Acta Mechanica Slovaca **28 (4): 44 - 52,** December **2024**
https://doi.org/10.21496/ams.2024.029

Acta Mechanica Slovaca
ISSN 1335-2393
www.actamechanica.sk

Finite Element Analysis of Hydroxyapatite-Coated Titanium and Steel Hip Implants: Impacts on Stress Redistribution

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Abstract: This stress redistribution was consistent across both material types, highlighting the coatings' role in enhancing the load-bearing capacity of the implants. Furthermore, titanium implants exhibited lower stress concentrations compared to steel implants, confirming titanium's superior mechanical properties and biocompatibility. These findings suggest that the combination of titanium implants with HA coatings can substantially improve implant durability and performance, providing critical insights for optimizing hip implant designs to enhance patient outcomes. This study employs the Finite Element Method (FEM) to analyse and to mitigate stresses on hip implants, focusing specifically on the impact of Hydroxyapatite (HA) coatings on stress distribution. We examined both steel and titanium implants to assess the influence of material properties on stress patterns within the implant components. Our results demonstrated that HA coatings effectively shifted peak stress concentrations from the implant stem to the coating itself, leading to a significant reduction in overall stress levels. Specifically, the maximum stress in the steel stem without coating (model 1) decreased from 140.6 MPa to 66.1 MPa with the addition of the HA coating (model 2). Similarly, the maximum stress in the Ti–6Al–4V stem without coating (model 3) reduced from 96.9 MPa to 51.9 MPa with the coating (model 4). This stress redistribution was consistent across both material types, highlighting the coatings' role in enhancing the load-bearing capacity of the implants. Furthermore, titanium implants exhibited lower stress concentrations compared to steel implants, confirming titanium's superior mechanical properties and biocompatibility. These findings suggest that the combination of titanium implants with HA coatings can substantially improve implant durability and performance, providing critical insights for optimizing hip implant designs to enhance patient outcomes.

Keywords: Prostheses; Hydroxyapatite coatings; Biocompatibility; Mechanical performance; Finite element modelling

1. Introduction

Hip prostheses are crucial medical devices designed to restore mobility and alleviate pain in patients with damaged hip joints, typically caused by arthritis, fractures, or congenital deformities [1]. By replacing the natural hip joint, these implants significantly improve the quality of life for affected individuals. Advances in materials science and engineering have led to the development of durable and biocompatible prosthetics, enhancing their performance and longevity [2,3]. A thorough understanding of hip biomechanics is essential for the design and successful implantation of hip prostheses,

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ensuring both optimal functionality and patient safety [4].

A key element in the design of modern hip prostheses is the application of Hydroxyapatite (HA) coatings, a biocompatible ceramic material known for its ability to promote osteointegration by forming a strong chemical bond with the surrounding bone tissue [5,6]. This bond enhances implant stability and supports the long-term success of the prosthesis. HA coatings are particularly advantageous in uncemented hip prostheses, where they directly interface with the bone, minimizing micromovements at the implant site and reducing the risk of inflammation, infection, or fibrous tissue formation at the bone-prosthesis interface [7]. Additionally, these coatings mimic the mineral composition of natural bone, which encourages cellular activity and accelerates bone healing and regeneration around the implant. However, the influence of HA coatings on stress distribution within the prosthesis, as well as their role in mitigating stress shielding effects and ensuring optimal load transfer to the surrounding femoral bone, remains an area requiring further in-depth research to enhance the design and durability of hip implants.

This study employs Finite Element Method (FEM) analysis to evaluate the influence of HA coatings on stress distribution in uncemented hip implants, reflecting current clinical practice. Unlike previous studies that use simplified models, this work focuses on accurately capturing the direct interaction between the HA coating and the bone, excluding cement, as it is not appropriate for this application. Special attention is given to the mechanical behaviour of the HA layer under loading conditions typical of daily activities. Additionally, a mesh convergence study was performed to ensure the reliability of the simulation results.

By comparing the performance of steel (bio-steel) and titanium (Ti–6Al–4V) implants with and without HA coatings, this study aims to provide new insights into the role of HA in improving implant longevity and performance, contributing to the optimization of future hip prosthesis designs.

2. Methodology

2.1. FEM creation

2.1.1. Geometry

To analyse the impact of Hydroxyapatite (HA) coatings on uncemented hip prostheses, a comprehensive 3D model of the total hip replacement was developed using Computer-Aided Design (CAD) techniques. The model consists of the femoral stem, femoral bone (both cortical and cancellous bone), and the HA coatings.

The geometry creation process began with detailed anatomical scans of the femur, obtained using high-resolution CT imaging, which provided accurate representations of the bone structure and enabled the precise distribution of cortical and cancellous bone tissue necessary for the Finite Element Method (FEM) analysis. These scans ensured that the prosthesis was tailored to the patient's unique bone structure for optimal stress transfer and integration. The femoral stem was designed according to clinical specifications, optimizing its shape and dimensions to ensure proper load transfer and stability within the bone.

High-resolution CAD software, such as SolidWorks and mesh-mixer, was employed to model the femoral stem's surface with precision, which is essential for accurately accommodating the HA coatings. The femoral bone was modeled in detail, considering the density variations between cortical and cancellous bone to achieve realistic load distribution during the FEM analysis.

The Hydroxyapatite coatings were applied to the femoral stem in the model, with a uniform thickness of 0.08 mm, closely replicating real-world applications. The 0.08 mm thickness of HA coatings is optimal for promoting osteointegration, effectively redistributing stresses, and ensuring durability without risking delamination or hindering bone remodeling. These coatings enhance the prosthesis' biocompatibility by promoting osseointegration and reducing the risk of inflammation. Given the importance of capturing realistic mechanical behaviour, a mesh convergence study was performed to ensure the accuracy of the simulation results, and appropriate element sizes were used to model the thin HA layer effectively.

The precise CAD model served as the foundation for the FEA, allowing for a detailed analysis of stress distribution and deformation under various load conditions. By accurately representing the direct interaction between the bone and the HA coating, the model provides valuable insights into how these coatings impact the mechanical performance of hip prostheses and their integration into the femoral bone.

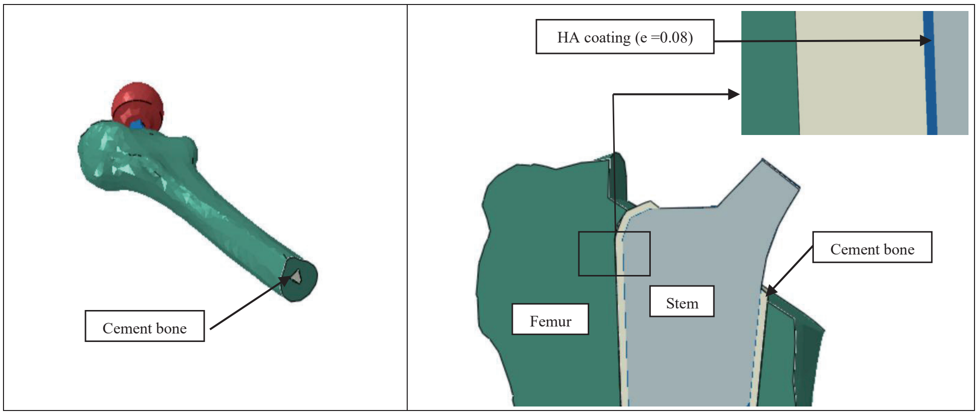

Figure 1: Schematic representation of the (CAD) model.

2.1.2. Mechanical properties

The mechanical properties used in this Finite Element (FE) model include those of Ti–6Al–4V, Cobalt–Chromium alloy, cortical bone, Hydroxyapatite (HA), and steel. These properties were selected based on values commonly reported in the literature and are within the same order of magnitude as those used in other studies. Given the wide variety of HA coating configurations - such as variations in porosity, crystallinity, and structure, which can arise from different coating techniques - special care was taken to choose appropriate properties that reflect typical clinical applications of HA coatings.

In this analysis, a linear elastic, homogeneous, and isotropic condition was assumed for all materials, despite the brittle nature of HA. The rationale behind this simplification is to focus on the global stress distribution in the implant-bone system, rather than localized failures in the coating itself. However, it is acknowledged that HA is a ceramic material with brittle behaviour, and the limitations of using linear elasticity for HA are considered when interpreting the results.

Table 1: List of the values of elastic modulus and Poisson's ratio used in the finite element models.

Structure	*Young's modulus (GPa)*	*Poisson's ratio*
Ti–6Al–4V [2]	110	0.32
Cobalt–chromium alloy [2]	220	0.3
Cortical bone [8]	13.6	0.3
Hydroxyapatite [9-17]	155	0.3
Bio-steels [10]	210	0.29

2.1.3. Loads and boundary conditions

In this study, a static load was applied to simulate the physiological forces experienced by a hip prosthesis during daily activities. Specifically, the load represents the weight-bearing condition of a 70 kg person. However, it is well-documented that during activities such as walking or standing on one leg, the hip joint experiences forces significantly greater than the individual's body weight, often ranging from 3 to 10 times body weight.

To reflect these real-world conditions more accurately, we applied an axial load of 3,500 N (approximately five times body weight), which better represents the load experienced by the hip during typical activities like walking or single-leg stance. This adjustment aligns with clinical studies that indicate hip joints endure loads several times higher than body weight during movement.

The load was applied vertically along the femoral head of the prosthesis, ensuring a realistic distribution of forces through the prosthesis to the femur. Boundary conditions were defined by fixing the distal end of the femur to restrict translational movement in all directions, while allowing rotation, to simulate the natural constraints of the femur within the body. These conditions enable an accurate assessment of the prosthesis' structural performance and stress distribution under normal physiological conditions.

2.1.4. FEM Mesh

The mesh properties of the components in the study are as follows: the stem is composed of 4784 elements of type C3D4 (4-node linear tetrahedron), the Hydroxyapatite Coatings consist of 1092 elements of the same type, the femur comprises 35,850 C3D4 elements, and the bone cement is made up of 3564 C3D4 elements. All

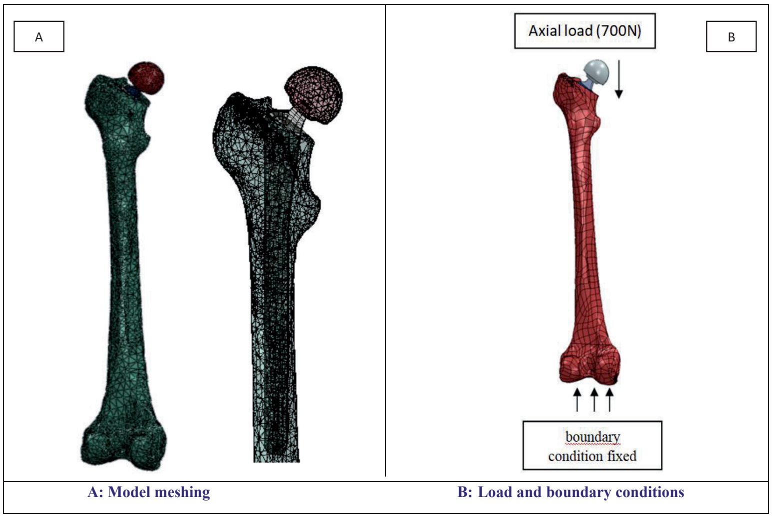

Figure 2: Mesh and boundary conditions of the analysed (FE) model.

components utilize the C3D4 element type, which is a 4-node linear tetrahedron suitable for modeling complex geometries (fig 2). Tetrahedral meshes are generally preferred over hexahedral meshes for free-form complex geometries due to their superior adaptability to intricate shapes and computational efficiency in such contexts [18].

3. Discussion and Results

The results of this study offer a comprehensive analysis of stress distribution across all components of a hip prosthesis, focusing on the effects of material selection and Hydroxyapatite (HA) coatings. The study examined four distinct models (as summarized in Table 2), each designed to evaluate the magnitude and distribution of stresses within the prosthetic structure, highlighting areas of stress concentration that are critical to the longevity and performance of the implant.

Table 2: Details of analysed hip (FE) models.

Models	*Material of Stem*	*Hydroxyapatite Coatings*
Model 1	Bio-Steel	Without
Model 2	Bio-Steel	with
Model 3	Ti–6Al–4V	Without
Model 4	Ti–6Al–4V	with

The results revealed significant differences in stress distribution between the models, particularly regarding the presence of HA coatings and the material properties of the prosthesis stem. Key findings from the analysis include:

Material Influence: Titanium (Ti–6Al–4V) consistently demonstrated superior performance compared to Bio-Steel in terms of stress reduction. Titanium implants, both with and without HA coatings, exhibited lower stress levels at the femoral stem compared to their steel counterparts. This indicates better load transfer and reduced risk of implant failure, reinforcing the preference for titanium alloys in modern hip prosthesis design.

Impact of Hydroxyapatite Coatings: The application of HA coatings had a significant impact on reducing stress concentrations at the implant stem. For both Bio-Steel and titanium models, the addition of HA coatings resulted in a notable decrease in peak stress. This reduction is particularly important in load-bearing scenarios, where high-stress concentrations can lead to implant wear or failure over time. By redistributing the load from the implant stem to the HA-coated surface, the coatings enhance the load-bearing capacity of the prosthesis and promote better integration with the surrounding bone tissue.

Stress Concentration: Critical areas of stress concentration were observed at the bone-implant interface, particularly in models without HA coatings. These stress concentrations can lead to micro-movements or loosening of the prosthesis over time, highlighting the importance of coating technology in mitigating such risks.

Overall, the findings underscore the potential benefits of combining titanium implants with Hydroxyapatite coatings for improved durability and performance. The HA coatings not only enhance biocompatibility but also play a pivotal role in optimizing stress distribution, ultimately improving the long-term outcomes of hip replacement surgeries.

3.1. Stress distribution at the stem in all FE models

The finite element analysis (FEA) of stress distribution at the femoral stem revealed significant variations across the different models, particularly in relation to the material of the implant stem and the presence of Hydroxyapatite (HA) coatings. As illustrated in Figure 4, the stress distribution in the uncoated steel implant model (Model 1) showed the highest recorded stress of 140.6 MPa, reflecting the greater stiffness and load concentration in steel compared to titanium.

In the titanium implant model (Model 3), the peak stress was considerably lower, at 96.9 MPa, indicating better load distribution properties due to the more favourable elastic modulus of Ti–6Al–4V. This lower stress in the titanium model suggests a reduced likelihood of stress shielding and potential long-term implant complications.

The presence of HA coatings significantly mitigated stress concentrations in both the steel and titanium implants. For the HA-coated steel implant (Model 2), the peak stress dropped to 66.1 MPa, a 53% reduction compared to the uncoated version. Similarly, the HA-coated titanium implant (Model 4) demonstrated the lowest recorded stress of 51.9 MPa, a 46% reduction from its uncoated counterpart.

These results clearly demonstrate the beneficial role of Hydroxyapatite coatings in redistributing stresses, particularly at the stem-bone interface, which is critical for the longevity and performance of hip prostheses. The significant reduction in stress levels with HA coatings suggests improved mechanical stability and enhanced integration with bone tissue, reinforcing the importance of coating technology in modern implant design (Figure 4).

3.2. Stress distribution at the cement bone

The stress distribution at the cement-bone interface across the four finite element (FE) models is depicted in Figure 5. The analysis revealed noteworthy variations in maximum stress levels, reflecting the impact of both the material of the stem and the presence of Hydroxyapatite (HA) coatings.

Model 1 (Bio-Steel without HA) exhibited a

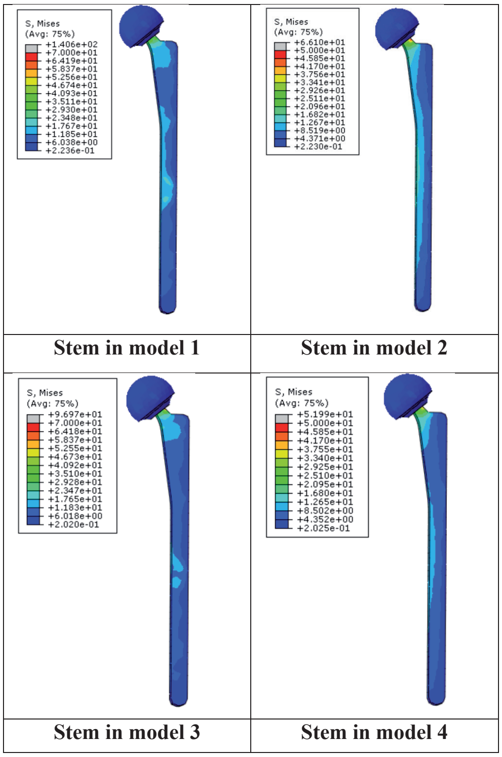

Figure 3: Distribution of Von Mises stresses in stems.

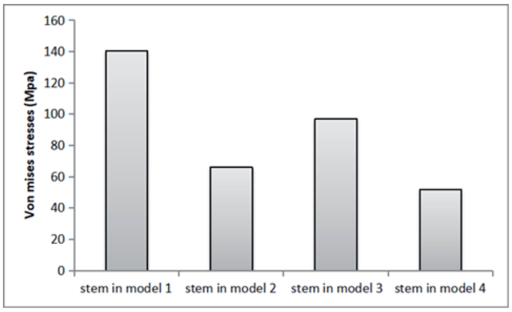

Figure 4: Peak Von Mises stresses in stems in all models.

maximum stress of approximately 2.45 MPa. This stress level indicates a moderate distribution of forces within the cement layer, which can influence the longevity of the interface.

Model 2 (Bio-Steel with HA) showed a slight reduction in maximum stress, measuring about 2.2456 MPa. The HA coating appears to have a beneficial effect in alleviating stress concentrations at the cement-bone interface, contributing to improved integration and stability.

In Model 3 (Ti–6Al–4V without HA), the maximum stress increased to around 2.784 MPa. This finding highlights the importance of material

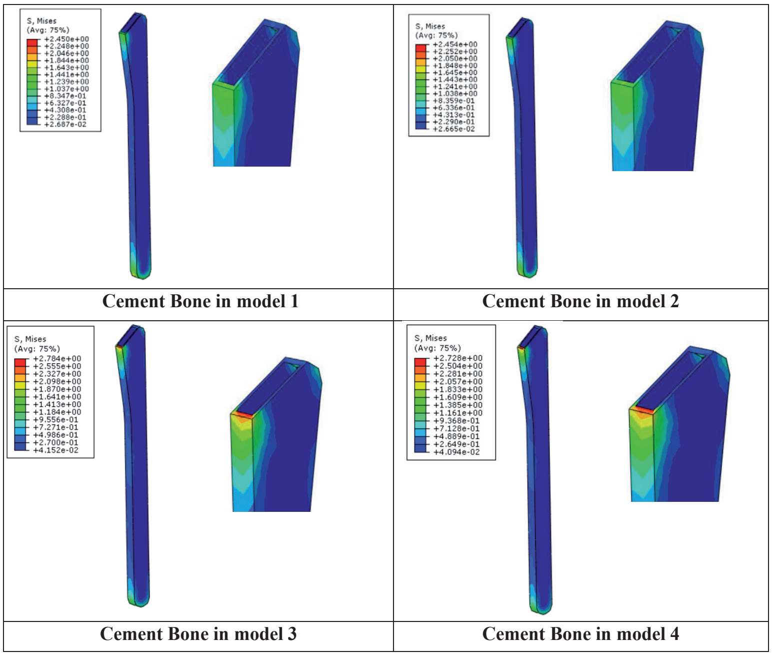

Figure 5: Distribution of Von Mises stresses in cement bone in all models.

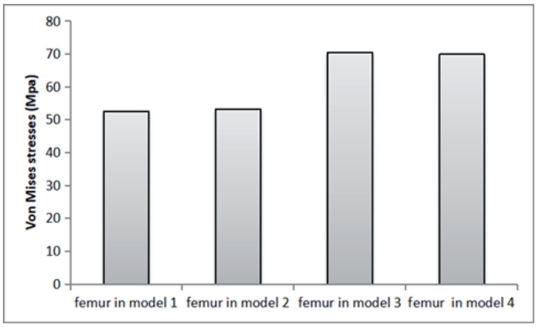

Figure 6: Peak Von Mises stresses in cement bone in all models.

properties in load distribution; the titanium stem, despite its lower overall stress at the stem, induces higher stress at the cement-bone interface.

Model 4 (Ti–6Al–4V with HA) displayed a maximum stress of approximately 2.728 MPa, which is lower than that of Model 3 but still higher than both Bio-Steel models. The presence of HA helps to moderate stress levels, although the titanium's inherent properties contribute to higher stress in the cement layer compared to the steel counterpart.

Figure 6 illustrates these distributions, emphasizing the critical nature of material choice and coating application in managing stress at the cement-bone interface. These findings underscore the importance of optimizing both the implant materials and the integration techniques to enhance the long-term stability of hip prostheses.

3.3. Stress distribution at the Hydroxyapatite Coatings

Figure 7 illustrates the stress distributions within the Hydroxyapatite (HA) coatings for both steel and titanium stems. The analysis reveals significant stress levels, with values approximately 117.6 MPa for the steel stem (Model 2) and 120.3 MPa for the titanium stem (Model 4).

These observed stress values highlight the critical role of the HA coatings in managing load distribution across the prosthesis. The coatings serve not only to enhance biocompatibility but also to absorb and redistribute peak stresses away from the underlying stem, which is crucial for minimizing the risk of failure and promoting osseointegration.

The reduced stress levels in Models 2 and 4, compared to their uncoated counterparts (as indicated in Figure 5 and Figure 6), demonstrate the effectiveness of HA coatings in mitigating stress concentrations. This reduction is particularly important as it contributes to the long-term durability of the prosthetic implant, potentially leading to improved patient outcomes and reduced complications.

Overall, these findings emphasize the significance of HA coatings in optimizing the

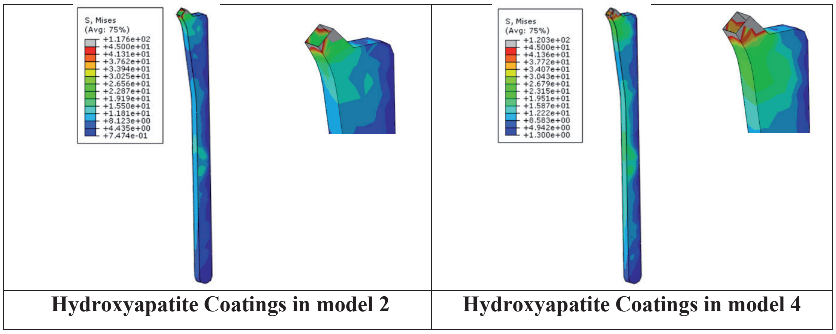

Figure 7: Distribution of Von Mises stresses in Hydroxyapatite coating.

mechanical performance of hip prostheses, reinforcing the importance of further exploration into coating technologies for enhanced implant stability.

3.4. Stress distribution at the femur

Figure 8 presents the stress distributions within the femur bone across the four finite element (FE) models. The analysis highlights notable differences in maximum stress levels, reflecting the impact of both the stem material and the presence of Hydroxyapatite (HA) coatings.

Model 1 (Bio-Steel without HA) recorded a maximum stress of approximately 52.6 MPa, indicating a moderate stress level in the surrounding femur bone.

Model 2 (Bio-Steel with HA) showed a slight increase in maximum stress, reaching about 53.3 MPa. This minimal change suggests that the HA coating may contribute to a marginal redistribution of stress, although the overall impact is limited in this case.

In Model 3 (Ti–6Al–4V without HA), the maximum stress significantly increased to around 70.5 MPa. This elevation highlights the tendency of titanium implants to concentrate stress in the femur bone, potentially raising concerns about long-term bone health and stability.

Model 4 (Ti–6Al–4V with HA) exhibited a maximum stress of approximately 69.9 MPa, indicating a slight reduction due to the HA coating but still reflecting a high level of stress compared to the steel models.

These findings underscore the importance of material selection and coating application in managing stress distributions within the femur bone. The elevated stress levels associated with titanium implants, even with HA coatings, highlight the need for further investigation into alternative designs and materials that could mitigate stress concentrations and promote better bone integration.

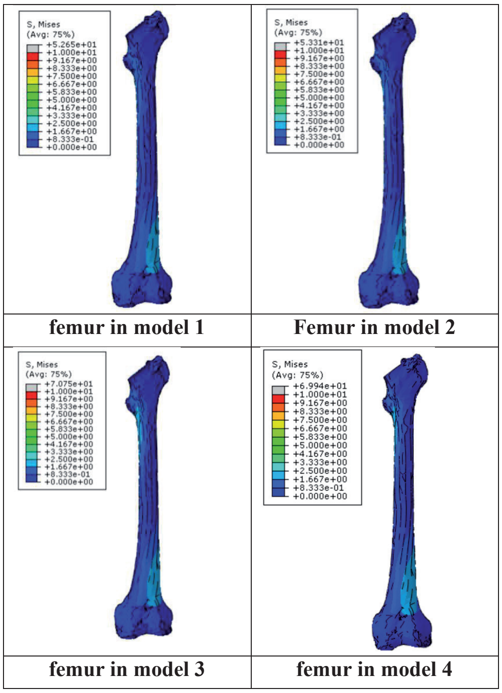

Figure 8: Distribution of Von Mises stresses in femur in all models.

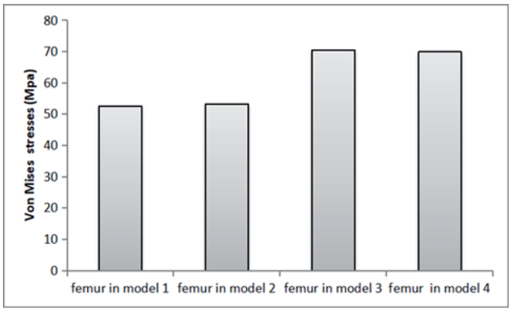

Figure 9: peak of Von Mises stresses in femur in all models.

4. Conclusion

This study employed the finite element method (FEM) to analyze the stress distributions on hip implants under a load exceeding 700 N, simulating the condition of standing on one leg. The analysis provided a detailed assessment of stress across all components of the hip implant model, with a focus on the effects of Hydroxyapatite (HA) coatings.

Two types of implants—steel and titanium—were evaluated to determine how material properties influence stress distribution within the implant components. By comparing these materials, the study aimed to identify the combination of implant material and surface coating that reduces stress concentrations and enhances implant durability.

The results indicated a measurable impact of HA coatings on stress distribution patterns. In uncoated implants, the highest stress concentrations were observed within the implant stem. However, the application of HA coatings shifted these peak stresses from the stem to the coating itself, consistently across both steel and titanium implants. This suggests that HA coatings redistribute stress, potentially lowering the risk of stress-related failures in the implant stem.

Further analysis revealed that HA coatings not only altered the location of peak stresses but also reduced their overall magnitude. For both steel and titanium implants, peak stress values were lower in coated implants compared to their uncoated counterparts. For instance, the maximum stress in uncoated steel implants decreased from 140.6 MPa to 66.1 MPa with the addition of HA coating, while in titanium implants, the stress reduced from 96.9 MPa to 51.9 MPa with the coating. This indicates the role of HA coatings in enhancing the load-bearing capacity of implants by providing an additional layer of stress absorption and distribution.

Additionally, the material properties of the implants influenced the observed stress patterns. Titanium implants, known for their biocompatibility and favourable mechanical properties, exhibited lower stress concentrations than steel implants, regardless of coating. This highlights titanium's suitability as an implant material.

In conclusion, this study emphasizes the role of HA coatings in managing stress distribution in hip implants. The results show that HA coatings shift peak stresses from the implant stem to the coating while significantly reducing their magnitude, with stress reductions of approximately 53% for steel implants and 46% for titanium implants. The combination of titanium implants with HA coatings presents a promising approach to improving implant performance and longevity. Future research should focus on the long-term clinical validation of these findings and explore the effects of dynamic loading conditions on coated implants.

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