A novel model for porous scaffold to match the mechanical anisotropy and the hierarchical structure of bone

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1. Introduction

Scaffolds play an important role in tissue regeneration since they provide temporary mechanical support within the defect. The ideal scaffold used for bone regeneration should possess mechanical properties that can match the bone properties [1]. The mechanical properties of bone are related to its hierarchical structure [2]. Therefore, porous scaffolds with hierarchical structure have been proposed to mimic the mechanical behavior of bone [3].

Numerous progresses have been made in the last two decades with respect to the scaffold materials, fabrication techniques and applications [1,4]. According to the experimental results using imaging technology [5], bone exhibits an anisotropic nature both in the extracellular bone matrix and in the morphology of the intertrabecular pores [6,7]. Correspondingly, the quantitative analysis of the mechanical behavior has been carried out by micromechanics [8–10] and finite element analysis (FEA) [5,11,12]. FEA is an effective approach to study stress/strain distributions of the scaffold and can also be used to develop poromechanics parameters [13], which influence the transport of pore fluid, hence nutrients, and the mechanobiology of tissue regeneration and growth. One of the challenges in the scaffold design is to determine a continuum-level material model for the scaffold which can mimic the morphology and the mechanical behavior of the natural bone. In our previous work, we proposed a porous hierarchical scaffold [14,15], whose mechanical properties close to the natural bone could be tailored. However, the previous scaffold model could not simulate the structural and the mechanical anisotropy of the bone.

We have, therefore, proposed a novel porous anisotropic hierarchical scaffold. The elastic–plastic behavior of the scaffold is studied using FEA. The mechanical properties and the relationship between the structural and the mechanical anisotropy of the scaffold are investigated for different porosities.

2. Anisotropic model of the scaffold

To model the anisotropic morphology, the spherical pores used in our previous work [14,15] are replaced with the prolate spheroidal pores. The geometry of the one-level unit cell is represented by a cube (side length 2a) from which a prolate spheroid with the same centroid, is excised, as seen in Fig. 1(a).

The prolate spheroid is described as

\[ \frac{x^2}{a^2} + \frac{y^2}{b^2} + \frac{z^2}{c^2} = 1 \]

where \( a \) is the semi-major axis, \( b \) is the semi-minor axis, and \( c \) is the ratio of the semi-major axis to the semi-minor axis.
to the semi-minor axis. The two-level unit cell is composed of $n \times n \times n$ one-level unit cells (side length $2a^{(2)} - n \times 2a^{(1)}$), from which a prolate spheroid (semi-minor axis $e^{(2)}$) and semi-major axis $\beta e^{(2)}$ with the same centroid (Fig. 1(e)), is excised. The process is repeated for the higher level unit cell. For the $k$-level unit cell, it is noted that $a^{(k)}$ and $e^{(k)}$ must meet the condition $1 < e^{(k)}/a^{(k)} < \sqrt{\beta^2 + 1}/\beta$ in order to form interconnecting pores for cellular activity. The overall area of the $k$-level unit cell is $A^{(k)} = 4(a^{(k)})^2$. The one-level unit cell porosity calculated as $p^{(1)} = V_p^{(1)}/V_u^{(1)}$, where $V_p^{(1)}$ and $V_u^{(1)}$ are the pore volume and the unit cell volume, respectively. Through the simple geometric operation, the pore volume $V_p^{(1)}$ can be expressed as $V_p^{(1)} = \frac{3}{4}\pi\beta(a^{(1)})^3 - \frac{\pi(a^{(1)})^2(4\beta a^{(1)} - 4\beta a^{(1)} - 2a^{(1)} + 4\beta^2(a^{(1)})^3 + 2(a^{(1)})^3)}{2\beta^2}(e^{(1)})^2)$. Subsequently, the porosity of the $k$-level self-similar structure can be approximately expressed as $p^{(k)} = 1 - (1 - p^{(1)})^k$. It is noted that the porosity range decreases as $\beta$ increases for the $k$-level scaffold, which is demonstrated in Fig. 2(a) and (b) for one-level and two-level scaffolds, respectively. Particularly, for the one-level and two-level unit cells with $\beta = 1$, the porosity $p^{(1)}$ and $p^{(2)}$ are in the ranges of 52.4% to 96.5% and 75.5% to 99.7%, respectively, as seen in Fig. 2.

In the FEAs, the one-level model is formed by $3 \times 3 \times 3$ one-level unit cells, while the two-level model is formed by $3 \times 3 \times 3$ two-level unit cells, as seen in Fig. 1(c, g, and h). The basic mechanical constants of the bovine cortical bone used here are $E_s = 15 \text{ GPa}$, $\sigma_s = 225 \text{ MPa}$ and $\nu_s = 0.3$ [15], where $E_s$ is the Young's modulus, $\sigma_s$ is the yield stress in uniaxial loading test, and $\nu_s$ is Poisson's ratio.

3. Results and discussion

To demonstrate the mechanical anisotropy of the proposed model, we designed uniaxial loading tests for both of the one-level
and two-level scaffolds in Z- and X-directions, respectively. The mechanical behavior of the scaffold is studied for different \( \beta \) values and porosities.

### 3.1. Scaffold’s strain–stress relationship

In Fig. 3, we illustrate the scaffold’s elastic–plastic behavior in different directions for both one-level and two-level models with \( \beta = 1.35 \). Fig. 3(a) shows the strain–stress relationship of the one-level model with porosity ranging from 66% to 92% in Z-direction loading, while Fig. 3(b) shows the strain–stress relationship of the one-level model with the corresponding porosities in X-direction loading. It can be observed that the stiffness and strength in Z-direction are much higher than that in X-direction. It is also seen that the scaffolds soften as they enter the plastic stage. Fig. 3(c) and (d) show the strain–stress relationship of the two-level model with \( \beta = 1.35 \). Similar trends are observed as the one-level model. Regardless of \( \beta \), we observed the stiffness and the strength increase as the porosity decreases, which is also confirmed by the scaffolds based on calcium phosphate [5]. Furthermore, the unhomogenized stress distribution [15], which plays an important role in the material failure, is also observed within the scaffold as reported in the glass–ceramic scaffold model [10].

### 3.2. Structure’s Young’s modulus and strength

The structure’s Young’s modulus and strength are shown in Fig. 4. For the comparison, we have normalized structure’s Young’s...
modulus and strength with the Young's modulus and strength of cortical bone, namely $E^{(k)}|_{E_s}$ and $\sigma_s^{(k)}|_{\sigma_s}$, for the one-level and two-level model. It is seen from Fig. 4(a and c) that when $\beta = 1$, the one-level and two-level structure's Young's modulus has no difference between $Z$-direction and $X$-direction, since the geometry is isotropic in this case. However, as $\beta$ increases, the structure's Young's modulus exhibits a big difference in $Z$-direction and $X$-direction, as seen in Fig. 4(a and c). In particular, when $\beta$ is 1.35, the ratio $E_s^{1(1)}|_{E_s^{1(1)}}$ for one-level scaffold is in the range of 1.76 to 4.93 as the porosity varies from 66% to 88%, while when $\beta$ is 1.20, the ratio $E_s^{1(1)}|_{E_s^{1(1)}}$ for one-level is in the range of 1.46 to 7.91 as the porosity varies from 65% to 93%, as shown in Fig. 4(e). As for the two-level scaffold, when $\beta$ is 1.35, the ratio $E_s^{2(1)}|_{E_s^{2(1)}}$ is in the range of 2.77 to 3.67 as the porosity varies from 86% to 96%, while $\beta$ is 1.20, the ratio $E_s^{2(1)}|_{E_s^{2(1)}}$ is in the range from 2.22 to 2.44 as the porosity varies from 84% to 96%, as seen in Fig. 4(e). The same trend has been observed for the normalized strength of the one-level and two-level models in Fig. 4(b, d and f). Thus, we can see that mechanical anisotropy is affected by the parameter $\beta$, where a larger $\beta$ leads to a higher mechanical anisotropy. The modulus of bone parallel to the longitudinal axis is about 1–5 times larger than that normal to the bone axis [20], which can be easily implemented by controlling $\beta$ in our model. It is also noted that for a fixed value of parameter $\beta$, higher porosity intensifies mechanical anisotropy in one-level scaffold but its effect on two-level scaffold is not significant, as demonstrated in Fig. 4(e and f). Furthermore, Fig. 4(a) and (b) show a quasi-linear dependence of structure's stiffness and strength on porosity for one-level scaffold, which can be confirmed by the micromechanical approaches [9,19,21], while this dependence is not so clear for two-level scaffold.

**4. Conclusions**

The stress–strain relationship of a porous anisotropic scaffold with hierarchy is parametrically studied for different $\beta$ values and porosities. It has been found that mechanical anisotropy depends on the parameter $\beta$, where a larger $\beta$ leads to higher mechanical anisotropy. The proposed scaffold matches the bone's anisotropic behavior and the structural hierarchy. The scaffold's structure is simple and can be achieved easily in manufacturing with controllable porosity and anisotropy. Thus, the scaffold is a promising candidate for bone regeneration.
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