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RESEARCH ARTICLE

Finite Element Analysis of Hip Implants with Different Lattice Structures Using Additive Manufacturing Materials

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ABSTRACT – A hip implant is surgically placed to replace damaged components and restore the patient's mobility. Although hip implants are widely used, there is a need to improve their mechanical performance while minimizing weight. Traditional designs often compromise between strength and weight, which can lead to implant failure. This research presents the optimization of hip implant design to minimize weight while maintaining bio-mechanical strength under physiological loading conditions. The primary objective of this study is to investigate the mechanical behavior of hip implants using three different lattice structures for designing the lightweight hip implant. The results show that at 50% of the lattice level, the cubic lattice has the highest deformation of 0.13 mm, the triangle lattice has a similar deformation of 0.13 mm, while the hexagonal lattice has a lower deformation of 0.12 mm. The maximum equivalent stress of the cubic lattice is 363.7 MPa, and the triangle lattice is 364.82 MPa. Meanwhile, the hexagonal lattice has a lower value, at 280.97 MPa. All three lattice structures with 10%, 30%, and 50% lattice have different structural integrity, where the hexagonal lattice implant has the maximum level of stress distribution and structural integrity, particularly at higher lattice levels. Additionally, the cubic lattice minimizes 15.49% of mass, the triangular lattice minimizes 15.72% of mass, and the hexagonal lattice minimizes 15.84% of mass, which makes the hexagonal lattice ideal for hip implants to achieve optimal mechanical performance and lightweight structure. In conclusion, the combination of finite element analysis and additive manufacturing can enhance the orthopaedic implant design, especially for hip implants.

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1. INTRODUCTION

The hip joint is important for the mobility of a person and overall health. Modern medical engineering has significantly improved the human musculoskeletal system through the development of artificial bone implants [1], [2]. The hip joint is a ball-and-socket joint that plays an important role in supporting the human body's weight and increasing mobility, like walking and running. Sometimes these joints get fractured due to degenerative disease and injuries [3]. At that time, the patient required hip replacement surgery using a hip implant to restore mobility in daily life. Hip implants are surgically placed to replace damaged or diseased femoral bone to mimic the natural bone functions [4]. Nowadays, hip replacement has become the most successful approach to restoring mobility and relieving pain in millions of patients worldwide. Normally, a hip implant contains several parts: femoral stem, acetabular cup, femoral head, plastic liner and femoral neck, which are a combination of metal and ceramic components as shown in Figure 1(a). Together, these components are allowed to relieve pain and help return to an active lifestyle. However, effective hip implants depend on surgical precision, design, material choice, and manufacturing methods [5], [6].

Commonly used biomaterials are titanium-based alloys, cobalt-chromium alloys, stainless steel, and ceramics etc. These materials have higher biocompatibility, corrosion resistance, and maximum bio-mechanical performance, which makes them suitable for medical implant manufacturing [2], [7]. After selecting the materials, the optimal design can be selected using finite element analysis (FEA). FEA is an advanced tool for investigating the implant's mechanical behavior and performance with real-life loading conditions [8] - [12]. Furthermore, additive manufacturing (AM) plays a crucial role in fabricating the hip implant [13]. AM has transformed the hip implant production process by enabling patient-specific, lightweight, and detailed designs. AM employs layers from computer-aided design (CAD) data and allows the creation of complex geometries that are more attached to the human body, which was previously difficult to manufacture by conventional methods [14]. AM techniques like direct metal laser sintering (DLMS), selective laser melting (SLM), selective laser sintering (SLS), and electron beam melting (EBM) are methods used to manufacture hip implants [7], [14]. The metal is melted through the laser and creates the optimal shape of the given geometry. This technology is very beneficial for developing patient-specific implants and structures that can be adapted to individual needs [15]. Figure 1(b) shows the X-ray of different hip implant designs inside the femoral bone. Meanwhile, Figure 1(c) shows the schematic diagram of the powder bed fusion AM using the SLS technique. It is one of the most suitable methods for printing the hip implant.

A study was presented by [16] in which they conducted FEA on orthopedic hip implants with bioinspired lattice structures composed of Inconel 718 superalloy. Their research focused on optimizing the design of the hip implant using advanced lattice structures under in vivo loading conditions. The results demonstrated that the functionally graded lattice

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significantly improves the structural integrity of the implant, allowing it to endure twice the in vivo load compared to traditional solid implants. This suggests that these lattice structures can be an appropriate and efficient alternative for solid implants to provide higher biocompatibility and reduce the manufacturing cost [16]. Abate et. al. (2021) [17] investigate the design and optimization of hip implants with cellular structures to enhance bone tissue ingrowth and reduce stress shielding. FEA was used to evaluate the structural behavior of the hip cellular implants, and optimization techniques were used to improve their mechanical performance. They introduced optimized cellular hip implants fabricated using SLM with Ti-6Al-4V material. Additionally, the lattice topology of Vin tiles (a type of lattice) with different strut thicknesses and unit cell sizes stimulates bone tissue growth and biomechanical strength in solid implants. FEA was used to determine the mechanical properties, and experimental tests were conducted to determine the stiffness under static loading conditions. The results showed that the optimized cellular hip implant had 62% greater stiffness and 50% less weight than the solid part. Porous cellular implants of 56% and 58% have the potential for orthopedic and prosthetic applications to enhance bone resorption [17]. Tallon et al. (2020) [18] investigated the effect of additively manufactured micro-lattice reinforced plates. They highlighted the potential of additive manufacturing materials to improve the mechanical properties of lattice structures. Finally, they showed the potential of these micro-lattices for energy absorption applications [18]. Galarreta et al. (2020) [19] presented a validated FEA method for porous structures to understand the mechanical behavior of complex lattice structures. The study presented the structural behavior of interconnected three-dimensional lattices at both macro and microscopic levels. The lattice structure was created using polyhedral structures and evaluated through numerical and experimental studies. They found that these lattices can significantly enhance the stiffness and isotropic behavior. Additionally, the experimental data demonstrated that these lattices show the same stiffness and energy density as the materials, even at low relative density (20%). The study suggests that an interconnected type lattice can be a suitable choice for designing lightweight and high-strength components for different applications [19]. Vangelatos et al. (2020) [20] compared the mechanical performance of interconnected three-dimensional lattices and highlighted the need for detailed analysis to optimize the lattice structure under loading-bearing conditions. Similarly, Shah et. al (2020) [21] presented an overview of lattice structures, including different structures, production methods, and materials used in their production.

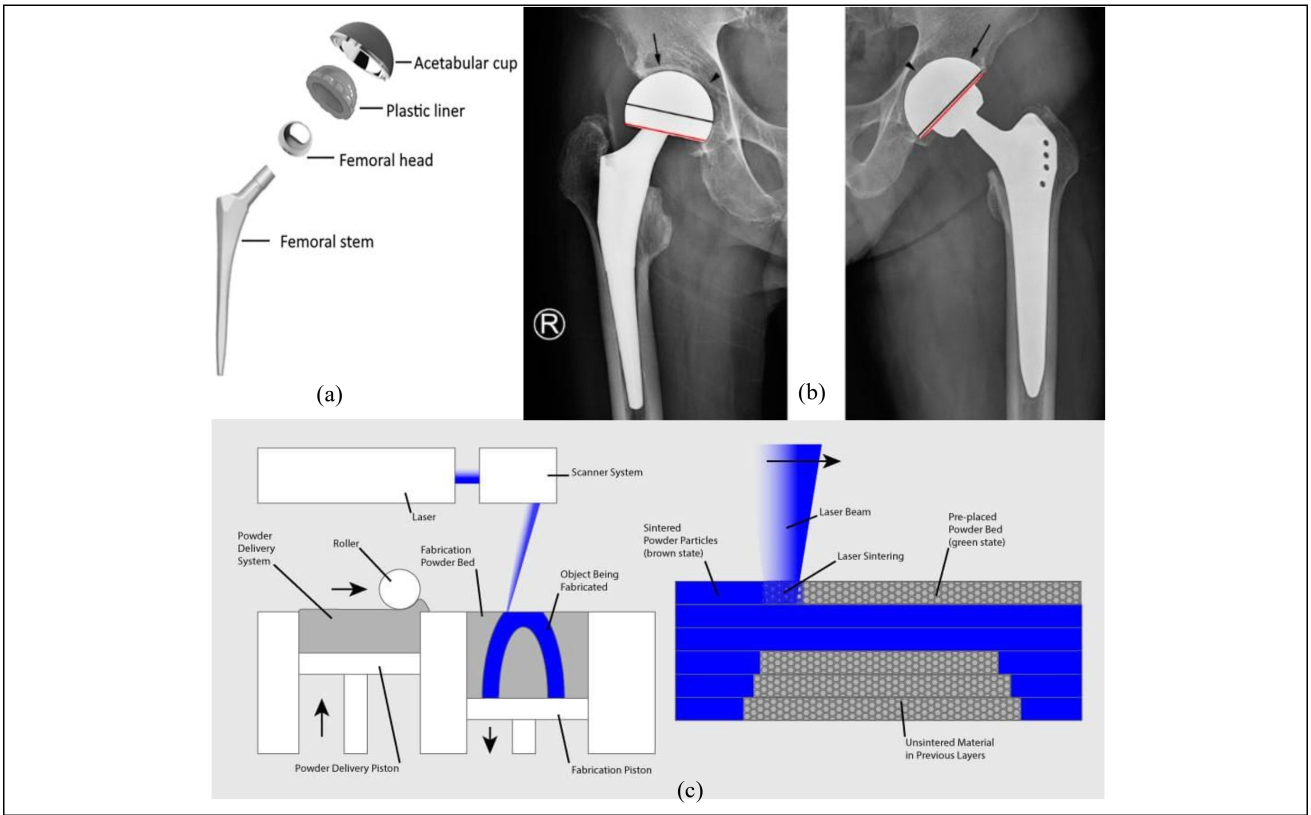


Figure 1. (a) Different parts of the hip implant (b) X-ray view of hip implant design inside the femoral bone (c) Powder bed AM process [22][23][24]

This overview highlights the need for further research to improve the use of lattice structures in lightweight applications. Traditional solid implants are mechanically strong but heavy, which can cause patient discomfort and different biomechanical problems. Lattice structure with the ability to reduce material consumption and improve stress distribution. This offers a promising solution, but their mechanical performance must be thoroughly evaluated to ensure they meet the required criteria for durability and strength. The problem addressed in this study is how to effectively design and analyze lattice structures for hip implants using FEA. FEA is a useful tool for investigating the mechanical performance of hip implants. Furthermore, the combination of FEA and AM can play a significant role in designing patient-specific hip implants. However, the lattice structure hip implant manufactured with AM materials enables the creation of patient-specific hip implant designs with a higher level of biocompatibility because lattice implants stimulate bone growth by allowing increased oxygen and nutrient transfer. The primary objective of this study is to investigate the mechanical behavior of hip implants using three different lattice structures for designing the lightweight hip implant. In conclusion, the implementation of AM materials in lattice-structured hip implant design based on FEA will be a significant contribution to the community by increasing the knowledge of implant design, the mechanism, and overall performance. The next section will present the materials and methods used in this study.

2. METHOD AND MATERIAL

This study uses commercial software Ansys (Ansys version: Ansys 2024R2) to evaluate the performance of Titanium Alloy (Ti6Al4V) for hip implants, assessing how lattice level and shape affect biomechanical performance. Initially, three different lattice-structured hip implants were developed with varying lattice percentages, and then the model was imported into Ansys Workbench. Secondly, the material properties were determined for the analysis, and finally, the meshing and boundary conditions were applied to run the analysis. However, the finite model was validated with the previous study conducted by [11], where researchers initially conducted finite element analysis of hip implant using 3065 N loads and evaluated equivalent von Mises stress of 650.93 MPa. In this study, the model was validated using the same boundary conditions and design prior to running the analysis. The evaluated von Mises stress was approximately 668.13 MPa, resulting in an error percentage of 2.64%. Figure 2 shows the validation of the finite element model using a previous study. The following subsection will discuss the methodology of this study in detail.

2.1 Lattice Structure of the Hip Implant

This study focuses on three basic lattice structures: cubic, triangular, and hexagonal. Results included analyzing total deformation, von Mises stress, and equivalent elastic strain, assessing structural integrity, and weight reduction based on FEA. Advanced manufacturing technologies like additive manufacturing provide precise control of the lattice, personalizing implants for patient-specific needs. In this study, three types of lattices have been considered. These are low lattice (<10%), medium lattice (10% - 30%), and high lattice (50%), respectively. However, Figure 3 shows the hip implant design with three different levels of lattice. Lattice type, density range (0 to 0.5 mm), and lattice cell size (2 mm) are selected and applied to the model. Lattice values, from low to high, are adjusted to retain structural integrity while minimizing weight. Space Claim tools are used to introduce the lattice selectively. The final design is measured against the standard simulation to confirm weight, strength, and durability improvements. Finally, the next subsection will discuss the material selection of the hip implant.

2.2 Material Selection

Metal alloys are the best material for developing solid metal hip implants due to their mechanical properties, advantages, and the wide range of materials used in medical implants [25]. The material selection of hip implants is an important process that ensures the functionality and longevity of the implant in the human body. Biocompatibility, mechanical properties, corrosion resistance, fatigue performance, osseointegration, and manufacturability are key considerations [26] - [30]. The implant must endure significant loads during activities such as walking and running without deforming or failing. Additionally, the material must be biocompatible, meaning it will not cause adverse harm or toxicity when in contact with living tissue. Titanium alloys such as Ti-6Al-4V are popular choices due to their excellent biocompatibility. In this study, Ti-6Al-4V is selected for the analysis. Table 1 shows the material properties of Ti-6Al-4V. The next subsection will discuss the meshing and boundary conditions of the hip implant.

Table 1. Material properties of Ti-6Al-4V [31]

Density	Elastic Modulus	Poisson Ratio	Yield Strength	Ultimate Yield Strength
4.43 g/cm³	114 GPa	0.3	880 MPa	900 MPa

2.3 Meshing and Boundary Conditions

Initially, the mesh convergence test was conducted to get the optimal size of the mesh. It is found that geometry with a 1mm mesh shows good results during analysis. The mesh quality was confirmed by the mesh metric quality, skewness, and element quality, where the quality is greater than 85% based on aspect ratio and skewness, which is sufficient for analysis. So that mesh is created using the element size of 1 mm, where the number of nodes is 35759, and the number of elements is 20285. After creating the mesh, boundary conditions are applied to the implant for further analysis. It is seen that the world population statistics in North America have the highest body mass of any continent, which is 80.7 kg. More than 70% of the North American population is obese, and it is 6% of the world's population. Asia has the lowest body mass of any continent, 57.7 kg, and it has 61% of the global population [32]. In this study, a 980N force is applied in the negative direction of Y, which is equivalent to 100Kg of body weight, representing the maximum body weight ratio. Then, a fixed-support constraint is used at the end of the implant to simulate a grip within the body. Fixed support is almost half of the geometry because the femoral stem part will be inside the femoral bone. Finally, Figure 4 (a) shows the mesh convergence study of the hip implant. After that, Figure 4 (b) shows the created mesh on the hip implant, as well as the applied force direction and fixed support on the hip implant design.

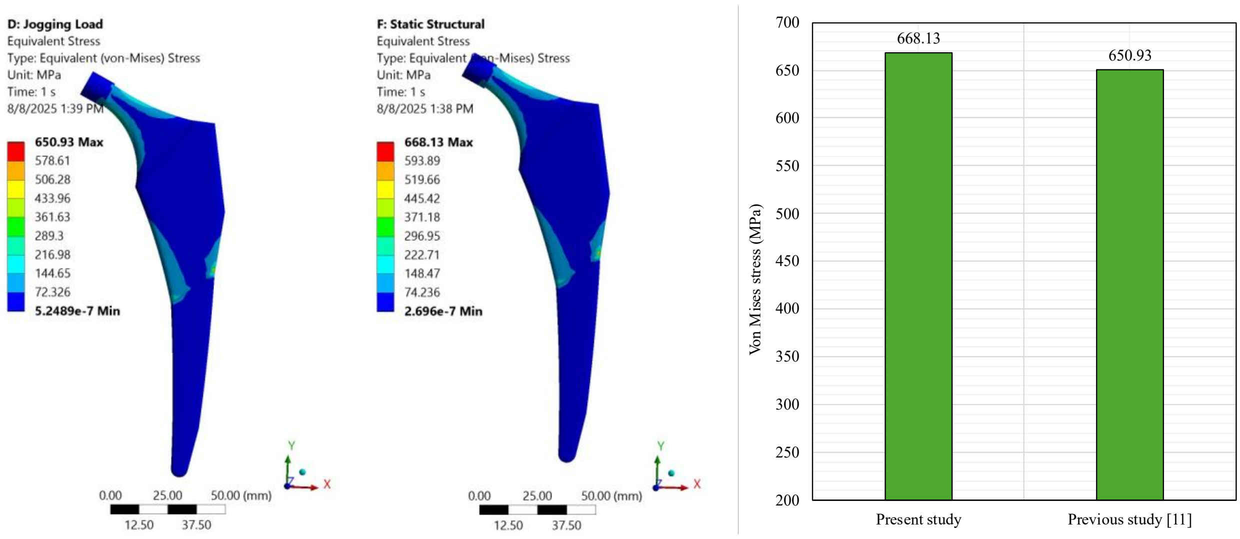


Figure 2. Validation of the finite element model using previous study

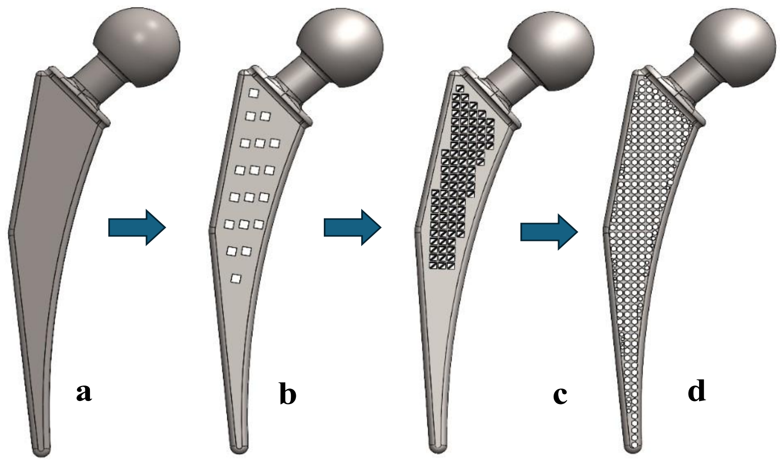
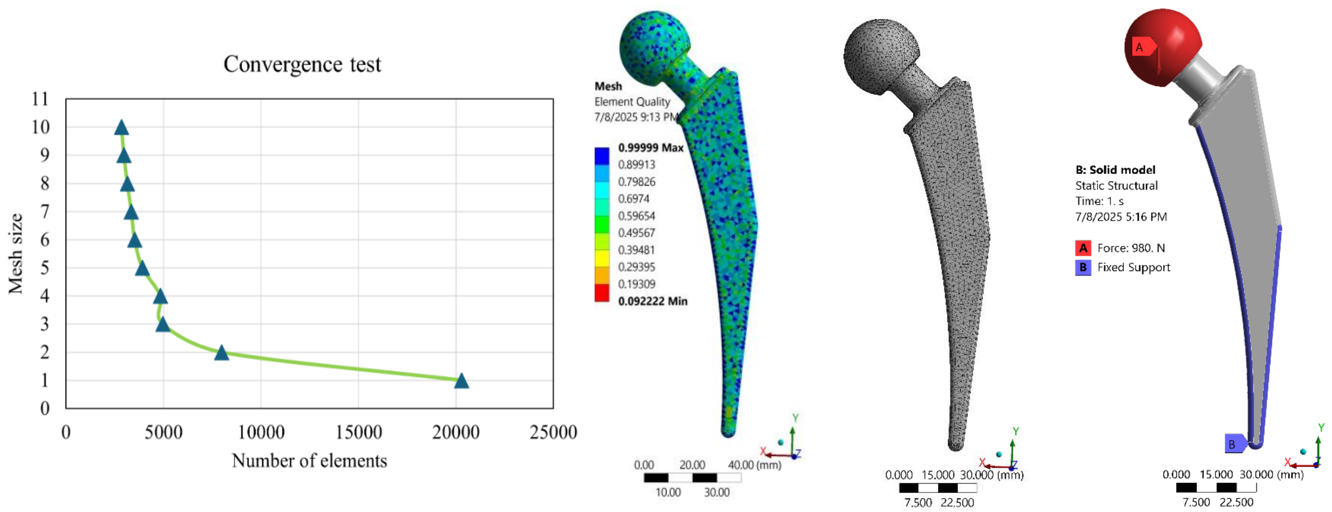


Figure 3. Hip implants design with lattice shape and level: (a) Solid design, (b) Cubic-lattice 10%, (c) Triangle-lattice 30%, (d) Hexagon-lattice 50%



(a) (b) (c)

Figure 4. Mesh and Boundary Condition: (a) Mesh convergence study (b) Meshing and boundary conditions

3. RESULTS AND DISCUSSION

3.1 Total Deformation

Figure 5 shows the total deformation of different designs of lattice-structured hip implants and various levels of lattice. There are three types of lattices: cubic, triangular, and hexagonal. Additionally, there are three levels of lattice containing 10% lattice, 30% lattice, and 50% lattice. In the cubic lattice, the maximum change in deformation at 10% of the lattice is 0.092 mm; at 30% of the lattice is 0.11 mm; and at 50% of the lattice is 0.13 mm. In the triangle lattice, the maximum change in deformation at 10% of the lattice is 0.09 mm; at 30% of the lattice is 0.11 mm; and at 50% of the lattice is 0.13mm.

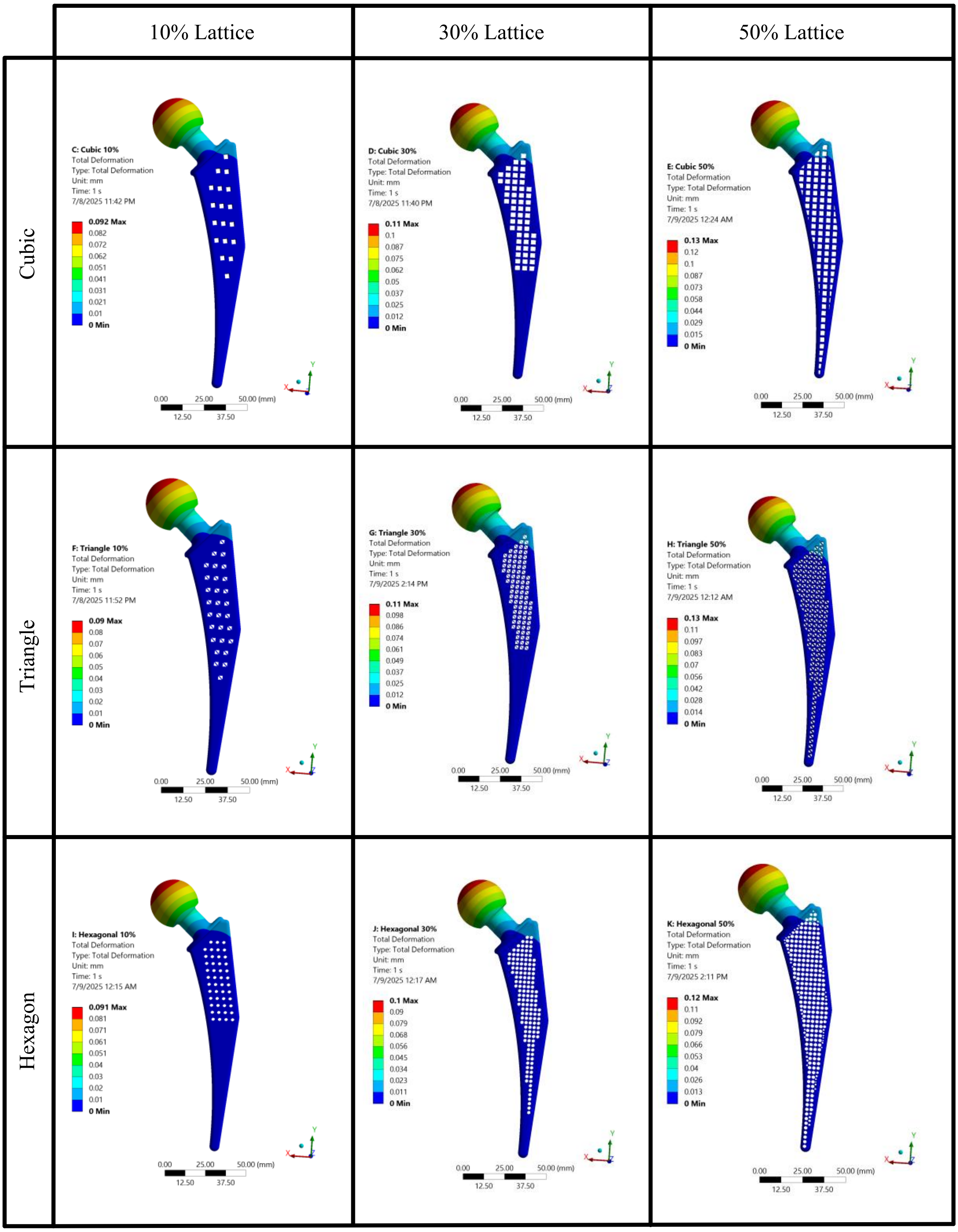


Figure 5. The visualization of total deformation on hip model design

In hexagonal lattices, the maximum change in deformation at 10% of the lattice is 0.091 mm; at 30% of the lattice is 0.10 mm; and at 50% of the lattice is 0.12 mm. It is seen that the total deformation of all models is very low, which is in an acceptable range. However, the cubic lattice structure shows the highest number of deformations of all lattice levels. The deformation increases significantly with the increase in the number of lattice percentages. The triangular lattice structure shows increased deformation, but it is slightly lower than the cubic lattice structure. Apart from these, the hexagonal lattice structure shows less overall deformation than other structures. The symmetry and geometric arrangement of lattice structures influence the mechanical behavior of deformation. The cubic lattice structure, with its simple and uniform arrangement of lattice structures, tends to distribute loads less efficiently, which leads to higher deformation.

The total deformation of hip implants is an important factor used to evaluate implant performance, which helps reduce the risk of implant failure. Higher deformation on the hip implants can cause discomfort and restrict the patient's daily activities. Minimizing implant deformation can ensure that the behavior of the implant is similar to that of the natural bone. A high level of deformation increases the chance of implant failure over time. On a hip implant, the load-bearing area is subjected to physiological forces so that higher deformation can cause material fatigue and wear. Total deformation also allows the study of the distribution of stress over the implant's different Gruen zones. An implant with less deformation can distribute stress more effectively, which minimizes the effects of stress shielding. Finally, the geometric arrangement and symmetry of lattice structures contribute to their mechanical behavior under load. A thicker lattice, with its simpler structure, appears to be less capable of distributing stress effectively, leading to higher deformation. In contrast, hexagonal and triangular lattices, particularly hexagons, show greater load distribution, resulting in lower overall deformation. The superior performance of the hexagonal lattice is likely due to its more complex and stable geometry, which allows it to resist deformation under the load. Additionally, the graphical representation of the maximum total deformation is shown in Figure 6.

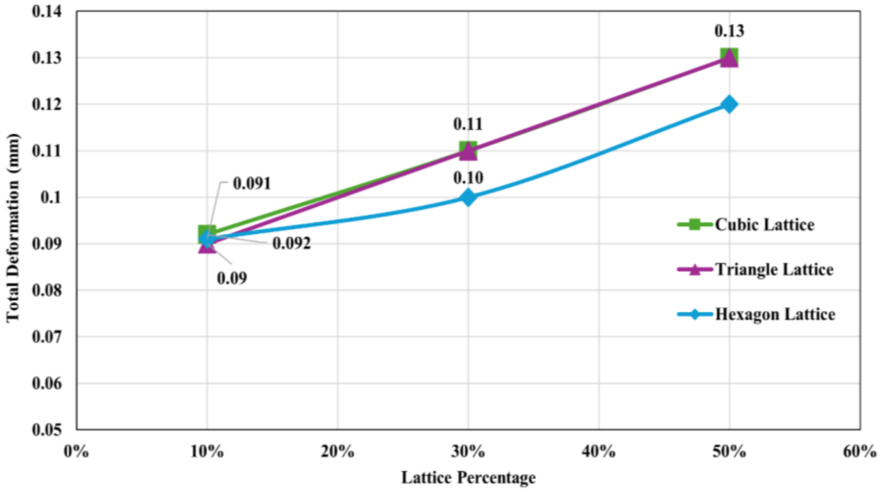


Figure 6. Total deformation with different structures and lattice levels

3.3 Equivalent Stress (von Mises)

The equivalent of von Mises stress is crucial for evaluating the implant's strength and durability because it predicts the material's yield and failure. Von Mises stress helps to identify the implant's weak point, where material might be overloaded. This allows us to know the proper distribution of the materials and optimize the design while maintaining flexibility. As a result, it ensures the load bearing and stress distribution are properly distributed, which allows for the prevention of implant failure and implant loosening due to the stress shielding effects. This is why the implant von Mises stress needs to mimic the natural bone's yield strength. If the implant von Mises stresses closer to the natural bone's yield strength, it will prevent the reduction of bone density and implant failure. Figure 7 shows the equivalent stress of different designs of lattice-structured hip implants and various levels of lattice. There are three types of lattices: cubic, triangular, and hexagonal. Additionally, there are three levels of lattice containing 10% lattice, 30% lattice, and 50% lattice. In the cubic lattice, the maximum equivalent stress (von Mises) is 363.7 MPa at 10% of the lattice, 294.78 MPa at 30% of the lattice, and 299.38 MPa at 50% of the lattice level. In the triangular lattice, the maximum equivalent stress (von Mises) is 268.46 MPa at 10% of the lattice, 305.35 MPa at 30% of the lattice, and 364.82 MPa at 50% of the lattice. In the hexagonal lattice, the maximum equivalent stress (von Mises) is 230 MPa at 10% of the lattice, 229.24 MPa at 30% of the lattice, and 280.97 MPa at 50% of the lattice. The high stress levels of cubic and triangular structures in all levels of lattice percentage are due to the inability to efficiently distribute internal forces, leading to high local stresses. On the other hand, the hexagonal lattice shows the minimum equivalent stress in all lattice levels compared to the other two lattice structure models. However, all lattice structures have lower equivalent stress than the material yield strength (880MPa), which indicates that the structure effectively manages stress under high loads, potentially making it stronger for long-term or high-load applications.

The stress analysis is important to understand how much internal force per unit area the structure can endure before failure. High stress levels often lead to a high risk of component failure, particularly if they are sustained loads. The cubic and triangular lattice experiences the highest stress, indicating that it is under significant internal forces, which may cause failure as the load increases. Finally, the hexagonal lattice can reduce stress under real-life loads, showing its inherent geometric advantage in load distribution, making it less vulnerable to stress-related failure. The identified stress patterns indicate that the cubic lattice leads to high stress levels due to inefficient load distribution. The geometric advantage of the hexagonal lattice helps to increase stress distribution, reducing the likelihood of stress-related failure, which makes the hexagonal lattice a more suitable choice for high-load applications. Additionally, the graphical representation of the maximum equivalent stress is shown in Figure 8. Although the all-lattice model has an acceptable equivalent von Mises stress, the lower equivalent von Mises stress in the hexagonal lattice hip implant model makes it ideal among all lattice structure hip implant models. However, Figure 9 shows the mass reduction of the lattice hip implant at different levels and the structure of the lattice hip implant. The initial solid model of the hip implant has a mass of 112.98 g. After integration of the cubic lattice structure, with 50% of lattice level, the mass has been minimized by 15.49 % and the final mass became 95.48 g. Similarly, after integration of the triangular lattice, it minimized 15.72 % of mass, and the final mass became 95.22 g. Finally, after integration of the hexagonal lattice, it minimized 15.84% of mass, and the final mass became 95.07 g. It is seen that a hexagonal lattice with a 50% level of lattice minimizes the maximum amount of mass from the solid model, which makes the model lightweight and has long-term stability.

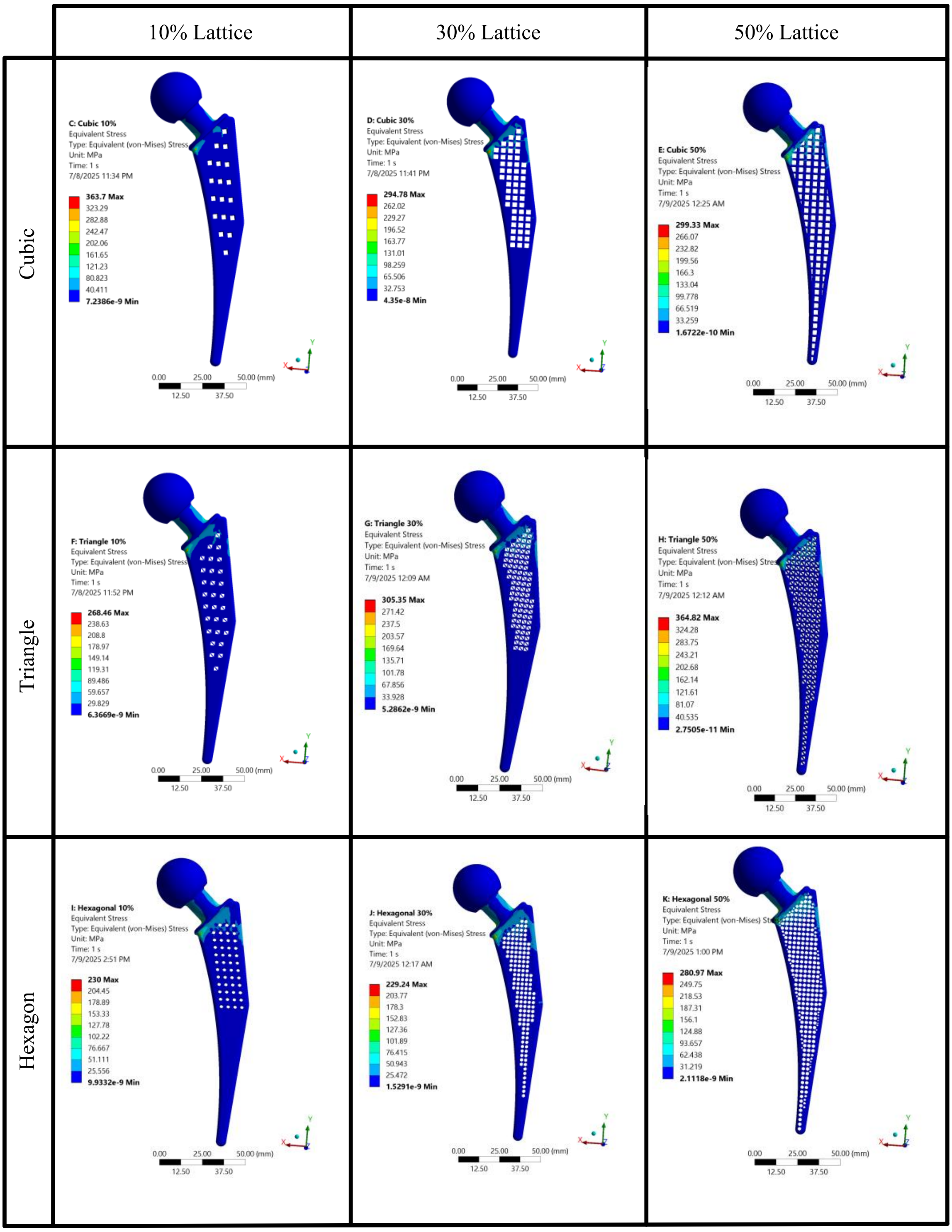


Figure 7. The visualization of equivalent von Mises Stress on hip model design

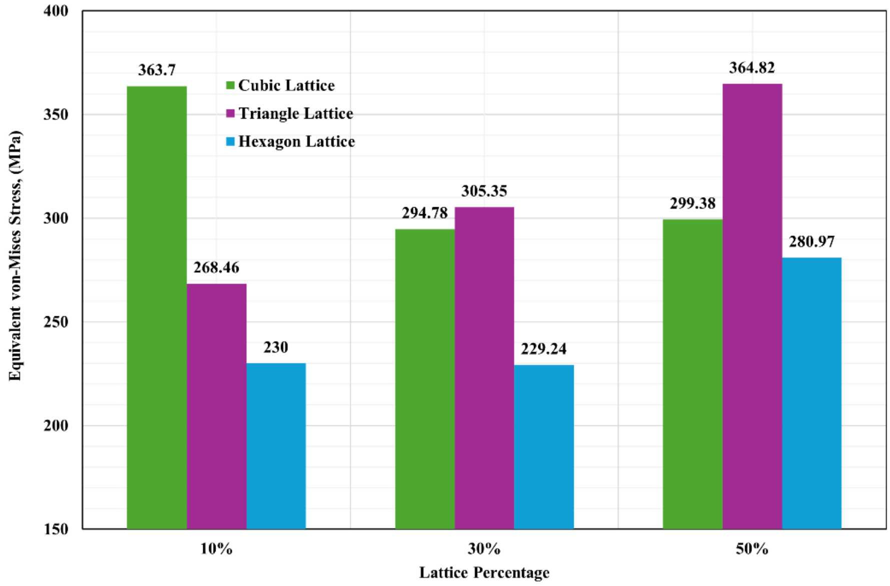


Figure 8. Equivalent von Mises stress with different structures and lattice levels

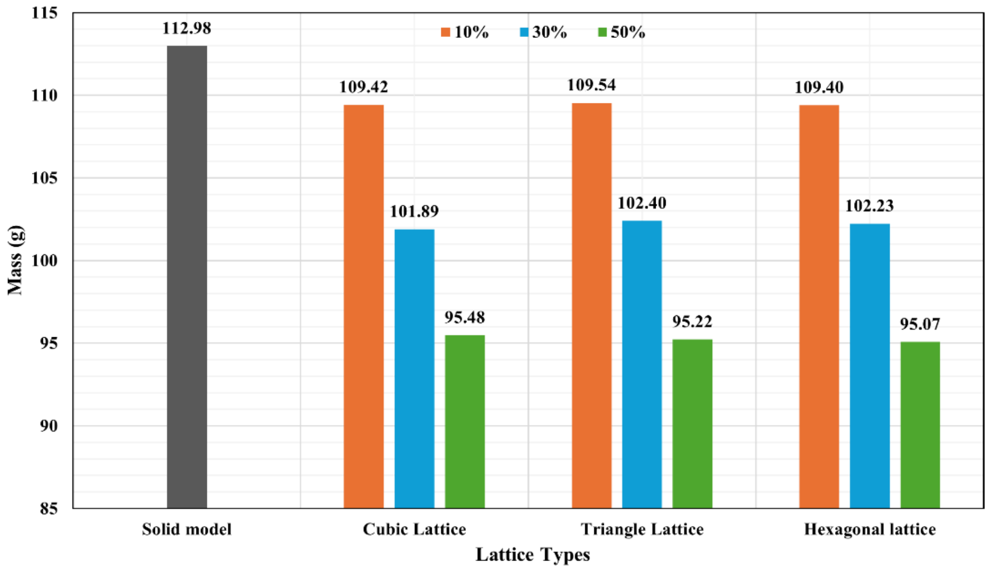


Figure 9. Mass reduction of different lattice structures and lattice levels

Based on the analysis of total deformation, equivalent stress, and lightweight structure, the hexagon lattice is the most advantageous structure for applications requiring high strength and durability, such as hip implants. The hexagonal lattice has the lowest total deformation and manages stress and strain effectively, especially in high-load conditions. This indicates that it has better stiffness and an efficient load distribution capability, which is important for reducing material fatigue and ensuring long-term stability. Although the cubic lattice and triangular lattice structures are flexible, their high deformation, strain, and stress levels make them less suitable for applications where structural integrity is essential. However, all three lattice structures have advantages; hexagonal lattices consistently outperform triangular and cubic ones in stress distribution and structural integrity, particularly at higher lattice levels. This makes the hexagonal lattice ideal for applications that require optimal mechanical performance and durability. It is because a hexagonal pattern includes six symmetries, where each node is connected to closer nodes than in cubic or triangular lattices. This creates a more interconnected network. The addition of interconnectivity in a hexagonal lattice enhances its ability to distribute stress more evenly. In a hip implant, this reduces stress concentrations, making the structure more resistant to deformation under load. Due to the increased number of connections between nodes, hexagonal lattices can offer superior strength-to-weight ratios. This is essential for applications such as implants, where mechanical strength and lightweight properties are essential.

4. CONCLUSIONS

The current study focuses on optimizing hip implant design using FEA and AM. It also focuses on the effect of lattice form and the type of lattice structure. However, the FEA of lattice structure hip implant and AM techniques are utilized to reduce weight and increase mechanical strength. The hexagonal design with the 50% level of lattice under 980N loading conditions shows the lowest von Mises stress, indicating superior strength and weight distribution. Software tools such as

SolidWorks and Ansys demonstrate that implants are compatible with mechanical, manufacturability, and patient-specific standards. The study fulfills the aim of developing a hip implant design by modifying the lattice and evaluating strength and material loss with integrated software tools. Where the results indicate that,

- Total deformation: In the cubic lattice, the maximum change in deformation at 10% of the lattice is 0.092 mm; at 30% of the lattice is 0.11 mm; and at 50% of the lattice is 0.13 mm. In the triangle lattice, the maximum change in deformation at 10% of the lattice is 0.09 mm; at 30% of the lattice is 0.11 mm; and at 50% of the lattice is 0.13 mm. In hexagonal lattices, the maximum change in deformation at 10% of the lattice is 0.091 mm; at 30% of the lattice is 0.10 mm; and at 50% of the lattice is 0.12 mm.
- Equivalent von Mises stress: In the cubic lattice, the maximum equivalent stress (von Mises) is 363.7 MPa at 10% of the lattice, 294.78 MPa at 30% of the lattice, and 299.38 MPa at 50% of the lattice. In the triangular lattice, the maximum equivalent stress (von Mises) is 268.46 MPa at 10% of the lattice, 305.35 MPa at 30% of the lattice, and 364.82 MPa at 50% of the lattice. In the hexagonal lattice, the maximum equivalent stress (von Mises) is 230 MPa at 10% of the lattice, 229.24 MPa at 30% of the lattice, and 280.97 MPa at 50% of the lattice.
- Mass reduction: Cubic lattice minimizes 15.49% of mass, Triangular lattice minimizes 15.72% of mass, and hexagonal lattice minimizes 15.84% of mass. The initial mass was 112.98 g, then after reduction, the mass became 95.07 g.

In summary, the cubic lattice has the highest total deformation and equivalent stress, while the hexagonal lattice has the highest structural integrity, lowest deformation, and stress. Additionally, a hexagonal lattice reduces the maximum amount of mass to make it a lightweight structure. So, the hexagonal lattice is the most suitable choice for applications that require optimum mechanical performance and durability. It simulates the maximum weight-bearing stress, proving the real-world applicability of the implant. However, this study evaluated the performance of the general lattice-structured hip implant. The future work will focus on designing a hip implant with a complex lattice pattern with lattice unit cells and evaluating the stress shielding effect on different Gruen zones.

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CONFLICT OF INTEREST

The authors declare no conflicts of interest.

AUTHORS CONTRIBUTION

A.A. Noman: Conceptualization, Methodology, Formal analysis, Software, Writing.

M.S. Shaari: Conceptualization; Methodology; Acquisition of funds, Resources, Supervision, Writing - review & editing.

M.R.M. Akramin: Writing - review & editing.

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