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Solid-Lattice Stem Optimization Design for Hip Implants

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Abstract. The goal of this study is analyzed and design a methodology to reduce stem mass, through topology and lattice optimization of a Ti-6Al-4V hip implant, meeting yield stress requirements. Four optimization cases were studied: Topology optimization (1), Lattice design 100% (2), Lattice design 50% (3), Lattice design 25% (4). Five load cases from a study were applied for each optimization cases: Combined (LC1), standing-up (LC2), standing (LC3), going up stairs (LC4), jogging (LC5). The optimized cases design reduced stem mass approximately by 30% (1), 5% (2) ,8% (3) and 2% (4), compared with the total stem hip Ti-6Al-4V implant.

Keywords: Optimization, Lattice, Topology, Stem, Implant

Introduction

Artificial bio-parts have been around for over a thousand years. Medicine and engineering come together to create a manufactured substitute that would be integrated within an organic body. Hip implant surgeries have become successful among orthopaedic surgeries. A damage hip joint was replaced by surgery for an artificial one. Total hip arthroplasty (THA) is being implemented in large numbers worldwide. The hip joint can fracture due to various reasons. For instance: a road accident, falling down, osteoporosis, or a disease that affects joint tissues like rheumatoid arthritis [1], [2].

Almost 10% of these surgeries fail due to many reasons [1]. The dislocation of the ball in the liner or bone cement not adhering to the hip stem. Sometimes the ball section is forced out of the cup/liner section. This is mainly caused by the individual variation in sizes and shapes of every human hip joint. To solve the problem a hip implant can be design based on the patient's hip joints [3], [4].

There are various geometrical parameters of the hip joint which specify the overall shape of the joint. The parameters directly influence the accuracy of the resulting patient-specific implant geometry [5].

The implant material selection is crucial. The strength of this material should be enough to hold the body weight, also it needs to be flexible, since the joint is moving frequently. The most important criteria is the biocompatible property. Three different materials, with their maximum stress are presented for this purpose, CoCr (296.13 MPa), Ti6Al4V (294.02 MPa), 316L SS (294.51 MPa) [3].

The contact force is an important parameter during design phase. Not only the design but, also tests on strength, fixation, wear and friction of implants. Hip contact forces should be calculated from daily activities. Some studies measured the contact force of patients during frequent activities [6], [7], [8].

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Nowadays, with the introduction of additive manufacturing, doctors and engineers have more room for optimising the hip implants parts. It allows great freedom and specific designed parts [9].

Lattice optimization emphasises the mass of the material on the parts where high strength/performance is required. As a result, a mesh-like lattice is suggested in the solid part of the hip implant, a structure that could only be achieved using additive manufacturing techniques [10].

It is clear how 3D printing can be beneficial to hip implant surgery. A high technical demand is needed as advanced computer skills. This means that to produce viable results there must be a collaboration between medical and engineering and other technical teams [11], [12], [13].

A topology and lattice optimization of a hip prosthesis were produced applying OptiStruct, where fatigue and loads were considered. As a result, a reduction of 50% of stress shielding was achieved in comparison with a conventional hip implant. A prototype was then printed using Ti-6Al-4V [14].

An experimental investigation about lattice structures for optimised process parameters was generated by OptiStruct. Roughness was quantified and associated with the mechanical properties. The optimised structure enabled crushing behaviour and excellent energy absorption qualities [15].

The lattice structure satisfies bone ingrowth requirements. Results shows that 41,9% bone loss for the optimized lattice implant of the fully solid titanium in retrospective conditions. An optimized implant was tested into a patient of weigh about 860 N and age of 25 years. Loads as: slow walking, climbing up and down stairs in extreme case of them were investigated previously. This paper contributed to reduce the risk of periprosthetic fracture and probability of revision surgery [16].

The main intention of this paper is to reduce mass of the stem hip implant component through topology and lattice optimization, making it suitable to resist some cases of loads of a normal basic daily patient life.

1. Materials and Methods

A finite element method was applied to investigate von misses stress and to optimize a hip implant design as result of applied forces Figure 1. A Hip implant model were design. The geometry of this implant was founded on the Smith & Nephew Synergy titanium Ti-6AI-4V cementless size 13 standard offset stem Figure 2. Four cases were studied: Hip implant for topology optimization (1), Hip implant 100% lattice body (2), hip implant 50% lattice body (3) and hip implant 25% lattice body (4). Loads and boundary conditions are applied to each case. Topology and lattice optimizations are completed using a general hip implant design. Lattice bean diameter, length and percentage of mass reduction were optimized based on obtained results. Finally, von misses stress was evaluated and compared to the material maximum yield stress.

1.1. Materials

The titanium Ti-6Al-4V material was idealized as isotropic material. The mechanical properties of titanium offer a wide range of applications. Due to its yield strength and weight. Titanium alloys are use in aerospace engines, frames, gear, small part machining and medical implants [17] .

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Property	Value
Density	4.51 g/cm^3
Tensile strength	240 MPa
Max Yield stress	910 MPa
Modulus of Elasticity	114 GPa

Table 1. Titanium Mechanical properties Ti-6AI4V [17].

1.2. Loads and boundary conditions

Load cases, from a study were analysed and applied [18]. Where the measure loads as: Standing up, standing, stairs, and jogging can be seen in Table 2. In this study the Abductor, Iliopsoas and Vastus Lateralis applied loads to these bodies were neglected at the combined load (LC1). The lower face of the steam body was fixed as constrain and, the loads cases were applied to the stem neck for all cases as the ISO standards, as can be seen at Figure 3, [18].

Load Cases (LC)	Location	F_x(N)	F_y (N)	F_z(N)
Combined (LC1)	Head	262	-36	-681
Standing Up (LC2)	Head	650	204	-1428
Standing (LC3)	Head	576	121	-1947
Stairs Up (LC4)	Head	712	657	-2000
Jogging (LC5)	Head	774	771	-2852

Table 2. Load cases forces.

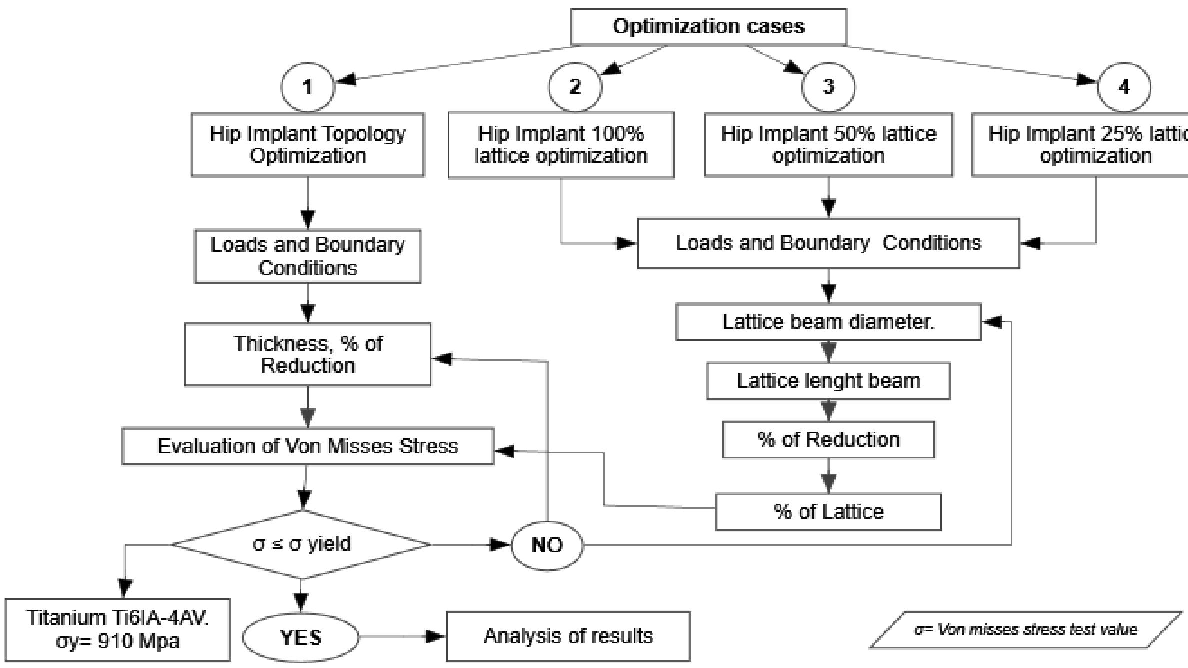

Figure 1. Stem hip implant design and optimization process (own source).

1.3. Von misses stress criteria

To evaluate the von misses stress criteria, a failure theory is used to predict part performance and durability using Inspire Altair software 2019.3.3. With this analysis, areas which have exceeded the peak stress can be identified and modified if is needed, or variation parameters can be done.

1.4. Topology and Lattice optimization

The main objective of topology optimization is to reduce the hip implant mass as the case 1 shows. Meanwhile, lattice optimization was carried in 3 solid spaces (cases 2, 3 and 4), which are represented with shell and tetra elements. Face and body centred cubic with vertical struts unit cells by Inspire Altair software Figure 4. The lattice space was built by beam elements since the diameters can be changed. The design variables were the beam diameter, length of the lattice beams, the percentage of lattice fill and percentage of mass reduction. Based on the manufacturability and cell size which varies from (1.2 - 3) mm, max bean diameter selected for the cases vary between (1.3 - 10) mm and the beam length between (3 - 4 mm). The mas target varies from (30-50) %. The objective of topology and lattice is to minimize the total volume to save material and manufacture time.

2. Results and Discussion

Lattice regions were divided in three cases 2, 3 and 4 (100%, 50%, and 25%) to analyse and interpret the effective space objective to the different optimization simulation results. The optimized solid-lattice design for each case are shown in Table 4. The optimized solid-lattice implants reduce the mass of the steam. The maximum von misses stress results after optimization process do not overcome the maximum yield stress of titanium Ti-6Al-4V 910 MPa. Moreover, in some cases the stress overcome the maximum yield stress, those cases need to add walls to the final design.

Through the optimization driven design process, the optimized implant case (1) reduced the mass body by almost 30%, case (2) 5%, case (3) 8%, and finally case (4) 2% compared to the generic implant of Ti-6AI-4V. The generic stem mass is 90.7 grams (red bar), Figure 5.

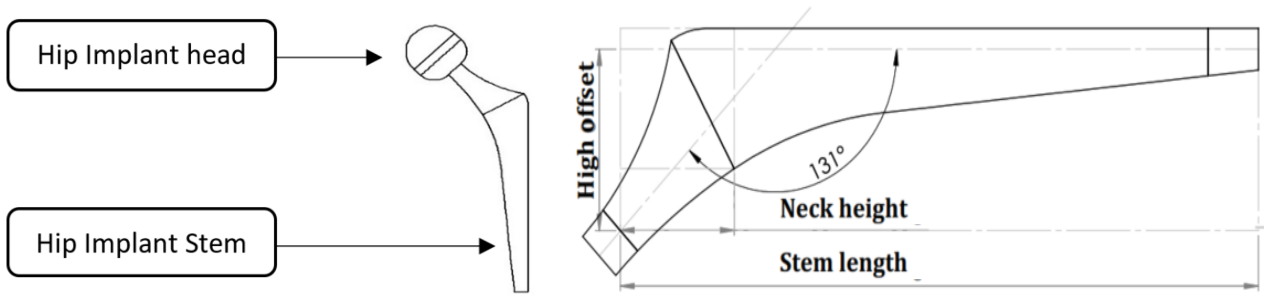

Figure 2. Total Hip implant Titanium Ti-6AI-4V and stem component (own source).

Figure 3 Loads and constrains (own source).

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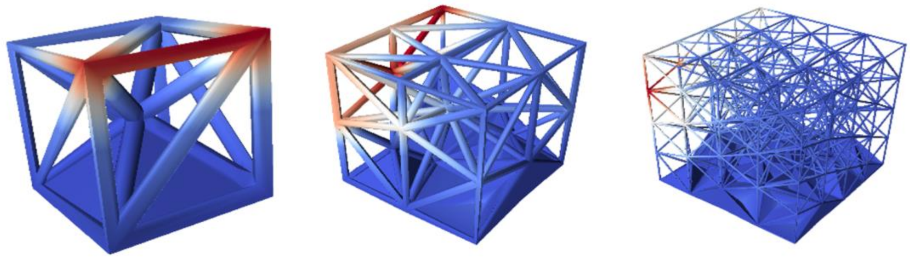

Figure 4. Nodes and lattice beams lengths and diameters structure (own source).

Optimization Cases	Load cases	Max value before Optimization (MPa)	Max value After Optimization (MPa)	Length (mm)	Max Diameter (mm)	Mass target (%)	Fill (%)	Element size (mm)	Mass after optimization (kg)
1	LC1	559	580	-	-	50	-	2.1	53
	LC2	1191	1093	-	-	50	-	2.1	81
	LC3	1187	1188	-	-	50	-	2.1	89
	LC4	879	1274	-	-	50	-	1.2	83
	LC5	1371	1360	-	-	50	-	2.1	62
2	LC1	559	892	4	6	30	10	2.1	85
	LC2	746	861	4	6	40	90	2	74
	LC3	852	930	4	6	50	90	3	86
	LC4	903	1025	4	10	50	50	3	61
	LC5	903	1018	4	10	50	50	2.5	86
3	LC1	339	675	4	6	30	10	3	74
	LC2	823	902	4	6	30	10	2.5	88
	LC3	987	961	4	8	30	90	2	59
	LC4	691	916	4	8	30	50	3	88
	LC5	719	976	4	8	30	60	3	68
4	LC1	531	649	4	1.3	30	10	3	89
	LC2	572	586	4	2	35	90	2.5	65
	LC3	596	817	4	3	35	90	1.5	90.3
	LC4	689	891	3	3	30	90	1.5	69
	LC5	618	867	3	3	40	90	2.1	90.5

Table 3. Von misses stress values, optimization characteristics and mass after optimization for each case.

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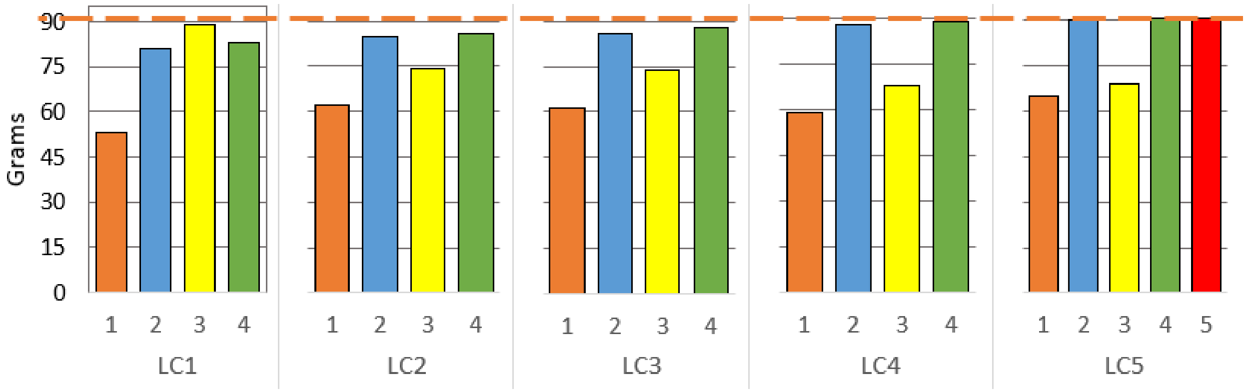


Figure 5. Stem weight comparison between load cases and optimization cases. Red bar represents the total weight of genetic standard 13 stem (own source).

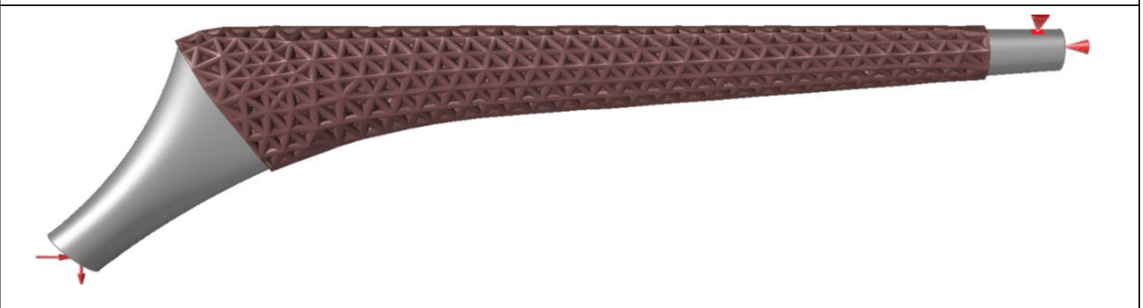
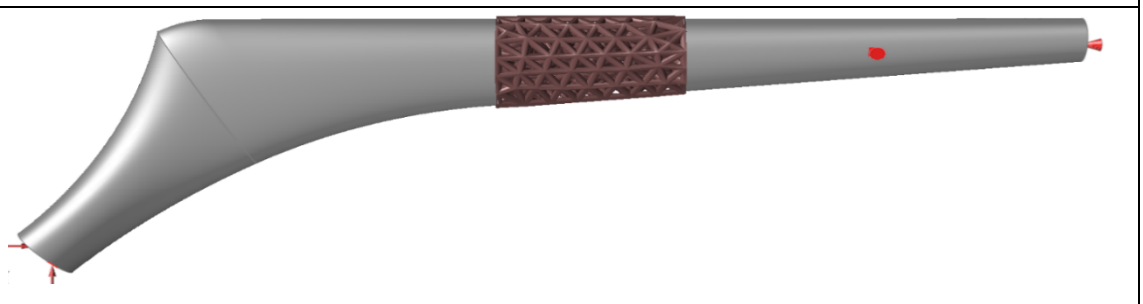
O.C	*Stem hip topology and lattice optimization implants*
1	
2	
3	
4	

Table 4. Stem topology and lattice optimization implants cases (1), (2), (3) and (4) design results.

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Conclusions

This methodology can be employed to design standard hip implant prostheses and reduce printed time and cost. Customized prostheses can be constructed and metal-printed for specific patient's geometry and bones, getting the best possible treatment outcomes for everyone.

Nevertheless, there are some limitations for this study. An analysis with femur bone, Iliopsoas, abductor, and vastus lateralis is needed. Besides and study of fatigue to survive cycles, for each case can give an approximate stress result and a new criterion for optimization. A real optimized 3D metal printed model must be required to compare and analysed results. However, some details work is needed before manufacturing process.

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