The effect of pore geometry on the mechanical properties of 3D-printed bone scaffold due to compressive loading

M J Jahir-Hussain.1, N A Maaruf.1, N E F Esa.1, N Jusoh.1,2*

1School of Biomedical Engineering and Health Sciences, Faculty of Engineering, Universiti Teknologi Malaysia, MALAYSIA.
2Medical Devices and Technology Centre (MEDITEC), Institute of Human Centered Engineering, Universiti Teknologi Malaysia, MALAYSIA.

*Corresponding author: norhana@utm.my

Abstract. Bone substitutes are derived from biological products or synthetic bone substitutes such as ceramics, polymers, metals, and organic or non-organic bone substitutes. Emerging three-dimensional (3D)-printing technologies are enabling the fabrication of bone scaffold with the precise specifications. 3D-printing allows controlled material placement for configuring porous tissue scaffolds with tailored properties such as mechanical stiffness, nutrient transport, and biological growth. Therefore, bone scaffolds with good biological and mechanical properties are needed to be used as a bone substitute in bone tissue engineering. However, inadequate mechanical strength is the major problem in current bone scaffolds fabrication. Therefore, the aim of this study is to design and to simulate the mechanical properties of 3D printed polylactic acid (PLA) bone scaffold with different pore geometries, which are circular, square, hexagonal and triangular. The scaffolds were designed and were simulated by using SolidWorks in determining the mechanical properties. Finite Element Analysis (FEA) of the PLA bone scaffold indicates that scaffolds with hexagonal pore shape has compressive strength of 241.0 MPa, which is matches with the human bone properties.

1. Introduction
Bone tissue defect become a major problem which brings tremendous harms to health and reduce the quality of life. Bone grafting is very important to patients who are affected by the loss of bone tissues or bone defect caused by any disease or trauma. Bone health is vital for a human being since it provides the body with a frame to allow movement and protection. The ideal bone substitutes should meet precise specifications such as biocompatible, bioresorbable, osteoconductive, osteoinductive, porous, mechanically resistant, easy to use, safe and cost-effective. Current gold standards for bone injury medical treatments focused on replacing the lost bone with bone grafting such as autografts, allogeneic or autogenous. These bone grafting techniques are limited by many aspects. Therefore, bone scaffold plays an important role in bone grafting treatment.

With the use of 3D-printed bone scaffold in bone tissue engineering, it can be an alternative treatment which helps to overcome drawbacks found in the traditional way of bone grafting such as autograft and allograft and reduces the chances of getting an infection, immune rejection and chronic donor-site pain which occurs in current clinical treatment. Although normal 3D printing and
bioprinting can produce a porous scaffold, but there still have challenges in the predesigned geometries or architecture [1]. For example, the pore geometries play a crucial role in the bone tissue engineering by tuning the process of tissue regeneration including cell proliferation, cell adhesion, vascularization, nutrients and oxygen [2,3].

Therefore, a suitable bone scaffold with both biological and mechanical properties are needed to be used as a bone substitute in bone tissue engineering. However, inadequate mechanical strength is the major problem in fabricating the bone scaffolds. Ideally, a scaffold should have appropriate mechanical properties consistent with the human anatomy. Due to the complicated stress environment of human skeleton system, mechanical properties are essential in establishing firm connections with the newly formed tissue. Biomechanical property of an ideal scaffold has to be same with the type of bone that going to be replaced and have comparable strength to the native bone tissue to withstand both physiological loads and to avoid the occurrence of stress shielding [4,5]. The mechanical properties are dependent on intrinsic mechanical properties of the material used and on geometrical features [6]. The most important factor that influence to the mechanical properties of the scaffold is the architecture of bone scaffold such as pore shape, pore distribution and strut thickness [7]. Therefore, here we designed and simulated the mechanical properties of 3D printed PLA bone scaffold with different pore geometries in predicting the suitable pore shape in improving the strategies in bone scaffold design and optimization. Selected parameters such as porosity and compressive strength were analyzed to find out the best scaffold model to be used as a bone scaffold in tissue engineering.

2. Finite Element Analysis
SolidWorks 2018 is used in designing the 3D-printed scaffolds with different pore geometries, which are circular, square, hexagon and triangular, as shown in Figure 1. The scaffolds are designed with 10.40 mm in diameter and 14.40 mm in length as the outer cylinder dimensions. The pore size and strut size are same for all geometries, which are 1.0 mm and 1.4 mm, respectively.

![Figure 1. A) Scaffold with different pore shape and, B) unit cell, and C) the pore dimensions](image-url)
To predict the compressive strength of the designed scaffold, Finite Element Analysis (FEA) was carried out by using the SolidWorks software. PLA filament material properties were used in the simulation as shown in Table 1.

| Properties       | Value                  |
|------------------|------------------------|
| Mass density     | 1240 - 1260 kg/m³     |
| Poisson’s ratio  | 0.33 N/A               |
| Tensile strength | 37 N/mm²               |
| Yield Strength   | 37 N/mm²               |

Before conducting the simulations, the scaffold models were meshed for better convergence, as shown in Figure 2. The bottom part of the design was fixed and load of 2000 N which is approximately of 5 times of body weight was applied on the top surface of the scaffolds to determine the behaviour and structure of the scaffold under the compressive loading [8].

![Figure 2. Distributed 2000N load applied part and fixed part.](image)

3. Result and Discussions
PLA become the most common filaments used in 3D printing. It is a synthetic material which is normally used for scaffold printing for bone tissue engineering. In the application of tissue engineering, PLA was the first polyester used due to its biocompatibility and biodegradability. PLA is a biodegradable and non-toxic material which will degrade to form lactic acid which is normally present in the human body once implanted in the body [9]. Ideally, PLA is suitable material for the bone scaffolds due to its Young’s Modulus which is from 0.35GPa up to 4.14 GPa that is almost similar to bone tissue [10].
Figure 3 shows the volumetric properties of bone scaffolds after applying PLA material’s properties. Even though the outer cylinder dimensions for the four designs were same, the volume of each scaffold design differs due to the presence of pores with different shapes in each design that also leads to the variation in mass, volume and weight of the bone scaffold designs.

![Table showing volumetric properties of bone scaffolds](image)

*Figure 3. Volumetric properties of bone scaffolds after applying PLA material scaffold models with different pore shape, A) Circular B) Square C) Hexagonal and D) Triangular*

Compressive strength is normally used to determine the mechanical behaviour of a bone substitute. Compressive strength or compression strength is defined as the capacity of a material or structure to withstand load bearings which tends to reduce the size of the material. Since the fabrication of these bone scaffolds intended to be used as bone substitute materials, it is very important to make sure the bone scaffolds compressive strength in 90 MPa to 230 MPa which is similar to the human cortical bone compressive strength range [11]. By using the Finite Element Analysis, the compressive stress of the scaffolds has been analysed based on Von-misses contour plot, as shown in the Figure 4.
Figure 4. Von-misses contour plots for scaffold models with different pore shape, A) Circular B) Square C) Hexagonal and D) Triangular

Mechanical properties such as the porosity and surface area were calculated from the volumetric properties. Meanwhile, the values for compressive strength was obtained by taking the highest value of Von-misses contour plot from Finite Element Analysis [12]. On the other hand, the specific strength, also known as the strength-to-weight ratio was calculated based the ratio of compressive strength to volume of each scaffold design [13]. Table 2 shows the mechanical properties of the scaffolds.

|                  | Circular Pore Scaffold | Square Pore Scaffold | Hexagonal Pore Scaffold | Triangular Pore Scaffold |
|------------------|------------------------|----------------------|-------------------------|--------------------------|
| Porosity (%)     | 75.64                  | 69.93                | 73.57                   | 62.99                    |
| Surface Area (mm²) | 1602.46                | 1795.92              | 1673.28                 | 1988.21                  |
| Compressive Strength (MPa) | 127.9          | 140.7                | 241.0                   | 255.2                    |
| Specific Strength (MPa/mm³) | 0.14            | 0.16                 | 0.27                    | 0.33                     |
As shown in Table 2, different pore geometry has different porosity. The scaffold with circular pore shape has the highest porosity which is 75.64% while scaffold with triangular pore has the lowest porosity which is 62.99%. On the other hand, square pore scaffold and hexagonal pore scaffold have a porosity of 69.93% and 73.57%, respectively. So, it can be clearly seen that geometries of the pore effects the porosity of the bone scaffold due to the surface area of the designed bone scaffolds. Apart from porosity, surface area is also factor while designing a bone scaffold since larger surface area can increase the bone healing process and promote more protein adsorption site and facilitate interaction between scaffolds and cells [12].

Besides, the porosity of material has a significant impact on the compressive strength. An increase in the porosity will reduce the strength of the material, but this effect also can greatly be influenced by pore size, pore shape and pore distributions [9]. According to the results obtained from the Table 2, it clearly shows that scaffold design with the lowest porosity has highest compressive strength, which is triangular pore scaffold. Whilst the scaffold with the highest porosity has lowest compressive strength which is the circular pore scaffold.

However, hexagonal pore scaffold with the porosity of 73.57% has a compressive strength of 241.0 MPa, while square pore scaffold with the porosity of 69.93% has lower compressive strength about 140.7 MPa. It proves that the geometry of pore also affects the mechanical strength of bone scaffold. Scaffold porosity is an important criterion in designing bone scaffold with porosity more than 65% is suitable for bone scaffold [14]. Besides, it is very important to make sure mechanical strength such as compressive strength is matched with the human bone properties. From this study circular and square pore scaffold have 127.9 MPa and 140.7 MPa of compressive strength, respectively which matches with the human cortical bone, range in between 90-230 MPa.

As shown in Table 2, triangular pore scaffold has the highest value of specific strength, 0.33 MPa/mm³ whilst circular pore scaffold has the lowest value of specific strength, 0.14 MPa/mm³. Specific strength (strength-to-weight ratio) of the bone scaffold is one of the important factors in considering the suitable scaffold since the natural bone itself is a structural composite material that has a very high specific strength with the tubular shape of bone that can resist a bending force that causes compression on one side and tension on the reverse side [15]. Hence, the hexagonal pore scaffold having a porosity of 73.57%, compressive strength of 241.0 MPa and specific strength of 0.27 MPa/mm³ is suitable for both desired biological and mechanical properties. Furthermore, this scaffold design has more curvature and corner on pore shape that helps in cells and scaffold interaction thus improving the biological properties of the artificial bone.

4. Conclusions
PLA bone scaffold with four different pore geometries were designed and were simulated for the mechanical properties. The finding shows that pore shape has a significant role in mechanical properties due to the stress distributions on the scaffold models. Finite Element Analysis results showed that mechanical properties such as stress was strongly depending on both porosity and pore geometry. Overall, the porosity of the designed scaffolds is within the optimum range, and the mechanical properties such as compressive strength obtained matched with the mechanical properties of human bone. Hexagonal pore shape bone scaffold was the best design to be used due to its porosity and compressive strength which is similar to human bone properties.

Acknowledgement
The authors would like to acknowledge Universiti Teknologi Malaysia for funding through Research University Grant Scheme Tier 2 (Q.J130000.2651.17J03).

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