

Modeling and Design of Functionally Graded TPMS Scaffolds for Hydrogel-Based Osteochondral Tissue Engineering

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INTRODUCTION: Hydrogel-based osteochondral (OC) tissue engineering requires support structures that can surround the hydrogel to bear physiological loads. Using digital light processing (DLP) 3D printing, we previously made a composite hydrogel scaffold with a graded octet-truss architecture that matched OC stiffness, with ~1 MPa in cartilage-like regions and ~10 MPa in bone-like regions. However, strut-based lattices like the octet-truss have linked design features (topology, strut aspect ratio, node geometry) that can cause stress concentrations and mechanical instability, which narrows the useful strain range and creates uneven strains inside an infilling hydrogel^{1,2}. In contrast, triply periodic minimal surface (TPMS) architectures have smooth, continuous surfaces and independently tunable features such as curvature, relative density, and unit-cell size, which can support more uniform and efficient load transfer. Despite these advantages, TPMS geometries have not been systematically studied as reinforcing scaffolds for soft tissue regeneration. In this study, we use finite element modeling (FEM) to evaluate how TPMS topology, relative density, and unit-cell size affect internal strain fields for use in hydrogel-infilled, DLP-printed composite scaffolds and use these results to design graded TPMS structures that match the native OC stiffness profile.

METHODS: Finite element analysis (FEA) was used to quantify mechanical behavior and internal gel strain in hydrogel-infilled TPMS scaffolds under compressive loading. Six TPMS designs: Gyroid, Diamond, and I-Wrapped Periodic (IWP) in sheet (S) and solid (L) forms and an octet-truss design were modeled as $3 \times 3 \times 2$ mm³ cubes and analyzed at 15%, 25%, and 35% relative density (with octet-truss only at 25%), yielding 19 models. Unit-cell effects were designed in Gyroid sheet and solid scaffolds at 25% density with 0.5-, 1.0-, and 1.5-mm unit cells. TPMS surfaces were generated in MSLattice, hydrogel-infilled and tetrahedrally meshed in Simpleware, then imported into Abaqus under 5% confined uniaxial compression. Simulations produced spatial maps and histograms of maximum principal strain to compare internal strain distributions across geometries and design parameters. Spatial maps and histograms of maximum principal strain were generated to compare internal strain distributions across architectures and design parameters.

RESULTS: FEM simulations of a diamond-sheet TPMS (DLP printed material shown in grey, Figure) under 5% confined compressive loading produced predominately compressive strain fields in the infilling hydrogel. In contrast, diamond solid trusses produced larger compressive magnitudes and higher intra-gel strain variance, which increased with relative density (RD) of the structure. In gyroid sheet models, hydrogel within centrally located TPMS cells showed relatively uniform compressive strains. In contrast, gyroid solid architectures produced heterogeneous strain fields with compressive and tensile strains with localized regions of high strain. Increasing the RD increased the minimum and maximum hydrogel strain magnitudes for both architectures. In the IWP sheet lattice, large pore-like regions in the TPMS architecture shielded the infilling hydrogel while the surrounding network carried predominantly compressive strains, thus producing a heterogeneous, bimodal strain distribution. In contrast, IWP solid architectures produced even greater heterogeneity: hydrogel adjacent to solid elements was largely tensile whereas strains in the neighboring infilling gel were compressive. In comparison to TPMS structures, the octet-truss showed large compressive strains with uneven strain fields, despite similar overall strain ranges.

DISCUSSION: Gyroid and diamond sheet TPMS architectures distribute hydrogel strain fields more evenly than solid variants, as well as IWP and octet-truss lattices. While prior studies report that TPMS RD influences scaffold stiffness³, our results show that RD minimally influences the strain distribution within an infilling hydrogel. This finding suggests that TPMS scaffold designs can maintain structural stiffness while maintaining sufficient interior volume to enable a relatively uniform strain niche for hydrogel-encapsulated cells under compressive loading. Guided by these findings, our ongoing work involves DLP-printing of uniform (bone or cartilage) and functionally graded (osteochondral) TPMS scaffolds, validating printability with X-ray microscopy (XRM) and scanning electron microscopy (SEM), and mechanical testing to validate structural stiffness. Taken together, our FEM analyses and concurrent validation provide a basis for rational TPMS selection to deliver prescribed scaffold stiffness and hydrogel strain environments suitable for cartilage and bone applications in vitro and in vivo

SIGNIFICANCE/CLINICAL RELEVANCE: This work supports the use of TPMS-based designs for DLP-printed scaffolds in osteochondral tissue regeneration. Our results show that TPMS architectures are tunable and can maintain uniform internal gel strain fields, which we predict will help guide functionally graded implants that better match the cartilage–bone interface and may improve load transfer and tissue repair.

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Figure: FEA-predicted internal gel strain for (A) Diamond, (B) Gyroid, and (C) IWP TPMS sheet and solid scaffolds at 15–35% relative density, and (D) octet-truss with mean internal gel strain comparison at 25% relative density.

