Smart Hip Implant

Finite Element Analysis Final Report

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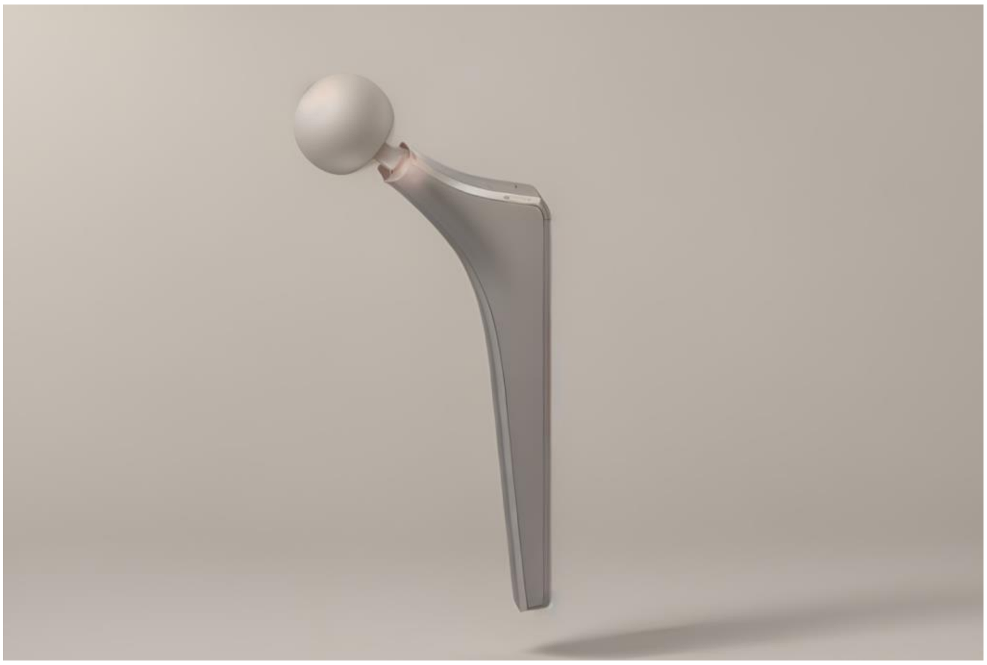

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1 Introduction

In today's era of significant medical advancements and increased aging, the field of artificial joint implantation is undergoing a revival. Hip implants are designed to mimic the complex biomechanics of the hip joint and thus need to adapt to the complex environment of daily activities.

The report outlines the design process using finite element analysis (FEA) of a hip implant, with the following criteria:

- lightweight to reduce stress on the surrounding bones and tissues.
- effective life should be at least 15 years (equivalent to five million loading cycles).
- have 5 natural frequencies within the frequency range of 100Hz to 3000Hz.
- be made of Titanium alloy or Stainless Steel.

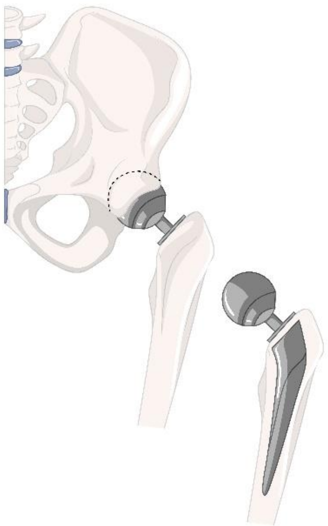

Figure 1: A hip implant [1]

2 Methods

2.1 CAD Model

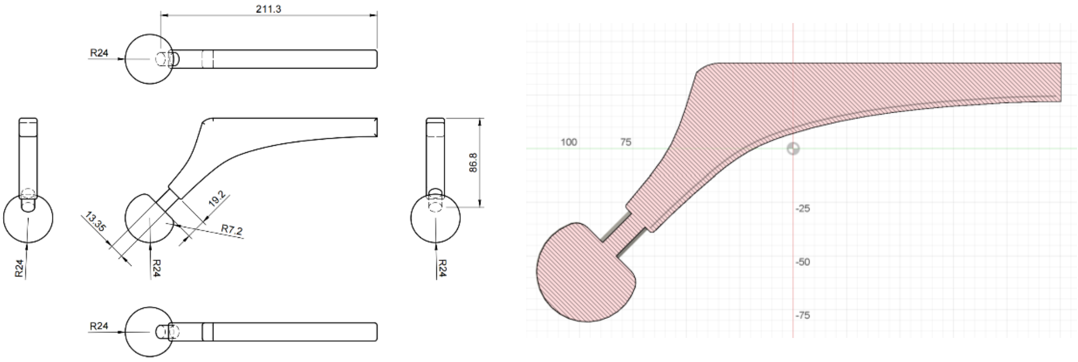

Figure 2: dimensions of the initial hip implant design

Using Fusion 360, an initial model of the hip implant was designed and engineering drawings were generated to show various dimensions. To closely reflect real-world scenarios, the diameter of the head was set at 48mm, and the length of the stem and neck was 211.3mm, based on data from articles on ScienceDirect [2] and NCBI [3]. The initial model has a simple and compact appearance, maintaining lightweight while also allowing ample room for later improvements. To ensure structural strength and durability, the entire implant is solid.

	Diameter (mm)	Length (mm)	Thickness (mm)
Head	48.0	--	--
Neck	12.8	19.2	--
Stem	--	199.0	17.6

Table 1: main dimensions of the initial hip implant

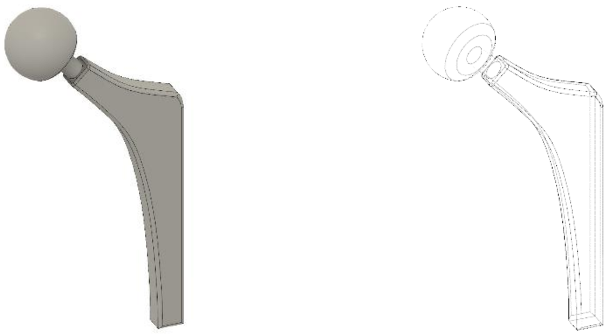

Figure 3: 3D CAD model of initial design

2.2 Assumptions

Here are some assumptions that might cause errors and limitations during FEA tests:

- The structure of the hip implant is considered only in terms of the head, neck, and stem, and these three parts are treated as a single solid entity.
- The safety factor is not considered.

- The gravity of the person and the hip implant is not considered; the only load is on the implant's head, which is along the axis of the body and oscillates between zero and 2,490N.

2.3 Materials

In this scenario, Titanium alloy (Ti-6AL-4V) and Stainless Steel (316L) were chosen as materials for the hip implant. This selection is based on their excellent biocompatibility, high strength-to-weight ratio, and corrosion resistance, making them the most commonly used materials for medical implants. [4]

Material	Composition (%)	Density(kg/m^2)	Yield Strength (MPa)	Modulus of Elasticity (MPa)
Titanium alloy (Ti-6AL-4V)	90Ti--6Al--4V	4.43×10^3	880	113800
Stainless Steel (316L)	67Fe--17Cr--12Ni 2Mo--1Mn	8×10^3	205	193000

Table 2: Material properties

2.4 Boundary Conditions

Fixed Support

Hip implants are embedded in the femur. In order to mimic the boundary conditions produced by the contact between the implant and the femur, it is assumed that the implant's stem is fixed from its tail to approximately halfway through its length.

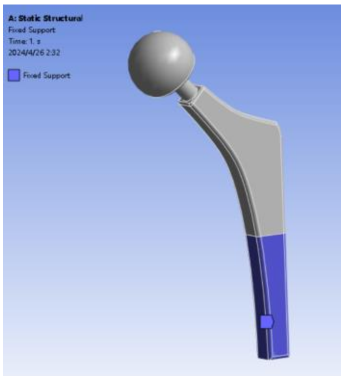

Figure 4: Fixed Support

Loading

Hip implants are subjected to loads produced in daily activities, such as walking. For this project, it is assumed that the implant's head is subjected to a vertical force which is along the axis of the body and oscillates between zero and 2,490N.

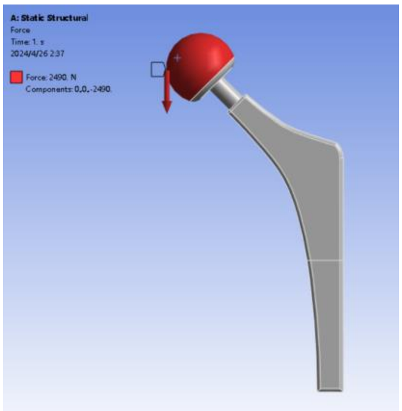

Figure 5: Loading

However, this load is used only for fatigue life analysis, and no load or gravity is required for frequency analysis. This is because the calculation of natural frequencies is not influenced by external forces in this project. The purpose of the analysis is to determine the inherent vibration characteristics of the system when there are no external forces acting on it.

2.5 Fatigue Analysis Parameters

S-N Curve

For fatigue simulations, it's essential to obtain the material's S-N curves, which show the stress amplitudes that could lead to fatigue failure after specified load cycles. This data helps predict the material's fatigue life under certain stress levels and cycles, assessing the durability and reliability of components in real conditions. Ansys includes these S-N curves, enabling quick and reliable access to these values.

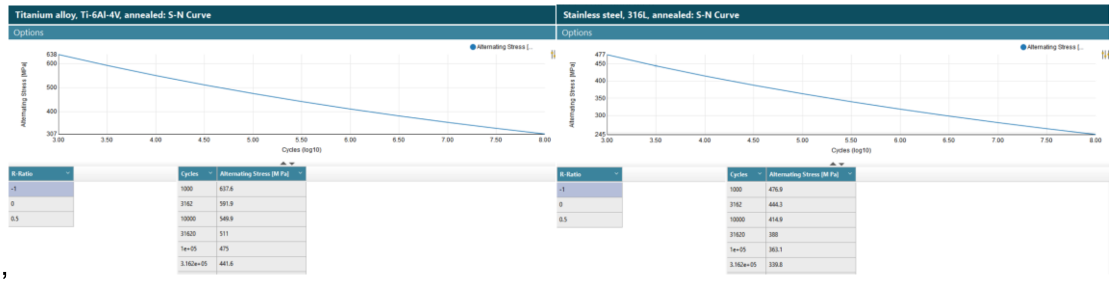

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Figure 6: S-N curves of the two materials

Fatigue Tool

Since the load oscillates between zero and 2,490N, the loading type should be changed from fully reversed to zero-based [5]. For hip implants, stress tends to concentrate in the neck area, so using max shear stress can more accurately predict fatigue life. Hip implants often endure high stresses from activity that are continuous and variable. The Gerber theory curve declines more gradually at higher stresses compared to Goodman and Soderberg curves, meaning it more realistically reflects the material's fatigue behaviour under high stress levels [6].

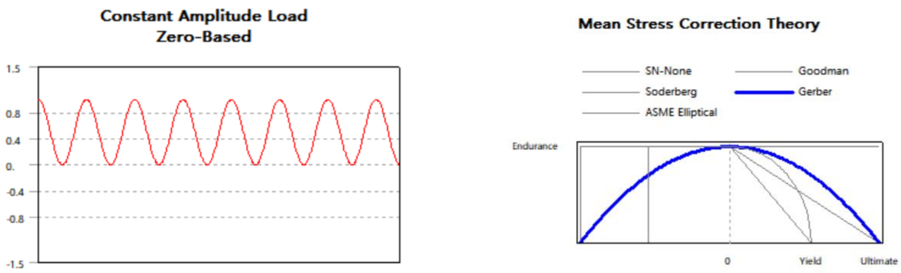


Figure 7: zero-based loading type and Gerber correction

2.6 Frequency Analysis Parameters

$$\omega = \sqrt{\frac{k}{m}}$$

The formula above calculates the natural frequency, where ω represents the natural frequency in radians per second, k is the stiffness of the system, and m is the mass. This equation highlights the relationship between stiffness, mass, and vibrational characteristics.

According to the criterion in the assumptions, the implant must have 5 natural frequencies within the range of 100Hz to 3000Hz. This requirement is aimed at enhancing the dynamic compatibility and safety of the implant, preventing harmful resonance effects during everyday activities.[7]

3 Results

3.1 Mesh Refinement

Initial Mesh

An initial mesh helps quickly check structure design, boundary conditions, and material properties to ensure proper configuration. A 12mm global mesh was used for initial results, aiding in further refinement and identifying areas needing local attention.

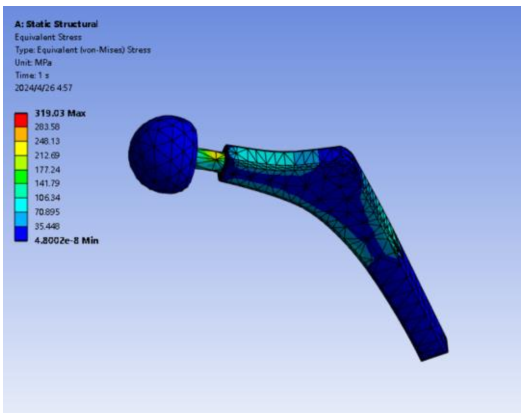
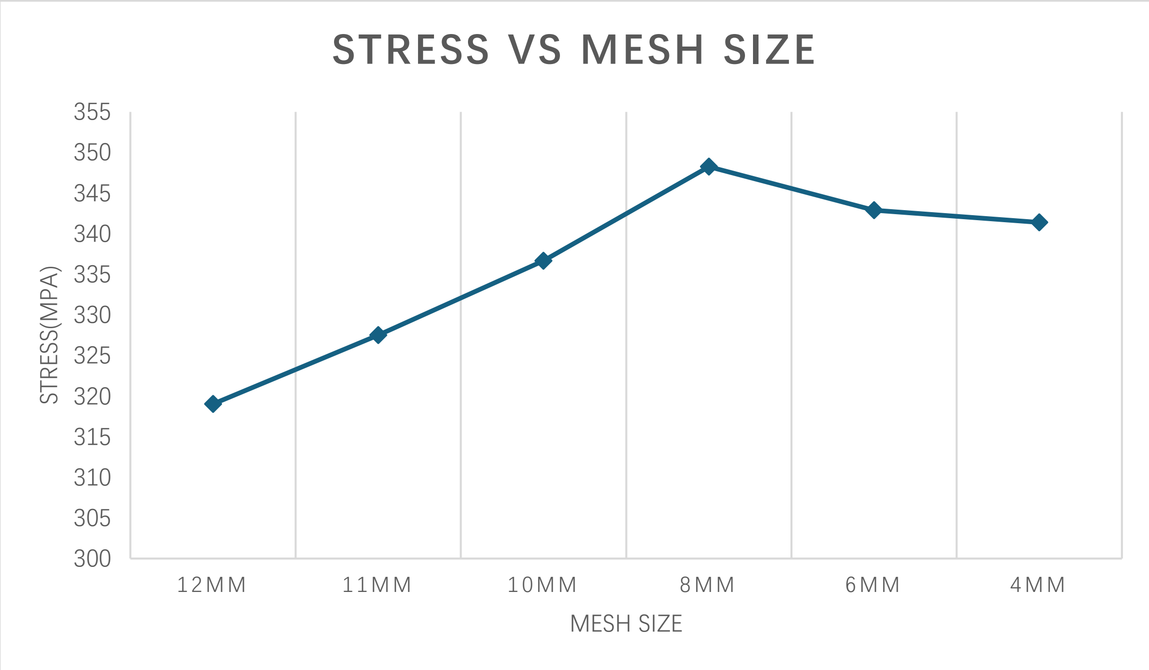


Figure 8: initial global mesh (12mm)

Sanity check 1: The maximum stress concentration occurred in the neck part, measured at 319.03MPa, which is less than the alternating stress for 5 million loading cycles on the S-N curve. Therefore, the model and initial mesh are deemed reasonable.

Global Refinement

To make the results more stable and reliable, the mesh density of the entire model needs to be increased. Therefore, the mesh size was gradually reduced from 12mm to 4mm. From the chart below, it can be observed that the maximum equivalent stress converges towards 340 MPa.



Local Refinement

To enhance resolution and increase the accuracy of capturing max equivalent stress, local mesh refinement was introduced. The mesh size in areas of high stress concentration, specifically the neck and stem regions, was reduced from 4mm to 1mm.

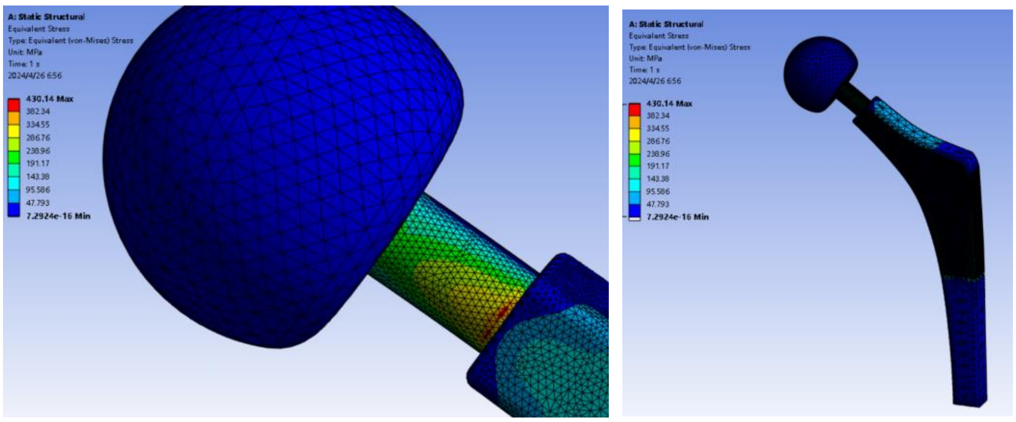


Figure 9: local refinement (1mm)

After the local mesh control, the max equivalent stress increased from 341.41 MPa to 430.14 MPa, a growth of 26%.

Sanity check 2:

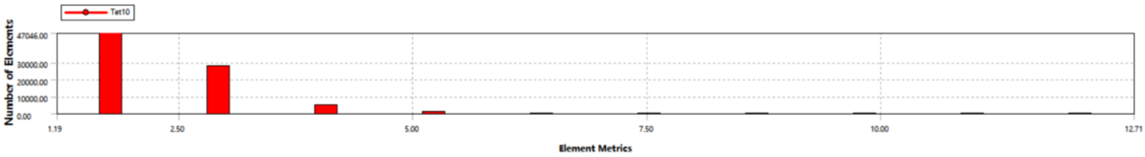


Figure 10: aspect ratio of local refinement

Over 98% of the elements have an aspect ratio within the range of 1 to 5, indicating that the significant increase in stress is not due to improper mesh division or low-quality mesh. Thus, the local refinement has evidently led to more accurate outcomes.[8]

3.2 Initial Design Results

Static Analysis

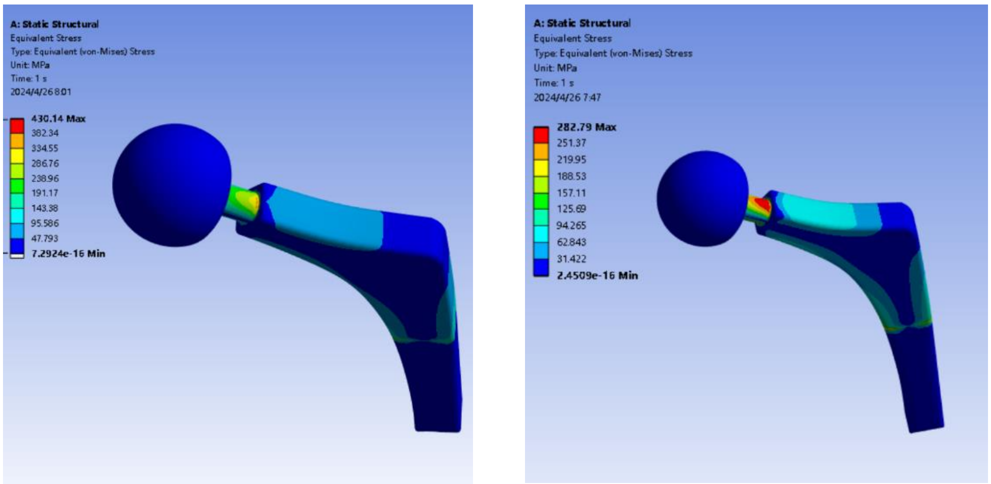


Figure 11: initial static results (left: titanium, right: stainless steel)

The max equivalent stresses for the two materials occurred in the neck, with titanium experiencing 430.14 MPa and stainless steel 282.79 MPa. Both were below their respective alternating stress values for 5 million loading cycles on the S-N curves, suggesting that the hip implants could withstand a fatigue life of 15 years. For titanium, the max equivalent stress was significantly lower than its yield strength (880 MPa), so no plastic deformation occurred. However, for stainless steel, the max equivalent stress exceeded its yield strength (205 MPa). While plastic deformation does not necessarily mean failure, for hip implants, it can alter the load-bearing capacity and the distribution of forces, potentially affecting the movement of surrounding tissues, thus reducing performance and comfort.

Fatigue Analysis

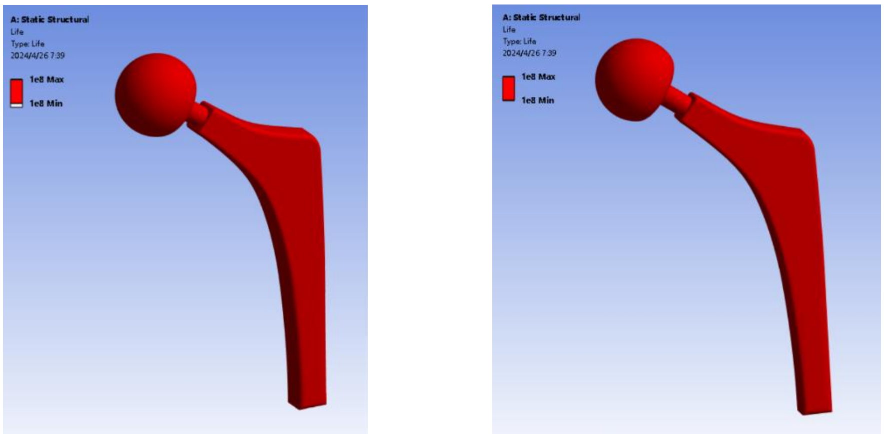
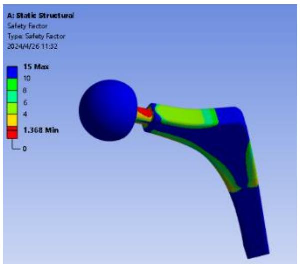


Figure 12: initial fatigue results (left: titanium, right: stainless steel)

The loading cycles for both metal implants have reached 100 million, far exceeding the criterion of 5 million. Therefore, under the current loading conditions, neither material would experience fatigue. This indicated that the model design and material selection were highly suitable for the anticipated operating environment, capable of withstanding repetitive stress well beyond the normal operational range without performance degradation.

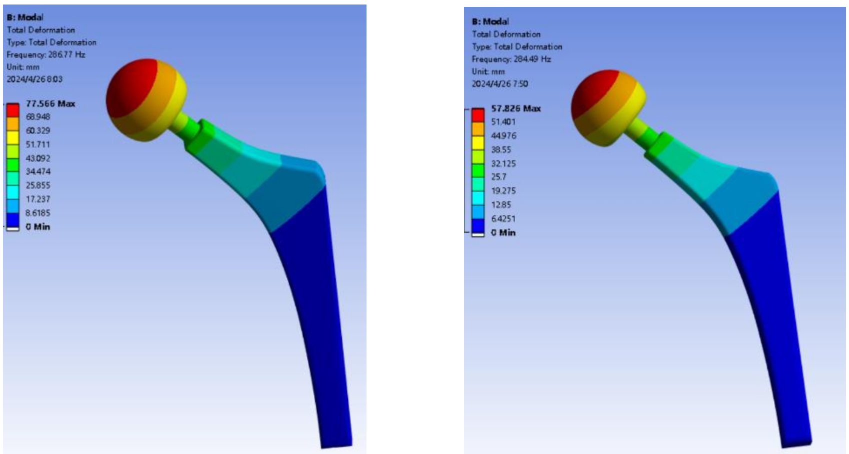


Sanity check 3:

$$\text{safety factor} = \frac{ultimate\ stress}{allowable\ stress}$$

After inserting the safety factor in the fatigue tool and solving, it was determined that the minimum safety factor for both implants was greater than 1. This once again proved that the design is theoretically capable of withstanding the anticipated loads.

Frequency Analysis



Tabular Data

	Mode	Frequency [Hz]
1	1.	287.57
2	2.	424.42
3	3.	1176.
4	4.	1475.5
5	5.	1614.8
6	6.	3008.1

	Mode	Frequency [Hz]
1	1.	285.95
2	2.	418.39
3	3.	1182.6
4	4.	1455.7
5	5.	1586.1
6	6.	2985.2

Figure 13: initial frequency results (left: titanium, right: stainless steel)

Under loading conditions, the head of the implants experienced the most significant deformation. The titanium implant had 5 natural frequencies within the range of 100Hz to 3000Hz, with the sixth frequency at 3008.1Hz, just slightly exceeding the range. The stainless steel implant already has 6 natural frequencies within the range of 100Hz to 3000Hz. In summary, the initial designs of both materials met the criteria in the assumptions, thereby ensuring the safety and comfort of the implants.

Sanity check 4:
From the results obtained, changing the material from titanium to stainless steel did not significantly alter the natural frequency. This is because the natural frequency (ω) is directly proportional $\frac{E}{\rho}$,

$$Titanium = \frac{elastic\ modulus}{density} = \frac{113.8\ \text{GPa}}{4.43 \times 10^3 kg/m^2} = 0.0257$$

$$Stainless\ Steel = \frac{elastic\ modulus}{density} = \frac{193\ \text{GPa}}{8 \times 10^3 kg/m^2} = 0.0241$$

The similar ratios confirm the validity of the test results.[9]

3.3 Iterative Design

Although the initial design has met most of the criteria, there were still two areas that need improvement through CAD model modifications:

- Avoid plastic deformation in stainless steel due to high stress concentration in static analysis.
- Ensure the titanium implant also has 6 natural frequencies within the range of 100Hz to 3000Hz.

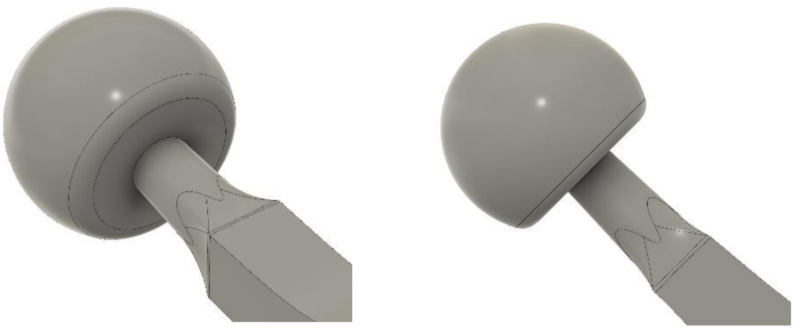
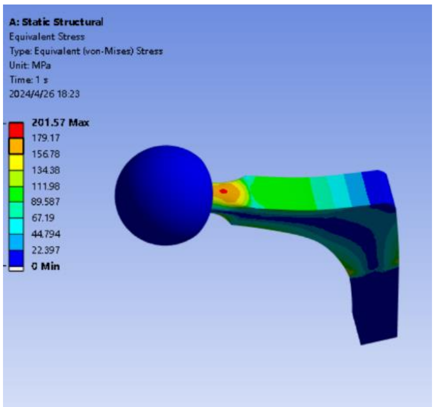


Figure 14: iterative design (large fillet, extended neck)

Improvement:

- Use a 25mm large fillet feature to merge the neck and stem into a continuous structure.
- Extend the length of the neck from 19.2mm to 30.5mm.

Static Analysis



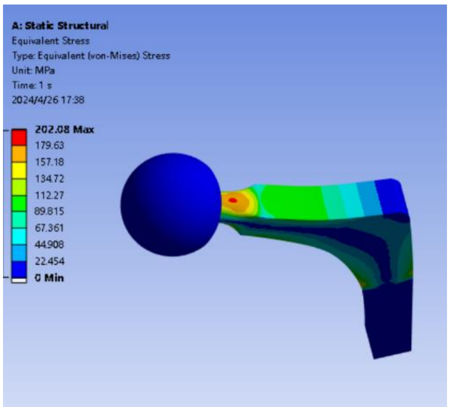


Figure 15: revised static results (left: titanium, right: stainless steel)

The initial static analysis revealed that the maximum equivalent stress was primarily concentrated at the junction of the neck and stem due to sharp edges. Therefore, the large fillet design merges the neck and stem into a more coherent and smoother structure, reducing stress concentration. After the second simulation, the maximum equivalent stress of the revised stainless steel implant was 202.08 MPa, which is below its yield strength of 205 MPa, thus preventing any plastic deformation.

Fatigue Analysis

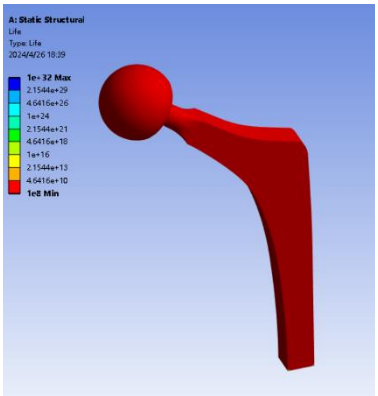
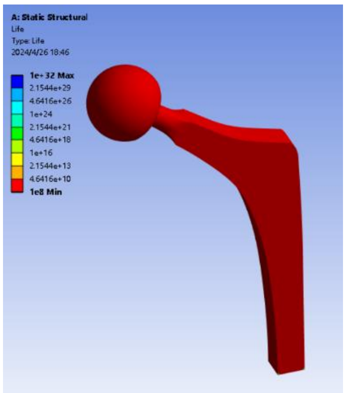
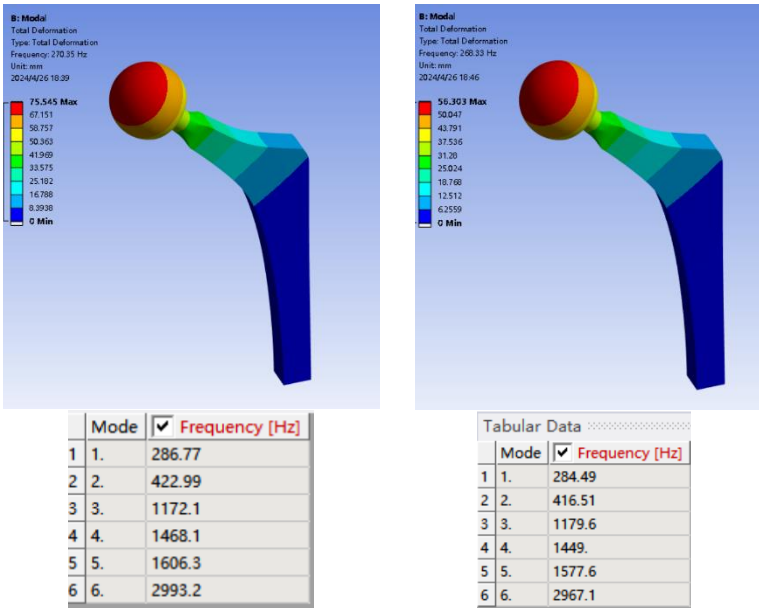



Figure 16: revised fatigue results (left: titanium, right: stainless steel)

After improving the CAD model, the minimum loading cycles for both materials remained at 1×10^8, which was still much higher than the criterion of 5×10^6. However, an observed maximum loading cycle of 1×10^{32} was an unrealistic figure, as all materials and structures had performance limits. This issue might be caused by setting the load size too conservatively.

Frequency Analysis



	Mode	Frequency [Hz]
1	1.	286.77
2	2.	422.99
3	3.	1172.1
4	4.	1468.1
5	5.	1606.3
6	6.	2993.2

	Mode	Frequency [Hz]
1	1.	284.49
2	2.	416.51
3	3.	1179.6
4	4.	1449.
5	5.	1577.6
6	6.	2967.1

Figure 17: revised frequency results (left: titanium, right: stainless steel)

According to the frequency formula mentioned before, to lower the overall natural frequency, one must increase mass while reducing structural stiffness. Therefore, the revised design achieves a reduction in stiffness and an increase in the mass of the implant by extending the neck, bringing the six modes of natural frequency for both titanium and stainless steel within the range of 100Hz to 3000Hz. Additionally, the extended neck can also help improve the range of motion of the joint and reduce interference with surrounding soft tissues.

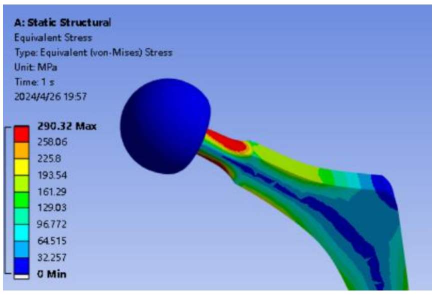
Sanity check 5:

From the research, the average mass of a hip implant is approximately 450g [10], although this can vary with size changes. The table below summarizes the mass and key dimensions of the hip implants for the initial design, iteration, and 0.73 times scaled iteration**.**

	Titanium alloy Mass	Stainless Steel Mass	Head Diameter	Plastic Deformation
Initial Design	0.67728 kg	1.2186 kg	48mm	Yes
Iterative Design	0.69499 kg	1.2505 kg	48mm	No
0.73 times scale Iterative Design	0.27036 kg	0.48645 kg	35mm	Yes

Table 3: Mass Summary

The first two designs, regardless of the material used, had a mass exceeding 650g. Such weight could potentially impose an additional burden on patients, particularly for elderly patients, as heavier implants may increase the risk of fractures. To achieve a lightweight goal, the dimensions of the iterative design were scaled down to 0.73 times, resulting in a mass and size that are closer to realistic expectations. However, after static and frequency analysis, the reduced mass and size caused plastic deformation in the stainless steel implant and pushed the sixth mode of natural frequency for both materials out of the desired range.



	Mode	Frequency [Hz]
1	1.	367.16
2	2.	547.73
3	3.	1724.
4	4.	2082.1
5	5.	2260.3
6	6.	4126.8

Figure 18: 2nd iteration issues

Moreover, it was found that titanium alloy, compared to stainless steel, has a lighter mass and higher yield stress. From multiple perspectives, titanium alloy is a more ideal material for implants.

4 Discussion

4.1 FEA Accuracy and Limitations

CAD Modelling Error

- The 3D model was independently created, which may result in a shape that is not conducive to implantation and a structure that may not be sufficiently flexible or comfortable.
- The model was incomplete, lacking components like the insert and cup.
- Analysing only one size of hip implant limits personalization, potentially leading to poor fit and increased complications.

These errors in the 3D model could lead to inaccuracies, making the analysis results potentially less applicable to real-world situations.

Incomplete Condition Settings

FEA simplifies real-world problems, often involving assumptions and approximations that can affect accuracy. In this scenario, for example:

- Not considering the gravity of the person and the hip implant.
- Load direction was always vertical
- Not specifying the exact location of fixed supports.

Numerical Error

- The simplified load values used in simulations was too low.
- S-N curves of materials sourced from Ansys, which might not be entirely accurate.
- Some referenced data might come from unreliable sources.

Discretisation Error

- FEA relies on mesh quality, but hardware constraints prevent extremely fine meshes.
- Detecting very small sharp edges that could impact stress distribution is difficult.

4.2 Conclusion

In the initial design, implants made of both materials met a 15-year lifespan, achieving 100 million loading cycles. However, the stainless steel implant exhibited plastic deformation in static analysis, and the titanium alloy implant required one more mode of natural frequency, prompting model improvements. In the iterative design, both materials met the criteria for all three analyses, but a final sanity check revealed impractically heavy designs, leading to a quick second iteration where the model was scaled down to 73% of the first iteration size. This reduction again led to plastic deformation and exceeded the 3000Hz range for the sixth mode of natural frequency.

Future designs should aim to keep natural frequencies within a safe range while reducing mass and enhancing stiffness, such as using more aggressive fillets and streamlined designs at the neck to distribute stress concentration or incorporating small support structures to slim down the neck for lower mass, all while keeping material cost considerations in mind.

Despite errors and oversights, the results of this report can still serve as a conceptual reference for further improvements and designs of hip implants through FEA analysis.

Total word count: 2456 (Excluding the title page, table of contents and references)

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