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Design and analysis of cementless hip-joint system using functionally graded material

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Functionally Graded Materials (FGM) are extensively employed for hip plant component material due to their certain properties in a specific design to achieve the requirements of the hip-joint system. Nevertheless, if there are similar properties, it doesn't necessarily indicate that the knee plant is efficiently and effectively working. Therefore, it is important to develop an ideal design of functionally graded material femoral components that can be used for a long period. A new ideal design of femoral prosthesis can be introduced using functionally graded fiber polymer (FGFP) which will reduce the stress shielding and the corresponding stresses present over the interface. Herein, modal analysis of the complete hip plant part is carried out, which is the main factor and to date, very few research studies have been found on it. Moreover, this enhances the life of hip replacement, and the modal, harmonic, and fatigue analysis determines the pre-loading failure phenomena due to the vibrational response of the hip. This study deals with the cementless hip plant applying the finite element analysis (FEA) model in which geometry is studied, and the femoral bone model is based in a 3D scan.

1. Introduction

In the success of hip replacement, prosthesis stiffness is very significant [1]. Two occurrences happen due to the stiffness incongruities between the femoral prosthesis and hosted bone. The mentioned occurrences are stress shielding and micromotion. Both of these are caused by low and high prosthesis stiffness. In the case of stress shielding, due to the more eminent rigourousness of the prosthesis as

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compared to the bone, loads that are present on the hip joint move to the distal end from the proximal part. Though there is a similarity between the bones' behavior and engineering material behavior, the bone is an alive tissue and is capable of rebuilding harmonizing to the environment, whether mechanical or chemical. It is the load reduction due to which the bone loses its strength and can cause a failure of the prosthesis and the THR (Total Hip Transplant) [2]. The prosthesis stiffness or rigidity methods can be represented by optimization of material property and geometry for improving THR stiffness life and bone stiffness configuration. In the past, researchers have replaced the conventional materials, and a good example of it is application of composite in femoral prosthesis [3].

Fig. 1 shows the 3D modeling of the hip joint system. The first part of the figure shows the hip joint with the femoral head and femoral stem, while the last picture shows the internal structure of the bone. Meshing is done on the component for the analysis. It was the biological structure from where the concept of functionally-graded materials or the FGMs were taken. The changes that occur between the cortical bone and spongy bone in the cortex make a layer with an internal surface that shows the gradation of functions of biological structures [4]. FGMs have been selected according to the changes that occur in their mechanical properties and those FGMs can be employed for giving shape to the newly-developed prosthetic devices. The mechanical attributes of FGMs can be dealt with by altering the bulk of separate stages of every material. Those FGMs are used to enhance the load-bearing capacity [5]. For example, the femoral prosthesis and the acetabular cup, which are made of an FGM, show a higher toughness and higher wear-resistant if associated with a metallic counterpart. Bondok and Enab [6] made an analysis that is also called the FEA or Finite Element Analysis. In their work, they discovered less shielding that takes place on the tibia tray. Weinans et al. [7] came up with the concept of stress shielding and interface shear stress and stress attitude by adding the FG prostheses in the THR.

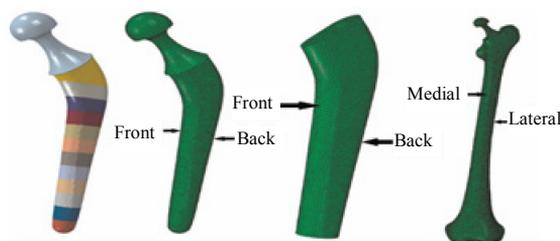


Fig. 1. Part modeling

Biomaterials should have the capacity to fulfill the requirements that range from biological to mechanical characteristics. These include corrosion resistance, strength, bioactivity, fatigue durability, etc. If the material used has single composition and stable structure, it may not be able to satisfy all the requirements [8]. However, if there is a structure available of a tailored material, it will have

the capability to fulfill multiple functions in a single component. Now, there is an observable growth in the last twenty years in the usage of composites. The hybrid material utilizing the FGM belongs to a class of elastic grading materials and is also multi-functional. Therefore, the FGMs provide a structure that can be applied in making engineered biomaterials. This category of material is now very prominent and famous in biomedical applications. For dental implants, the most applicable ones are the FGMs [8]. Now, the concept of usage of an FGM with aluminum titanium and porosity gradation is a good option to lower the stress-shielding effects of wear on the polyethylene and the surrounding bones. It also enhances the fixation and bioactivity of the bone-implant border. These kinds of properties can reduce the aseptic problems and increase the lifetime of the implant. However, if the general properties of the FGM combining with those of the knee joint, don't guarantee a good result there will be a need for the development of an optimal design of the FGM femoral component to get success. Moreover, the computational design optimization can ensure the best performance for the components of the hip joint and allow for classifying the sensitive variables to create an improved control plan.

There are works and studies done by different authors that deal with the enhancement of mechanical properties of prostheses for bone and the corresponding implant stiffness, which can lower the stress shielding and increase the longevity of the THR. As far as this study is concerned, it deals with the development of original prosthetic devices from an FGM with altered mechanical attributes. These attributes are considered in both transverse and mesial planes. The FEA was engaged to recognize the strain energy, and in the primary stages to gain, the von Mises pressure of interfaces like cement, bone, and prostheses was employed. The adjustment of the properties of the Functionally Graded (FG) prostheses can be done by varying the volume fraction gradient. In the present research works, we have carried out a finite element analysis of a Cementless Hip-Joint System using a Functionally Graded Material to investigate its life and other factors affecting it. Modal analysis and harmonic analyses were performed on it. The natural frequencies of the designed system and the corresponding deformation were determined by the ANSYS Workbench. During this investigation, we also measured the factor of safety. A discussion of the fatigue life of the hip joint system was also incorporated. It is worth mentioning that this is a complete FGM-based analysis.

2. Literature review

In engineering design, the selection of material is one of the most hectic tasks. As there are more than two lac materials, therefore, the choice is very difficult. There are other things to be kept in mind like considering the meeting requirements and characteristics that are to be used. It took twenty years for the researcher to look for the most appropriate material. This is one of the most important stages of finding an appropriate material in engineering design. Then, the usage of each

material needs a methodology of selection and this can be an important task in solving the problem. This task requires a decision-making process and it needs experience and appropriate methods of engineering. The significance of problem-solving difficulty can be comprehended by considering different examples from daily life. For example, an airplane consists of 2 to 6 million parts of different materials, a submarine of 120 thousand parts, a car of 25 to 20 thousand parts, and a tractor of 15 to 20 thousand parts [9–11].

Conventional selection is a method that is both old and simple. In this method, one obtains information about the performance characteristics of materials from the supplier and manufacturers. In addition to it, there are also other methods such as computer-based material selection [12–15]. Zha [16] introduced designs for the elimination method. It became possible to find out the location of the material groups. Another available method is an information-based system, but its usage is limited due to its complexity and the necessity of processing an extensive knowledge. There are some other methods, however, these didn't allow the material to be weighed regularly [17]. In previous years, some researchers came up with different methods to provide the strategy for a better material selection. In the following years, weight property record was utilized by Findik and Turan [18]. For the sifting options, some analysts offered a methodology called the master framework-based material determination [19]. To put it plainly, the meaning of connection point has drawn huge attention from numerous researchers who concentrate on a wide scope of controls. On the opposite side, the FEA or Finite Element Analysis is a solid method that has been utilized by numerous specialists [20]. So, this study provides an insight into the FEA method for patient-specific and biomedical applications. In previous years, the development of new materials and material selection has become very significant for the control of biological and mechanical properties of the tissues in living bodies. There is also a threat of dysfunctionality when damaged tissues are replaced with artificial ones. Therefore, the selection of material should be very careful and it should readily meet the morphological and/or physiological requirements. As far as missing body parts are concerned, the prostheses can be treated as their replacement. A critically diseased organ must be removed. Injuries, tumors, gangrene, or inflammation damage the organs very badly. By removing the unhealthy organ, the rest of the body can be cured. Otherwise, the rest of the body can be badly affected. These types of implants are present in the problematic region using auxiliary materials such as the bone cement and the surgery equipment [21, 22]. There are four steps for the selection of prosthetic organs. The first is to set goal parameters that ensure strength, low cost, and corrosion resistance. The second is to choose the material for the candidate, keeping goal parameters in mind front. Again, keeping the goal parameters in mind and ranking the candidates is the third step. The fourth and final step is the selection of an optimal material for the specific cases. The design solutions must guarantee have enough mechanical and biological performance and low manufacturing cost, therefore, there is a high need for artificial replacements. In 1938, the THA was first introduced and was

used in more than three lac operations, and since then such operation have been carried out all over the world [23]. In bioengineering, the THA is the most popular research area and there is a great population of patients that require replacement of the hip joint. Most importantly, the number of young patients is also increasing. It is due to lifestyle changes [24]. Various publications in the field of biomedical engineering reveal that different methods are used for material selection. Though, there is not any standard method that one can claim is the most appropriate one. However, further research and investigation can provide a better understanding in the future. Some investigators and researchers introduce different methods for the selection of material. These include the Analytic Hierarchy Process (AHP) [25], AHP integrated VIKOR method (Vise Kriterijumska Optimizacija Kompromisno Resenjemeaning) [26], also, the MULTIMOORA or Multi-Objective Optimization Based On Ratio Analysis [27]. However, none of them takes into account an easy-to-understand explicit math of the femur. To best of author's knowledge, there isn't any examination that reviews the response of composite materials specifically to femur's vibrational dynamics. The vibrational behavior and wear of materials used to replace the joint decides on many problems which lead to the loosening of a prosthesis. Metallic alloys, polyethylene, and ceramics are presently the materials used. The ceramics used are made up of alumina and zirconia manufactured originally. When in contact with ceramics, wear of the UHMWPE is very low, low in the Co-Cr alloy, and heavy in steel.

3. Methodology

A 3-dimensional (3D) framework of a human femur was created utilizing the Pro/Engineer programming. The models of the bone and the prosthesis were accustomed to the limited component programming package ABAQUS where they were embedded into a solitary limited component (FE) model and an intermingling trial was executed on the FE (finite element) model. The static examination was applied to recreate a virtual test setup for the embedded thighbone, on the most elevated power and torsional effect generated due to the typical strolling and step climbing, respectively. The heap was applied on the focal point of the inflexible top of the femoral prosthetic device dependent on the heap design, including the heel strike, single-leg position, push off, toe-off, and swing stage during the stride, as demonstrated in Fig. 2. The hip contact power and the muscular tissue stacking at the hip joint depended on the examination by Bergmann et al. [28]. The femur was fastened at the distal end of the hip joint. Surface-to-surface contact with limited slipping and an erosion constant of 0.3 was chosen for the bone prosthesis in the non-established implantation [29]. To adjust the heaps and the material attribute to the cortical bone, a datum from the framework was characterized in the ABAQUS, with z -hub corresponding to the distinguished mid-plane of the femur and x -hub corresponding to the ab-axial shape of the femoral condyles in the cross over a plane.

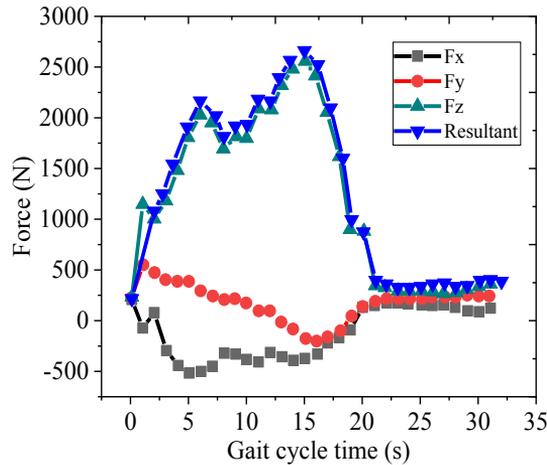


Fig. 2. Loading pattern

Today’s hip-femoral prostheses include either titanium alloy (Ti) or chromium-cobalt (CrCo). Moreover, hydroxyapatite (HA) is widely used as a biomaterial in orthopedic applications. The FGM was therefore designed using three different material models, Ti, CrCo, and HA, as listed in Table 1. In this study, Ti–HA, CrCo–HA, and CrCo–Ti–HA were considered as the substance combinations. 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; $\nu_{xy} = 0.51$, $\nu_{xz} = \nu_{yz} = 0.31$ GPa) and the light bone was characterized as an isotropous substance with Young’s modulus of 2.13 GPa and Poisson’s ratio of 0.3. The cortical bone was viewed as a transitionally isotropic

Table 1. Material model

Material Group	Material Model	First Phase	Second Phase	Gradient Exponent	Third Phase	Gradient Exponent
G1	Material1	Ti	–	–	HA	0
	Material2	Ti	–	–	HA	1
	Material3	Ti	–	–	HA	5
G2	Material4	CrCo	–	–	HA	0
	Material5	CrCo	–	–	HA	1
	Material6	CrCo	–	–	HA	5
G3	Material7	CrCo	Ti	1	HA	0
	Material8	CrCo	Ti	1	HA	1
	Material9	CrCo	Ti	1	HA	5
G4	Material10	CrCo	Ti	5	HA	0
	Material11	CrCo	Ti	5	HA	1
	Material12	CrCo	Ti	5	HA	5

flexible substance, while the springy bone, the hydroxyapatite (HA), and the titanium composite (Ti) were viewed as direct isotropous versatile substances. To allocate material attributes of the cortical bone, the flexible attributes were embedded into the ABAQUS by choosing the kind of design variables in form of meshing sizing as shown in Table 2. The FG (functionally graded) prosthesis comprised beds of Ti (titanium composite) and HA (hydroxyapatite), with a variety of moduli of versatility of the FGM (E), along the lengthwise and spiral bearings.

Table 2. Type of elements and numbers

Element type	Mesh global size (mm)	Total hip replacement components	Number of elements n	Total number of elements
3D tetrahedral element	6	Stem	3 735	71 297
		Cement	3 288	
		Femur	64 274	
	3	Stem	13 475	279 533
		Cement	8 964	
		Femur	257 094	
	2	Stem	78 705	689 175
		Cement	48 971	
		Femur	561 499	

4. Results

To clarify the impact of numerous substance models on pressure conveyance Figs. 3 and 4 show Young's modulus and elasticity variety along the length of the femoral master's proposal from lateral to the proximal terminal as a component of the substance kind and number of elements n . Initially, the strain in the femoral prosthesis is diminished. The materials, in the end, revealed the von Mises pressure influence on the proximal part of the femur, and the least pressure influence on their gathering on the femoral prosthesis. In all of the material models, the von Mises pressure along the length of the neck showed a comparative behavior. The stress began with a low value, rose to a high, and afterward it started diminishing. The von Mises strain changed imperceptibly with n and in each subplot, the bends were covered appropriately. For the different substance models, the greatest von Mises feelings of anxiety are 224.6, 61.5 MPa, and 251.96 MPa at the back and front of the neck, respectively.

Fig. 5 illustrates the von Mises pressure on the femur and femoral prosthetic device to depict the effects of various material examples on pressure dispersion. The von Mises pressure zone in the proximal piece of femur expanded with increasing n . Initially, the stress in femoral prosthetic device is diminished. Immediately,

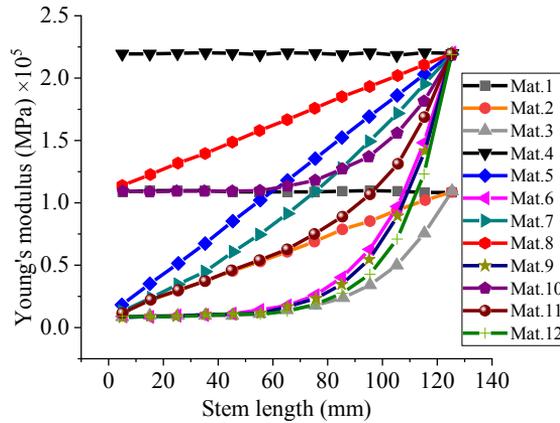


Fig. 3. Stem Young's modulus variation

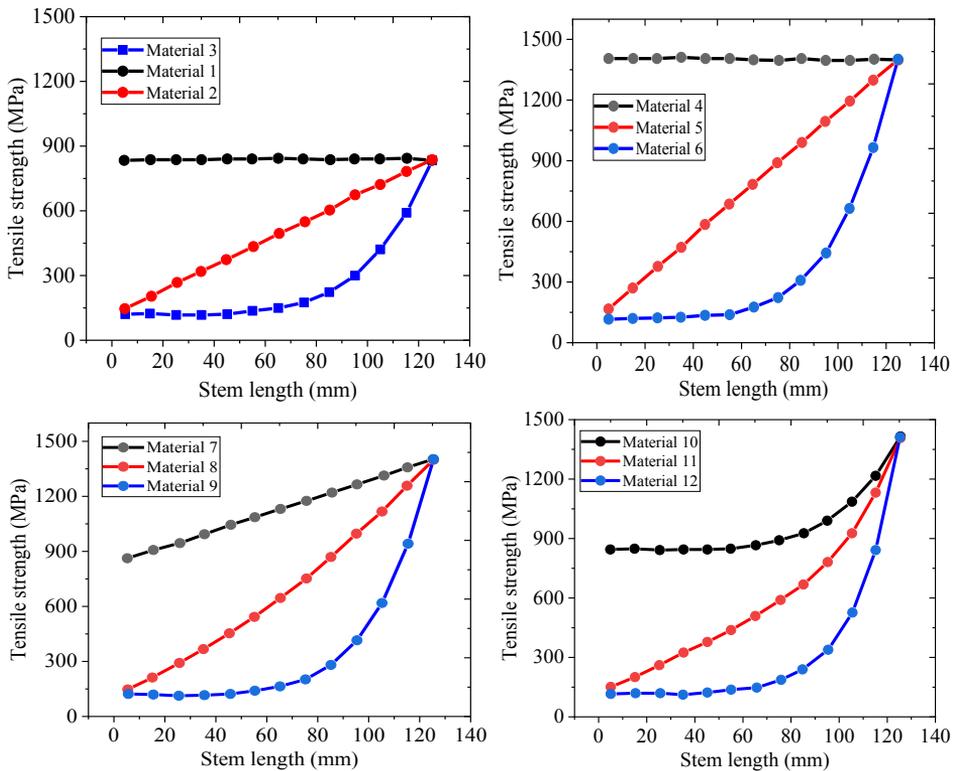


Fig. 4. Functionally graded materials tensile strength from distal to proximal

materials 3 (three), 6 (six), 9 (nine), and 12 (twelve) showed von Mises pressure influence on the proximal piece of the femur and the base pressure attains maximum in the femoral prosthetic device at their assembly.

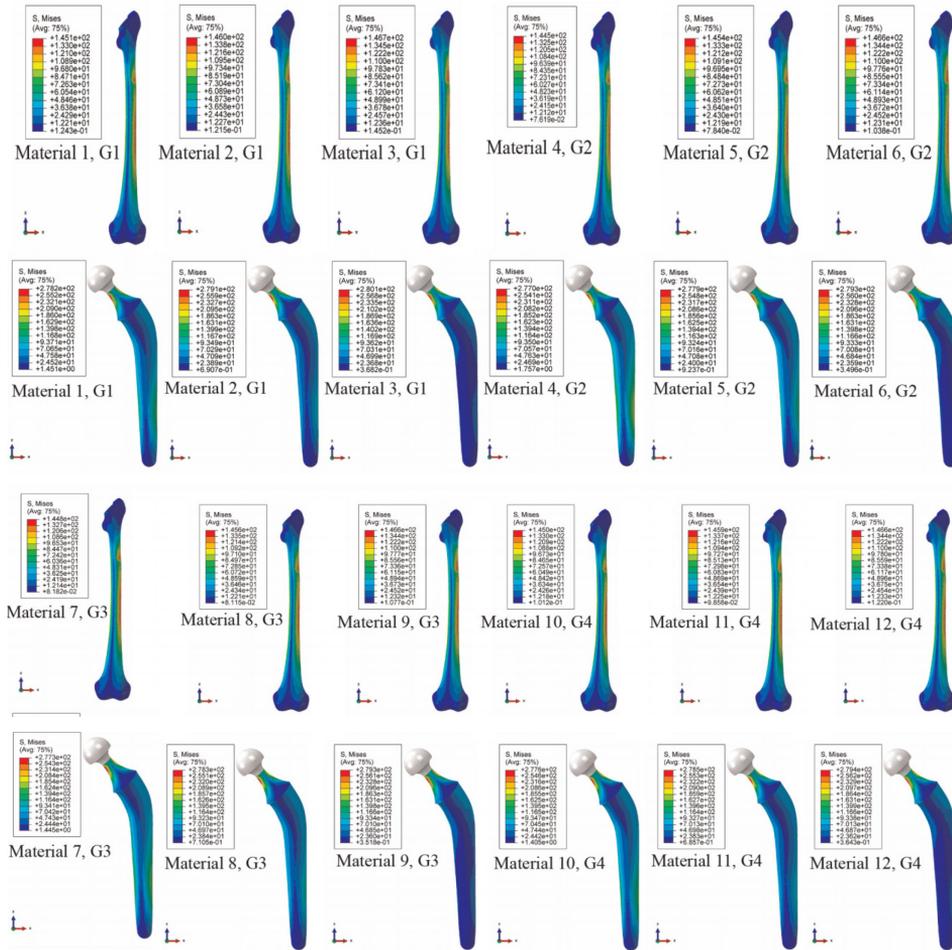


Fig. 5. Comparison of von Mises stress distribution in the femoral prosthesis and femur for various material models

The material models were dependent in terms of the von Mises pressure at the stem of the femoral prosthetic device. Its way, however, was indistinguishable from that found on account of the neck along the length, framing inward bends. As shown in each subplot, the most extreme von Mises pressure diminished as n was raised. In correlation, on the rear and forepart sides of the stem, the stems built of materials 3 and 4 showed the most reduced and most elevated estimations of maximal von Mises pressure, individually. The pressure consistently rose from the insignificant incentive to approach the distal end, where the feeling of anxiety drastically expanded. At the distal end of the concrete sheet, the sharp ascent in pressure diminished with an increment in n . In each subplot, the strain bend incline improved as n was expanded and the pressure changed possibly over the length

of concrete. The strain had an underlying high incentive on the front side of the concrete sheet that diminished to a negligible value in the long run. The strain rose to a most extreme value and kept on declining a short time later. Two pressure tops were at the front of the concrete sheet, one at the anatomy bit and the other at the distal end of the concrete bed. The proximal pinnacle pressure influence expanded, while as n increased, the pinnacle pressures an incentive at the distal end diminished. The pressure on the inward surface advanced at the anatomy end to the focal point of the femur for an area of the femur length. The pressure started from a low value and afterward rose to a high value. The von Mises pressure influence hence began with a sharp decline and kept on climbing right away. For the outside surface of the bone, the strain of von Mises was estimated for the entire size of the femur. On account of the internal surfaces of the average and sidelong areas, at roughly the stem length, the weight on the external surface diminished. This drop-in strain was to some degree more modest than the same lessening found on the inner surfaces. In the femur split up, the stem is arranged on the parallel and mean sides due to which both the inner and the outside turns up resulted in an increased bend angle and a larger von Mises strain.

5. Modal and harmonic analysis

Harmonic response analysis is a form of linear dynamic analysis that is used to assess how a mechanism responds to excitation at particular 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 its harmonic response. Complex displacements or amplitudes, as well as phase angles, are returned. Stresses may be computed at various frequencies and phase angles [1]. The load applied to the linear model in a harmonic response analysis is a steady-state sinusoidal load at a fixed frequency. Loads can change by varying time, but excitation occurs at a fixed frequency.

Modal analysis helps one to establish the vibrational characteristics of a mechanical system or a component that indicates movement under complex loading conditions for various sections of the structure. In the design 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 commonly described by the modal analysis are: the natural frequency, the damping factor, the modal mass, and the mode form. Fig. 6 illustrated five different frequencies that were determined for the hip joint in the modal analysis. As shown in Fig. 7 the maximum value of stress generated under the influence of force is

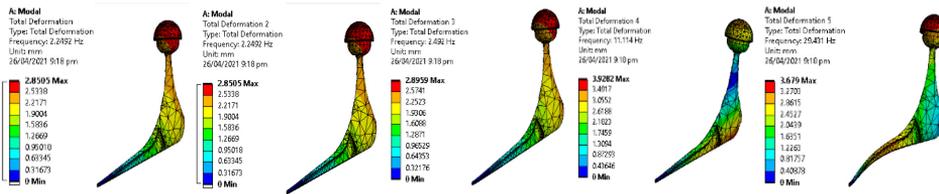


Fig. 6. Modal frequencies of hip-joint

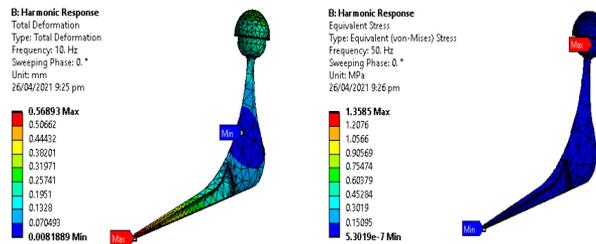


Fig. 7. Deformation and equivalent stress of hip-joint in harmonic response (estimated pressure reaction at the neck)

19.527 MPa and the maximum deformation determined in the harmonic analysis is 0.32778 mm.

The amplitude and the phase angle for the harmonic analysis of the hip joint under the application of forces are shown in Fig. 8.

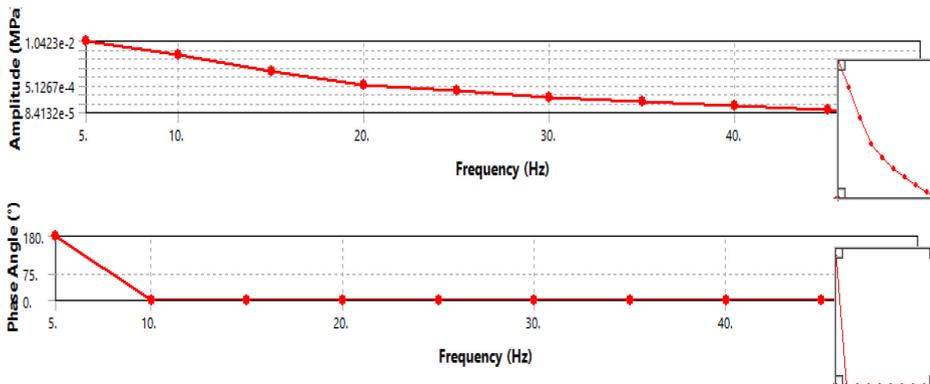


Fig. 8. Frequency response of the assembly

6. Fatigue analysis

Fatigue is a cyclic mechanism of damage accumulation in a material that undergoes fluctuating pressures and stresses. Fatigue analyses themselves typically include one of two approaches: The Stress-Life (S-N) or the S-N (Total Life) method

because there is no difference between creation or propagation of a crack, or the Local Strain (e-N) method, commonly called the Crack Initiation method that only relates to the initiation of a crack. Fatigue analysis of hip joints is conducted using the Static Structural analysis. A force of 50 N is applied at the joint portion of the structure and the bottom of the component is fixed. The analysis is conducted by considering the Goodman's stress correction theory. The graph (Fig. 9) shows the endurance limit of the hip joint under the application of the force. It also shows the constant load amplitude.

The fatigue life and the factor of safety have been measured as shown in Fig. 10. The maximum life obtained is $1e6$ and the value of the factor of safety is 5.

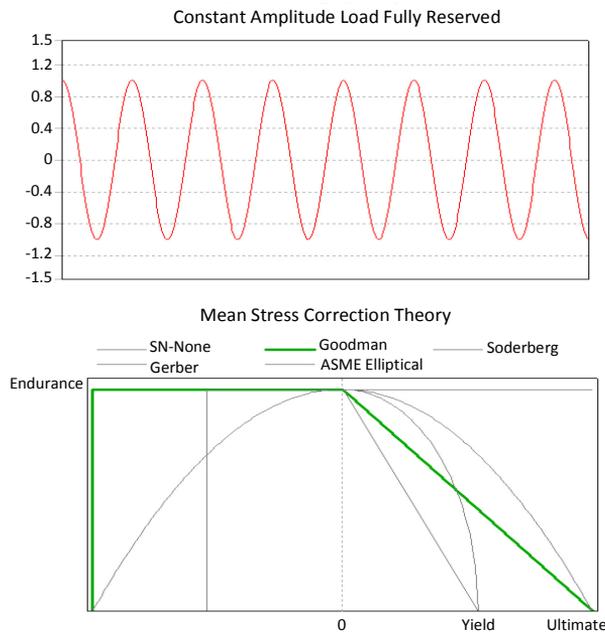


Fig. 9. Graph of constant amplitude load and stress correction theory

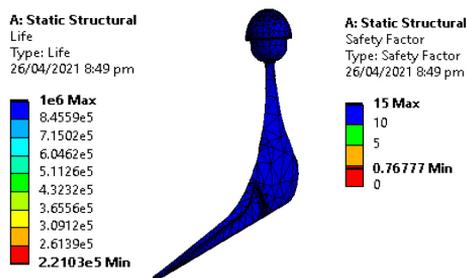


Fig. 10. Fatigue life and factor of safety

7. Discussions

To construct another generation of femoral prostheses, the ebb and flow research intended to enforce the FGMs in the field of femoral prosthetic device. This was done to decrease the pressure on the femoral prosthetic device and maintaining equilibrium in the solidness of the prosthetic device and encompassing unresolved issues like abnormal pressure and loads that cause failure. The FEA was employed to examine the impact of the FGMs on the activity of stress during stride in the THR (total hip transplant) parts. Additionally, the FEA was applied for verifying the results of this report. The FEA was completed with conventional substances, in particular, Ti and CrCo, in the femoral prosthesis. This research has confronted a few downsides. For example, the calculation of the femoral prosthesis and the surface completion were not thought of. Also, the failure of the femoral prosthetic items which were practically appraised was not expected. Also, the shortcoming is regularly the modest number of parcels in the piecewise arrangement. To survey the weariness strength, weakness investigation on the FGM femoral prosthetic device ought to be presented.

Figs. 11 and 12 present the details of pressure that were estimated at the neck of the femoral prosthetic device. The behavior of von Mises pressure at the neck's

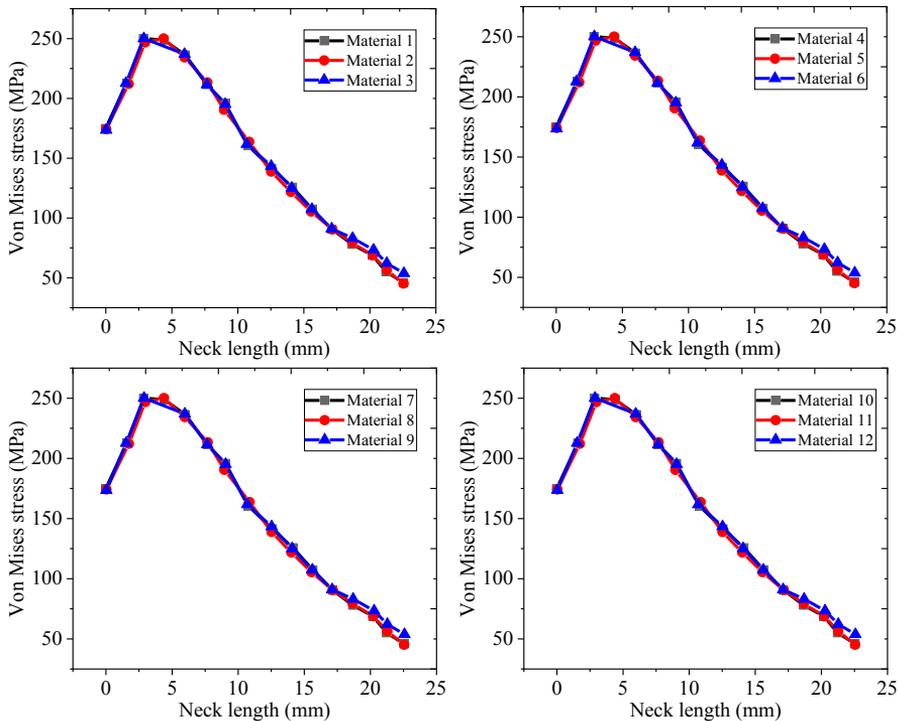


Fig. 11. Distribution of stress on the front of the neck

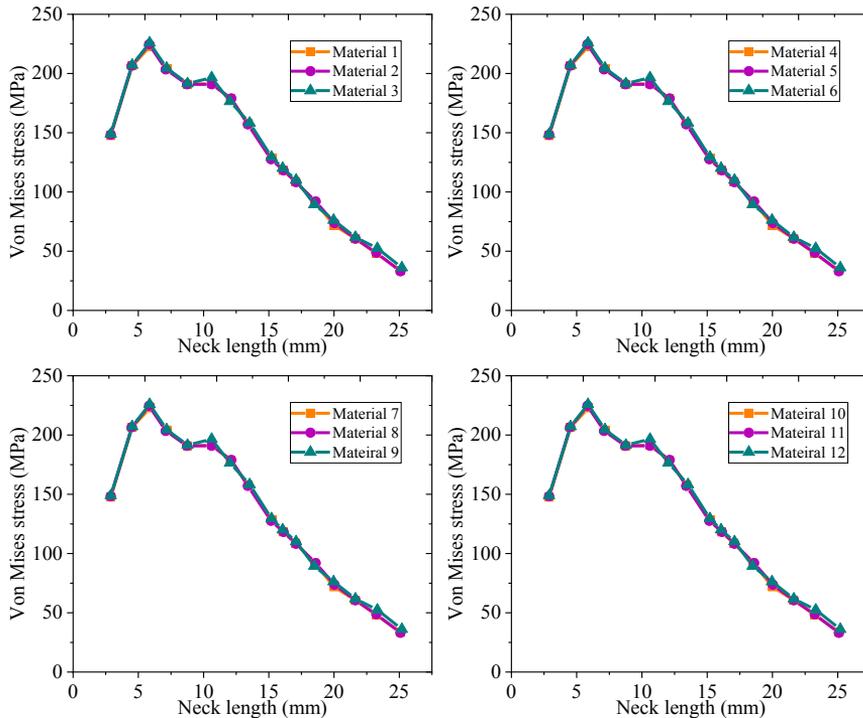


Fig. 12. Distribution of stress on the back of the neck

length was comparable for all material frameworks. The pressure began from lowest value, raised to a greatest one, and afterward began to decrease continuously. The von Mises pressure altered somewhat with n and the bends were covered accordingly in each subplot. The greatest von Mises pressures that was recorded for various material prototypes were 224.66 ± 1.5 MPa and 251.96 ± 1 MPa at the backward and face of the neck, separately. The von Mises weight at the stem of the femoral prosthetic device was dependent upon the material frameworks, as demonstrated in Fig. 5. Notwithstanding, its way all through the distance was like that saw in the case of the neck, making con-cavern bends. The most extreme von Mises pressure diminished in each part of the design assembly under test as n increased. In addition, the stems built of materials 3 and 4 showed the least and most elevated estimations of the greatest von Mises weight on the backward and face positions of the stem, respectively.

Besides, the indicated pathways didn't conclusively exceed the most extreme pressure on the THR segments. The critical points in creating the current inserts are associated with improving the lifetime and life span of the prosthesis. Perhaps the main source of the THR imperfection is the strain protecting that happens as an outcome of inconsistency amongst the mechanical attributes of the bone and those of the prosthesis. A prosthesis is a lot stiffer than a bone when it is produced

using customary materials (Ti combination and CrCo). This way, the prosthesis takes the biggest part of the heap, which maintains a strategic distance from its stem deep down. Bones are living tissues that react to the current stacking conditions, as opposed to designed materials. Thus, the tissue remodels and comes up short on the construction of its cortical layer. As a result, the THR failure may happen, and an amendment medical procedure might be required. Like this, it is essential to create novel materials with mechanical attributes that align to the bone, and the FGMs are proposed as a preferred substitute. The application of pressure distribution on the THR segments in this investigation showed varying effects dependent on the materials utilized in the models. The pressure dispersion on the collar, for example, was steady and independent of the material utilized in the model. Then again, this examination showed that by changing n in individual FGM models, the von Mises weight at the stem, concrete, and bone can be ensured and set to the ideal level. Therefore, the pressure of von Mises falls by over 30% to 50% in the stem, with respect to the class of segments, depending on the action of weight on the inner and external surface of the concrete sheet. Taking all things together with the material model classes, the pinnacle pressure at the lateral finish of the concrete sheet was eliminated by an increment of n . Then again, as n was raised, the underlying pressure expanded on the proximal finish of the front of the concrete, although this pressure was equivalent to or not exactly equal to the pinnacle pressure at the distal segment. The solidified practically evaluated prosthesis can be supplanted with concrete-less prosthesis to take care of this issue. The pressure in the femur part whereas the stem was detected expanded with incrementing of n . The unexpected decrease of strain on the bone's inward surface diminished as n increases in the examination. The FGMs subsequently can supplant materials that are utilized in hip-joint implant plan and production and are fit for lessening pressure protecting. In the examination, the strain of von Mises decreases more than the rigidity in the practically evaluated femoral prosthesis. In this way, the stem composed of FGMs bears a protected arrangement of stresses during the walk. The improvement in n brought about an enormous uniform dispersion of pressure on the concrete layer's interior and outer surfaces. Taking all things together with the material model classes, the pinnacle pressure at the distal finish of the concrete sheet was recorded by increasing n . While, as n was raised, the underlying pressure expanded on the proximal finish of the front of the concrete, although that pressure was equivalent or not exactly equivalent to the pinnacle pressure at the distal bit. To address this issue, the solidified practically reviewed prosthesis can be supplanted with a cementless prosthesis. The pressure in the femur portion where the stem was found increased by increasing n . To limit pressure protection, this pressure improvement is required. The sudden decrease of strain on the bone's inward surface diminished as n increased in an examination. The FGMs likewise can supplant parts previously utilized in the plan and assembling of inserts and which are equipped for limiting pressure protecting.

8. Conclusion

Neck pressure changes don't rely upon the prosthetic material properties. At the point when the FGMs were employed in the femoral prosthetic device, the strain on the stem was limited. Then, the application of pressure distribution on the concrete sheet was more reliable and the weight on the bone expanded, which was basic in limiting pressure protecting. Subsequently, in building up another generation of hip prosthetic parts accommodating AVB; LDF for limiting strain protecting, the 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, the FGMs can be powerful biomaterial substitutes in delivering another generation of hip prosthetic parts designed for decreasing pressure protecting, consequently expanding the lifespan of the substitution of the prosthesis. It can be concluded that this was an optimized designed requiring a lower amount of material as compared to previous research works, which ensures that our model was more techno-economically feasible. Moreover, after the applied material reduction, the natural frequency and deformation response exhibited by our model was quite satisfactory. The factor of safety was improved even using the same boundary condition in the ANSYS, as discussed in the manuscript. In previous studies, natural frequencies were not discussed with respect to deformations. Hence, one must admit that the present model is more efficient in terms of material, cost, natural frequency, deformation response, and the prosthesis quality. All these properties are discussed in their respective sections.

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