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Title of the doctoral dissertation: **"Microfluidic-Assisted 3D Printing of Functionally Graded Porous Biomaterials"**

Abstract

Engineering spherical-based porous metamaterials in a cost-effective manner with controlled architecture across multiple length scales remains a central challenge in advanced additive manufacturing, including in biofabrication. Conventional scaffold fabrication methods typically rely on stochastic templating strategies that can only ensure limited control over pore size distribution, spatial organization, and compositional gradients, making it difficult to replicate the structural complexity of hierarchical biological materials. To overcome these limitations, this doctoral thesis presents a microfluidic-assisted 3D printing platform for the on-demand fabrication of porous functionally graded biomaterials.

A microfluidic flow-focusing droplet generator was designed to generate highly monodisperse emulsions that determine the resulting pore architecture. By precisely regulating the flow rates of the continuous and dispersed phases, droplet size was finely tuned, enabling controlled pore-size distributions in the resulting materials. Building on this concept, the droplet generator was integrated with an extrusion-based 3D printing system, allowing the direct deposition of emulsion-based inks into predefined architecture, enabling simultaneous control over macroscopic scaffold geometry and microscopic pore architecture while accommodating relatively low-viscosity material inks. Beyond hydrogel systems, the platform's versatility was further demonstrated by the fabrication of porous ceramic constructs via templated printing, followed by sintering, preserving the designed pore architecture. Finally, the system was expanded by integrating a passive microfluidic micromixer, which enables real-time modulation of the matrix composition during extrusion, enabling the fabrication of functionally graded soft biomaterials with spatially controlled physicochemical and mechanical properties within a single printing process.

Together, these technological developments establish a microfluidic-integrated manufacturing strategy capable of programming porosity, composition, and architecture within a single fabrication

workflow, enabling structural control from microscale pore templating to macroscale scaffold design and providing a scalable route to the fabrication of hierarchical, functionally graded porous materials for future biomedical applications.