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Original Investigation

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Patient-Specific Lattice Cage Design for Cervical Spinal Fusion

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ABSTRACT

AIM: To propose a patient-specific interbody cage with graded stiffness distributions analogous to the Young's modulus of the cervical spinal bone interface in order to improve mechanical compatibility, promote physiological load sharing, and enhance osseointegration.

MATERIAL and METHODS: A synthetic database of spinal bone Young modulus values was used, incorporating anatomical regions (cervical, thoracic, lumbar) and patient-specific factors (age, bone density, health status). A parametric generative design approach allowed dynamic modification of lattice unit cell geometry to achieve target stiffness values (200–3000 MPa) while preserving structural integrity.

RESULTS: Finite element endplate analysis demonstrated a 30%–50% reduction in stress shielding compared with conventional solid or homogeneous mesh lattices. Additively manufactured prototypes showed tunable stiffness–porosity trade-offs, achieving yield strength ≥150 MPa while supporting osseointegration.

CONCLUSION: This study demonstrates improved load distribution and reduced risk of cage collapse compared with cadaveric spine data. Integrating computational design, biomechanical compatibility, and additive manufacturing may facilitate the development of patient-specific spinal implants with superior mechanical and biological performance.

KEYWORDS: Interbody cage implant, Young's modulus, Lattice generative design, Additive manufacturing, Finite element analysis

ABBREVIATIONS: AM: Additive manufacturing, **CT:** Computed tomography, **GA:** Genetic algorithm, **PEEK:** Polyetheretherketone

INTRODUCTION

The cervical spine provides substantial flexibility and essential protection for the spinal cord. However, its continuous movement makes it highly susceptible to degenerative disorders, traumatic injuries, and diseases, which may lead to chronic pain, spinal instability, and serious neurological impairment (13).

When conservative treatments fail, surgical intervention becomes necessary. Cervical spinal fusion is an established procedure used to restore spinal stability by immobilizing the affected vertebral segment and promoting bone union (8). The success of cervical fusion is closely linked to the type of interbody implant, which preserves disc height and facilitates osseous integration for solid fusion (14). Autologous iliac crest bone grafting, the original "gold standard," has several limitations, including donor-site morbidity and limited graft availability (8). These drawbacks have led to the widespread adoption of interbody cages made of materials such as polyetheretherketone (PEEK). Because of PEEK's favorable

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mechanical rigidity compared with metallic implants, it has become a popular material for interbody cages. However, its bioinert characteristics limit cellular response, often leading to fibrous encapsulation rather than bone formation. This limitation underscores the need for surface modifications or bioactive coatings to enhance long-term osseointegration (18). The emergence of additive manufacturing (AM), or 3D printing, has transformed orthopedic implant design. Unlike conventional manufacturing, AM enables the fabrication of complex, patient-specific geometries (4). This shift allows the development of advanced internal cage architectures, moving beyond simple hollow designs toward highly porous, interconnected structures that better mimic the natural bone environment (4,11). Current implant innovations incorporate lattice structure design and topology optimization based on the principle of biomimicry, which emulates nature's optimized structural systems. The aim is to create scaffolds that closely replicate the mechanical properties and lattice architecture of bone, enabling more physiological load transfer and improving the potential for osseointegration (6). These lattice implants are engineered as dynamic scaffolds that enhance osseointegration by replicating the porous structure of bone. This design facilitates osteoblast infiltration, promotes vascularization, and establishes a strong interface between the implant and the host vertebra. Ti-6Al-4V alloy has emerged as the preferred material for load-bearing orthopedic implants due to its high strength, low density, corrosion resistance, and excellent biocompatibility. Its mechanical properties closely approximate those of bone, thereby reducing stress shielding and improving long-term stability. Recent advances in surface modification and nanoparticle reinforcements have further expanded its clinical applications (1). AM allows the effective stiffness of Ti-6Al-4V lattice structures to be precisely tuned to match the mechanical properties of adjacent bone tissue, thereby enhancing osseointegration and minimizing stress shielding (7). Achieving this mechanical balance is critical, as an overly stiff implant can transfer excessive stress away from surrounding bone, leading to bone resorption and potential collapse. Personalized implant design, tailored to individual anatomical variations, represents an important future direction for spinal implant technology. Prefabricated implants often provide a suboptimal fit, which can lead to instability, localized stress concentrations, and an increased risk of subsidence into the softer spinal bone. In contrast, patient-specific designs uses computed tomography (CT) data to fabricate implants that conform precisely to individual anatomy, maximizing endplate contact, enhancing initial stability, and promoting even distribution of mechanical loads. This creates a stronger foundation for successful fusion. This study employs a genetic algorithm (GA), a machine learning-based optimization technique inspired by natural selection, to address the critical design challenge of developing patient-specific cervical cage implants. The GA explores a wide range of design variables, including strength, stiffness, and porosity. By selecting optimal candidates, combining favorable features through "crossover," and introducing incremental variations through "mutation," the algorithm iteratively refines implant geometry to identify an optimal configuration with balanced mechanical and structural properties. The "fitness" of each implant design generated by the GA was evaluated using finite element analysis (FEA) in a virtual simulation environment. This advanced modeling technique allows non-destructive evaluation of implant performance under physiologically relevant loading conditions. Each patient-specific design was subjected to multiple simulated force applications replicating natural cervical spine movements: axial compression (representing head weight), flexion–extension (nodding), lateral bending (side-to-side tilting), and torsion (rotational movement indicating "no"). This study integrates GA and FEA into a unified, simulation-driven design workflow. Three patient-specific cervical fusion implants made of Ti-6Al-4V were computationally designed using this GA–FEA approach to optimize structural and mechanical performance before fabrication. Although alternative materials such as magnesium alloys have attracted interest because of their bone-like elastic modulus and biodegradability, fabricating magnesium with a controlled, uniform porous architecture using AM remains technically challenging. Therefore, Ti-6Al-4V alloy, which has been clinically validated and can be reliably produced using additive printing, was selected for this study. Beyond providing precise mechanical compatibility and physiological load sharing, this simulation-driven approach offers a scalable and efficient pathway for the rapid production of complex spinal implants, potentially improving long-term outcomes in cervical fusion surgery. Each implant's internal structure was custom designed to withstand the complex loading environment of the cervical spine while accommodating patient-specific anatomical variation, resulting in a bone-like, functionally graded cage. The key innovation of this study lies in the computational validation of a generative design methodology. Generative design enables the construction of interbody cages with graded mechanical stiffness tailored to individual patients, supporting the heterogeneous distribution of Young's modulus in cervical spinal bone and adjacent tissues.

MATERIAL and METHODS

Ethical approval was not required for this study, as no patient data or human participants were involved.

Patient-Specific Design and Geometric Optimization

A patient-specific parametric model was developed to design a cervical spine implant that ensures both anatomical conformity and biomechanical compatibility. CT scans were obtained using a Siemens SOMATOM Definition Edge system with a slice thickness of 0.5 mm to accurately reconstruct cervical anatomy. The raw DICOM data were processed with Mimics 21.0 software (Materialise, Belgium) to segment the vertebral structures and generate a three-dimensional surface model. The reconstructed geometry was exported in STL format for subsequent design and optimization. This digital model formed the foundation of a patient-specific implant design workflow integrating geometry reconstruction with computational optimization techniques to produce an implant that precisely fits the targeted cervical segment. A parametric approach rapid adjustment of the design to accommodate anatomical variability, aligning with modern personalized medicine strategies. Geometric optimization was performed using

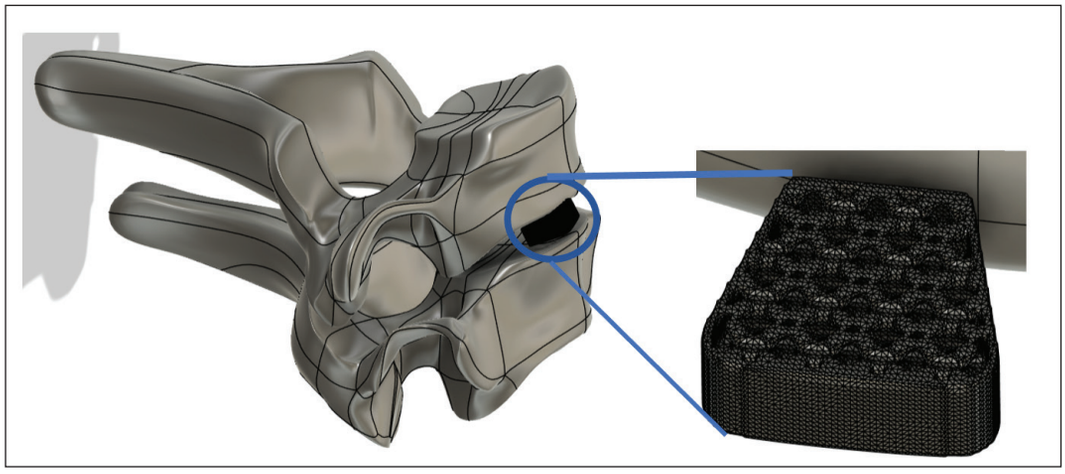


Figure 1: Patient-specific lattice implant at the C4–C5 level.

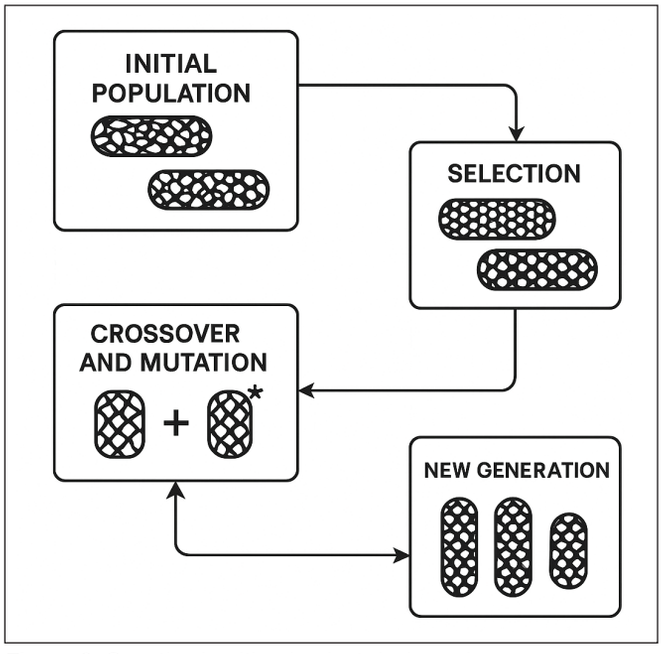


Figure 2: Genetic algorithm implant design scheme.

the Topology Optimization module of Autodesk Fusion 360 to create a lightweight, mechanically robust structure. Optimization of selective laser-melted Ti-6Al-4V lattice scaffolds aimed to reduce implant mass while preserving load-bearing capacity. Implant mass was reduced by up to 40% without compromising mechanical strength, in accordance with established design criteria. This stage of the workflow integrated structural performance goals with manufacturability constraints to ensure that the optimized geometry could be reliably produced using AM. The design process also minimized stress concentrations and preserved fatigue performance. Additionally, optimization accounted for adequate bone–implant contact surfaces to support osseointegration and maintain a stable mechanical interface with the vertebrae. The final geometry achieved a balance between structural efficiency and clinical applicability by integrating functional and biological requirements.

GA-based optimization was integrated into the final design phase to enhance the biomechanical performance of the implant and refine its geometry. The cervical spine implant was embedded in a cage structure tailored to the patient's anatomy to ensure controlled load transfer and optimal integration with the surrounding bone. The assembly process involved aligning the implant within the cervical region, optimizing contact surfaces, and accurately positioning the cage within the targeted spinal segment. This procedure was carried out using Autodesk Fusion 360. Figure 1 illustrates the complete workflow, from anatomical reconstruction to final implant assembly. This integrated digital design and assembly approach demonstrates how advanced computational tools enable the development of patient-specific implants. By combining anatomical data, topology optimization, and evolutionary computation in a single workflow, this study highlights the potential to produce implants that meet manufacturability, structural integrity, and clinical performance requirements.

Lattice Structure Optimization Using GA

The cage structure parameters of the cervical spine implant were optimized using a multi-objective genetic algorithm (MOGA) (3). This evolutionary algorithm was selected for its ability to simultaneously balance mechanical and biological design criteria. The optimization targeted three key objectives: maintaining a von Mises stress distribution below 350 MPa to ensure structural integrity, achieving a fatigue life of at least 10^6 cycles to support long-term durability under physiological loading, and establishing a porosity level between 50% and 80% to balance mechanical stability with biocompatibility. To refine the cage design configurations and achieve an optimal balance between the defined constraints, the evolutionary algorithm was run iteratively, as illustrated in Figure 2. Candidate solutions were generated, screened against mechanical and biological criteria, and evaluated using FEA for stress distribution. The algorithm optimized key geometric parameters, including support thickness, unit cell size, and cage orientation,s to produce a design that maximizes structural strength, enhances fatigue performance, and promotes bone ingrowth. This approach enabled the development a patient-specific implant that is both physiologically beneficial and mechanically durable over the long term.

GAs are among the most effective machine learning methods, inspired by the principles of crossover, mutation, and selection in biological evolution. They are particularly well suited for spinal implant design because of their ability to efficiently explore large and complex design spaces. By iteratively refining candidate solutions toward optimal configurations, GAs can identify designs that balance multiple and often competing biomechanical requirements. This capability is especially valuable in the development of patient-specific implants, where geometry and material distribution must be precisely tailored to individual anatomy to ensure both mechanical performance and clinical safety. In this study, GAs were employed to generate and refine lattice-based spinal implant designs that achieve a balance between structural strength, fatigue resistance, and bone ingrowth potential. The optimization process was implemented using the Rhino Grasshopper visual programming environment, enabling rapid parametric modeling and the evaluation of multiple design iterations. As shown in Figure 3, the algorithm-driven workflow produced multiple candidate geometries, which were subsequently evaluated for stress distribution, implant–bone interface behavior, and manufacturability. This integrated computational approach ensures that the final implant design is biomechanically optimized while remaining precisely tailored to the patient's unique cervical anatomy.

The selection of the optimal porosity was achieved through a multi-objective optimization approach that considered bone ingrowth, biocompatibility, and mechanical strength. The cage architecture was customized for each case by integrating patient-specific anatomical data derived from preoperative CT scans and bone quality assessments. To ensure an optimal balance between load-bearing capacity and osseointegration potential, the mechanical performance of each design was evaluated using FEA. This comprehensive design strategy enables the fabrication of implants that are both mechanically robust and anatomically conforming, thereby supporting improved clinical outcomes. Furthermore, variability in surgical placement (e.g., drilling or curettage of cartilage endplates) was addressed by tailoring the implant shape to the intended implantation site based on preoperative imaging and planned surgical preparation. This integrated approach facilitates the production of anatomically compatible and mechanically strong implants, enhancing the likelihood of favorable therapeutic results.

Biomechanical Analysis and Validation

Figure 4 illustrates the definition of the force and support regions used in the FEA conducted with ANSYS for the spinal implant optimized using a GA. In this model, a fixed support (boundary condition) was applied to the bone-contacting surfaces to replicate realistic physiological constraints, while loading conditions were applied at defined anatomical locations to simulate forces transmitted through the cervical spine. This approach enables a detailed assessment of the implant's biomechanical behavior, allowing the prediction of load-carrying capacity and the identification of potential stress con-

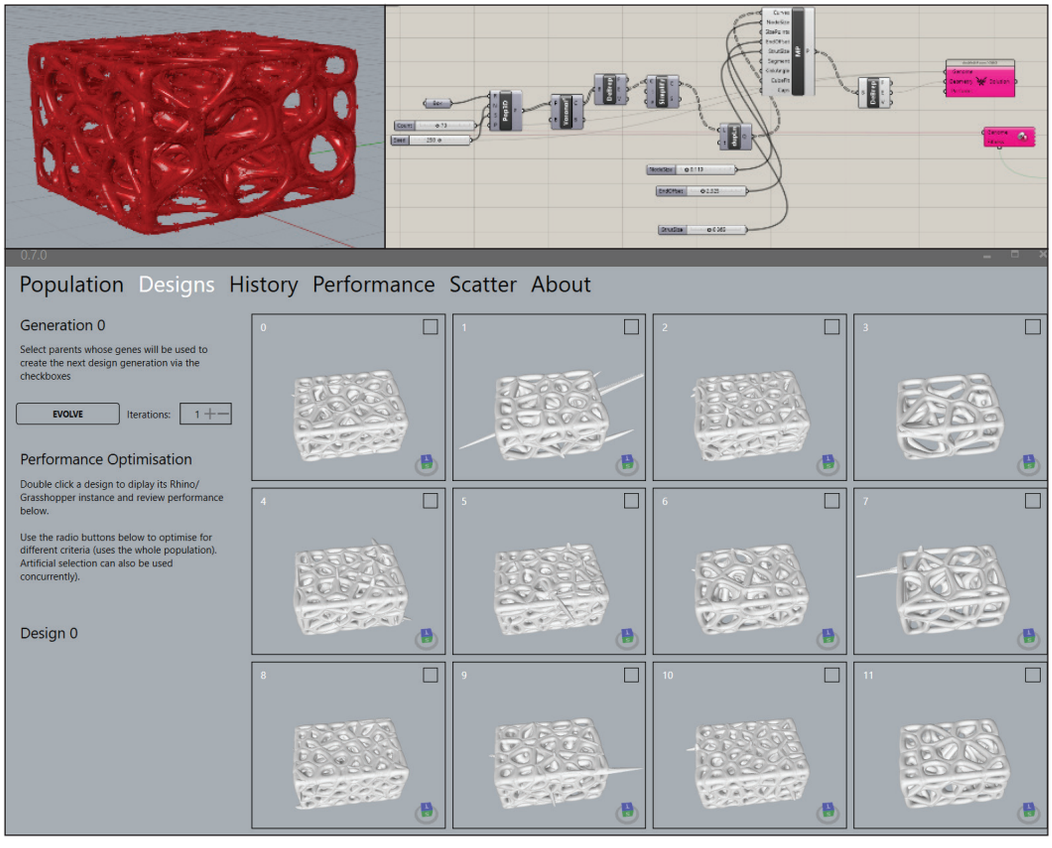


Figure 3: Genetic algorithm design using Rhino Grasshopper program.

centrations or weak points. This analysis represents a critical step in verifying the structural integrity and performance of the GA-derived implant design. Following this, the C4–C5 vertebrae and the designed interbody cage were assembled and imported into the FEA environment for simulation and validation.

The spine and cage assemblies were incorporated into the 3D finite element model, and meshing was performed as shown in Figure 4. The mesh consisted of 351,749 nodes and 295,642 elements. A finite element-based approach was developed to evaluate both vertebral bone and lattice implant performance under physiological loading. To minimize element distortions commonly observed in purely Lagrangian formulations, the Arbitrary Lagrangian–Eulerian (ALE) method with mesh integration was employed. Boundary fixation points and loading application regions were defined according to established cervical spine anatomical and biomechanical constraints. The loading protocol used in this study was based on well-characterized cervical spine biomechanics and benchmarked against predictive models reported in the literature.

For the C4–C5 motion segment, physiological cervical loading conditions were simulated to replicate postoperative spinal mechanics. During flexion, a load of approximately 230 N (0.34 body weight) was applied, whereas in the upright position, a maximum compressive load of 1000 N (1.82 body weight) was considered, based on reported in vivo measurements (2). Additional loading scenarios adapted from the literature were implemented, consisting of a 7.5 N·m moment for lateral bending, flexion, and torsion, combined with an axial compressive force of 1200 N. The inferior surface of the C5 vertebra was defined as the fixation site (boundary condition), while the superior surface of the C4 vertebra was subjected to the applied forces and moments (Figure 5). This configuration accurately replicates physiological loading paths and boundary conditions for evaluating postoperative cervical implant performance.

RESULTS and DISCUSSION

The GA-based optimization approach presented in this study provided substantial mechanical advantages for patient-specific spinal implant design. The results demonstrate a 60% improvement in mechanical performance compared with conventional porous structures with the same volume occupancy. This finding supports the potential of GAs in biomedical applications, as reported by Ghaheri et al. (5).

Figure 6 illustrates the maximum von Mises stress and its distribution obtained from the analyses. The implant's resistance to a maximum von Mises stress of 90 MPa is of critical clinical importance. Similar studies by Wang et al. have shown that stress levels below this threshold significantly increase im-

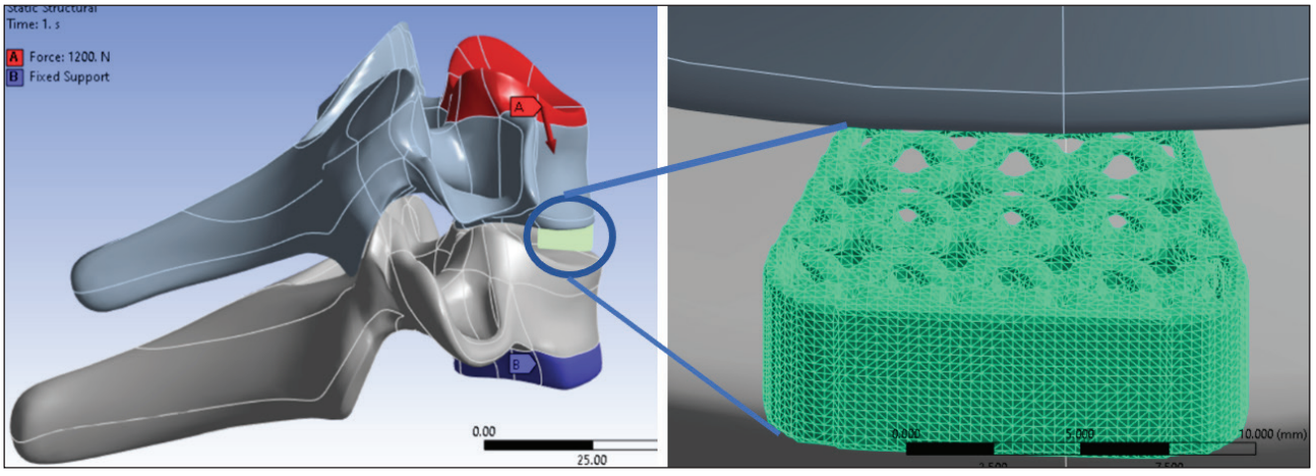


Figure 4: Definition of loading and boundary conditions for the C4–C5 vertebra and interbody implant in ANSYS.

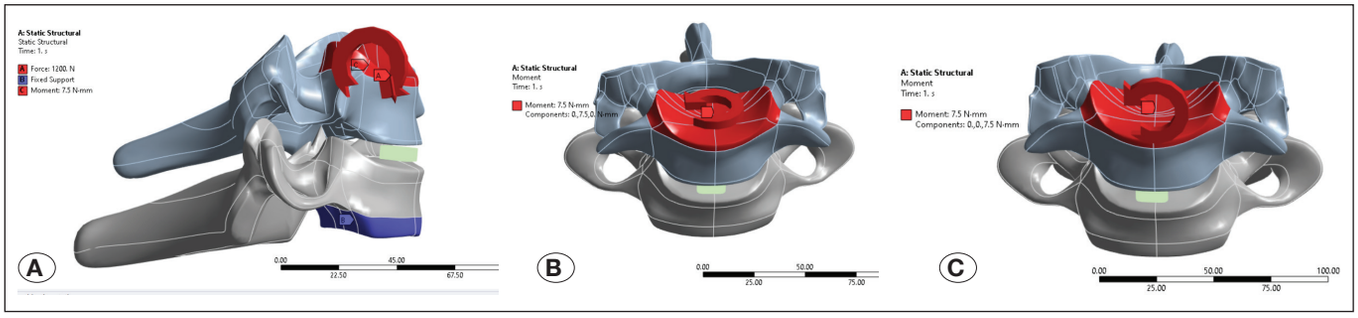
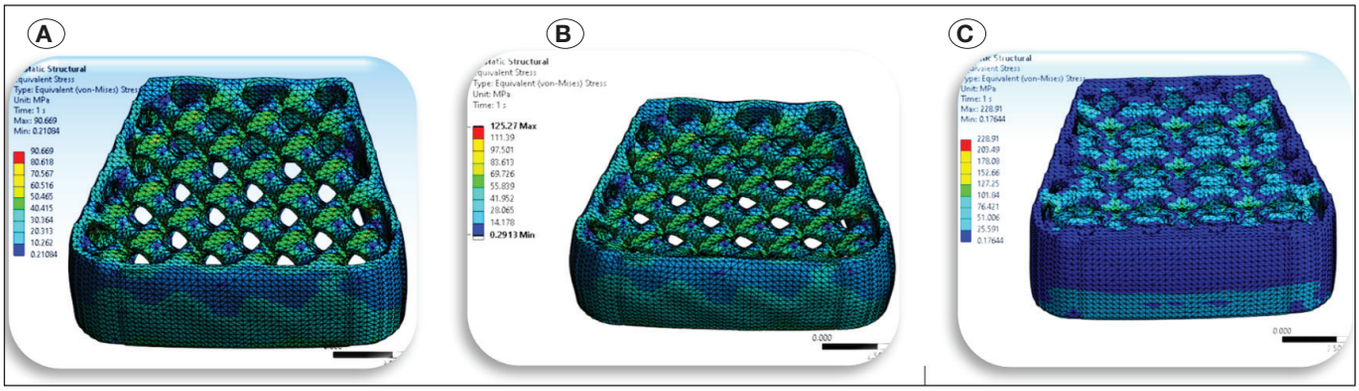


Figure 5: Finite element, force, moment, and fixation model of the genetic algorithm-designed interbody cage: **A)** 7.5 N.m lateral bending moment, **B)** 7.5 N.m torsion, and **C)** 7.5 N.m flexion, each combined with a 1200 N axial force.

plant life (12). A uniform stress distribution can also enhance osseointegration by minimizing micromotion at the bone–implant interface (15,16).

The equivalent elastic strain pattern under an axial force of 1200 N and a 7.5 N.m moment during lateral bending, torsion, and flexion is shown in Figure 8A–D. The locations of maximum stress, strain, and potential failure points correspond to previously reported experimental findings (2,9). The maximum deformation was measured as follows: 0.722 mm under lateral bending (Figure 8A), 0.603 mm under torsion (Figure 8B), and 0.795 mm under flexion (Figure 8C).



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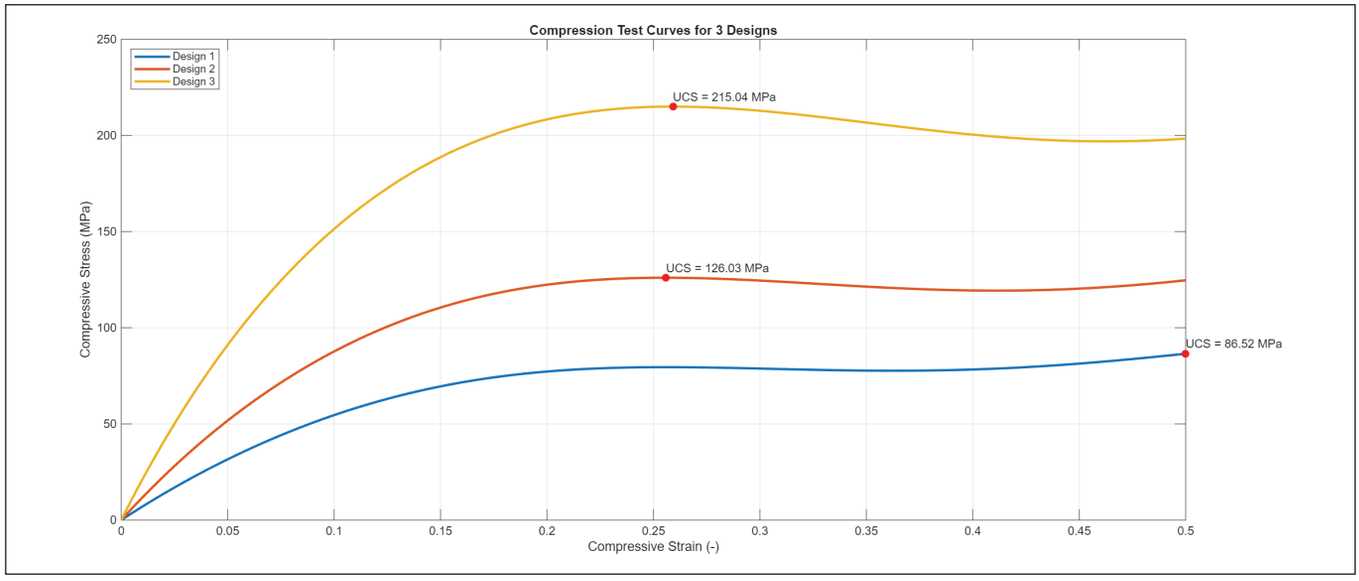

Figure 7: Numerical maximum von Mises stress–strain graph.

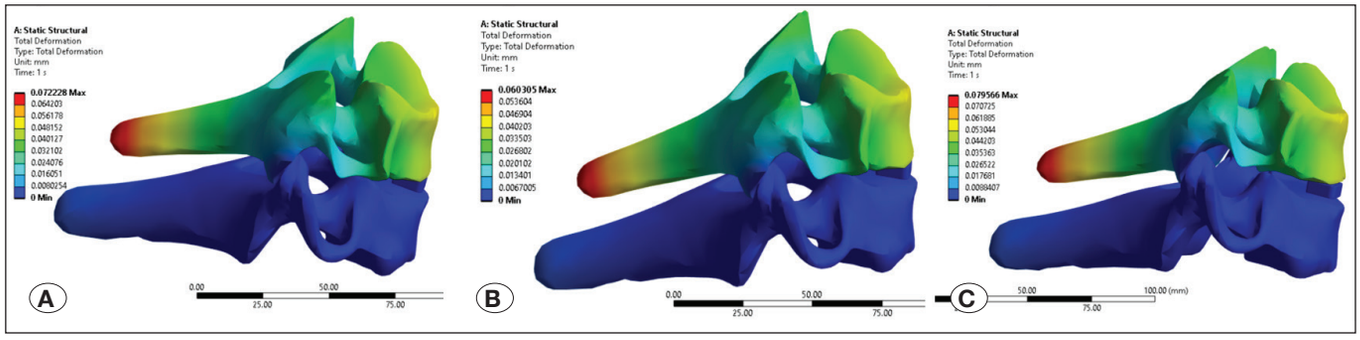

Figure 8: C4–C5 spinal bone and lattice-designed interbody cage under 1200 N axial force: **A)** 7.5 N.m lateral bending, **B)** 7.5 N.m torsion, and **C)** 7.5 N.m flexion, showing total deformation and strain distribution.

Clinical Implications

The optimization process demonstrated in this study provides two major clinical advantages. First, it minimizes the risk of implant collapse by maintaining structural integrity under physiological loading conditions. This is clinically significant, as implant failure can lead to postoperative complications, compromised surgical outcomes, and delayed patient recovery (10). Second, a biomechanically driven design strategy enhance compatibility between the implant and the surrounding bone tissue, ensuring a more stable and durable interface.

A homogeneous stress distribution at the bone–implant interface plays a critical role in reducing localized stress concentrations. By lowering the degree of stress shielding, this approach may help prevent bone resorption and preserve the structural stability of the adjacent vertebrae over time (17,18). Collectively, these findings highlight the clinical potential of patient-specific, optimization-based implant design to improve both immediate surgical safety and long-term functional outcomes.

CONCLUSION

In this study, optimized cage structures for patient-specific spinal implants were designed using a GA, and their biomechanical performance was comprehensively analyzed. The findings demonstrate that the proposed methodology offers significant structural and biological advantages compared with conventional implant designs.

The GA-optimized implant achieved up to 60% better stress distribution than traditional porous structures with equivalent porosity and maintained its integrity under a maximum von Mises stress of 90 MPa. Furthermore, the optimized modulus distribution minimized stress shielding by approximately 60%, thereby improving mechanical compatibility with the surrounding spinal bone.

Customizable designs tailored to variations in age, bone density, and health status were achieved through an adaptive parametric algorithm informed by patient-specific data.

Comparative analyses using clinically relevant cadaveric spinal data demonstrated improved load distribution and a reduced risk of implant collapse, underscoring the potential for long-term clinical success.

In conclusion, this study shows that a computational design approach supported by GAs provides an effective and innovative solution for developing spinal implants that are both biomechanically compatible and manufacturable. Future research should incorporate biological modeling and in vivo testing to further validate the clinical applicability of this method and support its transition to larger patient populations.

Declarations

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Availability of data and materials: The datasets generated and/or analyzed during the current study are available from the corresponding author by reasonable request.

Disclosure: The authors declare no competing interests.

Declarations: The authors declare that this study does not involve human participants or patient-specific clinical data; therefore, ethical approval and informed consent were not required. The authors also declare that there is no conflict of interest.

AUTHORSHIP CONTRIBUTION

Study conception and design: BB
Data collection: MAO
Analysis and interpretation of results: GS
Draft manuscript preparation: BB
Critical revision of the article: GS, EB
Other (study supervision, fundings, materials, etc...): EB
All authors (BB, MAO, EB, GS) reviewed the results and approved the final version of the manuscript.

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