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Comparative Analysis of Hip Implant Geometry Modifications using Finite Element Analysis

[1]Vinod Kumar Mahor, [2]Aditya Kumar Litoria, [3]Girish Kumar Khare

[1]Mtech Scholar, Department of Mechanical Engineering, Oriental Institute of Science & Technology, Bhopal India,
[2]Assistant Professor, Department of Mechanical Engineering, Oriental Institute of Science & Technology, Bhopal India.
[3]Associate Professor, Mechanical Engineering, Oriental Institute of Science & Technology, Bhopal India.
[1]vinodmahor53@gmail.com, [2]adityalitoriya@oriental.ac.in, [3]girishkhare@oriental.ac.in

* Corresponding Author: Aditya Kumar Litoria

Abstract: *This study investigates the effects of geometry modification on hip implant models through finite element analysis (FEA) using ANSYS software. Three different cases of hip implant designs were analyzed, with fixed loads applied to the stem and forces applied to the cup at a 16-degree angle. Results show varying levels of deformation, stress, and strain across the cases, with Case 2 exhibiting the lowest values. Furthermore, comparisons with previous studies reveal improvements in deformation, stress, and strain metrics. The findings suggest that Case 2 offers the most suitable geometry among the tested designs. Additionally, the study underscores the importance of further research on micromotion and dynamic conditions for hip implants.*

Keywords: *Hip Implant, Geometry Modification, Finite Element Analysis, ANSYS, Deformation, Stress, Strain, Micromotion, Dynamic Conditions*

I.INTRODUCTION

The key joint in the human body that provides stability is the hip joint. Age and several variables that affect wear and tear dictate that these joints require reconstruction by implants during hip replacement surgery. Within the field of hip implants, one of the most widely utilized materials for hip joints is the cobalt-chromium alloy consisting of titanium and stainless steel. Aseptic loosening has made it possible to prevent joint revision operations by tightening the design criteria for hip joint implants. For the stem and acetabula structures, there are various options for shapes and materials. It becomes more difficult for one to decide on the design and material of hip implants with knowledge. Hip replacements can be caused by a variety of intricate factors, including overload, injuries, accidents, replacement hip problems, and patient carelessness. If the artificial hip joint is produced, the bone in the pelvis or high thigh, for example, will crack. Additionally, the prosthetic hip joint can be released. Loosening of the hip joint (shaft or socket) may also be brought on by an injury, an increase in osteoporosis, or a severe abrasion (metal or plastic) including the inflammation of scar tissue or allergies. Patients report a deep, unpleasant, and emotionally draining discomfort in the event of a loosening and an unstable gait. These are made worse over time [1].

Additional causes for hip pain and issues include impinged sores, excessive or insufficient strain on the hip muscles, improper alignment of hip detachments or critical hip muscles, bursitis, enlarged tendons, destroyed muscle fibers, production of bone spores, plastic inlay of therapy, etc [2].

The surgical procedure known as a total or partial hip replacement involves removing and replacing some hip joint components with prosthetics, or artificial pieces. As of right now, the most often utilized joint prosthesis materials are titanium-based alloys, specifically Ti-6Al-4V & Ti-6Al-7Nb, which register as biomaterials in the ASTM standard. Even though failure is inevitable, current research has focused on developing more precise predictive and design procedures to avert catastrophic implant failure .Numerous research involving whole or partial hip arthroplasty have used numerical techniques to try to improve the overall reliability of implant design. A scratch on the prosthesis's surface during use or general maintenance is perpetually linked with increased tension in those regions and the creation of a space where cracks can propagate. [3] In terms of prosthesis architecture, thorough analyses of various load scenarios are required to guarantee the safety of its mechanical operations. Static FEM studies are usually used in literature when referring to body weight through loads. However, the impact of weight and abrupt movement can raise the prothesis's load by as much as 10–20%, and frequently considerably more, therefore this should be considered when assessing the likelihood that the prothesis will break or collapse from damage caused by use. In order to evaluate the discrepancy between results predicted in routine import testing and in true loads in operation, the prosthesis should be evaluated under highest points of actual load expected during the process and in conjunction with static loads corresponding to the body mass [4].

A.Hip Joint

The hip joint, which joins the lower extremities to the pelvic fabric, is a synovial joint ball and socket. The femur head articulates through the acetabulum of the pelvic (hip) joint [5]. Due to their multiaxial nature, the hip joints can bend, extend to abduct, adduct, rotate internally, rotate externally, and revolve around one another. But because it's meant to bear weight, this joint doesn't have the stability and strength of the glenohumeral (shoulder) joint. This joint transfers all of the upper leg's weight to the lower limbs when one is standing. The strongest seal in the human body is the hip sealant.

B. Articular surfaces

The hip joint is a structure made up of the ellipsoid head of the femour and the hemispheric acetabulum concavity on the lateral side of the hip bone. Except for the rough central depression, or fovea capitis, which is a linked surface to a femoral head ligament (ligamentumterescapitisfémoris), the femoral head is lined by articular (hyalin) cartilage eventually [6].

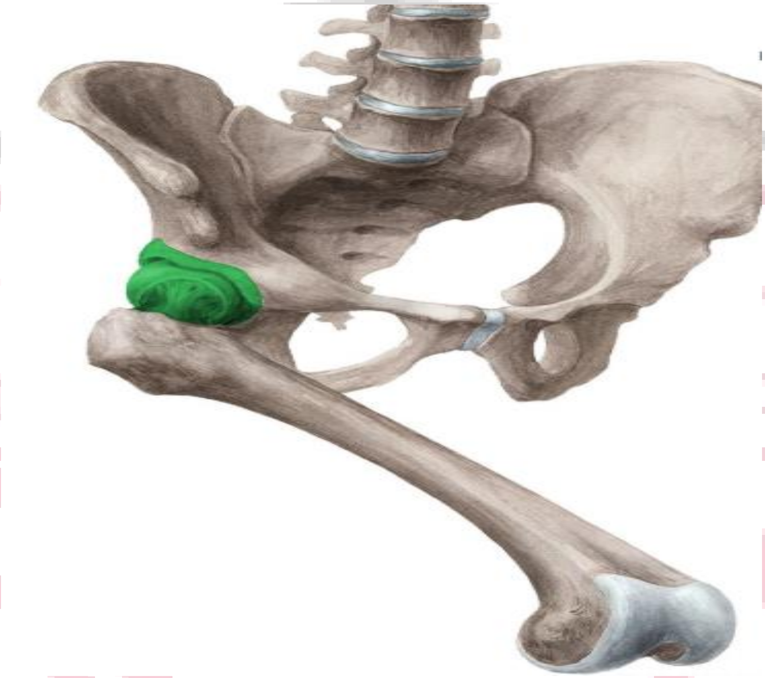

Figure 1.Hip joint (Articulatiocoxae)

The acetabulum is produced by the union of the pubic, ischium, and ilium bones. It is important because it essentially stabilizes the head of the femur, which helps to keep the hip joint stable. The acetabulum, a noticeable semi-mune zone, is referred to as the lunary surface covered in articular cartilage. The upper and lateral sides of the acetabulum are taken up by the surface of the lunar body, which creates an incomplete ring. Most of the body weight is carried by the bigger antero-superior region. The notch in the acetabulum is formed by the weak bottom portion of the acetabulum [7].

C. Movements

Three dimensions of freedom are available for movement at the hip joint, which is a ball and socket joint: flexion, expansion, abduction, a position of outward rotation, internal rotation, and its entire circumference.

The leg is brought to the spine by the hip joint folding. When the knee is flexed, When the thigh comes into touch with the anterior abdominal wall, the hip joint may also bend. The motion reaches around 120 degrees when bending passively and about 145 degrees when bending vigorously. When the knee is bent, hip bending is limited by hamstring strain [8].

The thigh and spine are divided by the hip joint extension. The extension is limited to about 30° by the morphology of the joints above the vertical point and the strain of the capsular ligaments.

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Figure 2. Abduction of thigh

D. Artificial Hip joint

The most powerful protect in the human body is the hip. The time youngsters learn to walk, their hips need to be quite heavy. As people grew young, they were subjected to an immense wear and strain in their hip joints. Walking may become painful and stiff if the wear is too great. A lot of people are now inquiring as to whether having a hip replacement might improve their quality of life. In order to relieve discomfort and increase leg movement, a weak natural hip joint is replaced with an artificial hip joint during this important procedure. And just what is a man-made hip [9].

A prosthesis, or replacement part of the body, typically consists of two or more components, such as an artificial hip. It usually comprises of an attached ball on top of the trunk, a stalkthat slides into the femur, and a cup that rests on the acetabulum to provide the ball with a smooth gliding surface.

Figure 3. Configuration of hip joint

Prosthetic materials and surface treatments have evolved over time, much like the prosthetics themself. The earliest artificial hips were constructed of glass around a century ago, but most of them cracked within a few months. Pyrex, gold, bakelite, and other plastics have also been attempted and discarded for various explanations [10].

The components of the bone replacement were screened using several types of cement. The stable surface of cementless models permits bone cells to proliferate. Cementless torsos work better with all acetabular bowls [11].

The manufacturing of a secure, artificial, bone-fixed surface with little component friction is a major factor in determining the effectiveness of a total hip replacement. Artificial hip joints composed of metallic femoral head jointing with meta-acetabular connection are used as low Wear Loggies and substitutes for conventional HMWPE bearings [12].

II. LITERATURE REVIEW

Kumaran et al (2022) The effect it has on the lumbar spine, but the hip and sacroiliac joint (SIJ) have not been studied in relation to different SS angles. As such, a biomechanical awareness of the effect on the spinopelvic complex is required.According to the current study, the biomechanical load on the hip joint, SIJ, and lumbar spine is impacted by changes in SS. While treating LL, including SS, is crucial, individuals with excessive SS may also have adverse effects on their hip joint, SIJ, and IVDs. Clinicians should plan conservative or surgical therapies based on the knowledge that a single parameter modification can influence several joints.

Chethan et al (2022) The key works have been highlighted and then there is a thorough explanation of various design factors and wear-related problems with hip joints. The tribological behavior of implants under various circumstances is given more attention. It is still unclear how wear in the backing cup affects the acetabular cup and trunnion junction of hip implants. There haven't been many studies done to optimize taper design and lower the taper junction's wear rate.

EkoSaputra et al (2023) It uses the method of finite element simulation to examine the mobility of the hip joint during human movements based on the measured range of motion. The finite element simulation can be used to anticipate the impingement between the acetabular liner cup lip and the femoral neck in a contact scenario. It is shown that the von Mises stress at the point of impingement is greater than the material's yield strength.

Celine Gutmann et al (2023) the implant's design stage The implant's life expectancy may be boosted if this is resolved. Modest design adjustments can greatly extend the implant's life. It was shown that the linear wear rate somewhat increased when the TTR decreased. The implant with the lowest wear rate overall was determined to have a TTR of 6 mm and a 1 mm chamfer. The implant can be 3D printed and tested on a hip simulator to confirm these findings.

HaoGe,et al (2023) This study's objective was to use an analysis of finite elements to examine The distinctive Spacer's mechanical stability, which was achieved by applying an annular armature that mimics trabecular bone structure. By increasing the skeleton diameter from 3 to 4 mm, the strains on the medial and lateral sides of the AD-Spacer and K-Spacer necks decreased. The tension of the other skeletons was concentrated at the neck, whereas the stress of the annular skeleton was equally distributed on its medial and lateral sides. Compared to femurs with AD-Spacer, femurs with K-Spacer had a greater mean stress in the proximal femur.

Ikhsan et al (2023) This study aimed to know the effect of hip joint implant fenestrations on the maximum stress produced.The results obtained are that in the dynamic load of the SS 316 L material is not safe because the maximum stress value produced is higher than the yield strength value, while the Ti-6Al-4V material is safe under dynamic load because the maximum stress value is lower than the yield strength.

OBJECTIVES

- Creating a 3D FEM model of an artificial hip joint with a variety of designs.
- To analyse von-mises stress, strain and deformation under different cases.
- To compare the performance of hip joint with different geometry modification in terms of von-mises stress, strain and deformation.

III. METHODOLOGY

We are going to provide a FEM-based static structural analysis of the hip joint in this paper. One type of prosthesis, or synthetic body part, is an artificial hip, which usually consists of two or more parts. It typically consists of a cup that slides into the acetabulum and gives the ball a smooth gliding surface, a ball that is attached to the top of the stem, and a stem that slides into the femur. Unusual displacement, pressure, and stress will be the features of the show. This model is a first step toward simulating the hip joint, which may inspire more research on the selection of manual materials to enhance the security requirements of next item development. The medial-lateral direction experiences the greatest amount of stress; as a result, the stresses in the other directions are not as important. A body weight-based scale factor can be used to calculate the stress in the other sites. For the FEA of each stem, a rectangular cross-section was taken as given. In order to perform a static structural breakdown, the bottom portion of the stem will be secured, and as illustrated a load of 250 N applied at a 27° angle will be applied to the implant's surface.

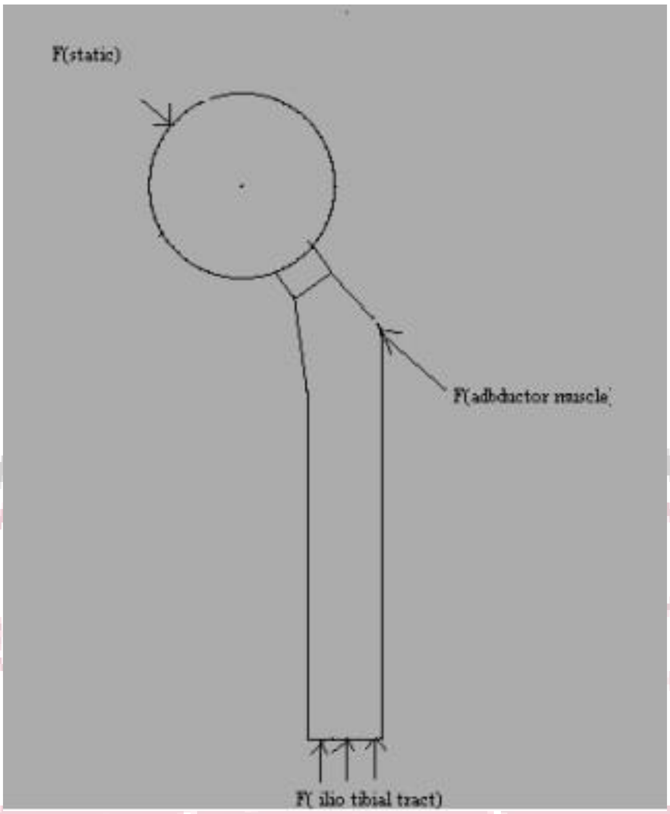


Figure 4. Hip joint

A. Analysis Methods

For simple issues such prism bar torsion or beam bending, closed-shaped solutions are necessary. Series solutions to differential equations are employed as indirect methods for the investigation of far more complex structures, such as plates and shells. For structural problems with relatively simple limitations of geometry, charging, but boundaries, those conventional approaches must be implemented. Only one neck length and one head size were used in this investigation.

B. Meshing

ANSYS models the symmetric hip joint using the Cartesian coordinate system. This unit is defined by the eight freedom nodes that each node has: translations in the x, y, and z axes. It is resistant, slippy, swollen, flexible, and has a great potential for deformation. In a combined formulation, it may also model the deformations of almost incompressible elastoplastic materials and completely incompressible hyperelastic materials. The geometry, node location, and coordinate system for that element are displayed in the figure. Both nodes and the characteristics of orthotropic or anisotropic materials are contained in the input data. The element is in the coordinated directions in both the orthotropic and anisotropic directions.

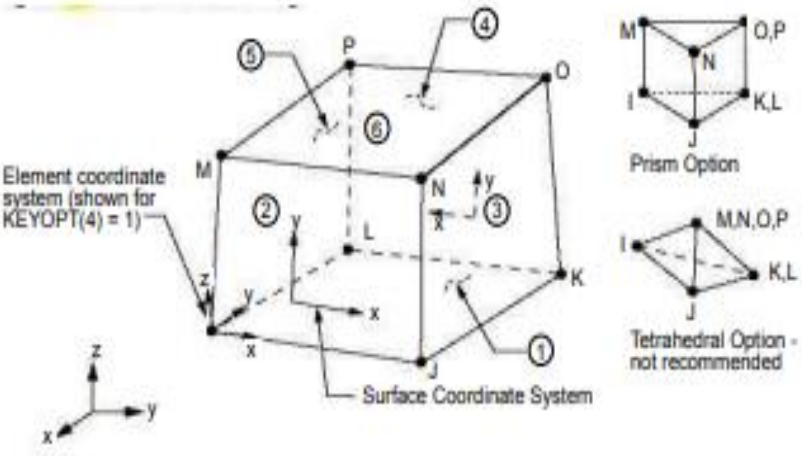


Figure 5.Solid 45 8-node geometry

After the elements have automatically meshed, you must use EORIENT to reorient them. SOLID191 elements for EORIENT can be paired with an element of the same orientation, or the orientation can be adjusted to run as parallel to a specific axis as feasible. The element of the c axis is specified as usual in the curved reference plane. The average projection in the I-J and M-N reference planes is the x-axis' default element. The total level count (up to 100) must be set (NL). Only half of the qualities, including the properties of the intermediate layer, should be accomplished if the layers have a symmetrical property around the thickness of an element (LSYM = 1). Characteristics at all levels can be related otherwise (LSYM = 0). Within the element's plane, the material properties of every layer may be orthotropic. This layer 191 identifies the hip joint (Figure 6).

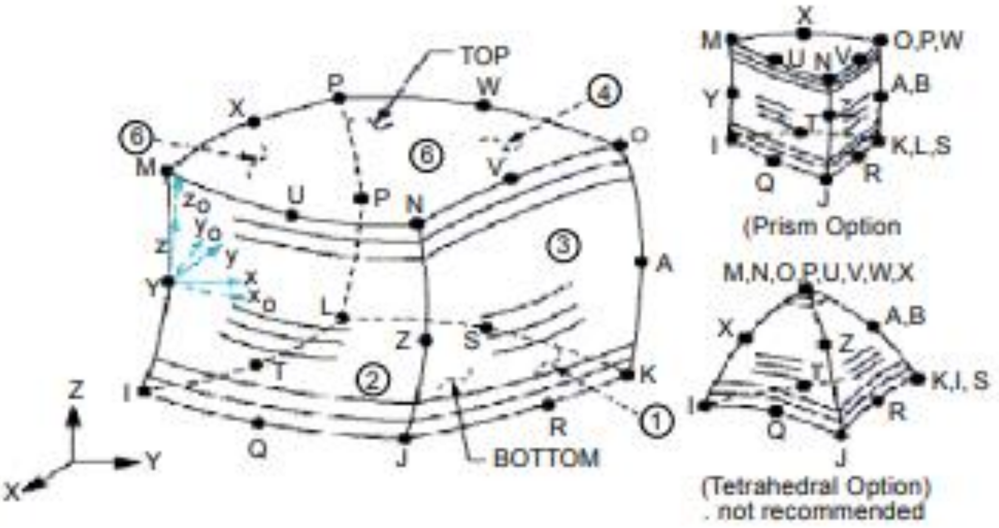
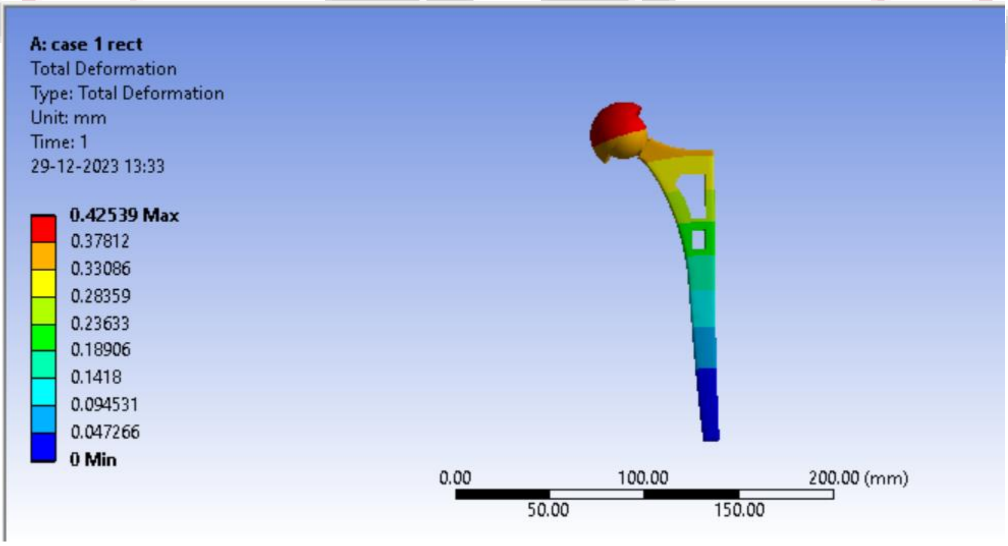


Figure 6. Layered 191 20-node geometry

IV. RESULTS AND DISCUSSIONS

The direct solution methodology involves two distinct steps: a direct replacement and a reverse replacement, as the name of the method suggests. Direct replacement is used to continue the breakdown process.

The hip stems are designed with low stress, displacement, and wear at a very high fatigue life in mind. High stress and displacement stem designs were then optimized for low stress and displacement combinations, and the cross-section with a circle at the medial end and a square at the lateral end proved to have the right design features.



A: case 1 rect
Total Deformation
Type: Total Deformation
Unit: mm
Time: 1
29-12-2023 13:33

Figure 7. Total Deformation of case - 1

Figure 7. shows total deformation of case -1 hip model. The minimum total deformation of 0 mm and maximum total deformation of 0.42539 mm is observed in hip model.

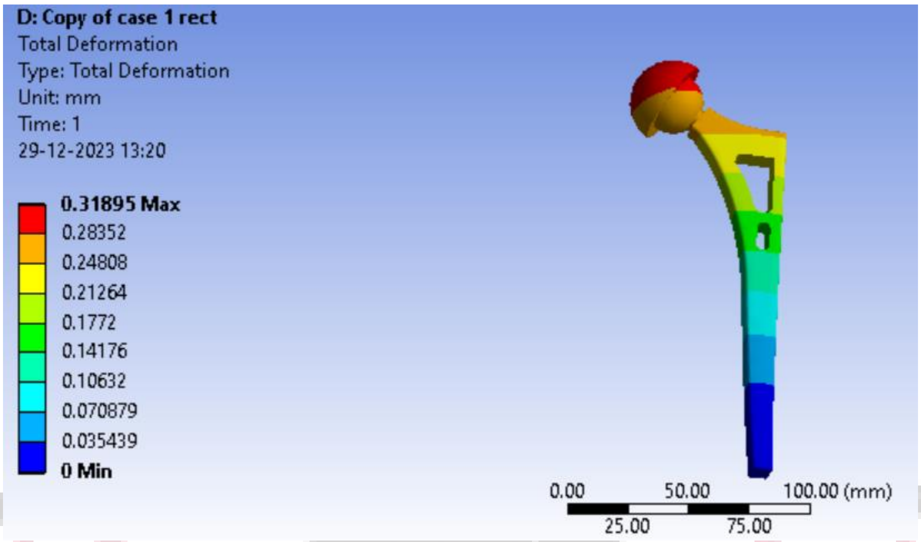


Figure 8. Total Deformation of case – 2

Figure 8. shows total deformation of case-2. The minimum total deformation of 0 mm and maximum total deformation of 0.31895 mm is observed in hip model.

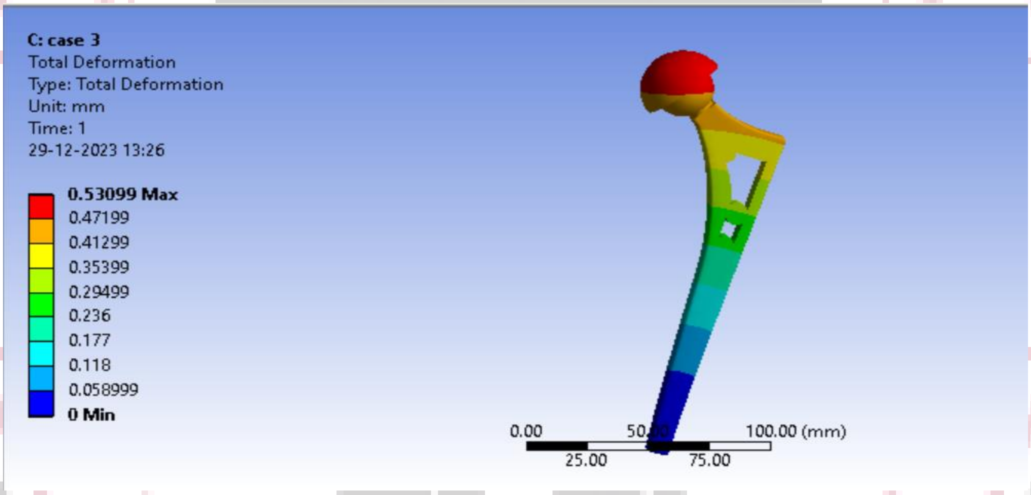


Figure 9.Total Deformation Case - 3

Figure 9.shows total deformation of case-3. In the hip joint model, the maximum and minimum deformation are 0.53099 mm and 0 mm, respectively. The maximum deformation observed in a steel ball of an artificial hip joint under an applied load is likely due to the material properties of the steel and the design considerations of the hip joint. Steel is known for its strength and durability, but it is not immune to deformation under stress. When a load is applied to a steel ball, it experiences a combination of plastic and elastic deformation.

Equivalent Stress

Considering equivalent stress, also known as von Mises stress, enables any arbitrary three-dimensional stress state to be represented as a single positive stress value, it is frequently utilized in design work. The maximum equivalent stress failure theory, which is used to forecast yielding in a ductile material, includes equivalent stress. The value of the von Mises stress is used to predict whether a certain material will yield or fracture. Metals and other ductile materials are the main applications for it. According to the von Mises yield criterion, a material will yield if its von Mises stress under load is equal to or higher than its yield limit under simple tension, which is simple to ascertain experimentally.

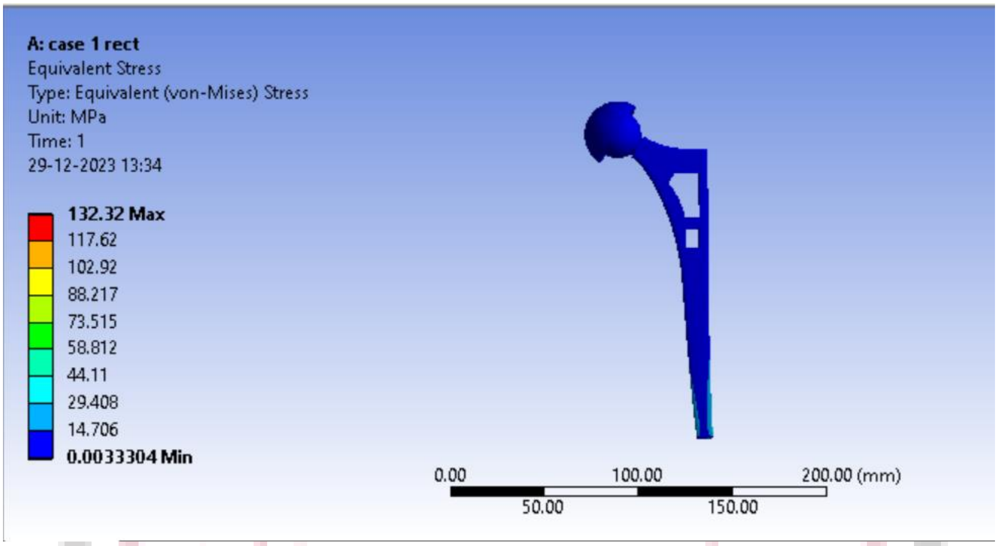


Figure 10. Von – Misses stress of case – 1

Figure 10. shows the Von – Misses stress of case-1. The minimum von mises stress of 0.0033304 MPa and maximum von mises stress of 132.32 MPa is observed in hip model.

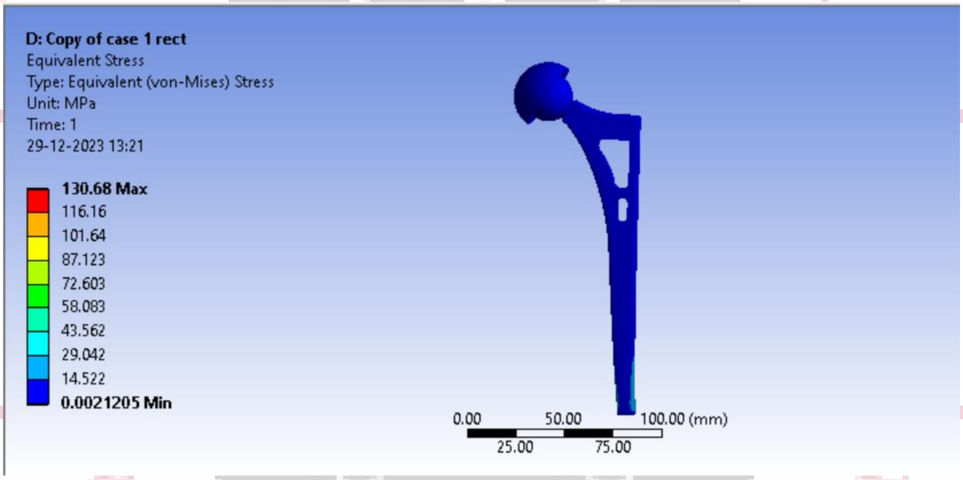


Figure 11. Von – Misses stress of Case – 2

Figure 11. shows the Von – Misses stress of case-2 . The minimum von mises stress of 0.0021205 MPa and maximum stress of 130.68 MPa is observed in hip model.

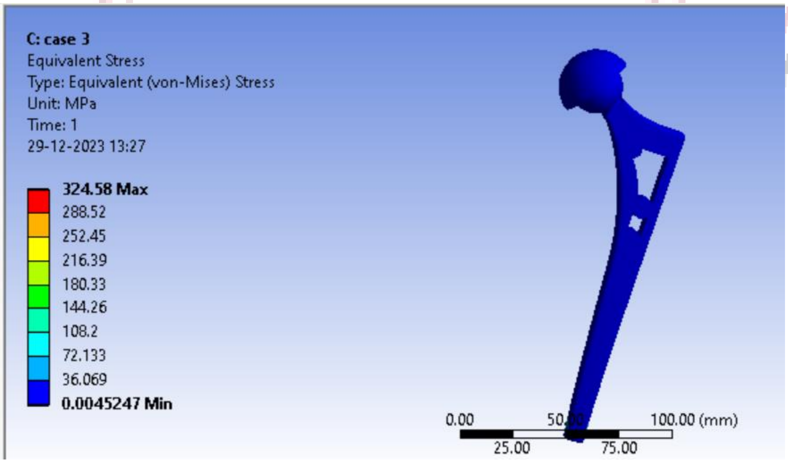
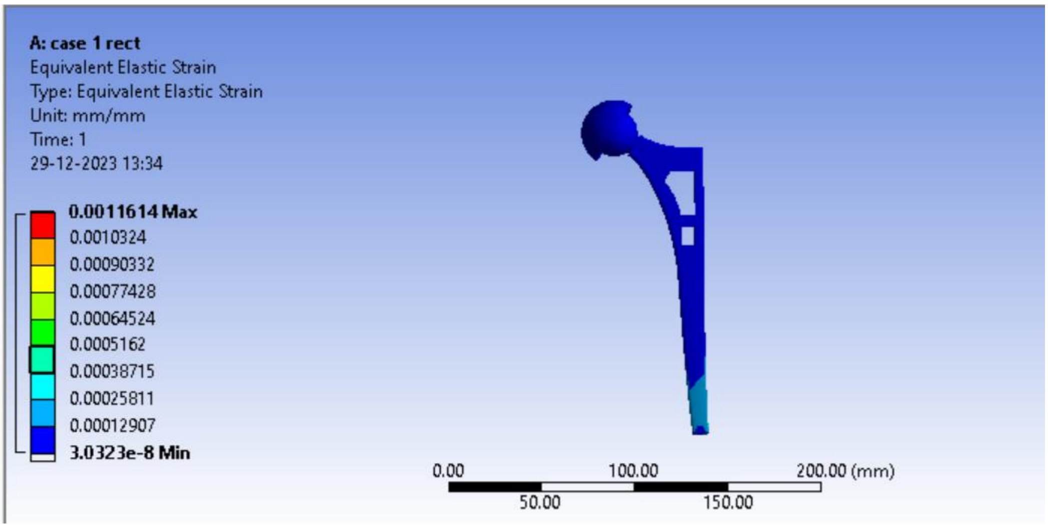


Figure 12. Von – Misses stress of Gray cast iron hip model

Figure 12. shows the Von – Misses stress of case-3 hip model. The minimum von mises stress of 0.0045247 MPa and maximum stress of 324.58 MPa is observed in hip model. Steel, while strong and durable, has a defined yield strength,

beyond which plastic deformation occurs. The applied load on the steel ball may exceed its yield strength, leading to the development of maximum stress.The design of the artificial hip joint involves the distribution of loads to ensure that the joint functions properly. However, certain regions, such as the contact point between the ball and socket, may experience higher stress concentrations. The geometry and loading conditions can contribute to localized stress maxima.The Hertzian contact stress theory is applicable to the contact points between two elastic bodies. In the case of a hip joint, the ball and socket experience significant contact stresses, and the applied load can result in elevated stresses at these points.The mechanics of the hip joint, including the range of motion and the load-bearing capacity, play a role in determining the stress distribution. Factors such as joint misalignment or improper fitting of the components can lead to increased stress concentrations.



A: case 1 rect
Equivalent Elastic Strain
Type: Equivalent Elastic Strain
Unit: mm/mm
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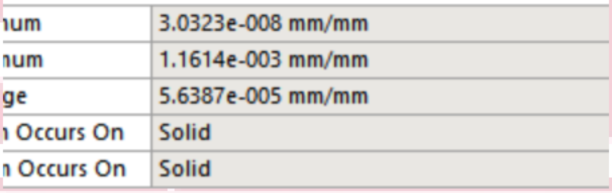
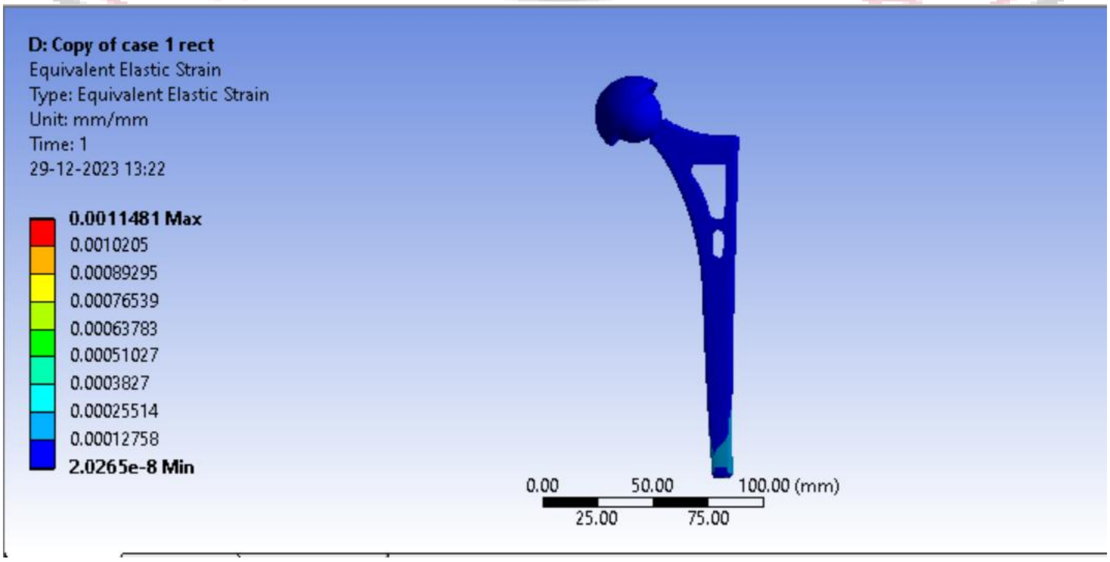
Figure 13. Equivalent elastic strain of Case - 1



um	3.0323e-008 mm/mm
um	1.1614e-003 mm/mm
ge	5.6387e-005 mm/mm
Occurs On	Solid
Occurs On	Solid

Figure 13. shows Equivalent elastic strain of case-1 hip model. The minimum von mises strain 3.0323e-8 mm/mm and maximum strain 0.0011614 mm/mm is observed in hip model .



D: Copy of case 1 rect
Equivalent Elastic Strain
Type: Equivalent Elastic Strain
Unit: mm/mm
Time: 1
29-12-2023 13:22

Figure 14. Equivalent elastic strain of Case - 2

Figure 14. shows Equivalent elastic strain of case-2 hip model. The minimum elastic strain of 2.0265e-8 mm/mm and maximum strain of 0.0011481 mm/mm is observed in hip model.

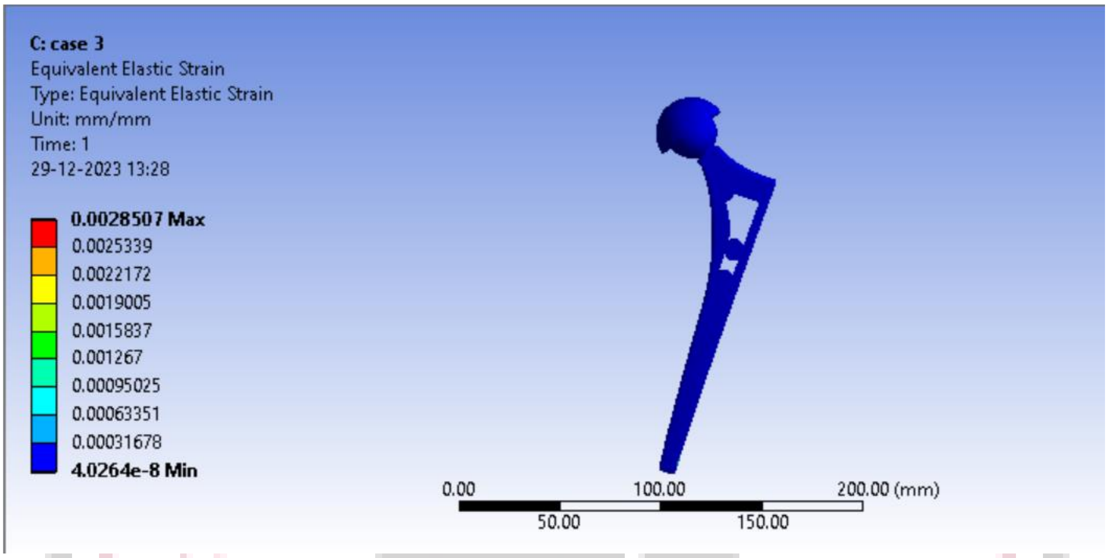


Figure 15. Equivalent elastic strain of Case - 3

Figure 15. shows Equivalent elastic strain of case-3 hip model. The minimum von mises strain 4.0264e-8 mm/mm and maximum strain 0.0028507 mm/mm is observed in hip model. The material used in the artificial hip joint, especially at the lowest end, may have specific mechanical properties that influence its deformation behaviour. Different materials have different moduli of elasticity and yield strengths, affecting how they respond to applied loads.The geometry of the hip joint components, particularly at the lowest end, can contribute to strain concentration. Irregularities or stress risers in the design may cause localized deformation and strain.The way the applied load is distributed across the joint components can result in varying levels of strain. If the load distribution is uneven, certain regions may experience higher strains than others.The mechanics of the hip joint, including the articulation of components and their interactions during movement, can influence strain distribution. Misalignment, improper fit, or issues with joint mechanics may lead to increased strain at the lowest end.

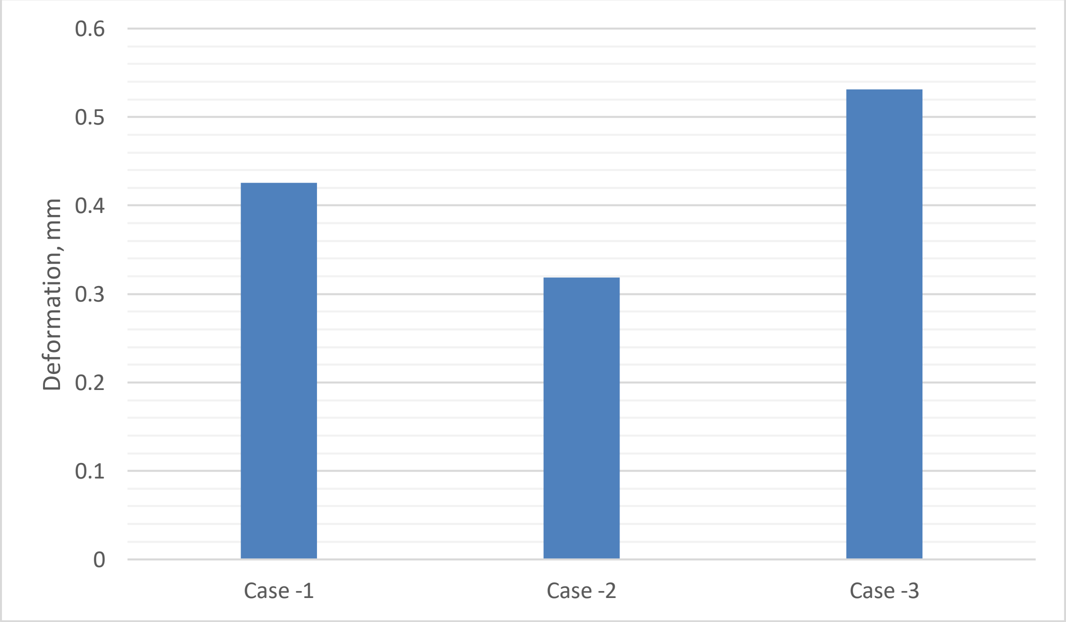


Figure 16. Variation of deformation across three cases

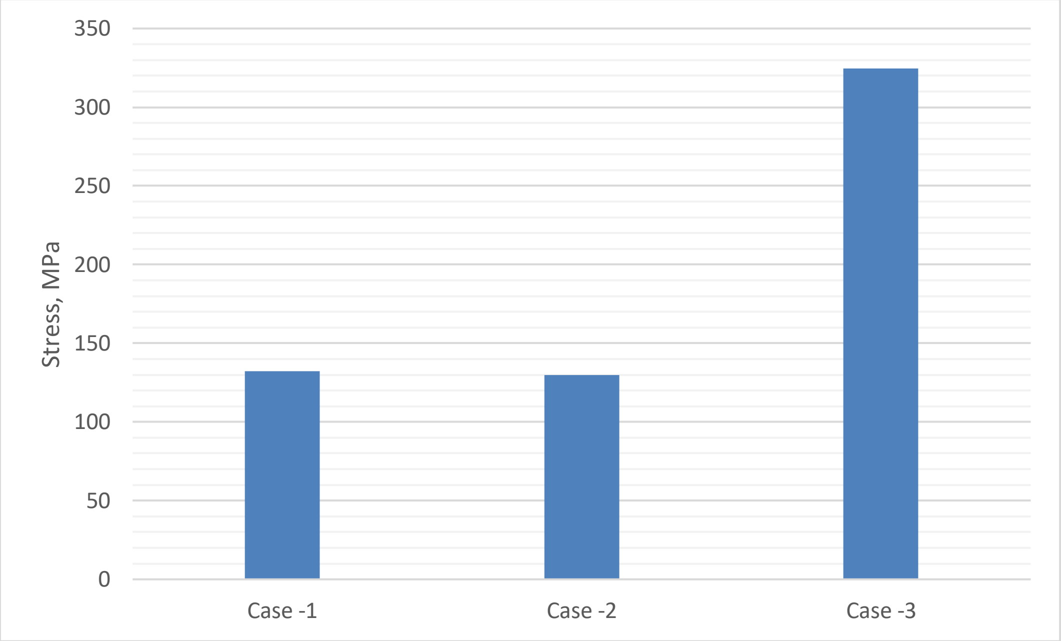


Figure 17. Variation of stress across three cases

From figure 17. it is clear that max. deformation is observed in case 3 (0.53099 mm) and min. deformation is observed in case 2 (0.31895mm). From figure 17. it is clear that max. stress is observed in case 3 (324.58 MPa) and min. stress is observed in case 2 (130 MPa). From figure 18. it is clear that max. strain is observed in case 3 (0.0028) and min. strain is observed in case 2 (0.114).

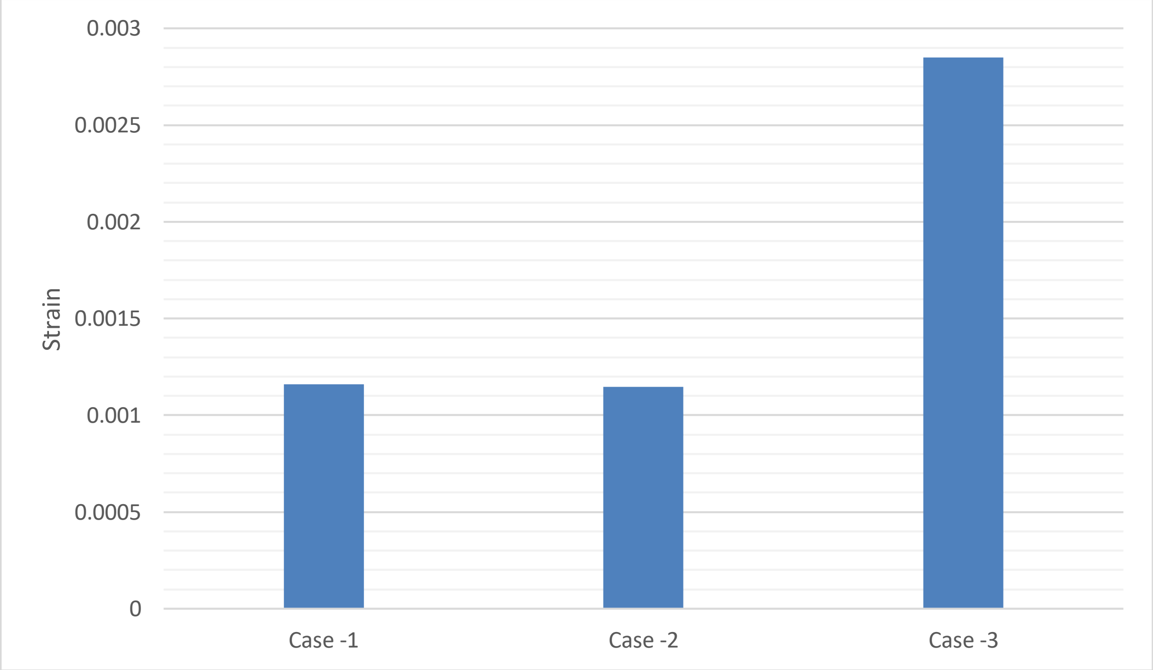


Figure 18. Variation of strain across three cases.

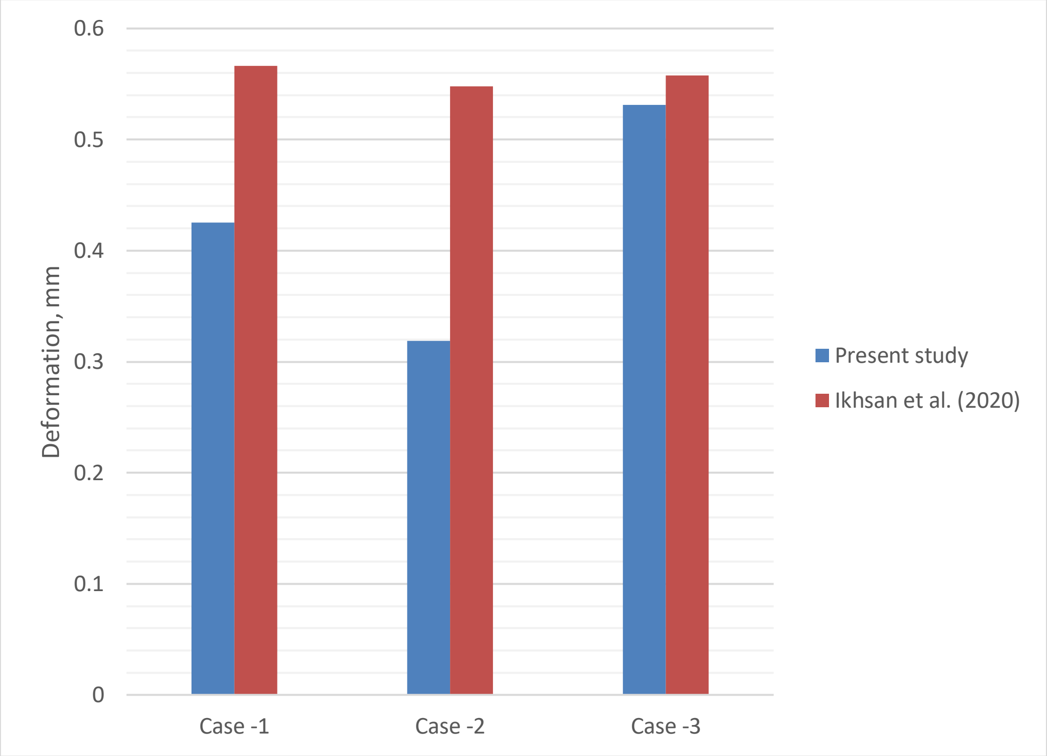


Figure 19. Comparison of deformation

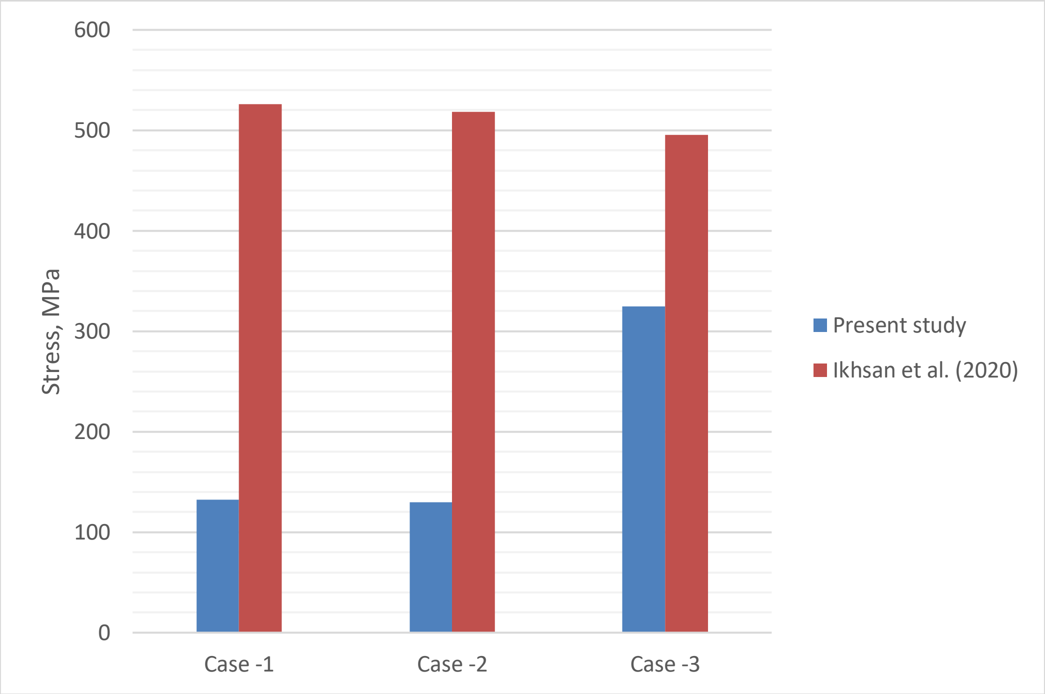


Figure 20. Comparison of stress

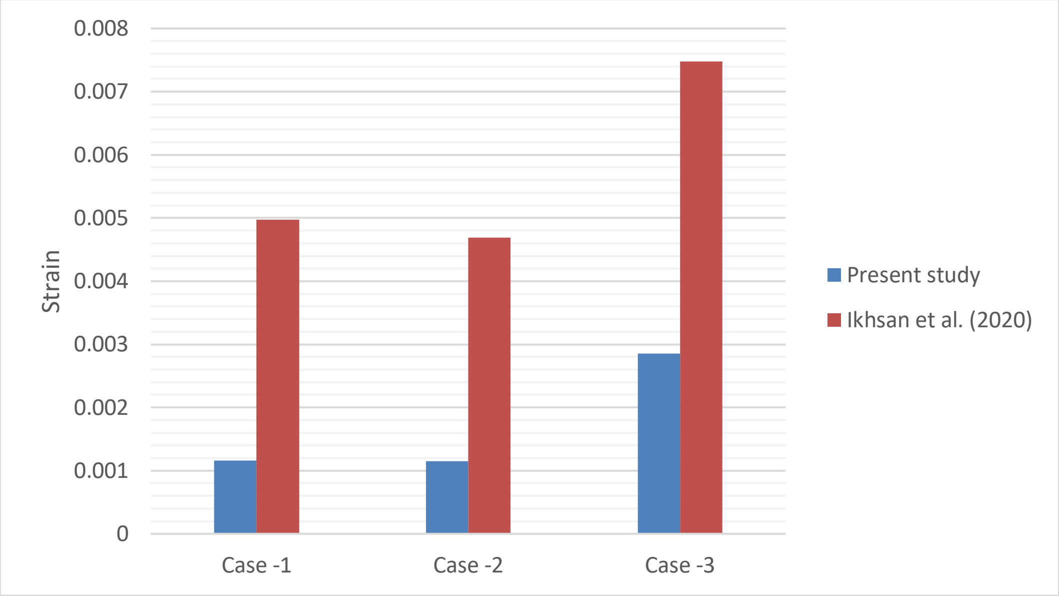


Figure 21. Comparison of strain

From figure 21it is observed that all the reported results were reported the lowest value of deformation, stress and strain as compared to previous study.

V.CONCLUSION

The analysis of hip implant geometry modifications reveals distinct differences in deformation, stress, and strain across the tested cases. Case 2 emerges as the most promising design, exhibiting the lowest levels of deformation, stress, and strain compared to Cases 1 and 3. These findings highlight the significance of geometric adjustments in optimizing hip implant performance. Moreover, the study emphasizes the need for future investigations into dynamic conditions and micromotion to enhance the reliability of hip implants.

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