International Journal of Scientific Research & Engineering Trends
Volume 8, Issue 1, Jan-Feb-2022, ISSN (Online): 2395-566X

Modeling and Simulation of 3D Scaffold for Bone Tissue Regeneration

Geetha Bala Subramani
Co-Founder & Lead operation,
Medcuore Medical Solutions Private Limited,
Chennai.

Asst. Prof. Vijayalakshmi V, Nithyasree B, KiruthikaV
Department of Biotechnology,
Vel Tech Rangarajan Dr. Sagunthala R&D Institute of Science and Technology, Avadi.

Corresponding author – medcuoreresearch2021@gmail.com

Abstract- The major problem in the use of scaffold for bone tissue engineering is the requirement of porous structure along with the regeneration properties. Identification of material with suitable biological and mechanical properties is a major challenge in the field of bone tissue engineering. In this study, Poly-lactic acid (PLA) and Polyethylene Terephthalate Glycol (PETG) were used as material for the designing of 3D scaffold for bone tissue regeneration. 3D scaffold designs were modeled by using PLA and PETG materials with different shapes using rhino software. The mechanical properties of designed 3D scaffold models were simulated and analyzed by using Ansys software. Based on the simulation, the suitable designsof both PLA and PETG materials were selected. The selected 3D scaffold designs were fabricated using fused deposition modeling (FDM) technique. The fabricated 3D scaffold designs were analyzed based on its porosity; the suitable material was identified as PLA while compare with PETG. Therefore, it was concluded that PLA will be the suitable material rather than PETG for the application of bone scaffold.

Keywords- Poly-lactic acid (PLA), polyethylene Terephthalate glycol (PETG), Bone regeneration, 3D printing, Bio-scaffold, composite materials.

I. INTRODUCTION

The primary objective of Tissue Engineering is a regeneration or replacement of tissues or organs damaged by disease, injury or congenital anomalies (1). At present, Tissue engineering repairs damaged tissues and organs with artificial supporting structures called scaffolds. These are used for attachment and subsequent growth of appropriate (2).

During the cell growth gradual biodegradation of the scaffold occurs and the final product is a new tissue with the desired shape and properties. In recent years, research workplaces are focused on developing scaffold by bio-fabrication techniques to achieve fast, precise and cheap automatic manufacturing of these structures (3, 4). Most promising techniques seem to be rapid prototyping due to its high level of precision and controlling. However, this technique is still to solve various issues before it is easily used for scaffold fabrication (5). In this article we fabricated printing of clinically applicable scaffolds with use of commercially available devices and materials.

This study, focused on "scaffolding" on a field of bone tissue replacement (6). 3D printing is a process whereby a real object is created starting with a virtual 3D digital model. This technology is capable to fabricate a super complex geometry or features by accurately follow the computer-aided design (CAD) model (7, 8). The fabrication requires appropriate materials that gradually released and overlapped in layer-by-layer fashion by 3D printer named Fussed Deposition Modeling (FDM).

The type of material chosen is crucial to ensure the printed object that can be used for further settings and applications. Various types of metals, polymers, ceramics and composites (9, 10) were used for scaffold (Fig 1.1).

Hence, we were used poly lactic acid and polyethylene terephthalate glycol as biomaterials for modeling of scaffold.

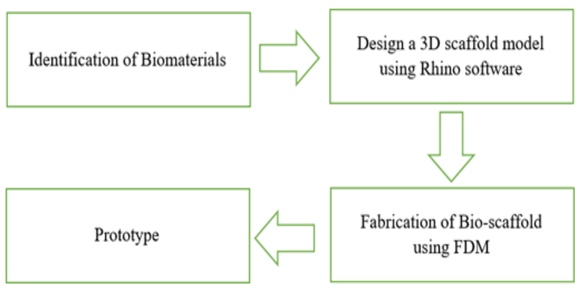

Fig 1. Flow chart for 3D printed scaffold.

Scaffolds are supporting materials used in tissue engineering applications to repair or restore damaged tissues (Fig 1.2). Biomaterials are used to fabricate scaffolds. There are different types of biomaterials including biopolymers, bio-ceramics and biodegradable metals. Biomaterials have to be biocompatible and non-toxic (11).

1. Surface Properties:
Scaffolds with the necessary surface chemistry and properties promote cell attachment, proliferation, and differentiation, 3D scaffold it mimics the extra cellular matrix (ECM), The cells should create its own extracellular matrix (ECM) while is consume for the scaffold biodegradation to deliver indistinguishable 3D microstructures for the damaged sites.

2. Physical Properties:
Scaffolds should be three-dimensional, highly interconnected porous networks and have the appropriate porosity, pore size, and pore structure for cell growth and transport of nutrients and metabolic waste.

3. Mechanical Properties:
It is important to design a matrix with mechanical properties (stress and strain) that mimic the properties of tissue in the immediate surrounding area of the defect.

4. Degradation Properties:
Scaffolds should be biodegradable and possess an appropriate degradation rate in order to mimic the cell/tissue growth in vitro or in vivo.

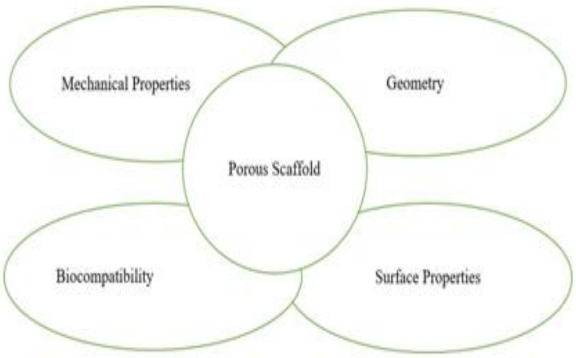

Fig 2. Schematic representation for properties of ideal scaffold.

The drawbacks of existing model, explains that in previous years they were used implants as a supporting material to replace the damaged bones due to some reactions like allergy, inflammation, necrosis these are the conditions will occur in the body while using the metal implants to overcome these drawbacks we were used Scaffolds as supporting material to the bone and that Scaffolds will be made up of biomaterials to replace these implants.

The aim of the current study is to synthesize the highly porous and structured bio-scaffold using 3D printing technology that provides an appropriate environment for the regeneration of bone tissue.

II. MATERIALS & METHODS

1. Design a 3D scaffold:
The scaffold was designed and modelled using a solid based fused deposition method. The design part was started with the computer aided design for 3D porous scaffold architecture using rhinoceros' software and simulation using ANSYS software. Once the 3D printing part is finished the 3d scaffolds were cool down at room temperature and removed from the bed.

The mechanical properties of the sample are derived from the stress-strain analysis and equivalent strain. In this analysis we are using two standard material properties (PETG & PLA) and with the results of the scaffold, we compared the results from equivalent stress, equivalent strain, stress-strain curve.

III. RESULTS AND DISCUSSION

1. Fabrication of Designed Model Prototype:
Table 1.1 showed the results of fabricated designs with different pore size and radius for PLA & PETG. Design 3a showed the fabricated prototype of circle design made up of PETG & PLA with radius of pipe 0.5mm and size of pore 0.1mm.

Table 1. Fabricated designs with different pore size and radius for PLA & PETG.

S. No	Name of the design	Radius ofpipe (mm)	Size ofpore (mm)	Fabricated prototype (PETG)	Fabricated prototype (PLA)
1.	Design 3a	0.5 mm	0.1 mm		
2.	Design 3ab	0.35 mm	0.5 mm		
3.	Design 3ac	0.25 mm	1 mm		
4.	Design 3b	0.2 mm	2 mm		

Design 3ab showed the fabricated prototype of circle design made up of PETG & PLA with radius of pipe

0.35mm and size of pore 0.5mm. Design 3ac showed the fabricated prototype of circle design made up of PLA & PETG with radius of pipe 0.25mm and size of pore 1mm. Design 3b showed the fabricated prototype of circle design made up of PLA & PETG with radius of pipe 0.2 mm and size of pore 2mm.

From the fabricated prototype designs, (Design 3b) circle design made up of PLA & PETG with radius of pipe 0.2 mm & size of pore 2mm were compared. It was observed that circle design made up of PLA with radius of pipe 0.2 mm & size of pore 2mm was better than PETG based on the formation of pores. Further, (Design 3b) circle design made up of PLA & PETG with radius of pipe 0.2 mm and size of pore 2mm were analyzed by using ANSYS software to study and compare its mechanical properties.

IV. SIMULATION STUDY

From the result of fabrication, the best fabricated prototype designs were analyzed by using ANSYS simulation software to study its mechanical properties. The steps for the simulation process.

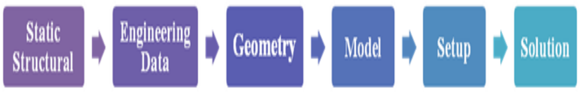

Fig 3. Steps used for the simulation process

The first step was static structural, the option available in the Ansys software to study the mechanical properties of designed model. The second step was to update the data in the engineering data fig 3.1. After that we were uploaded the model to the geometry column. The third step was mesh process, which was important to distribute the force into all over the surface of designed model. The fourth step was to setup all the properties like total deformation, equivalent elastic strain, maximum shear elastic strain, equivalent stress, maximum shear stress.

At the final step, solution button will appear, by clicking on it, the solution of designed model was found. The simulation results were analyzed and the best suitable material was selected for the fabrication of scaffold for bone tissue regeneration.

1. Total deformation:

Fig 3.2 showed the deformation of the scaffolds when a compression force of 27N is applied. As observed, PLA scaffolds designed with 2mm of filament distance had a maximum deformation of 1.3467mm, while scaffolds designed with PETG material of 2mm had a maximum deformation of 1.6021mm (Fig 3.3). This 2-3D scaffold prototype with extraordinary pore diameters have been acquired with the aid of using different scale elements and thickening factors (Fig 3.4). These scaffold models had porosities ranging from 60% to 80%. The geometry details of the single-unit prototype are mentioned in Table.

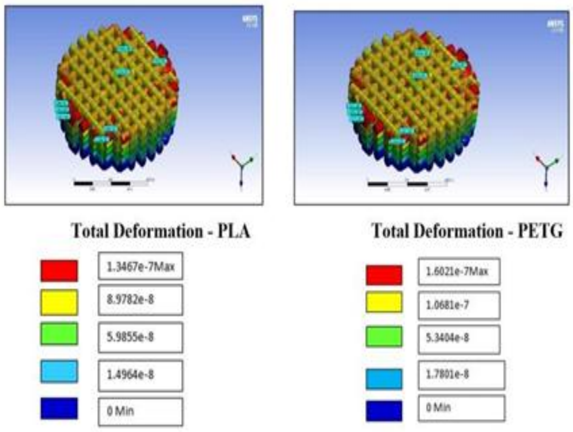

Fig 4. Total Deformation of PLA & PETG.

2. Equivalent Elastic Strain:

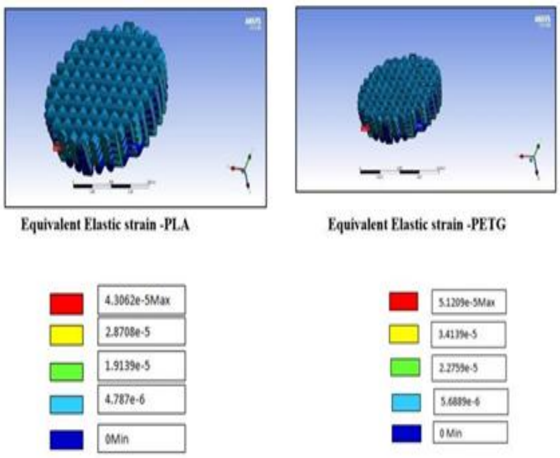

Fig 5. Equivalent Elastic Strain of PLA & PETG.

3. Equivalent Stress:

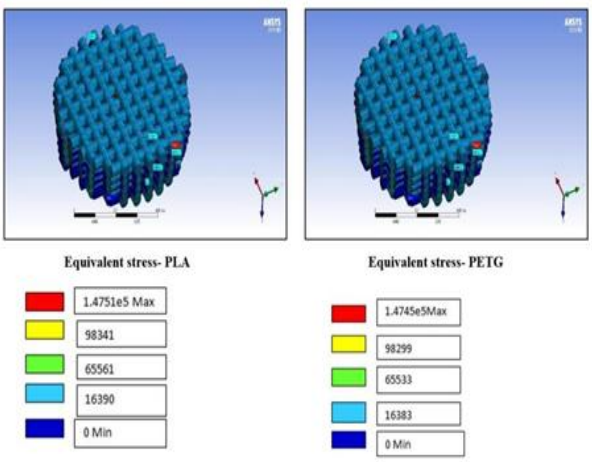

Fig 6. Equivalent Stress of PLA & PETG.

According to the research studies, the wall shear stress has a greater significant influence on the cell proliferation than the fluid stress, but the inlet strain affects the mass flow of the nutrient liquid in a scaffold without delay. Based on the results, it seems that scaffolds designed with a filament distance of 2mm made of PETG material is not suitable for bone applications due to the high deformation that compromises the slope of the pores and consequently, to the spreading of cells to the internal regions of the scaffold and the supply of oxygen and nutrients.

V. CONCLUSION

Structural design plays a critical role in improving the mechanical properties of porous 3D scaffold. A significant advantage of 3D printed scaffold is that it can construct orderly structure for porous materials with full controlled manner of the geometrical parameters. PLA is slightly easier to print and cost effective than PETG. As per our study the total deformation of PLA scaffold is lesser than compared to PETG scaffold, So PLA is preferred for further analytical studies.

3D printed technology shows a great potential in fabricating the porous scaffolds with improved strength in tissue engineering. The 3D-printed bilayer bone scaffold fabricated in this study can possibly be improved and utilized as an appropriate scaffold for bone tissue engineering and as a synthetic graft material in reconstruction of bony defects.

REFERENCES

[1] Hassan, M. H., Omar, A. M., Daskalakis, E., Hou, Y., Huang, B., Strashnov, I., &Bártolo, P. (2020). The Potential of Polyethylene Terephthalate Glycol as Biomaterial for Bone Tissue Engineering. Polymers, 12(12), 3045.
[2] Miller, R. A., Brady, J. M., & Cutright, D. E. (1977). Degradation rates of oral resorbable implants (polylactates and polyglycolates): rate modification with changes in PLA/PGA copolymer ratios. Journal of biomedical materials research, 11(5), 711719.
[3] Fernandez de Grado, G.; Keller, L.; Idoux-Gillet, Y.; Wagner, Q.; Musset, A.M.; Benkirane-Jessel, N.; Bornert, F.; Offner, D. Bone substitutes: A review of their characteristics, clinical use, and perspectives for large bone defects management. J. Tissue Eng. 2018, 9.
[4] Damien, C.J.; Parsons, J.R. Bone graft and bone graft substitutes: A review of current technology and applications. J. Appl. Biomater. 1991, 2, 187–208.
[5] Haugen, H.J.; Lyngstadaas, S.P.; Rossi, F.; Perale, G. Bone grafts: Which is the ideal biomaterial? J. Clin. Periodontol. 2019, 46, 92–102.
[6] Alexopoulou, M.; Mystiridou, E.; Mouzakis, D.; Zaoutsos, S.; Fatouros, D.G.; Bouropoulos, N. Preparation, characterization and in vitro assessment of ibuprofen loaded calcium phosphate/gypsum bone cements. Cryst. Res. Technol. 2016, 51, 41–48.
[7] Pryor, L.S.; Gage, E.; Langevin, C.-J.; Herrera, F.; Breithaupt, A.D.; Gordon, C.R.; Afifi, A.M.; Zins, J.E.; Meltzer, H.; Gosman, A.; et al. Review of Bone Substitutes. Craniomaxillofac. Trauma Reconstr. 2009, 2, 151–160.
[8] Andriotis, O.; Katsamenis, O.L.; Mouzakis, D.E.; Bouropoulos, N. Preparation and characterization of bioceramics produced from calcium phosphate cements. Cryst. Res. Technol. 2010, 45, 239–243. [CrossRef]
[9] Profeta, A.; Huppa, C. Bioactive-glass in Oral and Maxillofacial Surgery. Craniomaxillofac. Trauma Reconstr. 2016, 9, 1–14. Appl. Sci. 2021, 11, 4253 16 of 18
[10] Hoque, J.; Sangaj, N.; Varghese, S. Stimuli-Responsive Supramolecular Hydrogels and Their Applications in Regenerative Medicine. Macromol. Biosci. 2019, 19, 1–16.
[11] Rajabi, A.H.; Jaffe, M.; Arinzeh, T.L. Piezoelectric materials for tissue regeneration: A review. ActaBiomater. 2015, 24, 12–23.
[12] Xu, Z., Omar, A. M., &Bartolo, P. (2021). Experimental and numerical simulations of 3D-printed Polycaprolactone scaffolds for bone tissue engineering applications. Materials, 14(13), 3546.
[13] Liu, F.; Vyas, C.; Poologasundarampillai, G.; Pape, I.; Hinduja, S.; Mirihanage, W.; Bartolo, P. Structural evolution of PCL during melt extrusion 3D printing. Macromol. Mater. Eng. 2018, 303, 1700494.
[14] Dzobo, K.; Thomford, N.E.; Senthebane, D.A.; Shipanga, H.; Rowe, A.; Dandara, C.; Motaung, K.S.C.M. Advances in regenerative medicine and tissue engineering: Innovation and transformation of medicine. Stem Cell. Int. 2018, 2018, 2495848.
[15] Vyas, C.; Pereira, R.; Huang, B.; Liu, F.; Wang, W.; Bartolo, P. Engineering the vasculature with additive manufacturing. Curr.Opin. Biomed. Eng. 2017, 2, 1–13.
[16] Madrid, A.P.M.; Vrech, S.M.; Sanchez, M.A.; Rodriguez, A.P. Advances in additive manufacturing for bone tissue engineering Scaffolds. Mater. Sci. Eng. C 2019, 100, 631– 644.
[17] Stevens, M.M.; George, J.H. Exploring and engineering the cell surface interface. Science 2005, 310, 1135–1138.
[18] Ghassemi, T.; Shahroodi, A.; Ebrahimzadeh, M.H.; Mousavian, A.; Movaffagh, J.; Moradi, A. Current Concepts in Scaffolding for Bone Tissue Engineering. Arch. Bone Jt. Surg. 2018, 6, 90–99.
[19] Chen, Q.; Zou, B.; Lai, Q.; Wang, Y.; Zhu, K.; Deng, Y.; Huang, C. 3D printing and osteogenesis of loofah-like hydroxyapatite bone scaffolds. Ceram. Int. 2021, 47, 20352– 20361.
[20] Ribeiro, J.F.; Oliveira, S.M.; Alves, J.L.; Pedro, A.J.; Reis, R.L.; Fernandes, E.M.; Mano, J.F. Structural monitoring and modeling of the mechanical

deformation of three- dimensional printed poly (ε-caprolactone) scaffolds. Biofabrication 2017, 9, 025015.
[21] Lu, L.; Zhang, Q.; Wootton, D.M.; Chiou, R.; Li, D.; Lu, B.; Lelkes, P.; Zhou, J. Mechanical study of polycaprolactone-hydroxyapatite porous scaffolds created by porogen-based solid freeform fabrication method. J. Appl. Biomater. Funct. Mater. 2014, 12, 145–154.
[22] Hou, Y.; Wang, W.; Bártolo, P. Investigating the Effect of Carbon Nanomaterials Reinforcing Poly (ε-Caprolactone) Printed Scaffolds for Bone Repair Applications. Int. J. Bioprint. 2020, 6, 266.
[23] P.X. Ma Scaffolds for tissue fabrication, Mater. Today 7 (5) (2004) 30 40.
[24] W.Y. Zhou, Selective laser sintering of poly (L-lactide)/carbonated hydroxyapatite porous scaffolds for bone tissue engineering. Ph.D. Thesis, Mechanical Engineering, The University of Hong Kong, 2007.
[25] P.A. Holmes, Biologically produced PHA polymers and copolymers, in: D.C. Bassett (Ed.), Developments in Crystalline Polymers, Elsevier Applied Science, London, 1982.
[26] C. Lucchesi, B. Ferreira, E. Duek, A. Santos, P. Joazeiro, Increased response of Verocells to PHBV matrices treated by plasma, J. Mater. Sci. Mater. Med. 19 (2) (2008).