






## PAPER

# Topological Optimization of the Femoral Stem: A Comparative Study between Titanium Ti-6Al-4V and Cobalt-Chromium Alloy

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## ABSTRACT

The present study evaluates the structural behavior of a topologically optimized femoral stem, comparing two metallic materials commonly used in orthopedics: Ti-6Al-4V titanium and cobalt-chrome alloy (CoCr). The three-dimensional model was developed in SolidWorks and analyzed using finite element simulations in ANSYS, following the guidelines of ASTM F2996-20. Six optimized configurations were defined by varying the percentage of retained mass (25%, 35%, and 45%) for each material, assessing displacements, von Mises stresses, and mass reduction. The results show that the configurations with higher retained mass (J1 and J5) exhibited less deformation and more uniformly distributed stresses, remaining within the elastic regime. The optimized design in Ti-6Al-4V with 25% retained mass stood out, achieving a 27.9% weight reduction with high structural safety factors. This study confirms that topological optimization, when applied to clinically approved metallic materials, enables the development of orthopedic implants that are stronger, lighter, and mechanically compatible, contributing to sustainable surgical solutions.

## KEYWORDS

topology optimization, femoral stem, mass reduction, structural optimization, orthopedic implants

## 1 INTRODUCTION

Total hip arthroplasty (THA) is one of the most common and effective surgical procedures for restoring joint function in patients with severe femoral joint damage, whether caused by degenerative diseases, trauma, or malformations [1], [2], [3]. In this procedure, the design and proper selection of the femoral stem are crucial to achieve efficient biomechanical integration and favorable load distribution during the patient's daily activities [4], [5], [6].

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Currently, the structural design of implants has evolved thanks to the use of advanced computational techniques, including topological optimization [7], [8], [9], [10], [11]. This tool allows you to redesign the internal geometry of a component while maintaining its structural and functional integrity, by redistributing the material based on the applied stresses [12], [13]. By eliminating mechanically unnecessary areas, a reduction in mass is achieved without compromising the rigidity or stability of the implant, which is especially relevant for orthopedic applications [14].

In recent years, topological optimization has become an important tool in the design of femoral stems, allowing for a reduction in implant mass without compromising its mechanical strength or biomechanical functionality. Recent research has shown that the use of materials such as Ti-6Al-4V and optimized porous structures can significantly reduce the phenomenon of “stress shielding” and improve the bone integration of the implant [1], [14], [15], [16], [17]. In particular, the application of metamaterial-type structures and functional gradients has made it possible to develop stems with mechanical properties closer to those of human bone, resulting in better load transfer and a reduction in periprosthetic bone resorption [14]. At the same time, finite element simulations have facilitated the prediction of structural behavior under physiological conditions, contributing to more appropriate personalization of implant design [15], [17].

On the other hand, the use of additive manufacturing technologies has significantly expanded the manufacturing possibilities for femoral stems with complex designs derived from computational optimization processes. Various studies have incorporated metallic alloys in topologically optimized configurations to improve fatigue resistance and the primary stability of the implant [1], [12], [13], [18]. The inclusion of internal porous structures, whether through additive manufacturing or hybrid techniques, has shown substantial improvements in the biomechanics of the stem by reducing stress concentrations and allowing for proper ossification at the bone-implant contact area [1]. Likewise, multiscale analyses have shown that varying the relative density within the stem volume allows for better stress distribution and adapts the design to diverse physiological loading scenarios [12].

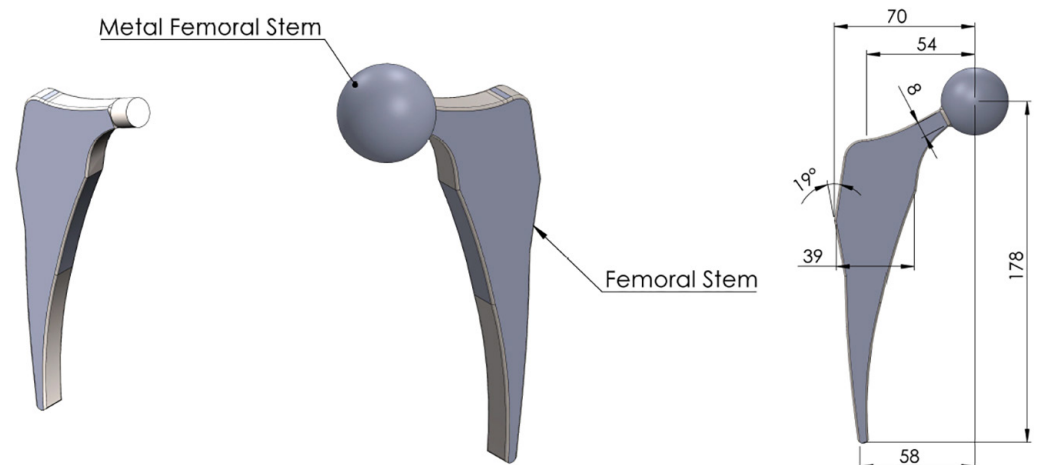
In this context, the present study aims to evaluate the static behavior of a femoral stem subjected to topological optimization, using two metallic materials commonly employed in orthopedics: Ti-6Al-4V titanium and cobalt-chromium alloy. The simulations are carried out using the finite element method in ANSYS software, in accordance with ASTM F2996-20, which pertains to the computational analysis of implantable medical devices. This approach makes it possible to identify the material that demonstrates the best performance in terms of stresses, deformations, and structural strength, thereby contributing to the design of lighter implants that are mechanically compatible with human anatomy [19], [20]. The present study delves into the static behavior analysis of a topologically optimized femoral stem, focusing on two widely used metallic materials in orthopedic applications: Ti-6Al-4V titanium and cobalt-chromium alloy. By employing finite element method simulations through ANSYS software, the research adheres to the ASTM F2996-20 standard, which governs the computational analysis of implantable medical devices. Similarly, in other fields of engineering, the usefulness of combining computational design with innovative processes has become evident, as in 3D animation, where curriculum development seeks to integrate technical precision with creativity in professional training [21]. This methodological

approach enables a comprehensive evaluation of stress distribution, deformation patterns, and overall structural integrity of the femoral stem under various loading conditions.

The comparative analysis of Ti-6Al-4V titanium and cobalt-chromium alloy aims to discern the material that exhibits superior performance characteristics in the context of femoral stem implants. By assessing factors such as stress concentration, strain distribution, and overall mechanical compatibility with human bone, the study seeks to contribute valuable insights into the development of optimized implant designs. The ultimate goal is to facilitate the creation of lighter, more efficient femoral stems that not only meet the stringent mechanical requirements of orthopedic applications but also enhance patient comfort and long-term implant success rates. This study has the potential to significantly impact the field of orthopedic biomechanics, offering a data-driven approach to material selection and implant design optimization.

## 2 MATERIALS AND METHODS

The three-dimensional model of the femoral stem used in this study was designed to represent a typical metallic hip implant. The geometry considers a shape that is anatomically compatible with the femoral canal, ensuring adequate load distribution during the simulation. Figure 1 shows an overview of the implant system, composed of the spherical femoral head and the metallic stem, which constitute the main focus of the structural analysis and topological optimization developed in this work. The design was modeled in SolidWorks software, which allowed for the definition of geometric details and the preparation of the model for subsequent export to the Ansys finite element simulation environment.



**Fig. 1.** Anatomically compatible three-dimensional model of the metallic femoral stem prior to topological optimization [22]

The simulation considered two materials widely used in biomedical applications: Cobalt-Chromium alloy (CoCr alloy) and Titanium Ti-6Al-4V. Table 1 shows their main mechanical properties, which were used as input parameters in the topological optimization process of the femoral stem in ANSYS.

**Table 1.** Mechanical properties of the materials used

Material	Density (Kg/m <sup>3</sup> )	Modulus of Elasticity (GPa)	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	References
CoCr alloy	8500	200	612	1503	[23] [24]
Ti-6Al-4 V	4500	114	880	930	[25], [26], [27], [28], [29], [30]

## 2.1 Simulation setup for topology optimization

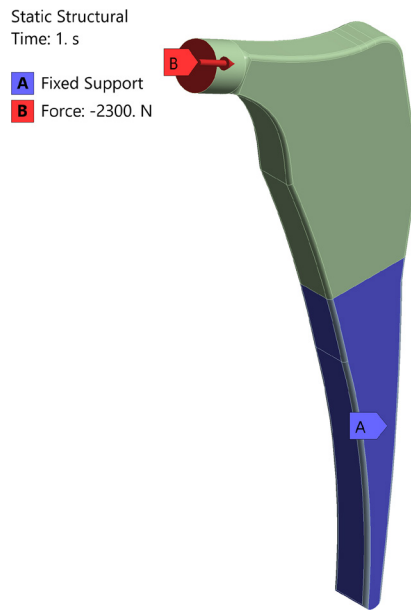
In Table 2, the planning of the topological optimization iterations to be carried out on the femoral stem model is presented. Three different configurations of the Response Constraint parameter have been defined, varying the percentage of mass to be retained between 25% and 45%. In each case, the optimization objective will be the minimization of structural compliance (stiffness maximization), with the output variables evaluated being the final mass, the maximum von Mises stresses, and the total deformation of the model. This table provides a comparative framework that will be important for the analysis of results in later stages of the study.

**Table 2.** Iteration matrix for the comparative analysis of the structural topological optimization of the femoral stem

Iteration	Material	Configured Retained Mass Percentage	Optimization Objective	Control Variable	Indicators to Analyze
J1	CoCr alloy	25%	Minimize compliance	Mass percentage	Mass, von Mises stress, total deformation
J2	CoCr alloy	35%	Minimize compliance	Mass percentage	Mass, von Mises stress, total deformation
J3	CoCr alloy	45%	Minimize compliance	Mass percentage	Mass, von Mises stress, total deformation
J4	Ti-6Al-4V	25%	Minimize compliance	Mass percentage	Mass, von Mises stress, total deformation
J5	Ti-6Al-4V	35%	Minimize compliance	Mass percentage	Mass, von Mises stress, total deformation
J6	Ti-6Al-4V	45%	Minimize compliance	Mass percentage	Mass, von Mises stress, total deformation

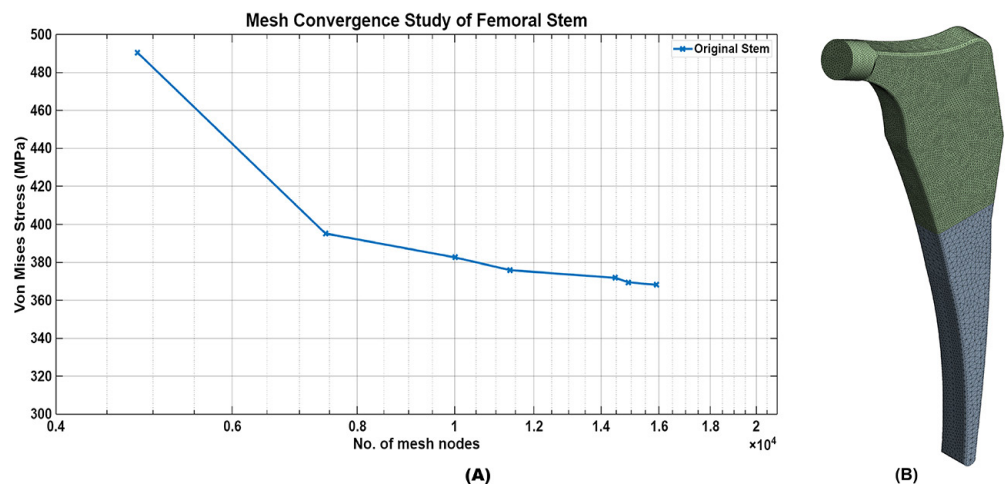
## 2.2 Boundary conditions and meshing

With the goal of ensuring a realistic representation of the load borne by the human body, the boundary conditions of the femoral stem were defined in accordance with the guidelines of the ASTM F2996-20 standard [31], which establishes criteria for the application of loads in finite element simulations of implantable medical devices. In this study, the distal end of the stem was completely fixed using a fixed support, and an axial force of 2300 N was applied to the femoral head (see Figure 2). This loading and restraint configuration has previously been used and validated in relevant studies related to the structural analysis of orthopedic stems. [32], [33], [34], [35], [36].



**Fig. 2.** Boundary conditions of the femoral stem

To ensure the accuracy of the results in the finite element analysis, a refined mesh was applied to the femoral stem model, as shown in Figure 3. The generated mesh consisted of 114,954 nodes, ensuring an appropriate balance between numerical accuracy and computational cost. Additionally, a mesh convergence study was conducted, verifying that the variations in results between successive refinements were minimal, which validates the quality of the mesh used [4], [36], [37], [38].



**Fig. 3.** Mesh convergence analysis of the femoral stem: (A) Convergence curve of von Mises stress as a function of the number of nodes, and (B) Refined mesh of the femoral stem

### 3 RESULTS AND DISCUSSIONS

#### 3.1 Static analysis original stem

Figure 4 shows the results of the static analysis of the original femoral stem made of Ti-6Al-4V alloy, where a maximum total deformation of 0.142 mm was obtained, located in the proximal region of the implant, indicating greater flexibility

of the material under the applied load. Regarding the equivalent von Mises stress, the maximum recorded value was 404.87 MPa, also concentrated in the transition zone near the neck of the stem. These results show that titanium allows for greater deformations without exceeding stress limits, which could favor load distribution—an aspect that will be contrasted with the CoCr model and the optimized version.

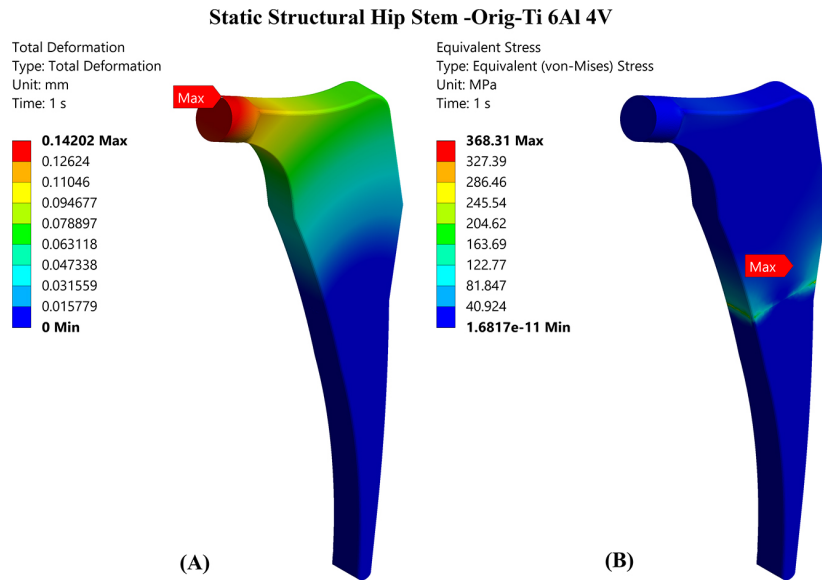


Fig. 4. Distribution of total deformation and equivalent stress in the original Ti-6Al-4V femoral stem: (A) Total deformation, (B) von Mises equivalent stress

Figure 5 shows that the maximum total deformation in the CoCr alloy femoral stem was 0.081 mm, located in the proximal area, while the equivalent von Mises stress reached a maximum of 408.5 MPa in the same region. These results indicate that, although the material offers high rigidity, it presents stress concentrations that could compromise its long-term performance, which will be compared with the titanium model and the optimized version.

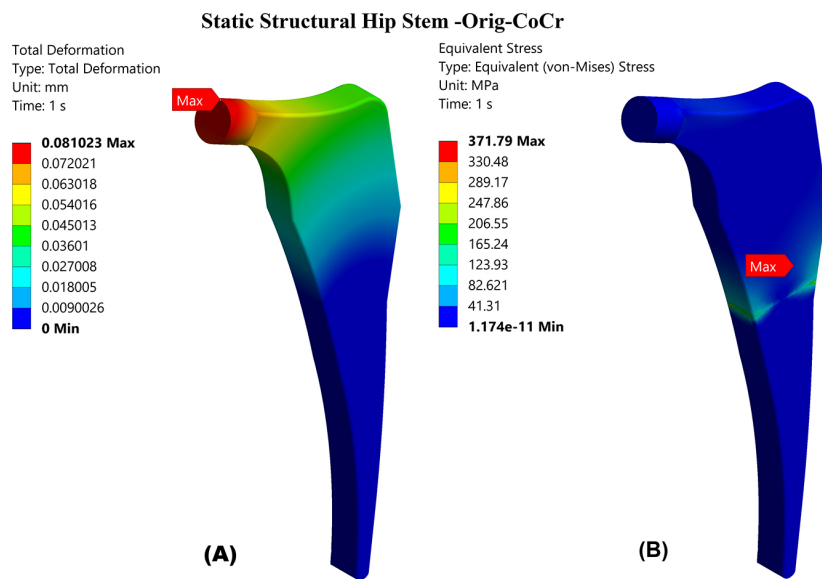
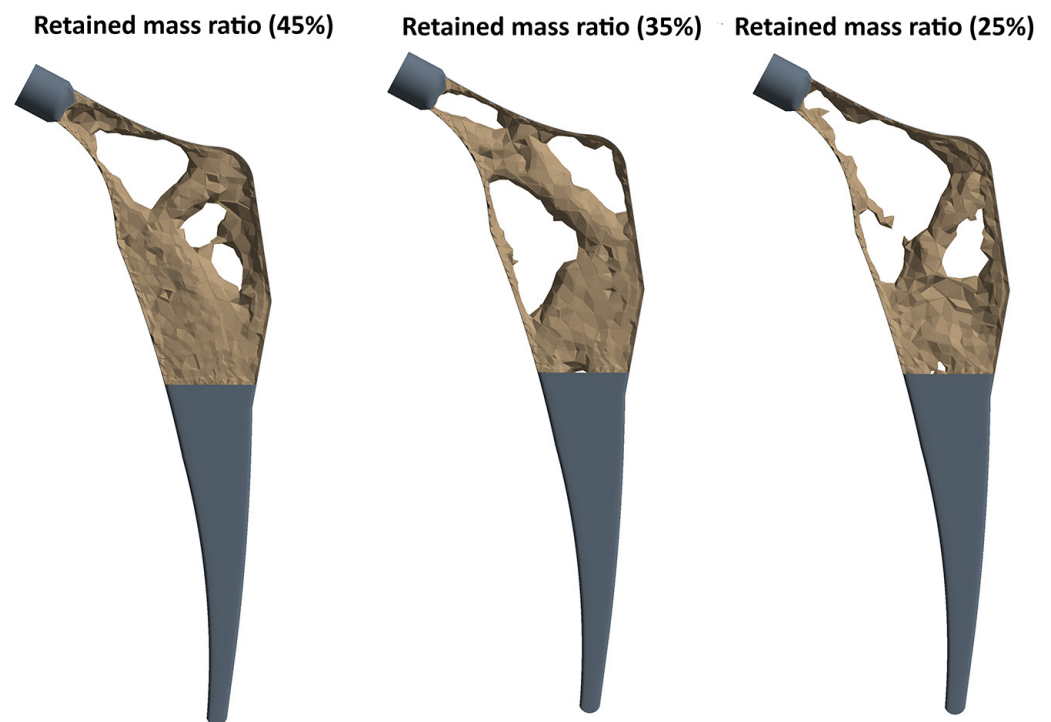


Fig. 5. Distribution of total deformation and equivalent stress in the original femoral stem made of CoCr alloy: (A) Total deformation, and (B) von Mises equivalent stress

### 3.2 Topology optimization stem

For each retained mass configuration (25%; 35%; and 45%), the ANSYS software executed a variable number of iterations until reaching a convergent shape. Figure 6 shows the visual results for each stage, differentiating the regions with higher and lower topological density. These representations allow for a preview of the structural distribution that the algorithm considers most efficient. As observed, the lower the percentage of retained mass, the more material was marked for removal, and the number of iterations needed for the simulation to converge also increased. In subsequent simulations, only the outline of the casting generated by the Ansys software was considered, while the original thickness of the femoral stem was kept constant.



**Fig. 6.** Resulting configurations of the femoral stem after topological optimization with different retained mass ratios (45%, 35%, and 25%)

### 3.3 Static analysis of optimized stem

In Figure 7, the total deformation of femoral stems optimized with Titanium Ti-6Al-4V is shown for three levels of material retention: 25% (A), 35% (B), and 45% (C). Model (A) exhibited the greatest deformation (0.24874 mm), indicating lower structural rigidity. As the retained mass increased, the displacements progressively decreased, being 0.21704 mm in (B) and 0.1714 mm in (C), reflecting an improvement in mechanical stability with a greater preserved volume.

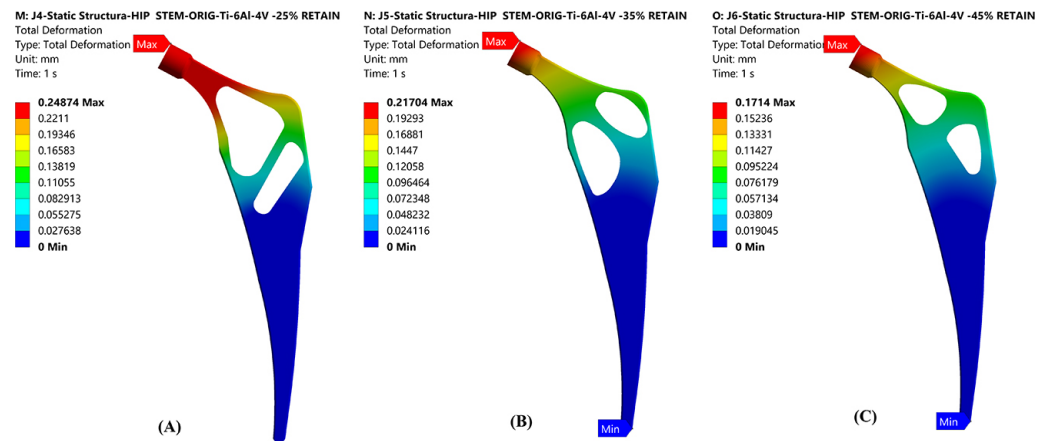


Fig. 7. Maximum deformation in the optimized femoral stem with Ti 6Al 4V for three levels of material retention (A: J4–25%, B: J5–35%, and C: J6–45%)

Figure 8 shows the equivalent von Mises stress for the same configurations. Case (A) recorded the highest stress (622.06 MPa), while models (B) and (C) reached similar but lower values (380.88 MPa and 380.9 MPa, respectively), with a more homogeneous distribution. These results indicate that design (C) is the most efficient, as it combines low deformation with controlled stresses.

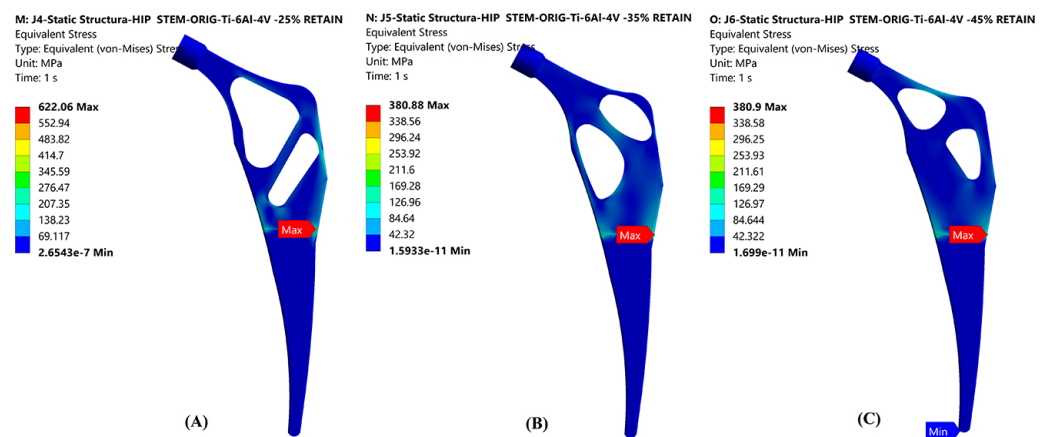


Fig. 8. Maximum stresses in the femoral stem optimized with Ti 6Al 4V for three levels of material retention (A: J4–25%, B: J5–35%, and C: J6–45%)

Figure 9 shows the total deformation of the optimized femoral stems in three configurations with material retention of 25% (A), 35% (B), and 45% (C), using Cobalt-Chromium alloy. Model (A) exhibited the greatest deformation (0.14182 mm) due to its lower structural stiffness. In (B), the deformation was reduced to 0.12382 mm, demonstrating an improvement in the balance between weight and stiffness. Model (C) showed the least deformation (0.097777 mm), indicating a mechanically more stable design with an adequate structural response to static loads.

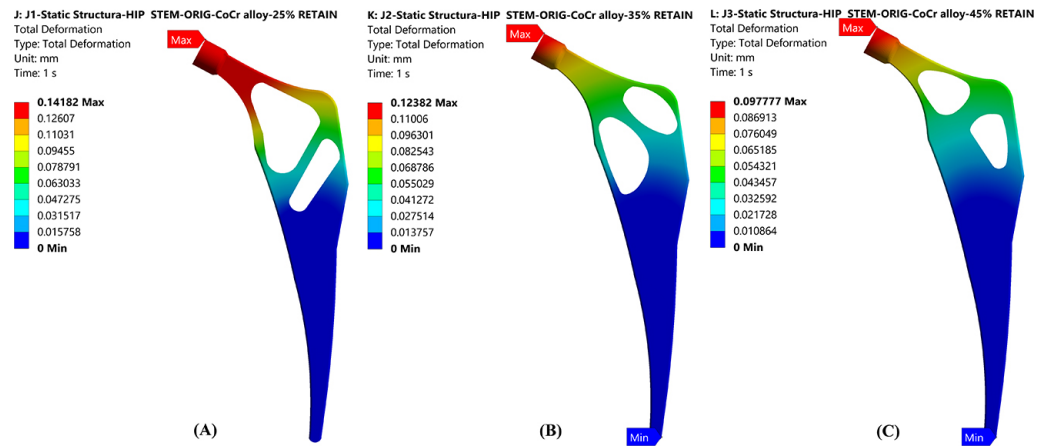


Fig. 9. Total deformation in the femoral stem optimized with CoCr alloy for three material retention levels (A: J1–25%, B: J2–35%, and C: J3–45%)

In Figure 10, the equivalent (von Mises) stress is analyzed for the same configurations. Model (A) reached a maximum stress of 625.87 MPa, with high concentration in critical areas. In contrast, models (B) and (C) exhibited similar stresses (384.12 MPa and 383.89 MPa, respectively), but with better internal distribution. These results indicate that model (C) combines low deformation and controlled stress levels, positioning it as the most efficient option from a biomechanical standpoint.

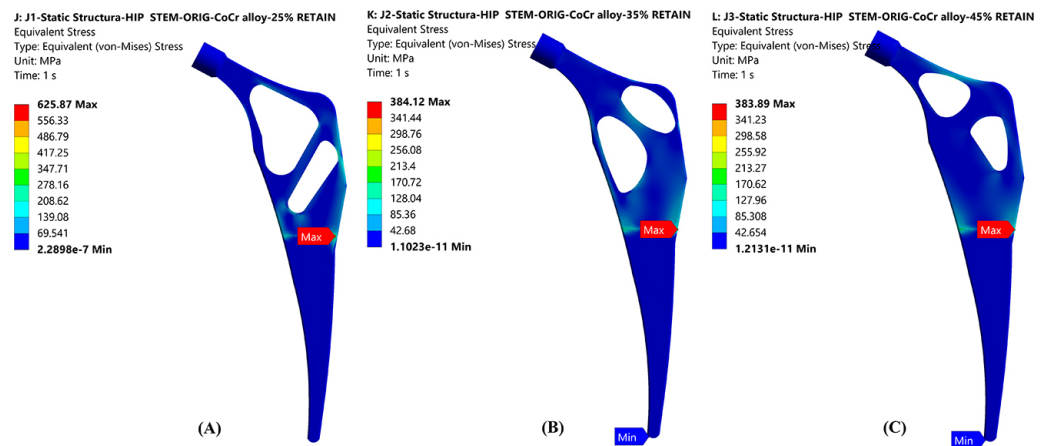


Fig. 10. Maximum stresses in the optimized femoral stem with CoCr alloy for three levels of material retention (A: J1–25%, B: J2–35%, and C: J3–45%)

### 3.4 Discussions

The results shown in Figure 11 demonstrate that the configurations with the lowest retained mass (J1 and J4) reached the highest von Mises stress values, exceeding 620 MPa, accompanied by greater deformations, which reflects a decrease in structural stiffness. This trend is consistent with what was reported by Tuninetti et al. [13], who observed that the models with extreme structural reduction also showed critical stress concentrations in the stem neck. Likewise, the study of Munteanu et al. [18], it recorded in an optimized stem stress and strain values of 349 MPa and 0.741 mm, respectively. In contrast, our study shows that configurations with 35% retained mass (J2 and J5) achieve an optimal balance between maximum stress (approximately 380 MPa) and low strain (0.249 mm and 0.124 mm, respectively), thus improving structural efficiency. This performance surpasses that of the model evaluated by Ceddia [1],

who reported stresses of up to 810 MPa in Ti-6Al-4V stems, as well as the multiscale study of Xiao et al. [12], where stresses exceeding 640 MPa were observed under certain loading conditions. Compared to these studies, our proposal shows a lower and more homogeneous stress distribution, higher safety factors, and less deformation, highlighting its mechanical strength and suitability to orthopedic design criteria.

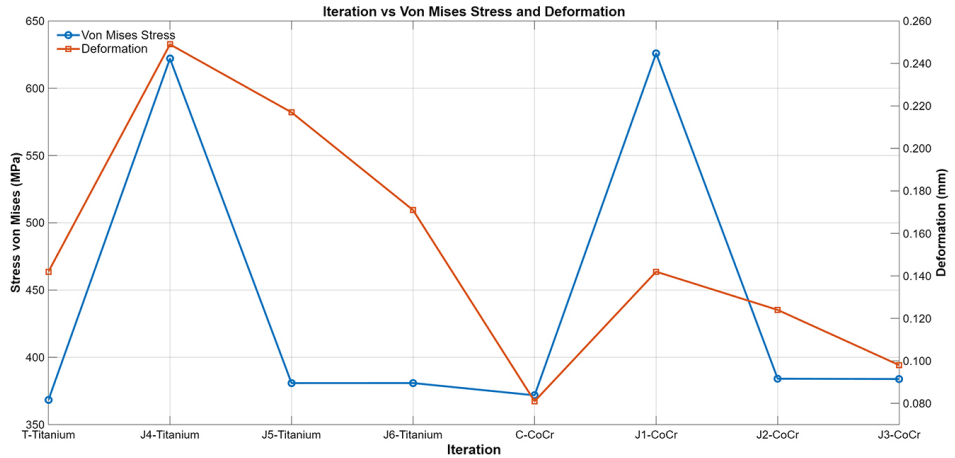


Fig. 11. Comparison of equivalent von Mises stress and total deformation in the different iterations of topological optimization of the femoral stem

As shown in Figure 12, configurations J1 and J5 managed to reduce the implant mass by 27.9% and 20.4%, respectively, while remaining within mechanical safety limits, which represents a significant improvement compared to other studies. For example, the study by Munteanu et al. [18], a 15% mass reduction was achieved, similarly in the study by Ceddia [1], the weight reduction achieved was 30% using topological optimization, with greater displacement than the initial one. Likewise, the article by Zdobyskyi et al. [15] on nanocomposite stems concludes that up to 30% of the material can be reduced without affecting strength, although this is achieved using carbon-reinforced polymers. Unlike these approaches, our work achieves similar reductions using metal alloys (Ti-6Al-4V and CoCr) that are commonly used in FDA-approved clinical applications, in compliance with standards such as ASTM F2996-20. These results further support that topological optimization can be effectively implemented in metallic materials, maintaining structural performance and providing solutions that are more applicable in the real surgical environment.

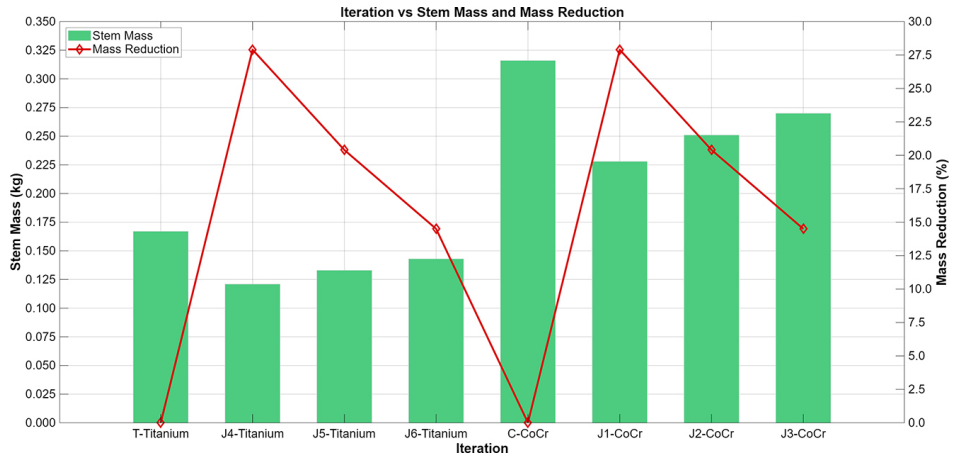


Fig. 12. Variation of the femoral stem mass and percentage of reduction obtained throughout the topological optimization iterations

## 4 CONCLUSIONS

This study demonstrated that topological optimization is an effective strategy for reducing the weight of femoral stem implants without compromising their structural integrity. Through finite element simulations in ANSYS, Ti-6Al-4V and CoCr alloys were evaluated in six optimized configurations. The results showed that configurations J1 (CoCr) and J5 (Ti-6Al-4V) exhibited the lowest von Mises stresses (622.06 MPa and 384.12 MPa, respectively), which remained within the elastic regime of their respective alloys, as well as the lowest deformations (0.124 mm and 0.249 mm), with safety factors greater than 1.4. Between the two materials, the Ti-6Al-4V titanium alloy (J5 configuration) stood out as the optimal option by providing a lighter structure (27.9% reduction in mass), acceptable maximum stresses, and low deformation, which represents an advantage from a biomechanical standpoint. This work proposes a reproducible and low-cost alternative for the development of orthopedic implants using conventional manufacturing methods, contributing to the design of sustainable, efficient prosthetic solutions that are aligned with current clinical standards. This study's findings highlight the significant potential of topological optimization in enhancing femoral stem implant design. By employing finite element simulations in ANSYS, the researchers evaluated six optimized configurations using Ti-6Al-4V and CoCr alloys. The results revealed that configurations J1 (CoCr) and J5 (Ti-6Al-4V) exhibited superior performance, with the lowest von Mises stresses and minimal deformations, while maintaining safety factors above 1.4. These outcomes demonstrate that structural integrity can be preserved even with substantial weight reduction in implant design.

The Ti-6Al-4V titanium alloy, particularly in the J4 configuration, emerged as the optimal choice for femoral stem implants. This configuration achieved a remarkable 27.9% reduction in mass while maintaining acceptable maximum stresses and low deformation. Such characteristics are crucial from a biomechanical perspective, as they can potentially improve implant longevity, reduce the risk of stress shielding, and enhance overall patient comfort. Furthermore, the study's approach offers a reproducible and cost-effective method for developing orthopedic implants using conventional manufacturing techniques, paving the way for more sustainable and efficient prosthetic solutions that align with current clinical standards.

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