Finite element analysis of scaffold for large defect in femur bone

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Abstract. Treatment of segmental bone defects, especially in load bearing areas caused by fracture, tumour or infection is a complex procedure in orthopaedic surgery. Tissue Engineering (TE) has influenced the healing of tissues with an artificial scaffold. In bone tissue engineering, scaffold should provide mechanical stability, accommodate cells and guide for proliferation of cells in all directions. Due to the spatial variation in the micro-architectural parameters of bone such as pore size, pore shape and porosity, the design of scaffold to mimic the native bone is yet to emerge. The objective of this work is to design and analysis of scaffold for defect in femur bone diaphysis region and to study the stress–strain relationship between bone and scaffold under different loading conditions. The scaffolds were designed using unit block for segmental defect of femur bone diaphysis region. The internal architecture of each unit block was controlled by pore size and beam thickness (PS: BT) ratio. To mimic the native bone properties the scaffold was designed with open cellular structure with porosity of range 5% to 60%. The structural behaviour of each scaffold was performed using finite element method. The scaffold and intact bone segment was analysed using ANSYS. The maximum stress and displacement of scaffold were studied with biomaterial of hydroxyapatite. The results are comparable with literature and confirm that designed unit block may suitable for act as scaffold for tissue regeneration with scaffold can avoid the stress shielding effect between scaffold and living tissue.

1. Introduction

Bone is a complex structure, it is good example of natural composite and anisotropic material, when experienced in damage due to accident, tumour resection cavity; disease and aging are still a challenging task to orthopaedic surgery for repair and restore its functions. Even though bone has the regeneration ability to heal under physiologically similar environmental conditions, the defects exceed...
the critical size particularly in long load bearing bones has still problem in clinically. Currently, the gold standard treatment of a long bone defect is bone grafting, which involves the harvest of donor bone from a non-load-bearing site in the patient or filling with an artificial material [Niedhart C et al., 2003, Linhart W, et al., 2004]. However, there is a problem such as early failure of implant, aseptic loosening, immunology and stress shielding between implant materials due to mismatch of mechanical properties between bone and implant material. These leads to do multiple surgeries to restore the structure and function of the defect site [Rueger J M, 1998; Banes, A J et al., 2001; Schieker, M et al., 2008, Wieding, J et al., 2011]. To overcome these problems, recently bone tissue engineering (BTE) approach has been entered in large-scale to create or regenerate damaged organ/tissue [Langer, R. and Vacanti, J. (1993)].

In bone tissue engineering scaffold play vital role on provide mechanical stability, accommodate and guide for proliferation of cells in all three anatomical directions. The scaffold is a porous structure that acts as a template for bone tissue formation. The success of bone tissue regeneration depends on the technology used for generating reliable, fully integrated porous scaffolds with exact shape and size of the replacement bone site (Hutmacher, D.W et al., 2000, Hollister et al. 2002, Sun et al. 2004). The scaffold-guided tissue engineering approaches are still being in experimental level and yet clear what defines a so-called “ideal-scaffold” [Hutmacher, D.W. et al., 2004]. Instead of trying to reproduce exact internal bone micro architecture in the scaffold, many researchers are working on creation of simplified models, functionally equivalent to the tissue to be repaired in terms of stiffness, strength, density and porosity apart from the biological requirements. The design strategy of porous structures can effectively reduce the strength and stiffness of scaffolds and porous structures also provide sufficient space for new bone tissue ingrowth. The structural units of scaffold is designed through computer aided design (CAD), image-based design, implicit surface modelling and topology optimization [Giannitelli, S M et al. 2014]. The CAD-based methods provide a powerful tool for the modelling of 3D scaffold geometries like cylinders, spheres, and plates etc., arranged in rectangular or radial patterns [Cheah et al., 2003; Sun W, et al., 2005]. Most constructive approaches are based on regular arrangements of internal geometry filled with periodic distribution of unit cells. The functionally graded of porosity and stiffness of scaffolds with different structural configurations were designed using CASTS (Computer Aided System for Tissue Scaffolds), an in-house developed library system consisting of 13 different polyhedral units that can be assembled into scaffold structures. [Sudarmadji N, et al., 2011]. The finite element analysis (FEA) methods were used as tools to evaluate geometry of polyhedrons with pre-established criteria [Chantarapanich N, et al., 2012]. The lattice structure design optimized against specific loading conditions and numerical study on the scaffolds for large segmental defects of bone were performed with scaffolds loaded under biomechanical conditions [Wieding, J et al., 2014]. In the recent years, a variety of unit cell structures design and methodology have been presented in the literature. However, a universal methodology for the design of functionally graded scaffolds, automated optimization procedures and selection criteria for unit cells, characterization method for porous structure are yet to be established. The objective of this work is to design analysis and optimize the scaffolds for a segmental defect of femur bone diaphysis using finite element approach. To my knowledge very limited study has been focused on biomechanical behaviour of scaffold for segmental defect of load bearing bone for different loading conditions.

2. Material and methods

2.1. Design of porous unit block

The design strategy of porous structures of scaffold is followed by computer aided design (CAD) approach. The porosity and pore size of structure of unit block was controlled to reduce the strength and stiffness of scaffolds also to enhance the cell grows in the scaffold. In this work, unit
block of open cellular structures were created with controlled micro architecture for developing of scaffold for load bearing bone losses applications. The controlled micro architecture refers to a repeating array of unit-block to design scaffold structure with functionally graded structure. The internal architecture of each unit block was controlled by varying pore size and beam thickness (PS: BT) ratio. The effect of PS: BT ratio on the generation of unit block are possible to enclosed pore, it is desirable to investigate how the ratio between pore size and beam thickness (PS: BT) influences the geometry of open-cellular polyhedrons [Chantarapanich N et al., 2012]. The following four open cellular structures were designed with porosity of 5% to 60% without collapsing pores and manufacturing feasibility of scaffold using additive manufacturing technology of fused manufacturing system.

![Hexahedron, Cuboctahedron, Truncated hexahedron, Truncated Octahedron](image)

**Figure 1.** Representative unit block structures

### 2.2. Calculation of porosity of unit block

The porosity of a porous structure is defined as the ratio of the pore volume to the total volume of the structure. The material volume of porous unit block was found using Pro/E and bounded volume is one-unit cube volume. The porosity of each unit block was calculated as

\[
\text{Porosity in (\%)} = \left(1 - \frac{V_1}{V_2}\right) \times 100
\]

Where,
- \(V_1\) - Material volume of unit block
- \(V_2\) - Bounded volume of the Unit block.

### 2.3 Finite element analysis of unit block

In this study, the effective elastic moduli of porous unit blocks were studied using finite element analysis. The four biomaterial such as hydroxyapatite (HA), PLGA [poly (DLlactic- co-glycolic acid)] and PLLA [poly (L-lactic acid)] are considered. The material properties are assigned as linear isotropic of elastic moduli (E) for HA (E = 2GPa), PLA (E = 2.7GPa), PGA (E = 4.1GPa) and Poisson’s ratio is 0.3 was assigned [Sun W et al., 2005]. Each polyhedral one end is was allowing to displace to 1% length of unit block and the average reaction force (R_f) was calculated at the opposite fixed end of unit block using following relationship.

\[
\text{Effective elastic modulus (E}_{\text{eff}} = \frac{\sigma}{\varepsilon} = \frac{R_f \times L}{A^*U}
\]

Where,
Rf – Average reactional force at fixed face nodes of unit block.  
U - Displacement of unit block 1% of its length along the direction load applied.  
L - Length of the unit block.  
A – Cross-sectional area of constrained face of unit block.  

The effect of biomaterial on porosity and effective elastic modulus of each unit blocks were predicted and plotted as shown in figure 2.

![Figure 2](image1.jpg)  
**Figure 2.** Effect of biomaterial and porosity on the effective elastic modulus

### 2.4. Assessment of porosity and elastic modulus using CT Images

The porosity and elastic modulus of femur bone was evaluated from CT image data using the relationship between porosity and elastic modulus available in previous literature. The mean CT number was obtained using Mimics® software in Hounsfield Units (HU) from the femur bone CT data as per the protocol developed by The porosity was calculated in percentage was using relationships (p) = -0.0362 HU + 59.96 (Pandithevan P and Saravanakumar, (2009)) and elastic modulus E = - 0.53 (p) + 21.43 GPa [ Dong, X.and Guo. E X , 2004]. The porosity of femoral bone was calculated with corresponding CT number obtained from CT dataset of femur from region proximal to distal region as 5% to 40% and the average elastic modulus was calculated as 21.6 GPa.

![Figure 3](image2.jpg)  
**Figure 3.** Calculation of CT number in HU using MIMICS
3. Bio-Mechanical behaviour analysis of scaffold for segmental defect

The bio-mechanical structural analysis of scaffold was performed using ANSYS. The scaffold for segmental defect in diaphysis region was designed using unit block with porosity of 5% to 60%. The segmental defect of 8mm is considered in this study. The finite element model of segment of intact femur bone and scaffold was generated. The effective elastic modulus and structural behaviour of scaffold was performed under physiologically similar loading conditions. The stress distribution and maximum displacement were analysed.

3.1 Assessment of effective elastic modulus of scaffold for segmental defect

Finite element model of scaffold was developed for a segmental defect of femur. The scaffold was developed with unit block with porosity range 5% to 60% for the femur proximal to distal diaphysis region and their effective elastic modulus was calculated for biomaterial Hydroxyapatite (HA). The unit blocks were chosen from the library for different porosity. The scaffold was designed for maximum of 8mm height due to computational limitation. The external shape and size of scaffold is controlled to similar to intact femur as shown in figure 4. The designed scaffold was meshed using hypermesh with an average mesh size of 2mm tetra shape as shown in figure 5. The effective elastic modulus was predicted using the equation (2) for HA material and for the porosity of 5 to 60% which is tabulated in table 1.

![Figure 4. Scaffold - CAD Model](image1)

![Figure 5. Scaffold – meshed model.](image2)

![Figure 6. Scaffold – Finite element model.](image3)
3.2. Finite element analysis of femur bone and scaffold for segmental defect.

Finite element model was developed from CT images data set using commercially available Mimics® software with routing well established procedure followed for 3D reconstruction bone structure. The healthy femur bone CT images in DICOM file format were imported in to MIMICS and of region interest are properly threshold and healing are done on the crumbled part of the bone for generation of the 3D model. The noise level is reduced and then point cloud data file from MIMICS is imported into SolidWorks software, wherein cloud points are converted from the surface to solid by assigning the target point cloud size as random and a complete 3D model of femur bone are generated. The model was meshed using hyper mesh software with average element size of 2mm and tetra mesh shape. The boundary and loading conditions are the condylole face fully constrained and the compressive load of 3000 N (5 times of body weight) was applied on top femoral head surface. The material properties were assigned calculated value of in section 2.4. The average stress and maximum displacement value of healthy model was predicted using ANSYS as shown in figure 7.

![Finite element model of femur bone](image1)

![Finite element model of Scaffold for Segmental defect](image2)

**Table 1.** Effective elastic modulus of scaffold – HA

| Sl. No. | Porosity (%) | Effective elastic modulus (GPa) |
|---------|--------------|---------------------------------|
| 1       | 5            | 1.91                            |
| 2       | 12           | 1.80                            |
| 3       | 20           | 1.61                            |
| 4       | 40           | 1.52                            |
| 5       | 50           | 1.35                            |
| 6       | 60           | 1.19                            |
The scaffold external geometry we segmented from FE model of femur bone where maximum stress induced. The scaffold was assembled using appropriate porosity and performed Boolean operation to obtain segmental defect bone shape, In this work femur bone segment model was developed for 8mm height to avoiding of computational limitations. The finite element analysis was performed similar loading conditions followed for femur bone study.

4. Results and discussions

In this work, the biomechanical behaviour of porous scaffold for segmental defect of femur - diaphysis region was designed and evaluated structural behaviour of scaffold and femur bone model. The representative of open cellular structure of unit block was developed with different porosity and effective elastic modulus was predicted using finite element modelling approach for four bio-materials. We observed that, effective elastic modulus vary depends on geometry of unit block which shows clearly in comparison graph (figure 9.) for HA material. It is indicate that effective elastic modulus not only depends on porosity also depends on pore geometry of unit block.

![Figure 9. Relationship between effective elastic modulus and porosity of unit block - HA](image)

The structural behaviour of scaffold with boundary and loading conditions are the bottom face fully constrained and the compressive load of 3000 N was applied on top surface. The scaffold porosity of 5% to 60 % was evaluated with HA material properties. The average stress and maximum displacement of scaffold was obtained is listed in table 2.

Table 2 Stress and displacement value of scaffold with HA material properties

| Porosity (%) | Average Stress (MPa) | Maximum Displacement (mm) |
|--------------|----------------------|---------------------------|
| 5            | 0.1                  | 0.2                       |
| 10           | 0.2                  | 0.3                       |
| 20           | 0.3                  | 0.4                       |
| 30           | 0.4                  | 0.5                       |
| 40           | 0.5                  | 0.6                       |
| 50           | 0.6                  | 0.7                       |
| 60           | 0.7                  | 0.8                       |
| 65           | 0.8                  | 0.9                       |
| 70           | 0.9                  | 1.0                       |
| SL. No. | Porosity in % | Stress in MP | Displacement (mm) |
|--------|--------------|-------------|------------------|
| 1      | 5            | 35.9        | 0.0031           |
| 2      | 12           | 34.7        | 0.0035           |
| 3      | 20           | 34.2        | 0.004            |
| 4      | 40           | 8.0         | 0.0077           |
| 5      | 50           | 10.7        | 0.0089           |
| 6      | 60           | 11.6        | 0.012            |

The intact femur induced maximum stress and displacements are 36.3 MPa and 0.002mm respectively. The stress and displacement developed by scaffold is comparable with intact femur bone value. It indicates that designed scaffold with HA material may suitable for femur bone segmental defect, also minimize the stress shielding effect due to relative motion between bone and scaffold region between living bone and the surface of a load-bearing scaffold also can avoid aseptic loosening of scaffold. The limitation of this study, we have evaluated limited four biomaterials. For the versatility of design, scaffolds need to evaluate with multiple biomaterial. In contrast, the finite element analysis will help to understand and optimize the structural stability and porosities of scaffold. The FEA will minimize the cost-intensive to manufacturing, time-consuming and scarcity of biological specimen requirements for experimental test.

5. References

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