Prediction and Estimation of Scaffold Strength with different pore size

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Abstract. This paper emphasizes the significance of prediction and estimation of the mechanical strength of 3D functional scaffolds before the manufacturing process. Prior evaluation of the mechanical strength and structural properties of the scaffold will reduce the cost fabrication and in fact ease up the designing process. Detailed analysis and investigation of various mechanical properties including shear stress equivalence have helped to estimate the effect of porosity and pore size on the functionality of the scaffold. The influence of variation in porosity was examined by computational approach via finite element analysis (FEA) and ANSYS application software. The results designate the adequate perspective of the evolutionary method for the regulation and optimization of the intricate engineering design process.

1. Introduction

Tissue engineering with patient-specific approach including target specific tissues regeneration is developing the field of science. It is an evolving field of science that aspires to replace, repair or regenerate patient’s specific organs and tissues by applying knowledge in biomechanics into materials suitable medical application [1], [2].

Tissue engineering with patient-specific approach involves tissues from a patient body which is been extracted, and then multiplied in nutrient culture medium and introduce into a scaffold which is prepared with a specific bio-compatible material through 3D computer-aided design (CAD). It can be then grafted into the same person which is functional as a replacement tissue [3]. Various scaffolds utilized as the implant and in tissue engineering are manufactured by conventional approaches like – artificial bone grafts, biomaterial-based textiles, porous biomaterial which usually help to build scaffold which has simple and uniform structure, but is not efficient enough. [4]. The base material, the material property, the mechanical property, the pre-medium in the area of the scaffold, and the post-medium, mostly determined by deformation characteristics are critical variables for scaffold design and function. The porosity in scaffolds help in the formation of new tissue by providing volumetric space, diffusion, proliferation, and enhanced growth of connective tissue progenitors within the replaced area [5], [6], [7] have performed a stress-strain analysis of different CAD models by using structural analysis to calculate mechanical strain. [8], [9].

Such analysis could be performed by varying different geometrical properties or material properties simultaneously and helps to choose most suitable scaffold [7]. Lacroix, D., and Prendergast, P.J studies showed simulations and computational analysis of cell culture-based bioreactor used for
scaffold performances. It revealed the differentiation of tissues and regeneration in bones as a function of porosity, Young’s modulus at different loading condition. The endorsed material property can be optimized by rapid prototyping fabrication. [10], [11], [12], [13], [14]

![Scaffold images](image)

**Figure 1.** Scaffolds produced with varying pores sizes and pattern

2. Materials and Methods

2.1. Scaffolds design

Cylindrical porous scaffolds (28mm × 15mm) with varying pores size from were designed using a computer-aided design (CAD) software (SolidWorks, Dassault Systèmes S.A.). Three scaffolds were designed with pores size of 0.5mm, 1mm and 1.5mm maintaining the overall diameter of 28mm and thickness of 15mm.

2.2. Porosity calculation

The scaffold models with different pores sizes were used to calculate porosity by using Eq. 1[15] [16]

\[
\text{Porosity} = 1 - \left( \frac{V_{\text{solid}}}{V_{\text{total}}} \right) \times 100\%
\]

where \(V_{\text{solid}}\) = solid part volume and \(V_{\text{total}}\) = total scaffold volume.

2.3. Finite Element Analysis

The Von Mises stress (Equivalent Stress) distributions were calculated by using Ansys software (ANSYS, Inc, Pennsylvania, United States) and compared to the results from previous work done by (H. Shen, et al). The CAD models in IGS format were used to be analyzed in Static Structural Module in Ansys workbench. The symmetry conditions were assumed to be about the x–z and y–z planes (z at shorter axis) to reduce elements complexity. The meshing of the model was done using default mesh option on Ansys Mechanical toolbox. The material was assumed to isotropic and homogeneous which is on basis of optical microscopy [18]. Tests for mechanical property (Table 1) and FEA on Selective laser sintering processed Polycaprolactone [17,19]. The Young’s moduli were assumed to be 258 MPa on basis of Mori–Tanaka theory (Aboudi, 1991) The Poisson’s ratio was taken as 0.3.

3. Results and Discussions

3.1. Scaffolds Porosity

MATLAB R2014a (The Mathworks Inc.) was used to calculate porosity of the scaffold. A Finite Element Analysis(FEA) was done on the various design variables volume of solid (\(V_{\text{solid}}\)), the total volume of scaffold(\(V_{\text{total}}\)) Then, for the ideal porous structure, the calculation of solid’s volume (\(V_{\text{solid}}\)) and total scaffold’s volume(\(V_{\text{total}}\)) obtained by using Eq. 1. The porosity of the models can
be easily calculated from the design variables pores diameter and thickness and the total volume of the scaffold designed structure. The porosity (%) obtained was of 47-78% range depending on the scaffold structure. The porosity assumed to be uniform for the whole volume which is almost similar when scaffold obtained from precise fabrication method involving controlled rapid prototyping system. The porosity was found was dependent on pores size and pore gap. It increases with increase in pores gap and pores size. The increase in porosity helps in tissue regeneration by controlling permeability, mechanical strength, and cell growth [20]. The new cell formation occurs where porosity is high. Therefore, scaffold with high porosity should be preferred. However, the pores gap should be corresponding to the diameter of the pores should be within a practical limit to maintain the integrity of the fabrication process to produce stable scaffold structure [21]. It is because of the presence of pores size the pores interconnectivity is hampered during the polymer deposition. High scaffold interconnectivity is essential for proper inflow of nutrients in the surrounding tissue [22], [23]. Tough the increase in porosity decreases yield strength which also dependent on the pore distances.

![Plot of porosity(%) vs pores size](image)

**Figure 2.** Relationship between effective scaffold porosity for various scaffold architectures

### 3.2. Finite element analysis

Finite element analysis Compressive and effective tensile modulus for the geometries are predicted by FEA. The mechanical testing shows the better results of it (Fig. 3). The Finite element analysis data generally have a 30% error. The computational modulus reported shows the higher correlation with physically experimented data, than was previously reported selective laser sintering processed Polycaprolactone by Williams et al. [24], had a prediction averaging 100% using an image-based FEA method, and lately by Cahill et al. [25] where the degree of prediction was observed as 67%. The bulk modulus of the specimen was estimated using bulk gage specimen which had the higher density than the scaffolds (Table 1), therefore it could be possible that it will over-estimate the modulus efficiency of the scaffolds in all cases.

The FEA resulted in under-estimate the modulus efficiency of tensile specimens and over-estimate the modulus efficiency of compressive specimens. There was no element with bulk yield strength above 1% strain as shown by the von Mises stress distributions in (Fig. 4(a), 4(b), 4(c)). Data from stress distribution in test specimens exhibit relative lower stress concentrations in the scaffold’s solid part were shifting from the lower pores size to higher pores size, thus elucidating the slight change in mechanical properties between the lower pores size to higher pores size scaffolds (Fig. 3).
Figure 3. Relationship between Von Mises Stress for a various scaffolds pores size

Figure 4. Von Mises stress of PCL implant material with pore size (a) 0.5mm, (b) 0.75mm, (c) 1mm
Table 1. Porosity and Von Mises Stress values obtained by FEA analysis

| Pore size (mm) | Porosity (%) | Von Mises Stress (MPa) |
|---------------|--------------|------------------------|
| 0.5           | 78.45        | 244.33                 |
| 0.75          | 180.47       | 58.4                   |
| 1             | 62.02        | 278.57                 |

4. Conclusion

Computer Aided Design was developed by varying pores size and pores gap which changes the porous characteristics and subsequently the mechanical strength. The porous characteristics of the CAD models of the scaffold were calculated by MATLAB, while structural analysis was carried out with ANSYS to obtain mechanical properties.

On the basis of computational FEA result, it is concluded that the pore diameter and pore gap have a direct effect on its porosity and mechanical properties. The ANSYS data signifies that the increased pore size will increase porosity but decrease the mechanical strength. A compressive test shows a mechanical strength of scaffold was directly linked to the diameter and gap of the pores.

Non-uniform property of the scaffold indicates that mechanical properties were strongly dependent on the scaffold’s pore lay-down orientation. This software-based approach will help in reformative 3D scaffold advancement for a patient-specific application by reducing the necessity of physical experiments. This software data is useful in the development of physical scaffolds by rapid prototyping technology along with artificial biopolymers.

References

[1] G. F. Muschler, C. Nakamoto 2004, and L. G. Griffith, “Engineering principles of clinical cell-based tissue engineering.” J. Bone Joint Surg Am, vol. 86, pp. 1541-1558.
[2] G. Tripathi and B. Basu 2012, “A porous hydroxyapatite scaffold for bone tissue engineering: Physico-mechanical and biological evaluations,” Ceramics International, vol. 38, no. 1, pp. 341-349.
[3] A. Lucke, J. Tebmar, E. Schnell, G. Schmeer, and A. Gopferich 2000, “Biodegradable poly(D, L-lactic acid)-poly (ethylene glycol)-monomethyl ether diblock copolymers: structures and surface properties relevant to their use as biomaterials,” Biomaterials, vol. 21, pp. 2361-2370.
[4] J. Zeltinger 2001, “Effect of pore size and void fraction on cellular adhesion, poliferation, and matrix deposition,” Tissue Engineering, vol. 7, pp. 5.
[5] Roohani-Esfahani 2012, Z. F. Lu, J. J. Li, R. Ellis-Behnke, D. L. Kaplan, and H. Zreiqat, Effect of self-assembled nanofibrous silk/polycaprolactone layer on the osteoconductivity and mechanical properties of biphasic calcium phosphate scaffolds, Acta Biomaterialia, vol. 8, no. 1, pp. 302-312.
[6] I. Springer, B. Fleiner, S. Jepsen, and Y. Acil, culture of cells gained from temporomandibular joint cartilage on non-absorbable scaffolds Biomaterials, 22, pp. 2569-77.
[7] Jaecques 2004, H. V. Oosterwyck, L. Muraru, T. Van Cleynenbreugel, E. D. Smet, and M. Wevers, Individualised, micro CT-based finite element modelling as a tool for biomechanical analysis related to tissue engineering of bone, Biomaterials, vol. 25, pp. 1683-1696, 2004.
[8] Burkoth and K. S. Anseth 2000, “A review of photocrosslinked polyanhydrides: in situ forming degradable networks,” Biomaterials, 21, pp. 2395-2404.
[9] M. Lebourg, R. S. Serra 2008, J. M. Estelles, F. H. Sanchez, J. L. G. Ribelles, and J. S. Anton, Biodegradable polycaprolactone scaffold with controlled porosity obtained by modified particle-leaching technique, Journal of Materials Science, 19, pp. 2047-2053.
[10] M. E. Hoque 2012, Y. L. Chuan, and I. Pashby, “Extrusion based rapid prototyping technique - An advanced platform for tissue engineering scaffold fabrication,” Biopolymers, vol. 97, pp. 83.

[11] T. V. Cleynenbreugel 2006, J. Schrooten, V. Oosterwyck, and J. Vander Sloten, “Micro-CT-based screening of biomechanical and structural properties of bone tissue engineering scaffolds,” Medical and Biological Engineering and Computing, vol. 44, pp. 517-525.

[12] C. Margherita 2006, B. Federica, T. Manuela, and D. Gabriele, “Modeling evaluation of the fluid-dynamic microenvironment in tissue-engineered constructs: A micro-CT based model,” Biotechnology and Bioengineering, vol. 93, pp. 500-510, 2006.

[13] D. Lacroix and P. J. Prendergast 2002, “A mechano-regulation model for tissue differentiation during fracture healing: analysis of gap size and loading,” Journal of Biomechanics, vol. 35, pp. 1163-1171.

[14] D. Lacroix, A. Chateau, M. Ginebra, and J. Planell 2006, “Micro-finite element models of bone tissue-engineering scaffolds,” Biomaterials, vol. 27, pp. 5326-5334.

[15] Sun W. Starly B. Darling A. Gomez C. Computer-aided tissue engineering: application to biomimetic modelling and design of tissue scaffolds. Biotechnol Appl Biochem. .

[16] Lee K, Wang S. Lu L. Jabbari E. Currier B. Yaszemski M. Fabrication and characterization of poly (propylene fumarate) scaffolds with controlled pore structures using 3-dimensional printing and injection molding. Tissue

[17] Cahill S, Lohfeld S, McHugh P 2009. Finite element predictions compared to experimental results for the effective modulus of bone tissue engineering scaffolds fabricated by selective laser sintering. J Mater Sci Mater Med 20(6):1255–62.

[18] Williams JM et al 2005. Bone tissue engineering using polycaprolactone scaffolds fabricated via selective laser sintering. Biomaterials ;26(23):4817–27.

[19] Partee B, Hollister SJ, Das S. Selective laser sintering process optimization for layered manufacturing of CAPA_6501 polycaprolactone bone tissue engineering scaffolds. J Manuf Science Eng Trans ASME 2006;128(2):531–40.

[20] C. Sandino, J. A. Planell, and D. Lacroix, “A finite element study of mechanical stimuli in scaffolds for bone tissue engineering,” Journal of Biomechanics, vol. 41, pp. 1005-1014, 2008.

[21] L. Shor 2007, “Fabrication of 3D PCL/HAl2O Tissue Scaffolds and osteoblast-scaffold interactions in vitro,” Biomaterials, vol. 28, pp. 5291-5297,

[22] M. J. Silva, W. C. Hayes, and L. J. Gibson, “The effects of non-periodic microstructure on the elastic properties of two-dimensional cellular solids,” International Journal of Mechanical Sciences, vol. 37, pp. 1161-1177, 1995.

[23] B. Cohen, “Navigating through tissue expansion terminology,” J. Dermatol Surg Oncol, vol. 19, pp. 614-615, 1993.

[24] Williams JM 2005et al. Bone tissue engineering using polycaprolactone scaffolds fabricated via selective laser sintering. Biomaterials ;26(23):4817–27.

[25] Cahill S, Lohfeld S, McHugh P 2009. Finite element predictions compared to experimental results for the effective modulus of bone tissue engineering scaffolds fabricated by selective laser sintering. J Mater Sci Mater Med 20(6):1255–62.