Design and Fabrication of 3D-Printed Gyroid Architectures for Intervertebral Disc Replacement

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INTRODUCTION: Degenerative disc disease is a leading cause of chronic back pain and often requires surgery when conservative treatments fail. Current surgical options, including spinal fusion and disc arthroplasty, are limited by complications such as adjacent segment degeneration, implant wear, and mechanical properties that do not match those of the native intervertebral disc (IVD). In this study, we explored using three-dimensional (3D) printing with thermoplastic polyurethane (TPU) to engineer biomimetic disc replacements based on open Gyroid architectures.

METHODS: Three-dimensional models with different gyroid architectures were designed using Creo Parametric (version 6.0.6.0, PTC, Inc., Boston, MA). These structures were then fabricated using an Original Prusa i3 MK3S+ and MK4S+ 3D printer from Prusa Research in Prague, Czech Republic. To evaluate the impact of material stiffness on print quality and mechanical performance, three flexible thermoplastic polyurethane (TPU) filaments were used: FlexHard, FlexMed, and SemiSoft (Extrudr, Lauterach, Austria). The anatomical geometry of the intervertebral disc between L4 and L5 was adopted from the THUMS virtual human body model (Toyota Motor Corporation, Toyota, Japan). Due to manufacturing constraints, the superior and inferior surfaces of the disc were flattened to enable reproducible 3D printing and mechanical testing (Figure 2). Gyroid wall thicknesses (0.5, 0.75, and 1.0 mm) and unit cell sizes (4, 6, 8, and 10 mm) were defined according to previous studies, resulting in 12 unique gyroid configurations for each TPU filament. After exporting the model in STL format, slicing and toolpath generation were performed using PrusaSlicer (version 2.9.1). Microscopic evaluation confirmed high geometric fidelity between the designed and printed structures. Static compression testing identified samples operating within the physiological load and strain ranges (600–2000 N and 10–17.5%, respectively), which were subsequently selected for dynamic characterization. Dynamic compression tests were performed at 5 Hz for 700,000 cycles under a peak load of 2000 N to evaluate deformation and damping characteristics. All mechanical tests (static and dynamic) were conducted in compliance with DIN ISO 18192-1.

RESULTS SECTION: The results demonstrated that all gyroid TPU discs exhibited damping properties within the physiological range of native intervertebral discs (IVDs) (~16%). The FlexSemiSoft samples showed an initial damping of 17–18%, which stabilized at around 16% after an initial decrease. The initial damping of FlexMed samples was above 20%, but they converged to 15.5%-16.1%, with one sample reaching 13.5%. The FlexHard samples exhibited two distinct profiles, stabilizing between 15.7% and 16.5%. Stiffness increased with density across all filaments; FH samples most closely approximated the stiffness of native discs at lower densities. These results confirm the feasibility of using 3D-printed TPU gyroid structures to replicate the key mechanical and damping properties of human intervertebral discs (IVDs). This approach provides a foundation for developing patient-specific, biomimetic disc replacements. Future work will investigate medically approved TPU grades, biological responses under dynamic loading, and the influence of multiaxial stresses.

DISCUSSION: A geometric modification was introduced to more closely reflect the anatomy of the native intervertebral disc (IVD). This adjustment, together with a revised area of interest compared to Gross et al.'s approach [1], produced different outcomes regarding maximum force and pressure resistance. These differences translated into improved damping performance due to the enhanced flexibility of the modified disc structures. This damping behavior is physiologically relevant: in vivo, the IVD's ability to attenuate impact loads transmitted along the spine protects adjacent vertebral bodies, endplates, and neural structures from excessive mechanical stress. With a measured damping coefficient of approximately 16%, the 3D-printed TPU-based discs effectively dissipate some of the applied mechanical energy, closely replicating the shock-absorbing function of native disc tissue. By converting vibrational and compressive energy into heat or internal deformation, these discs reduce peak stress transmission and promote more even load distribution within the spinal motion segment. Therefore, maintaining adequate damping capacity is crucial for both structural longevity and preserving physiological load sharing and spinal stability.

REFERENCES: [1] Gross, V.; Zankovic, S.; Rolauffs, B.; Velten, D.; Schmal, H.; Seidenstuecker, M. *Frontiers in Bioengineering and Biotechnology* **2024**, *12*; [2] Barrey, C.Y.; Ponnappan, R.K.; Song, J.; Vaccaro, A.R. *International Journal of Spine Surgery* **2008**, *2*, 159-170 [3] Vogel, A.; Pioletti, D.P. Damping properties of the nucleus pulposus. *Clin. Biomech.* **2012**, *27*, 861-865.[4] Alkalay, R.N.; Vader, D.; Hackney, D. *Clin. Biomech.* **2015**, *30*, 211-218.

SIGNIFICANCE/CLINICAL RELEVANCE: Patient-specific intervertebral disc replacements that replicate the native disc's damping behavior represent a clinically significant advancement, as they have the potential to restore physiological load distribution and spinal mobility. Unlike current gold-standard treatments such as fusion or rigid cages, these biomimetic implants can absorb and dissipate mechanical energy, thereby reducing stress on adjacent segments and lowering the risk of degeneration.

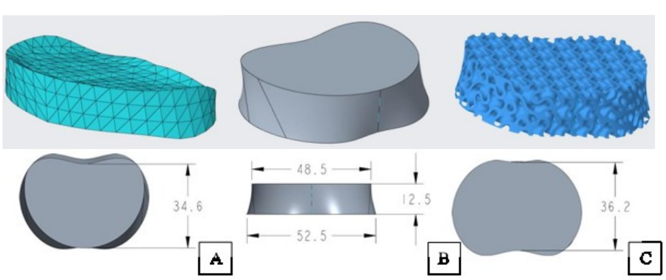

Figure 1: The evolution of the intervertebral disc model to 3D printing and Dimensions of the intervertebral disc: (A) Upper intervertebral disc depth (B) Intervertebral disc height/width and (C) lower intervertebral disc depth; with variation of Gyroid size (4, 6, 8, 10 mm) and Gyroid wall thickness (0.5; 0.75; 1.0 mm) resulted in 12 Gyroid structures tested per TPU Filament; all dimensions in [mm]

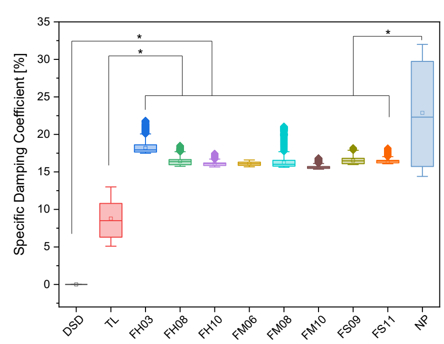

Figure 2: Specific damping coefficients for FlexSemiSoft (FS), FlexMed (FM), and FlexHard (FH) compared with those of human intervertebral discs. DSD…Pedicle Screw-Based Dynamic Stabilization Devices for the Lumbar Spine [2]; NP...nucleus pulposus [3]; TL...thoracolumbar IVD [4]. Significant differences with p<0.05 (*)