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Topology Optimization of Spinal Cage Designs for Improved Stress Distribution and Bone Graft Window

Meltem ERYILDIZ *1

Abstract

Interbody fusion is utilized as a treatment for spinal degenerative diseases. Spinal cages, also known as intervertebral cages or interbody fusion devices, are implants employed in spinal surgery to address these conditions and promote spinal stability. These cages are inserted into the intervertebral space between adjacent vertebrae, replacing the damaged or degenerated disc. Spinal cages aid in the distribution of loads and stress at the fusion site and often incorporate a dedicated area for bone graft material. In this study, a topology optimization approach was employed to develop distinct spinal cages featuring a bone graft window. The mechanical behavior of the spinal cages under loading conditions was simulated and evaluated using finite element analysis. Following optimization, a finite element model analysis estimated the maximum stresses and compared them to the initial model. For topology optimization, reductions of 30%, 50%, and 70% in mass were defined. Both the 50% and 70% mass-reduced designs, featuring an open window, are deemed suitable for bone graft placement and stress distribution.

Keywords: Interbody fusion, spinal cage, topology optimization, FEA, mass reduction

1. INTRODUCTION

A crucial component of the human body for connecting and supporting weight is the spine. The prevalence of spinal degenerative disorder has gradually increased with the aging of the population. Patients with spinal degenerative disorders who do not respond to conservative treatment frequently require surgical treatment. Spinal degenerative disorders can be effectively treated using interbody fusion [1]. The insertion of a fusion cage between the vertebrae is necessary for interbody fusion. The spinal interbody fusion cage is a small, porous, hollow implant with a form that can be either cylindrical or almost cuboid. It can restore physiological disc height by replacing the degenerative disc and disengaging the intervertebral body. The hollow and porous cage can be filled with bone grafts, which will allow bone to grow through the cage and lead to bony fusion. Additionally, it can boost fusion speed and mechanical strength [2]. The interbody fusion cage's size, shape, and bone-grafting capacity are crucial elements impacting how well the fusion will work. However, the majority of fusion cages currently in use have a universal design and merely vary in size. The use of universal interbody fusion cages may

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decrease the fusion rate and raise the likelihood of surgical failure due to mismatched sizes, shapes, and volumes of the bone graft window because of the wide variation in the pathological environments of patients. As a result, scientists are now concentrating primarily on designing interbody fusion cages [3].

Topology optimization is a computational design process used to optimize the material distribution within a given design space to achieve the best possible performance. It is commonly employed in engineering disciplines, such as mechanical, structural, and aerospace engineering [4, 5]. The goal of topology optimization is to determine the optimal layout or distribution of material within a predefined design domain, subject to specified constraints and objectives. The process starts with an initial design space, which represents the overall shape and boundaries of the structure or component being optimized [4-6].

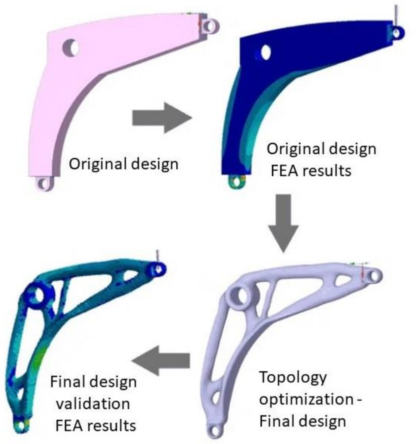

Figure 1 Topology optimization process

Using numerical methods and algorithms, topology optimization iteratively redistributes material within the design domain to maximize performance while satisfying design criteria. During the optimization process, regions with excessive material that do not contribute significantly to the desired performance are systematically removed or minimized, resulting in a more efficient design. At the same time, material is added or reinforced in areas where it is necessary to meet the performance requirements. Topology optimization considers various factors such as loads, boundary conditions, material properties, and manufacturing constraints. It often utilizes finite element analysis (FEA) techniques to simulate and evaluate the structural behavior under different conditions. As shown in the topology optimization process in Figure 1, the majority of topology optimization techniques are carried out by combining the concepts of CAD (Computer Aided Design), FEA, and various optimization algorithms in consideration of various manufacturing techniques [6, 7].

Topology-optimized structures exhibit complicated geometric configurations. Due to the difficulty of producing these novel structures using traditional methods (such as casting or machining), additive manufacturing offers a strong opportunity for topology optimization [8].

It has been demonstrated that topology optimization of fusion cages effectively increases the available area for bone grafts; however, stress shielding remains a concern [9, 10]. Zhong et al. [11] utilized topology optimization to design a new cage and investigate stress distribution in the lumbar spine. Tovar et al. [12] utilized finite element-based optimization techniques to achieve an optimal design for interbody implants. Chuah et al. [13] employed topology optimization to reduce the stress-shielding effect in spinal interbody cages by removing ineffective material from the design domain. The stress shielding effect can be minimized by designing porous implants that allow bone to grow into the implant. However, studies in this area are still insufficient and ongoing, so further investigation is needed. The aim of this study was to design a cage that minimizes the stress shielding effect while also maintaining its mechanical strength. To achieve this, a novel fusion cage with a bone graft window was designed using a topology optimization approach. The study also aimed to simulate and evaluate the mechanical behavior of the spinal cages under loading conditions through finite element analysis (FEA) and topology optimization methods. The specific objectives were to optimize the cage design by reducing its mass by 30%, 50%, and 70%, and to assess the resulting stress distribution and deformation.

2. MATERIAL AND METHODS

2.1. Initial Design of Spinal Cage

Spinal cages are typically implantable devices that are inserted into the intervertebral space, which is the area between two adjacent vertebrae in the spine. The primary purpose of a spinal cage is to provide stability, decompression, and support to the spine while promoting proper alignment and fusion of the vertebral segments. The spinal cage is a small, hollow, or partially hollow structure with a form that can be either cylindrical or almost cuboid. Key considerations in spinal cage design include the choice of materials, geometry, and biomechanical properties.

Solid models of the L3-L4 vertebrae and spinal cage were created using the CATIA V5R20 program. The dimensions of the cage rely on the usual distance between the L3-L4 vertebrae according to the model. As seen in Figure 2, the initial spinal cage design was created based on the L3-L4 vertebrae model. The standard type of XLIF cage has 18 mm of width. [14]. The cage height and length were chosen to preserve disc space and lordosis according to the L3-L4 model.

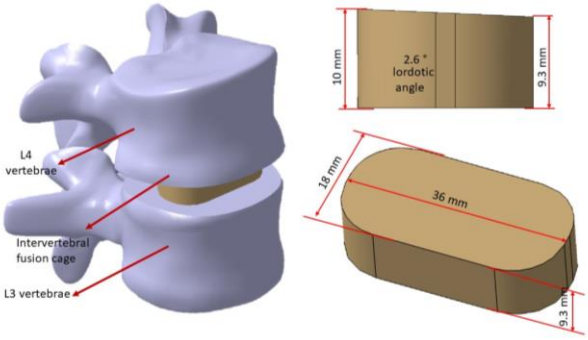

Figure 2 Initial spinal cage design

The materials used for spinal cages are usually biocompatible and can include titanium, stainless steel, or polymer-based composites. These materials should possess adequate strength and durability to withstand the forces exerted on the spine. In this study, stainless steel material was chosen due to its strength, durability, biocompatibility, radiopacity, and cost-effectiveness [15]. The total mass of the initial design was 0.450 kg.

2.2. Finite Element Model

After designing the spinal cage's CAD model, geometry was loaded into ANSYS Workbench 2022 R2 simulation software to build a finite element model. Statistical structural analysis was performed. Automatic meshing was applied to the model with resolution 7. Stainless steel was chosen as a material for the analysis and the material properties are shown in Table 1.

Table 1 The properties of stainless steel

Properties	Unit
Young modulus	195 GPa
Poisson’s Ratio	0.27
Yield Strength	250 MPa
Tensile Ultimate Strength	565 MPa
Density	7969 kg/m^3

Ansys was used to define the loads and boundary conditions that were applied to the spinal cage. A static, axial compressive force along the y-axis of 750 N was applied uniformly throughout the surface of L3 vertebrae, fixing L4 vertebrae as shown in Figure 3. The highest in vivo force recorded in a patient's lumbar spine when they were getting up from a chair was used to determine the load [16].

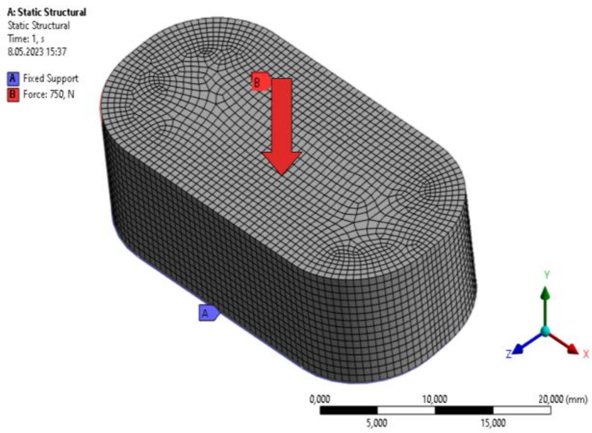

Figure 3 Finite element model of the spinal cage

2.3. Topology Optimization for Designing a Spinal Cage

The most effective design is produced using structural optimization methods using ANSYS that take into account several factors, such as mass, volume, strength, cost, etc. The objective of the structural optimization method is to create optimal designs that meet specific criteria. This method has the advantage of reducing time and money lost [17].

The design space was defined according to the dimensions of the spinal cage. The entire cage model was chosen as the design region and there was no exclusion region. 30%, 50%, and 70% mass reduction was defined for topology optimization. Minimizing compliance was stated as the goal. The maximum number of iterations was set at 100. The topology-optimized designs are shown in Figure 4.

3. RESULTS AND DISCUSSION

A structural analysis was performed to assess the effectiveness of the initial spinal cage design, revealing a displacement of 1.083 mm and a maximum von Mises stress of 3.0157 MPa. To verify the ability of the topology-optimized designs to withstand the applied load case, another structural analysis was conducted, as depicted in Figure 5, Figure 6, and Figure 7. The FEA and topology optimization results of the spinal cage designs are presented in Table 2. According to Table 2, the 50% mass-reduced spinal cage design exhibited the minimum von Mises stress

With a 70% reduction in mass, a weight loss of 29.14 g was achieved, but the maximum stress value did not decrease as significantly as in the 50% mass-reduced spinal cage, which had a weight loss of 19.99 g. A stiffer structure typically experiences lower deformations and displacements under the same applied load, while a less stiff structure tends to undergo larger deformations (Figure 5, Figure 6, and Figure 7). The stiffer design was created with a 30% mass reduction, while the least stiff design was achieved through a 70% mass reduction. Areas with lower stiffness may experience higher stresses due to increased deformation or localized load concentrations [18]. The findings of Zhong et al. [11] align with our results, supporting the general understanding that a stiffer structure tends to exhibit reduced deformations and displacements.

Moreover, an increase in volume can result in an increase in stiffness, assuming all other factors remain equal. When the volume of a structure increases, assuming the material properties remain the same, the additional material contributes to a higher resistance against deformation. This increased material volume leads to a higher stiffness or rigidity of the structure [19]. Srinivasan et al. [20] reported that an increase in the infill percentage results in the provision of more material, thereby leading to an improvement in strength. These findings align with the results obtained in our study.

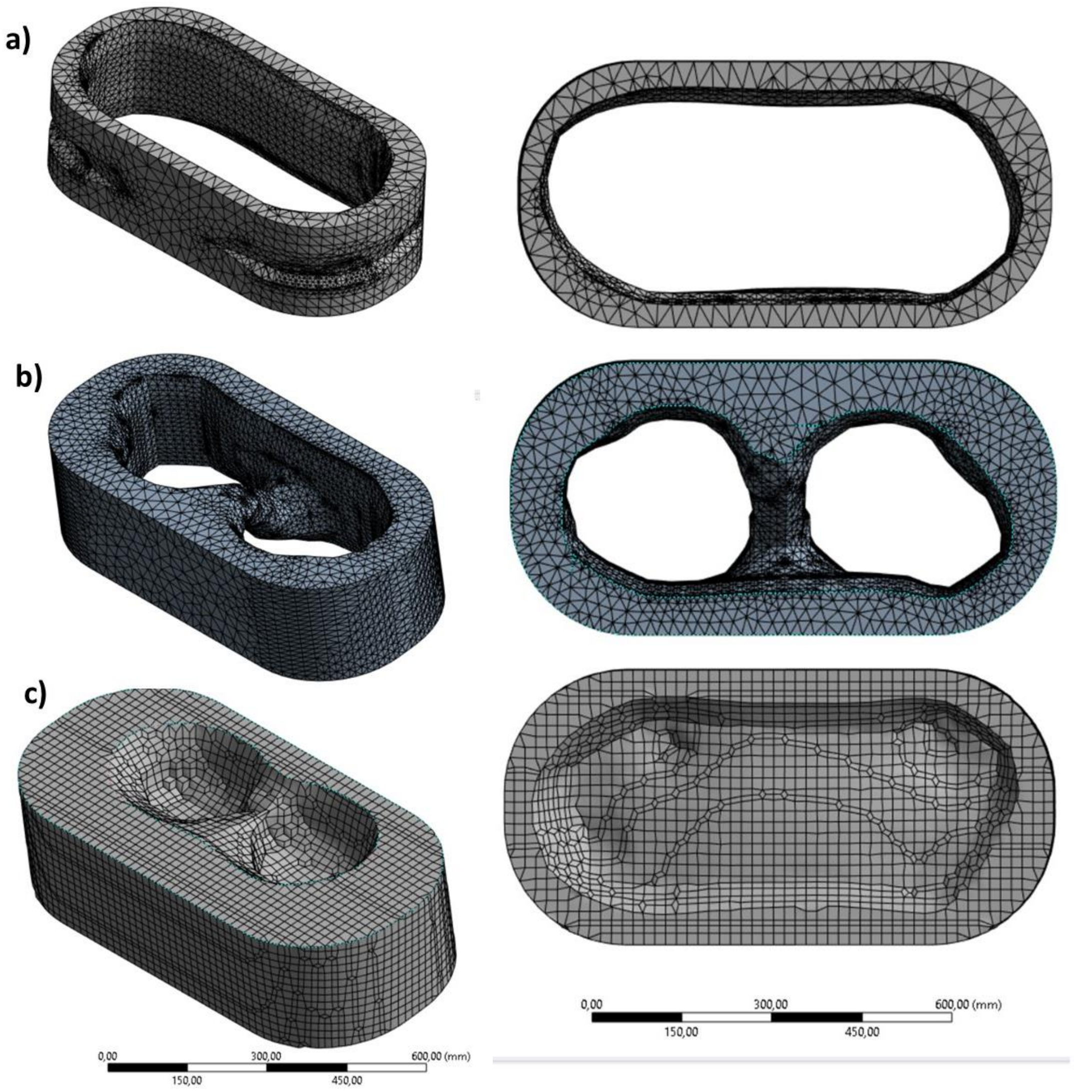

Figure 1 Topology-optimized spinal cages with varying levels of mass reduction: a) 30%, b) 50%, and c) 70%

Table 2 FEA results of the topology optimized the spinal cage designs

	Initial design	70% mass reduction	50% mass reduction	30%mass reduction
Von Mises Stress (MPa)	3.016	0.036	0.013	0.079
Deformation (mm)	1.082900	0.000054	0.000012	0.000008
Mass (g)	45.09	15.95	26.10	35.59
Volume (cm^3)	5743.7	2031.5	3324.5	4533.9
Weight loss (g)	------	29.14	18.99	9.5

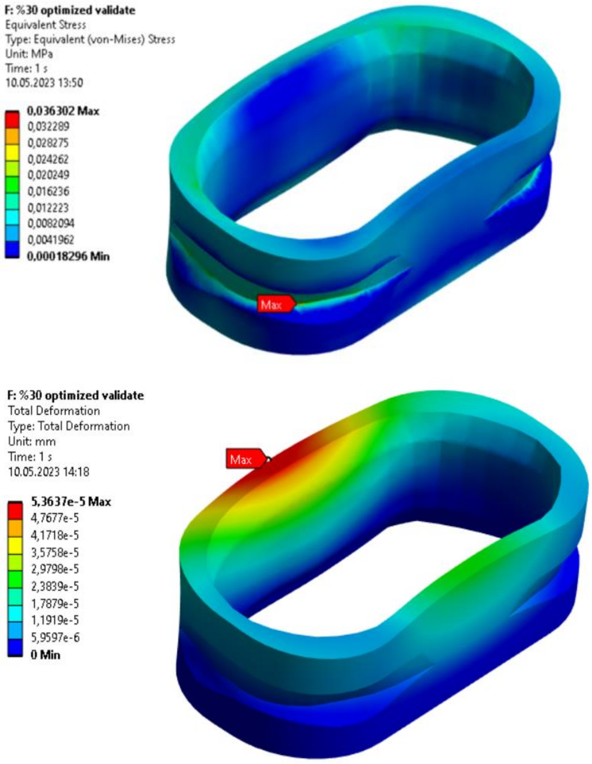

Figure 5 FEA results of 70% mass-reduced spinal cages: a) von Mises stress, b) total deformation

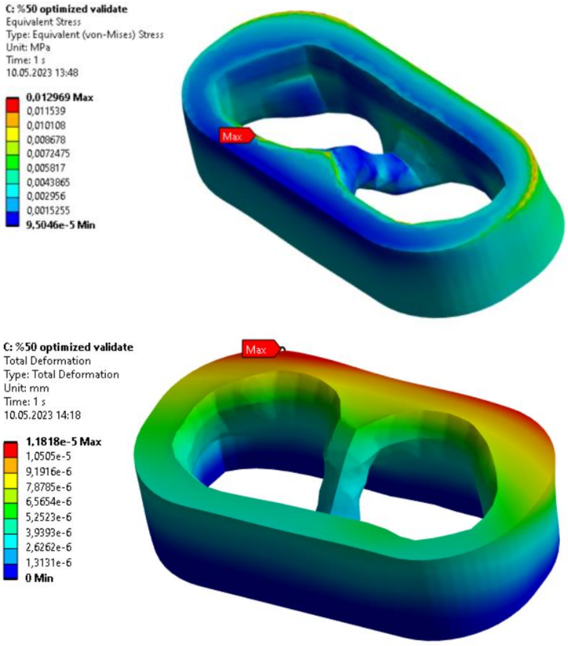

Figure 6 FEA results of 50% mass-reduced spinal cages: a) von Mises stress, b) total deformation

The strength of the topology-optimized spinal cage can still be considered acceptable. Under the load condition, the maximum von Mises stress of the initial design was 3.016 MPa. However, after a 50% mass reduction, this value decreased to 0.013 MPa. The maximum von Mises stress remains below the endurance limit of the material, typically ranging between 30% and 45% of its ultimate tensile strength, as indicated by the study conducted by Gültekin and Vahşi [21].

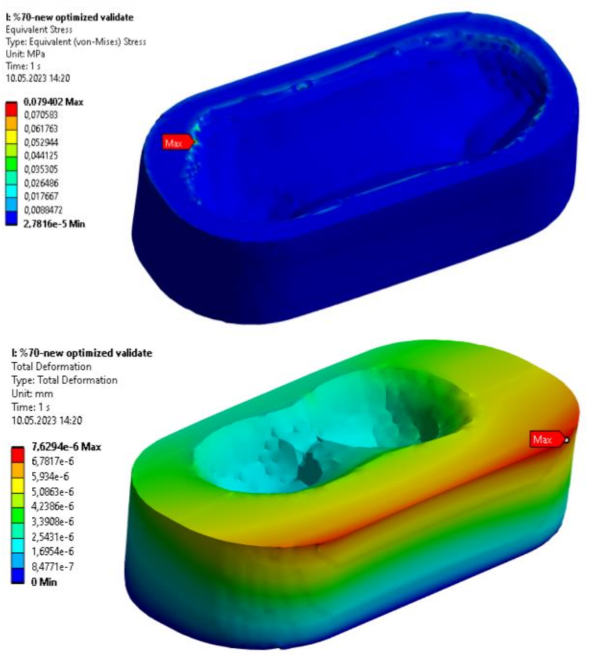

Figure 7 FEA results of 30% mass-reduced spinal cages: a) von Mises stress, b) total deformation

Both the 50% and 70% mass-reduced designs, featuring an open window, are considered suitable for bone graft placement. These designs have achieved a reduction in mass while maintaining the necessary structural integrity and functionality for their intended purpose. The presence of an open window indicates that a portion of the design has been modified or removed to allow for bone graft placement. During a spinal fusion procedure, the bone graft is typically inserted inside the spinal cage, promoting bone growth and facilitating fusion between adjacent vertebrae. [3, 9, 10] This modification ensures that the bone graft can be properly positioned and secured within the design.

4. CONCLUSION

This work proposes the design concept of a human spinal cage used for people with a spinal degenerative disorder. In order to determine the best material distribution, the spinal cage's topology was optimized. This resulted in a mass reduction of around 36 g as well as stress and deformation that met acceptance criteria. While retaining the essential structural integrity and functionality for the intended purpose, these designs had undergone a mass reduction. The window for the bone graft could be obtained through topological optimization. This bone graft window makes sure that the bone graft may be positioned and fixed within the design in the appropriate manner.

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Authors' Contribution

The author was responsible for the conception, design, data collection, analysis, interpretation of the research and, the author also drafted the manuscript and approved the final version for publication.

The Declaration of Conflict of Interest/ Common Interest

No conflict of interest or common interest has been declared by the author.

The Declaration of Ethics Committee Approval

This study does not require ethics committee permission or any special permission.

The Declaration of Research and Publication Ethics

The author of the paper declares that she complies with the scientific, ethical, and quotation rules of SAUJS in all processes of the paper and that she does not make any falsification of the data collected. In addition, she declares that Sakarya University Journal of Science and its editorial board have no responsibility for any ethical violations that may be encountered and that this study has not been evaluated in any academic publication environment other than Sakarya University Journal of Science.

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