INTRODUCTION

Trabecular bone is considered as a two-phase material structure consisting of an interconnected network of trabeculae (solid) and a pore space filled by a viscous fluid phase. Within a proper scale, compared to the typical size of cancellous bone specimen, the trabecular bone could be considered as a classic model of composite material. The mechanical properties of the porous material are dominated by the fashion of micro pores topology within the material (pore size, pore connectivity, pore distribution, etc.). The elasticity properties, indicate the strength of bone, are essentially a function to solid phase but reduced and modified by the appearance of the pores, and the flow of fluid through the pores brings nutrients to cells in the tissue matrix and also takes away their waste. Moreover, in bone tissue engineering, fluid permeability of cylindrical trabecular bone grafts was found to predict clinical success. In this study, first we developed a numerical experiment scheme to calculate the effective trabecular bone stiffness and fluid permeability based on the homogenization theory. The native bone properties, then, can provide a guide line for tissue engineering scaffold design. The tissue engineering scaffold for bone regeneration is designed to serve three primary criteria: (1) it must identify a growth region that will shape the bone regenerating, (2) it must provide temporary material properties around the defect area while bone tissue rejuvenates and (3) it must assist ingrowths of bone tissue and also allow to contain seeded cells, protein and/or genes to accelerate repair stage. A general hypothesis states that scaffold should be designed to mimic the healthy body environment and material properties, i.e. stiffness and strength which can provide support of the original bone function while perenpetaly maintaining an interconnected pore network for cell migration and nutrient transport. Many different methodologies have been developed to design and fabricate 3D scaffolds for bone regeneration, and these traditional techniques include fiber bonding, solvent casting, particular leaching, phase separation, and gas foaming. However, those approaches couldn’t provide precisely designing key factors of scaffold such as pore size, total porosity, poring shape, poring interconnectivity, scaffold permeability, and elastic stiffness. To overcome the limitation of scaffold design/fabrication, we proposed a multidisciplinary topology optimization approach to design internal architecture of a solid-fluid mixture scaffold to provide a biomimetic mechanical environment for bone tissue engineering.

METHOD

Study the phenomenon of fluid flow in porous materials gains great interest of bone tissue engineering model. The global fluid permeability tensor, which is defined by Darcey’s Law indicates to ability of fluid passing through a porous media. Utilizing the homogenization theory, the effective permeability can be constructed from the cell problems, which can be identified as a local steady-state stoke-flow through porous unit microstructure with periodic condition. The numerical solutions can be solved by using a Finite-Difference method on a Mark-and-Cell (MAC) grid of the interested domain. More detail of mathematical derivation of this method and numerical permeability analysis of different trabecular bone microstructure will be demonstrated in the presentation.

For 3D tissue engineering scaffold design, we followed authors’ previous work and introduce a topology optimization scheme to design internal architecture. The topology optimization method allows us to obtain the optimized structure without knowing the geometry in prior and it was first developed by Bendsøe and Kikuchi in 1988 for solid mechanics structural optimization. This algorithm is enhanced to be a multidisciplinary design optimization (MDO) method by tailoring the elasticity design for the solid part and the permeability maximization for the fluid part. The scaffold microstructure is considered as a three dimensional (3D) image consisting of solid and void voxel with periodic boundary condition (PBC) and the image model is treated as a fixed design domain during the optimization process. Thus, the material design is obtained by optimally distributing density within image voxels.

The objective function of this design optimization scheme is to maximize permeability of scaffold while preserving desired elastic stiffness. We demonstrate that the method can produce highly permeability solid-fluid mixture microstructures while provide anisotropic stiffness using accepted biomaterials without knowing its shape and geometry a priori. The subsequent engineered scaffold will provide a biomimetic mechanical environment while maintaining sufficient porosity and permeability for tissue ingrowths.

RESULT

The mechanical properties of trabecular bone are affected by different boundary conditions of anatomic location, which also dominate the geometry of inter trabeculae architecture. In order to study the correlation between properties (elasticity, porosity, and permeability), we used the homogenization method to perform a numerical experiment for trabecular bone from different human anatomic region. In Fig. 1, we demonstrate the relation between anisotropic permeability and porosities.

Using the native trabecular bone (Fig. 2a) properties as an objective for design tissue engineering scaffold, we also demonstrate the proposed multidisciplinary topology optimization scheme can converge to a scaffold microstructure to provide a biomimetic environment. Then, the complex 3D design model is ready to fabrication through a solid freeform fabrication (SFF) technique for further in-vivo experiment studies.