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INTEGRATING CAD AND 3D PRINTING FOR THE DEVELOPMENT OF POROUS BIOMIMETIC SCAFFOLDS

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ABSTRACT

The application of three-dimensional (3D) printing in tissue engineering is rapidly expanding due to its ability to create highly complex structures, produce patient-specific designs, and offer quick and cost-effective on-demand manufacturing. Identifying the appropriate biodegradable scaffolds composed of suitable biomaterials with optimal mechanical strength, biocompatibility, uniform degradation, pore size, and porosity is crucial. This study aimed to design a scaffold model using 3ds Max software and fabricate it through a suitable 3D printing technique. Using CAD in 3ds Max, prototypes of both porous cubic and randomized cylindrical porous scaffolds were modeled. These designs were then printed using engineered resin and polylactic acid (PLA), employing Stereolithography (SLA) and Fused Deposition Modeling (FDM) 3D printing techniques, respectively.

KEYWORDS: Scaffolds, porous cubic, randomized cylindrical, 3ds Max, polylactic acid, Stereolithography, Fused Deposition Modeling.

1. INTRODUCTION

3D printing technology has emerged as one of the medical field's fastest-growing innovations. The demand for patient-specific biomaterials has driven the adoption of modern production techniques. In recent years, 3D printing has found a wide range of medical applications, including craniofacial implants, dental molds, crowns, prosthetic parts, on-demand medical equipment, surgical models, scaffolds for bone and skin regeneration, organ printing, and tissues used in drug discovery, among many others.[1] Additive manufacturing, or 3D printing, enables the creation of flexible, highly complex, and modular scaffolds tailored to individual patients. These 3D-printed scaffold structures support the replacement and repair of fractured bone tissue. Bone scaffolds with intricate designs produced through additive manufacturing can replicate the mechanical properties of natural human bone, offering lightweight structures with customizable porosity levels. The Digital Image Correlation (DIC) method can be used experimentally to quantify mechanical stimulation and strain in bone scaffolds.[2] Additive manufacturing (AM) is an office-friendly technique where 3D parts are created using CAD models, which are then converted to STL format files to serve as input data for printing.[3] It is now possible to use software for medical image processing or reverse engineering to convert a patient’s CT, MRI, USG, CBCT, or even point cloud data into a CAD model. Once a CAD model of the patient's injured tissue is created, it can be used for various applications, such as developing physical models to research and plan complex surgeries, and designing custom implants, prosthetics, orthotics, and scaffolds for tissue engineering.[4] Patient CT or MRI data are typically stored in DICOM format, which includes multiple 2D images of a body part. Using various software, these DICOM files can be converted into CAD models. These models can then undergo finite element analysis and be transformed into faceted file formats like STL (stereolithography), PLY (polygon file Format), or VRML (virtual reality modeling language) for use in additive manufacturing. The faceted file is ultimately used to create a physical component with an AM machine.[5] Three-dimensional printing involves creating physical objects from digital files using CAD software to design 3D models.[6] These models are stored in file formats like STL and VRML, which are commonly used for 3D printing.[7] In Bone Tissue Engineering (BTE), cells, scaffolds, and cytokines are essential. Scaffolds, as 3D constructs, provide a temporary environment for extracellular matrix synthesis, cellular activity, oxygen transport, nutrition, and waste removal.[8] To support new bone tissue formation, these scaffolds must offer mechanical support and adapt over time. A key objective is the regulated delivery of growth factors to the defect site without losing bioactivity, crucial for new blood vessel formation. 3D porous scaffolds filled with cells and signaling molecules are often used to create a biomechanical environment that promotes cell attachment and differentiation, facilitating efficient neo-tissue formation.[9] Advanced 3D printing techniques overcome current fabrication limitations by providing precise control over scaffold architecture and pore structures. This study involves the creation of custom, computer-controlled tissue scaffolds designed to aid tissue regeneration. The prototypes developed include both porous cubic and randomized cylindrical scaffolds, which were created using CAD software like 3ds Max. These models were printed using biodegradable PLA material and 3D printing techniques such as Stereolithography (SLA) and Fused Deposition Modeling (FDM). Additionally, the compressive strength and porosity of the scaffolds were investigated to evaluate their suitability for tissue regeneration applications.

2. METHODOLOGY

The general methodology flow chart is illustrated in the Figure 1. It begins with a literature review, followed by CAD design of the porous scaffold, slicing, and printing. The scaffold design was created using 3ds Max software and saved in. stl format. This. stl file was then converted into G-code using slicing software (Cura) for 3D printing. The final step involved documenting the results of the printed scaffold.

2.1 Materials, software and printer selection

For the development of the scaffolds, PLA was utilized for the cyclindrical random porous scaffold, while engineering resin was chosen for the cubic scaffold. The scaffold designs were created using 3ds Max software, and slicing was carried out with Ultimaker's Cura. The cylindrical random porous scaffold was produced using Fused Deposition Modeling (FDM), whereas the cubic scaffold was fabricated using Stereolithography (SLA).

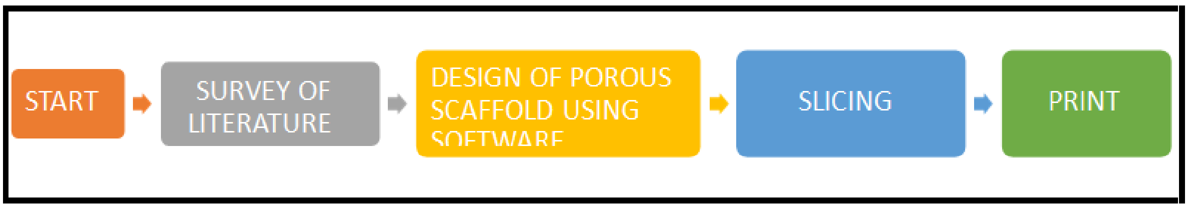

Figure 1: Chart depicting methodology.

2.2 Development of Porous Cubic scaffold design using 3ds max software

To develop a porous cubic scaffold of approximately 10mm x 10mm x 10mm using 3ds Max software, the process began with creating a horizontal base of the desired dimensions. This base was duplicated in the x-direction using the instance tool and then rotated by 90º to position it vertically. Multiple vertical bases were generated and placed over the horizontal bases using the move tool. These bases were grouped into layers, which were stacked sequentially, layer by layer, using the instance tool. Figure 2 illustrates these steps.

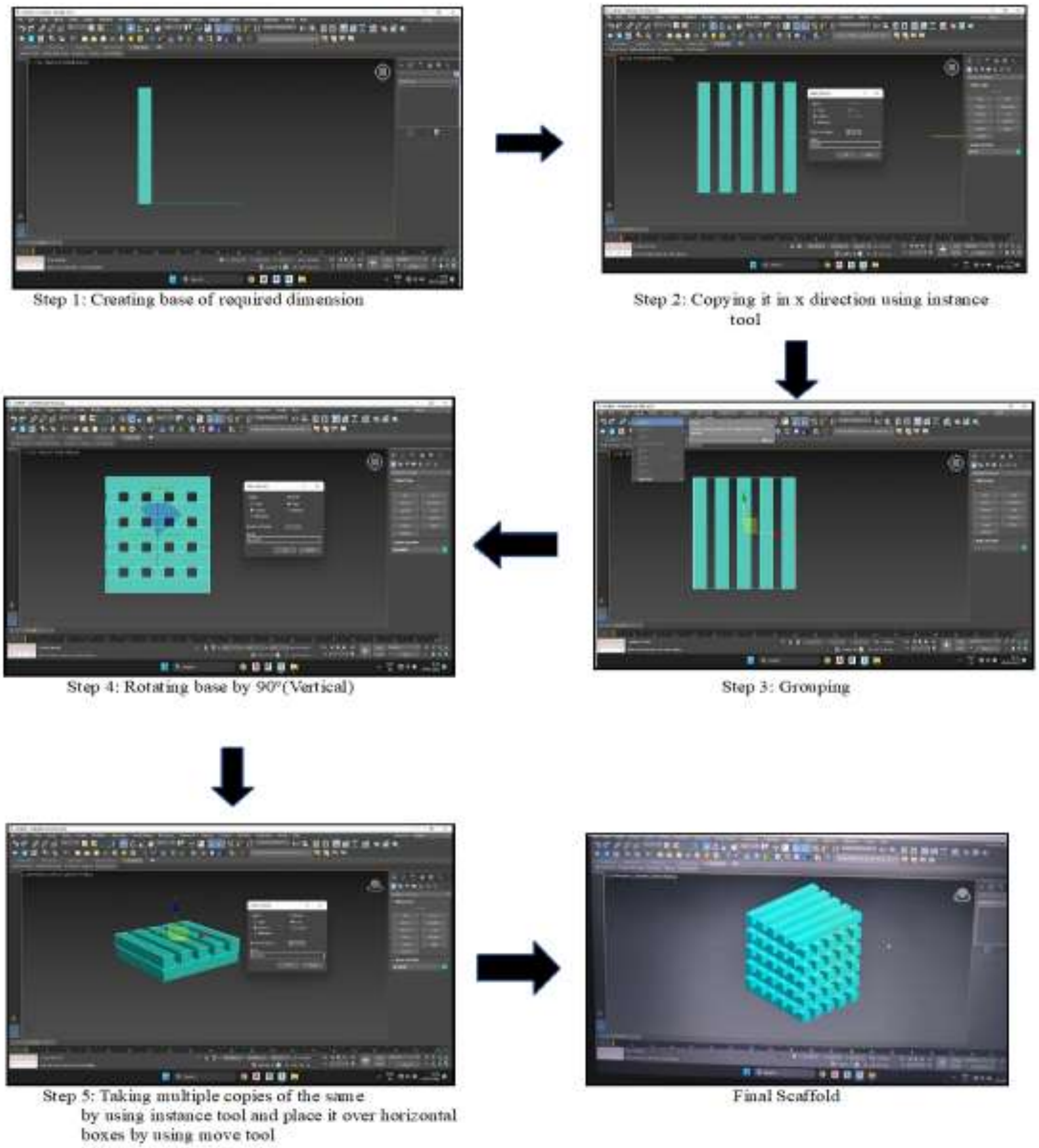

Figure 2: Steps involved in designing Porous cubic scaffold design using 3ds max software of porous cubic scaffold.

2.3 Development of Porous randomized cylindrical scaffold design using 3ds max software

To develop a porous randomized cylindrical scaffold design using 3ds Max software, begin by creating a cylinder with the specified dimensions of 5 cm in diameter and 2.2 cm in height. Next, randomly place distorted spheres within the cylinder to introduce the desired randomness. Then, use the Boolean tool to cut out the spheres from the cylinder, resulting in a porous structure. These steps collectively illustrate (Figure 3) the process of designing a porous, randomized scaffold using 3ds Max software.

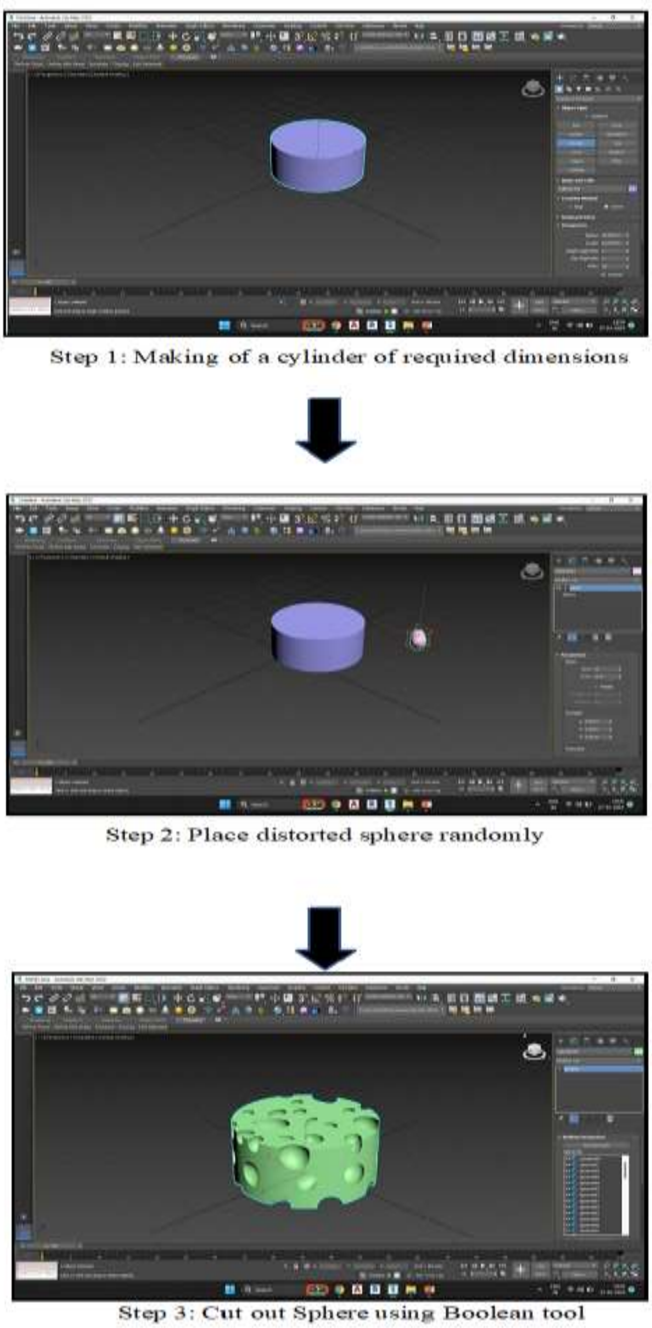

Figure 3: Steps for designing a porous randomized cylindrical scaffold using 3ds Max.

2.4 Evaluation of scaffolds

2.4.1 Compressive strength

To evaluate the structural behavior of both cubic and cylindrical scaffolds under compressive loading, they were tested using a servo-hydraulic testing machine (INSTRON 8801) equipped with a 2kN load cell. The uniaxial compressive tests were conducted at a constant deformation rate of 1.3 mm/min.[10] Before testing, each sample was carefully aligned at the center of the machine's base plate, and the load was applied gradually and continuously until the sample failed.

2.4.2 Finite elemental analysis for porosity calculation

The CAD data of the scaffolds developed using 3ds Max were all changed to .stl format and then translated into G-code sliced with Cura software. The porosity of the scaffolds was calculated using finite element analysis (FEA) by the CATIA V5 program.

3. RESULTS AND DISCUSSION

The designs were saved in .stl format and printed in 3D using PLA filament with the FDM technique to obtain randomized cylindrical porous scaffolds, whereas the SLA technique employing engineered resin material was used for cubic porous scaffolds. The images of the printed scaffolds are presented in Figure 4.

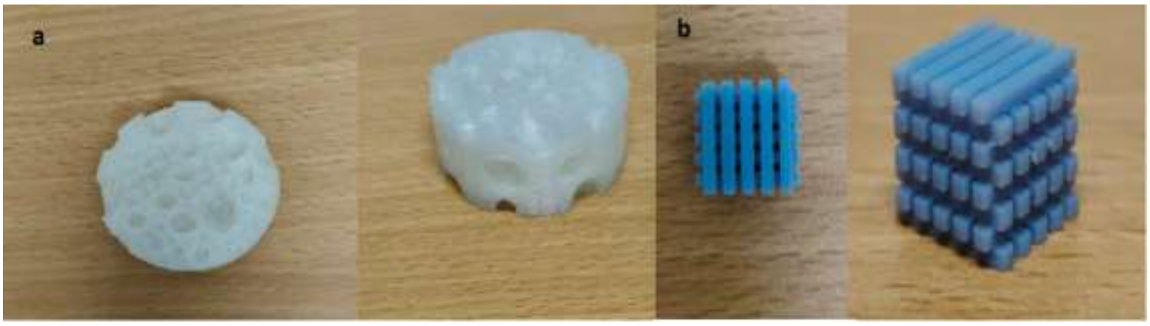

Figure 4 Top and front view of a) randomized porous cylindrical b) porous cubic scaffold.

3.1 Compressive strength

The ideal bone scaffold should be a porous biomaterial that promotes osteogeneration and matches the mechanical properties of bone.[11] Compressive strength, which measures a material's ability to withstand load-bearing forces, is crucial for evaluating bone substitutes. Since these scaffolds are intended for use as bone substitutes, their compressive strength is a key consideration in their fabrication.[10-12] It was found that the randomized cylindrical porous scaffold developed using a biodegradable material such as PLA had a maximum compressive strength of 2.37 MPa. In contrast, the porous cubic scaffold developed using engineered resin was a tougher material and could withstand higher compression loads, with a compressive strength of 8.59 MPa.

3.2. Finite elemental analysis for porosity calculation

Different pore geometries affect bone scaffold porosity due to variations in surface area, which also impacts bone healing and protein adsorption.[11] Higher porosity generally decreases compressive strength, influenced by pore size, shape, and distribution.[12] It was found that cubic porous scaffolds exhibited the lowest porosity (40%) and the highest compressive strength, while randomized porous cylindrical scaffolds, with the highest porosity (70%), had the lowest compressive strength.

4. CONCLUSION

In conclusion, the durability and mechanical properties of bone scaffolds are significantly influenced by their design and material composition. Testing revealed that cubic porous scaffolds made with SLA-engineered resin have higher compressive strength (8.59 MPa) and lower porosity (40%), making them more durable. Conversely, randomized cylindrical porous scaffolds made with FDM-PLA exhibited lower compressive strength (2.37 MPa) and higher porosity (70%), indicating reduced durability. While increased porosity negatively affects mechanical properties, PLA remains a viable choice for biodegradable scaffolds in applications where lower compressive strength is acceptable, such as in certain bone types. These results suggest that combining PLA with other polymers to enhance its elastic modulus may address its lower durability, opening avenues for further research and development in scaffold bio-fabrication for bone tissue regeneration.

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