A GENERALZED SCAFFOLD INTERNAL ARCHITECTURE DESIGN METHOD USING TOPOLOGY OPTIMIZATION

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INTRODUCTION

An often-proposed tissue engineering design hypothesis is that the scaffold should provide a biomimetic mechanical environment for initial function and sufficient porosity for cell migration and cell/gene delivery. To provide a systematic study of this hypothesis, the ability to precisely design and manufacture biomaterial scaffold is desired. Conventional methods for microstructure design and fabrication cannot provide detailed control of pore-size, interconnected channels, and uniform pore distribution[1]. Hollister et al. (2002) proposed a restricted design optimization method, which can ensure interconnected channels and uniform pore distribution. However, the design capability is still limited by the pore design parameters. The purpose of this study was to develop a robust design scheme for 3D internal scaffold architecture to match desired elastic properties and porosity simultaneously in the feasible domain, by introducing the Image-based Topology Optimization algorithm (also known as General Layout Optimization). With an initial target for bone tissue engineering, we demonstrate that the method can produce highly porous structures that match human trabecular bone anisotropic stiffness using accepted biomaterials.

METHOD

Design feasiblity

The design of internal architecture can be considered as design microstructure of composite material. Hence, we can use the theory of composite material introduced by Hashin and Shtrikman in 1963 [2], to construct a theoretical relation between material elasticity and porosity. By utilizing this relation, we can construct a well-defined design feasible domain that allow the design microstructure to achieve the desired elasticity while providing large porosity, or to achieve the target porosity while provideing sufficient stiffness.

Topology Optimization Scheme

Topology Optimization Method was first developed by Bendsϕe and Kikuchi in 1988[3] and their work was extended to design material microstructure by Sigmund in 1997[4]. The material 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.

To solve the topology optimization problem, we have first adapted the image-based homogenization technique, which allows us to obtain the effective global properties from microstructure image[5]. The weak form of the equilibrium constitutive equation (Eq.1) is solved numerically using Element-By-Element Preconditioning Conjugate Gradient (EBE-PCG), and characteristic displacements (χ) are obtained and used to construct the effective material stiffness matrix (Eq.2).

$$\int_Y (C_{ijkl} - C_{ijpq}\frac{\partial \chi_p^{kl}}{\partial y_q})\frac{\partial v_i}{\partial y_j} dY = 0 \tag{1}$$

$$C_{ijkl}^H = \frac{1}{|Y|}\int_Y (\delta_{im}\delta_{jn} - \frac{\partial \chi_m^{ij}}{\partial y_n})\cdot C_{mnpq}\cdot(\delta_{kp}\delta_{lq} - \frac{\partial \chi_p^{kl}}{\partial y_q})dY \tag{2}$$

C is the material stiffness matrix, and a superscript, H, donate to homogenized properties. Y is the microstructure design domain with PBC; χ is characteristic displacement and ν is virtual displacement.

Next, obtain the target properties used for design objective by computing effective trabecular stiffness from trabecular micro-CT images of specific anatomic sites. The design optimization problem can then be formulated as,

$$\begin{aligned} \min \quad & w_1\left\|C_{1111}^H - C_{1111}^*\right\|_{L_2} + w_2\left\|C_{1122}^H - C_{1122}^*\right\|_{L_2} + \ldots. \\ s.t. \quad & \\ & \text{Porosity Constraints} \\ & \text{Bounds on design variables} \end{aligned} \tag{3}$$

C is the material stiffness matrix, and objective function is defined by minimizing the L_2 norm of difference between effective properties with target properties. $\boldsymbol{w_i}$ are weighting and scale parameters for multiple objective case. Then, using Method of Moving Asymptotes (MMA)[6], as optimizer to update the design microstructure image in each optimization step, and the update scheme is terminated by the algorithm converged.

Algorithm Improvements

The current approach in literature, however, suffers from numerical difficulties when implemented in the 3D case. Several enhancements are proposed to address these numerical difficulties associated with topology microstructure design. (1) Because of the periodic boundary condition, the optimal layout is not unique and depends significantly on the initial input of the design procedure. An adaptive optimization scheme is used and begins with a uniform low-resolution image mesh as initial input. Once the sub-problem is converged, the result solution image mesh is refined to higher resolution and used as an initial guess for the next iteration of problem. The process ends when the best resolution is reached and converged. (2) Since the implementation model is image-based, we apply image-processing algorithms during the optimization scheme to ensure inner-channel connectivity and to avoid checkerboard image pattern. The Visualization Toolkit (VTK) image-processing library is utilized. (3) An integer programming technique, random-rounding, is also implemented to obtain a preferable solution from the final result.

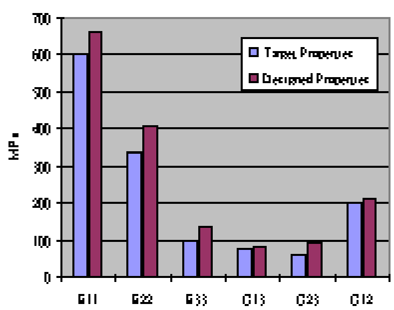
Fabrication

After the optimal result is converged, the design microstructure topology in voxel image format is converted to a standard .STL 3D format for post processing and fabrication via Solid-Free-Form Fabrication techniques (SFF). The following present design cases can either fabricate use Stereolithography techniques (SLA) or 3D inkjet printing techniques.

RESULTS

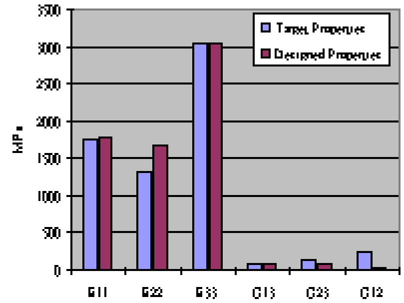
Human Distal Femur and Iliac Crest

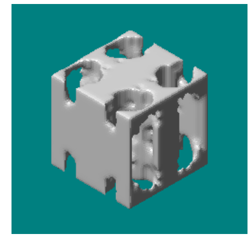
To demonstrate the proposed design algorithm, the objective properties of human bone were obtained by homogenized micro-CT scans of distal femur and iliac crest trabecular structure. Based properties for the designed microstructure were E=4GPa, and v=0.3, in the range of commonly used biomaterials. The following chart shows the result of design microstructure achieve distal femur properties.



Minipig Mandibular

In order to study the scaffold internal architecture design for mandibular condyle replacement, we construct a serials microstructure designs with different biomaterials and different porosity that provide same stiffness for the implant region of minipig. The following chart shows the result of design microstructure with 40% porosity.





Design Microstructure for Spinal Cage

Collaborate to develop a new approach for human spinal cage; the global scaffold design is synthesized by different microstructures design with different specified porosities. Simultaneously, the titanium-based microstructure is required to provide the extreme isotropic stiffness with associated porosity. The following figures demonstrate designs with 45% and 80% porosity, and more detail result will be presented in conference.

Porosity: 45 %

Porosity: 80%

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