Proposing a new design for segmental bone defect (SBD) tibial implant unit cell

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Abstract. One of the critical problems in designing and making an implant is to reduce the weight of the implant without compromising its mechanical properties and make it more porous that replicate the biomechanical properties of the bone. A new design is proposed for segmental bone defect (SBD) tibial implant unit cells rather than the existing design of Aaron Vance and Klaudio Bari (2018). Finite Element Analysis (FEA) was completed for the choice of the unit cell and to predict the implant performance. The optimization is carried out to reduce the mass of the existing unit cell design. The outcome of this research shows that the developed implant unit cell exhibits a mass of 1.06g, the maximum stress of 42.885 MPa, and a relative density of 0.2413. This is slightly lower than the existing unit cells to allow for the replacement of the existing implant unit cell with a porosity of 75.2% which is considered significant for the determination of the unit cell for global structure.

1. Introduction

Due to the anatomic mismatch of implant and bone, the rehabilitation of defective bone in segmental bones remains difficult. Orthopaedic implants are usually manufactured in solid pieces by using casting or forging, which results in the implant stiffer than the natural bone. Traditional manufacturing processes are limited to manufacture complex geometries so which results in the build such structure on the aspects of both mechanical and biocompatibility properties. Evolutions in Additive Manufacturing (AM) help to produce complex and small structure more easily. Development in Additive Manufacturing promoted the use of porous materials to perform desired functions with mechanical properties. The use of porous materials in manufacturing helps to build implants to perform like bone with more dimensional accuracy which leads to the use of Ti64 in the biomechanical field [1,2]. Researches show that repairs in long bones like Tibial, the defects which are longer than 2 cm will not grow back easily in such cases an implant is placed in between the defects with effective porosity which support re-growth of the tissue inside the implant.

A base unit cell is generated by CAD and is arranged one over another to obtain the desired global geometry. CT or MRI image of the tibial bone is used to carve the global geometry, the images are used to generation of three-dimensional (3D) model. The unit cells are regularly designed in cubic, honeycomb matrix, octahedral unit, and the arrangement of the unit cell to form the implant is based on the Kelvin cell [3,4]. Most of the implants are designed on the safety aspects which gives unit cell features an open cellular structure with tapered ends. The design and manufacturing process of the unit cell is highly related to the mechanical properties of the cellular structure directly. So, the design should be correlated with the parameters and repeatability of the aspects of manufacturing. Finite Element Method (FEM) is utilized to foresee the conduct of cellular structure to predict the
performance of the cellular structure. The usual approach is carried out to match the stiffness of the implant with the bone so the weight of the implant is not considered while developing the implant. However, this research was mainly concentrated in the sense that, to reduce the weight of the implant by re-design the existing design of the unit cell without compromising the mechanical properties.

In this research, a new design of unit cell is generated using CAD and structural analysis is carried out to examine the unit cell performance using ANSYS Workbench. The results are then compared with the existing unit cell which is designed by Aaron Vance, Klaudio Bari [1].

2. Materials and Methods

Ti6Al4V also sometimes called Ti64 which is widely using in the biomedical field. Ti64 is an alpha-beta titanium composite with high solidarity to weight proportion and astounding consumption opposition [5]. It is one of the most ordinarily utilized titanium composites and is applied where low thickness and astounding erosion opposition are fundamental, for example, aviation and biomechanical applications. The properties of Ti64 from the material data sheet and the ANSYS engineering data library are given in Tables 1 and 2.

| Table 1. Properties of Ti64 from Material data sheet [8] |
|----------------------------------|---------------|------------------|
| Property                        | Minimum       | Maximum          | Unit (S.I) |
| Density                         | 4.42          | 4.512            | mg/m³      |
| Bulk Modulus                    | 96.8          | 153              | GPa        |
| Compressive Strength            | 848           | 1080             | MPa        |
| Ductility                       | 0.05          | 0.18             |            |
| Elastic Limit                   | 786           | 910              | MPa        |
| Poisson’s Ratio                 | 0.31          | 0.37             |            |
| Young’s Modulus                 | 110           | 119              | GPa        |
| Tensile Strength                | 862           | 1200             | MPa        |

| Table 2. Properties to be considered in the engineering data library in ANSYS. |
|----------------------------------|------------------|------------------|
| Properties                      | Ti6Al4V (value)  | Unit            |
| Density                         | 4400            | Kg/m³           |
| Young’s Modulus                 | 104.8           | GPa             |
| Poisson’s Ratio                 | 0.342           |                 |
| Bulk Modulus                    | 110.55          | GPa             |
| Shear Modulus                   | 30.946          | GPa             |
| Compressive Ultimate Strength   | 1.43            | GPa             |
2.1. Unit cell design
Auto CAD 3D modelling was implemented to generate a 3D model of a unit cell. A single unit cell is designed with the parameters cross-sectional area of 100 (OD = 11.3 mm) and a height of 10 resulting in a bulk volume of 1000. Octahedral unit is used to design the model and the numbers of beams are considered fixed and are united as a solid structure, the bulk material density of Ti64 is 0.0044 g/cm³. Four sorts of existing unit cell design and its boundaries are considered for the systematic examination as appeared in Figure 1 every unit cell showed a mass (muc) of 1.27, 1.03, 1.12, and 1.09 g for A1, B1, C1 and D1 separately. The resultant unit cell densities were (ρuc) 0.0013 (A1), 0.0010 (B1), 0.0011 (C1), 0.0011 (D1) g/mm³. The unit cell design was investigated and analyzed regarding both relative densities (0.2868 (A1), 0.2326 (B1), 0.2529 (C1), 0.2461 (D1)), and stress profile. Because of the outcomes, the best-performing unit cell was chosen [1] to plan the anatomical SBD embed that appeared in Figure 2. The embed math that appeared in Figure 2 was created by triaxial direct designing of the best performing unit cell. Utilizing the 'Boolean Combine' and 'distinction' works the unit cell calculations were joined to shape a solitary part.

![Figure 1](image_url)

**Figure 1.** Existing Unit cell variants. [Source: Aaron Vance., Klaudio Bari., Compressive performance of an arbitrary stiffness matched anatomical Ti64 implant manufactured using Direct Metal Laser Sintering,2018]

![Figure 2](image_url)

**Figure 2.** SBD repair implant design [1]

The parameters considered on the existing unit cell are strictly followed at the stage of designing a new model of a unit cell, the cross-sectional area of 100, and a height of 10 resulting in a bulk volume
of 1000 [1]. From the cross-section area the outer circle radius figured out as 5.65 mm, it is commonly assumed that cellular structure unit cross-section shapes are octahedral. Figure 3 shows the top view of the proposed unit cell.

![Figure 3. Cross-section of sample1](image)

The above 2D model is in the form of an octahedral unit and the outer radius is considered as same as the existing unit cell and the inner radius taken as 4.15 mm and the model is designed and is extruded to a height of 10 mm shown in Figure 4. From the 8 faces along the vertical an elliptical shape is subtracted from the solid body to model the unit cell. In the inner cylinder both sharp ends are fillet with a radius of 0.03 mm which is considered as safety criteria [6]. The material properties are assumed as isotropic, a rib with a thickness of 1mm (Figure 5) is provided along the centre of the unit cell to arrest the bending of the columns while applying compressive force. Without the rib, while applying compressive force more force concentrated along the walls of the columns shown in Figure 6, which tents the body to bend outward to arrest the bending support, as well as the rib, is provided.

![Figure 4. 3D model of the proposed unit cell (S1)](image)
The CAD model is then exported as “iges” format to import in ANSYS 2016. Using the ‘Boolean’ and ‘union’ functions are used to form the unit cell as a solid part to perform single geometry.

2.2. Finite Element Analysis
Three-dimensional (3D) FEA was executed utilizing ANSYS Workbench on the new unit cell plan (Figure 4). Based on the FEA the mechanical properties like compressive stress, most extreme stretching, greatest stress excreting point can be examined. A mixed elemental matrix was used, the mesh primarily featured a 3-node Triangular shell element. Utilizing a mesh affectability examination, further work processing was completed until the Von Mises measures combined inside a 5% mistake. The work comprised of 0.05 mm mesh size with 13, 46,685 nodes, and 7, 84,092 elements. The boundary conditions were applied to recreate the actual test conditions the base surface of the unit cell was completely obliged in Uy (dislodging typical to stack) and an entirely concentric load was applied at the top face. To recreate the unit cell the load (FUA) applied was the result of the proportion of the area of the unit cell (AUA) to the area of bone (ABone) and a 1 kN axial load and the resultant power was 555.42 N to reproduction the unit cells. The cell structures were displayed as single sequence bodies, which were allocated Ti64 Bulk material properties. The non-direct material conduct was demonstrated utilizing the bilinear isotropic solidifying stress-strain (BISO) relationship dependent on mass material information got from the datasheet [7]. The material model included a Yield strength of 1.14 GPa, Young’s Modulus (EB) of 104.8 GPa, Density of 4428.78 kg/m3, Ultimate quality of 1.43 GPa, and Poisson's ratio of 0.342 from the FEA results.

3. Result
The unit cell S1 was examined utilizing both hand figuring and FEA, the consequences of which are summed up in Table 3. The unit cell density esteems were assessed utilizing Eq. (1); where the mass and volume were gotten from ANSYS. Further to this, the relative density of the unit cell to the mass material was investigated utilizing Eq. (2). Where \( \rho_{UC} \) is the density of the unit cell, \( m_{UC} \) is the mass of the unit cell and \( V_B(UC) \) is the volume of the mass material.

\[
\rho_{UC} = \frac{m_{UC}}{V_B(UC)} \tag{1}
\]

\[
\rho_{r(UC)} = \frac{\rho_{UC}}{\rho_B} \tag{2}
\]
\[ E_{(UC)} \approx E_B \cdot \rho_r^2 \]  \hspace{1cm} (3)

The general Young’s Modulus was then determined utilizing Eq. (3) where, \( E_B \) is the Young’s Modulus of bulk material, \( \rho_r \) is the relative density of the unit cell and \( \rho_B \) is the bulk material density. The overall densities of the unit cells were similar while displaying the greatest contrast of 18.90% between the designs at 0.2413. While the relative density of the unit cell was a key variable for porosity, it was additionally critical to examine the related stress conveyance.

**Table 3. Test Results**

| Property                              | Sample 1 |
|---------------------------------------|----------|
| Mass of unit cell (g)                 | 1.06     |
| Bulk volume                           | 1000     |
| Density                               | 0.00106  |
| Bulk material density                 | 0.0044   |
| Unit cell relative density            | 0.2413   |
| Compressive Stress (MPa)              | 2.885    |
| Relative Young’s modulus (GPa)        | 6.1      |

A numerical FEA was carried out on the unit cell (Figure 7) and the relative Von-Mises stresses associated with design S1 result maximum von Mises stress of 42.885 MPa under the applied load with a relative density of 0.2413.

![Figure 7. Sample S1](image)

While considering the existing unit cell designs shown in Figure 1 the analytical data from the FEA carried out on those 4 models shows that design D1 exhibited the lowest stress gradient [1] and D1 also exhibited the second-lowest von Mises stress and relative density of 43.65 MPa and 0.2461 respectively with a unit cell mass of 1.09g. So, the comparison is mainly carried out between unit cell D1 and sample S1 (proposed design). This shows that the proposed design result comparatively similar von-Mises stress and relative density (ref [1] & Table 4) and the mass and volume of the proposed sample S1 are obtained from ANSYS is 1.06 g and 241.35 respectively. Which result that...
the proposed design is optimized the mass of the unit cell with a 0.03g (while comparing with unit cell D1) decrement without compromising the mechanical properties is hence achieved.

Table 4. Unit cell properties.

| Properties                        | A1  | B1 | C1  | D1  | Sample S1 |
|-----------------------------------|-----|----|-----|-----|-----------|
| Unit cell mass, mUC (g)           | 1.27| 1.03| 1.12| 1.09| 1.06      |
| Unit cell bulk volume, VB (UC) (mm³) | 1000| 1000| 1000| 1000| 1000      |
| Unit cell density, ρUC (g/mm³)    | 0.0013| 0.0010| 0.0011| 0.0011| 0.00106 |
| Bulk material density, B (g/mm³)  | 0.0044| 0.0044| 0.0044| 0.0044| 0.0044   |
| Unit cell relative density, ρUC (UC) | 0.2863| 0.2326| 0.2529| 0.2461| 0.2413   |
| Bulk material Young's Modulus (EB) (GPa) | 104.80| 104.80| 104.80| 104.80| 104.80   |
| Relative Young's Modulus E(UC) (GPa) | 8.62 | 5.67 | 6.70 | 6.35 | 6.1      |
| σ(UC) (FEA max) (MPa)             | 23.66| 49.98| 62.30| 43.65| 42.88    |
| ΔL (m)                           | 2.07| 2.536| 2.776| 2.431| 2.07     |

4. Discussion
From the analyses, it is found that the mass of the unit cell is reduced by 0.03g with a maximum Von-Mises stress of 42.885 MPa and a relative density of 0.2413 with comparatively less deformation. The proposed design can be replacing the existing unit cell design without compromising the mechanical property.

5. Conclusions
This examination presents the enhancement of the SBD tibial implant unit cell by appropriate alteration on the design and advancement of a permeable Ti64 SBD repair implant that anatomically emulates the fragmented bone of the tibial segment.

- The new unit cell is displayed with a mass of 1.06 g and a volume of 241.35.
- The unit cell has an inside porosity of 75.2% which highlighting an appropriate cell structure.
- The proposed unit cell included with a most extreme von-Mises of 42.885 MPa and a relative density of 0.2413 was considered as significant for the choice of the unit cell for the implant.

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