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Static Analysis and Design of Innovative Porous Lumbar Interbody Cages

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Abstract

Background: Interbody discs play a major role in maintaining the spine and skeleton structures which may undergo damage. If damage is so severe that the disc cannot be repaired, implants, known as “interbody cages”, should be used.

Objectives: The present study aimed to propose a novel design with proper strength and resistance against axial disc torques.

Methods: The design and analysis of innovative anatomical cages comprised two stages, namely, cage design according to three different models and finite element analysis (FEA). The designs were based on the spine of a 15-year-old teenager without lumbar disc disease. To model the vertebrae, computed tomography (CT) scans and Digital Imaging and Communications in Medicine (DICOM) files were entered into Mimics Version 10.01 (Materialise Inc., Leuven, Belgium); then, the L4 and L5 spinal segments were modeled.

Results: The implants were fixed to the bottom level and subjected to a net force of 1000 N. Additionally, a moment load of 7.5 Nm in flexion, extension, axial rotation, and lateral bending was applied in these three cage models. Considering the application of 1000-N force, maximum and minimum stress and strain distribution rates were presented in three honeycomb, Islamic architecture, and porous gyroid cages.

Conclusion: Novel designs for lumbar cages were considered to achieve damping capacity, light weight, and high resistance. Considering the characteristics of the honeycomb, Islamic architecture, and gyroid structures, optimal designs were proposed for lumbar cages to achieve adequate strength and resistance against axial disc torques under normal conditions.

Keywords: Cage, Finite element, Implant, Interbody cage, Stress distribution

1. Background

Back pain is a common health concern worldwide, and more than 80% of adults experience this pain throughout their lives. This type of pain may be due to factors such as dehydration of the interbody disc, which leads to interstitial space and disc tightening. In more severe cases, the fibrous ring around the disc may be damaged, causing interbody disc herniation, nerve stimulation, and pain (1, 2). Posterior lumbar interbody fusion (PLIF), when performed on the back of the lumbar spine, is an ideal surgical method to repair a damaged disc. To improve biomechanical responses, bone grafts and spacer or interbody cages are placed in the interbody space to induce bone growth between the two vertebral bodies and increase the stability and strength of the spine (3).

Lumbar interbody tools, such as cages, are load-bearing surgical implants used for patients with spine instability, degenerative disc disease, spondylolisthesis, disc herniation, and back pain. Porous cages, in addition to rebuilding and maintaining the height of the interbody disc, are used in different types of artificial implants. The main advantage of porous materials is promoting bone tissue growth within the cage cavities; therefore, they can cause long-term stability (3, 4). Polyether ether ketone (PEEK) has been widely used in interbody fusion devices since 1990. This type of material is a proper alternative to metal lumbar interbody cages, as it has an elastic modulus (E¼ 3.6 GPa) relatively close to that of the cortical bone (E¼ 12 GPa) and reduces stress shielding. Moreover, PEEK is biocompatible, resistant, and radiolucent; and allows surgeons to monitor the cage position and bone growth (1). On the contrary, titanium cages are produced using the additive manufacturing (AM) method and exhibit better osteoblast adhesion and fusion relative to the PEEK cage (1, 5).

Since age, sex, and operation affect titanium cage subsidence, multiple studies have been published on the application of finite element analysis (FEA) and computed tomography (CT) scans to reduce the possible contributing factors for titanium cage subsidence (6). The FEA is a systematic method in medicine and medical engineering to determine the biomechanics of the body and to examine the distribution of mechanical stress before implant placement (7). Implant size mismatch causes damage to the endplates of the vertebrae. The small size of the implant causes subsidence, and its large size can cause damage to the nervous structure, increasing the risk of implant subsidence or filling (8).

The innovative development and improvement of the anatomical shape of cages can provide a better implant fit, which further improves force and load transfer, prevents cortical bone damage, and promotes the fusion process (8). Potentially, new spinal cages are designed to increase the possibility of a faster and more effective surgery and reduce the implant filler risk by ensuring a better fit with the shape, dimensions, and morphology of the patient's vertebrae (e.g., angle between the endplates, shape, and size)(8). Production of such cages according to ergonomic principles, besides using of techniques such as AM, can significantly reduce the costs. The AM technique, known as the 3D printing technique, is successful in medical equipment manufacturing. The capacity of this technique to produce customized 3D structures with a complex geometry and perfect reproducibility have revolutionized implantology (8).

2. Objectives

The present study aimed to design and develop porous lumbar cages according to their anatomical shape. Several models designed based on the anatomical shape and their 3D printing were investigated. Following the initial design, a static analysis was performed to investigate the initial strength.

In this study, FEA of three cages with three different designs and porosities (Islamic design, gyroid, and honeycomb) was performed to achieve an optimal design compared to the existing designs with shortcomings, such as fracture, subsidence, implant weight, and non-welding. The main novelty of the present study was the design of several porosity models to achieve a cage with an optimal structure. Among the three designs, the Islamic design showed adequate strength in the stress and bending finite element tests.

3. Methods

The design and analysis of innovative anatomical cages were performed in two stages: 1) cage design according to three different models, and 2) FEA. In this study, designs were based on the spine of a 15-year-old teenager without lumbar disc disease or lumbar surgery based on radiographic examinations. To model the vertebrae, CT scans and Digital Imaging and Communications in Medicine (DICOM) files, which is an image format used in medical imaging, were entered into Mimics Version 10.01 (Materialise Inc., Leuven, Belgium), and the vertebrae of interest (L4 and L5) were then modeled.

3.1. Materials

The PEEK is a common thermoplastic material in implants used in the body. Its advantages include biocompatibility and an elastic modulus close to that of the cortical bone, with radiolucent properties in imaging. It is a proper alternative to metal lumbar interbody cages, as it has an elastic modulus (E¼ 3.6 GPa) relatively close to that of the cortical bone (E¼ 12 GPa) and reduces stress shielding (5). Considering the force transfer to the implant, which causes osteoporosis of the adjacent bones over time, the stress shielding phenomenon is reduced. This material is considered a linear, elastic, isotropic, and homogeneous material (E=3.9e+09 N/m^2; Poisson's ratio, 0.4). In this study, the designs were based on PEEK.

To insert a cage between the vertebrae, there are various surgical methods, providing different designs. Posterior lumbar interbody fusion is a common method in fusion surgeries. The designs in this study were based on PLIF, because in vertebral cage designs, technical devices used for different surgeries should be considered. Therefore, implants were designed in CAD/CAM software (Dassault Systèmes SolidWorks Corp., Waltham, MA, USA).

3.2. Applied Geometric Design

The main purpose of lumbar cage design is to fill the intervertebral gaps and provide mechanical support. The spinal vertebrae also have certain slopes at the disc location. One of the main features of the designed cages in this study was the slope of L4 and L5 vertebrae in the designs. Model construction performed in Mimics software aimed to calculate the intervertebral gap and slopes of the vertebrae (Figure 1). One of the main

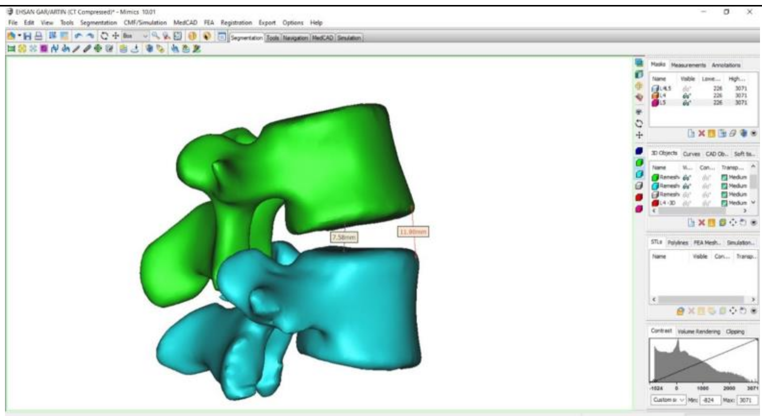

Figure 1. Modeling of L4 and L5 in the Mimics software and measurement of average distance, slope, and interbody space for the design of an interbody cage according to slopes

Figure 2. Industrial map of lumbar cage design 1 with a gyroid porous structure

goals of these innovative cage designs was to prevent rough load transfer and improper fusion. The dimensions of these designs were determined according to the average lumbar intervertebral gaps of adults.

The interbody cages were designed to provide the right conditions for bone fusion. In this study various porosities were considered to create the best bone fusion.

Design 1: This design included the cavities and porosities with high resistance and light weight. It contained three cavities, and a gyroid structure was used for the porosities (9). The slope of this cage was based on the modeling of the vertebrae in Mimics software (Figure 2).

Design 2: In this design, a honeycomb structure (hexagonal) was used, which is the most resistant structure (10); the slope value was considered in Mimics software, based on modeling and other designs (Figure 3).

Design 3: Since one of the features of interbody discs is their damping property, it was integrated in this design. Porosities were replicated according to the existing Islamic architectural patterns, where the basic design principles are used to avoid tension concentration. In this study, during PLIF surgeries, after removing the damaged disc and inserting the interbody cage, bone cement was used to increase resistance, fix the cage between the two vertebrae, and prevent failure. In this design, by allocating space inside the cage structure to inject the bone cement, we attempted to increase resistance and strength and model a damping structure similar to a cage (Figure 4).

The FEA of the design models was performed in SolidWorks software in the static mode. The Blended Curvature-Based mesher was used in this study. A force of 1000 N was distributed on the upper surface of the cage, and a torque of 7.5 Nm was applied to the center of gravity in the cage in different modes of flexion, extension, lateral bending, and axial rotation to simulate forces and torques applied to the interbody disc in different body positions (Figures 5-7).

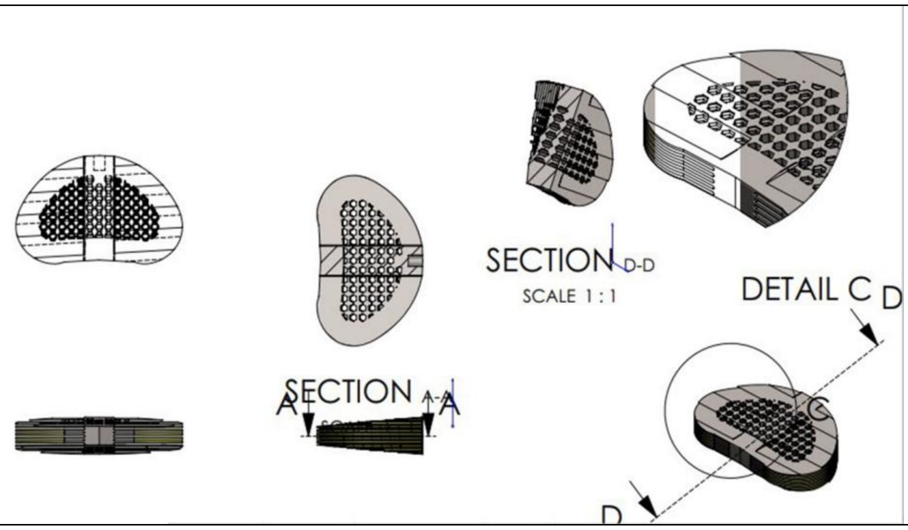

Figure 3. Industrial map of lumbar cage design 1 with a honeycomb porous structure

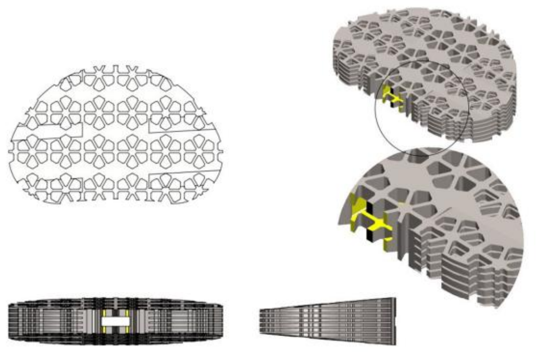

Figure 4. Industrial map of the lumbar cage design 1 with a porous Islamic architectural structure

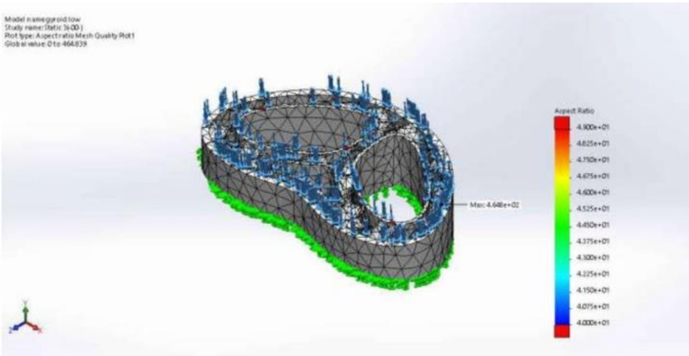

Figure 5. Lumbar cage mesh and force with a gyroid structure and application of a distributed force of 1000 N; the cage is fixed to the bottom

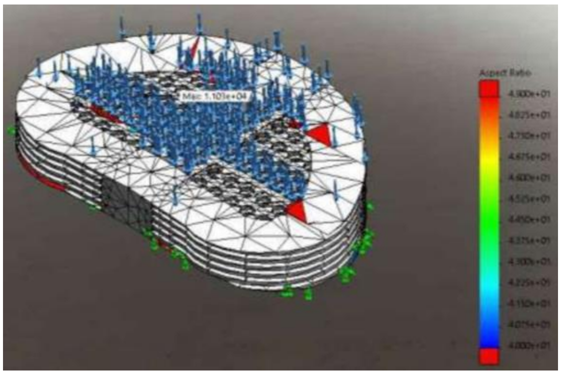

Figure 6. Lumbar cage mesh and force with a honeycomb structure and application of a distributed force of 1000 N; the cage is also fixed to the bottom

Figure 7. Lumbar cage mesh and force with an Islamic architectural structure and application of a distributed force of 1000 N; the cage is fixed to the bottom

4. Results

The proposed implants were designed based on the cage models obtained with different porosity structures. The cage models were fixed at the bottom and subjected to a net force of 1000 N; the minimum and maximum stress and strain rates in these implants are presented in Table 1. In this study, the Von Mises stress criteria were considered. A torque of 7.5 Nm in flexion, extension, axial rotation, and lateral bending was applied in these three cage models. These forces were selected based on average forces applied to the body, as reported in previous studies (11).

Due to the application of a force of 1000 N according to figures 8 and 9, the maximum and minimum stress and strain distribution rates in the three honeycomb, Islamic architecture, and porous gyroid cages are shown in Table 1.

Owing to the application of a torque of 7.5 Nm, according to figures 10 and 11, the maximum and minimum stress and strain rates in the three honeycomb, Islamic pattern, and porous gyroid cages are shown in Table 2.

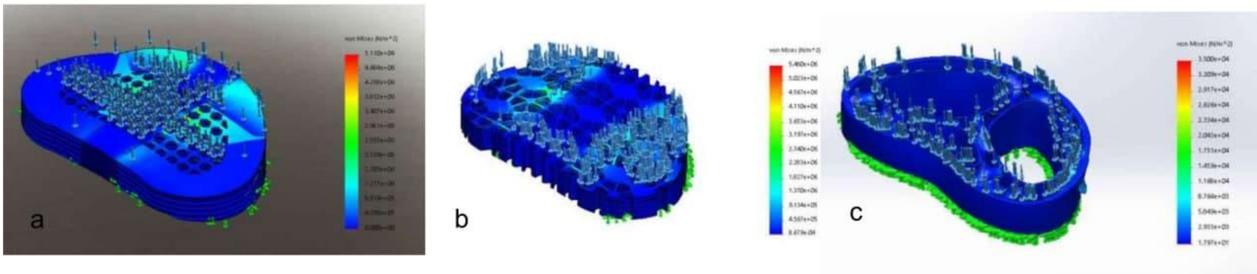

Figure 8. Stress distribution following the application of 1000 N force in the (a) cage with a honeycomb structure, (b) the cage with an Islamic architectural structure, and (c) the cage with a gyroid structure

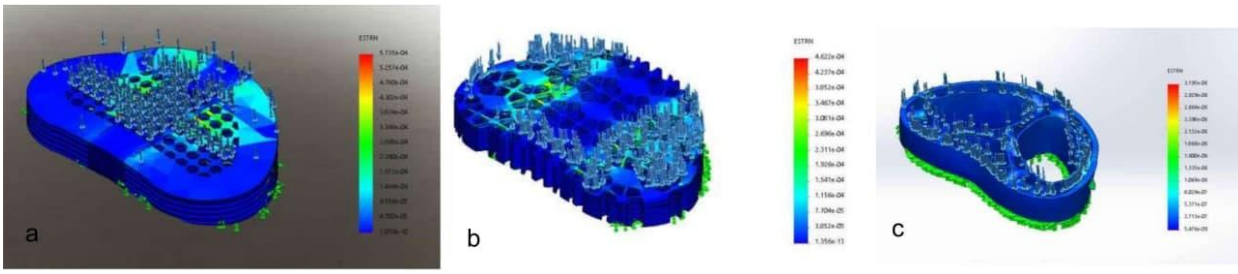

Figure 9. Strain distribution following the application of 1000 N force in (a) the cage with a honeycomb structure, (b) the cage with an Islamic architectural structure, and (c) the cage with a gyroid structure

Table 1. Minimum and maximum stress and strain rates for three designs following the application of a distributed force of 1000 N

	Minimum stress (N/m2)	Maximum stress (N/m2)	Minimum strain	Maximum strain
Design (1)	1.797e+01	3.500e+04	5.476e-09	3.195e-06
Design (2)	0	5.110e+06	1.010e-10	5.735e-04
Design (3)	8.679e-04	5.480e+06	1.356e-13	4.622e-04

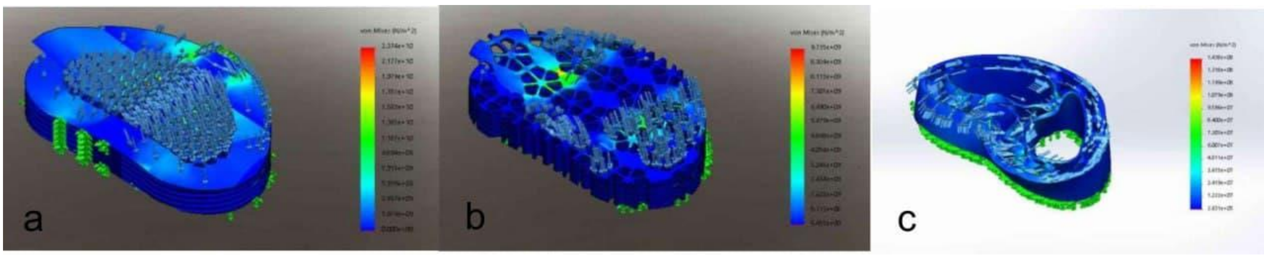

Figure 10. Stress distribution following the application of 7.5 Nm force in (a) the cage with a honeycomb structure, (b) the cage with an Islamic architectural structure, and (c) the cage with a porous gyroid structure

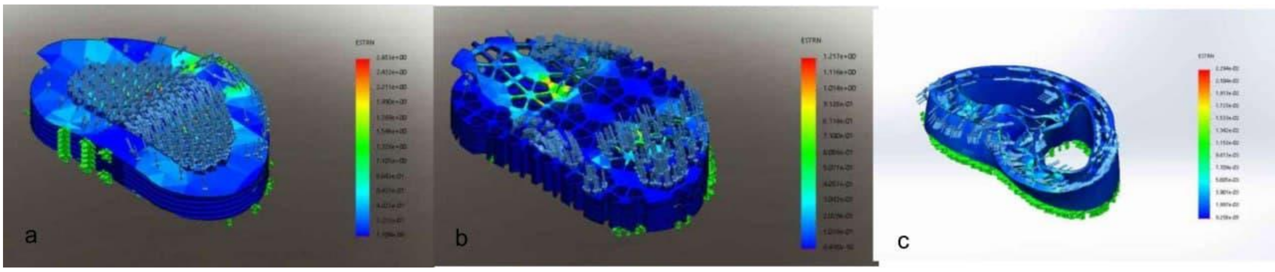

Figure 11. Strain distribution following the application of 7.5 Nm force in (a) the cage with a honeycomb structure, (b) the cage with an Islamic architectural structure, and (c) the cage with a porous gyroid structure

Table 2. Minimum and maximum stress and strain rates for three designs following the application of a distributed force of 7.5 Nm

	Minimum stress (N/m2)	Maximum stress (N/m2)	Minimum strain	Maximum strain
Design (1)	2.631e+05	1.438e+08	9.258e-05	2.294e-02
Design (2)	0	2.374e+10	1.104e-06	2.653e+0
Design (3)	5.455e+0	9.735e+09	4.499e-10	1.217e+0

5. Discussion

By investigating common cases of lumbar cages and evaluating risk factors, such as subsidence, innovative designs of porous cages were presented to increase the cage strength to an acceptable level and prevent damage. The designs included three models. The Islamic design appeared to be superior to other designs discussed in this study after tests on compressive and bending forces were conducted. The porous cage model with an Islamic architectural structure was a more suitable implant to replace the interbody disc due to its damping properties (e.g., interbody disc), and it can be applied in different body postures, such as extension (flexion), axial rotation, and lateral bending. This design showed suitable mechanical behaviors following the applied force, and the lateral layers of this cage showed damping movements (moving up and down).

To fix defects in the designed cages based on titanium and its alloys, carbon fiber and PEEK were used (12). Titanium cages, which were introduced in 1940, are biocompatible. However, the mismatch between the elastic modulus and the vertebra bone (50 times) leads to reduced stress shielding around the implant. Furthermore, according to investigations on the fusion state, it disrupts radiographs. Since the introduction of PEEK in 1990, many disadvantages of titanium alloys were eliminated. Considering the low infection rate of these cages, the design of suitable models in the future could help produce a suitable alternative for the spine (13, 14).

According to the results of static analysis of the designed porous cages, a suitable and uniform behavior was observed when a force of 1000 N was applied, and the strain rates of cages with honeycomb and Islamic architectural patterns were relatively low and similar; the gyroid cage showed a better strain behavior. Nevertheless, a porous cage with a gyroid structure did not show adequate strength and stability; instead, it showed significant deformation. These simulations suggest that this cage model is not suitable to fill the interbody space. Based on the comparison of the honeycomb cage model with the Islamic architecture model, a relatively good strength was observed in the honeycomb cage. However, a cage with an Islamic architectural structure was more suitable, because the damping property, similar to the cartilage property, was not defined, and in the long run, the cage was more resistant, and the patient was more relaxed. In future studies, to determine the advantages and disadvantages of these cages, stronger simulations in analytical software programs, such as Ansys engineering simulation software, are needed, and all boundary and environmental conditions should be considered.

Generally, two materials are most commonly used in conventional lumbar cages; namely, titanium alloy (Ti6Al4v) and PEEK. Titanium weighs more than PEEK, and due to its elastic modulus, it creates a stress concentration more than the bone and may fail. In a cage made of PEEK, the amount of subsidence increases depending on the type of material; however, the PEEK material is lighter and better facilitates fusion with the bone (15).

Despite being built of PEEK, the cages in the models detailed in this study, particularly the one with the Islamic architectural design, were shown to be stronger because of their design, which guarded against common failure and damage to these cages.

6. Conclusion

In this study, innovative designs, which were lighter and more resistant with damping properties, were proposed to replace the common designs of lumbar cages. Considering the characteristics of the honeycomb structure (hexagonal), Islamic architectural structure, and gyroid structure, optimal designs were proposed for the lumbar cage to achieve adequate strength and resistance against axial disc torques under normal conditions. Since in the three designs presented here, the Islamic architectural structure showed the greatest strength in the software analysis; it is possible to obtain more accurate results with this structure and conduct more detailed analyses by modeling the L4 and L5 intervertebral space, simulating spinal movements in daily human activities, and performing mechanical experimental tests.

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Footnotes

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