From MRI to Implant: Development of an Open-Source Computational Pipeline for Patient-Specific 3D Voronoi Meniscus Scaffold Generation With Anisotropic Voxel Correction and Regional Tribological Gradients

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Meniscus injuries are among the most common orthopedic conditions, with approximately 1 million surgeries annually. Injuries in the avascular zone cannot self-regenerate, and modern scaffolding approaches use generic geometries that lack patient-specific anatomy and region-specific transport optimization. This project presents a fully automated computational pipeline that converts MRI scans to patient-specific meniscus scaffolds featuring tribological porosity gradients in less than five minutes. The pipeline performs segmentation, anisotropic voxel correction, Voronoi-based lattice tessellation, regional gradient assignment, and multi-physics validation using Gibson-Ashby, Kozeny-Carman, Darcy's Law, and voxel-based FEA to ensure scaffolds are clinically compatible with patient-tailored geometry. Gradient scaffolds were designed with higher porosity in nutrient-transport zones and denser structure in load-bearing zones. Validation across hundreds of patient anatomies (Stanford SKM-TEA dataset) showed gradient scaffolds achieved significantly higher porosity and permeability, with enhanced directional transport properties and substantially lower mechanical modulus relative to uniform controls, all with large effect sizes. Gradient direction (tibial vs. femoral-facing) produced no significant differences, suggesting gradient presence rather than orientation drives transport improvement. Physical validation using PCL scaffolds fabricated via FDM 3D printing confirmed computational predictions, with gradient scaffolds demonstrating significantly faster PBS flow-through times and low dimensional error. The open-source pipeline (7,500+ lines of Python) offers a scalable, automated approach to patient-specific meniscus scaffold design from clinically available MRI data.

Awards Won:
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