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Design of Porous Metamaterials with Tunable Mechanical Properties for Bone-Tissue Engineering Applications

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ABSTRACT

Porous architected metamaterials are increasingly used for bone-tissue engineering due to their capacity to mimic the hierarchical structure and multifunctional behavior of native bone, combining interconnected pore networks with mechanically compatible stiffness and anisotropy. This study presents a computational framework for the design of architected scaffolds for tissue engineering based on triply periodic minimal surfaces (TPMS) and random bicontinuous structures with tailored mechanical and morphological properties. Such structures form a prominent class of mathematically defined topologies with smooth, continuous pore networks and high surface-to-volume ratios that support cell infiltration and nutrient transport while reducing stress concentrations.

Several complementary design approaches are presented in this work. Parametric control of implicit surfaces enables systematic tuning of porosity, wall thickness, and unit-cell orientation to target specific effective moduli and anisotropic elastic responses required for different biological tissues [1]. Multi-morphology grading enables smooth, mechanically consistent transitions across domains with different porosity [2]. Homogenization-based frameworks are used to evaluate effective stiffness tensors and quantify anisotropy indices, forming the basis of inverse design procedures [3]. Multi-objective optimization is then formulated to match target elastic properties of those of native tissues while satisfying constraints on porosity and manufacturability [4]. The resulting framework supports both topology-driven and data-driven porous architectures with explicitly optimized anisotropy for tissue engineering applications.

The suggested methodologies establish a unified design approach for patient-specific implants with optimized mechanical compatibility and structural functionality. The discussed applications-based case studies include TPMS adaptation to micro-CT references, comparison of lattice morphologies, and mimicking transition trabecular-cortical zone.

KEYWORDS

Porous metamaterials; bone tissue engineering; tunable anisotropy; triply periodic minimal surfaces (TPMS); random bicontinuous structures; multiscale optimization

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