ICCES, 2025, vol.33, no.3

Tech Science Press

DOI: 10.32604/icces.2025.012584

PROCEEDINGS

AI-Assisted Generative Inverse Design of Heterogeneous Meta-Biomaterials Based on TPMS for Biomimetic Tissue Engineering

Xiaolong Zhu, Feng Chen, Yuntian Chen, Wei Zhu and Xiaoxiao Han*

College of Mechanical and Vehicle Engineering, Hunan University, Changsha, 410082, China

*Corresponding Author: Xiaoxiao Han. Email: xiaoxiaohan@hnu.edu.cn

ABSTRACT

Human tissues and organs exhibit not only intricate anatomical architectures but also spatially heterogeneous distributions of elastic modulus—for example, between cancellous and cortical bone, across the epidermis, dermis, and subcutaneous layers, and between healthy and fibrotic liver tissues. Conventional biomaterials often fail to replicate such mechanical heterogeneity, thereby limiting their capacity to recreate biomimetic physiological microenvironments essential for applications like tissue regeneration and disease modeling. Meta-biomaterials, artificially engineered through the rational structural design of continuous materials, have emerged as a promising class of materials owing to their highly tunable mechanical and biological properties. These attributes have garnered significant attention in the realm of personalized biomedicine. However, constrained by traditional forward design methodologies, the development of meta-biomaterials with spatially varying elastic properties continues to face challenges such as low design efficiency, limited biomimetic fidelity, and inadequate biological performance. To overcome these limitations, this study introduces a generative inverse design framework for heterogeneous meta-biomaterials, leveraging AI-assisted algorithms in conjunction with Triply Periodic Minimal Surface (TPMS) theory. The design space is partitioned into discrete subregions, each assigned an optimal TPMS unit based on the target elastic modulus distribution. A smooth transition function is employed to seamlessly integrate adjacent units, forming a continuous and coherent meta-biomaterial structure. This approach enables not only fine-grained modulation of elastic modulus across space but also the co-optimization of permeability, specific surface area, and wall thickness. A series of meta-biomaterial prototypes with varying elastic modulus distributions were successfully designed and fabricated via 3D printing. Digital Image Correlation (DIC) measurements revealed strong concordance between the designed and experimentally measured modulus distributions. Furthermore, a centimeter-scale liver tissue scaffold was developed using patient-specific medical imaging data and fabricated through 3D bioprinting. In vitro cell experiments confirmed the scaffold's excellent biocompatibility. Overall, the proposed generative inverse design strategy demonstrates substantial potential for the development of next-generation biomimetic tissue scaffolds, offering a powerful tool for advancing the field of bioengineered medical devices toward greater physiological relevance and precision.

KEYWORDS

Meta-biomaterials; AI assisted design; triply periodic minimal surface; 3D printing; scaffolds

Funding Statement: The authors received no specific funding for this study.

Conflicts of Interest: The authors declare no conflicts of interest to report regarding the present study.