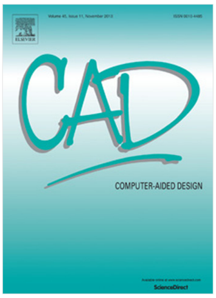

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Computational Design of Curvilinear Bone Scaffolds Fabricated Via Direct Ink Writing

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Abstract

Bone scaffold porosity and stiffness play a critical role in the success of critical-size bone defect rehabilitation. In this work, we present a computational procedure to design ceramic bone scaffolds to provide adequate mechanical support and foster bone healing. The scaffolds considered in our study consist of a lattice of curved rods fabricated via direct ink writing. We develop cellular solids models of the scaffold's effective elastic constants as functions of its geometric parameters, up to some unknown coefficients. To determine numeric values for these coefficients, we execute a computational design of experiments whereby effective elastic properties are obtained using numerical homogenization with the finite element method. In order to automate these experiments and circumvent re-meshing for every scaffold geometry, we project a representative volume element of the scaffold onto a fixed uniform mesh and assign an ersatz material for the analysis. We use these calibrated models in conjunction with finite element analysis and efficient gradient-based optimization methods to design patient-specific scaffolds (i.e., shape, location, and loading) by varying geometric parameters that can be controlled in the fabrication, namely the separation between rods in the lattice, and the printing path of the rods. At present, our methodology is restricted to 2-d idealizations of flat bones subject to in-plane loading. The optimization procedure renders element-wise values of these parameters. As this representation is not amenable to fabrication, lastly, we generate the final scaffold geometry by posing a differential equation whose solution is a function such that its level set lines at specified values correspond to the directrices of the rods in the scaffold. We present examples where we perform the maximization of stiffness of a scaffold implant with a constraint on porosity.

Keywords: Bone Scaffold, Design for Manufacturing, Structural Optimization, Direct Ink Writing

1. Introduction

Bone grafts are necessary to enhance biologic repair of defect sites which are too large to heal naturally, known as critical-size bone defects. Having surpassed four million annual procedures, there is a substantial and growing demand for bone grafts [1]. The current standard is the use of autografts, i.e. grafts from bone harvested from the patient's own body. However, several issues arise with autografts, including donor site morbidity, limited availability, and graft quality. Alternatively, surgeons use grafts donated from cadavers (known as allografts) but these are likewise limited in availability, may incite an immunogenic response, and although sterilized, do not preclude the possibility of disease transfer [2, 3, 4].

The alternative to biological origin grafts is synthetic scaffolds, which vary in materials, fabrication techniques and structure. These scaffolds are designed with considerations such as biocompatibility, osteointegration, osteoconduction, porosity, permeability, stiffness, manufacturing process, angiogenesis, cellular seeding, and growth factor delivery [5, 6]. Each of these design considerations dictates geometric and mechanical requirements on the scaffold. Angiogenesis of a defect site, for example, demands facilitated nutrient transport, waste removal and void regions to allow vasculature in-growth. This demand requires a large pore size and interconnectivity and consequently a high porosity scaffold [5, 6]. In load-bearing applications, stiffness requirements are paramount. A graft that is too stiff will exhibit low strain energy density and thus reduce the mechanotransduction necessary to induce bone growth and stave off bone resorption, a phenomenon called stress shielding [4, 7]. A graft that is too compliant, on the other hand, will not provide load-bearing support so as to return function to the afflicted region. Porosity is also an essential design consideration to promote osteoconduction, osteointegration, angiogenesis, nutrient and waste transportation, and osteoinduction [5, 6, 7].

In this work, we focus on porosity and stiffness so as to enhance scaffold implants through osteoconduction and adequate levels of mechanical support. Therefore, we must select a material system that renders scaffolds with feasible magnitude ranges for these two objectives, i.e., we must choose a fabrication technique which is conducive to high porosity, and use biocompatible materials with stiffness similar to that of bone. Here, we consider direct ink writing (cf., [8]) of ceramic hydroxyapatite (HA) scaffolds. By extruding colloidal HA through a nozzle in a layer-by-layer fashion, we have a high level of control of the porosity and stiffness. The ability to use

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