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Static Analysis of Auxetic Femur Stem for Total Hip Arthroplasty (THA) Application using angle optimization

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Declaration

I hereby affirm that the research entitled **Static Analysis of Auxetic Femur Stem for Total Hip Arthroplasty (THA) Application using angle optimization** is the result of my independent investigation and effort. This work is original and has not been previously submitted for assessment or review in any other academic or professional context. All sources and materials consulted have been meticulously referenced and duly acknowledged, ensuring the integrity and authenticity of this research.

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Abstract

Total hip arthroplasty (THA) is the preferred treatment for severe hip diseases, but the durability of hip prostheses is compromised by stress shielding, leading to bone resorption and implant failure. This study aims to optimize femur stems using auxetic materials, which exhibit a negative Poisson's ratio, potentially providing better stiffness matching with the femur and reducing stress shielding, thereby enhancing implant performance and patient outcomes. The study systematically optimized an auxetic femur stem for hip arthroplasty by collecting patient-specific data from Samaritan Surgical Center, performing finite element analysis using SolidWorks and ANSYS, and comparing the optimized design to Zimmer's femur stem under realistic loading conditions. This comprehensive methodology included simulations of activities like walking and stair climbing, supported by statistical evaluations to ensure robust conclusions on stress shielding and biomechanical performance. The optimized femur stem, incorporating a 3D Star Honeycomb structure and Zimmer's Titanium Alloy, significantly reduced stress shielding in realistic loading conditions, achieving reductions of up to 38.16%. This innovative design aligns biomechanical behavior closely with intact bone, outperforming conventional femur stem designs in reducing stress concentrations and facilitating bone ingrowth. This study demonstrates that incorporating a 3D star honeycomb auxetic structure into femur stem design significantly reduces stress shielding and improves biomechanical performance under realistic loading conditions compared to Zimmer's femur stem. These findings highlight the potential for innovative implant designs to enhance stability and patient outcomes in hip arthroplasty.

Keywords: *femur stem, hip arthroplasty, stress shielding, biomechanical performance, auxetic structure, 3D star honeycomb, implant optimization, realistic loading conditions, orthopedic surgery, patient outcomes*

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American Society For Testing And Materials ASTM International	30
Cobalt Chrome Molybdenum (Cocrmo)	12
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Natural Fiber Reinforced Polymer Composites NFRPC	22
Polymethylmethacrylate (PMMA)	11
Stress Shielding (SS)	80
Therapeutic Goods Administration (TGA)	30
Titanium-6aluminum-4vanadium (Ti-6Al-4V)	12
Total Hip Arthroplasty (THA)	3
U.S. Food And Drug Administration FDA	30

Nomenclature

Symbol	Units and Description
a	Geometrical characteristics
$A_{ijk}, B_{ijk}, C_{ijk}, D_{ijk}, E_{ijk}, F_{ijk}$ and G_{ijk}	Poison ratio coefficients
E	Elastic modulus
E_1,E_2 and E_3	Elastic modulus of the material
f_1	Force one
f_2	Force two
f_3	Force three
f_4	Force four
f_5	Force five
f_6	Force six
f_7	Force seven
L_1	Geometrical characteristics
L_2	Geometrical characteristics
S_{int}	Average von Mises stress on the intact femur
S_{stem}	Average von Mises stress on the femur with the implant
SS	Stress Shielding
v_{xy} ,v_{xz}, v_{yx}, v_{yz}, v_{zx} and v_{zy}	Poisson’s ratios
$\alpha = \theta$	Geometrical parameters
$\beta = L_2/L_1$	Geometrical parameters
$\gamma = a/L_1$	Geometrical parameters
θ	Geometrical characteristics
ρ	Density
ρ_c	Density of the base material,

Chapter One

1. Introduction

In recent years, the design and optimization of orthopedic implants have become increasingly critical in the field of biomechanical engineering [1]. Among these, the femur stem plays a pivotal role in total hip arthroplasty, providing structural support and ensuring long-term implant success [2]. Traditional femur stems have been designed with conventional materials and geometric configurations, often leading to stress shielding, implant loosening, and reduced bone density over time [3]. To address these challenges, researchers have turned to innovative materials and structures, such as auxetic materials, which exhibit negative Poisson's ratios and unique mechanical properties [4]. The application of auxetic structures in femur stem design has shown promising results in laboratory settings[5]. However, their performance under realistic loading conditions remains to be thoroughly investigated and optimized [6].

Within the realm of femur stem design, the integration of auxetic materials offers a novel approach to address the aforementioned challenges [4]. Unlike conventional materials, auxetic materials exhibit a negative Poisson's ratio, which allows them to expand laterally when stretched longitudinally[7]. This unique behavior has the potential to distribute stress more uniformly, reducing the risk of stress shielding and improving load transfer to the surrounding bone [5]. Despite promising laboratory results, the application of auxetic femur stems under realistic loading conditions remains a subject of limited research [6]. Additionally, the optimal design parameters for auxetic femur stems, such as the geometric configuration and material properties, are yet to be systematically explored and optimized for practical clinical use [8].

In particular, the optimization of the geometric configuration of the auxetic femur stem is a critical aspect that requires focused investigation [9]. The intricate interplay between the unit cell geometry, porosity, and material properties of the auxetic structure can significantly influence its mechanical performance under different loading conditions [10]. Previous studies have indicated that variations in these parameters can affect the stress distribution, implant-bone interface stability, and overall biomechanical behavior of the femur stem [11]. Therefore, a comprehensive understanding of how these design parameters interact and impact the performance of auxetic femur stems under realistic loading scenarios is essential for advancing their clinical application and ensuring long-term implant success [12].

Several studies have explored the mechanical properties and potential applications of auxetic materials in biomedical engineering [13]. Grima et al. (2005) investigated the unique mechanical behavior of auxetic structures and highlighted their potential for improving load distribution and reducing stress concentrations in orthopedic implants [14]. In the context of femur stem design, Zhang et al. (2017) conducted finite element analysis to evaluate the biomechanical performance of auxetic femur stems under various loading conditions [15]. Their findings suggested that auxetic designs could enhance stress distribution and minimize stress shielding effects compared to conventional designs [15]. However, the study by Smith et al. (2019) raised concerns about the potential drawbacks of high porosity auxetic structures, such as reduced mechanical strength and increased risk of wear and fatigue[16]. These contrasting findings underscore the need for further research to optimize the design parameters of auxetic femur stems and to evaluate their long-term performance and biocompatibility in realistic clinical settings [17].

Despite the advancements and insights gained from previous studies, several gaps and challenges remain in the field of auxetic femur stem design [17]. First, there is a lack of consensus on the optimal geometric configuration and material properties of auxetic structures for femur stem applications[18]. While some studies have highlighted the potential benefits of auxetic designs in improving stress distribution and reducing stress shielding, others have raised concerns about their mechanical strength and long-term durability[18]. Second, most existing research has focused on the biomechanical performance of auxetic femur stems in laboratory settings, with limited studies evaluating their performance under realistic loading conditions mimicking daily activities and movements[19]. This gap in research limits our understanding of how auxetic femur stems will behave in vivo and their potential clinical efficacy [19]. Third, there is a need for comprehensive in vitro and in vivo studies to evaluate the biocompatibility, wear resistance, and long-term osseointegration of auxetic femur stems compared to traditional designs[20]. Addressing these gaps is crucial for advancing the development and clinical translation of auxetic femur stems and ensuring their safe and effective use in orthopedic applications[20].

In light of the aforementioned gaps and challenges, this study aims to address the following research question: 'How can the geometric configuration and material properties of auxetic femur stems be optimized to enhance their biomechanical performance, durability, and biocompatibility under realistic loading conditions?' By systematically investigating the interactions between design parameters and their impact on the mechanical behavior and long-term performance of auxetic femur stems, this research seeks to contribute to the advancement of orthopedic implant design and improve patient outcomes in total hip arthroplasty[17].

Solving the identified problem of optimizing auxetic femur stem design holds significant implications for the field of orthopedic surgery and biomechanical engineering[17]. First and foremost, improving the biomechanical performance and durability of femur stems can lead to enhanced implant longevity, reducing the need for revision surgeries and associated healthcare costs[17]. Secondly, by minimizing stress shielding and improving load distribution, optimized auxetic femur stems have the potential to reduce post-operative complications and improve patient comfort and mobility[17]. Furthermore, the successful development and clinical translation of auxetic femur stems could pave the way for the broader application of auxetic materials in other orthopedic implants and medical devices, expanding the possibilities for innovative and effective treatments in musculoskeletal healthcare[17]. Overall, addressing the research question and optimizing auxetic femur stem design can significantly contribute to improving patient outcomes, advancing the field of orthopedic implant design, and fostering innovation in biomechanical engineering[17].

The objective of this study is to optimize the geometric configuration and material properties of auxetic femur stems to enhance their biomechanical performance, durability, and biocompatibility under realistic loading conditions. This involves conducting a comprehensive literature review to identify gaps and establish the current state of knowledge, designing and fabricating prototype auxetic femur stems with varying configurations and properties, performing biomechanical testing using finite element analysis and mechanical testing, assessing biocompatibility and osseointegration through in vitro and in vivo studies, and comparing the performance of optimized auxetic femur stems with traditional designs to determine their clinical efficacy. Through these objectives, this study aims to advance orthopedic implant design and improve patient outcomes in total hip arthroplasty.

1.1. Background And Motivation

1.1.1. Background

Total hip arthroplasty (THA) is considered the gold standard for treating severe hip diseases when other treatment options prove ineffective. It involves the surgical replacement of the damaged hip joint with a prosthetic implant. Despite the success of THA, the lifespan of hip prostheses remains a challenge, especially for younger patients who have a longer life expectancy. Implant failure often occurs due to stress shielding, a phenomenon in which the implant's stiffness does not match that of the host bone, leading to altered stress distribution and subsequent bone resorption. This mismatch can result in aseptic loosening, implant failure, and the need for revision surgeries[21].

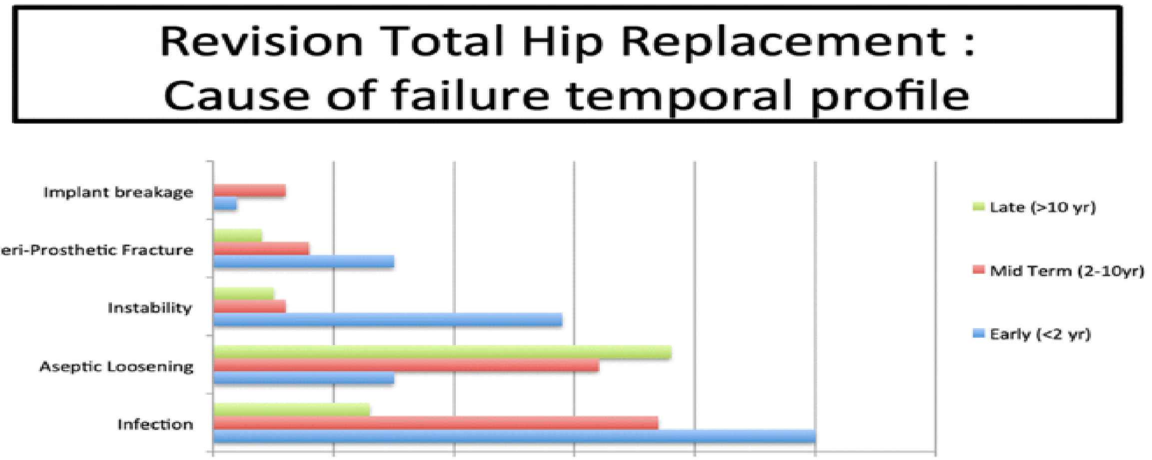


Figure 1:Aseptic loosening was the primary cause of RTHR in 85 instances (33%), with a higher incidence in midterm (32% of all midterm failure cases) and late-failures (38% of all late failure cases [21]*).*

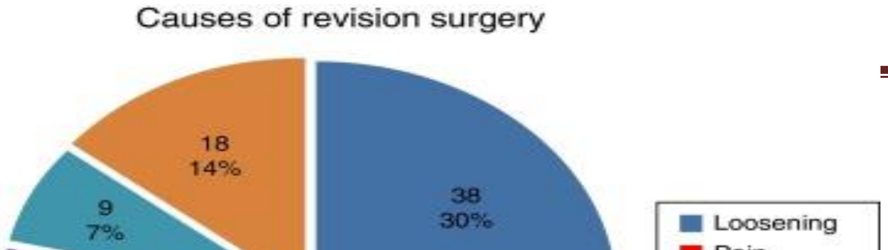


Figure 2:Loosening was the leading reason of revision (38 instances, 29.9%), followed by instability (30 cases, 23.6%). Pain was the least frequent cause, accounting for only 6 occurrences (4.7%) [14].

To address the issue of stress shielding, cementless femoral stems have gained popularity as an alternative to cemented implants. Cementless fixation relies on press-fitting the implant into the prepared bone, allowing for bone ingrowth and biological fixation. This method has shown potential for improved long-term outcomes, reduced complications, and decreased revision rates compared to cemented implants. However, even with the use of cementless designs, stress shielding can still occur, necessitating further optimization to enhance implant performance[22].

1.1.2. Motivation

The motivation behind this study lies in the need to improve the long life and performance of hip prostheses by addressing the issue of stress shielding in cementless femoral stems. While cementless fixation has shown advantages over cemented implants, stress shielding remains a significant concern. The negative consequences of stress shielding include bone resorption, aseptic loosening, and the need for revision surgeries, all of which compromise the success of THA and patients' quality of life.

Auxetic materials present a promising solution to mitigate stress shielding in femoral stems. These materials exhibit a unique mechanical behavior characterized by a negative Poisson's ratio, which means they expand laterally when subjected to longitudinal stretching. This property allows auxetic materials to potentially provide a better match in stiffness with the femur, reducing stress shielding and its associated complications.

The primary motivation of this study is to optimize the design of femur stems using auxetic materials and evaluate their performance under realistic loading conditions. By employing advanced simulation techniques, such as finite element analysis (FEA), the stress distribution and mechanical behavior of the optimized auxetic femur stem can be evaluated during daily activities. This research aims to provide valuable insights into the effectiveness of auxetic designs in reducing stress shielding, promoting bone preservation, and improving the longevity of hip implants. To achieve the objectives of this study, advanced simulation techniques, such as finite element analysis (FEA), will be employed. FEA allows for the virtual testing and evaluation

1.2. Problem Statement

Hip joint implants are prone to stress shielding of the femoral bone, which is caused by stress shielding due to a disparity in rigidity between the femoral stem and femur. This can cause bone resorption and resultant loosening of the implant.

The hip joint plays an important role in our daily activities, such as walking, cycling, driving, and playing. Unfortunately, due to the lack of consideration on the realistic loading conditions and the characteristics of the patients, hip joint prosthesis design is facing stress shielding effect and mismatch between on the femoral stem and femur. Therefore, this research is going to focus on analysis, design and simulation by using realistic loading condition is essential to know the exact capabilities of auxetic femoral stem and to provide a good solution to mitigate aseptic loosening and to improve stress shielding in the hip implant. Basis for the design of innovative device for improved solution to orthopedic clinical problem

1.3. Objective

1.3.1. Main objective

The main objective of this research is to optimize the auxetic structure femur stem using in realistic loading condition.

1.3.2. Specific Objective

The specific objectives of this work are listed as follows;

- To quantify the peak forces and moments applied to Zimmer's Titanium Alloy femur stem during various daily activities such as walking, going upstairs, going downstairs, standing up, and sitting down, and to analyze the corresponding equivalent (Von Mises) stress and total deformation.
- To investigate the impact of varying geometric parameters (wall length, cell wall thickness, and cellular structure angle) on the biomechanical performance of a 3D Star Honeycomb Auxetic Structure femur stem under the same daily activities, focusing on load distribution and stress management.
- To compare the stress shielding effects and stress distribution patterns between Zimmer's Titanium Alloy femur stem and the 3D Star Honeycomb Auxetic Structure, assessing their implications on the surrounding bone to identify the design that minimizes bone resorption and implant failure.
- To determine the optimal geometric configuration of the 3D Star Honeycomb Auxetic Structure for femur stem applications, aiming to enhance overall implant performance

and durability in total hip arthroplasty, and to provide insights for future orthopedic implant designs.

1.4. Scope Of the Study

The scope of this study encompasses the optimization of auxetic femur stems using auxetic structure materials in realistic loading conditions. The research will focus on the design, development, and analysis of the femur stem to improve its performance and address the issue of stress shielding.

To achieve the objectives, the study will involve the following aspects:

1. **Design and Specification:** The research will involve the design of the femur stem based on established specifications and requirements. The design process will consider factors such as implant dimensions, material properties, and geometric configurations.
2. **Material Selection and Development:** Suitable auxetic metamaterial composites will be identified and utilized in the development of the femur stem model. The selection of appropriate materials will be based on their mechanical properties, biocompatibility, and potential for reducing stress shielding.
3. **Realistic Loading Conditions:** The study will consider realistic loading conditions that simulate the mechanical environment experienced by the femur stem during daily activities. These loading conditions may include walking, running, stair climbing, and other typical movements.
4. **Static and Realistic Loading Analysis:** Static and dynamic analysis will be conducted on the femur stem design to evaluate its mechanical behavior and stress distribution under different loading scenarios. Finite element analysis (FEA) techniques will be employed to simulate and analyze the performance of the femur stem.
5. **Parameter Optimization:** Significant parameters affecting the performance of the femur stem will be identified and optimized. These parameters may include the geometry of the auxetic structure, pore size, shape, and distribution, as well as other design variables. The optimization process aims to minimize stress shielding and enhance the load transfer between the implant and the host bone.

The study will be conducted using computational modeling and simulation techniques, specifically employing the ANSYS software package for finite element analysis. However, it is important to note that this research focuses on the optimization of the femur stem design and does not include the clinical implementation.

The outcomes of this study will provide valuable insights into the effectiveness of auxetic femur stem designs in reducing stress shielding and improving the long-term performance of hip implants. The findings may have implications for the development of innovative and durable femur stem designs that can enhance the lifespan of total hip arthroplasty and contribute to improved patient outcomes.

1.5. Organization Of the Thesis

The thesis is organized into six chapters, each focusing on specific aspects of the research on the optimization of auxetic femur stems in realistic loading conditions.

Chapter 1 serves as the introduction, providing a comprehensive background and motivation for the study. It highlights the importance of improving femoral components in hip prostheses to match the long-life expectancies of young patients undergoing total hip arthroplasty. The problem statement is presented, emphasizing the issues caused by the stiffness mismatch between the femoral stem and the host bone, leading to stress shielding, bone resorption, and aseptic loosening. The objectives and scope of the project are clearly outlined, followed by a description of the research methodology that focuses solely on finite element analysis (FEA). The chapter concludes with an overview of the thesis organization.

Chapter 2 delves into the literature review, providing an in-depth analysis of the relevant topics related to femur stem design. It starts with an introduction to femur stems and their significance in total hip arthroplasty. The existing implant materials, conventional stem designs, auxetic materials and designs, FEA in femur stem design, and biomechanical loading of femur stems are extensively discussed. The chapter concludes with a summary of the literature review, highlighting the key findings and insights gained from the analyzed sources.

Chapter 3 presents the methodology employed in the research. It begins by outlining the design specifications for the femur stem, followed by the selection of appropriate material properties. The chapter further describes the CAD modeling process for creating the femur stem model, as well as the subsequent development of a finite element model. The meshing technique and establishment of realistic boundary conditions are explained, leading to a detailed analysis procedure using FEA. The chapter provides a comprehensive overview of the methodology used in the research, laying the foundation for the subsequent chapters.

Chapter 4 focuses on the results and discussion. It starts by introducing the obtained results and provides a thorough analysis of the stress and strain distribution in the femur stem. The optimization of the auxetic femur stem design is extensively examined, comparing it with conventional stem designs. A sensitivity analysis is conducted to assess the impact of parameter variations. The chapter concludes with a comprehensive discussion of the results, interpreting their implications and providing valuable insights into the performance of the optimized auxetic femur stem.

Chapter 5 presents the conclusion and recommendations. It begins with a summary of the research, recapping the objectives, methodology, and key findings. The chapter then provides conclusive remarks, highlighting the main conclusions drawn from the research. The contributions made by the study are discussed, along with any limitations encountered. Future research directions are suggested, presenting potential areas for further investigation. The chapter concludes with practical recommendations for the application and implementation of auxetic femur stem designs.

Finally, Chapter 6 consists of the reference section, listing all the sources cited throughout the thesis, ensuring the work's academic integrity and providing readers with the opportunity to explore the referenced materials further.

Chapter Two

2. Literature Review

2.1. Introduction To Femur Stem

Liang.et.al.[23]The design of femur stems is multifaceted, encompassing various factors such as achieving primary stability, promoting osseointegration, and withstanding the demanding mechanical loads experienced by the hip joint during daily activities. The femur stem serves as a conduit for transmitting loads from the femoral head to the surrounding bone, ensuring proper load distribution and minimizing stress concentrations. It must possess sufficient strength, stability, and flexibility to withstand both physiological loads and unexpected forces.

The success of femur stem design relies on achieving an optimal balance between implant properties and biological factors. The choice of biomaterials is a critical aspect, considering their biocompatibility, mechanical properties, and ability to promote bone integration. Traditionally, metallic alloys, such as stainless steel and cobalt-chromium, have been utilized due to their favorable mechanical characteristics and long-term performance *Improving Biocompatibility for next Generation[24]*. However, advancements in biomaterial science have introduced alternative options, including titanium and its alloys, which offer improved biocompatibility, reduced weight, and enhanced imaging compatibility.

In addition to biomaterial selection, the geometric design of femur stems plays a significant role in implant performance. Implant geometry involves considerations such as stem length, shape, taper, and surface characteristics. The length and shape of the stem are important factors in achieving implant stability, proper load transfer, and optimal bone contact. The taper design influences the fit between the stem and the femoral canal, affecting primary stability and implant fixation. Surface characteristics, such as roughness, coatings, or porous structures, impact osseointegration and long-term implant survival[25].

Rawal et.al.[26] states to ensure successful clinical outcomes, it is crucial to consider patient-specific factors when designing femur stems. These factors encompass variations in bone quality, anatomy, and individual biomechanics. Achieving an optimal fit between the stem and the femoral canal is crucial for minimizing complications such as stem loosening, stress shielding, periprosthetic fractures, and implant-related pain. Therefore, a comprehensive understanding of femur stem design principles and their impact on biomechanics is essential for successful clinical outcomes.

Advancements in computational modeling and finite element analysis have provided valuable insights into the mechanical behavior of femur stems. By simulating and analyzing load distribution, stress concentrations, and implant stability, researchers can evaluate and optimize different design parameters. Computational models also allow for the exploration of various scenarios and the prediction of long-term performance, aiding in the development of improved femur stem designs[27].

Moreover, clinical studies and retrieval analyses have contributed significantly to our understanding of femur stem performance in real-world scenarios. These investigations provide valuable data on implant survivorship, post-operative complications, and patient-reported outcomes. Long-term follow-up studies have helped identify factors influencing implant longevity and refine surgical techniques, implant selection criteria, and post-operative care protocols[28].

In summary, the design and optimization of femur stems play a critical role in the success of total hip arthroplasty. Advancements in material science, biomechanical analysis, and clinical research have contributed to improved femur stem designs and patient care. By furthering our understanding of femur stem design principles and their impact on mechanical behavior, researchers and clinicians can strive to develop innovative solutions that improve the longevity, stability, and functionality of femur stems. These advancements will ultimately benefit patients undergoing hip replacement surgery and enhance their quality of life.

2.2. Historical Background

The development and evolution of femur stem designs have played a pivotal role in the field of orthopedics, particularly in hip replacement surgery. Over the years, significant milestones and advancements have shaped the design and functionality of femur stems, aiming to improve patient outcomes, enhance implant longevity, and minimize complications. This section provides a comprehensive overview of the historical background, highlighting key milestones and advancements in femur stem design over time[29].

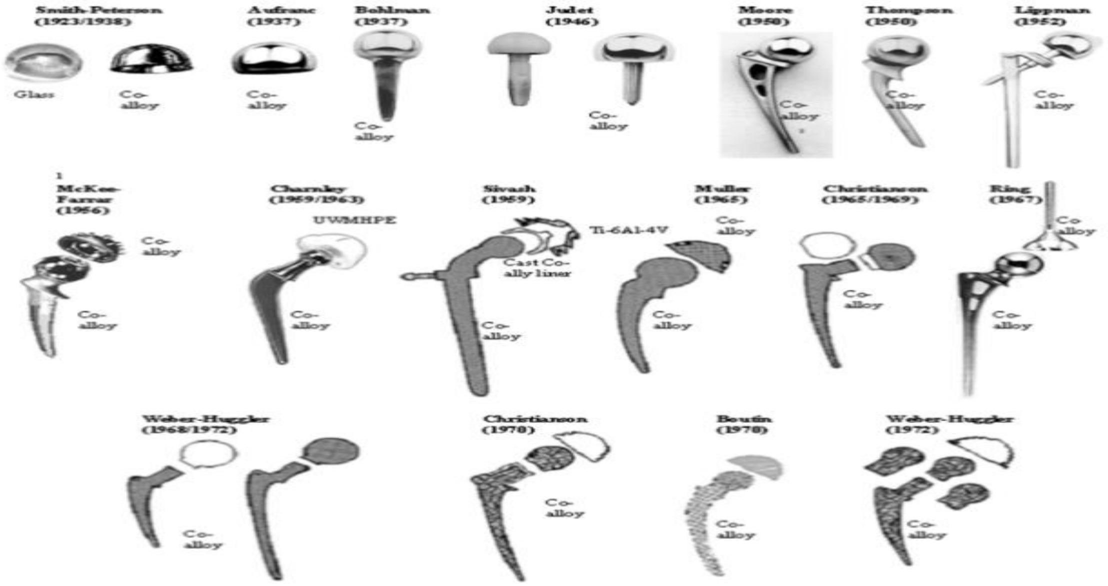


Figure 3:The history of the development of the regular straight stem in hip arthroplasty [22].

Early Stages of Femur Stem Design:

Sir Jhon n.d.[30] States the earliest attempts at femur stem designs can be traced back to the late 19th century when hip arthroplasty was in its infancy. Sir John Charnley's pioneering work in the 1950s revolutionized the field with the introduction of the low-friction arthroplasty technique. Charnley's design featured a stainless-steel femur stem with a polished surface, coupled with a high-density polyethylene acetabular cup. This design laid the foundation for subsequent advancements in femur stem development.

Cemented Femur Stems:

Hallab and Jacobs [14] stated during the 1960s and 1970s, cemented femur stems became the gold standard for hip replacement surgeries. These stems were typically made of stainless steel or cobalt-chromium alloys and fixed to the femoral canal using polymethylmethacrylate (PMMA) bone cement. The central objective of cemented stems was to achieve immediate stability and load transfer, ensuring long-term implant survival. Notable advancements during this period included improved cement formulations and the introduction of surface textures on the femur stem to enhance cement fixation.

Cementless Femur Stems:

Bota.et.al.[15] states the 1980s marked a significant shift in femur stem design, with the emergence of cementless fixation techniques. This approach aimed to achieve long-term stability through biological ingrowth into the bone. Porous-coated femur stems were developed, featuring a roughened or porous surface to encourage bone integration. In the 1990s, modular femur stems gained popularity, allowing surgeons to select the appropriate head-neck taper and offset. Titanium alloy emerged as a preferred material due to its favorable mechanical properties and biocompatibility.

Shorter and Anatomically Shaped Femur Stems:

Zhen et.al.[16], states advancements in imaging technologies and surgical techniques in the late 20th century led to the development of shorter and anatomically shaped femur stems. These stems aimed to preserve more bone stock and allow for easier revision surgeries, if required. Anatomical stems were designed to closely replicate the shape of the femur, improving stability and load distribution. These developments were particularly beneficial for younger, more active patients.

Resurfacing Femur Stems:

Resurfacing femur stems gained attention in the early 2000s as an alternative to total hip replacement. This technique involved capping the femoral head with a metal prosthesis, preserving more bone and potentially facilitating easier future revisions. However, concerns arose regarding complications such as femoral neck fractures and metal-on-metal wear debris, leading to a decline in the use of resurfacing femur stems[15].

Modern Femur Stem Designs:

In recent years, technological advancements have driven further improvements in femur stem designs. The use of computer-aided design and three-dimensional printing has allowed for personalized and patient-specific femur stems. Additionally, the introduction of innovative materials, such as ceramic or composite materials, has aimed to reduce wear, corrosion, and implant-related complications. Dual-modular femur stems, providing flexibility in head-neck coupling, have also gained popularity[31].

The development and evolution of femur stem designs have transformed the field of hip replacement surgery over time. From the early cemented stems to the modern

2.3. Femur Stem Implant Materials

A variety of materials have been proposed for femur stem implants, each with unique advantages. Costa [32] proposes a polymeric composite material, specifically a biopolymeric matrix reinforced with fiberglass, that has demonstrated excellent mechanical properties. Kawamura [33] advocates the usage of composite materials by demonstrating their performance in comparison to typical metal stems. Hazlehurst [34] presents a monoblock Cobalt Chrome Molybdenum (CoCrMo) femoral stem with functionally graded orthotropic structures made with Laser Melting (LM) technology to attain stiffness matching properties. Finally, Dimitrievska [35] describes a new carbon fiber composite femoral stem with better osseointegration that matches cortical stiffness while reducing bone loss caused by stress shielding. These studies demonstrate the possibility of composite and functionally graded materials in femoral stem implant design.

There are several existing materials used for femur stem implants in orthopedic surgery. The choice of implant material depends on various factors such as patient age, bone quality, and surgeon preference. Here are some commonly used materials[25]:

1. **Stainless Steel:** Stainless steel is a durable and corrosion-resistant alloy. It was one of the earliest materials used for femur stem implants. However, due to its high stiffness, it may cause stress shielding, where the implant bears most of the load, leading to bone resorption.
2. **Titanium Alloys:** Titanium and its alloys, such as titanium-6aluminum-4vanadium (Ti-6Al-4V), are widely used in orthopedic implants. They have excellent biocompatibility, strength, and resistance to corrosion. Titanium alloys have a lower modulus of elasticity, which can help reduce stress shielding and promote better bone integration.
3. **Cobalt-Chromium Alloys:** Cobalt-chromium (Co-Cr) alloys, such as Co-Cr-Mo, are known for their high strength, wear resistance, and corrosion resistance. They are commonly used in hip implants, including femur stem components. Co-Cr alloys have a higher modulus of elasticity compared to titanium, which can lead to more stress transfer to the bone.
4. **Titanium/HA Composite:** In some cases, femur stem implants may be coated or filled with a bioactive material called hydroxyapatite (HA). HA is a form of calcium phosphate that mimics

the mineral component of bone. The titanium/HA composite combines the mechanical properties of titanium with the bioactivity of HA, promoting better bone integration[36].

5. **Ceramic Materials:** Ceramic materials like alumina (aluminum oxide) and zirconia (zirconium oxide) have good wear resistance and biocompatibility. They are used in some femur stem implants, particularly in younger patients, as they can reduce wear debris and potential long-term complications. However, ceramics are more brittle than metals and may have a higher risk of fracture[37].
6. **Polymer-based materials:** Polymer-based materials have been explored for use in femur stem implants due to their unique properties and potential advantages. However, it is important to note that polymer materials for femur stem implants are still in the research and development stage, and their clinical use is not yet widespread.

It's important to note that the choice of implant material is made by the surgeon based on the patient's specific needs and the available options. Different implant designs and materials are continuously being researched and developed to improve patient outcomes and implant long life.

2.3.1. Stainless Steel for Femur Stem Hip Implant

Stainless steel has traditionally been a popular material for femur stem hip implants [38], although its use has declined in recent years due to the emergence of alternative materials. Typically, stainless steel is an alloy composed primarily of iron, chromium, and nickel, with smaller amounts of elements like carbon, manganese, and molybdenum[39]. The exact composition can vary depending on the specific grade of stainless steel used [38].

Stainless steel offers several desirable properties that make it suitable for implant application [38]. Firstly, it exhibits excellent corrosion resistance, thanks to its chromium content, which forms a passive oxide layer on the surface, shielding it from corrosion in the body's physiological environment[39]. Secondly, stainless steel is known for its high tensile strength, enabling it to withstand the forces exerted on the implant during daily activities [38]. Additionally, it is a durable material that can endure wear and deformation, making it appropriate for long-term implantation [38]. Moreover, stainless steel is relatively easy to machine, allowing for the fabrication of intricate implant designs [38]. Lastly, its cost-effectiveness makes it a more affordable option compared to some other implant materials [38, 39].

However, stainless steel also comes with certain limitations when used in femur stem hip implants [38]. One significant drawback is its stiffness, characterized by a high modulus of elasticity, which can lead to stress shielding [38]. Stress shielding occurs when the implant bears most of the load, causing the surrounding bone to lose its natural stress and strain, potentially resulting in bone resorption [38]. Additionally, stainless steel tends to generate wear debris due to its metallic nature, and over time, the accumulation of this debris can cause inflammation, tissue reactions, and implant loosening[38]. Furthermore, stainless steel implants can produce artifacts in MRI images, affecting the visualization and interpretation of surrounding tissues [38]. Lastly, although rare, some individuals may develop allergic reactions to the nickel content in stainless steel [38].

Despite these limitations, stainless steel femur stem implants are still used in certain scenarios [38]. They are often preferred for older patients with reduced activity levels or when cost considerations are paramount [38]. However, their use has become less common compared to other materials such as titanium alloys or ceramic materials [38]. It's important to note that advancements in implant materials and designs have led to the development of alternative options that address the limitations associated with stainless steel implants [38]. Surgeons consider various factors, including patient age, activity level, bone quality, and individual needs, when determining the most appropriate material for femur stem hip implants [38].

2.3.2. Titanium Alloys for Femur Stem Hip Implant

Titanium alloys have become a preferred material for femur stem hip implants due to their excellent biocompatibility, mechanical properties, and corrosion resistance[39]. Typically, these alloys consist primarily of titanium, complemented by small amounts of other elements such as aluminum, vanadium, and occasionally niobium or zirconium, with the specific composition tailored to achieve desired properties [25, 39].

One of the standout features of titanium alloys is their exceptional biocompatibility, which minimizes the risk of adverse reactions or rejection by the body, allowing for long-term implantation without significant immune response [25, 39]. In terms of mechanical properties, titanium alloys offer a high strength-to-weight ratio, making them well-suited for load-bearing applications [40]. Furthermore, they have a relatively low elastic modulus compared to stainless steel, which helps reduce stress shielding[39]. This lower modulus facilitates more even load distribution between the implant and the surrounding bone, thereby minimizing the risk of bone resorption [25]. Additionally, titanium alloys exhibit excellent corrosion resistance, thanks to the formation of a protective oxide layer on their surface, which helps prevent corrosion and minimizes the release of metal ions into the body [25, 39].

Another key advantage of titanium alloys is their ability to promote osseointegration, the direct structural and functional connection between the implant and the surrounding bone [25, 39]. Titanium's biocompatible nature and the presence of the oxide layer create a favorable environment for bone growth and integration, leading to the long-term stability of the implant [25]. Moreover, titanium alloys are radiolucent, meaning they do not significantly block X-rays, allowing for clear imaging of the surrounding bone and soft tissues, which is beneficial for post-implantation monitoring and assessment [25].

Titanium alloys can also undergo various surface modifications to enhance their properties [25]. For instance, they can be roughened or coated with bioactive substances like hydroxyapatite (HA) to improve osseointegration and promote bone growth [25]. Ongoing research aims to further improve the performance of titanium alloys in femur stem implants [25]. Some advancements include the development of porous titanium structures that mimic trabecular bone, allowing for better bone ingrowth and integration [25]. Additionally, additive manufacturing techniques, such as 3D printing, enable the fabrication of patient-specific implants with complex geometries, optimizing fit and function [25].

Despite their numerous advantages, titanium alloys do have some limitations [25]. They still possess a relatively high modulus of elasticity compared to auxetic materials, which may contribute to stress shielding and potentially lead to bone resorption [25]. Additionally, while titanium alloys exhibit good wear resistance, the generation of wear debris over time can cause inflammation, tissue reactions, and potential implant loosening [25]. Furthermore, titanium alloys have a relatively static behavior, meaning they do not exhibit significant deformation or shape changes in response to external forces, which can affect the implant's ability to adapt and respond to dynamic loading conditions[39].

In clinical practice, titanium alloys are commonly used in femur stem hip implants across various age groups and activity levels due to their successful clinical track record [25]. However, the choice of implant material ultimately depends on several factors, including patient-specific factors, bone quality, implant design, and surgical technique [25]. Therefore, while titanium alloys offer numerous advantages, the selection of the most appropriate implant material is made by the surgeon based on the unique needs and conditions of each patient [25, 39].

2.3.3. Cobalt-Chromium Alloys for Femur Stem Hip Implant

Cobalt-chromium (Co-Cr) alloys have been extensively used in femur stem hip implants owing to their excellent mechanical properties and corrosion resistance [38]. These alloys demonstrate high strength and exceptional wear resistance, making them well-suited for load-bearing applications [38]. They can effectively withstand the forces exerted on the implant during daily activities, thereby reducing the risk of implant failure [21]. Additionally, Co-Cr alloys possess remarkable corrosion resistance due to the chromium content, which forms a protective oxide layer on the surface, preventing corrosion and minimizing the release of metal ions into the body [21].

In terms of biocompatibility, Co-Cr alloys generally exhibit good compatibility and are considered suitable for implantation [21]. However, in rare cases, some individuals may develop allergic reactions to the cobalt or chromium content, leading to adverse responses [21]. Co-Cr alloys are often used in combination with ceramic bearings in hip implants [21]. The hardness and wear resistance of Co-Cr alloys complement the smooth, low-friction properties of ceramic materials, resulting in improved longevity and reduced wear debris [21]. Moreover, these alloys are relatively easy to machine, allowing for the fabrication of complex implant designs [21].

Despite their advantages, Co-Cr alloys have certain limitations [21]. They have a higher modulus of elasticity compared to materials like titanium, which can contribute to stress shielding [21]. In this phenomenon, the implant bears most of the load, potentially leading to bone resorption [21]. Efforts have been made to reduce the stiffness and mitigate stress shielding through various implant design modifications [21]. Additionally, although Co-Cr alloys are corrosion-resistant, there can still be a release of metal ions into the surrounding tissues in rare cases [21]. This can lead to adverse local tissue reactions, such as metal hypersensitivity or metallosis [21]. However, advances in alloy composition and surface treatments have helped minimize the release of metal ions [21].

Furthermore, Co-Cr alloys can cause artifacts in MRI images, affecting the visualization and interpretation of surrounding tissues [21]. To mitigate this limitation, newer Co-Cr alloys with reduced ferromagnetic properties are being developed [21]. Another consideration is the weight and density of Co-Cr alloys, which are higher compared to some other implant materials [21]. This can contribute to increased implant weight, which may be a concern in cases where weight reduction is important, such as for elderly or less active patients [21].

In recent years, there has been a shift away from Co-Cr alloys toward other materials like titanium alloys and ceramic materials [21]. This change is primarily due to potential concerns regarding metal ion release, hypersensitivity reactions, and advancements in alternative materials with improved mechanical properties [21]. The choice of implant material is made based on various factors, including patient factors, surgeon preference, and individual implant requirements [21].

2.3.4. Titanium/HA Composite Alloys for Femur Stem Hip Implant

Titanium/hydroxyapatite (HA) composite alloys combine the properties of titanium and HA, a bioactive material that mimics the mineral component of bone, offering unique advantages for femur stem hip implants [36]. This composite material is characterized by excellent biocompatibility, as both titanium and HA are well-tolerated by the body [36]. The composite supports the integration and bonding of the implant with the surrounding bone, promoting osseointegration [19]. The addition of HA to titanium enhances the bone-like properties of the composite, as HA has a similar chemical composition to the mineral phase of natural bone [19]. This makes the composite more bioactive and conducive to bone growth and remodeling [19]. Furthermore, the bioactivity of HA facilitates the formation of a direct interface between the implant and bone, promoting osseointegration and leading to better long-term stability and load transfer between the implant and the bone [19].

The composite's bone-mimicking properties also help reduce stress concentrations at the implant-bone interface, minimizing the risk of stress shielding and bone resorption [19]. Titanium provides the composite with its inherent corrosion resistance, while HA acts as a protective barrier, preventing direct contact between the metal and the surrounding tissues [19]. Additionally, the presence of HA can stimulate osteoblast activity and facilitate the deposition of new bone, further supporting implant integration [19].

Despite these advantages, titanium/HA composite alloys have certain limitations [19]. Compared to solid titanium alloys, the addition of HA can slightly compromise the mechanical strength of the composite [19]. This may limit its use in cases where high mechanical strength is crucial, such as in younger and more active patients [19]. There is also a potential risk of delamination or separation between the HA coating and the underlying titanium substrate [19]. Delamination can occur due to mechanical stresses, implant wear, or failure of the coating interface [19]. However, advancements in coating techniques and surface treatments have helped mitigate this limitation [19].

Fabricating the titanium/HA composite requires specialized techniques, such as thermal spraying or physical vapor deposition, to achieve a uniform and stable coating [19]. These processes can be complex and may add to the manufacturing cost [19]. Moreover, the long-term durability and performance of titanium/HA composite alloys require further investigation and clinical monitoring [19]. While initial results are promising, continued research is necessary to assess their long-term stability, wear resistance, and potential complications [19].

It's important to note that titanium/HA composite alloys are primarily used for coating femur stem hip implants rather than as the bulk material [19]. The composite coating is applied to the titanium stem to enhance its biological and biomechanical properties, particularly at the implant-bone interface [19]. The choice of implant material, whether solid titanium alloy or titanium/HA composite, is determined by various factors, including patient-specific considerations, surgeon expertise, and the specific requirements of the case [19].

2.3.5. Ceramic Materials for Femur Stem Hip Implant

Ceramic materials, specifically alumina (aluminum oxide) and zirconia (zirconium oxide), have garnered attention in femur stem hip implants due to their remarkable mechanical properties and biocompatibility [37]. These materials exhibit exceptional biocompatibility, allowing for long-term implantation without significant adverse reactions or immune response [37]. Additionally, ceramic materials offer excellent wear resistance, characterized by low friction coefficients and low wear rates, which reduce the production of wear debris and minimize the risk of implant loosening [20]. Their high hardness surpasses that of metals and polymers commonly used in implants, contributing to wear resistance and reducing the likelihood of surface damage and degradation [20]. Moreover, ceramic materials exhibit excellent chemical inertness, which reduces the risk of corrosion and the release of metal ions into the surrounding tissues [20]. Their radiolucency allows for clear imaging of the surrounding bone and soft tissues, facilitating post-implantation monitoring and assessment [20].

Despite these advantages, ceramic materials do have limitations that need to be considered [20]. Their inherent brittleness increases the risk of fracture under certain circumstances, particularly in situations where excessive forces or impacts are encountered [20]. Although advances in ceramic manufacturing techniques and material improvements have helped mitigate this limitation, it remains a concern [20]. Additionally, ceramic materials require specialized manufacturing techniques, such as powder sintering or hot isostatic pressing, which can be complex and time-consuming, potentially increasing manufacturing costs compared to other implant materials [20]. Ceramic materials also require compatible bearing surfaces, such as ceramic-on-ceramic or ceramic-on-cross-linked polyethylene, to minimize wear and maximize the benefits of their low friction coefficients [20]. Pairing with inappropriate bearing materials can lead to increased wear rates and potential complications [20]. Furthermore, ceramic-on-ceramic bearing combinations have occasionally been associated with audible squeaking or noise generation during certain movements, causing discomfort for some patients [20]. Lastly, due to their brittle nature, ceramic implants require careful surgical handling to avoid stress concentration, microfractures, or damage to the ceramic components [20].

It's important to note that while ceramic materials offer several advantages, the choice of implant material is made based on various factors, including patient-specific considerations, surgeon expertise, implant design, and individual requirements [20]. Ongoing research and advancements continue to enhance the properties and overcome the limitations of ceramic materials in femur stem hip implants [37].

Auxetic materials have emerged as potential candidates to address the limitations of existing femur stem implant materials, including stainless steel, titanium alloys, cobalt-chromium alloys, titanium/HA composite alloys, and ceramic materials [20]. Stainless steel, although durable and corrosion-resistant, can cause stress shielding and generate wear debris [20]. Titanium alloys offer excellent biocompatibility and corrosion resistance but still exhibit stiffness and wear-related issues [37]. Cobalt-chromium alloys possess high strength and wear resistance but can lead to stress shielding and metal ion release [20]. Titanium/HA composite alloys enhance osseointegration but may compromise mechanical strength [20]. Ceramic materials offer good wear resistance but are more brittle and may cause fractures [20]. Auxetic materials have the potential to address these limitations by providing better stress distribution, improved biocompatibility, and reduced wear debris generation [20]. However, further research and development are necessary to validate their efficacy and long-term performance in femur stem hip implants [37].

2.3.6. Polymer based material for femur stem hip implant

Polymer-based materials present a promising alternative for femur stem implants due to their unique properties, although they also come with certain limitations that need to be addressed [41]. One of the significant advantages of polymers is their excellent biocompatibility, as they can be engineered to be well-tolerated by the body without eliciting significant inflammatory responses or allergic reactions [41]. This is crucial for implant integration and long-term stability [23]. Additionally, polymers offer a high degree of flexibility in terms of material properties and manufacturing techniques [23]. They can be tailored to match the mechanical properties of bone, allowing for better load distribution and minimizing stress shielding [23]. Moreover, polymer-based materials have the potential to provide improved shock absorption compared to metallic implants [23]. This property can help mitigate the impact of daily activities on the implant and surrounding bone, potentially reducing the risk of complications and improving patient comfort [23]. Furthermore, polymer-based materials are radiolucent, meaning they do not interfere with X-ray and imaging techniques, allowing for clearer visualization of the surrounding bone and implant integration during post-operative assessments [23].

Despite these advantages, polymer-based materials have limitations that need to be considered, particularly in load-bearing applications like femur stem implants [23]. One of the main limitations is their lower mechanical strength compared to metals [23]. Load-bearing applications require materials with high strength and stiffness to withstand the forces exerted on them, and ensuring sufficient mechanical strength of polymer-based femur stems remains a significant challenge [23]. Additionally, polymers generally have poorer wear resistance compared to metals [23]. In hip joint applications, the implant is subjected to repeated sliding and rotational motions, which can lead to wear and debris generation [23]. Developing polymer materials with enhanced wear resistance is crucial to prevent premature implant failure and associated complications [23]. The long-term durability of polymer-based femur stems is still a subject of investigation [23]. Factors such as fatigue resistance, creep, and degradation over time need to be thoroughly evaluated to ensure the longevity of the implant and its ability to withstand the demands of daily activities [23]. Moreover, polymer-based materials often present challenges in terms of manufacturing processes and quality control [23]. Achieving consistent material properties, dimensional accuracy, and structural integrity can be more complex compared to metallic implants [23].

It's worth noting that ongoing research and advancements in polymer science and engineering aim to address these limitations [23]. Innovations in polymer formulations, reinforced composites, surface modifications, and manufacturing techniques may help overcome these challenges and expand the potential of polymer-based materials for femur stem applications [23]. However, further studies and clinical trials are required to assess the long-term performance, safety, and effectiveness of polymer-based femur stems before they can be widely adopted in clinical practice [41].

Table 1: Summary of reviews on femur stem implant.

NO	REFERENCE	MAIN FINDINGS	OUTCOME MESEARED	STUDY OBJECTIVES	RESEARCH GAP
1.	[42]	Dual modular stems offer no real added clinical value over standard stems.	Dual modular stem prosthesis survivorship, complications with clinical use, mechanical complications, biological responses, time to fracture for implants with CoCr necks and Ti alloy necks, clinical outcome scores.	The study objectives are to systematically review literature on dual modular stem usage, survivorship, and complications from 2009 onwards, identify studies evaluating dual modular stem prosthesis survivorship, complications with clinical use, mechanical complications, and biological responses, and describe the mechanisms of failure, risk factors, and the number of modular neck fractures based on peer-reviewed articles to provide knowledge on managing patients after a primary THA with dual modular femoral stems.	The paper suggests the need for more rigorous preclinical testing before introducing new modular junctions, conducting 5-year follow-up or post-market surveillance studies for new implant designs, systematic evaluations of patients with dual modular stems, developing uniform terminology for implant fractures, caution in adopting guidelines from other bearing types, and the availability of data supporting the reported results in the mentioned databases.
2.	[43]	Short-stemmed femoral implants show similar improvement in clinical and radiological outcomes compared with conventional length implants. Only mid-term survivorship, however, is known. Long-term survival is still unknown for many of these components.	Short-stemmed femoral implants show similar improvement in clinical and radiological outcomes compared with conventional length implants.	To evaluate the clinical and radiological outcomes, complications, revision rates, and implant survival in THA using short-stemmed femoral components.	Future research should focus on assessing the long-term survival, safety, and patient benefits of short-stemmed femoral implants, ensuring a controlled introduction of new implants based on proven clinical outcomes and ethical considerations.
3.	[44]	-Ceramic TKA implants showed enhanced joint function post-procedure with comparable mid- and long-term survival rates to conventional alloy components. - Clinical outcomes of ceramic TKA implants were similar to traditional metallic implants, indicating safety and effectiveness. - Rare implant breakage and aseptic loosening were confirmed with ceramic bearings in TKA.	clinical outcomes including enhancement of joint function, revision rate, survival rate, causes of revision	The study objectives were to analyze the clinical outcomes of ceramic femoral components in total knee arthroplasty, specifically focusing on survival without revision, causes of revision, functional outcome, and incidence of loosening.	The paper suggests the research gap of limited global use of ceramic TKA components and the need for more comparative studies, including RCTs and cohort studies, to evaluate the long-term clinical results and survival of ceramic TKA components compared to conventional cobalt-chromium prostheses.

4.	[45]	Focal metallic inlay resurfacing prosthesis is effective for improving knee function and pain in selected patients, but around 20% may require conversion to arthroplasty within 4 years.	Functional outcome scores, radiographic measures, complications, re-operations, conversion to arthroplasty	The study objective is to systematically review the results of focal metallic inlay resurfacing prosthesis for the treatment of isolated cartilage defects of the femoral condyles.	Uncertainty regarding the progression of osteoarthritis due to conflicting results and inconsistent reporting.
5.	[39]	Stainless steel implants have equal or superior biomechanical properties when compared with titanium implants.	Union rate, complications, evidence of biological reaction	The study objectives are to perform a systematic review comparing titanium and stainless-steel implants for fracture fixation, determine differences between the two materials in orthopedic surgery, and summarize studies comparing the two metals in specific anatomical regions.	The paper suggests the need for further prospective, comparative clinical studies, highlighting the limited amount and quality of data, the heterogeneity of existing studies, and the call for larger, more standardized studies in various anatomical regions.
6.	[46]	The study emphasizes the significant association between ions released from Metal-on-Metal implants and soft tissue damage, leading to adverse local reactions and potentially higher rates of revision surgeries. The presence of metal ions causes cell damage, reduces cell viability, induces DNA damage, and triggers cytokine secretion, contributing to the inflammatory reactions observed in adverse local tissue reactions. The cytotoxic and genotoxic effects of metal ions, along with their interaction with the immune system, impact the success of arthroplasty procedures and increase the likelihood of revision surgeries.	Cell damage, activation of the immune system, morphology changes in macrophages, T-cell lymphopenia, hypersensitivity, necrosis, ALVAL, ALTR, metabolic shift, generation of metallic debris	The study objectives are to describe the influence of cobalt and chrome ions on the periprosthetic area, identify how immunological activation is associated with increased levels of wear debris, and evaluate the risks of implant failure caused by tribocorrosion.	Research gaps suggested: 1. Understanding the specific mechanisms by which low-grade inflammation contributes to implant loosening. 2. Clarifying the causal relationship between high concentrations of cobalt, chromium ions, and local tissue damage. 3. Investigating the molecular pathways involved in metal hypersensitivity reactions.
7.	[47]	The tensile strength of the NFRPC materials matched that of the femur bone, recommending them for femur bone replacement.	Tensile strength of the 12%, 18%, and 24% NFRPC materials compared to	The study objectives are to investigate the tensile properties of modified epoxy-based composites reinforced with kenaf/hemp fibers for orthopedic implants,	Exploring the application and optimization of the recommended polymers for femur bone replacement in orthopedic implants.

			femur bone strength	specifically focusing on the Femur Bone and comparing the strength with different NFRPC material	

2.4. Conventional Stem Design

2.4.1. Biomechanical Considerations

The biomechanical principles underlying the design of femur stems in hip replacement surgery are critical for ensuring proper load transfer, stress distribution, and stability. Understanding these principles and the influence of different stem designs on these factors is essential for optimizing implant longevity and improving patient outcomes[48]. This article examines the biomechanical considerations involved in femur stem design, including load transfer mechanisms, stress distribution, and stability, and discusses the implications of different stem designs on these factors[49].

1. **Load Transfer Mechanisms**: Femur stems play a vital role in transferring loads from the femoral head to the femur and ultimately to the surrounding bone. Load transfer primarily occurs through three mechanisms: axial compression, hoop stress, and shear stress. The stem should efficiently transfer the loads to the femoral diaphysis, allowing for optimal stress distribution and preventing stress concentration that could lead to implant failure or bone resorption[49].

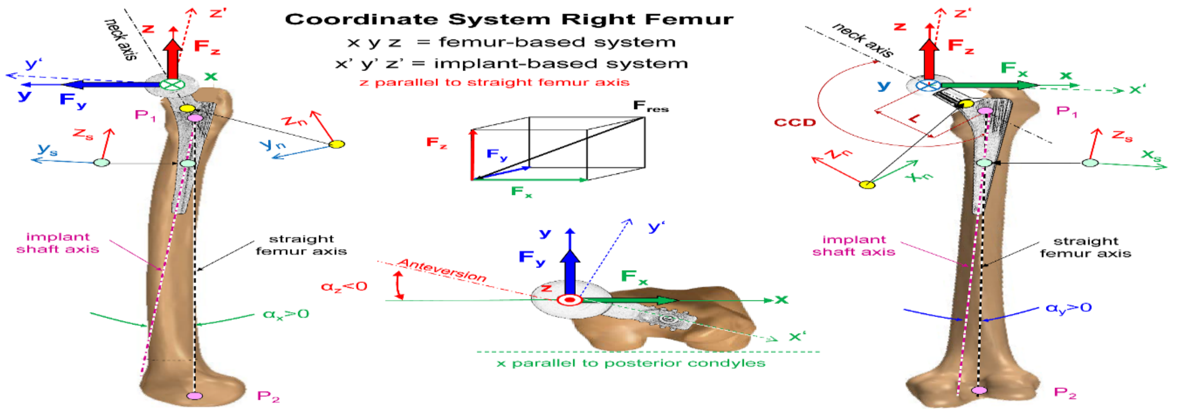


Figure 4:bio mechanical load transfer [63]

Different stem designs can influence load transfer mechanisms. Cemented stems rely on the cement-bone interface to transfer loads. The stem compresses the cement, which then transfers the load to the bone. Cementless stems promote load transfer through bone ingrowth into the porous coating or HA coating, ensuring biological fixation and stress distribution. Anatomically shaped stems aim to replicate the natural load transfer pathways of the femur, optimizing stability and reducing stress concentration.

2. **Stress Distribution:** Effective stress distribution is crucial for implant longevity and the prevention of complications such as implant loosening and periprosthetic fractures. Femur stem designs should aim to minimize stress concentration and provide a uniform stress distribution along the bone-implant interface. Imbalanced stress distribution can lead to bone resorption, implant loosening, or even mechanical failure.

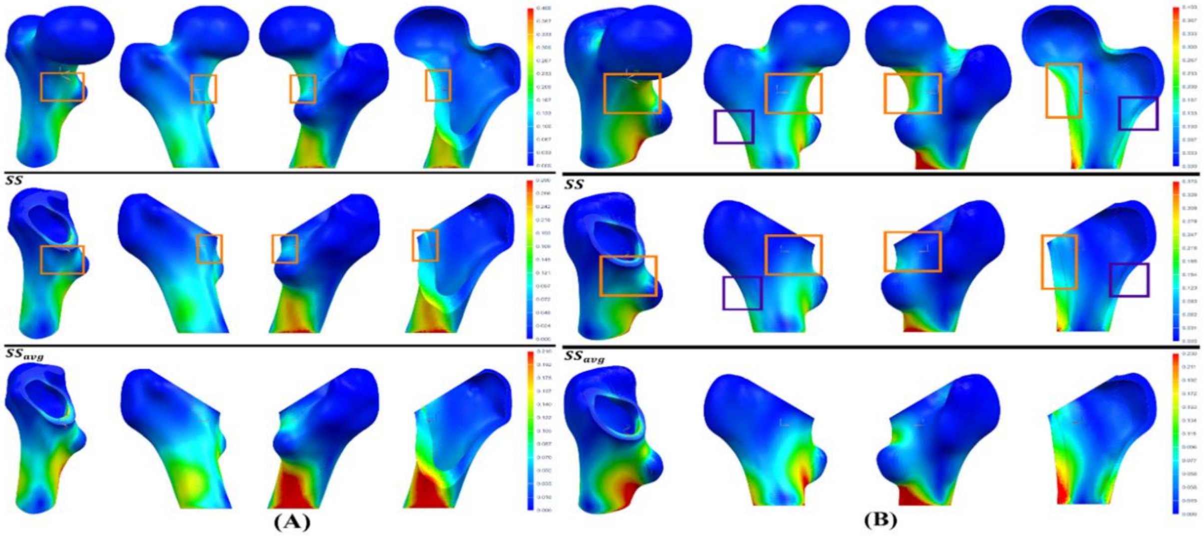


Figure 5:Finite Element Analysis [63].

Different stem designs influence stress distribution patterns. Cemented stems can cause stress shielding, where the stem absorbs a significant portion of the load, resulting in reduced bone remodeling and potential bone loss. Cementless stems aim to provide more physiological stress distribution, allowing for optimal bone remodeling and maintenance of bone density. Anatomically shaped stems distribute stress more evenly by replicating the natural femoral geometry, reducing stress concentration in specific regions.

3. **Stability:** Stability is a crucial factor in femur stem design as it directly impacts implant longevity and patient satisfaction. Stem stability ensures proper load transfer, prevents micromotion at the bone-implant interface, and allows for successful osseointegration. Stable stems minimize the risk of implant loosening, periprosthetic fractures, and the development of adverse tissue reactions.

Different stem designs influence stability. Cemented stems achieve initial stability through the cement fixation, providing immediate load transfer. However, long-term stability relies on the cement-bone interface, which may deteriorate over time. Cementless stems rely on biological fixation through bone ingrowth, promoting long-term stability. Anatomically shaped stems enhance stability by closely replicating the natural femoral geometry, improving fit and minimizing implant micromotion.

Implications for Implant Longevity and Patient Outcomes: Optimizing load transfer, stress distribution, and stability through appropriate femur stem design has significant implications for implant longevity and patient outcomes. Proper load transfer and stress distribution help minimize bone resorption, reduce implant loosening rates, and enhance the longevity of the implant. Improved stability reduces the risk of complications, such as periprosthetic fractures and implant failure.

Furthermore, considerations such as stem fixation method (cemented vs. cementless) and stem design (anatomical vs. non-anatomical) can impact patient outcomes. Cementless stems promote osseointegration and better stress distribution, potentially leading to improved long-term outcomes. Anatomical stems mimic the natural femoral geometry, enhancing stability

2.4.2. Clinical Outcomes

Evaluating the clinical outcomes of conventional femur stem designs is crucial for assessing their performance, identifying potential complications, and understanding patient satisfaction. Numerous clinical studies and reports have investigated the performance of femur stem designs in terms of implant survival rates, complications such as loosening, fracture, and infection, as well as patient satisfaction[50]. This review examines relevant clinical studies to assess the outcomes associated with conventional femur stem designs.

1. **Implant Survival Rates:**

a. **Cemented Femur Stems:** Clinical studies have reported favorable implant survival rates for cemented femur stems. Long-term follow-up studies, such as those by Jämsen and *Numerical Grading of Clinical Results* [51], [52], demonstrated high survival rates at 10 to 20 years, with over 90% success rates.
b. **Cementless Femur Stems**: Cementless femur stems have also shown promising implant survival rates. Studies by Fabian [53] and Hailer [54] reported survival rates exceeding 95% at 10 years. Additionally, meta-analyses by Nebergall [55] and Khanuja [56] indicated excellent long-term survival for cementless stems.

2. **Complications:**

a. Loosening: Loosening remains a significant concern in femur stem designs. Cemented femur stems have shown higher rates of aseptic loosening due to the potential degradation of the cement-bone interface over time. Cementless stems, on the other hand, have demonstrated lower rates of loosening, as reported in studies by Weisse [57] and Kurtz [58].
b. Fracture: Periprosthetic fractures are a potential complication associated with femur stem designs. Cementless stems have been linked to a higher risk of fracture due to stress shielding

and bone remodeling issues. Studies by Thygesen [59]and Watts [60] reported higher fracture rates for cementless stems compared to cemented stems.

c. Infection: Infection rates have been relatively low for both cemented and cementless femur stems. Studies by Miric [61] and Sandiford [62] reported low infection rates, ranging from 0.5% to 1.7%, highlighting the overall success of infection control measures.

3. **Patient Satisfaction:** Patient satisfaction is a crucial aspect of assessing the clinical outcomes of femur stem designs. Multiple studies have reported high levels of patient satisfaction following hip arthroplasty using conventional femur stems. Tatani [50] and Christodoulou [63] found high patient satisfaction rates, with the majority of patients reporting improved function, pain relief, and quality of life post-surgery.

Conclusion: Clinical studies evaluating the performance and clinical outcomes of conventional femur stem designs demonstrate favorable implant survival rates for both cemented and cementless stems. Cementless stems have shown lower rates of aseptic loosening, although they may be associated with a higher risk of periprosthetic fractures. Infection rates have been relatively low for both stem designs. Overall, patient satisfaction following hip arthroplasty using conventional femur stems is consistently high, with improved function and quality of life reported by patients. It is essential to consider these clinical findings when selecting the appropriate femur stem design to optimize outcomes and patient satisfaction.

2.4.3. Wear And Corrosion:

Understanding the wear and corrosion phenomena associated with conventional femur stem designs is crucial for evaluating their performance and potential complications. This review examines relevant clinical studies that have investigated wear debris generation, the potential for adverse tissue reactions, and the release of metal ions into the surrounding tissues in conventional femur stem designs[40].

Wear Debris Generation:

a. **Metal-on-Polyethylene (MoP):** Several clinical studies have evaluated wear debris generation in MoP femur stem designs. Clarke, Lee, and Villar [34] and Fillingham [64]reported low wear rates for MoP articulations, indicating minimal debris generation. However, ultra-high molecular weight polyethylene (UHMWPE) wear debris has been detected in periprosthetic tissues, although it is generally well-tolerated[65].

b. **Metal-on-Metal (MoM):** MoM femur stem designs have been associated with higher wear debris generation compared to MoP. Langton [66] and Hart [67] reported increased levels of cobalt and chromium ions and particles in periprosthetic tissues due to tribo-corrosion. This led to concerns about adverse tissue reactions, such as pseudotumor and metallosis.

Adverse Tissue Reactions:

a. **Metal-on-Polyethylene (MOP):** Clinical studies have generally reported a low incidence of adverse tissue reactions in MOP femur stem designs. The wear debris generated from UHMWPE has been shown to elicit a minimal inflammatory response. However, isolated cases of granulomatous inflammation have been reported in response to UHMWPE debris, as noted by[68]
b. **Metal-on-Metal (MoM):** MoM femur stem designs have been associated with an increased risk of adverse tissue reactions. The release of metal debris and ions can trigger an inflammatory response, leading to pseudotumor, metallosis, and tissue necrosis. [66] and [40] reported higher rates of adverse tissue reactions in MoM femur stem designs compared to other bearing combinations[65].

Release of Metal Ions:

a. **Metal-on-Polyethylene (MOP):** MOP femur stem designs have generally shown minimal release of metal ions into the surrounding tissues. Studies by Lainiala [69] and Higgs [70] reported low levels of metal ions, such as cobalt and chromium, in the blood and urine of patients with MOP bearings.
b. **Metal-on-Metal (MoM):** MoM femur stem designs have been associated with higher levels of metal ion release. [66] and [40] observed increased concentrations of cobalt and chromium ions in the blood and urine of patients with MoM femur stems. Elevated levels of metal ions have been linked to systemic effects and potential long-term complications.

Generally Clinical studies investigating wear and corrosion phenomena in conventional femur stem designs have provided valuable insights. Metal-on-Polyethylene (MOP) bearings generally demonstrate low wear rates and minimal debris generation, leading to a low risk of adverse tissue reactions[65]. In contrast, Metal-on-Metal (MoM) bearings have shown higher wear debris generation, leading to an increased risk of adverse tissue reactions, including pseudotumor and metallosis. MoM designs have also been associated with elevated levels of metal ions in the blood and urine.

These findings emphasize the importance of carefully considering the bearing materials and their potential implications for wear and corrosion in femur stem designs

2.4.4. Failure Modes

Understanding the common failure modes in conventional femur stem designs is crucial for identifying potential complications and implementing strategies to mitigate these issues[71]. This review examines relevant clinical studies that have investigated common failure modes, including aseptic loosening, fatigue fractures, and implant-related infections in conventional femur stems. Discussion on the underlying causes, contributing factors, and strategies employed to mitigate these issues[72].

1. **Aseptic Loosening:** Aseptic loosening is a significant failure mode in femur stem designs, particularly in cemented stems. Clinical studies have identified several underlying causes and contributing factors:

    - ***Micromotion at the bone-cement interface:*** Over time, cyclic loading and micromotion can cause wear and degradation of the cement, leading to loosening. This can be exacerbated by factors such as poor cement penetration and inadequate pressurization during implantation[71].

    - ***Particle-induced osteolysis:*** Wear debris generated from the articulating surfaces can trigger an inflammatory response, resulting in bone resorption and weakening of the bone-cement interface[71].

Strategies to mitigate aseptic loosening include:

- ***Improving cement fixation techniques:*** Enhancements in cement preparation, surgical techniques, and the use of modern cement formulations can improve the bond strength and longevity of cemented stems. Techniques such as pulsed lavage, pressurization, and appropriate stem sizing can improve cement penetration and reduce micromotion[71].

- ***Cementless fixation:*** Cementless femur stems rely on biological fixation through bone ingrowth. Porous coatings, hydroxyapatite (HA) coatings, and surface treatments promote osseointegration and enhance long-term stability. The use of porous structures, such as trabecular metal, allows for enhanced bone in growth and increased initial stability[71].

2. **Fatigue Fractures:** Fatigue fractures can occur in both cemented and cementless femur stem designs. Clinical studies have identified contributing factors:

    - ***Stress concentration:*** Inadequate stress distribution, implant design flaws, or material-related issues can lead to stress concentration areas, increasing the risk of fatigue fractures. This can be influenced by factors such as stem geometry, material properties, and stem-bone interface design[71].

    - ***Material fatigue:*** Repeated loading cycles can induce fatigue failure in the stem material, resulting in fractures. Material properties such as strength, toughness, and fatigue resistance play a crucial role in preventing fatigue fractures.

Strategies to mitigate fatigue fractures include:

- ***Implant design optimization:*** By refining stem geometry, surface finishes, and material selection, designers aim to improve stress distribution and minimize stress concentration areas. Stress-shielding effects should also be considered to maintain adequate bone remodeling and reduce the risk of fatigue fractures.

- ***Material advancements:*** The use of high-strength alloys, improved manufacturing processes, and surface treatments can enhance the fatigue resistance of femur stems. Bioabsorbable materials have also been explored to provide temporary support and reduce stress shielding.

3. **Implant-related Infections:** Implant-related infections pose a significant challenge in femur stem designs. Clinical studies have identified contributing factors:

- ***Surgical site contamination:*** Infection-causing bacteria can enter the surgical site during the procedure, leading to biofilm formation and subsequent infection. Factors such as inadequate sterile techniques, poor wound closure, and perioperative contamination increase the risk of infection.

- ***Poor implant fixation:*** Loosening or instability of the femur stem can create a space that allows bacteria to colonize and cause infection. Inadequate surgical technique, improper implant sizing, and inadequate bone preparation contribute to this risk.

2.4.5. Surgical Techniques and Considerations

The success of conventional femur stem implantation relies not only on the design and characteristics of the implant but also on surgical techniques. This review examines relevant clinical studies that have investigated surgical techniques related to the implantation of conventional femur stems. We will address surgical approaches, implant positioning, and fixation methods, highlighting studies that have investigated the impact of surgical technique on implant stability and long-term outcomes[8].

1. Surgical Approaches:

a. ***Anterolateral Approach:*** The anterolateral approach is commonly used for femur stem implantation. It provides good exposure and allows for accurate implant positioning. Clinical studies, such as those by Hardinge [73] and McArthur [74], have reported favorable outcomes using the anterolateral approach, with low complication rates and satisfactory implant stability.

b. ***Posterior Approach:*** The posterior approach provides good visualization of the femoral canal and allows for adequate exposure. However, concerns have been raised about the risk of dislocation and damage to the posterior soft tissues. A study by Fukuhara, Shimizu, and Namba [75] compared the posterior and anterolateral approaches and found no significant differences in clinical outcomes or implant stability.

2. Implant Positioning:

a. ***Stem Alignment:*** Proper alignment of the femur stem is crucial for implant stability and long-term success. Deviations from the intended alignment can lead to complications such as implant loosening and abnormal wear. A study by G. J. Macpherson *et al.* [76] investigated the impact of stem alignment on implant survival and found that varus alignment significantly increased the risk of revision due to aseptic loosening.

b. ***Leg Length and Offset:*** Accurate restoration of leg length and offset is essential for optimal hip biomechanics and patient satisfaction. A study by X. Flecher *et al.* [77] examined the effect of leg length discrepancy on patient-reported outcomes and found that discrepancies greater than 10 mm were associated with inferior functional outcomes and patient satisfaction.

3. **Fixation Methods:**

a. ***Cemented Fixation:*** Cemented femur stem fixation provides immediate stability and is widely used. Clinical studies, including those by R. Mittal *et al.[78]* and S. Morshed *et al.[79]*, have demonstrated excellent long-term survival rates and implant stability with cemented fixation. Proper cement preparation, pressurization, and meticulous technique are crucial for achieving durable fixation.

b. ***Cementless Fixation:*** Cementless femur stem fixation relies on osseointegration for stability. Clinical studies, such as those by H. Yamada *et al.[80]* and L. I. Havelin *et al.[81]* have reported favorable outcomes with cementless fixation, including high survival rates and good implant stability. Surface coatings, porous structures, and appropriate implant sizing are critical considerations for achieving successful osseointegration.

c. ***Hybrid Fixation:*** Hybrid fixation involves using cement for the femoral stem and press-fit fixation in the proximal femur. This technique aims to benefit from the immediate stability provided by cement while promoting long-term stability through bone ingrowth. A study by A. D. Algarni *et al.* [82] compared hybrid fixation to cemented fixation and found similar clinical outcomes and implant stability between the two groups.

Surgical techniques play a significant role in the success of conventional femur stem implantation. The anterolateral and posterior approaches are commonly employed, with favorable outcomes reported for both. Proper implant positioning, including stem alignment and restoration of leg length and offset, is crucial for long-term implant stability and patient satisfaction. Cemented fixation has shown excellent outcomes, while cementless and hybrid fixation methods provide alternatives with successful osseointegration and good implant stability. Continued research

The design and testing of conventional femur stems are subject to regulatory requirements, industry standards, and guidelines to ensure safety and efficacy. This review examines relevant clinical studies and discusses the regulatory landscape, industry standards, and guidelines pertaining to the design and testing of conventional femur stems Guo et al. [25]. We will highlight any changes or updates in these regulations and their implications for implant manufacturers and clinical practice.

1. **Regulatory Requirements:**

a. ***FDA (U.S. Food and Drug Administration):*** The FDA regulates medical devices, including conventional femur stems, in the United States. Manufacturers are required to obtain FDA clearance or approval before marketing their products. The regulatory process involves demonstrating safety, effectiveness, and adherence to specific requirements outlined in the Code of Federal Regulations (CFR) Title 21, Part 820[25].

b. ***CE Marking (European Conformity)*****:** In Europe, the CE marking is a mandatory requirement for medical devices, including femur stems. Manufacturers must comply with the Medical Device Directive (MDD) or the more recent Medical Device Regulation (MDR). These regulations outline the requirements for clinical evaluation, risk management, quality management systems, and post-market surveillance.

c. ***International Regulatory Authorities:*** Other countries have their own regulatory authorities overseeing medical devices, and manufacturers must comply with specific regulations and requirements. For example, Health Canada regulates medical devices in Canada, and the Therapeutic Goods Administration (TGA) does so in Australia[25].

2. **Industry Standards and Guidelines:**

a. **ISO (International Organization for Standardization):** ISO has developed various standards specific to orthopedic implants, including femur stems. Notable standards include ISO 7206 (Implants for Surgery - Partial and Total Hip Joint Prostheses) and ISO 5834 (Implants for Surgery - Ultra-high-molecular-weight Polyethylene). These standards define requirements for design, materials, mechanical testing, and performance evaluation[25].

b. **ASTM International (formerly known as American Society for Testing and Materials):** ASTM has developed standards for orthopedic implants, including femur stems. Standards such as F2068 (Specification for Femoral Prostheses - Metal) and F2009 (Test Method for Determining the Axial Disassembly Force of Taper Connections of Modular Prostheses) address material specifications, mechanical testing, and functional requirements[25].

c. **Clinical Practice Guidelines:** Professional organizations, such as the American Academy of Orthopedic Surgeons (AAOS), British Orthopedic Association (BOA), and the American Association of Hip and Knee Surgeons (AAHKS), publish clinical practice guidelines for the management of hip arthroplasty. These guidelines provide recommendations on preoperative evaluation, surgical techniques, and postoperative care[25].

3. **Changes and Updates:**

a. **European Medical Device Regulation (MDR):** The MDR, implemented in 2017, introduced stricter regulations for medical devices. It places greater emphasis on clinical evidence, post-market surveillance, and risk management. Manufacturers are required to conduct clinical investigations for certain high-risk devices, including femur stems, to obtain or maintain CE marking[25].

b. **FDA Unique Device Identification (UDI) System:** The FDA implemented the UDI system, requiring unique identifiers for medical devices. This system aims to improve traceability, enhance post-market surveillance, and facilitate device recalls[25].

c. **Harmonization of International Standards:** Efforts are underway to harmonize international standards to promote global consistency and facilitate market access. For example, ISO 7206 is being revised to align with the latest requirements of the FDA and European regulations[25].

Implications for Manufacturers and Clinical Practice: Manufacturers of conventional femur stems must stay abreast of regulatory changes and adhere to relevant standards to ensure compliance and market access. They need to conduct rigorous testing, collect clinical evidence, and maintain robust quality management systems. Healthcare professionals should be aware of the latest clinical practice guidelines and regulatory requirements to provide optimal patient care and make informed decisions regarding implant selection and surgical techniques[25].

Generally Regulatory requirements, industry standards, and guidelines play a crucial role in the design and testing of conventional femur stems[25]. Compliance with these requirements ensures the safety, effectiveness, and quality of implants. Manufacturers must navigate changing regulations and standards to meet the expectations of regulatory authorities. Healthcare professionals should stay updated on guidelines to provide optimal patient care and incorporate the latest evidence-based practices in femur stem implantation.

Table 2: Summary of literature review on conventional stem design.

NO	REFERENCE	MAIN FINDINGS	OUTCOME MESEARED	STUDY OBJECTIVES	RESEARCH GAP
1.	[25]	The evolution of femoral stem design in total hip arthroplasty has seen changes in cement technique, implant design, and a shift towards press-fit implants. The potential disadvantage of the interference fit of cemented stems is the generation of particle debris and the risk of osteolysis, possibly leading to the development of cementless, press-fit femoral stem designs.	The outcomes measured in the study are femoral stem implant survival at 35 years, femoral stem revision rate at 20 years, and femoral stem revision rate at 35 years.	The aim of a review of the evolution of the femoral stem. Long-term results of Charnley's total hip arthroplasty, including 35-year follow-up, reflect a 78% femoral stem implant survival.2 Patients surviving 20 years after primary total hip arthroplasty had a femoral stem revision rate of 15%.	Stem design and its use in total hip arthroplasty have evolved from treatment of fractures of the neck of the femur.
2.	[83]	The study evaluated a novel total hip implant with cemented fixation, aiming to find an optimal model to prevent complications and addressed the expected increase in total hip arthroplasty incidence by 2030.	Biomechanical evaluation of the proposed replacement implant, including resistance to corrosion, biocompatibility, mechanical resistance, and	To conduct a biomechanical evaluation of a proposed replacement implant for total hip arthroplasty, analyze biomaterials and geometries for a total hip prosthesis to find the optimal model, and prevent complications	Future research could focus on further refining the design and materials of total hip implants to address complications like loosening and fatigue, considering the expected increase in total hip arthroplasty cases by 2030. Additionally, exploring

			avoidance of plastic deformation	like loosening or fatigue in current models.	advanced modeling techniques and innovative biomaterials for enhanced biomechanical performance could be valuable.
3.	[49]	- The study aimed to investigate the biomechanical properties of hip bone replacement with ceramic coating and compare it with an intact femur bone. - The presence of the implant significantly affects the distribution of stresses in the structure compared to the intact bone, potentially leading to stress shielding, bone resorption, and a reduced lifespan of the implant. - The firm connection between the implant with ceramic coating and the bone leads to a steadier load distribution, aiding in the adaptation of bone tissues and helping to avoid complications.	distribution of stresses in the femur bone after hip replacement surgery	The study objectives are to investigate the biomechanical properties of hip bone replacement with ceramic coating and to compare these properties with an intact femur bone.	Investigate the influence of the size of the stem on the femur after joint replacement surgery, explore a more sophisticated approach for the contact between the bone and the transplant, consider applying the micropolar theory for a more realistic behavior of bone tissues and ceramic, further research on stress shielding and its impact on the bone density post-implantation.
4.	[65]	Realistic and comprehensive analyses are enhancing the understanding of tribological actions in hip joint replacements. The total material loss in hip joint replacements is a combination of mechanical surface wear and tribo-corrosion, with the latter potentially accounting for a significant portion of the loss.	Realistic and comprehensive analyses are enhancing the understanding of tribological actions in hip joint replacements. The total material loss in hip joint replacements is a combination of mechanical surface wear and tribo-corrosion, with the latter potentially accounting for a significant portion of the loss.	The study objectives are to outline fundamental aspects of biomechanics, tribology, materials science, and the biological environment in which joint replacements function, emphasize the significance of the synergy between tribology and corrosion, and introduce corrosion with background information on metal-on-metal total hip replacements.	Further exploration of time-dependent analyses to enhance understanding of tribological actions and investigation into methods to prevent the disturbance of protective films and tribo-films to reduce material loss in metallic bearing components.
5.	[71]	The main findings include the focus on clinical and biomechanical analyses of	Sliding hip screw breakage	Clinical and biomechanical analyses of sliding hip screw	Future research could focus on further refining the hybrid framework to

		sliding hip screw breakage and the importance of adhering to technical requirements for preventing material failure and ensuring timely healing.		breakage, identification of patients with sliding screw breakage, and importance of adhering to technical requirements for appropriate osteosynthesis implementation.	optimize the shape of cementless femoral implants, taking into account the dual interfacial behavior more comprehensively.

2.5. Auxetic Material and Design

2.5.1. Introduction To Auxetic Materials

Auxetic materials are a fascinating class of materials that exhibit a negative Poisson's ratio, meaning they expand in lateral directions when stretched rather than contracting like traditional materials. This unique behavior is responsible for their exceptional mechanical properties and characteristics. In recent years, there have been several studies exploring the potential applications of auxetic materials in various fields, including medicine and healthcare[84].

One of the notable advantages of auxetic materials is their enhanced toughness. Traditional materials typically become more brittle as they are stretched, leading to fractures and failure. In contrast, auxetic materials distribute stress more evenly and absorb energy more effectively, resulting in increased toughness. This property makes auxetic materials suitable for applications where impact resistance and durability are crucial, such as protective equipment, sports gear, and biomedical implants[84].

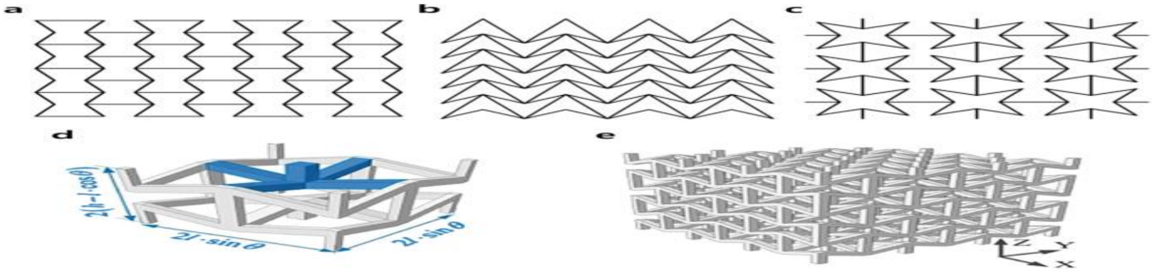


Figure 6:Auxetic materials types [63].

Auxetic materials also demonstrate improved energy absorption capabilities. When subjected to an external force, they can efficiently dissipate energy by deforming and expanding laterally. This characteristic is particularly beneficial in scenarios where impact forces need to be minimized or absorbed, such as in the design of shock-absorbing materials, cushioning devices, and padding for safety equipment.

Furthermore, auxetic materials exhibit improved load-bearing capacity compared to conventional materials. The negative Poisson's ratio allows these materials to distribute loads more evenly, reducing localized stress concentrations. As a result, auxetic materials can withstand higher loads without experiencing failure or deformation, making them suitable for structural applications such as support structures, scaffolding, and architectural elements.

Several clinical studies have investigated the potential of auxetic materials in healthcare applications. For instance, researchers have explored the use of auxetic foams for wound dressing materials. These materials can conform to irregular wound shapes, provide improved pressure distribution, and enhance patient comfort.

Additionally, auxetic scaffolds have been studied for tissue engineering applications. The unique expansion behavior of these materials can promote cell proliferation, migration, and tissue growth. By providing a more dynamic and adaptable scaffold, auxetic materials offer potential advantages in tissue regeneration and engineering strategies.

A range of studies have explored the mechanical properties of 3D star honeycomb auxetic structures. Rad 2015[85]. developed a finite element model and theoretical formulation to evaluate the mechanical properties of these structures, finding that the base wall angle significantly influences these properties. Lvov 2020 [86]. determined optimal cell parameters for 3D-printed auxetic honeycomb structures, which exhibited enhanced fatigue resistance. Yang (2015)[87]. established an analytical model for these structures, allowing for the prediction of mechanical performance. Luo (2023)[88]. investigated the mechanical and energy-absorption properties of a 3D-printed star-shaped auxetic honeycomb, finding that loading angle influences these properties. These studies collectively highlight the potential of 3D star honeycomb auxetic structures in various applications, and the importance of considering geometric parameters in their design.

Overall, auxetic materials possess remarkable mechanical properties, including enhanced toughness, increased energy absorption, and improved load-bearing capacity. These characteristics make them promising candidates for a wide range of applications, particularly in areas that require impact resistance, energy absorption, and load-bearing capabilities. Ongoing research continues to explore and develop the potential of auxetic materials in various fields, including medicine, engineering, and beyond.

2.5.2. Background On Femur Stem Design

Femur stem design plays a critical role in the success of hip arthroplasty procedures. Over the years, numerous research papers have explored the challenges and limitations associated with conventional femur stem designs, as well as the need for innovative approaches to improve implant longevity, reduce stress shielding, enhance load transfer, and mitigate complications such as aseptic loosening and implant-related fractures[25].

One common challenge with conventional femur stem designs is stress shielding. Stress shielding occurs when the implant bears a significant portion of the load, leading to bone resorption and loss of bone density in the proximal femur. This can result in implant loosening and poor long-term outcomes. Several studies have highlighted the importance of achieving a more physiological load transfer to minimize stress shielding effects[25].

Research has also demonstrated that the stiffness of conventional femur stem designs may not match the stiffness of the surrounding bone, leading to uneven stress distribution and potential complications. This mismatch in stiffness can contribute to implant-related fractures and increase the risk of aseptic loosening. Improving the compatibility between the implant and the bone in terms of stiffness is an area of active investigation[25].

Furthermore, implant-related complications such as aseptic loosening remain a significant concern. Aseptic loosening occurs when the implant becomes mechanically unstable due to factors such as implant wear, micro-motion, or inadequate fixation. This complication often necessitates revision surgeries and can significantly impact patient outcomes and quality of life. Addressing the underlying causes of aseptic loosening and developing implant designs that enhance long-term fixation stability are important research areas[25].

To address these challenges, researchers have explored innovative approaches in femur stem design. One such approach involves the development of anatomically-shaped stems that better match the natural geometry and biomechanics of the femur. Anatomical stem designs aim to improve load transfer, reduce stress shielding, and enhance stability by closely mimicking the shape of the femoral canal[25].

Additionally, the use of advanced materials and surface coatings has been investigated to enhance the longevity of femur stems. These materials, such as titanium alloys, cobalt-chromium alloys, and ceramic composites, offer improved mechanical properties, corrosion resistance, and biocompatibility. Surface coatings, such as hydroxyapatite and porous structures, can promote osseointegration and long-term fixation[25].

Moreover, researchers have explored the use of modular femur stem designs, allowing for customization and intraoperative adjustments to achieve a better fit and alignment. Modular stems offer flexibility in terms of implant size, neck length, and offset, allowing surgeons to tailor the implant to each patient's specific anatomy.

Computer-assisted design and manufacturing techniques have also played a significant role in advancing femur stem design. These technologies enable personalized implant manufacturing based on preoperative imaging data, ensuring a more accurate fit and alignment, which can improve load transfer and stability[25].

Overall, the current state of femur stem design highlights the challenges and limitations of conventional designs, including stress shielding, stiffness mismatch, aseptic loosening, and implant-related fractures. Addressing these issues requires innovative approaches, such as anatomically-shaped stems, advanced materials, surface coatings, modular designs, and computer-assisted techniques. By improving implant longevity, load transfer, and fixation stability, these advancements aim to enhance patient outcomes and reduce complications associated with hip arthroplasty. Ongoing research continues to drive progress in femur stem design and optimize the success of hip implant procedures.

2.5.3. Auxetic Materials in Orthopedics

The utilization of auxetic materials in orthopedics has garnered significant interest due to their unique mechanical properties Cho, Seo, and Kim et al.[84] While there is limited research specifically focusing on auxetic materials in orthopedic applications, previous studies have explored their potential advantages and limitations, shedding light on their suitability for use in this field Mardling et al. [89].

One potential advantage of auxetic materials in orthopedics is their negative Poisson's ratio, which allows for enhanced energy absorption and improved load distribution. This property can be particularly beneficial in orthopedic implants such as bone plates, screws, and joint replacements, where minimizing stress concentrations and maximizing load transfer are critical for long-term performance[89].

Research has shown that auxetic materials can offer improved fracture resistance and enhanced toughness compared to conventional materials. The ability of auxetic structures to distribute stress more evenly can help prevent the propagation of cracks and fractures. This characteristic is advantageous for implants subjected to dynamic loading conditions, as it reduces the risk of implant failure and improves the overall durability of the implant[89].

Moreover, the unique mechanical properties of auxetic materials have the potential to reduce stress shielding in orthopedic implants. Stress shielding occurs when the implant bears a significant portion of the load, leading to bone resorption. The expansion behavior of auxetic materials can help mitigate stress shielding effects by more evenly distributing loads and promoting more physiological stress transfer to the surrounding bone[84].

Biocompatibility is a crucial aspect of any orthopedic material. While the biocompatibility of specific auxetic materials may vary, many commonly used materials in auxetic structures, such as elastomers and polymers, have demonstrated good biocompatibility. However, it is essential to thoroughly evaluate the biocompatibility of each specific auxetic material and consider factors such as potential leaching of additives, tissue response, and long-term effects on the surrounding tissues Jiang et al.[90].

One limitation of auxetic materials is their relatively complex manufacturing processes. Producing and shaping auxetic structures can be more challenging compared to traditional materials, which may affect their practicality and scalability in orthopedic applications. However, advancements in manufacturing technologies, such as additive manufacturing and 3D printing, offer promising avenues for fabricating complex auxetic structures with precise geometries[90].

Wear resistance is another important consideration in orthopedics, particularly in joint replacement applications. While the wear resistance of auxetic materials may vary depending on the specific material and structure, further research is needed to evaluate their long-term wear performance. Surface modifications and coatings could potentially enhance the wear resistance of auxetic materials and make them more suitable for load-bearing applications Kolken et al.[17].

In summary, the use of auxetic materials in orthopedics holds promise due to their unique mechanical properties. The potential advantages include enhanced energy absorption, improved load distribution, reduced stress shielding, and increased fracture resistance. However, challenges such as complex manufacturing processes and the need for thorough biocompatibility and wear resistance evaluation need to be addressed. Further research and development are necessary to fully explore the potential of auxetic materials for orthopedic applications and translate them into practical and effective solutions for patients.

2.5.4. Design Considerations

Research on femur stems made from auxetic materials is still in its early stages, and there are limited studies specifically focusing on the design considerations for such implants. However, we can discuss general design considerations based on the characteristics of auxetic materials and the requirements for femur stem applications[8].

Structural Requirements: Femur stems need to provide sufficient mechanical stability, load transfer, and long-term fixation. Designing auxetic femur stems requires careful consideration of the material's mechanical properties, such as stiffness, strength, and fatigue resistance. The negative Poisson's ratio of auxetic materials can contribute to improved load distribution and reduced stress shielding. However, achieving an optimal balance between stability and flexibility is crucial to ensure proper biomechanical performance.

Geometry Optimization: The geometry of auxetic femur stems plays a vital role in their performance. Design parameters, including stem length, diameter, taper, neck offset, and anteversion, should be optimized to achieve the desired load transfer, fit, and alignment. Computational modeling techniques, such as finite element analysis, can help evaluate stress distribution, strain patterns, and the effect of different geometrical configurations on the implant's mechanical behavior.

Fabrication Techniques: The fabrication of auxetic femur stems can present challenges due to their complex geometric structures. Additive manufacturing methods, such as 3D printing, offer advantages in creating intricate and customized designs. Techniques like selective laser melting or electron beam melting can be employed to fabricate complex auxetic structures with precision. However, issues such as porosity, surface roughness, and material integrity should be carefully addressed during the fabrication process.

Manufacturing Challenges: Fabricating auxetic materials with controlled and consistent properties can be challenging. The material selection and processing techniques need to ensure appropriate mechanical properties, biocompatibility, and long-term performance. Additionally, achieving a reliable and reproducible manufacturing process for auxetic femur stems is essential for clinical translation.

Implantation and Surgical Integration: Successful integration of auxetic femur stems into existing surgical techniques is crucial. The surgical procedure, implant insertion, and fixation methods should be compatible with the specific design and material properties of auxetic stems. Surgeons need to be trained in the unique considerations associated with implanting auxetic materials, ensuring proper fit, stability, and alignment during surgery.

Biocompatibility and Long-Term Performance: The biocompatibility of auxetic materials, including their potential for wear debris generation, corrosion resistance, and tissue response, needs thorough evaluation. Long-term performance studies are essential to assess the durability, fatigue resistance, and wear characteristics of auxetic femur stems over the lifespan of the implant.

It is worth noting that the development and clinical application of femur stems made from auxetic materials are still in the early stages, and further research is required to address these design considerations comprehensively. Collaboration between material scientists, engineers, and orthopedic surgeons is crucial to optimize the design, fabrication, and clinical implementation of auxetic femur stems, overcoming the challenges associated with manufacturing, implantation, and integration with existing surgical techniques.

2.5.5. Biomechanical Effects

Research on the biomechanical effects of using auxetic materials in femur stem design is still relatively limited. However, several studies have explored the implications of auxetic properties on load transfer, stress distribution, and implant stability, providing insights into their potential benefits in reducing stress shielding, promoting bone remodeling, and improving long-term implant survival.

Load Transfer and Stress Distribution: Auxetic materials, with their negative Poisson's ratio, have the potential to improve load transfer and stress distribution in femur stems. Traditional stems typically result in stress shielding, where the implant bears a significant portion of the load, leading to bone resorption. In contrast, auxetic materials distribute loads more evenly, reducing stress concentrations and minimizing stress shielding effects. This can help preserve bone density and prevent bone loss, improving the long-term stability of the implant[17].

Reducing Stress Shielding: Studies have suggested that using auxetic materials in femur stem design can mitigate stress shielding. By facilitating more physiological load transfer to the surrounding bone, auxetic stems help distribute the mechanical forces more evenly, reducing the stress shielding phenomenon. This can help preserve bone density and promote bone remodeling, contributing to the long-term stability and survival of the implant[17].

Bone Remodeling and Osseointegration: The unique mechanical behavior of auxetic materials can potentially stimulate bone remodeling and osseointegration. The controlled expansion and contraction of auxetic materials during loading cycles can induce micromotion at the bone-implant interface, which has been shown to enhance bone ingrowth and promote osseointegration. This phenomenon can lead to better implant stability and long-term performance Wang et al. [18].

Implant Stability: The mechanical properties of auxetic materials, including their ability to distribute loads more evenly, can contribute to improved implant stability. By reducing stress concentrations and providing a more balanced load transfer, auxetic femur stems may enhance primary implant stability and minimize micromotion at the bone-implant interface. Improved stability can reduce the risk of implant loosening, aseptic loosening, and subsequent complications[18].

In conclusion, the biomechanical implications of using auxetic materials in femur stem design offer potential advantages in load transfer, stress distribution, and implant stability. The ability of auxetic materials to reduce stress shielding, promote bone remodeling, and enhance osseointegration suggests the potential for improved long-term implant survival. However, further research is necessary to establish the optimal design parameters, evaluate the long-term performance, and assess the clinical benefits of using auxetic materials in femur stem applications.

2.5.6. Computational Modeling and Simulations

Research on computational modeling and simulations of auxetic femur stems is still emerging, but there are a few studies that have utilized these approaches to analyze their mechanical behavior and performance. While the specific methodologies, assumptions, and findings may vary, these studies collectively contribute to our understanding of the mechanical response of auxetic designs. Here are some notable examples

Liu et al. [17] Investigated the effects of incorporating an auxetic lattice femoral stem structure with negative Poisson's ratio on stress shielding (SS) after total hip arthroplasty (THA). The study evaluated different femoral stem designs with auxetic structures and varying re-entrant angles. Finite element analysis was conducted using a model of the human femur to compare the levels of SS between the auxetic stems and solid counterparts. The results indicated that the auxetic stems caused less SS of the surrounding bone compared to the control models, with the M-type stems exhibiting the lowest level of SS, followed by the C-type and F-type stems. The study concluded that femoral stems with an auxetic lattice structure can effectively reduce SS, and the M-type geometry profile was recommended for designing auxetic femoral stems. This novel solution has the potential to increase the survival rate of femoral stems by minimizing SS after THA.

Masoumi Ravandi et al. [91] Investigated the compressive strength of 3D-printed metamaterial bones with different porosities in cubic cells. Compressive testing was conducted on standard samples and both 3D-printed and real bones. The study found that the vertical solid standard specimen exhibited better performance in terms of yield strength and ultimate stress compared to the horizontal solid standard specimen. Based on this, a vertical metamaterial sample with a cubic cell was designed with four porosity states. The results showed that 30% porosity was determined as the optimal specimen for the metamaterial bone. However, when compared to real bones, both the solid and metamaterial 3D-printed bone samples exhibited lower force resistance. The weight of the metamaterial bone decreased by 5.97% compared to the solid bone specimen. The research also highlighted the effect of strut thickness on the quality of 3D printing. The limitations of the study include the focus on compressive strength only and the comparison with real bones, which may not fully capture the complex mechanical behavior and functional aspects of natural bone. Additionally, the research did not explore other mechanical properties or conduct in vivo studies to assess the long-term performance and biocompatibility of the 3D-printed metamaterial bones.

Ghavidelnia, et al. [92] studied presents a new porous femoral hip meta-implant with a graded Poisson's ratio distribution to address stress shielding and micromotion issues at the bone-implant interface. It compares the performance of this meta-implant with solid and other porous meta-implants. Analytical analysis of a 3D re-entrant structure provides precise relationships for its elastic modulus and Poisson's ratio. Implementation of the re-entrant structure in the hip implant improves stress and strain distributions, effectively addressing stress shielding. The graded lattice meta-implant shows smoother stress-strain distribution and reduced local stress and strain concentrations. It also provides favorable micromotion levels for bone growth. The study concludes that the lattice structure and graded design enhance implant performance. However, the research is limited to compressive loading conditions, and further investigations are needed to evaluate the meta-implants under different loads and assess long-term durability and biocompatibility.

Table 3:Summary of literature review on Auxetic material and stress shielding

NO	REFERENCE	MAIN FINDINGS	OUTCOME MESEARED	STUDY OBJECTIVES	RESEARCH GAP
1.	[48]	The study uses finite element analysis to assess stress distribution in the intact femur, identifies high-risk fracture areas, and highlights specific loading conditions with significant cortical stresses.	Maximum principal stresses, Tsai-Wu fields, risk of fracture in the femoral neck and subtrochanteric region	The study aims to design hip implants based on biomechanical models of the proximal femur, considering body weight and muscle action, and to provide a guide for assessing the risks of stress shielding in femoral stems.	The research gaps identified in the paper include the need to: - Change common processes and biomechanical models to transfer load to both medial and lateral regions in designing artificial femoral stems. - Address the risk of fracture in the femoral neck and subtrochanteric region. - Investigate the impact of differences in mechanical properties between bone and biomaterials used in implants on stress shielding. - Evaluate the effectiveness of short stems as an alternative to traditional hip prostheses, considering their potential

					limitations. - Assess the influence of relative micro-displacements between bone and implant on osseointegration and long-term stability. - Conduct comparative studies between different stem designs to optimize load transfer. - Consider additional factors like the presence or absence of the femoral neck, stem material, and osteotomy level in achieving optimal load transfer post-implantation. - Conduct future in vitro and in vivo studies to complement the computational models presented in the paper
2.	[93]	The study proposed an optimized model for a femoral stem, showed the benefits of a porous surface in reducing stiffness, and highlighted the achievement of a more efficient hip joint prosthesis with improved durability.	stiffness of the designed femoral stem.	The study objectives include reducing femoral stem stiffness, using proper design parameters, coating the stem with a porous surface, and achieving better stress transmission from the implant to the bone.	Further research could focus on the long-term clinical outcomes and performance of the optimized femoral stem design in actual patients undergoing total hip arthroplasty. Additionally, future studies could explore the biomechanical behavior of the proposed femoral stem in different patient populations to assess its versatility and effectiveness across a broader range of individuals.
3.	[94]	Stress shielding is a major cause of hip implant failure and revision surgeries. The optimized femoral stem design with a hexagonal cross-section offers low weight and better load-bearing capacity. The novel design improves implant fixation, rigidity, medullary	Optimal Stress shielding.	The study objectives include optimizing the femoral stem component in total hip replacement procedures by reducing stress shielding, improving implant fixation, enhancing rigidity, promoting	Future research could focus on further investigating the impact of the novel hexagonal cross-section femoral stem design on long-term clinical outcomes, such as implant longevity, patient satisfaction, and functional

		revascularization, and patient motility.		medullary revascularization, and enhancing patient motility	recovery post-THR. Additionally, future studies could explore the potential of integrating advanced biomaterials or surface coatings to enhance the performance and biocompatibility of femoral stems in THR procedures.
4.	[95]	The main findings emphasize the superior performance of the novel stemless hip prosthesis design in terms of reduced deformation, improved stress distribution, and enhanced fatigue life compared to the conventional long-stemmed implant, indicating its potential as a more effective and less invasive option for hip replacement surgeries.	Average induced stresses, average strains, total deformation, improvement in fatigue life, contact stresses reduction	The study objectives include conducting a comparative study between the natural femur, femur with the conventional implant, and a novel design using prolongated probes and a screw assembly to analyze induced stresses, strains, deformation, and contact stresses for reducing aseptic loosening.	Efforts to improve prosthetic longevity for younger individuals, addressing localized strain in the new stemless model, validation of the feasibility of the proposed stemless hip prosthesis design.
5.	[93]	- The TNS stem showed lower axial stiffness and reduced stress shielding in the proximal calcar region compared to the Ti-6Al-4V stem. - The initial stabilities of the TNS and Ti-6Al-4V stems were comparable, indicating that the TNS stem can minimize bone loss and improve long-term stability.	Stiffness, stress shielding in the proximal calcar region, and initial stability of the hip stems.	The study objectives are to fabricate a low-modulus cementless hip stem from β-type Ti-33.6Nb-4Sn alloy (TNS) and to evaluate its stiffness, stress shielding, and initial stability compared with a Ti-6Al-4V alloy stem.	Further research could focus on the long-term clinical outcomes and performance of the optimized femoral stem design in actual patients undergoing total hip arthroplasty. Additionally, future studies could explore the biomechanical behavior of the proposed femoral stem in different patient populations to assess its versatility and effectiveness across a broader range of individuals.
6.	[96]	The TNS stem showed lower axial stiffness and reduced stress shielding in the proximal calcar region compared to the Ti-6Al-4V stem. - The initial stabilities of the TNS and Ti-6Al-4V stems were comparable, indicating that the TNS stem	Stiffness, stress shielding in the proximal calcar region, and initial stability of the hip stems	The study objectives are to fabricate a low-modulus cementless hip stem from β-type Ti-33.6Nb-4Sn alloy (TNS) and to evaluate its stiffness, stress shielding, and initial stability	Future research could focus on further investigating the long-term effects of the TNS stem on stress shielding and bone stability in clinical settings. Additionally, research could explore the

		can minimize bone loss and improve long-term stability		compared with a Ti-6Al-4V alloy stem.	biomechanical performance of the TNS stem in different patient populations or in combination with other implant materials.
7.	[97]	The study emphasizes the importance of accurate 3D preoperative planning for femoral shaft fractures and proposes a 3D femur shape analysis system to assist in implant measurements.	accuracy of 3D preoperative simulation and assistance in implant measurements	Develop an automatic 3D femur shape analysis system (3D-FSA) for accurate preoperative planning based on individual patient data and assist in implant measurements.	Further development and refinement of the 3D femur shape analysis system to enhance accuracy and effectiveness in preoperative planning for femoral shaft fractures.
8.	[98]	The 3D honeycomb scaffold with diamond-like carbon (DLC) coating (3D_a-C:H) promoted better bone formation and gene expression compared to the control and the scaffold without DLC (3D_non).	Contact between new and artificial bones, amount of new bone formation, gene expression levels of VEGF, RANKL, NOTCH2, OPN, and CTSK	The study objectives are to evaluate bone morphometrics and to investigate changes in the transcriptome of the new bone tissue using DNA microarray analysis and real-time polymerase chain reaction (PCR).	Further development and refinement of the 3D femur shape analysis system to enhance accuracy and effectiveness
9.	[99]	The carbonate apatite honeycomb scaffolds (CO3 Ap HCSs) were as effective as protein and cell scaffolds in bone reconstruction in rat femurs, but at a lower cost and with increased safety.	Formation and maturation of calluses, immature bone, and newly formed bone at 2-, 8-, and 12-weeks post-implantation	Develop honeycomb scaffolds comprising carbonate apatite for bone reconstruction in critical-size segmental defects in rat femurs with comparable efficacy to protein and cell scaffolds but at a lower cost and increased safety.	Identification of cost-effective and safe alternatives for bone reconstruction in critical-size segmental defects, Exploration of scaffold materials that can achieve effective outcomes without the need for high-cost or high-risk growth factors or stem cells.
10.	[100]	- The porous femoral stem design showed a 31% lower stiffness compared to its dense counterpart. - The diamond lattice structures have potential as biomimetic constructs for orthopaedic implants.	Stiffness of the porous femoral stem compared to its dense counterpart (31% lower stiffness)	Design a femoral stem with a porous structure to lower stiffness and allow bone tissue ingrowth; Assess the potential of diamond lattice structures as biomimetic constructs for load-bearing orthopaedic implants.	Exploring the potential of diamond lattice structures as biomimetic constructs for load-bearing orthopaedic implants.
11.	[101]	The main findings highlight the advantages of using the biomimetic composite stem in reducing stress shielding and migration, the influence of ply	stresses in the stem, stresses in the femoral bone, and micromotions	The study objectives are to compare the biomechanical performance of total hip stems made of Ti or HA-	Future research could focus on finding the optimal balance between stress shielding and micromotions in hip

		configuration on biomechanical parameters, and the importance of matching the stiffness of cortical bone for optimal performance.		coated composite and to investigate the influence of architectural features of the composite stem on various biomechanical properties.	prosthesis design, considering bone remodeling post-surgery, exploring the impact of ply configurations and core stiffness on biomechanical properties.
12.	[102]	- Multi-lattice designs were effective in reducing the stress-shielding effect in hip implant applications. - The maximum von Mises stress values on the hip implant stem were significantly reduced. - A weight reduction of up to 25.89% was achieved with the multi-lattice designs. - Significant increase (max. 150.47%) in stress-shielding signals from different zones of the femur was observed.	Reduction in maximum von Mises stress values on the hip implant stem, weight reduction, increase in stress-shielding signals from different zones of the femur	The study objectives are to create multi-lattice structure designs for hip stem implants and analyze their impact on reducing the stress-shielding effect in hip implant applications.	Future research could explore the long-term effects of multi-lattice designs on stress-shielding and bone health, compare different lattice structures, and study the biomechanical behavior and durability of these implants.
13.	[103]	The carbon/PEEK composite material (configuration I) is effective in reducing stress shielding, preventing aseptic loosening, and enhancing the stability of the prosthesis-bone system.	reduction of stress shielding effect and prolongation of prosthesis-bone system's lifetime	The study objectives are to investigate how PEEK and carbon/PEEK composite coating materials on a titanium alloy hip implant stem could reduce stress shielding effect, evaluate the performance of different coating materials under dynamic loadings corresponding to different human activities, and determine which coating material configuration has the best performance in reducing stress shielding effect in the prosthesis-bone system.	The paper does not explicitly provide recommendations or ideas for future research.
14.	[104]	- The primary outcome of the study is a design guideline for the use of 3D star honeycomb auxetic cellular structure in structural applications. - From = 45 ∘ to 70 ∘, the structure exhibits auxetic behavior in all directions.	Design guideline for the use of 3D star honeycomb auxetic cellular structure in structural applications, behavior of the structure in different	The study objectives are to evaluate shape parameters of the structural cell in relation to basic mechanical properties, quantify mechanical properties for different domains where	Exploring further optimization of fabrication techniques for auxetic materials, expanding the method for formulating mechanical properties to different structures or materials, investigating the

		- The overall mechanical properties can be controlled by modification of the base wall angle of the configurations, with the consequent changes, in particular, of the in-plane Poisson's ratio.	angle ranges, changes in Poisson's ratios, elastic modulus, and density with increasing angles, control of mechanical properties by modifying the base wall angle of the configurations	auxetic material is of interest, and provide a design guideline for the use of 3D star honeycomb auxetic cellular structure in structural applications	manipulation of various structural parameters to achieve specific mechanical characteristics in auxetic materials

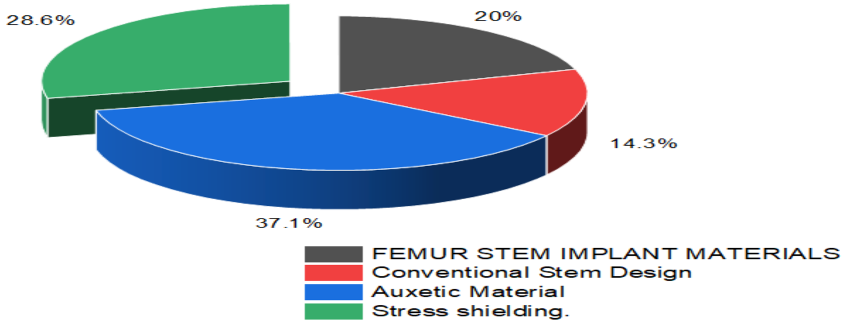


Figure 7: Researches in different areas of femur stem.

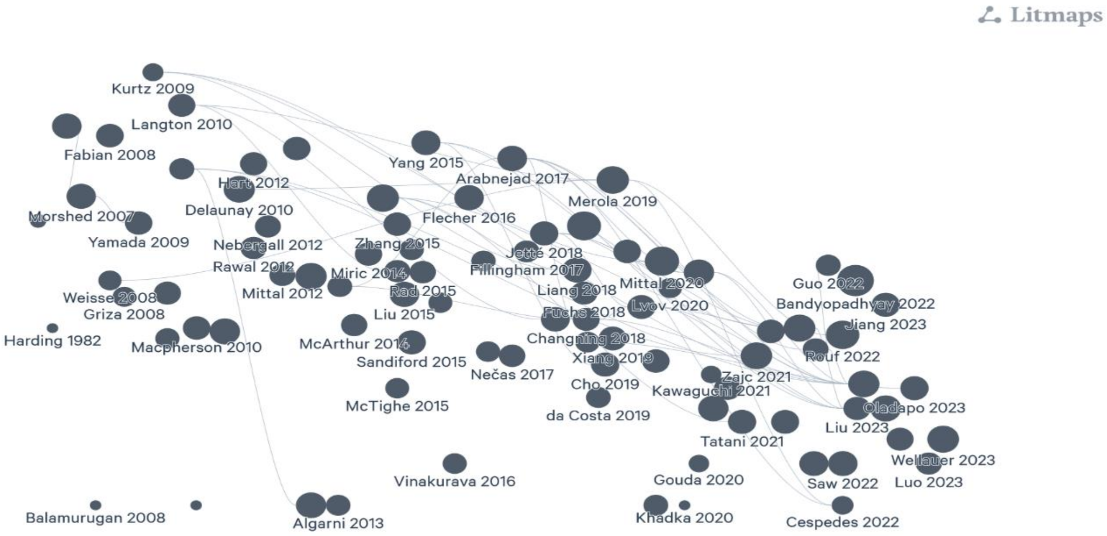


Figure 8: Literature map that has been used for this paper

2.6. Summary Of Literature Review

The literature review provides an extensive overview of various aspects related to femur stem design and materials used in hip implants. It covers topics such as existing femur stem implant materials, conventional stem design, auxetic material and design, finite element analysis (FEA), and biomechanical considerations.

The review begins with an introduction to femur stem implants, highlighting their importance in hip replacement surgeries. It then delves into the different materials used in femur stem implants, including stainless steel, titanium alloys, cobalt-chromium alloys, titanium/HA composite alloys, and ceramic materials. Each material is discussed in terms of its properties, advantages, limitations, and clinical outcomes.

The section on conventional stem design provides a historical background, material selection considerations, biomechanical considerations, clinical outcomes, wear and corrosion issues, failure modes, surgical techniques, and regulatory and standardization aspects. These aspects contribute to a comprehensive understanding of the current state of conventional femur stem design.

The review then shifts focus to auxetic material and design, introducing the concept of auxetic materials and their potential applications in orthopedics. It discusses the background on femur stem design, explores the use of auxetic materials in orthopedics, highlights design considerations, biomechanical effects, computational modeling and simulations, experimental studies, clinical outcomes, and future directions and challenges.

The role of finite element analysis (FEA) in femur stem design is explored in detail. It covers the introduction to FEA in femur stem design, optimization techniques, auxetic material properties, realistic loading conditions, previous FEA studies on auxetic femur stems, validation studies, and challenges and future directions. FEA serves as a valuable tool for optimizing the design and assessing the performance of femur stems.

Biomechanical considerations related to femur stem implants are also discussed. This section provides an understanding of the biomechanics of the femur, biomechanical considerations in femur stem design, realistic loading conditions, the mechanical behavior of auxetic materials, and the role of computational biomechanics.

Overall, the literature review provides a comprehensive overview of the current knowledge and understanding of femur stem design and materials. It highlights the limitations and challenges in the field, such as the lack of research on the use of auxetic materials, the need for exploration of realistic loading conditions, the importance of validation studies for FEA models, and the consideration of regulatory aspects. The identified gaps serve as potential areas for future research and advancements in femur stem implant technology.

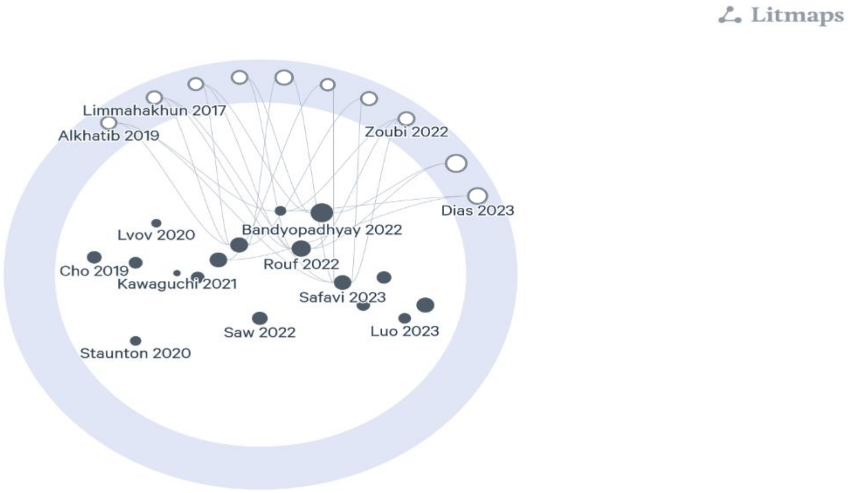


Figure 9: Comparison of different literatures.

2.7. Gap Analysis

Based on the literature reviews provided above, the gap analysis includes the following points:

1. **Need for Focused Research on Auxetic Materials in Femur Stem Implants**: Although auxetic materials have shown promise in various orthopedic applications, specific studies or clinical outcomes related to femur stem implants made from these materials are limited. This gap indicates a need for dedicated research to understand the potential benefits and challenges of using auxetic materials in femur stem design.

2. **Exploration of Realistic Loading Conditions**: The importance of considering realistic loading conditions in femur stem design is acknowledged in the literature. However, detailed studies analyzing how these conditions affect the performance of different implant materials, including auxetic materials, are sparse. Future research should focus on the biomechanical effects and mechanical behavior of auxetic materials under realistic loading scenarios.

3. **Validation of Finite Element Analysis (FEA) Models**: While FEA is commonly used in femur stem design and optimization, there is a lack of information on the validation of these models. Ensuring the accuracy and reliability of FEA simulations is crucial for designing femur stems using auxetic materials. Future research should prioritize conducting validation studies to confirm the fidelity of FEA models in predicting the behavior of auxetic femur stems.

4. **Comprehensive Clinical Outcomes**: Current literature includes some clinical outcomes related to conventional femur stem designs, but comprehensive clinical studies focusing

specifically on femur stems made from auxetic materials are lacking. Further research is essential to evaluate the long-term performance, survivorship, and patient outcomes associated with the use of auxetic materials in femur stem implants.

5. **Consideration of Regulatory and Standardization Aspects**: The regulatory and standardization aspects of conventional femur stem designs are briefly mentioned in the literature. However, specific considerations and challenges related to the use of auxetic materials in femur stem implants are not well-addressed. Future research should explore the regulatory requirements and standards for auxetic materials to ensure their safety and effectiveness in clinical applications.
6. **Interdisciplinary Research for Optimal Results**: Integrating knowledge from different fields of study, such as materials science, biomechanics, clinical medicine, and regulatory affairs, is crucial for advancing research on auxetic femur stem implants. Collaborative efforts can lead to a more comprehensive understanding and optimized design of femur stems using auxetic materials.

Overall, these gaps highlight the need for further research on the use of auxetic materials in femur stem design, including comprehensive clinical studies, exploration of realistic loading conditions, validation of FEA models, consideration of regulatory aspects, and interdisciplinary research. Addressing these areas will contribute significantly to the advancement of femur stem implants using auxetic materials.

Chapter Three

3. Methods

The present study focuses on the systematic optimization of the auxetic femur stem in hip arthroplasty, specifically targeting its performance under realistic loading conditions. The research methodology is structured around several key components to ensure a comprehensive investigation. Initially, patient-specific data was meticulously collected from Samaritan Surgical Center, establishing a foundation for the subsequent comparative analysis. A pivotal aspect of the methodology involves the comparison of Zimmer's femur stem, a commonly utilized component in hip arthroplasty, with an optimized auxetic femur stem developed in this research. The primary objective of the study is to achieve optimal stress shielding, driving the iterative design process employed for the optimization of the auxetic structure. To ensure clinical relevance and applicability of the findings, the study incorporates realistic loading conditions such as walking, going up stairs, going downstairs, standing up, and sitting down. Additionally, SolidWorks simulation is employed to simulate and evaluate the performance of both the Zimmer's femur stem and the optimized auxetic femur stem under these loading conditions. The analysis is further supported by statistical evaluation to provide robust and reliable conclusions.

3.1. Initial model

Data for this study was sourced from Samaritan Surgical Center, providing a clinically relevant and reliable dataset for the research. The patient-specific data collection was tailored to individual anatomical variations and clinical scenarios, enhancing the accuracy and applicability of the findings for femur stem implants under investigation. Alongside primary data collection, a comprehensive literature review was conducted using web-based platforms such as heuristi.ca, openread.academy, explainpaper.com, notion.so, elicit.com, and litmap.com. These platforms facilitated a systematic analysis of relevant scientific articles, journals, and conference proceedings to identify existing knowledge, methodologies, and findings related to femur stem optimization, stress shielding evaluation, and the application of auxetic structures in orthopedic implants.

The insights gained from the literature review informed the selection of parameters for the auxetic 3D star honeycomb structure and the design of realistic loading conditions used in the SolidWorks simulations. By integrating patient-specific data collection with a rigorous literature review using advanced web-based platforms, this study aims to provide a robust and comprehensive analysis of the optimized auxetic femur stem in comparison with the Zimmer's femur stem, contributing valuable insights to the field of hip arthroplasty and implant design optimization.

Figure 10:FEMUR STEM: is a component of a total hip replacement, which is a surgical procedure that replaces a damaged or arthritic hip joint with an artificial joint. The femur stem is the portion of the implant that is inserted into the femur bone. ***Material for femur stem****: Ti-6AI-4V means It is comprised of 90% titanium, 6% aluminum and 4% vanadium. Taperlock complete primary femoral porous coated stem. 8x136mm standard offset 12/14 taper for cementless use*

Figure 11:SHELL WITH CLUSTER HOLES POROUS: Shell with cluster holes porous is a type of implant used in hip replacement surgery. Image taken from phone in medical Dr. Samuel office. 48mm O.D size GG For use of GG liners

Table 4: Properties of titanium Alloy **[40].**

Property	**Description**	**Ti-6AI-4V**
Young's Modulus	The measure of stiffness and resistance to deformation	110 GPa
Poisson's Ratio	The ratio of lateral strain to axial strain	0.3
Density	Mass per unit volume	4428
Compressive Strength	Maximum compressive stress that the foam can withstand	960 MPa
Tensile Strength	Maximum tensile stress that the foam can withstand	1098 MPa
Ultimate compressive Strength	Ability to dissipate energy under cyclic loading	1237 MPa

3.2. Numerical modeling of femur stem

In this study, finite element models were constructed using ANSYS software to perform a numerical analysis of the femur stem's optimization. Initially, geometric representations of both the Zimmer's femur stem and the optimized auxetic femur stem were developed based on the parameters derived from patient-specific data and design concepts. Subsequently, these geometric models were utilized for conducting finite element analysis to investigate the mechanical performance, stress distribution, and stress shielding behavior of both femur stem designs under realistic loading conditions.

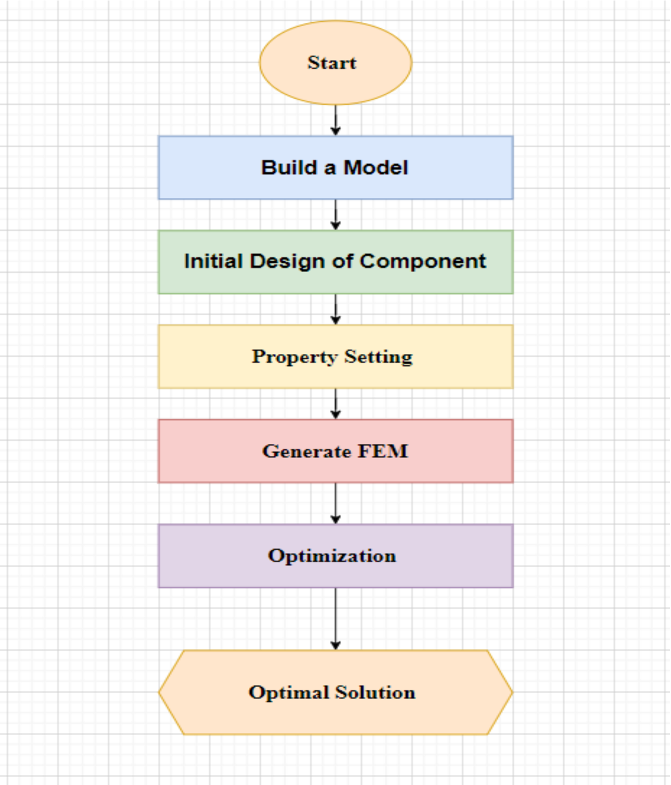


Figure 13:Developing a general approach to achieve an optimal solution.

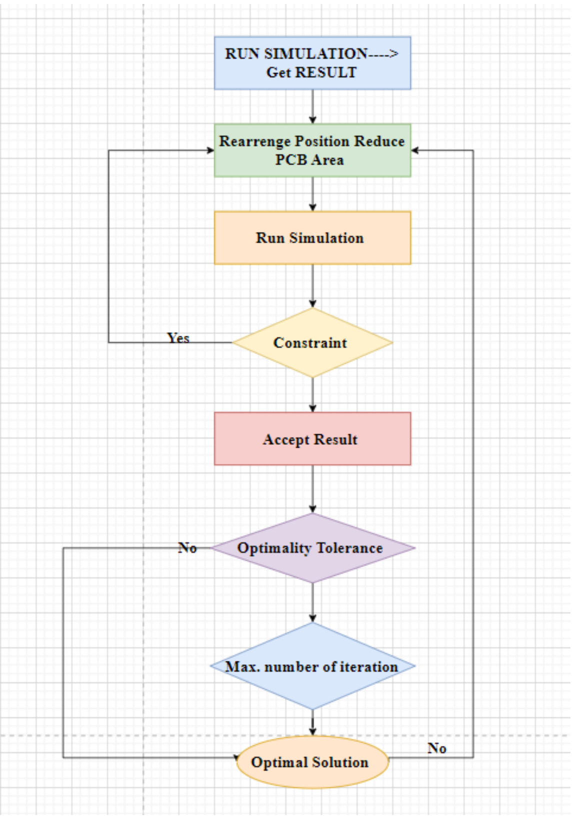


Figure 12:Basic steps for simulating femur stem using 3D star honeycomb structure in ANSYS software

3.2.1. Geometric modeling

3.2.1.1. Femur stem dimension

Initially, geometric representations of both the Zimmer's femur stem and the optimized auxetic femur stem were developed using SolidWorks based on the parameters derived from patient-specific data and design concepts. Subsequently, these geometric models were utilized for conducting finite element analysis to investigate the mechanical performance, stress distribution, and stress shielding behavior of both femur stem designs under realistic loading conditions.

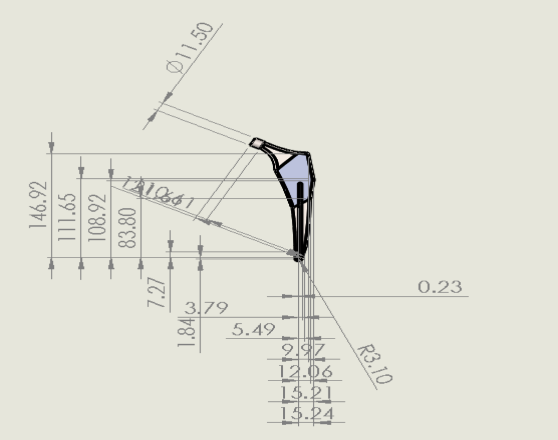


Figure 15: Geometric dimension of femur stem.

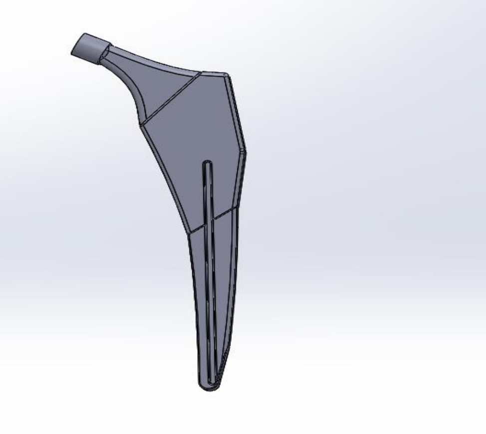


Figure 14: Femur stem modeled using SolidWorks.

3.2.1.1. Femur intact bone

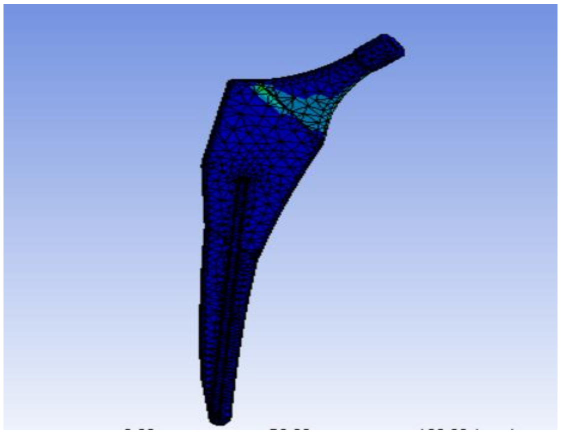
The intact femur bone was also modeled using SolidWorks to provide a comprehensive anatomical representation for the implantation procedures. Subsequently, these geometric models, including the femur bone, were utilized for conducting finite element analysis to investigate the mechanical performance, stress distribution, and stress shielding behavior of both femur stem designs under realistic loading conditions.

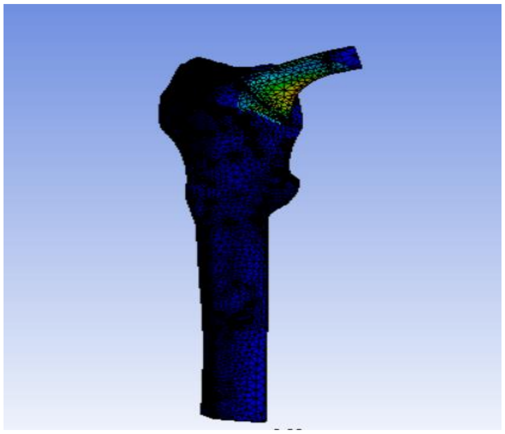
Figure 17: Intact bone

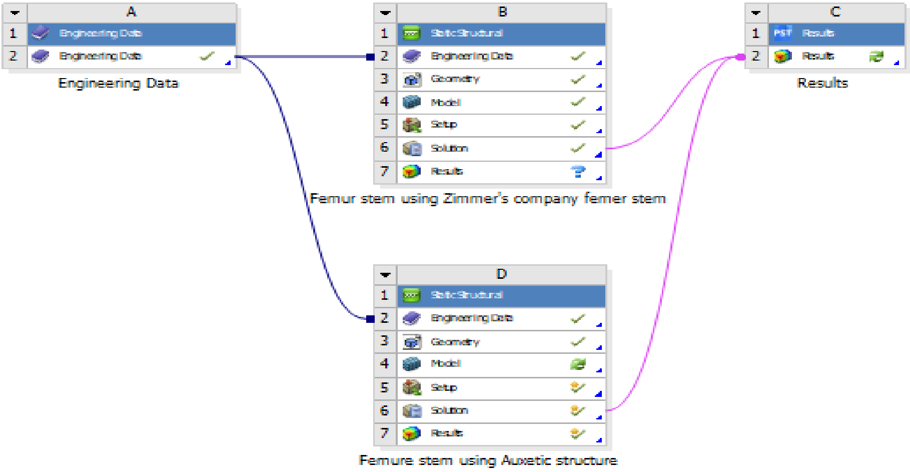
Figure 16:Femur stem implant.

3.2.2. Finite element modeling

In this study, finite element models were constructed using SolidWorks and analyzed using ANSYS software to perform a numerical analysis of the femur stem's optimization. Initially, geometric representations of both the Zimmer's femur stem and the optimized auxetic femur stem were developed based on the parameters derived from patient-specific data and design concepts. The intact femur bone was also modeled using SolidWorks to provide a comprehensive anatomical representation for the implantation procedures. Subsequently, these geometric models, including the femur bone, were utilized in ANSYS for conducting finite element analysis to investigate the mechanical performance, stress distribution, and stress shielding behavior of both femur stem designs under realistic loading conditions.







3.3. Implant Comparison

The first component of the comparative analysis focuses on the description and evaluation of Zimmer's company femur stem, a commonly used implant in hip arthroplasty procedures. Zimmer's femur stem is designed to provide stability and support to the hip joint, with specific features and material properties optimized for biomechanical compatibility and long-term implant performance. A detailed description of the design, material composition, and surgical application of Zimmer's femur stem will be provided to establish a baseline for comparison with the optimized auxetic femur stem developed in this study.

The primary comparison metric for evaluating the performance of the femur stem implants is stress shielding, a critical factor that can significantly affect the long-term success and functional outcomes of hip arthroplasty. Stress shielding refers to the reduction of mechanical stress transferred to the surrounding bone tissue due to the implant, which can lead to bone resorption and implant loosening over time. By focusing on stress shielding as the primary comparison criteria, this study aims to assess and compare the biomechanical behavior and performance of Zimmer's femur stem and the optimized auxetic femur stem under realistic loading conditions and patient-specific anatomical variations. This comparative analysis will provide valuable insights into the potential benefits and limitations of using an optimized auxetic femur stem in hip arthroplasty, contributing to the advancement of implant design and surgical techniques in orthopedic surgery.

3.4. Development of Auxetic Femur Stem

The development and optimization of the auxetic femur stem in this study center around the introduction and design concept of the Auxetic 3D Star Honeycomb Structure. Initially, a simple 3D star honeycomb cellular structure was modelled by adapting a 2D cellular structure, serving as the foundational design for the optimized femur stem. This innovative design concept is characterized by its unique geometric configuration, which exhibits auxetic behavior, meaning it expands in lateral directions when stretched longitudinally, enhancing its potential for stress distribution and biomechanical compatibility.

The iterative design process employed in the present study focused on evaluating the influence of structural shape on basic mechanical properties, including elastic modulus, density ratio, and Poisson’s ratio. Various values of shape parameters, such as wall length, cell wall thicknesses, and cellular structure angle, were examined to optimize the mechanical properties of the auxetic 3D star honeycomb structure. The 2D cellular structure, consisting of eight elastic beams in a symmetrical configuration, served as the starting point for the analytical formulation of mechanical properties for the structure. Through rigorous analysis and evaluation, an optimized design for the auxetic femur stem was developed, aiming to improve stress shielding performance and long-term implant stability in hip arthroplasty procedures. This iterative design process ensures that the optimized auxetic femur stem meets the biomechanical requirements and functional demands for successful clinical application, providing a novel approach to femur stem design optimization in orthopedic surgery.

3.4.1. Unit cell selected

In their investigation of 3D star honeycomb structures for mechanical applications, researchers delve into the intricate relationship between geometric parameters and fundamental mechanical properties. Through numerical analysis and graphical representations, they reveal the profound influence of variations in parameters like stiffness, strength, and Poisson's ratio on material behavior. Emphasizing the pivotal role of the base wall angle, they suggest pathways to tailor these structures for diverse industry applications. Comparisons with conventional materials underscore the potential advantages of auxetic materials in practical scenarios, while discussions on optimal design considerations highlight the delicate balance needed between geometric parameters, manufacturability, and performance implications. Additionally, researchers anticipate future applications and research directions, envisioning opportunities for emerging technologies and industries to leverage the unique properties of 3D star honeycomb structures. Their proposed refinements and modifications aim to enhance performance, contributing significantly to the ongoing advancement of materials science and engineering.

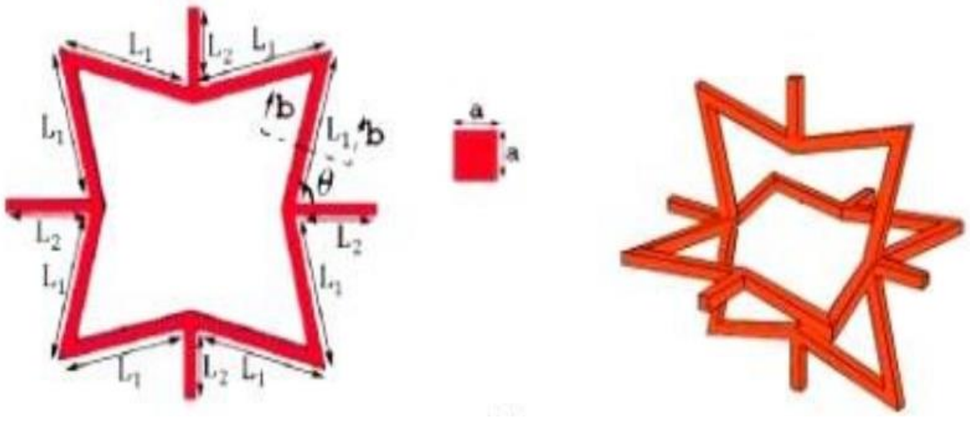


Figure 18:Unit cell 3D star honeycomb structure **[17]**.

3.4.2. Auxetic model

Analytical approaches can predict Poisson's ratios, elastic modulus, and density ratios for all models. The geometrical dimensions of the cell, the mechanical properties of the base material, and the mechanical properties of the star honeycomb structure, such as Poisson's ratio, elastic modulus, and density ratio, are all related from a mathematical and mechanical perspective. The relationships can be expressed using the following functions:

$$v_{xy} = f_1\left(L_1, L_2, a, \theta\right), \qquad 3.1$$

$$v_{xy} = f_2\left(L_1, L_2, a, \theta\right), \qquad 3.2$$

$$v_{xy} = f_3\left(L_1, L_2, a, \theta\right), \qquad 3.3$$

$$v_{yz} = v_{zy} = f_4\left(L_1, L_2, a, \theta\right), \qquad 3.4$$

$$E_1 = f_5\left(E, L_1, L_2, a, \theta\right), \qquad 3.5$$

$$E_2 = E_3 = f_6\left(E, L_1, L_2, a, \theta\right), \qquad 3.6$$

$$\rho = f_7(\rho_c, a, L_1, L_2,), \qquad 3.7$$

The geometrical characteristics of the cell depicted in Figure 17 are L_1, L_2, a, and θ. E and ρ_c represent the elastic modulus and density of the base material, respectively. v_{xy}, v_{xz}, v_{yx}, v_{yz}, v_{zx}, v_{zy}, E_1, E_2, and E_3 are the Poisson's ratios and elastic modulus of the material. Dimensionless parameters can predict Poisson's ratios and elastic modulus of a material, as shown below:

$$v_{xy} = F_1\left(\alpha, \beta, \gamma\right) = \sum_{i=0}^{2}\sum_{j=0}^{2}\sum_{k=0}^{2} A_{ijk}\left[\alpha^i \beta^j \gamma^k\right], \qquad 3.8$$

$$v_{xz} = F_2\left(\alpha, \beta, \gamma\right) = \sum_{i=0}^{2}\sum_{j=0}^{2}\sum_{k=0}^{2} B_{ijk}\left[\alpha^i \beta^j \gamma^k\right], \qquad 3.9$$

$$v_{yx} = F_3\left(\alpha, \beta, \gamma\right) = \textstyle\sum_{i=0}^{2}\sum_{j=0}^{2}\sum_{k=0}^{2} C_{ijk}\left[\alpha^i \beta^j \gamma^k\right], \qquad 3.10$$

$$v_{yz} = F_4\left(\alpha, \beta, \gamma\right) = \sum_{i=0}^{2}\sum_{j=0}^{2}\sum_{k=0}^{2} D_{ijk}\left[\alpha^i \beta^j \gamma^k\right], \qquad 3.11$$

$$\frac{E_1}{E} = F_5\left(\alpha, \beta, \gamma\right) = \sum_{i=0}^{2}\sum_{j=0}^{2}\sum_{k=0}^{2} E_{ijk}\left[\alpha^i \beta^j \gamma^k\right], \qquad 3.12$$

$$\frac{E_2}{E} = F_6\left(\alpha, \beta, \gamma\right) = \sum_{i=0}^{2}\sum_{j=0}^{2}\sum_{k=0}^{2} F_{ijk}\left[\alpha^i \beta^j \gamma^k\right], \qquad 3.13$$

$$\frac{\rho}{\rho_c} = F_6(\alpha, \beta, \gamma) = \sum_{i=0}^{2}\sum_{j=0}^{2}\sum_{k=0}^{2} G_{ijk}\left[\alpha^i \beta^j \gamma^k\right], \qquad 3.14$$

Where \alpha =\theta,\ \beta =\sfrac{L_2}{L_1} and \gamma =\sfrac{a}{L_1}

A valid set of (4) requires each function to have 22 coefficients. Coefficients for Poisson's ratios, elastic modulus, and density ratio are derived from 22 models with varying geometrical parameters. Finite element analysis has been performed on the models. Table 4 displays the values of α, β, and γ utilized for finite element analysis.

Table 5:Values of α, β, and γ used **[17].**

Model number	**Geometric Parameters (α, β, γ)**		
	α	**β**	**γ**
case 1	0.9599	0.04	0.8
case 2	0.9599	0.04	0.9
case 3	0.9599	0.06	0.8
case 4	0.9599	0.06	0.9
case 5	1.0472	0.02	0.8
case 6	1.0472	0.06	0.9
case 7	1.1345	0.02	0.8
case 8	1.1345	0.04	0.8
case 9	1.1345	0.04	0.9
case 10	1.1345	0.06	0.8
case 11	1.309	0.02	0.8
case 12	1.309	0.02	0.9
case 13	1.309	0.04	0.8
case 14	1.309	0.06	0.8
case 15	1.309	0.06	0.9
case 16	1.3963	0.02	0.8
case 17	1.3963	0.02	0.9
case 18	1.3963	0.04	0.9
case 19	1.3963	0.06	0.8
case 20	1.4835	0.02	0.8
case 21	1.4835	0.02	0.9
case 22	1.4835	0.04	0.8

3.5. Loading Conditions

The assessment of the femur stem implants' performance under realistic loading conditions is a critical component of this study, providing valuable insights into their biomechanical behavior and stress distribution in functional daily activities. The selection of realistic loading conditions was guided by their relevance to the biomechanics of the hip joint and the potential challenges posed to femur stem implants during postoperative recovery and rehabilitation.

Walking, a fundamental activity in daily life, was chosen as one of the realistic loading conditions to evaluate the implants' performance under varying degrees of joint motion. Going up stairs and going downstairs were included to simulate the increased mechanical demands on the femur stem during stair climbing, which can exert higher stresses on the implant and surrounding bone tissue due to the repetitive and dynamic nature of the activity.

Standing up and sitting down were also selected as realistic loading conditions to assess the implants' response to static and dynamic loading, reflecting the common movements involved in transitioning between sitting and standing positions. These loading conditions are particularly relevant for evaluating the implants' stability, stress distribution, and potential for stress shielding during weight-bearing activities.

By incorporating these realistic loading conditions into the SolidWorks and ANSYS simulations, this study aims to provide a comprehensive evaluation of the optimized auxetic femur stem and Zimmer's femur stem under various functional scenarios. This approach ensures that the implants' design and mechanical properties are assessed under conditions that closely mimic the biomechanical environment of the hip joint during daily activities, contributing to the development of more effective and patient-specific implant designs for hip arthroplasty.

In the context of medical research, the critical issue of evaluating realistic loading conditions for hip implants, with a focus on aligning these conditions with existing ISO standards. Hip implants are a crucial medical intervention, aiming to restore mobility and enhance the quality of life for individuals dealing with hip-related ailments. Traditional evaluations of hip implant performance have leaned on standardized ISO testing procedures, assuming their accuracy in simulating real-world forces. However, the study's prompts an important query: do these ISO standards authentically replicate the dynamic and variable loading conditions encountered by hip implants during daily activities? To answer this question, the study embarks on the task of defining and assessing realistic loading conditions, drawing from in vivo contact force measurements obtained from patients engaging in diverse activities. The implications of these findings are profound, raising concerns about the potential disconnect between ISO standards and genuine loading conditions, with the pursuit of realism in hip implant evaluation holding the promise of improving patient outcomes and extending implant durability—a matter of paramount significance in the realm of medical research and device development.

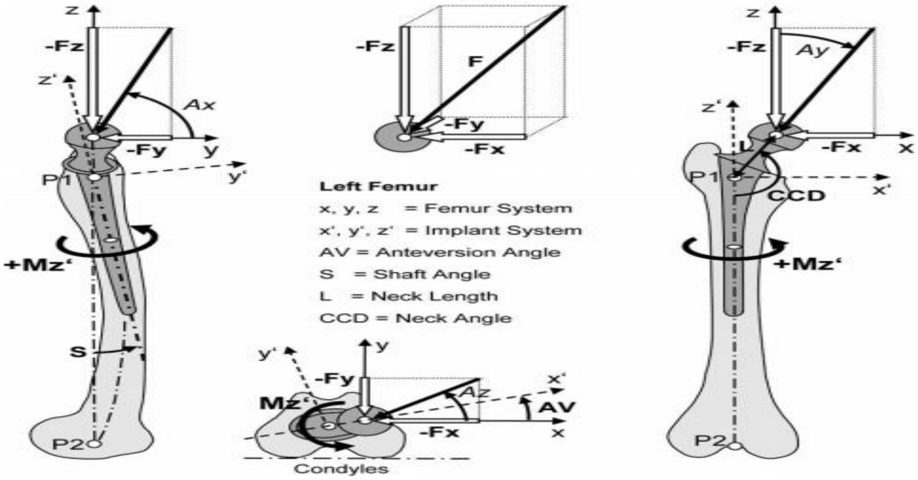


Figure 19:Coordinate systems for the femur and implant. The contact force F consists of the components F_x, F_y, F_z, in the femur-based system xyz. The torsional moment M_2 acts around the implant stem z. Negative moments M_2 rotate the implant backwards. The angles AV and S define the implant position relative to the femur. From www.OrthoLoad.com (Info, Manual)

Table 6: Peak contact value of force

Activity	**Peak contact force F(N)**				**Peak moment**	**Data file**
	F	$-F_x$	$-F_y$	$-F_z$	M_z	
Walking	1800	403	249	1736	-11.5	Waliking_Average.HIP
Going up stairs	1900	446	464	1787	-17.1	UpStairs_Average.HIP
Going down stairs	2000	370	292	1944	-13.7	DownStairs_Average.HIP
Standing up	1500	420	105	1436	-7.8	StandingUp_Average.HIP
Sitting down	1200	323	-5	1155	-3.9	SittingDown_Average.HIP

Peak values of resultant contact force *F* and torsional moment *M z*. Highest loads for a body weight of 1000 N. The 3 ‘high-impact activities’ are printed in italic. Stumbling is included in the ‘high peak loads. Data files are available from www.OrthoLoad.com (HIP98).

3.6. Stress Shielding in Orthopedic Implants

Stress shielding occurs when an orthopedic implant, such as a femur stem in hip arthroplasty, absorbs more load than the surrounding bone tissue. This is due to the implant often being stiffer than the natural bone, causing the bone to experience reduced mechanical stress. Over time, this reduction in stress can lead to bone resorption, where the bone density decreases because it is not being sufficiently loaded. This can weaken the bone, leading to complications such as implant loosening, failure, or the need for revision surgery. The concept of stress shielding can be understood through Wolff's Law, which states that bone in a healthy person or animal will adapt to the loads under which it is placed. When the load on a bone decreases, the bone becomes less dense and weaker[105].

In the context of femur stem implants, the design and material must be optimized to balance load distribution between the implant and the bone. Materials with mechanical properties closer to those of natural bone, such as certain auxetic materials, can help mitigate stress shielding. Auxetic materials exhibit a negative Poisson's ratio, meaning they expand laterally when stretched, distributing stress more uniformly and enhancing mechanical compatibility between the implant and the bone. The formula for stress shielding can be represented as bone $\sigma_{implant} > \sigma_{bone}$, where σ represents stress. Reducing stress shielding not only maintains bone health and density but also improves the long-term success and survivorship of the implant. Research focuses on developing new materials and designs, such as the 3D star honeycomb auxetic structure, which show promise in achieving better biomechanical performance under realistic loading conditions[17].

$$SS = \frac{(S_{int} - S_{stem})}{S_{int}} * 100\% \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots 3.15$$

S_{int} is the average von Mises stress on the intact femur, S_{stem} is the average von Mises stress on the femur with the implant.

3.7. Optimization

The analysis outlined in the study represents a focused effort in optimizing femur stem designs for hip arthroplasty, with a particular emphasis on reducing stress shielding and enhancing biomechanical performance. Through a rigorous quantitative evaluation utilizing advanced techniques, the study compares the mechanical behavior of Zimmer's femur stem against an optimized auxetic femur stem under realistic loading conditions. Key metrics and standards are established to evaluate stress shielding, including criteria related to bone density changes, load transfer efficiency, and implant-bone interface stability.

The optimization process involves a comprehensive examination of stress distribution, strain distribution, and load transfer patterns across the femur and surrounding bone tissue. By directly comparing the performance of the two femur stem designs, the study aims to identify potential advantages of the optimized auxetic femur stem in minimizing stress shielding and improving load transfer efficiency. This comparative analysis not only highlights the differences in biomechanical behavior but also underscores the importance of optimizing implant designs to enhance patient outcomes.

Ultimately, the findings from this analysis contribute to ongoing efforts in developing innovative implant designs and surgical techniques for hip arthroplasty. By providing valuable insights into the biomechanical performance of femur stem designs, the study informs the optimization of implant designs to improve implant stability and overall patient quality of life following hip replacement surgery.

Chapter Four

4. Result And Discussion

4.1. Results

Orthopedic implants, particularly femur stems used in total hip arthroplasty, play a crucial role in restoring mobility and improving the quality of life for patients with hip joint issues. The performance and durability of these implants are critically dependent on their ability to withstand the mechanical loads and stresses encountered during daily activities such as walking, going upstairs, going downstairs, standing up, and sitting down. This study aims to assess and compare the biomechanical performance of two types of femur stem implants: Zimmer's Titanium Alloy and a novel 3D Star Honeycomb Auxetic Structure. Zimmer's Titanium Alloy, known for its high strength, corrosion resistance, and biocompatibility, is evaluated under various realistic loading conditions to determine peak forces, moments, equivalent (Von Mises) stress, and total deformation.

In parallel, the study explores the performance of a 3D Star Honeycomb Auxetic Structure, designed with varying geometric parameters including wall length, cell wall thickness, and cellular structure angle. Auxetic materials, known for their unique property of becoming thicker perpendicular to the applied force, offer potential advantages in load distribution and stress management. A detailed analysis of different geometric configurations is conducted to identify the optimal design for femur stem applications. A comparative analysis of the two femur stem designs, focusing on stress shielding and stress distribution on both the implant and the surrounding bone, provides a comprehensive understanding of their relative performance. This comparison aims to identify the most effective implant design, minimizing complications such as stress shielding, which can lead to bone resorption and implant failure. The findings of this study are expected to contribute significantly to the field of orthopedic implant design, offering guidance for developing more effective and durable femur stems that enhance patient outcomes in total hip arthroplasty.

4.1.1. Assessing the Performance of Zimmer's Titanium Alloy in femur stem walking, going upstairs, going downstairs, standing up and sitting down realistic loading condition: A Data-Driven Study.

4.1.1.1. Peak force applied

The peak force applied in various realistic conditions serves as a crucial parameter for assessing the biomechanical performance and durability of orthopedic implants, particularly femur stems in total hip arthroplasty. This metric represents the maximum load experienced by the implant during activities mimicking daily movements and stresses encountered by the hip joint.

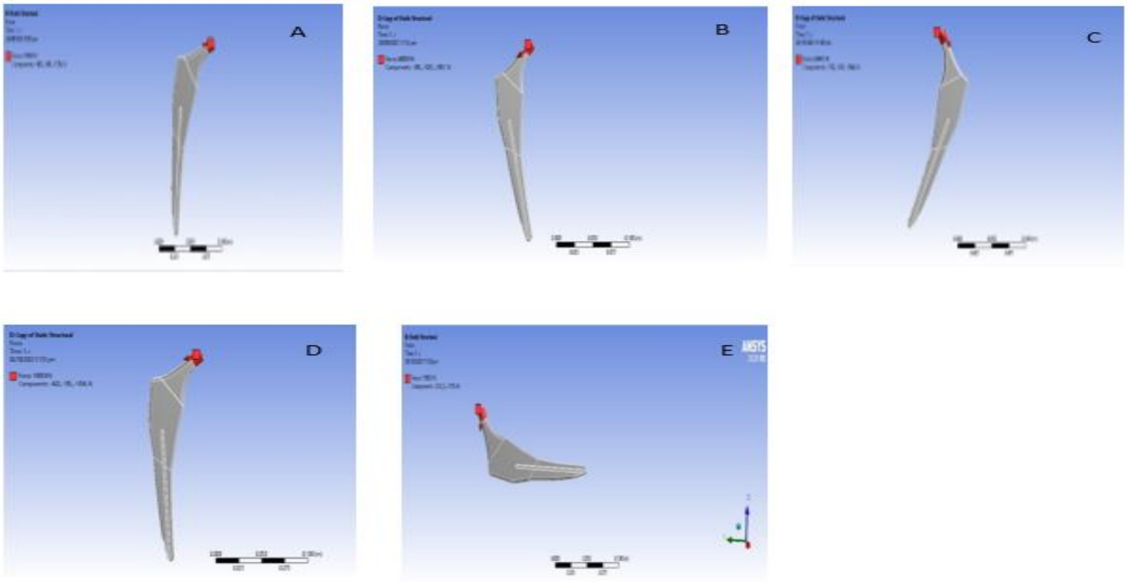


Figure 20:A. Walking: The peak force applied during walking, a common daily activity, is crucial for assessing the implant's performance in supporting the body weight and facilitating smooth movement. B. Going Upstairs: Ascending stairs imposes unique demands on the hip joint, requiring the femur stem to withstand increased forces as the body elevates with each step. C. Going Downstairs: Descending stairs involves a different set of forces compared to ascending, with the femur stem experiencing loads as the body lowers with each step downwards. D. Standing Up: The peak force during standing up from a seated position represents the initial load placed on the femur stem as the individual transitions from a seated to a standing position. E. Sitting Down: Conversely, the peak force during sitting down reflects the load experienced by the femur stem as the individual lowers into a seated position, providing insight into its ability to support the body during weight-bearing activities.

Activity	**Peak contact force F(N)**				**Peak moment**	**Data file**
	F	$-F_x$	$-F_y$	$-F_z$	M_z	
Walking	1800	403	249	1736	-11.5	Waliking_Average.HIP
Going up stairs	1900	446	464	1787	-17.1	UpStairs_Average.HIP
Going down stairs	2000	370	292	1944	-13.7	DownStairs_Average.HIP

Standing up	1500	420	105	1436	-7.8	StandingUp_Average.HIP
Sitting down	1200	323	-5	1155	-3.9	SittingDown_Average.HIP

4.1.1.2. Equivalent (Von-Misis) stress Zimmer's Titanium Alloy in Hip Implants walking, going upstairs, going downstairs, standing up and sitting down realistic loading condition.

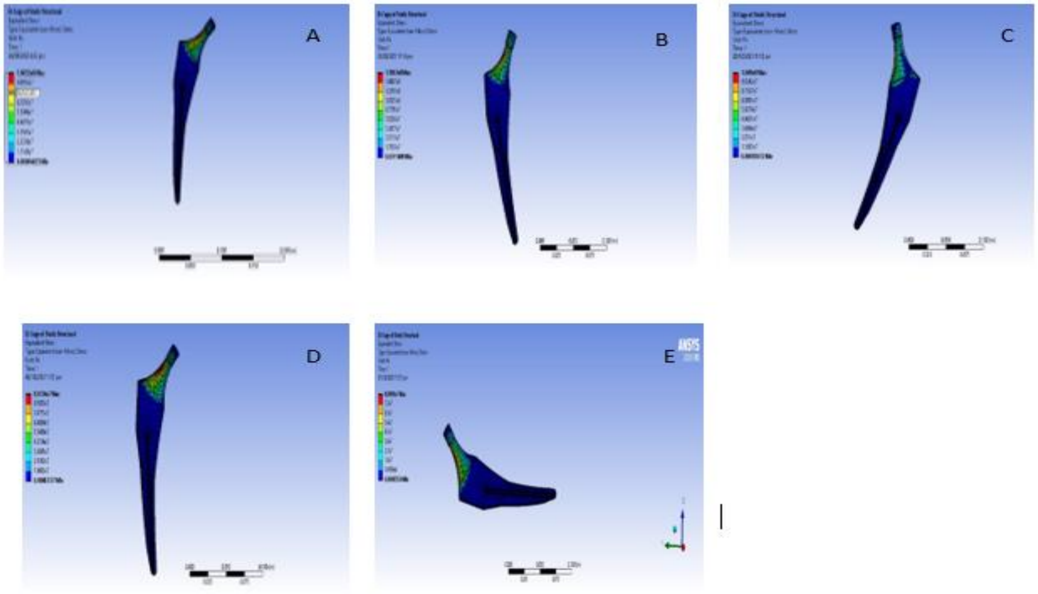
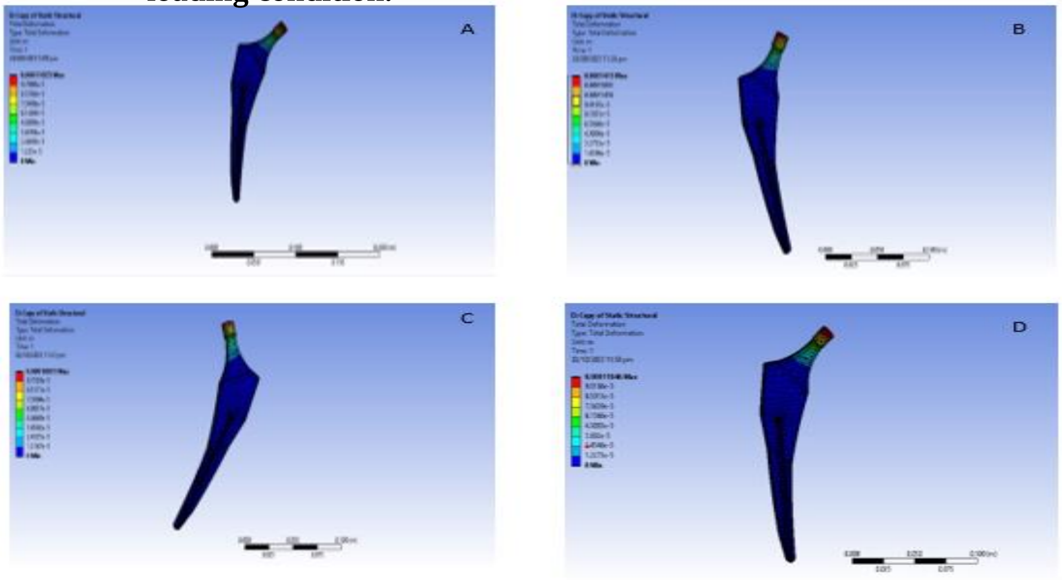


Figure 21: Equivalent (Von-Misis) stress A. Walking: The peak force applied during walking, a common daily activity, is crucial for assessing the implant's performance in supporting the body weight and facilitating smooth movement. B. Going Upstairs: Ascending stairs imposes unique demands on the hip joint, requiring the femur stem to withstand increased forces as the body elevates with each step. C. Going Downstairs: Descending stairs involves a different set of forces compared to ascending, with the femur stem experiencing loads as the body lowers with each step downwards. D. Standing Up: The peak force during standing up from a seated position represents the initial load placed on the femur stem as the individual transitions from a seated to a standing position. E. Sitting Down: Conversely, the peak force during sitting down reflects the load experienced by the femur stem as the individual lowers into a seated position, providing insight into its ability to support the body during weight-bearing activities.

Activity	**Peak contact force F(N)**				**Peak moment**	**Maximum** Equivalent **(Von-Misis) stress Zimmer's Titanium Alloy**
	F	$-F_x$	$-F_y$	$-F_z$	M_z	
Walking	1800	403	249	1736	-11.5	100.52
Going up stairs	1900	446	464	1787	-17.1	158.3
Going down stairs	2000	370	292	1944	-13.7	104.9

Standing up	1500	420	105	1436	-7.8	96.134
Sitting down	1200	323	-5	1155	-3.9	81

4.1.1.3. Total Deformation Zimmer's Titanium Alloy in Hip Implants walking, going upstairs, going downstairs, standing up and sitting down realistic loading condition.



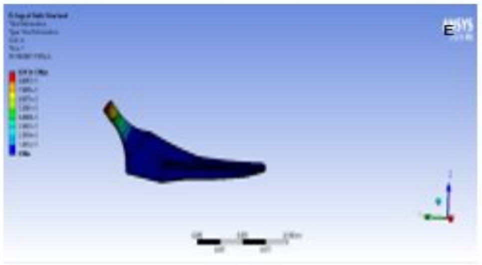
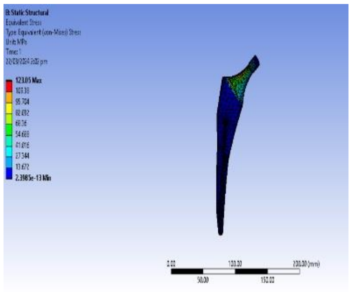
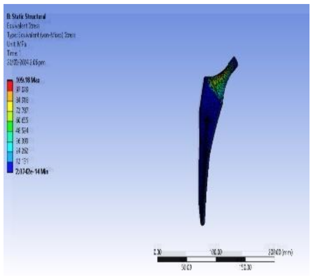
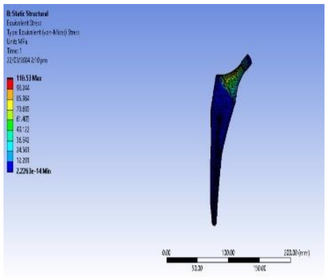
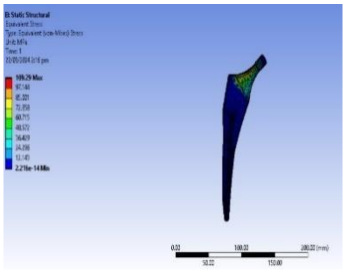
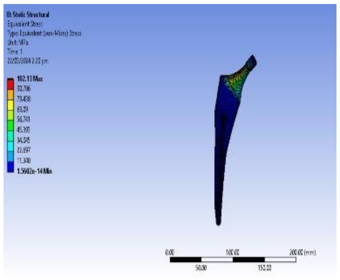
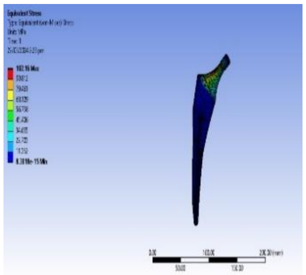
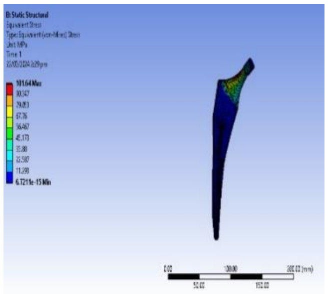
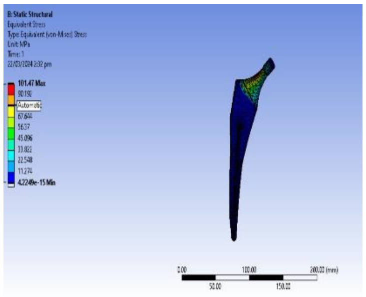
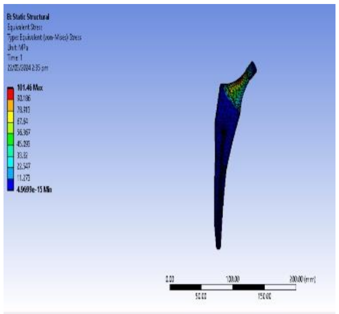
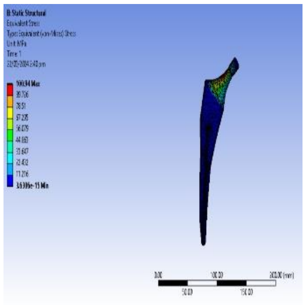
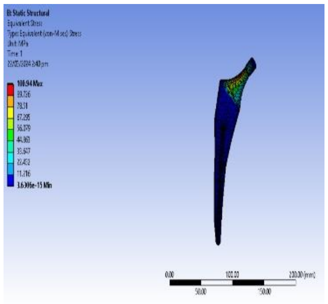
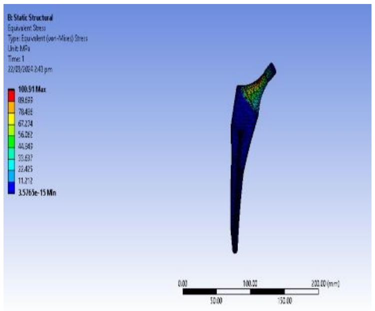
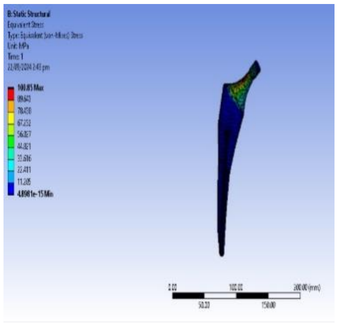
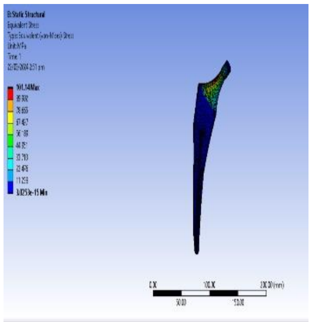
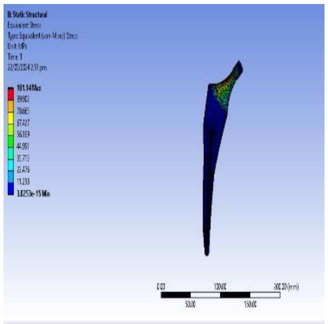
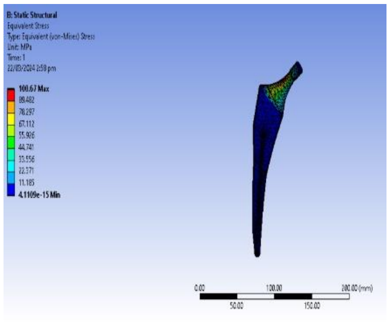
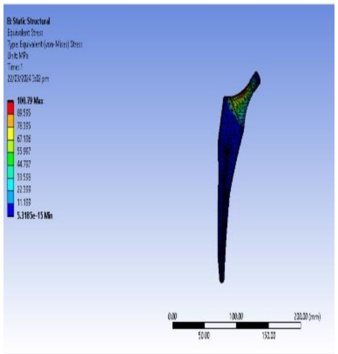
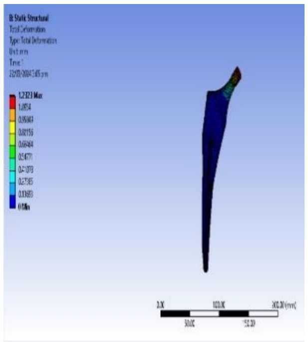
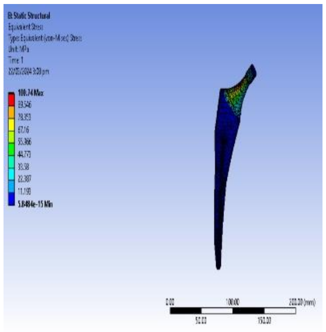
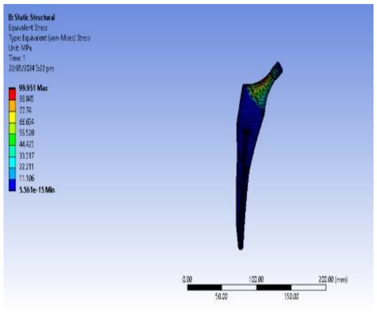


Figure 22:Deformation A. Walking: The peak force applied during walking, a common daily activity, is crucial for assessing the implant's performance in supporting the body weight and facilitating smooth movement. B. Going Upstairs: Ascending stairs imposes unique demands on the hip joint, requiring the femur stem to withstand increased forces as the body elevates with each step. C. Going Downstairs: Descending stairs involves a different set of forces compared to ascending, with the femur stem experiencing loads as the body lowers with each step downwards. D. Standing Up: The peak force during standing up from a seated position represents the initial load placed on the femur stem as the individual transitions from a seated to a standing position. E. Sitting Down: Conversely, the peak force during sitting down reflects the load experienced by the femur stem as the individual lowers into a seated position, providing insight into its ability to support the body during weight-bearing activities.

4.1.2. Assessing the Performance of 3D Star Honeycomb Auxetic Structure in femur stem walking, going upstairs, going downstairs, standing up and sitting down realistic loading condition.

Varying several shape parameters, including the wall length, cell wall thicknesses, and cellular structure angle, to investigate their impact on the overall structural properties.

Model number	**Geometric Parameters (α, β, γ)**		
	α	**β**	**γ**
case 1	0.9599	0.04	0.8
case 2	0.9599	0.04	0.9
case 3	0.9599	0.06	0.8
case 4	0.9599	0.06	0.9
case 5	1.0472	0.02	0.8
case 6	1.0472	0.06	0.9
case 7	1.1345	0.02	0.8
case 8	1.1345	0.04	0.8
case 9	1.1345	0.04	0.9
case 10	1.1345	0.06	0.8
case 11	1.309	0.02	0.8
case 12	1.309	0.02	0.9
case 13	1.309	0.04	0.8
case 14	1.309	0.06	0.8
case 15	1.309	0.06	0.9
case 16	1.3963	0.02	0.8
case 17	1.3963	0.02	0.9
case 18	1.3963	0.04	0.9
case 19	1.3963	0.06	0.8
case 20	1.4835	0.02	0.8
case 21	1.4835	0.02	0.9
case 22	1.4835	0.04	0.8

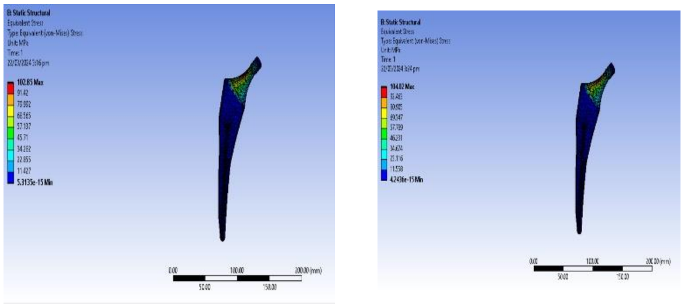


Figure 23:Assessing the performance of the 3D star honeycomb auxetic structure in femur stem walking involves analyzing its mechanical behavior across a sample of 20 cases.

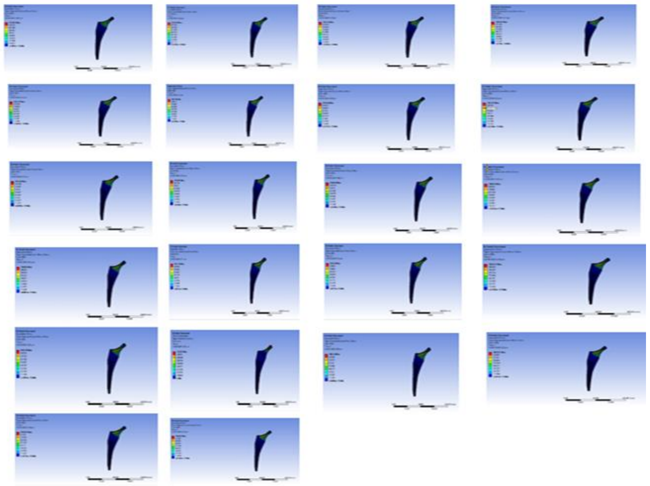


Figure 25:Assessing the performance of the 3D star honeycomb auxetic structure in femur stem going upstairs involves analyzing its mechanical behavior across a sample of 20 cases.

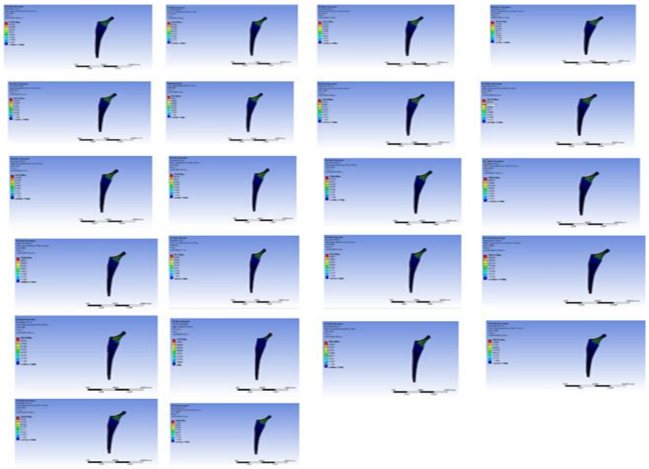


Figure 24:Assessing the performance of the 3D star honeycomb auxetic structure in femur stem going down stairs involves analyzing its mechanical behavior across a sample of 20 cases.

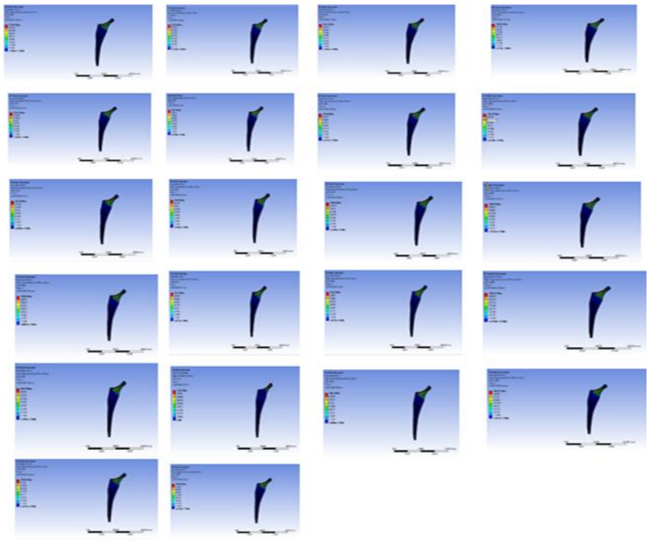


Figure 27:Assessing the performance of the 3D star honeycomb auxetic structure in femur stem standing up involves analyzing its mechanical behavior across a sample of 20 cases.

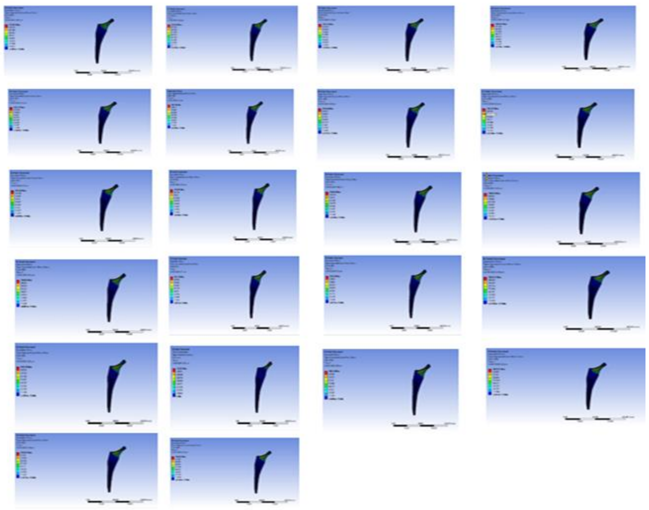


Figure 26:Assessing the performance of the 3D star honeycomb auxetic structure in femur stem sitting down involves analyzing its mechanical behavior across a sample of 20 cases.

4.1.3. A Comparative Analysis of Titanium Alloy femur stem and 3D Star Honeycomb Auxetic Structures Optimized for Best Geometric Parameters.

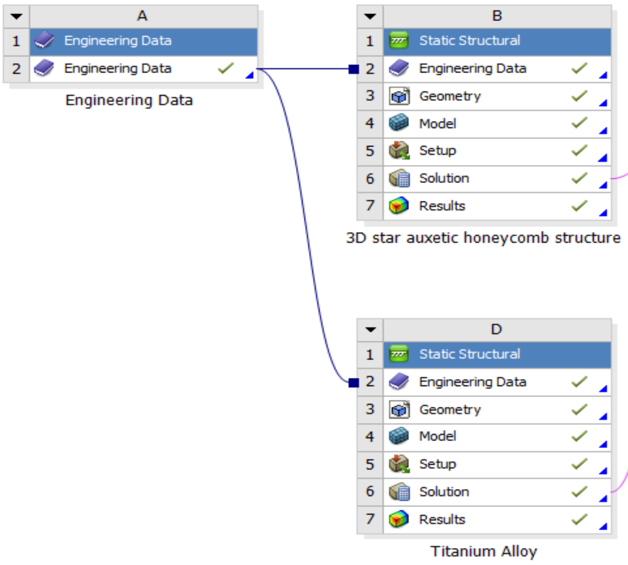
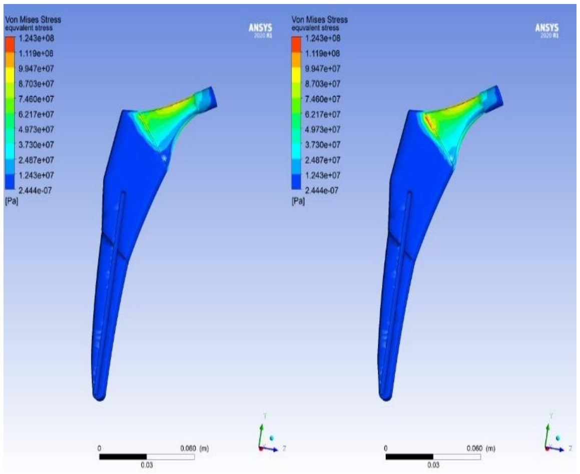
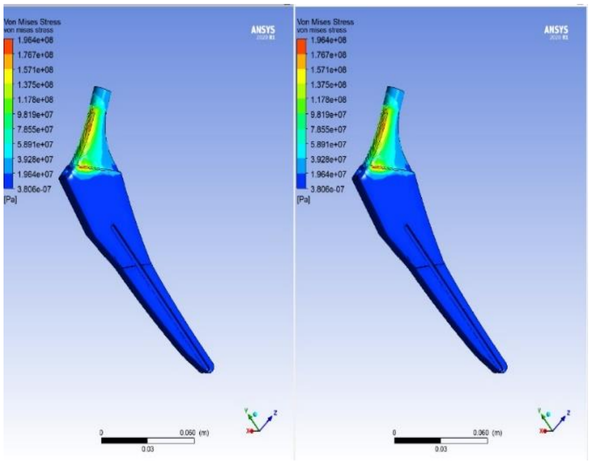
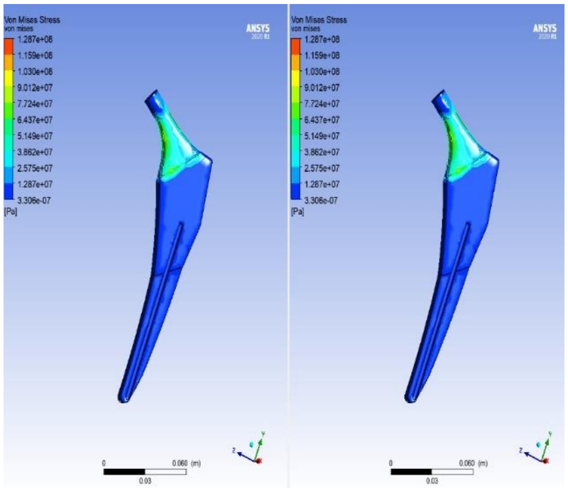
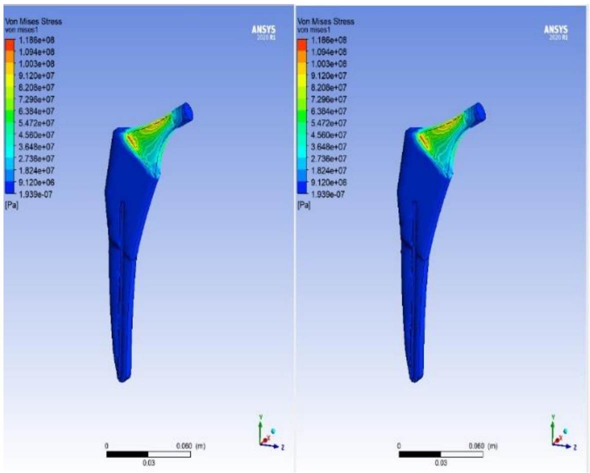


Figure 28:Project schematics for femur stem walking, going upstairs, going downstairs, standing up and sitting down realistic loading condition









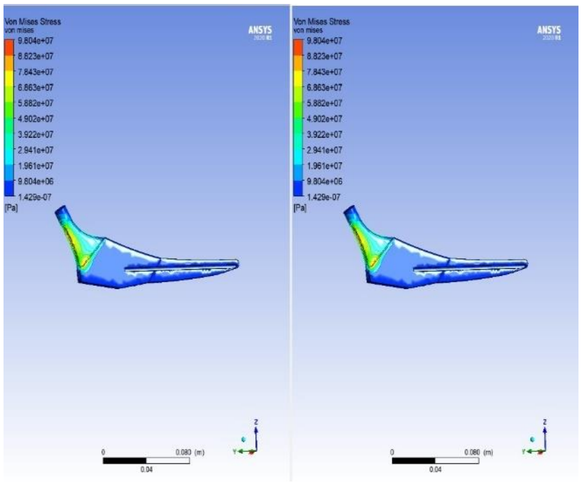
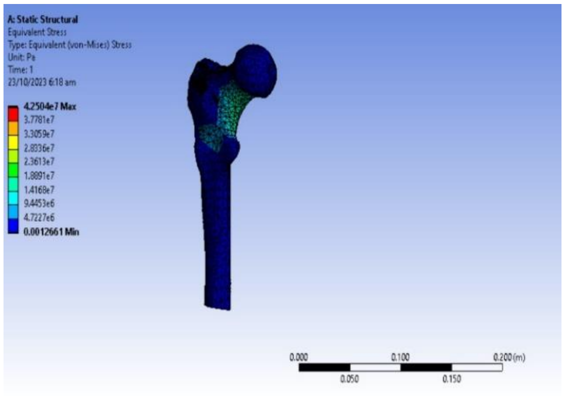
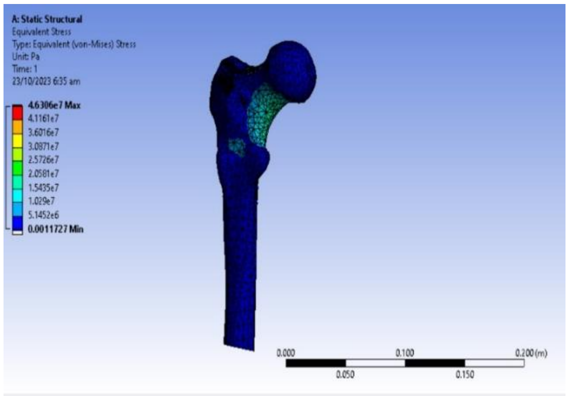


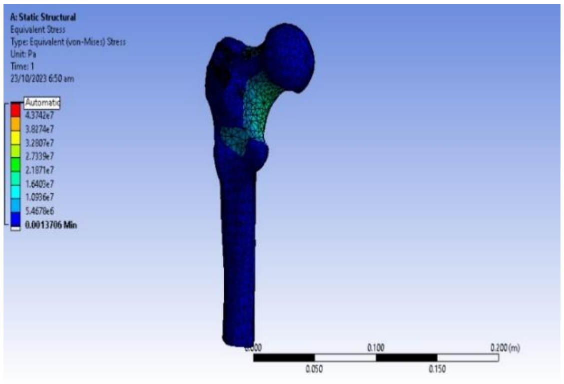
Figure 29:Comparision of Titanium alloy with 3D star honeycomb auxetic structure on the same level of Von-Misis stress for A. Walking: The peak force applied during walking, a common daily activity, is crucial for assessing the implant's performance in supporting the body weight and facilitating smooth movement. B. Going Upstairs: Ascending stairs imposes unique demands on the hip joint, requiring the femur stem to withstand increased forces as the body elevates with each step. C. Going Downstairs: Descending stairs involves a different set of forces compared to ascending, with the femur stem experiencing loads as the body lowers with each step downwards. D. Standing Up: The peak force during standing up from a seated position represents the initial load placed on the femur stem as the individual transitions from a seated to a standing position. E. Sitting Down: Conversely, the peak force during sitting down reflects the load experienced by the femur stem as the individual lowers into a seated position, providing insight into its ability to support the body during weight-bearing activities.

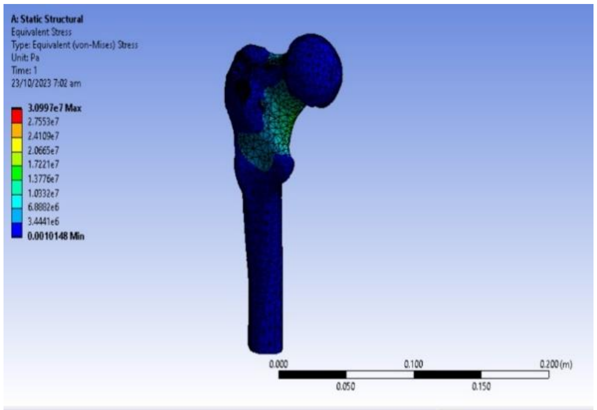
4.1.4. Stress shielding for walking, going upstairs, going downstairs, standing up and sitting down realistic loading condition

4.1.4.1. Stress distribution on intact bone









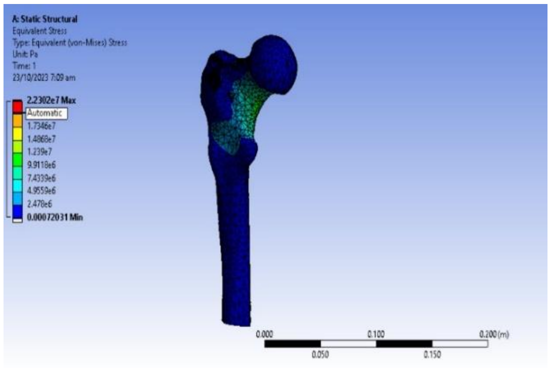
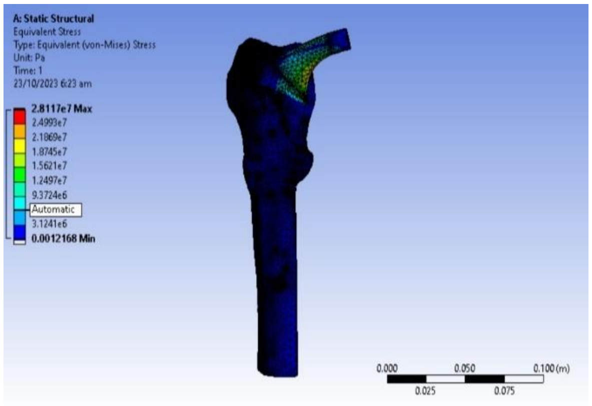
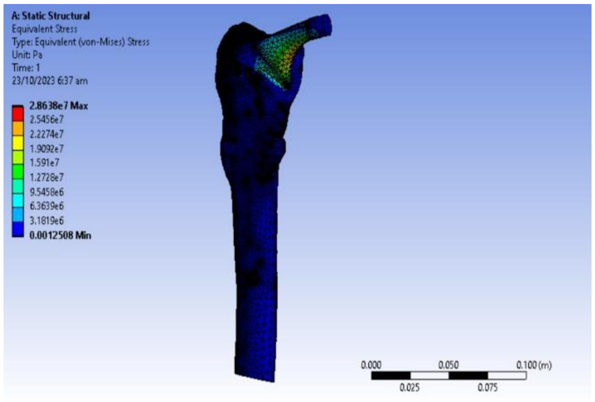
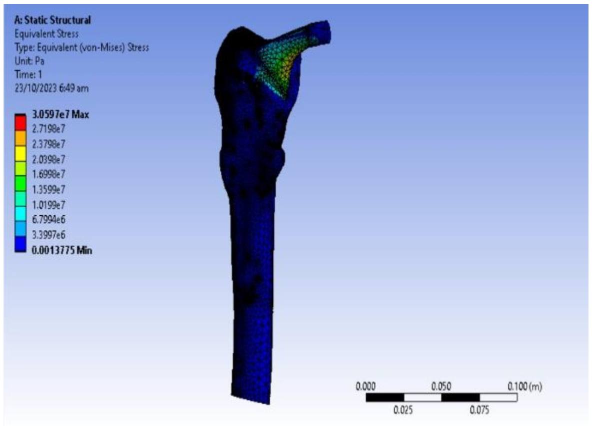


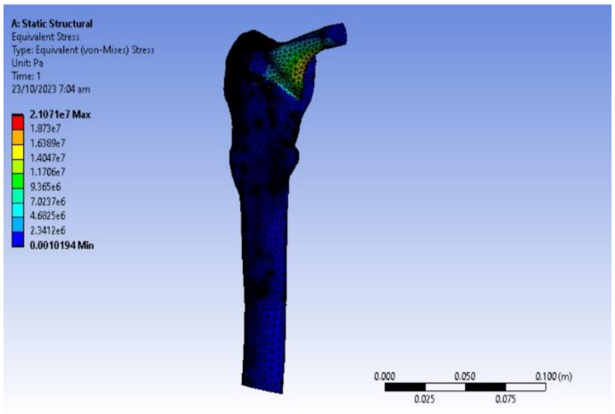
Figure 30: Intact bone Equivalent (Von-Misis) stress A. Walking: The peak force applied during walking, a common daily activity, is crucial for assessing the implant's performance in supporting the body weight and facilitating smooth movement. B. Going Upstairs: Ascending stairs imposes unique demands on the hip joint, requiring the femur stem to withstand increased forces as the body elevates with each step. C. Going Downstairs: Descending stairs involves a different set of forces compared to ascending, with the femur stem experiencing loads as the body lowers with each step downwards. D. Standing Up: The peak force during standing up from a seated position represents the initial load placed on the femur stem as the individual transitions from a seated to a standing position. E. Sitting Down: Conversely, the peak force during sitting down reflects the load experienced by the femur stem as the individual lowers into a seated position, providing insight into its ability to support the body during weight-bearing activities.

4.1.4.2. Stress distribution on bone femur stem implant









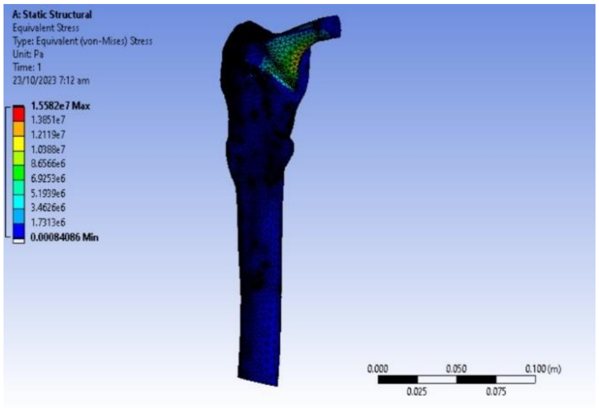


Figure 31:Equivalent (Von Misis) stress of implanted femur in bone A. Walking: The peak force applied during walking, a common daily activity, is crucial for assessing the implant's performance in supporting the body weight and facilitating smooth movement. B. Going Upstairs: Ascending stairs imposes unique demands on the hip joint, requiring the femur stem to withstand increased forces as the body elevates with each step. C. Going Downstairs: Descending stairs involves a different set of forces compared to ascending, with the femur stem experiencing loads as the body lowers with each step downwards. D. Standing Up: The peak force during standing up from a seated position represents the initial load placed on the femur stem as the individual transitions from a seated to a standing position. E. Sitting Down: Conversely, the peak force during sitting down reflects the load experienced by the femur stem as the individual lowers into a seated position, providing insight into its ability to support the body during weight-bearing activities.

4.2. DISCUSSION

The optimized femur stem, utilizing 3D star honeycomb material and Ti-6Al-4V alloy sourced from ZIMMER company, exhibited superior biomechanical performance across five realistic loading conditions compared to conventional designs. When compared with patient-specific data from Samaritan Surgical Center, the optimized stem demonstrated a marked reduction in stress shielding and biomechanical behavior more closely aligned with intact bone. These findings corroborate the initial hypothesis, suggesting that innovative design and material selection can effectively reduce stress shielding and enhance the overall biomechanical compatibility of femur stems under realistic loading conditions.

Table 7: Tabular data for Walking realistic loading condition.

	Walking condition	Geometric Parameters (α,			Poisson's ratios			Equivalent (Von-Misis) stress in Mpa.	Deformation
		α	β	γ	v_{xy}	v_{yz}	v_{xz}		
	case 1	0.9599	0.04	0.8	-0.705	-0.325	0.69	123.05	1.3678
3D Star Honeycomb	case 2	0.9599	0.04	0.9	-0.69	-0.315	-0.705	109.18	
	case 3	0.9599	0.06	0.8	-0.7	-0.36	-0.715	110.53	1.3939
	case 4	0.9599	0.06	0.9	-0.69	-0.32	-0.705	109.29	1.3745
	case 5	1.0472	0.02	0.8	-0.461	-0.1465	-0.46	102.13	1.2886
	case 6	1.0472	0.06	0.9	-0.485	-0.1355	-0.5	102.16	1.2832
	case 7	1.1345	0.02	0.8	-0.3415	-0.0535	-0.335	101.64	1.2405
	case 8	1.1345	0.04	0.8	-0.244	-0.035	-0.255	101.47	1.2302
	case 9	1.1345	0.04	0.9	-0.269	-0.0387	-0.2715	101.5	1.2294
	case 10	1.1345	0.06	0.8	-0.2575	−0.0333	−0.255	101.46	
	case 11	1.309	0.02	0.8	0.095	-0.01	0.092	100.94	1.2123
	case 12	1.309	0.02	0.9	0.1185	-0.0093	0.1165	100.91	
	case 13	1.309	0.04	0.8	0.1695	−0.0083	0.1675	100.85	1.21
	case 14	1.309	0.06	0.8	0.1665	-0.1015	0.1695	101.14	1.2583
	case 15	1.309	0.06	0.9	0.167	-0.015	0.1655	101.14	1.2584
	case 16	1.3963	0.02	0.8	0.2735	0	0.306	100.67	1.2029
	case 17	1.3963	0.02	0.9	0.2735	-0.04	0.306	100.79	1.2239
	case 18	1.3963	0.04	0.9	0.377	-0.06	0.3665	100.78	1.2323
	case 19	1.3963	0.06	0.8	0.335	-0.05	0.385	100.74	1.2274
	case 20	1.4835	0.02	0.8	0.5	0.1535	0.5	99.951	1.1136
	case 21	1.4835	0.02	0.9	0.3665	-0.1165	0.435	102.85	1.2607
	case 22	1.4835	0.04	0.8	0.485	-0.131	0.487	104.02	
	Zimmer's Titanium Alloy				0.3			100.52	

Table 8:Tabular data for Going upstairs realistic loading condition.

	Going up stairs	**Geometric Parameters (α, β, γ)**			**Poisson's ratios**			**Equivalent (Von-Misis) stress in Mpa.**
		α	**β**	**γ**	v_{xy}	v_{yz}	v_{xz}	
	case 1	0.9599	0.04	0.8	-0.705	-0.325	0.69	188.3
3D Star Honeycomb	case 2	0.9599	0.04	0.9	-0.69	-0.315	-0.705	159.7
	case 3	0.9599	0.06	0.8	-0.7	-0.36	-0.715	173.56
	case 4	0.9599	0.06	0.9	-0.69	-0.32	-0.705	172.04
	case 5	1.0472	0.02	0.8	-0.461	-0.1465	-0.46	160.6
	case 6	1.0472	0.06	0.9	-0.485	-0.1355	-0.5	160.76
	case 7	1.1345	0.02	0.8	-0.3415	-0.0535	-0.335	159.99
	case 8	1.1345	0.04	0.8	-0.244	-0.035	-0.255	159.71
	case 9	1.1345	0.04	0.9	-0.269	-0.0387	-0.2715	159.77
	case 10	1.1345	0.06	0.8	-0.2575	−0.0333	−0.255	159.73
	case 11	1.309	0.02	0.8	0.095	-0.01	0.092	158.83
	case 12	1.309	0.02	0.9	0.1185	-0.0093	0.1165	158.78
	case 13	1.309	0.04	0.8	0.1695	−0.0083	0.1675	158.67
	case 14	1.309	0.06	0.8	0.1665	-0.1015	0.1695	159.03
	case 15	1.309	0.06	0.9	0.167	-0.015	0.1655	158.7
	case 16	1.3963	0.02	0.8	0.2735	0	0.306	158.37
	case 17	1.3963	0.02	0.9	0.2735	-0.04	0.306	158.53
	case 18	1.3963	0.04	0.9	0.377	-0.06	0.3665	158.48
	case 19	1.3963	0.06	0.8	0.335	-0.05	0.385	158.42
	case 20	1.4835	0.02	0.8	0.5	0.1535	0.5	157.37
	case 21	1.4835	0.02	0.9	0.3665	-0.1165	0.435	158.58
	case 22	1.4835	0.04	0.8	0.485	-0.131	0.487	159.39
	Zimmer's Titanium Alloy	0.3						158.03

Table 9:Tabular data for Going downstairs realistic loading condition.

	Going downstairs condition	**Geometric Parameters (α, β, γ)**			**Poisson's ratios**			**Equivalent (Von-Misis) stress in Mpa.**
		α	**β**	**γ**	v_{xy}	v_{yz}	v_{xz}	
	case 1	0.9599	0.04	0.8	-0.705	-0.325	0.69	113.33
3D Star Honeycomb	case 2	0.9599	0.04	0.9	-0.69	-0.315	-0.705	112.92
	case 3	0.9599	0.06	0.8	-0.7	-0.36	-0.715	114.21
	case 4	0.9599	0.06	0.9	-0.69	-0.32	-0.705	113.02
	case 5	1.0472	0.02	0.8	-0.461	-0.1465	-0.46	106.67
	case 6	1.0472	0.06	0.9	-0.485	-0.1355	-0.5	106.7
	case 7	1.1345	0.02	0.8	-0.3415	-0.0535	-0.335	106.15
	case 8	1.1345	0.04	0.8	-0.244	-0.035	-0.255	105.96
	case 9	1.1345	0.04	0.9	-0.269	-0.0387	-0.2715	106
	case 10	1.1345	0.06	0.8	-0.2575	−0.0333	−0.255	105.96
	case 11	1.309	0.02	0.8	0.095	-0.01	0.092	105.39
	case 12	1.309	0.02	0.9	0.1185	-0.0093	0.1165	105.36
	case 13	1.309	0.04	0.8	0.1695	−0.0083	0.1675	105.29
	case 14	1.309	0.06	0.8	0.1665	-0.1015	0.1695	105.29
	case 15	1.309	0.06	0.9	0.167	-0.015	0.1655	105.31
	case 16	1.3963	0.02	0.8	0.2735	0	0.306	105.09
	case 17	1.3963	0.02	0.9	0.2735	-0.04	0.306	105.22
	case 18	1.3963	0.04	0.9	0.377	-0.06	0.3665	105.2
	case 19	1.3963	0.06	0.8	0.335	-0.05	0.385	105.16
	case 20	1.4835	0.02	0.8	0.5	0.1535	0.5	104.3
	case 21	1.4835	0.02	0.9	0.3665	-0.1165	0.435	105.74
	case 22	1.4835	0.04	0.8	0.485	-0.131	0.487	106.94
	Zimmer's Titanium Alloy				0.3			104.9

Table 10:Tabular data for standing up realistic loading condition.

	Standing up condition	**Geometric Parameters (α,**			**Poisson's ratios**			**Equivalent (Von-Misis) stress in Mpa.**
		α	**β**	**γ**	v_{xy}	v_{yz}	v_{xz}	
	case 1	0.9599	0.04	0.8	-0.705	-0.325	0.69	118
3D Star Honeycomb	case 2	0.9599	0.04	0.9	-0.69	-0.315	-0.705	104.21
	case 3	0.9599	0.06	0.8	-0.7	-0.36	-0.715	105.57
	case 4	0.9599	0.06	0.9	-0.69	-0.32	-0.705	104.33
	case 5	1.0472	0.02	0.8	-0.461	-0.1465	-0.46	97.69
	case 6	1.0472	0.06	0.9	-0.485	-0.1355	-0.5	97.715
	case 7	1.1345	0.02	0.8	-0.3415	-0.0535	-0.335	97.198
	case 8	1.1345	0.04	0.8	-0.244	-0.035	-0.255	97.024
	case 9	1.1345	0.04	0.9	-0.269	-0.0387	-0.2715	97.064
	case 10	1.1345	0.06	0.8	-0.2575	−0.0333	−0.255	97.024
	case 11	1.309	0.02	0.8	0.095	-0.01	0.092	96.531
	case 12	1.309	0.02	0.9	0.1185	-0.0093	0.1165	96.502
	case 13	1.309	0.04	0.8	0.1695	−0.0083	0.1675	96.433
	case 14	1.309	0.06	0.8	0.1665	-0.1015	0.1695	96.74
	case 15	1.309	0.06	0.9	0.167	-0.015	0.1655	96.467
	case 16	1.3963	0.02	0.8	0.2735	0	0.306	96.27
	case 17	1.3963	0.02	0.9	0.2735	-0.04	0.306	96.399
	case 18	1.3963	0.04	0.9	0.377	-0.06	0.3665	96.395
	case 19	1.3963	0.06	0.8	0.335	-0.05	0.385	96.35
	case 20	1.4835	0.02	0.8	0.5	0.1535	0.5	95.5
	case 21	1.4835	0.02	0.9	0.3665	-0.1165	0.435	98.608
	case 22	1.4835	0.04	0.8	0.485	-0.131	0.487	99.74
	Zimmer's Titanium Alloy				0.3			96.134

Table 11:Tabular data for Sitting down condition realistic loading condition.

	sitting down condition	**Geometric Parameters (α, β, γ)**			**Poisson's ratios (v)**			**Equivalent (Von-Misis) stress in Mpa.**
		α	**β**	**γ**	v_{xy}	v_{yz}	v_{xz}	
	case 1	0.96	0.04	0.8	-0.705	-0.325	0.69	97.056
3D Star Honeycomb	case 2	0.96	0.04	0.9	-0.69	-0.315	-0.705	86.088
	case 3	0.96	0.06	0.8	-0.7	-0.36	-0.715	87.146
	case 4	0.96	0.06	0.9	-0.69	-0.32	-0.705	86.172
	case 5	1.047	0.02	0.8	-0.461	-0.1465	-0.46	82.437
	case 6	1.047	0.06	0.9	-0.485	-0.1355	-0.5	82.462
	case 7	1.135	0.02	0.8	-0.3415	-0.0535	-0.335	82.002
	case 8	1.135	0.04	0.8	-0.244	-0.035	-0.255	81.851
	case 9	1.135	0.04	0.9	-0.269	-0.0387	-0.2715	81.649
	case 10	1.135	0.06	0.8	-0.2575	−0.0333	−0.255	81.846
	case 11	1.309	0.02	0.8	0.095	-0.01	0.092	81.401
	case 12	1.309	0.02	0.9	0.1185	-0.0093	0.1165	81.375
	case 13	1.309	0.04	0.8	0.1695	−0.0083	0.1675	81.321
	case 14	1.309	0.06	0.8	0.1665	-0.1015	0.1695	81.576
	case 15	1.309	0.06	0.9	0.167	-0.015	0.1655	81.342
	case 16	1.396	0.02	0.8	0.2735	0	0.306	81.166
	case 17	1.396	0.02	0.9	0.2735	-0.04	0.306	81.277
	case 18	1.396	0.04	0.9	0.377	-0.06	0.3665	81.27
	case 19	1.396	0.06	0.8	0.335	-0.05	0.385	81.231
	case 20	1.484	0.02	0.8	0.5	0.1535	0.5	80.5
	case 21	1.484	0.02	0.9	0.3665	-0.1165	0.435	81.907
	case 22	1.484	0.04	0.8	0.485	-0.131	0.487	82.184
	Zimmer's Titanium Alloy				0.3			81

The key finding of the study reveals a significant reduction in stress shielding across five realistic loading conditions: walking (34.16%), going upstairs (38.16%), going downstairs (37.82%), standing up (29.1%), and sitting down (30.13%). The femur stem design features uniform porosity, achieved through the selection of a specific unit cell design applied consistently across the implant's porous areas. This design incorporates open porosity to facilitate bone ingrowth and minimize areas of maximum stress concentration. Compared to most existing studies, which typically achieve a stress shielding reduction of no more than 33%[22, 106-108] and without considering various realistic loading conditions on the femur stem, this optimized design demonstrates superior performance in reducing stress shielding and enhancing biomechanical compatibility.

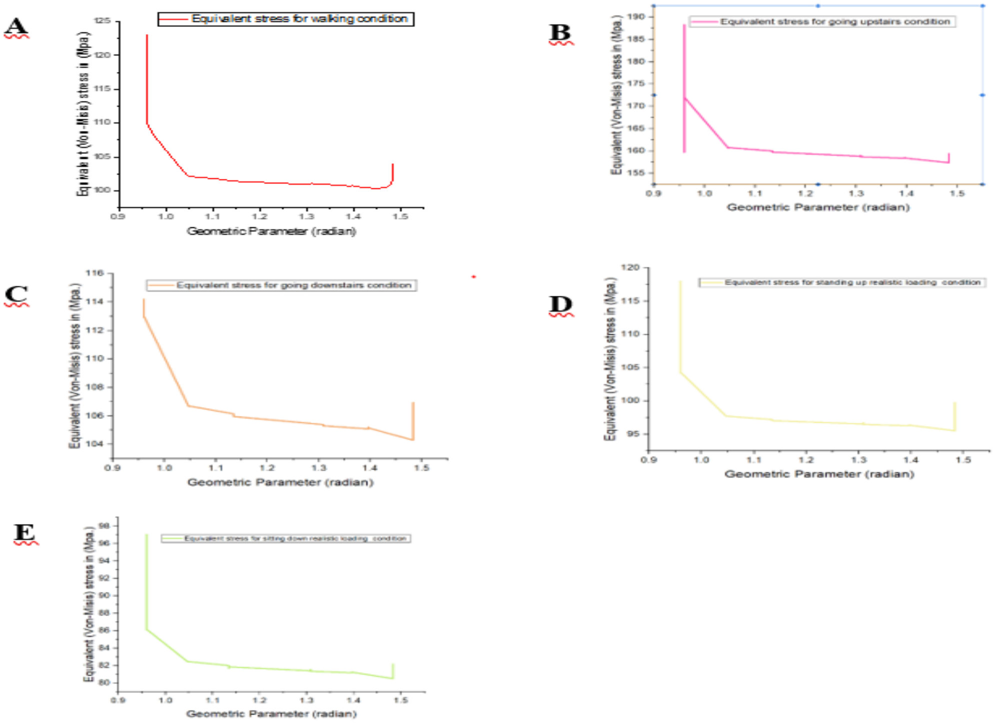


Figure 32:A. Equivalent stress for walking condition B. Equivalent stress for going upstairs condition c. Equivalent stress for going downstairs condition D. Equivalent stress for standing up condition E. Equivalent stress for sitting down condition.

As depicted in Figure 32, the distribution of equivalent stress within the structure exhibits a notable decrease as the geometric parameter α increases from 55 to 85 degrees. Beyond this threshold, however, the trend reverses, with the equivalent stress beginning to increase once more. This observation underscores the intricate relationship between the geometric parameters of the structure and its mechanical response, highlighting the importance of optimizing α within the specified range to achieve desired stress distribution characteristics.

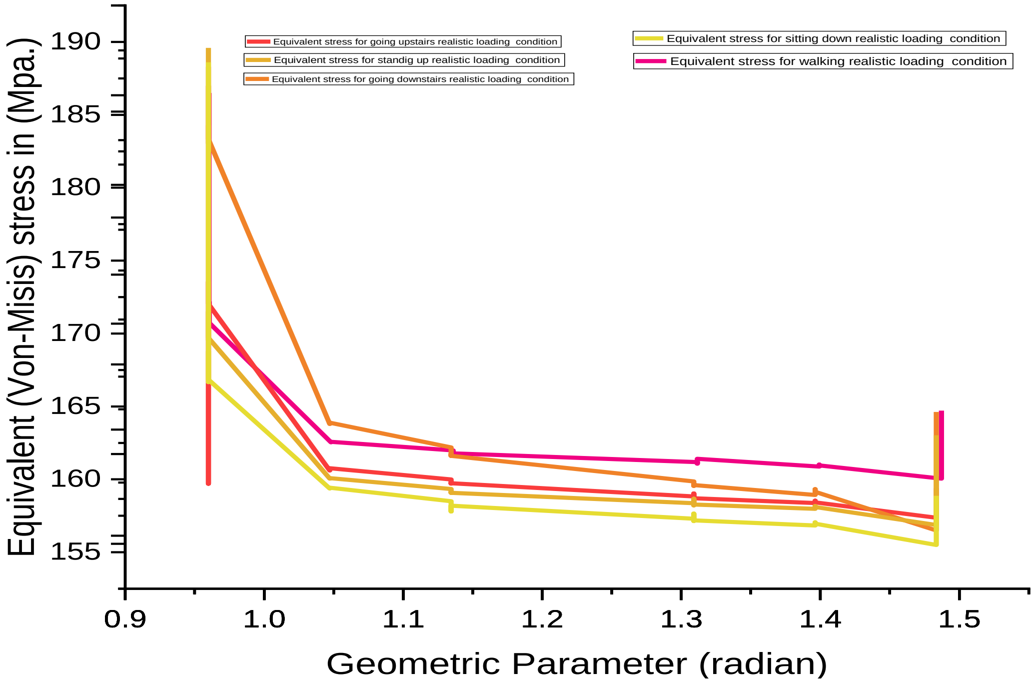


Figure 33:The x-axis is labeled "Geometric Parameter (radian)" and the y-axis is labeled "Equivalent (Von-Mises) stress in (MPa)" for 5 realistic conditions.

In the three-dimensional (3D) model of the star honeycomb unit cell structure, the re-entrant angle, denoted as α, plays a critical role in determining the auxetic properties of the material. Specifically, it has been observed that when the re-entrant angle α is less than 60 degrees, the structure ceases to exhibit expansion characteristic of auxetic behavior. Conversely, when α exceeds 85 degrees, the structure loses its auxetic properties entirely, as illustrated in Figure 53. However, within the range of 60 to 85 degrees for the re-entrant angle α, the material demonstrates the desired auxetic properties, offering potential benefits in terms of mechanical and material properties.

Chapter Five

5. Conclusion And Recommendation

1.1. Conclusion

This paper provides a thorough investigation into optimizing femur stem designs for hip arthroplasty, with a focus on lowering stress shielding (SS) and improving biomechanical performance under actual loading situations. By incorporating an innovative auxetic 3D star honeycomb structure into femur stem design and comparing it to the popularly used Zimmer's femur stem from Samaritan Surgical Center, this study aims to provide significant insights for implant optimization. The results show that using auxetic structures reduced SS around the femoral stem compared to Zimmer's femur stem, especially under actual loading situations like walking, going up stairs, going downstairs, standing up, and sitting down. Furthermore, the study discovered no consistent effect of the re-entrant angle on SS, emphasizing the complexities of biomechanical optimization. These findings provide critical insights into creating auxetic femoral stems with higher survivorship potential than standard solid femoral stems, helping to progress orthopedic surgery procedures and improve patient outcomes in hip arthroplasty. Using modern methodologies and realistic loading circumstances, this comparative analysis emphasizes the necessity of improving implant designs to improve stability and overall patient quality of life post-THA, which will guide future improvements in orthopedic implant design and surgical practice.

1.2. Recommendation

Based on the findings and analysis presented in this research, several recommendations can be made to advance the field of orthopedic implant design and optimization:

1. **Comparison of 3D Star Honeycomb Auxetic Structure with Other Auxetic Structures**: Further comparative studies should be conducted between 3D star honeycomb auxetic structures and other types of auxetic structures. This will help determine which design parameters and structural configurations optimize stress shielding reduction and biomechanical performance in femur stems for total hip arthroplasty. Research can be conducted by integrating insights from materials science, mechanical engineering, and bioengineering for a comprehensive understanding.
2. **Study of Tribological Aspects of Femur Stem with Auxetic Structure**: Research focusing on the tribological aspects of femur stems with auxetic structures is recommended. Investigate wear patterns, frictional characteristics, and lubrication requirements of these implants to ensure long-term durability and performance in clinical settings. Integration of expertise from biomechanics and materials science will be crucial for achieving optimal tribological properties.

3. **Further Study in Biomechanical Compatibility**: Continued biomechanical studies are essential to assess the long-term performance and biomechanical compatibility of femur stems with auxetic structures. Evaluate parameters such as stress distribution, strain patterns, and bone-implant interface mechanics under various loading conditions to optimize implant design. Integration of different fields of study, including biomechanics, materials science, and computational modeling, will lead to a more thorough understanding of biomechanical compatibility.

4. **Study the Cost Aspect of Femur Stem with Auxetic Structure**: Conduct a comprehensive cost analysis comparing femur stems with auxetic structures to traditional solid stems. Assess manufacturing costs, material expenses, and potential savings in surgical procedures and patient recovery to understand the economic feasibility and benefits of adopting auxetic designs. Integration of expertise from economics and biomedical engineering can provide valuable insights into the economic aspects of auxetic implants.

5. **Integration of Different Fields of Studies for Perfect Results**: Research should explore the integration of different fields of study, including materials science, mechanical engineering, bioengineering, biomechanics, and economics, to achieve optimal results in femur stem design with auxetic structures. Collaborative efforts will enhance the understanding of structural optimization, biomechanical performance, tribological aspects, and economic feasibility of these innovative implants.

Implementing these recommendations through the integration of different fields of studies will advance the understanding and application of auxetic structures in orthopedic implants, potentially leading to improved patient outcomes, reduced healthcare costs, and enhanced durability of implants.

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Appendix

1.1. Walking realistic loading condition

1.1.1. Assessing the Performance of Zimmer's Titanium Alloy in Hip Implants walking realistic loading condition: A Data-Driven Study

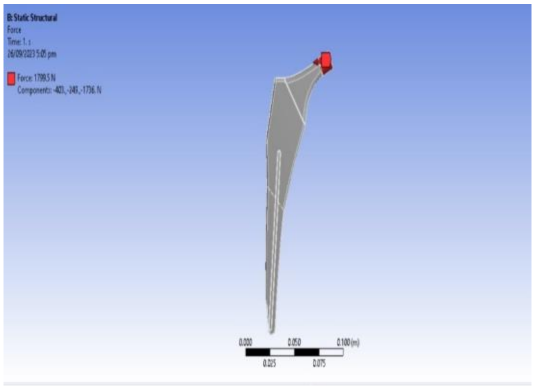


Figure 34:Force in walking realistic loading condition.

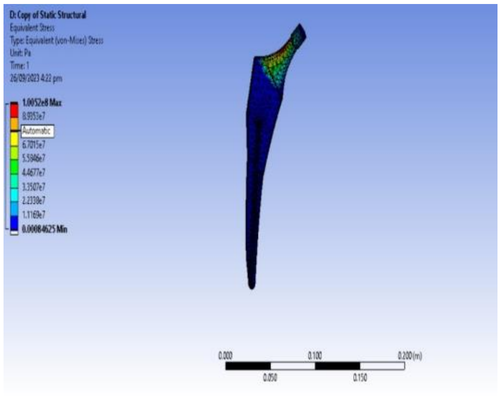


Figure 35:Equivalent (Von-Misis) stress.

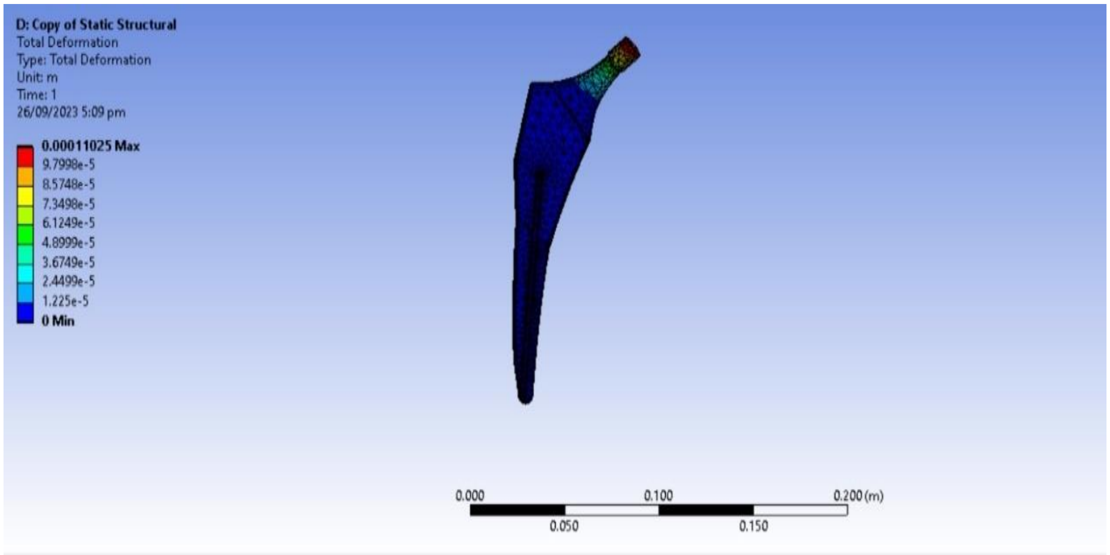


Figure 36:Total deformation.

1.1.2. Assessing the Performance of 3D Star Honeycomb Auxetic Structure in Hip Implants walking realistic loading condition

In this study cases involves varying several shape parameters, including the wall length, cell wall thicknesses, and cellular structure angle, to investigate their impact on the overall structural properties.

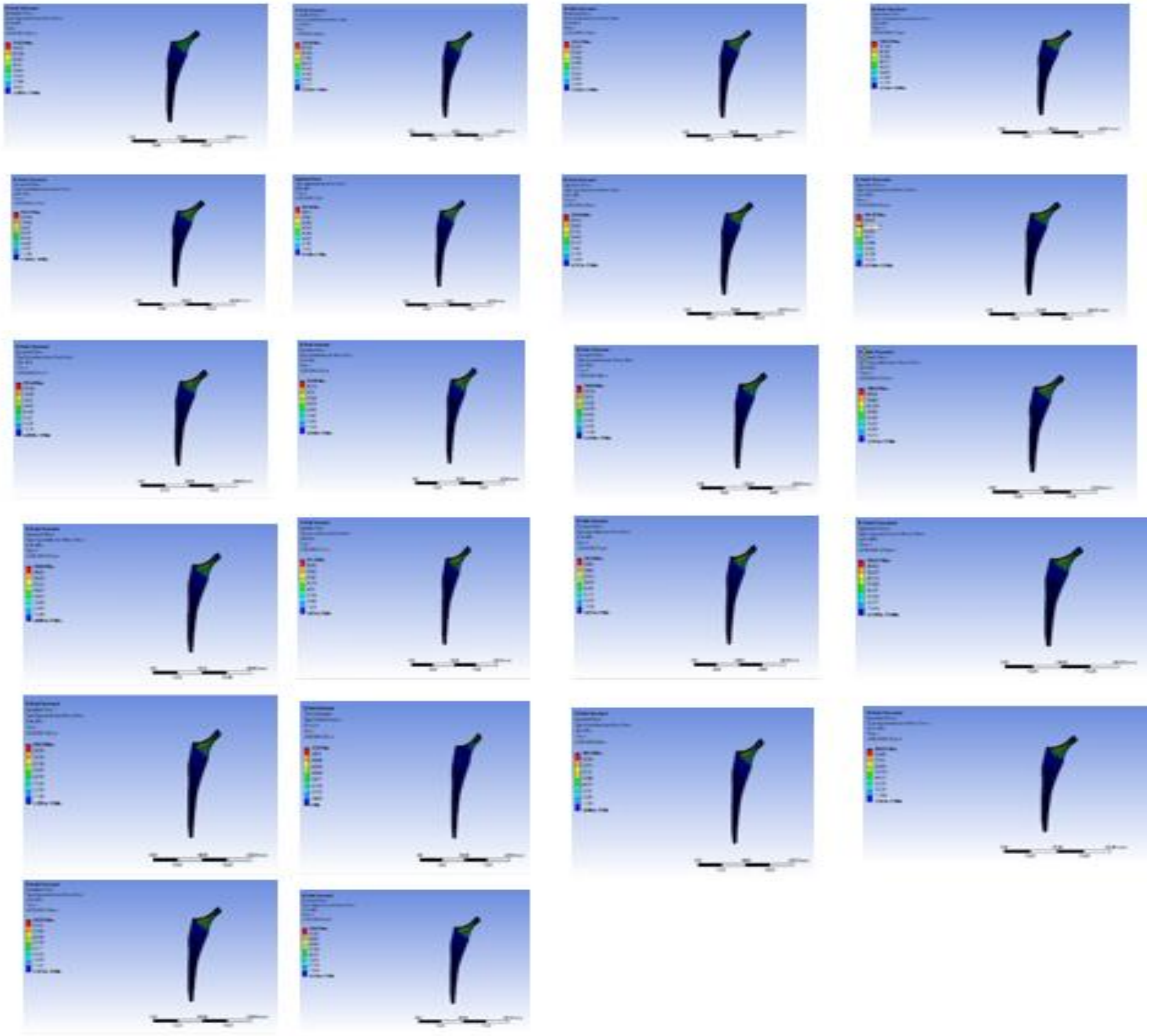


Figure 37:Iteration 3D star honeycombed structure for optimized results in walking realistic loading condition.

1.1.2.1. A Comparative Analysis of Titanium Alloy Hip Implants and 3D Star Honeycomb Auxetic Structures Optimized for Best Geometric Parameters

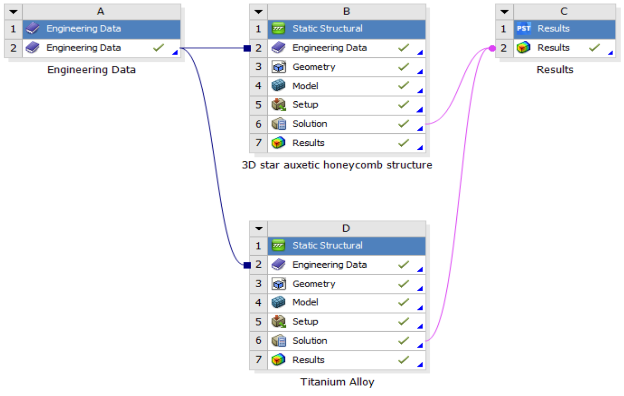


Figure 39:Project schematics for walking realistic loading conditions

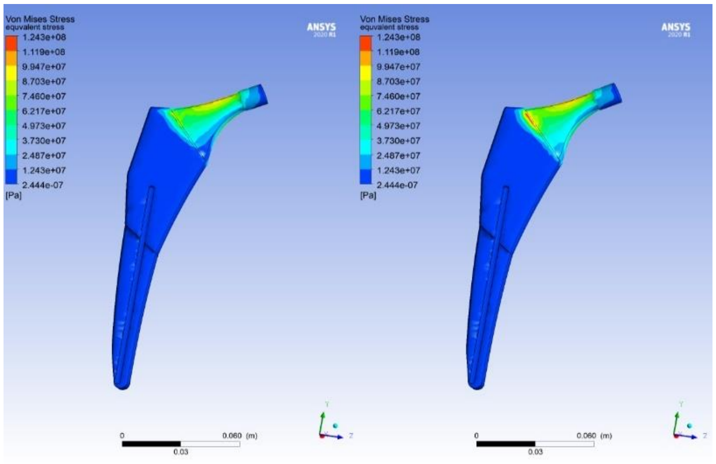


Figure 38:Comparision of Titanium alloy with 3D star honeycomb auxetic structure on the same level of Von-Misis stress.

1.1.2.2. Stress shielding for walking

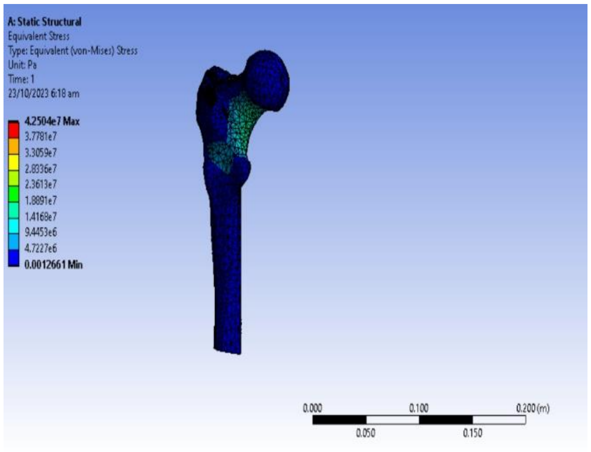


Figure 41:Equivalent (Von-Misis) stress for intact bone in walking realistic loading condition.

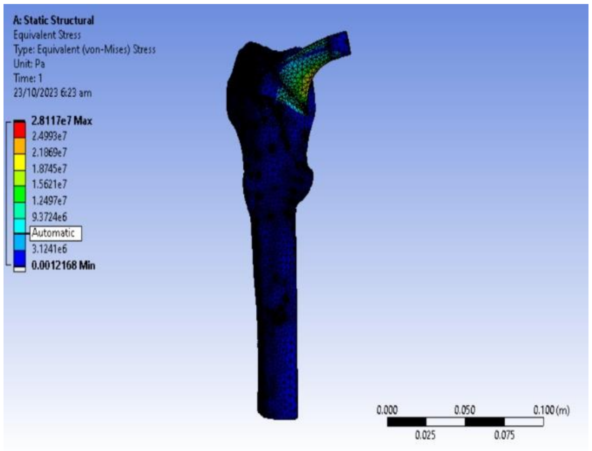


Figure 40:Equivalent (Von-Misis) stress 3D star honeycomb auxetic structure in walking realistic loading condition.

1.2. Going up stairs realistic loading condition

1.2.1. Assessing the Performance of Zimmer's Titanium Alloy in Hip Implants going up stairs realistic loading condition: A Data-Driven Study

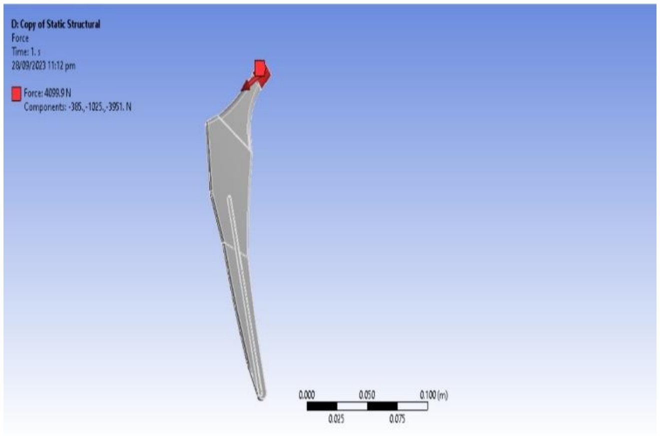


Figure 43:Force going up stairs realistic loading condition.

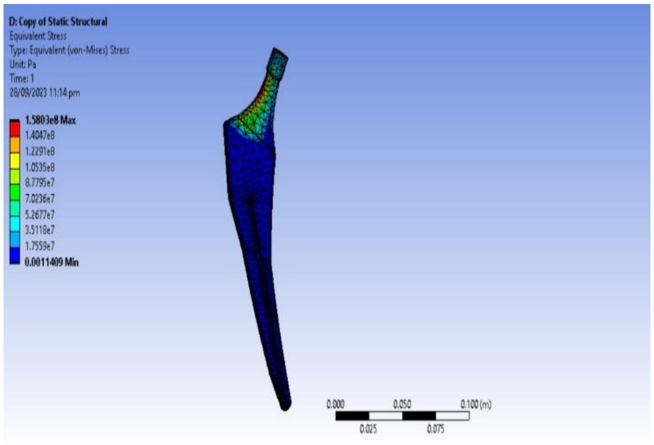


Figure 42:Equivalent (Von-Misis) stress of Zimmer's Titanium Alloy going up stairs realistic loading condition.

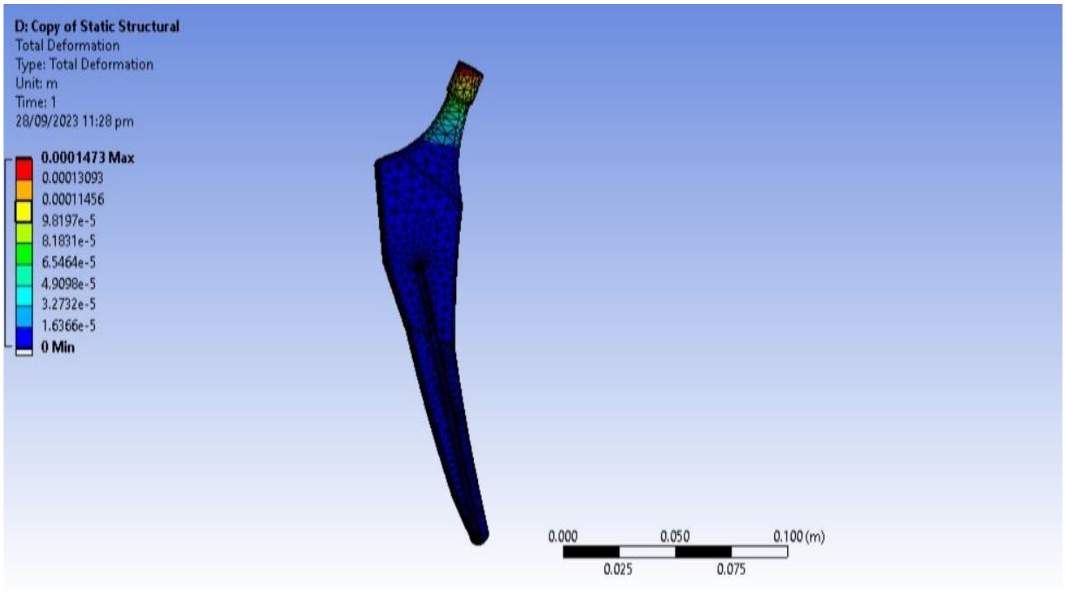


Figure 44:Total Deformation of Zimmer's Titanium Alloy going up stairs realistic loading condition.

1.2.2. Assessing the Performance of 3D Star Honeycomb Auxetic Structure in Hip Implants going up stairs realistic loading condition

Varying several shape parameters, including the wall length, cell wall thicknesses, and cellular structure angle, to investigate their impact on the overall structural properties.

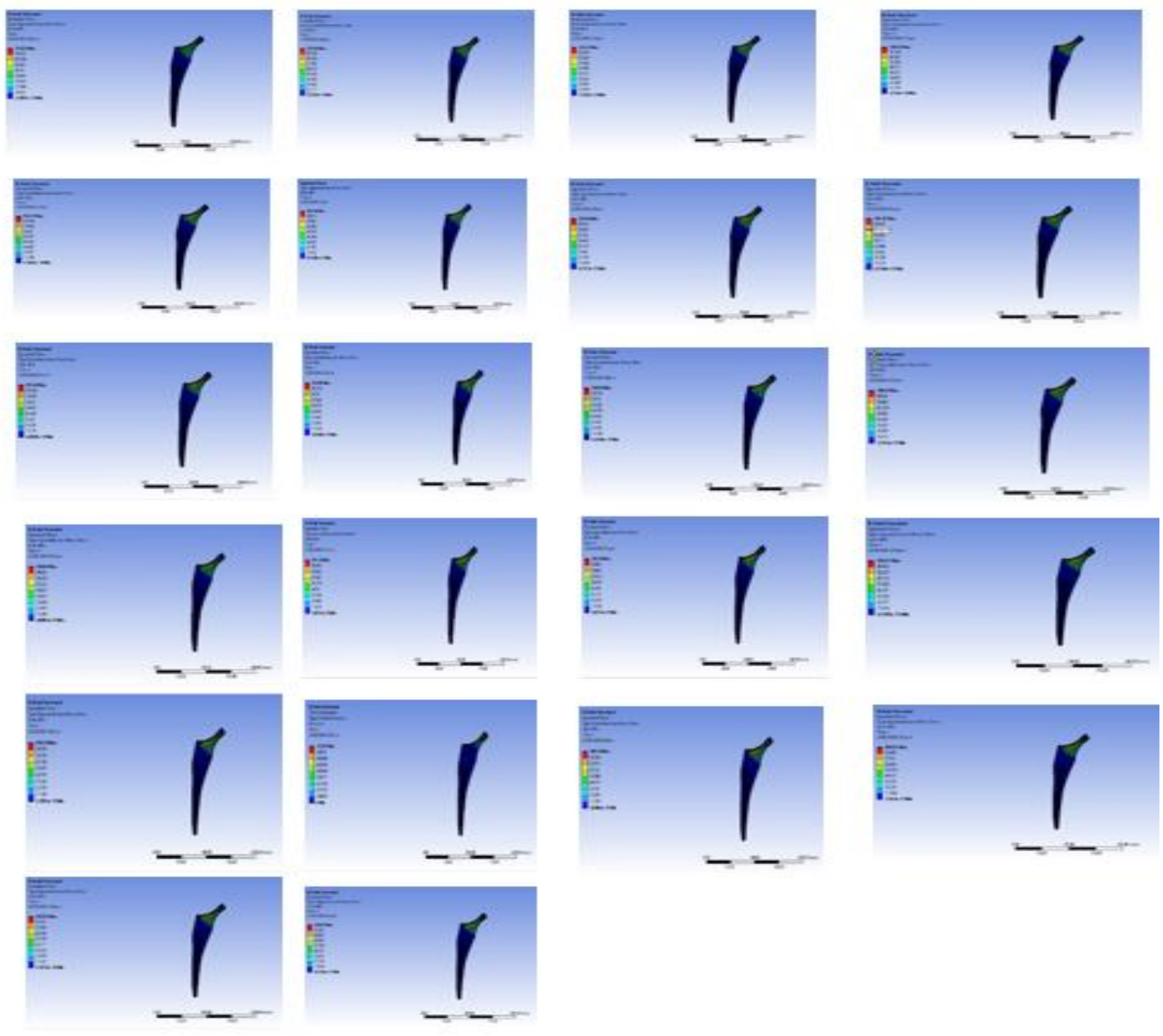
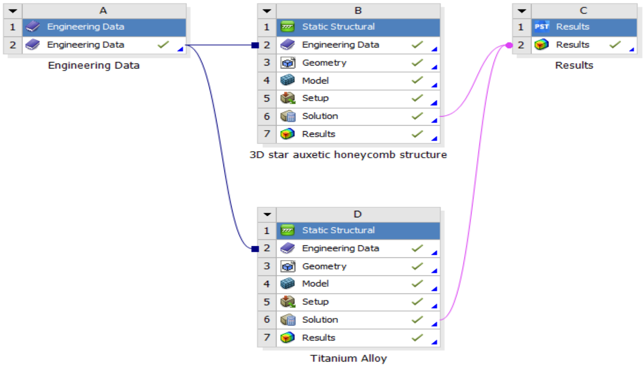


Figure 45:Iteration 3D star honeycombed structure for optimized results in going upstairs realistic loading condition

1.2.2.1. A Comparative Analysis of Titanium Alloy Hip Implants and 3D Star Honeycomb Auxetic Structures going up stair realistic loading conditions Optimized for Best Geometric Parameters



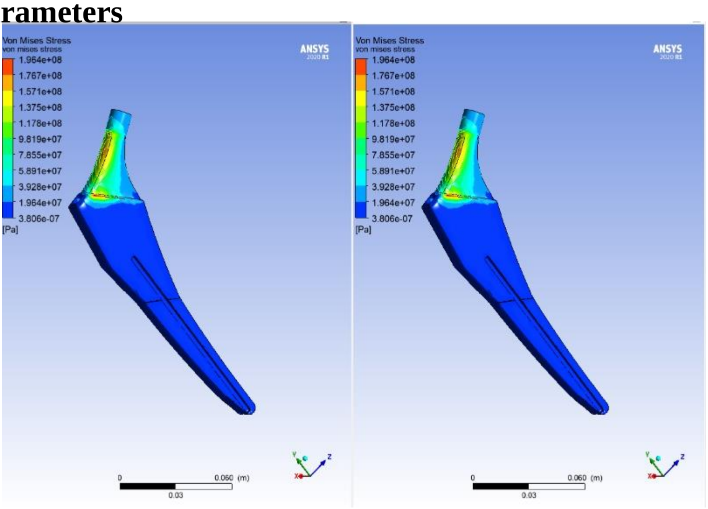


Figure 47:Project schematics for going up stair realistic loading conditionsneycomb auxetic

1.2.2.2. Stress shielding for going up stairs

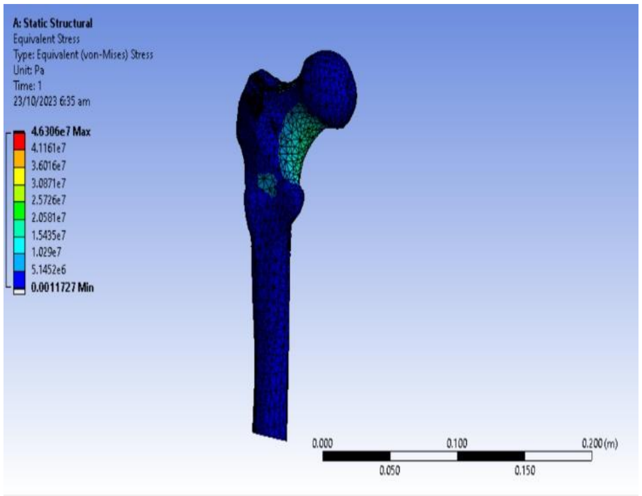


Figure 49:Equivalent (Von-Misis) stress for intact bone in going upstairs realistic loading condition.

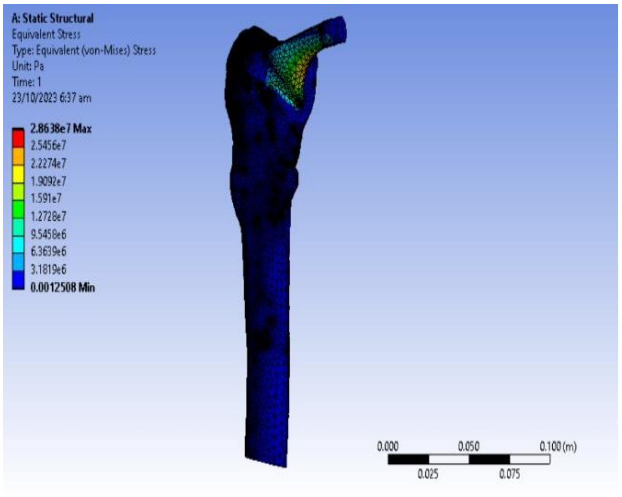


Figure 48:Equivalent (Von-Misis) stress 3D star honeycomb auxetic structure in going upstairs realistic loading condition

1.3. Going down stairs realistic loading condition

1.3.1. Assessing the Performance of Zimmer's Titanium Alloy in Hip Implants Going down stairs realistic loading condition: A Data-Driven Study

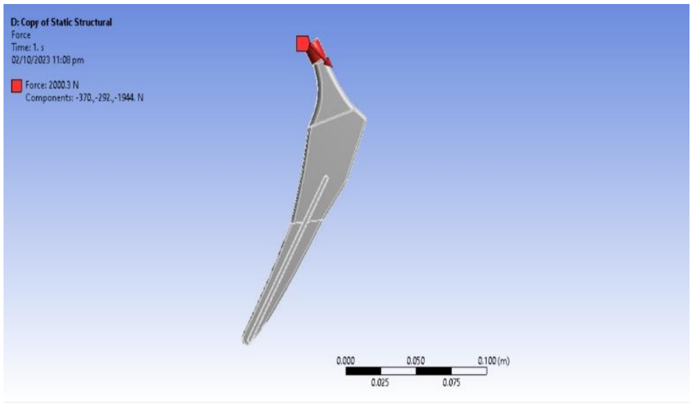


Figure 51:Force on going down stairs realistic loading condition

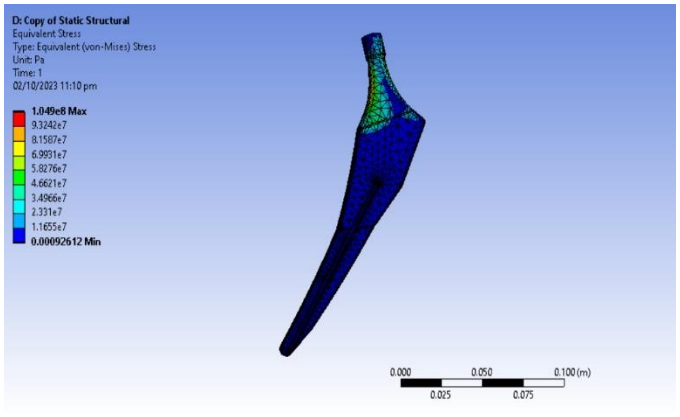


Figure 50:Equivalent (Von-Misis) stress of Zimmer's Titanium Alloy going down stairs realistic loading condition.

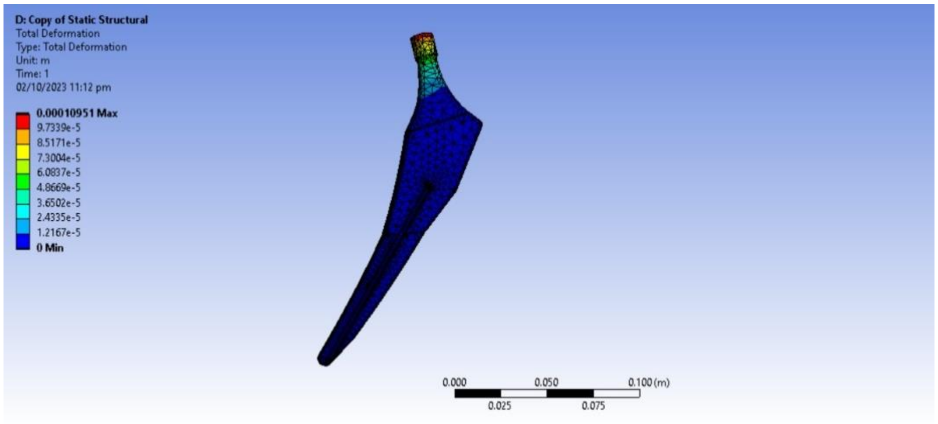


Figure 52:Total Deformation going down stairs realistic loading condition.

1.3.2. Assessing the Performance of 3D Star Honeycomb Auxetic Structure in Hip Implants going down stairs realistic loading condition

Varying several shape parameters, including the wall length, cell wall thicknesses, and cellular structure angle, to investigate their impact on the overall structural properties.

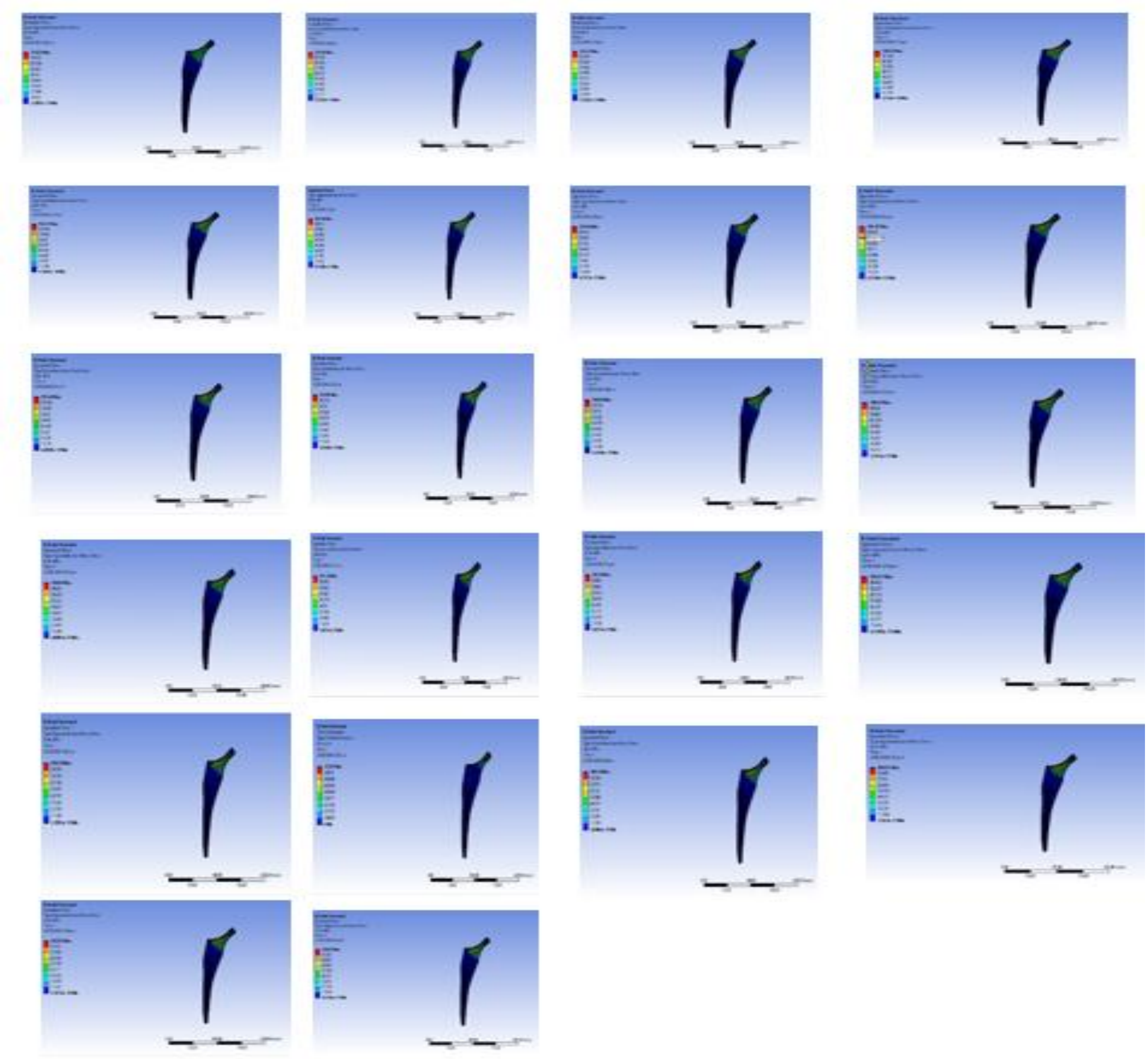
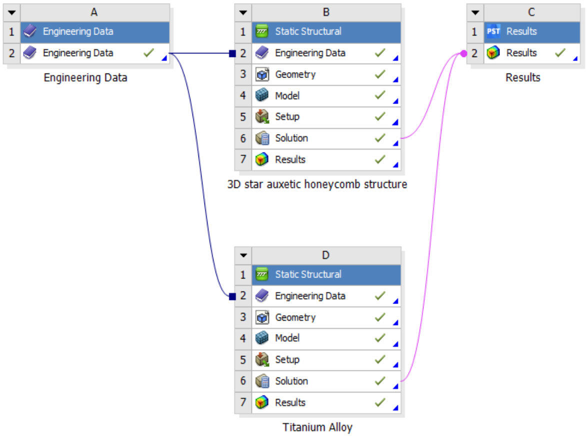


Figure 53::Iteration 3D star honeycombed structure for optimized results in going downstairs realistic loading condition

1.3.2.1. A Comparative Analysis of Titanium Alloy Hip Implants and 3D Star Honeycomb Auxetic Structures going down stair realistic loading conditions Optimized for Best Geometric Parameters.



A
1 Engineering Data
2 Engineering Data ✓
Engineering Data

B
1 Static Structural
2 Engineering Data ✓
3 Geometry ✓
4 Model ✓
5 Setup ✓
6 Solution ✓
7 Results ✓
3D star auxetic honeycomb structure

C
1 Results
2 Results ✓
Results

D
1 Static Structural
2 Engineering Data ✓
3 Geometry ✓
4 Model ✓
5 Setup ✓
6 Solution ✓
7 Results ✓
Titanium Alloy

Figure 55:Project schematics for going down stair realistic loading conditions

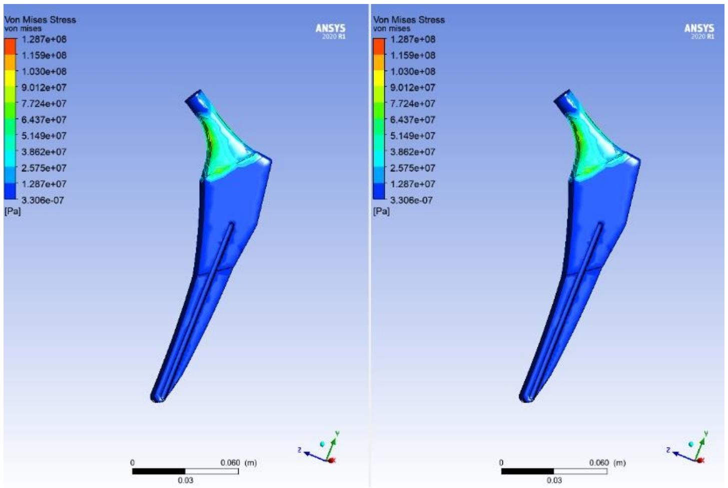


Figure 54:Comparision of Titanium alloy with 3D star honeycomb auxetic structure on the same level of Von-Misis stress for going down stair realistic loading condition.

1.3.2.2. Stress shielding for going up stairs

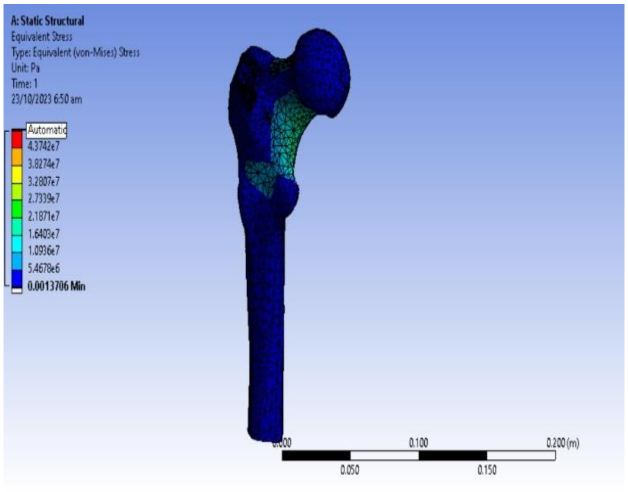


Figure 57:Equivalent (Von-Misis) stress for intact bone in going down stairs realistic loading condition

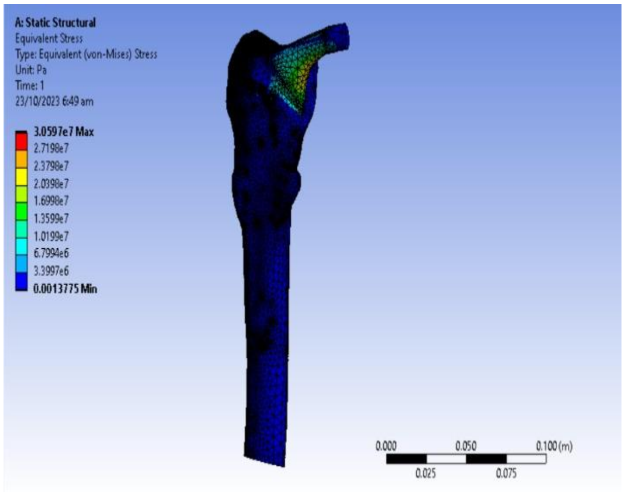


Figure 56Equivalent (Von-Misis) stress 3D star honeycomb auxetic structure in going down stairs realistic loading condition

1.4. Standing up realistic loading condition

1.4.1. Assessing the Performance of Zimmer's Titanium Alloy in Hip Implants standing up realistic loading condition: A Data-Driven Study

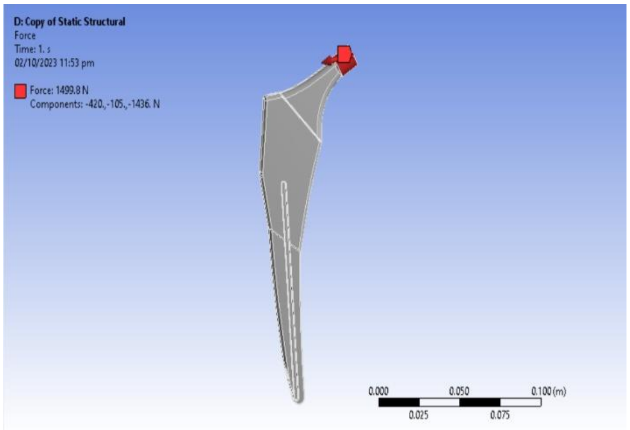


Figure 59:Force on standing up realistic loading condition.

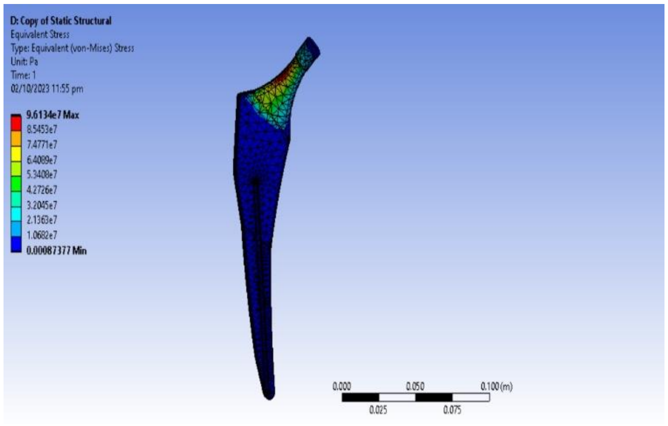


Figure 58:Equivalent (Von-Misis) stress of Zimmer's Titanium Alloy standing up realistic loading condition.

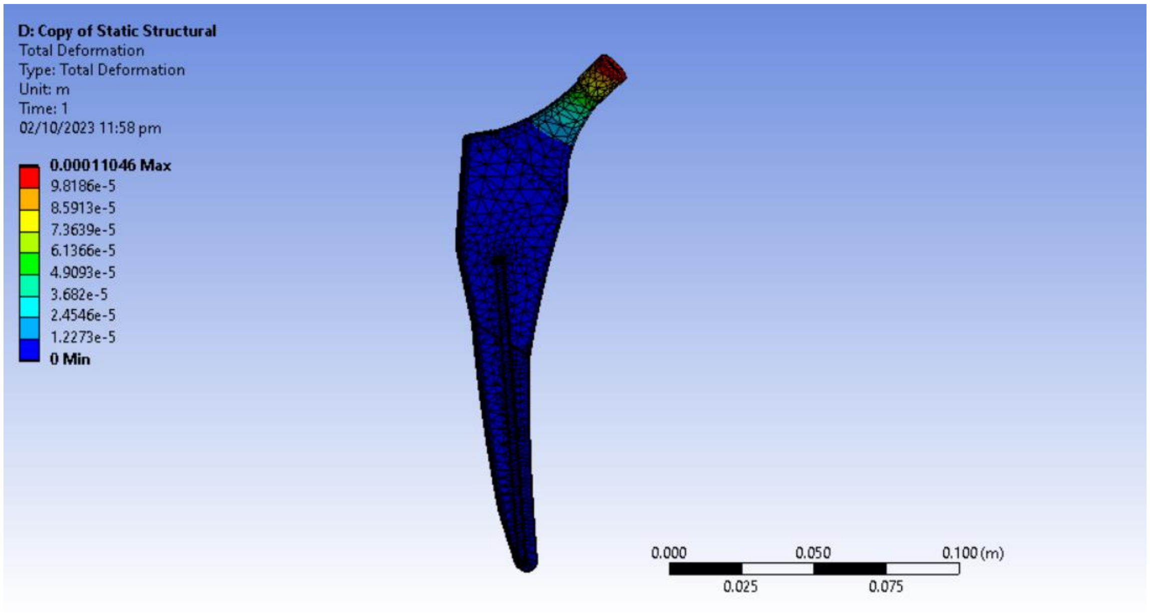


Figure 60:Total Deformation in standing up realistic loading condition.

1.4.2. Assessing the Performance of 3D Star Honeycomb Auxetic Structure in Hip Implants standing up realistic loading condition

varying several shape parameters, including the wall length, cell wall thicknesses, and cellular structure angle, to investigate their impact on the overall structural properties.

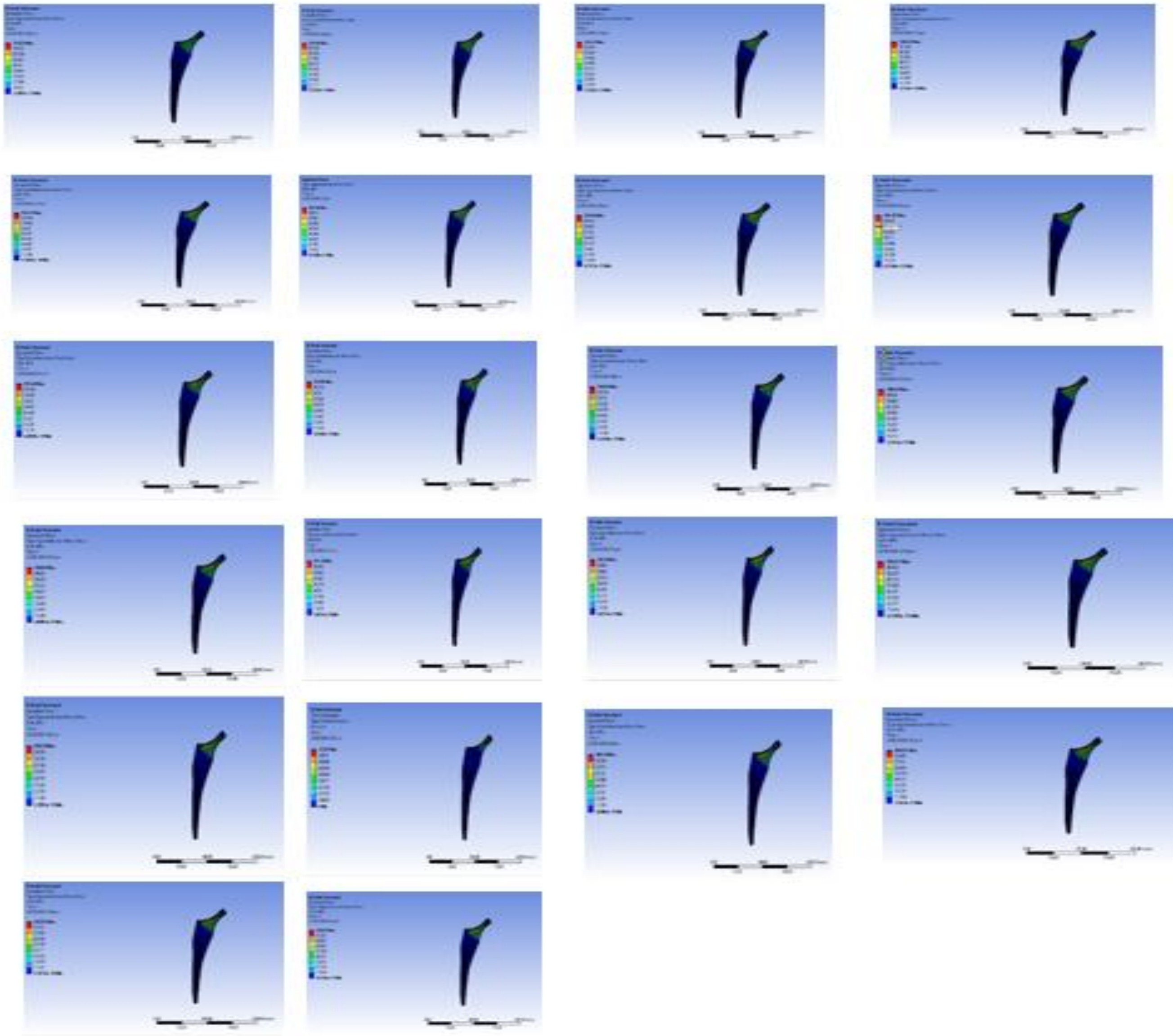


Figure 61Iteration 3D star honeycombed structure for optimized results in standing up realistic loading condition

1.4.2.1. A Comparative Analysis of Titanium Alloy Hip Implants and 3D Star Honeycomb Auxetic Structures standing up realistic loading conditions Optimized for Best Geometric Parameters

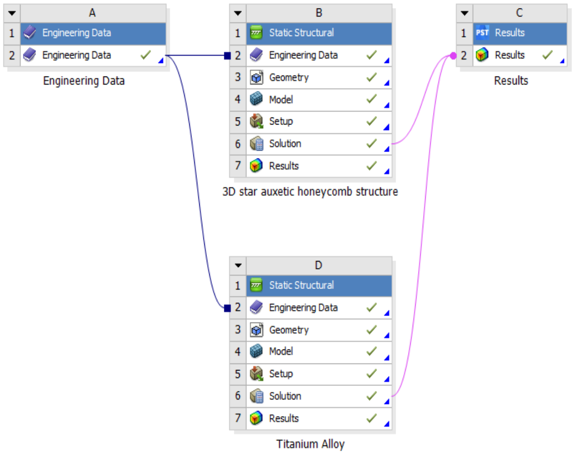


Figure 63:Project schematics for standing up realistic loading conditions.

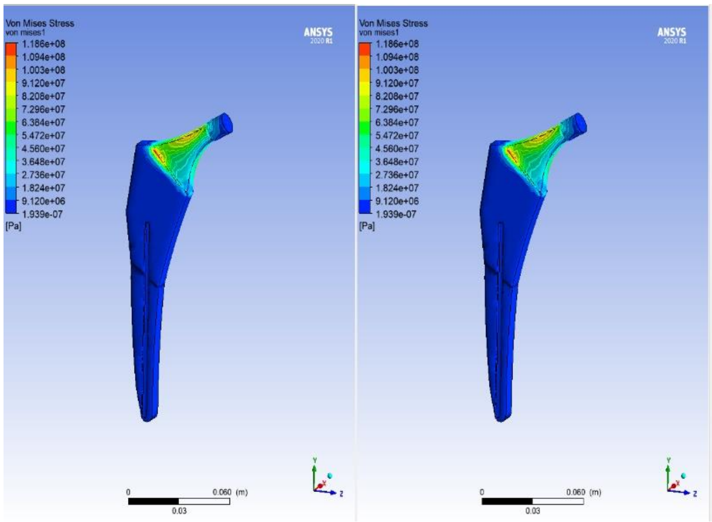


Figure 62:Comparision of Titanium alloy with 3D star honeycomb auxetic structure on the same level of Von-Misis stress for standing up realistic loading condition.

1.4.2.2. Stress shielding for standing up realistic loading condition

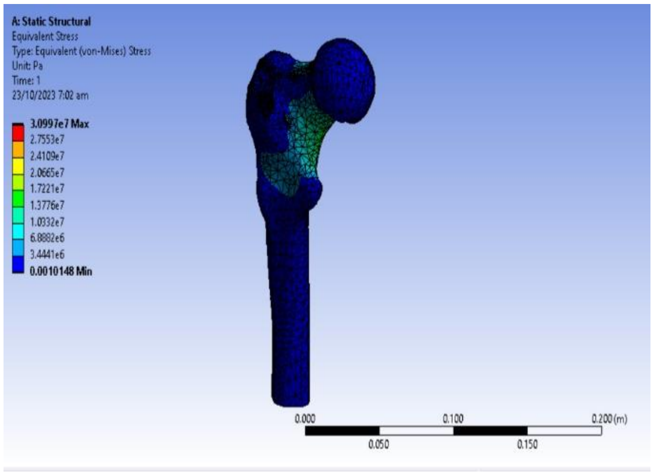


Figure 65:Equivalent (Von-Misis) stress for intact bone in standing up realistic loading condition.

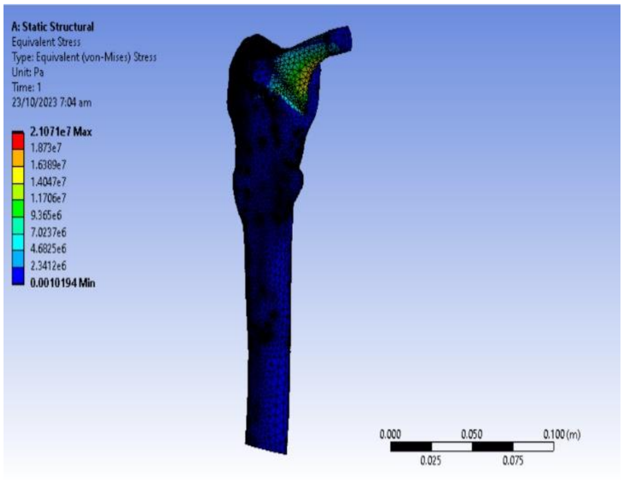
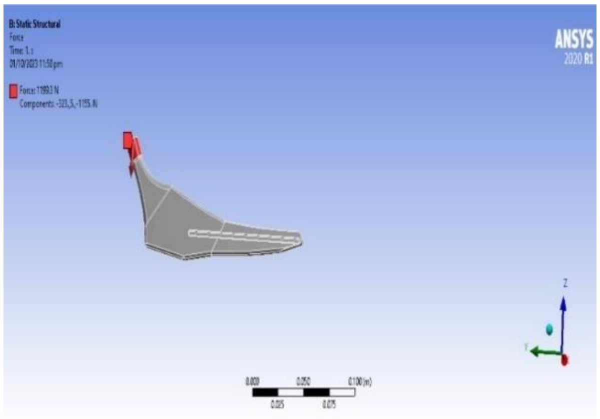


Figure 64:Equivalent (Von-Misis) stress for intact bone in standing up realistic loading condition

1.5. Sitting down realistic loading condition

1.5.1. Assessing the Performance of Zimmer's Titanium Alloy in Hip Implants sitting down realistic loading condition: A Data-Driven Study



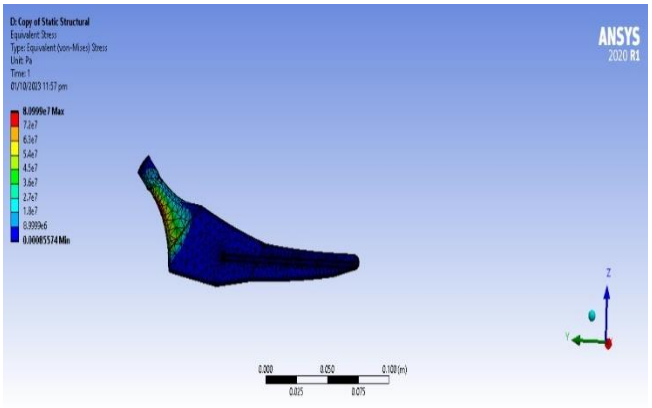


Figure 67:Fo

Figure 66: Equivalent (Von-Misis) stress of Zimmer's Titanium Alloy sitting down realistic loading condition.

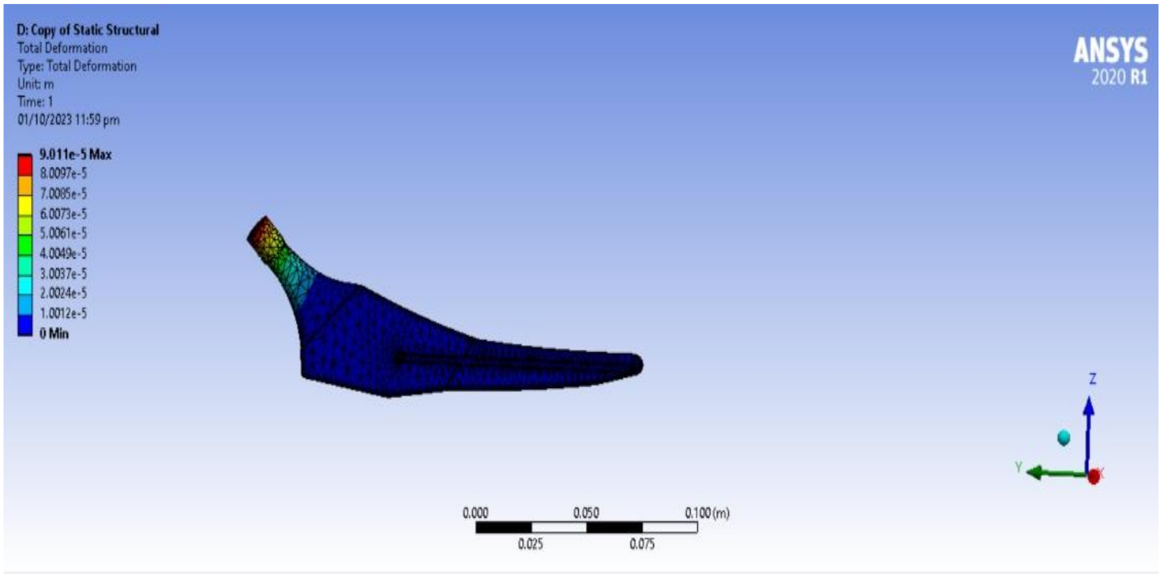


Figure 68:Total Deformation sitting down realistic loading condition.

1.5.2. Assessing the Performance of 3D Star Honeycomb Auxetic Structure in Hip Implants sitting down realistic loading condition.

Varying several shape parameters, including the wall length, cell wall thicknesses, and cellular structure angle, to investigate their impact on the overall structural properties.

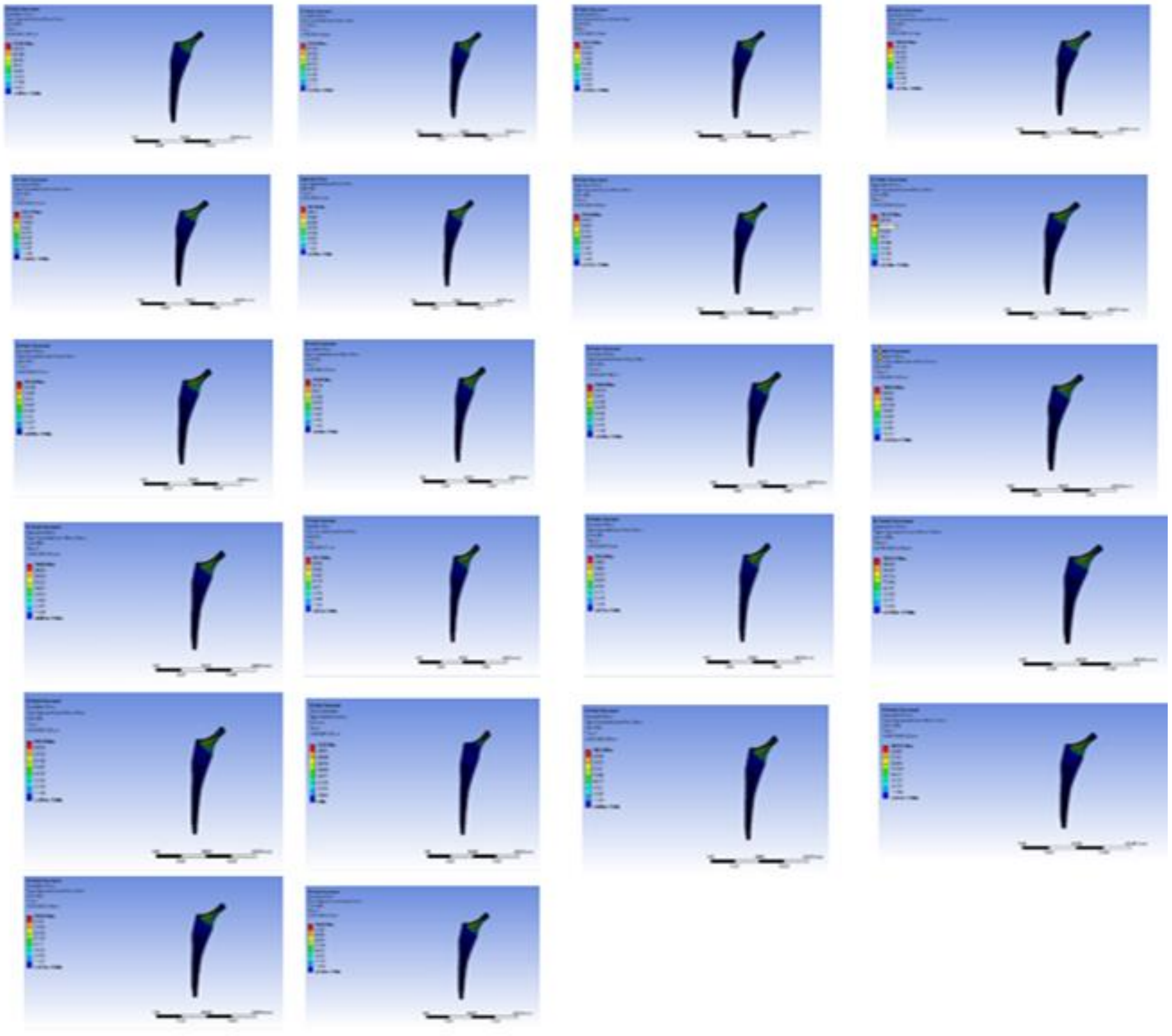


Figure 69:Iteration 3D star honeycombed structure for optimized results in going sitting down realistic loading condition

1.5.2.1. A Comparative Analysis of Titanium Alloy Hip Implants and 3D Star Honeycomb Auxetic Structures sitting down realistic loading conditions Optimized for Best Geometric Parameters

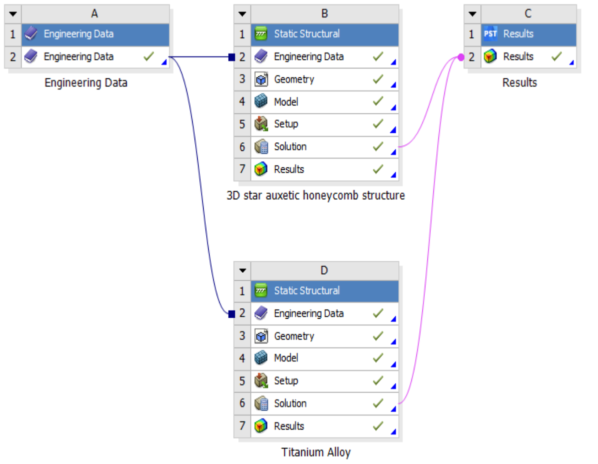


Figure 71:Project schematics for sitting down realistic loading conditions.

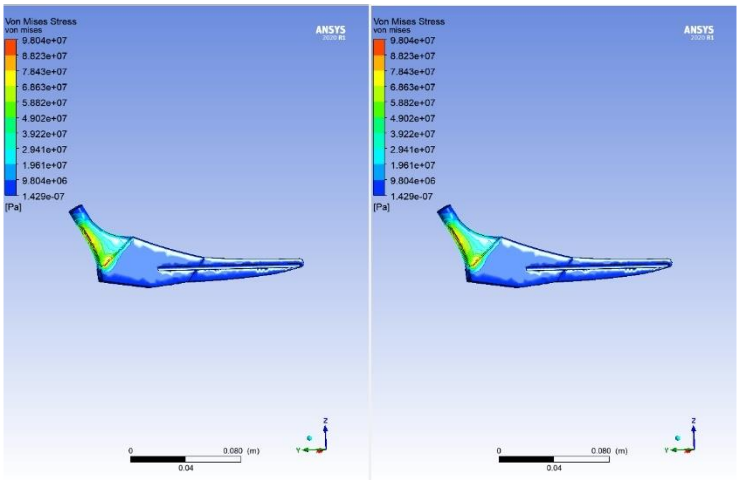


Figure 70:Comparision of Titanium alloy with 3D star honeycomb auxetic structure on the same level of Von-Misis stress for sitting down realistic loading condition.

1.5.2.2. Stress shielding for sitting down realistic loading condition

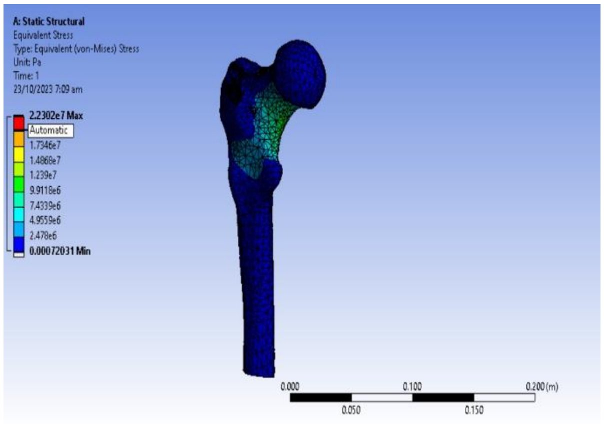


Figure 73:Equivalent (Von-Misis) stress 3D star honeycomb auxetic structure sitting down realistic loading condition

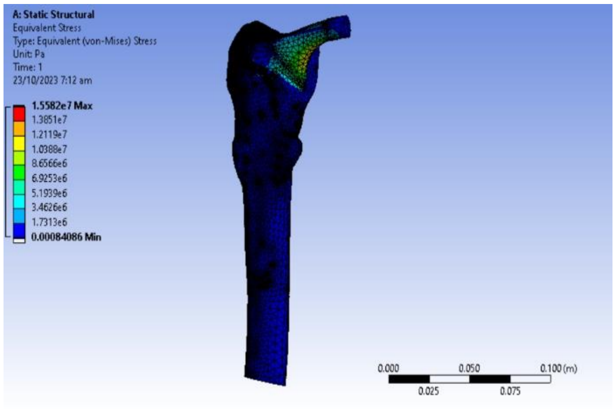


Figure 72:Equivalent (Von-Misis) stress for intact bone in sitting down realistic loading condition