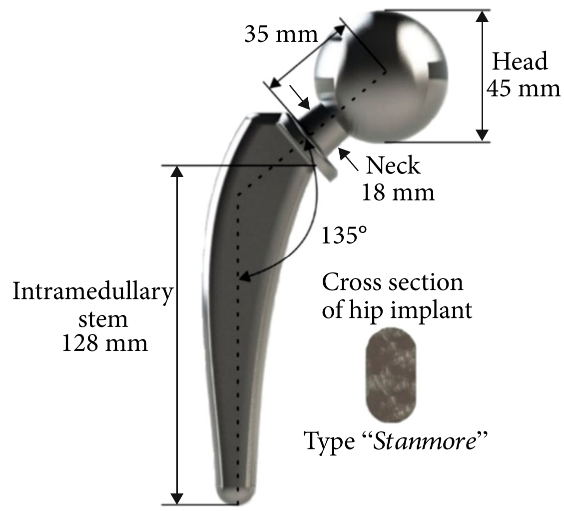

Figure 2: CAD model of human femur.

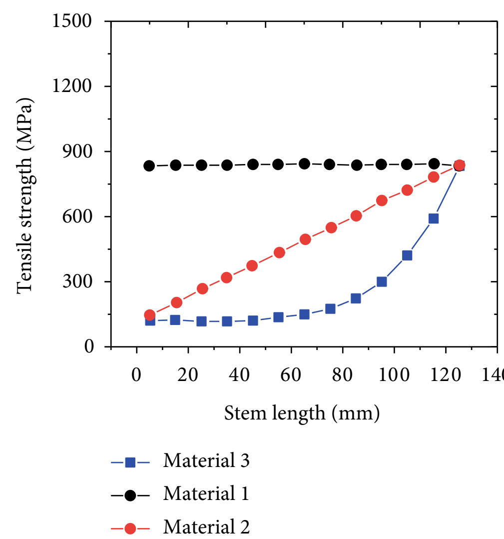

Figure 3: Functionally graded materials tensile strength from distal to proximal.

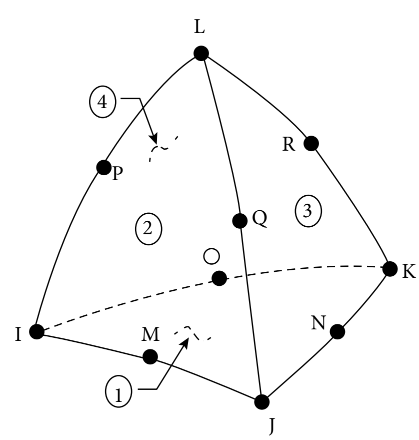

Figure 4: Three-dimensional element (SOLID187) used in this work.

materials (FGMs). The hip prosthesis is made by varying the exponent values using 0, 1, and five, respectively, for changing the gradient composition of FGM. The pressure variation across the neck is independent of the prosthetic fabric. There is reduction of strain inside the FGMs' femoral prosthesis. Some other advantages are extra uniform distribution at the cement layer and increase in strain on the bone, which allows in reduction of pressure protection [17].

Abdellah et al. introduced a novel method in which by virtue of varying cross section of cemented hip prosthesis with the help of changing profile and size based on reality. The self-regulated method turned into an applied method and observed that cement damage and pressure defense are two facets of the coin. So as to have a balance, geometrical optimization of the implant go sections is required. The approach evolved will be improved further by way of incorporating the evolutionary fashions of damage assessment and implementing a more realistic model of the femur. Further to it is able to help in analyzing the adjustments in floor structure as well as in implant duration [16, 17].

All has studied prosthesis by means of adjusting elastic modulus and also altering the quantity fraction gradient exponent inside the radial, longitudinal, and longitudinal-radial instructions. Four cases (considering attachment of the prosthesis with the spongy bone and two instances of

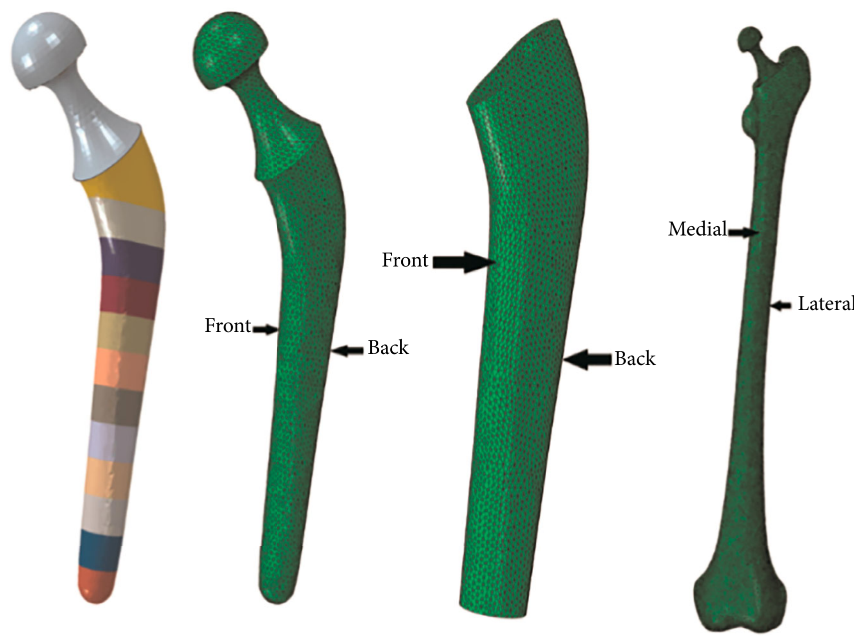

Figure 5: Stem (a), cement, geometry of femur, and mesh (b).

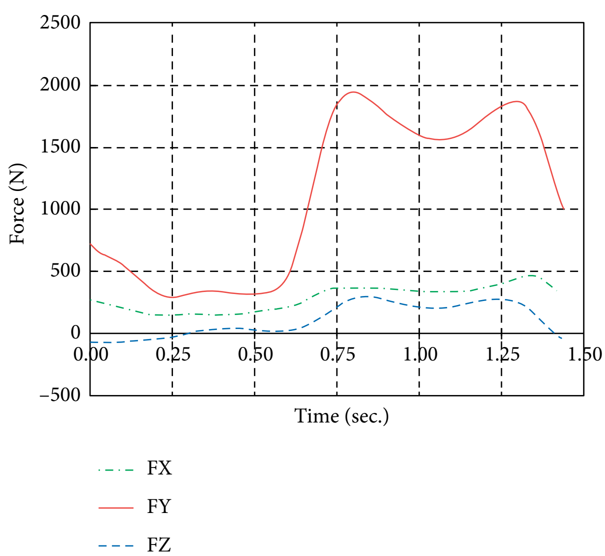

Figure 6: Loading pattern.

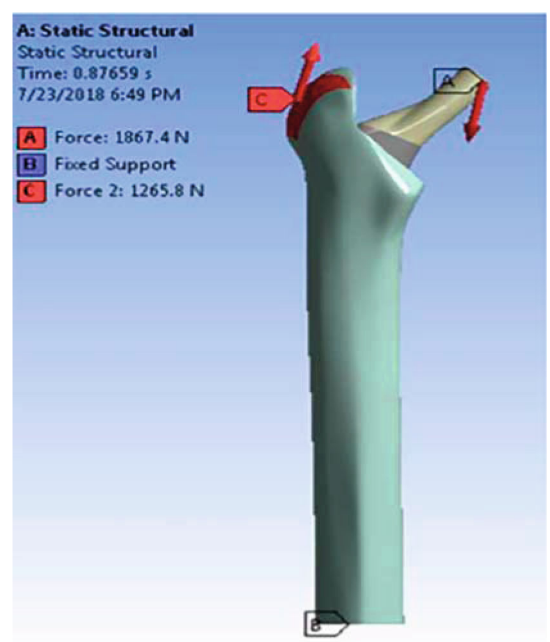

Figure 7: Loading boundary condition.

implemented loading) are studied. The functionally graded prostheses added extra SED in the bone and confirmed an excellent improvement that resulted into femur from resorption changing the gradient formulation with the increase in the exponent values. The extra pressure aroused in the bone and cement layer by way of adopting and increasing the gradient of volume fraction. A decrease in the prompted interface stresses occurred on the interface of bone-prosthesis by variation of volume gradient due to changing in the exponent values. The radial variation of gradient due to exponent values has greater impact as compared to changes in longitudinal direction [18–21].

In the present research works, we have carried out fatigue analysis using ANSYS for analyzing the cementless hip joint system using a functionally graded material to investigate its life and other factors affecting it. In addition to it, modal and harmonic analysis is performed, which is not performed earlier for hip joint as per best of our knowledge. This makes this research as a unique study from modal and harmonic analysis point of view. The contribution of study to perform the harmonic analysis is to evaluate the

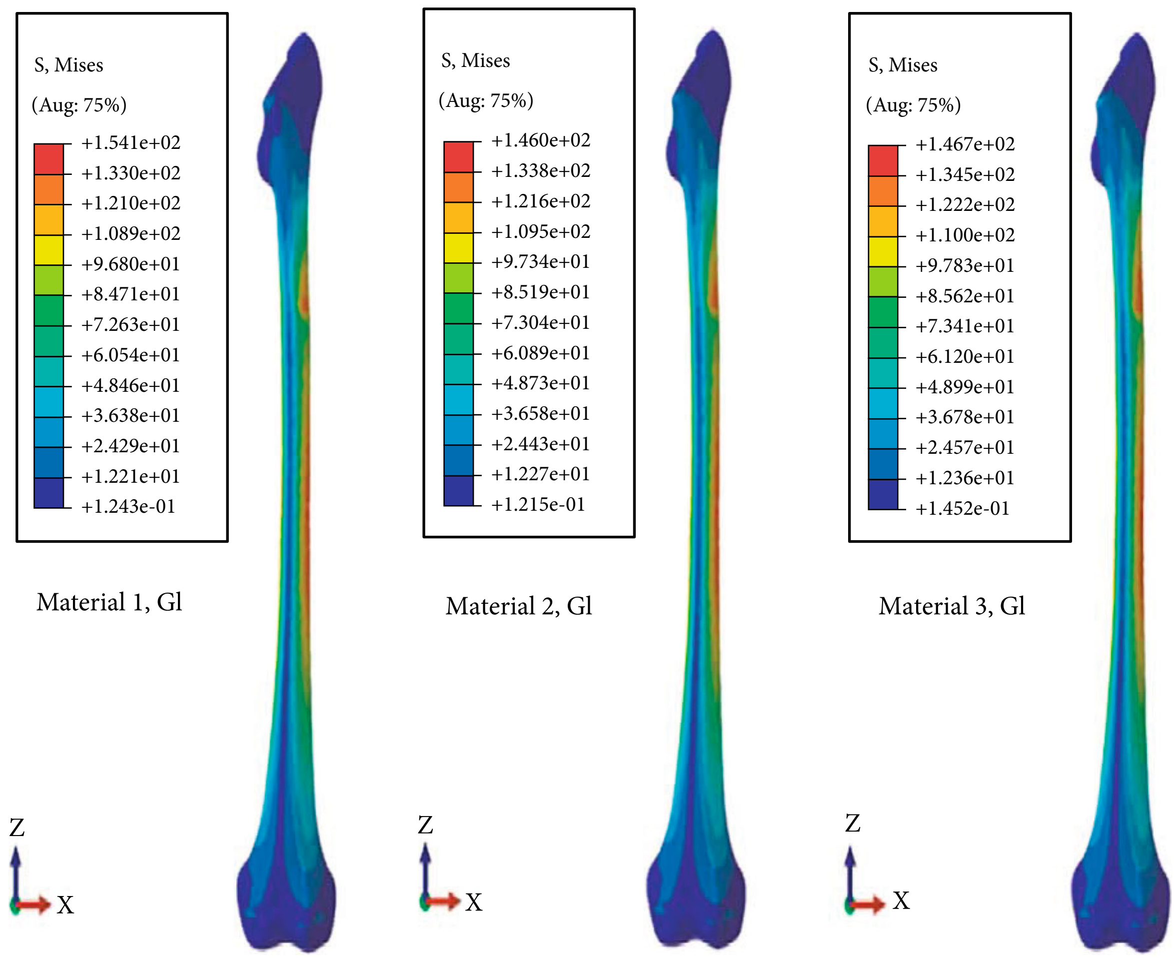

Figure 8: Von Mises stresses distribution in stem.

dynamic effect of time-varying loading such as during climbing, moving on stairs, and carrying overweight.

2. Methods and Theory

2.1. Fatigue Analysis. The analysis is conducted by considering Goodman's stress correction theory.

The relationship between alternating and mean stress using Goodman equation is given by

$$\frac{\sigma_a}{\sigma_f{}'} + \frac{\sigma_m}{\sigma_u} = 1, \tag{1}$$

where σ_a is the alternating stress, $\sigma_f{}'$ is the effective alternating stress, σ_m is the mean stress, and σ_u is ultimate tensile stress (41.5 MPa).

Equation (2) can be utilized for determining the mean stresses and Equation (3) for finding the alternating stresses as given in (as shown in Table 1)

$$\sigma_m = \frac{\sigma_{max} + \sigma_{min}}{2}, \tag{2}$$

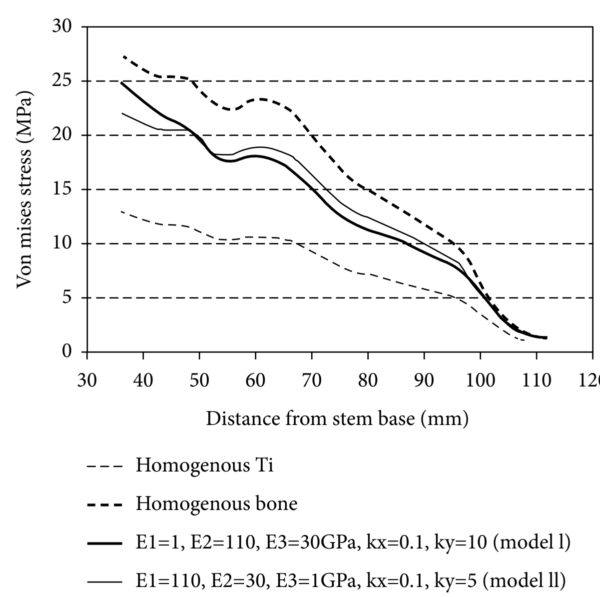

Figure 9: Von Mises stress distribution in the proximal medial bone [1].

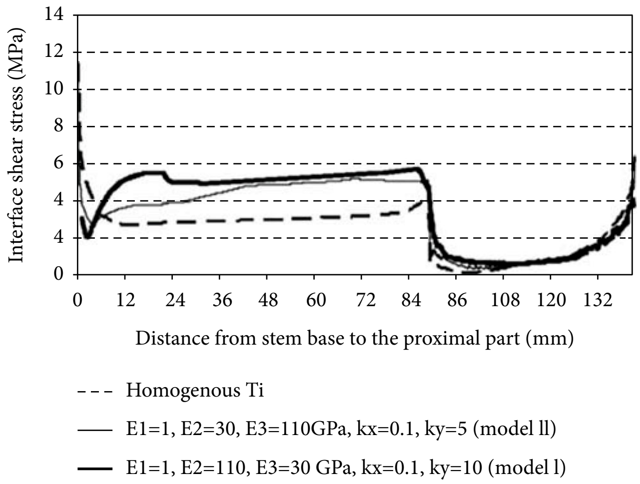

Figure 10: Distribution of shear stresses at lateral interface of stem/bone [1].

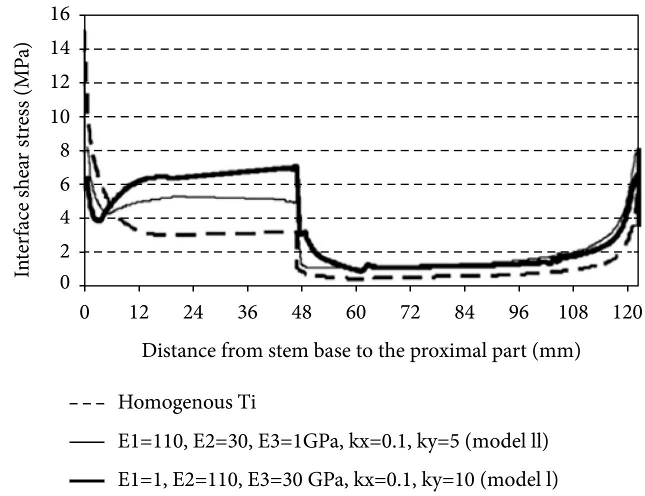

Figure 11: Distribution of shear stresses at medial interface of stem/bone [1].

$$\sigma_a = \frac{\sigma_{\max} - \sigma_{\min}}{2}. \quad (3)$$

Re-arranging Equation (1) gives alternative stresses

$$\sigma_f = \frac{\sigma_a}{(1 - \sigma_m/\sigma_u)}. \quad (4)$$

The fatigue life can be determined using effective alternating stresses [16]

$$\sigma_f = \left(aN^b\right), \quad (5)$$

$$N = \left(\frac{\sigma_f{}'}{2}\right)^{\frac{1}{b}} \text{cycles}, \quad (6)$$

where $\sigma_f{}'$ is the effective alternating stress

$$a = \frac{0.9 * (\sigma_u)^2}{\sigma_e}, \quad (7)$$

$$b = -\frac{1}{3} \log \frac{0.9 * \sigma_u}{\sigma_e}. \quad (8)$$

Now the number of cycles to failure for each load case is decided by the usage of effective alternating stress as given inside the Table 2.

Number of cycles against different load cases can also be determined with the help of alternating stresses.

It is assumed that cycle 1 arises at one time, cycle 2 occurs twice, and cycle 3 occurs three times. The fatigue existence of hip joint version is calculated by means of using Palmgren linear harm rule. This rules states that failure is predicted when the sum of ratio will become either 1 or $100\% \sum (n/N) \geq 1$.

The safety factor found is more than one, which indicates that the part is safe under design. The average life

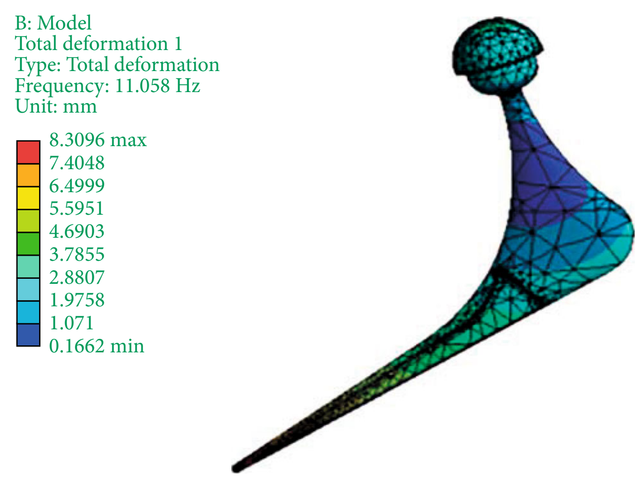

Figure 12: Mode #1 of stem.

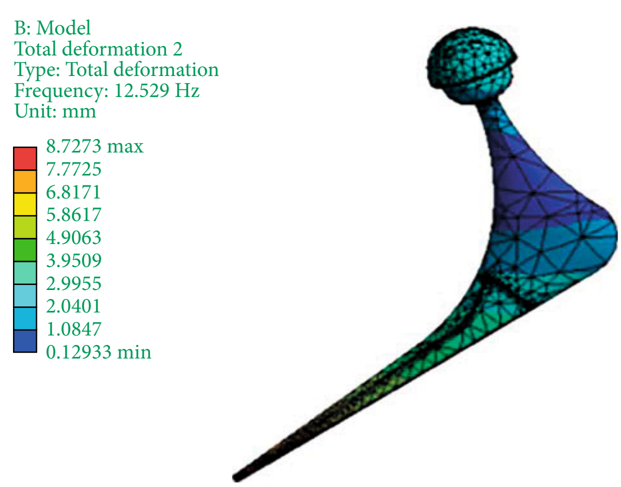

Figure 13: Mode #2 of stem.

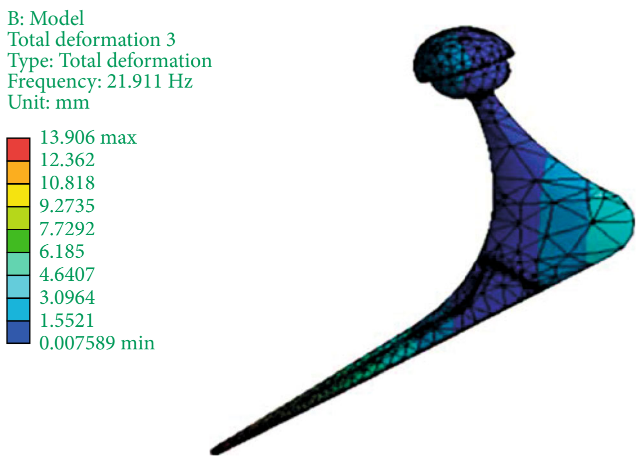

Figure 14: Mode #3 of stem.

expectancy can be calculated by taking the inverse of fatigue life expectancy of the model 0.3284×10^5 cycles.

The graph below shows the endurance limit of the hip joint under the application of the force. It also shows the constant load amplitude (Figure 1).

2.2. CAD Model and Material Properties. A CAD model having three-dimensional view of a human femur was created utilizing the Solid Works® shown in Figure 2.

2.3. Properties of FGM Femoral Stem Implant Coating. In orthopedic applications, typical hip femoral prostheses broadly used biomaterial comprised of either titanium alloy (Ti) or chromium-cobalt (CrCo) and hydroxyl-apatite (HA). In this study, FGM is therefore designed using three different combinations as defined in Table 2.

The mechanical attributes of the materials applied in the cortical bone were assumed dynamically isotropic ($E_x = E_y = 11.5$ GPa, $E_z = 17$ GPa; $G_{xy} = 3.6$ GPa, $G_{xz} = G_{yz} = 3.3$ GPa; $v_{xy} = 0.51$, $v_{xz} = v_{yz} = 0.31$ GPa).

3. Finite Element Analysis

FEM model is developed in ANSYS Workbench. The element type SOLID187 is a ten-node element (see Figure 4). Due to irregular geometry, elements are tetrahedral in shape. It has 3 degree of freedom per node. Meshed model is shown in Figure 3. Loading pattern for a normal person considered in this work is as shown in Figure 4. Loading boundary condition applied on FEM model is shown in Figure 5. Bottom of stem is considered fixed, as shown in Figures 6 and 7.

4. Results and Discussions

4.1. Static Structural Analysis. Figure 8 shows the von Mises stress in the femoral prosthesis and femur to illustrate the impact of numerous substance models on stress transmission. The materials, in the end, revealed thelon Mises pressure's influence on the proximal part of the femur and the least pressure influence on their gathering on the femoral prosthesis.

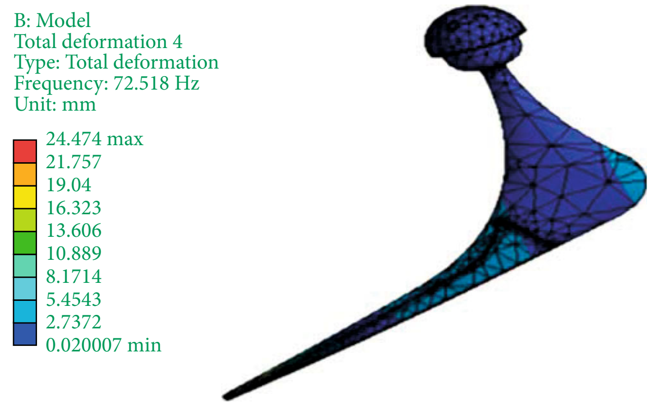

Figure 15: Mode #4 of stem.

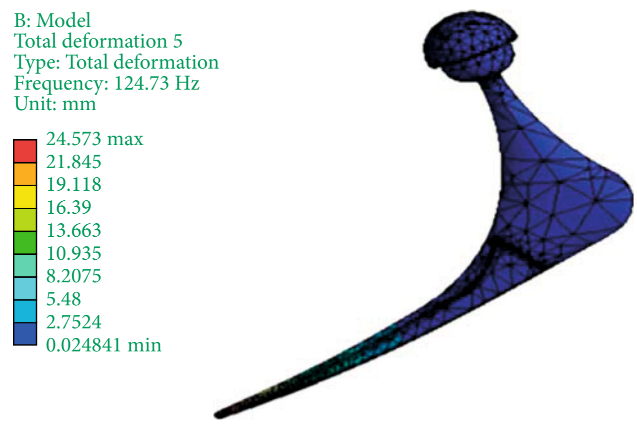

Figure 16: Mode #5 of stem.

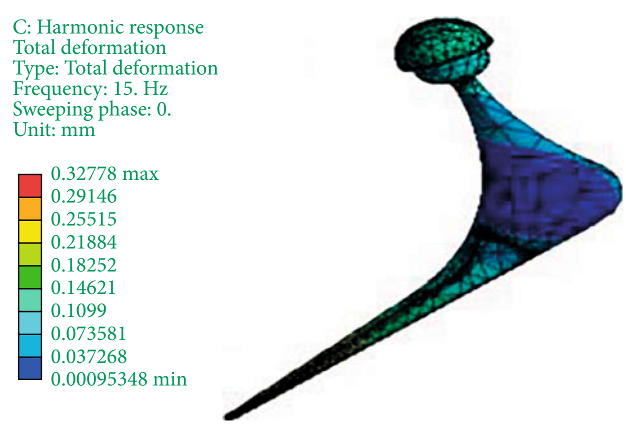

Figure 17: Deformation of hip joint in harmonic response.

Figures 9–12 are reproduced showing the von Mises distribution from a study carried out by [1]. The results obtain through FEA are closely matching with earlier studies.

4.2. Modal Analysis. Modal analysis helps one to establish the vibration characteristics of a mechanical system or a component that indicates movement under complex loading conditions for various sections of the structure. In the design

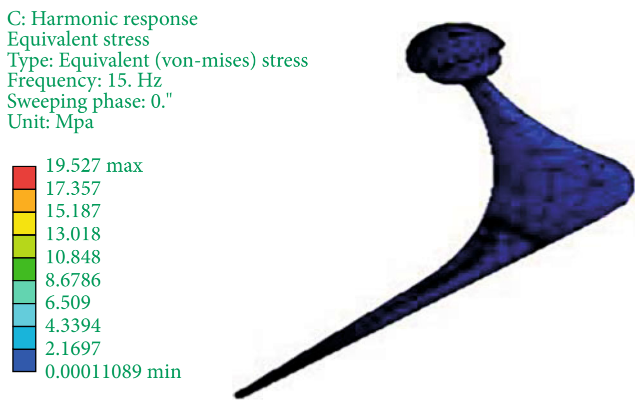

Figure 18: Equivalent von Mises stress of hip joint in harmonic response.

of a structure for complex loading conditions, natural frequencies and mode forms are the critical parameters. The dynamic properties of a system concerning modal parameters are commonly described by modal analysis: the natural frequency, the damping factor, the modal mass, and the mode form. Four different frequencies are determined for the hip joint in the modal analysis, as shown in Figures 12–18.

4.3. Harmonic Analysis. Harmonic analysis is a type of linear dynamic analysis that helps to evaluate how a mechanism responds to excitation at specific frequencies. It is also known as frequency response analysis. A modal analysis is needed before performing a harmonic response analysis since the input frequencies for a harmonic response analysis are the outputs of a modal analysis. Harmonic response analysis is commonly used to measure the stresses caused by continuous harmonic loading on machinery, automobiles, or process devices, such as rotor imbalance or cyclic loading in a combustion engine. The steady-state response of a linear elastic system to a series of harmonic loads of specified frequency and amplitude can be determined using harmonic response. Complex displacements or amplitudes, as well as phase angles, are returned. The load applied to the model steady-state load has fixed frequency. Loads can change by varying time, but excitation occurs at a fixed frequency.

The maximum amount value of stress generated under the influence of force is19.527 MPa, and the maximum deformation determined in the harmonic analysis is 0.32778 mm.

5. Conclusion

FGMs can be powerful biomaterial substitutions, expanding the lifetime of the substitution and preventing the prosthesis from slackening. More importantly, the stress shielding phenomenon decreases. Hence, FGMs can be powerful biomaterial substitutes in delivering another generation of hip prosthetic parts designed for decreasing pressure protecting, consequently expanding the life span of the substitution of the prosthesis.

It can be concluded that this was an optimized design requiring less amount of material as compared to previous research works which ensure that our model was more techno-economically feasible.

Moreover, after the applied material reduction, the natural frequency and deformation response exhibited by our model were quite satisfactory. The deflection comes out to be 0.33 mm at frequency of 15 Hz. The equivalent von Mises stress is found to be 19.5 MPa. These values are closely matching with previous studied by [1].

The safety factor found is more than one, which indicates that the part is safe under design. The anticipated life of stem model is 0.3284×10^5 cycle.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

There is no potential conflict of interest in our paper.

Authors' Contributions

The author has seen the manuscript and approved to submit to your journal.

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