Christian Tello
10731107

COLORADO SCHOOL OF
MINES

AMFG 421 | Design for Additive Manufacturing
Project 2: Total Hip Replacement
Professor Kevin Ehlmann

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Total Hip Replacement

Introduction

In this study, Lattice design will be explored as a means of improving the displacement and functionality of traditional total hip replacements for those who would need to undergo the procedure. Lattice design with respect to additive manufacturing means that the design space (shape) that is turned into a lattice structure becomes composed of “struts”(which stress and compress like 2-D members) instead of solid material. This has the effect of reducing the weight of the design while maintaining the shape’s stiffness, and creating a part with strength values that inhibit bending. Implementing a lattice design means that the part can be additively manufactured without the need for support material, and fills the entirety of the design space (as opposed to topology optimization) This allows for precise optimization in biomedical applications because the total perimeter of the shape will remain predictable. The strength of a lattice increases proportionally with the density of the lattice increases, Total hip replacements (also known as total hip arthroplasty), are a surgical procedure that is conducted on patients who have suffered a damaged hip through arthritis or other external factors that lead to a fracture. The hip is essentially a ball and socket joint which experiences loading very dynamically throughout the day, and the procedure is substantially invasive that the process that is done must only be done once in the lifetime of the individual. Some of the obstacles being faced by patients and biomedical device designers are that over time, if the femoral stem of the hip replacement is bearing too much of the load, this can lead to an overall reduction in the bone density surrounding the implant, and makes the area unhealthy and less likely to survive fracture and could lead to further damage in the case of a fall, this is commonly referred to as shield stressing. The other obstacle is that the tip of the implant can “press” onto the bone and cause pain to the user. Lattice design introduces the ability to reduce the stiffness at the tip of the stem (increase the displacement), and the lattice’s semi-dense structure allows for the bones to grow into and create a bond with the titanium insert. The purpose of this study was to create a fully latticed total hip replacement, that would have double the displacement of a traditional THR, at the tip of the “Taper”.

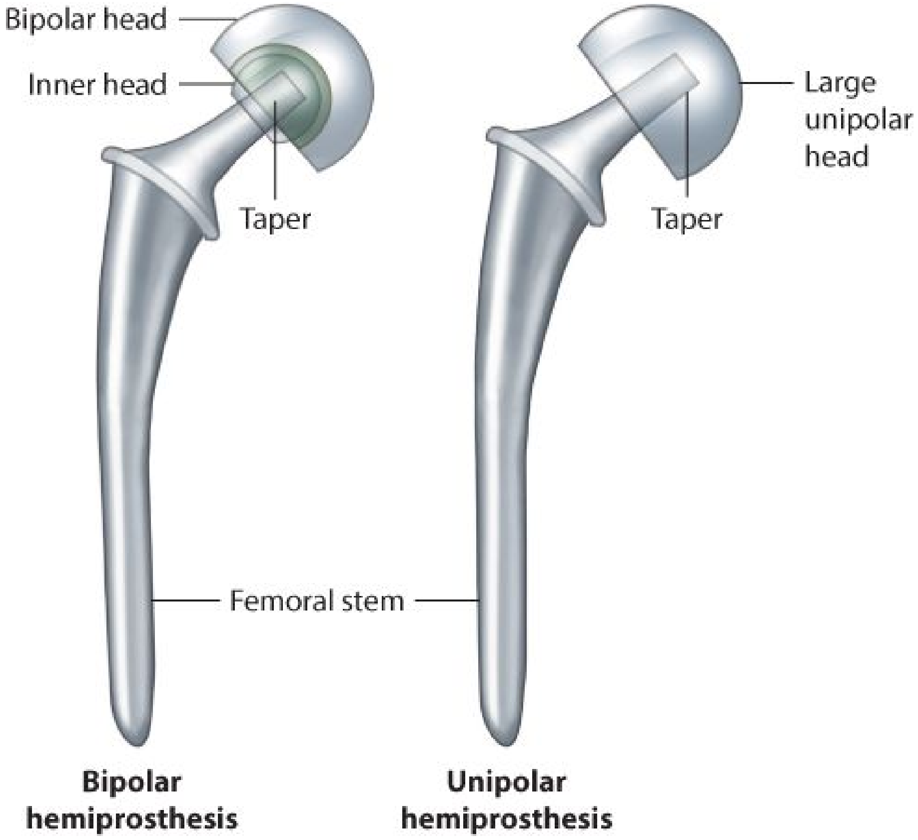


Figure 0. Traditional Total Hip Replacement

Methods

The traditional total hip replacement (seen in figure 0) is made of Ti-6Al-4V, a titanium alloy composed of the elements seen in table 1, that is non-reactive with the cells inside of the body. In this study, that will be the declared material with the following properties shown in Table 2.

Table 1: Ti-6Al-4V Composition

Components	Weight %
Aluminum	6
Iron	Max 0.25
Oxygen	Max 0.2
Titanium	90
Vanadium	4

Table 2: Material Properties of Ti -6Al-4V

Tensile Strength, Ultimate	950 MPa
Tensile Strength, Yield	880 MPa
Elongation at Break	14%
Modulus of Elasticity	113.8 GPa
Compressive Yield Strength	970 MPa

With the metal selected, and thus the components and properties decided, it was important to load the THR with the worst case scenario loading scheme to ensure that it would be a lifetime replacement. The initial design as seen in figure 1 displays the initial design, loads, and supports that had a nominal displacement of 1.79 mm.

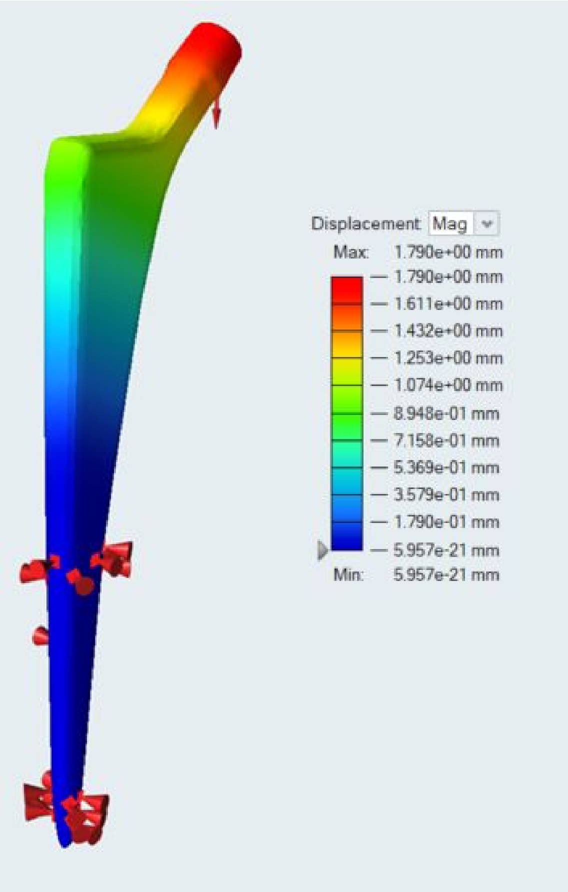
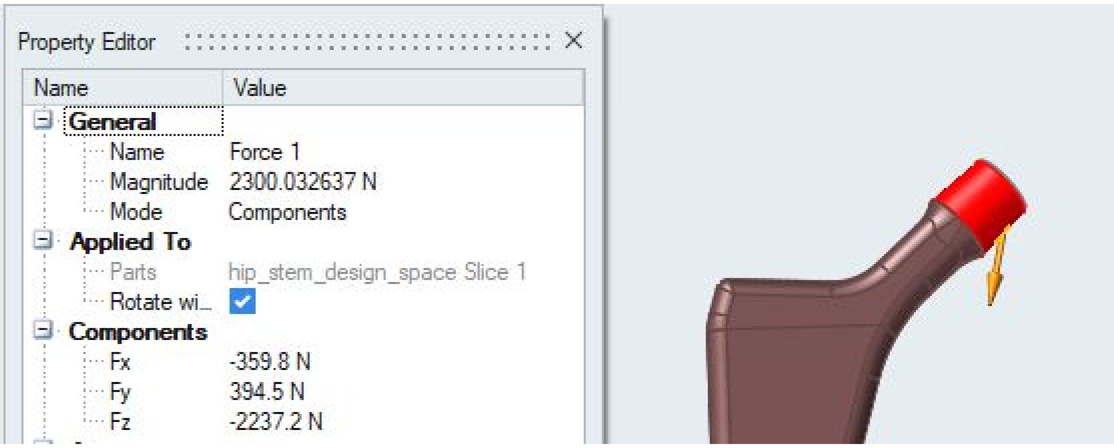


Figure 1. Initial Design, Loading, and Support

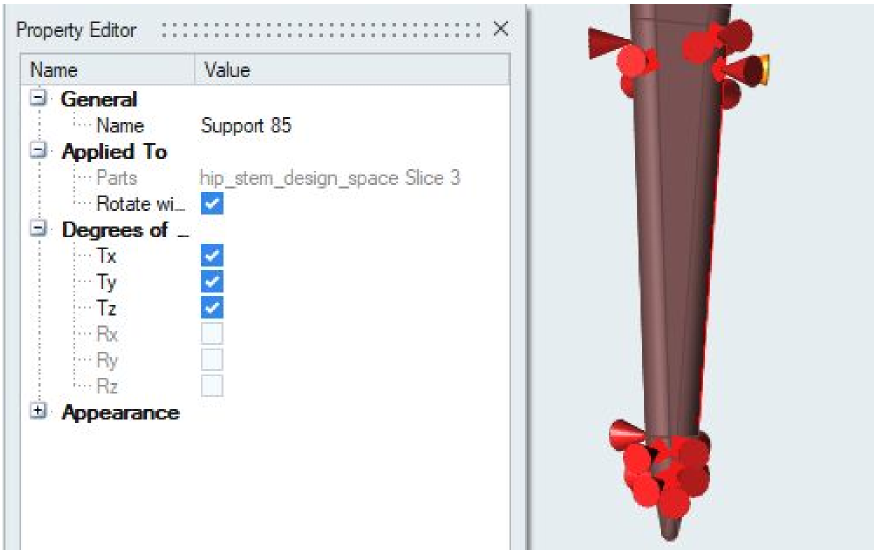
Figure 2, shows the magnitude and direction of the load applied to the taper, it is based on the biomechanical knowledge that the force that occurs in the hip joint while in movement is ~6-7 times greater than the body weight of the individual. The importance of over estimating is due to the fact that stresses in the femoral component can lead to fracture of the bone or the implant if not accounted for properly.



Name	Value
General	
Name	Force 1
Magnitude	2300.032637 N
Mode	Components
Applied To	
Parts	hip_stem_design_space Slice 1
Rotate wi...	☑
Components	
Fx	-359.8 N
Fy	394.5 N
Fz	-2237.2 N

Figure 2. Magnitude, and directional load components on taper

Figure 3 shows the properties of the supports used to simulate the “hold” on the femoral stem of the implant. There were 20 supports applied at various locations near the stem, with each eliminating only 3 degrees of freedom (translation in the X, Y, and Z direction).

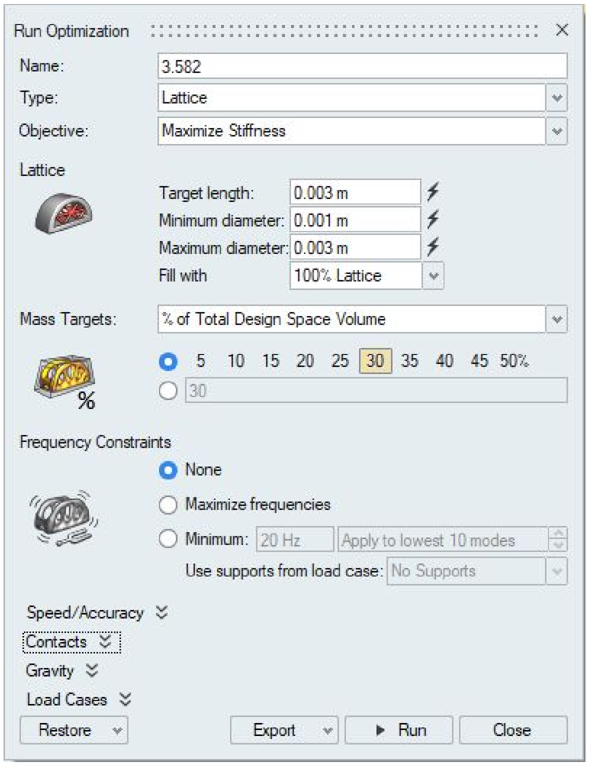


Property Editor

Name	Value
General	
Name	Support 85
Applied To	
Parts	hip_stem_design_space Slice 3
Rotate wi...	☑
Degrees of ...	
Tx	☑
Ty	☑
Tz	☑
Rx	☐
Ry	☐
Rz	☐
Appearance	

Figure 3. Layout of the Supports used in the FEA and Lattice study

Figure 4 consists of all of the parameters selected to run the lattice study. The objective function running in the background of the optimization study was to maximize stiffness. This is due to the fact that the first priority is the proper functionality of the THR, with the idea to tune the lattice parameters to create the lattice that will fulfill the design requirements of a displacement of ~3.58mm. The target length within the "Lattice" options corresponds to the "edge length" of the individual struts within the lattice, as well as the size of the elements used to conduct the finite element analysis study. The minimum and maximum diameter options are constraints placed on the diameters of the struts. A length to diameter ratio greater than 3 risks the study becoming a solid with voids as opposed to a true lattice structure, but the parameters selected fulfill this requirement. The fill with option was essential to the fulfillment of the design requirements, as any option less than "100% Lattice" meant that the design space would be filled with solid and lattice elements, which greatly reduced the overall displacement in the component. The mass target was selected as "% of total design space" because there was only one design space, and there wasn't a mass target, this was set to 30%. In this study none of the other options were changed from the default/accounted for.



Run Optimization

Name: 3.582

Type: Lattice

Objective: Maximize Stiffness

Lattice

Target length: 0.003 m

Minimum diameter: 0.001 m

Maximum diameter: 0.003 m

Fill with 100% Lattice

Mass Targets: % of Total Design Space Volume

● 5 10 15 20 25 30 35 40 45 50%

○ 30

Frequency Constraints

● None

○ Maximize frequencies

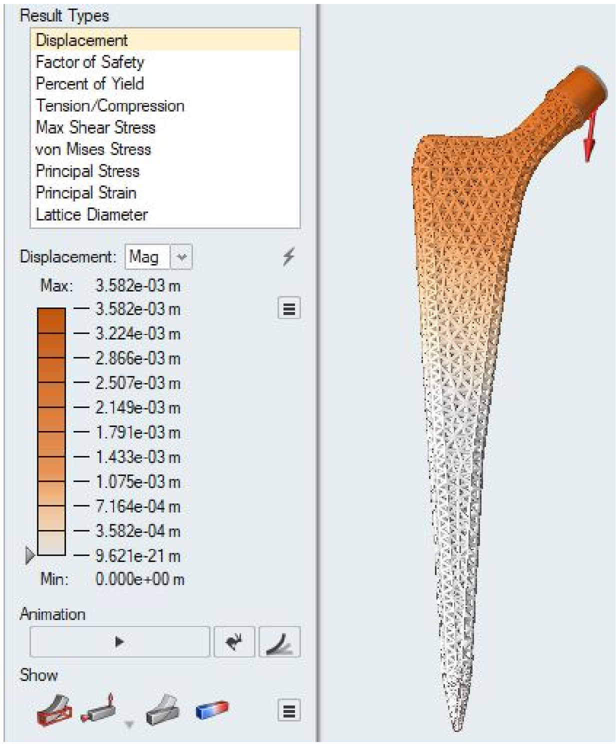
○ Minimum: 20 Hz Apply to lowest 10 modes

Use supports from load case: No Supports

Figure 4. Lattice Study Parameters

Results

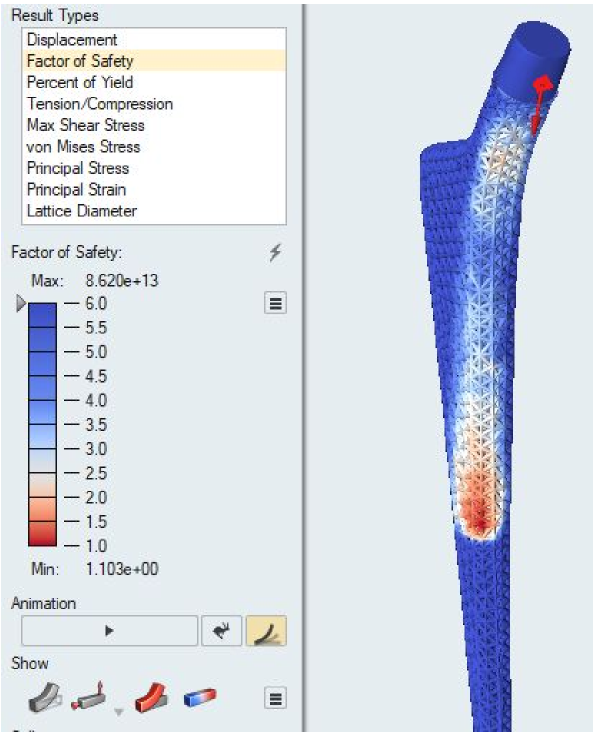
This study resulted in a predicted displacement that was 2 thousandths of a mm away from the targeted value, while still maintaining a factor of safety greater than 1 across the entire component, which fulfills the design requirement of reducing stiffness at the “taper”, this can be seen in figures 5 and 6. There is a large stress concentration along the femoral stem at the approximate location where the supports were added, but this didn’t prove to be a cause for failure of the design.


Displacement: Mag

Max: 3.582e-03 m

Min: 0.000e+00 m

Figure 5. Predicted Displacement of the THR (Maximum: 3.582)


Factor of Safety:

Max: 8.620e+13

Min: 1.103e+00

Figure 6. Factor of Safety of the THR (Minimum 1.103)

With these core parameters fulfilled, the focus was drawn toward the effective creation of the lattice that would allow for bone growth to bond the bone to the insert and reduce shield stressing, especially around the areas with the greatest factor of safety (least stress). Figure 7 shows the lattice diameters along the THR, and figure 8 shows a close up view of the lattice itself.

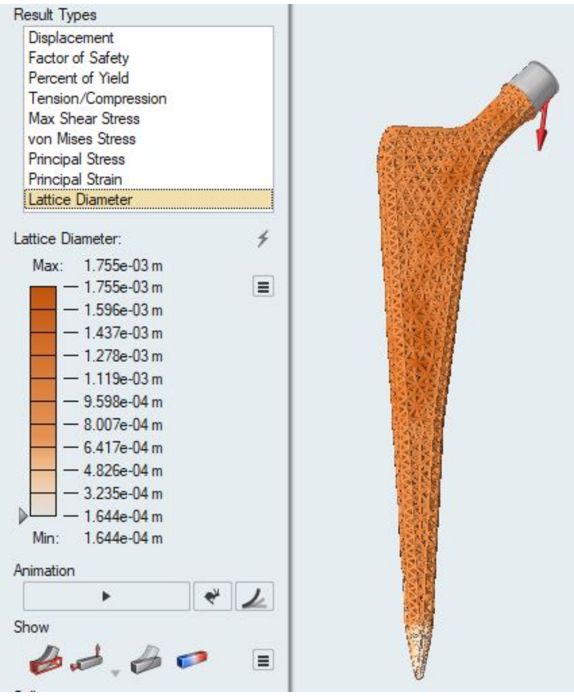


Figure 7. Lattice Diameter

Figure 7 shows that the model struggles to stay within the design constraints. The lattice diameter at the tip of the femoral stem can’t maintain its diameter of 1mm as the stem leads to a point. This could prove to be problematic depending on the type of process used to create the stem, but the lattice as seen in figure 8 in the middle of the model does keep within the design constraints.

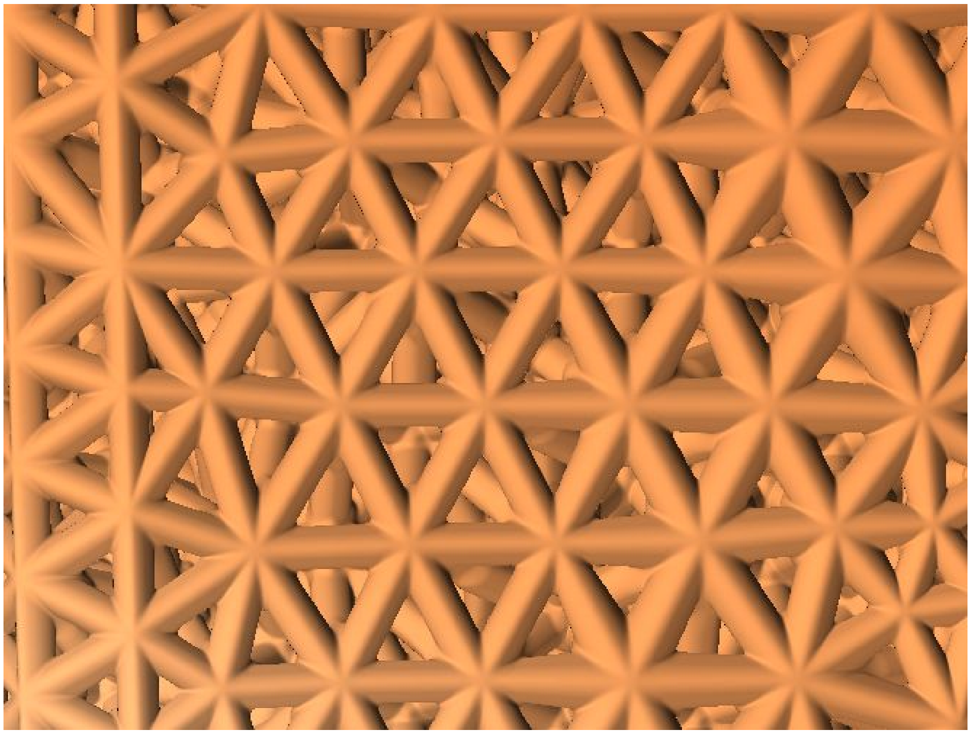


Figure 8. Close-Up of the Lattice

Figure 8 shows that the full lattice was effectively completed throughout most of the model, and the gaps may allow for bone growth. Studies conducted show that the optimal pore diameter is 0.3mm to 0.5mm in diameter for bone scaffolding, which would work at the femoral tip, but may not yield the optimal result around the remaining 90% of the THR.

Discussion

The objective of the project was to create a THR design that would have twice the nominal displacement of 1.79, within a tolerance of 0.1mm, while reducing overall shield stressing, and preventing the loss of bone density. This objective was achieved, but the secondary goal of creating a lattice structure that would promote bone growth was not fulfilled optimally. The ideal diameter of the pores for bone growth would be 0.3mm to 0.5mm, and this objective couldn’t be confirmed due to a lack of knowledge of altair inspire, and an inability to measure the distance across the lattice triangles.