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Lightweight of Artificial Bone Models Utilizing Porous Structures and 3D Printing

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Abstract

The lightweight of artificial bone models is one of the most important and challenging topics in the precision medicine (individualized medicine), and porous structures are the first choice to achieve the lightweight. This paper presents a porous structure based lightweight framework of artificial bones, and it consists of porous analysis, modeling and optimization of lightweight, and practical validation. Specially, firstly, the triply periodic minimal surface (TPMS) is exploited to design the porous structures of lightweight. Secondly, a modeling of lightweight is constructed according to the stress condition and the geometric analysis, then, an optimal solution of the lightweight model can be obtained using the finite element analysis. Finally, the 3D printing is utilized to manufacture the lightweight models, which will be further used for practical verification and feedback correction. The experiments show that the lightweight bone models not only meet the specified requirements, such as fully-connected porous structures and conditions of external force, but also have obvious advantages in terms of structure stability, lightweight controllability and individual compatibility, which are ideal for the personalized precision medicine.

Keywords: Lightweight; Bone model; Porous structure; Triply periodic minimal surface; 3D printing

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1. Introduction

The rapid developments of computer science and related disciplines have provided a new solution for the production of biomimetic bone in biomaterials and tissue engineering [6,10,15]. The manufacture of biological tissue scaffold is a challenge in the cultivation of biological tissue, especially for the cultivation of bone tissue, which has extremely high requirements in the aspects of tissue permeability, mechanical stability, and adhesion of osteocyte [33]. The porous structure of triply periodic minimal surface [8,35] has the potential to achieve the lightweight of bone models and meet the medical requirements of bone tissue.

The bone structure has its particular properties, such as high hardness, lightweight, and impact resistance. Therefore, a high-quality lightweight is essential to the biomimetic bone manufacturing [11,36]. There are two basic prerequisites for lightweight, one is that it should minimize the impact of lightweight process on the physical properties of the model, and the other is that the lightweight process has no effect on the geometric characteristics of the model [13]. For the lightweight of bone models, the regular cross-structures are the most widely used support structures [19], because they are easy to design, analyze and manufacture. However, these structures also have some shortcomings, such as the uneven distribution of stress, against to osteocyte growth. Recently, new support structures have been explored to better achieve the lightweight of biomimetic bone. Sudarmadji et al. [31] proposed multifunctional gradient scaffolds that can dynamically adjust the structures according to the medical data while met the requirements of biomimetic bone. Choy et al. [9] constructed a controllable gradient scaffold to accomplish the lightweight. There are also a large number of other lightweight work, including size

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parameter optimization, shape and geometry optimization, and topology optimization [4,18,22,24,32,37]. Castro et al. [7] used a long cylinder to replace the internal solid to achieve the lightweight of the sheet. Robinson et al. [30] proposed a special network analysis method to automatically segment the internal entities of the solid model, and achieve the lightweight by construct the internal structure using circular thin layers. Maier et al. [23] constructed a lightweight modeling to transfer the natural microstructures to bionic. In addition, the honeycomb structures were also used to process the lightweight of models [5,16,36]. The structure of these methods almost has sort of shortcomings, such as the structure is anisotropic, the structure is not fully connected, and the structure has poor controllability, therefore, the applications of these methods are limited.

Porous structure is considered to be one of the most effective way to realize the lightweight of models and improve the applicability of objects. They have a large number of successful experiments and applications in many fields, such as ceramic manufacturing [37], photographic materials [27], material catalytic adsorption [26], and so on. Although traditional porous structures (such as cellular structure and scaffold structure) are easy to manufacture and achieve lightweight, they have the problems of structure anisotropy, stress concentration and porous uncontrollability [17]. Other porous structures, such as the space of diamond atoms [2,3], the structures of plant roots [25], were also utilized in biomimetic design. The researchers have developed different types of porous structures according to the applications, and applied them to material design and physical manufacturing [12]. Yan et al. [33] proposed the effect of stress shielding and answered the problem of what kind of structures can be applied to biomimetic bone. For the human native bones, the elastic modulus of the structure is approximate in the range of 4-10Gpa. The modern manufacture technology and nano-materials can make the artificial bone far beyond the required range. However, a high-strength artificial bone will bring to more serious stress concentration in the joint interface between the artificial bone and the native bone, and it will shorten service life. Therefore, it is most appropriate to optimize the structure and properties of the artificial bone model to emulate those traits of human native bone, such as hardness, lightweight, and structures. Recently, triply periodic minimal surfaces were excavated to material and structure design [1,34,35], which exhibit superior characteristic of smoothness, connectivity and controllability. Responding to these well propertied, we intend to solve the lightweight of biomimetic bone using the porous structures of triply periodic minimal surfaces.

Moreover, 3D printing has developed rapidly in recent years and is an important symbol of the third industrial revolution [20]. It has brought changes in manufacturing processes and production patterns, which contain the following characteristics: 1) It is unrestricted to the complexity and diversity of product, making the manufacturing cost irrelevant; 2) It is easy to use and suit for customization; 3) It lowers material and manufacturing costs, and making manufacturing more environmentally friendly. Therefore, 3D printing has attracted broad attention in many fields, including the lightweight of models [15,14,28]. In addition, these research activities have provided solutions from the views of printing cost, the feasibility of printing process, and the stability of printing models, respectively. Previous studies of 3D printing offer available experiences and valuable reference to help us perfect the lightweight of biomimetic bone.

In this approach, our efforts are dedicated to obtain the lightweight of artificial bones while making the porous structures and stress performance close to the properties of native bones. We devise a lightweight framework that consists of porous analysis, modeling and optimization, and practical verification, as shown in Figure 1. The pipeline of our lightweight framework. Specifically, the triply periodic minimal surface is firstly exploited to design the porous structures of lightweight. Then, construct the lightweight modeling according to the constraints and the geometric analysis, and optimize the modeling using finite element analysis in an iterative process. Finally, 3D printing is utilizing to produce the models for practical verification and feedback correction that will make the lightweight results more reliably. The primary contributions of this paper can be summarized as follows: 1) We propose a complete lightweight framework of artificial bones using porous structures. 2) We exploit triply periodic minimal surfaces to construct the porous structure that has the properties of full connectivity and porous controllability, and utilize 3D printing to verify the validation of the proposed method. This approach supplies a spectrum of choices for porous structures, provides theoretical guidance for the design and optimization of the lightweight of artificial bones, and also expands its applications.

The remainder of this approach is organized as follows. We give a brief description of the proposed lightweight framework in Section 2. We present the proposed lightweight framework in Section 3, including lightweight oriented analysis of the porous structure, modeling and optimization of TPMS based lightweight, and 3D printing based practical verification and correction. We demonstrate our experimental results from various aspects in Section 4. Finally, we conclude our paper in Section 5.

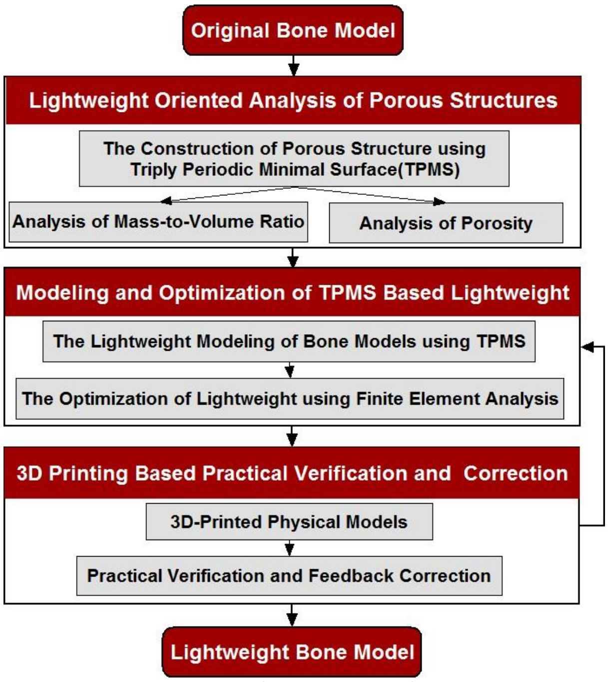


Figure 1. The pipeline of our lightweight framework

2. Overview of Proposed Method

Tissue engineering techniques typically use porous structures, which could provide a three dimensional template for cell adhesion and organ formation. Therefore, the porous structures must have the following characteristics:

- They should be fully connected that is beneficial for the cell growth as well the transport of nutrition and metabolic wastes.
- They should have the appropriate surface for cell adhesion, increase breeding and variation.
- They should have good mechanical properties to meet the medical stress conditions.
- They should be biocompatible or bioabsorbable to accommodate cell or tissue growth.

In order to better emulate the human bone, this paper presents a complete lightweight framework that consists of "analysis-modeling-optimization-validation" to meet the aforementioned requirements, and a feasible solution is provided for the proposed method. The lightweight process is as follows:

Firstly, the lightweight oriented porous structures are constructed. In this approach, we use triply periodic minimal surface to design the porous structures, and analyze the influence of porosity and mass-to-volume ratio through three parameters: porous-size parameter C, period parameter T, and offset parameter O.

Secondly, according to the specified constraints and geometric analysis, the lightweight problem is modeled using the porous structures. Then, finite element analysis is exploited to analyze the modeling, and an optimized lightweight model can be obtained in an iterative processing.

Finally, 3D printing is utilized to manufacture the entity models that are provided for practical verification using stress testing machine. If the lightweight model does not satisfy the specified requirements, a feedback correction is applied according to the detected error. The final lightweight bone model can be obtained until the model satisfies all the requirements.

The method to detect cervical cancer using image analysis can be divided into five steps: image preprocessing, image segmentation, feature extraction, feature selection, and pattern classification.

3. The Lightweight Framework of Artificial Bone

3.1. Lightweight Oriented Analysis of Porous Structures

Triply periodic minimal surface (TPMS) is a kind of minimal surfaces that the mean curvature of any point on the surface is zero, and it is the surface with the smallest surface area. The parameter representation of TPMS is the Weierstrass equation, which can be expressed as follows:

$$\begin{aligned} x &= \mathrm{Re}\int_{\omega_0}^{\omega} e^{i\theta}(1-\tau^2)F(\tau)d\tau \\ y &= \mathrm{Re}\int_{\omega_0}^{\omega} e^{i\theta}(1+\tau^2)F(\tau)d\tau\,, \\ z &= \mathrm{Re}\int_{\omega_0}^{\omega} e^{i\theta}2\tau F(\tau)d\tau \end{aligned} \tag{1}$$

where $i^2=-1, \tau=\tau_1+i\tau_2, F(\tau)=(1-14\tau^2+\tau^8)^{-1/2}$. The Cartesian coordinates of any point are expressed as the real part (Re) of the contour integral estimated from the complex plane of the fixed point and the variable point. The periodic surface of TPMS can also be generally defined as

$$\phi(r) = \sum_{k=1}^{K} \mathrm{a}_k \cos[2\pi(h_k \cdot r)/\lambda_k + p_k] = C \tag{2}$$

where a_k is the magnitude factor, h_k is the *k*-th lattice vector, r is the location vector, λ_k is the wave length of periods, p_k is the phase shift, and *C* is the porous-size parameter, and it is a minimal surface when *C*=0.

According to the characteristics and structures of bone tissue scaffold, there are four types of TPMS could be used as the candidates, namely P-surface, G-surface, D-surface, and I-WP surface, as shown in Figure 2. Four kinds of TPMS candidates The selection of TPMS will be discussed in the experimental section. These four kinds of surfaces are expressed as

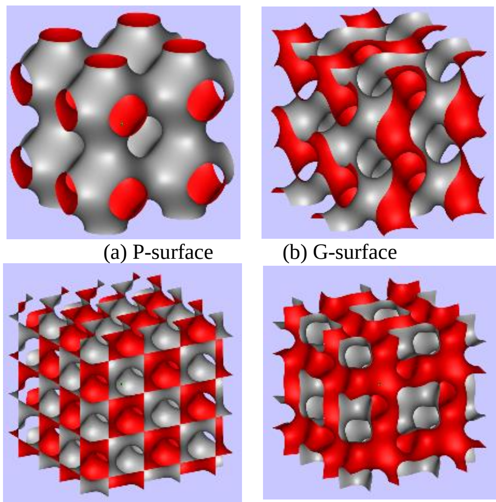
$$\phi_P(r)=\cos(X)+\cos(Y)+\cos(Z)=C\,, \tag{3}$$

$$\phi_G(r) = \sin(X)\cos(Y) + \sin(Z)\cos(X) + \sin(Y)\cos(Z) = C\,, \tag{4}$$

$$\phi_D(r) = \cos(X)\cos(Y)\cos(Z) - \sin(X)\sin(Y)\sin(Z) = C\,, \tag{5}$$

$$\begin{aligned}\phi_{I-WP}(r) = {}& 2[\cos(X)\cos(Y) + \cos(Y)\cos(Z) + \cos(Z)\cos(X)] \\ &- [\cos(2X) + \cos(2Y) + \cos(2Z)] = C\end{aligned}\,, \tag{6}$$

where $X = 2T\pi x$, $Y = 2T\pi y$, $Z = 2T\pi z$, and *T* is the period parameter with the default value *T*=1.

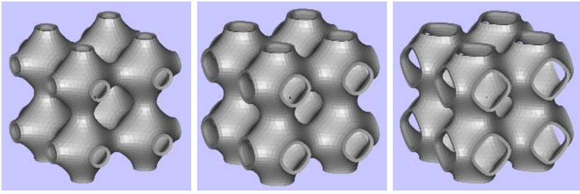


(a) P-surface (b) G-surface

(c) D-surface (d) I-WP surface

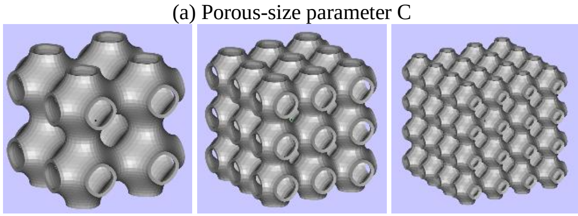
Figure 2. Four kinds of TPMS candidates

The porous structures can be constructed using TPMS. There are three main parameters that have impact on the porous structures: porous-size parameter C (porous size), period parameter T (period of porous structures where T is the number of period number in unit 1 of a given axis), and the offset parameter O (wall thickness, O is the percentage of edge length of the bounding box of one period cell). These parameters are used to control the porous size, the porosity, and the wall thickness, respectively. Take the porous structure of P-surface for example (as shown in Figure 3. The effect of different parameters on the porous structures), we can see that the effect of these parameters on porous structures.



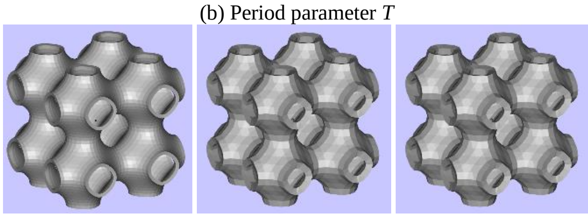
C=0.5 C=0 C=-0.5

(a) Porous-size parameter C



T=2 T=3 T=4

(b) Period parameter T



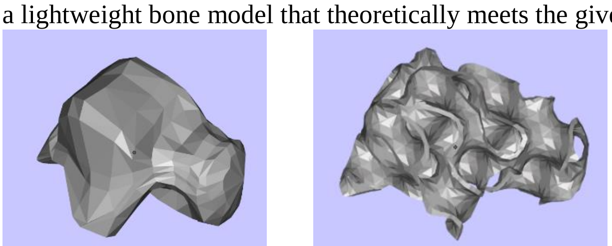
O=5% O=10% O=15%

(c) Offset parameter O

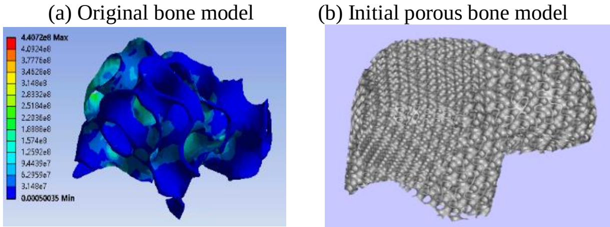
Figure 3. The effect of different parameters on the porous structures

3.2. Modeling and Optimization of TPMS Based Lightweight

Given a bone model (Figure 4 (a)) and the constraints (external force condition, porosity and threshold of porous size), an initial bone model with porous structures is firstly constructed (Figure 4 (b)) using Boolean operation [21] between the bone model and porous structures. Secondly, the finite element method [29] is utilized to analyse the porous bone model, and a distribution of stress can be obtained (Figure 4 (c)). Thirdly, if there are regions where the stress requirement are not satisfied with the given threshold, the period parameter $T = T + 1$, the offset parameter O can be adapted to fit the specified porosity, and the porous-size parameter $C=0$ is fixed. Repeat the second and third procedures until the porous bone model meets the stress requirement. Optionally, the porous-size parameter C can be used to adjust the porous size according to the requirement of porous size. Finally, we obtain a lightweight bone model that theoretically meets the given requirements (Figure 4 (d)).



(a) Original bone model (b) Initial porous bone model



(c) Stress analysis of porous model (d) The lightweight bone model

Figure 4. The processing of lightweight bone model

It is important to note that there is only one parameter *T* that needs to be optimized during the actual iterative processing. The offset parameter *O* can be calculated automatically according to the period parameter *T* and the given porosity. The porous-size parameter *C* is used to control the porous size (if *C*=0, the internal surface of porous structures is TPMS that has the minimal surface area), and it has little effect on porosity, therefore, *C* is set to 0 in our experiments.

3.3. 3D Printing Based Practical Verification and Correction

A complete lightweight framework should contain a feedback in an optimum iterative procedure, including entity models manufacturing by 3D printing, practical verification using stress testing machine, and feedback correction according to the error detection. Specifically, the entity models are firstly produced using 3D printers. Then, we utilize the stress testing machine (RG1-5 microcomputer control electronic universal testing machine, as shown in Figure 5) to verify the stress condition of the printed models. According to the testing data, a feedback correction is proposed by adjusting the modelling parameter *T*, to make sure that the lightweight models meet both the theoretical and practical requirements. The iteration process of feedback is listed as follows:

Case 1: The printed models do not satisfy the stress requirement. Firstly, the local regions that have large deformation are detected, and the period parameters of these local regions are adjusted $T = T + 1$. At this point, a local updated lightweight model is obtained. Then, implement the finite element method based stress analysis and the practical verification again, until the updated model satisfy both the theoretical and practical stress requirements.

Case 2: The printed models satisfy the stress requirement, and the stress is much less than the given threshold (10%). The period parameter of the entire model is adjusted $T = T - 1$. Then, implement the practical verification from the beginning.

Case 3: The printed models satisfy the stress requirement, and the weight cannot be reduced. The feedback is ended, and the final lightweight bone model is obtained.

Moreover, the verification and feedback are closely related to the manufacturing processes and experimental environment (temperature and humidity). In order to minimize the random error caused by the environment, our experience working in conditions: temperature is kept at 20-25 ℃ and humidity is adjusted to 50 ± 10%. To reduce the impact of 3D printing based manufacture, we use a high-precision and low-cost 3D printing method: Digital Light Processing (DLP) to do the testing. The stereo lithography appearance (SLA) based 3D printer is employed to process the models in the same procedure (set different material properties) as aforementioned in practical applications.

Figure 5. The stress testing of 3D printed model (RG1-5 microcomputer control electronic universal testing machine)

4. Experiments

4.1. The Selection of Porous Structures

In this approach, we discuss four types of porous structures: P-surface based porous structure (P), G-surface based porous structure (G), D-surface based porous structure (D), and I-WP surface based porous structure (I-WP). For comparison and visual purposes, we set the size of porous structures 1 * 1 * 1 mm, the porosity 70% (close to human native bones), and the parameters T = 1, C = 0. Under the above constraints, the offset parameter of P is O = 5.1%, the offset parameter of G is O = 3.8%, the offset parameter of D is O = 3.0%, and the offset parameter of I-WP is O = 3.2%.

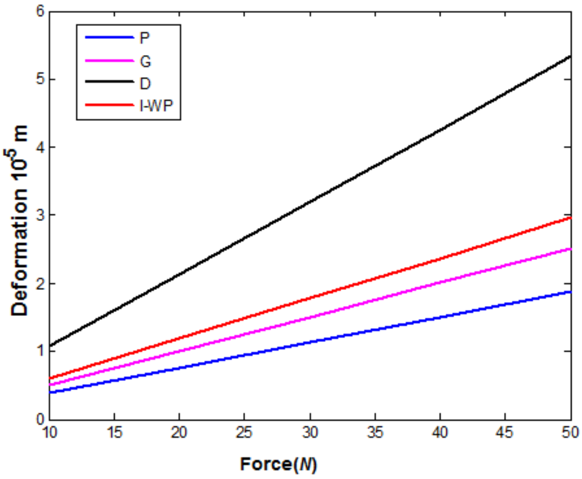


Figure 6. The curves of applied external force and the maximum deformation of porous structures

shows the relationship between applied external force and the maximum deformation of the porous structures. It can be seen that D porous structure has the largest deformation, and the other three kinds of porous structures have similar performances (P has the smallest deformation). However, we found that deformation of G mainly concentrated in the boundary and corners, and if we eliminate the impact of these regions, the performance of G is the best (the deformation is the smallest, and the stress is uniformly distributed, as shown in Figure 7). Moreover, the porous structure of G is also the most similar to the structures of human native bones (Figure 8) .Therefore, we select G as the porous structure of lightweight in this approach.

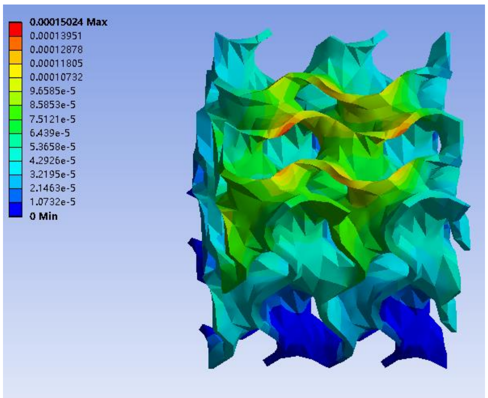


Figure 7. The stress distribution of G porous structure

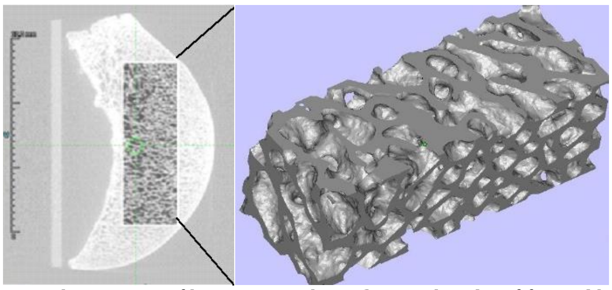


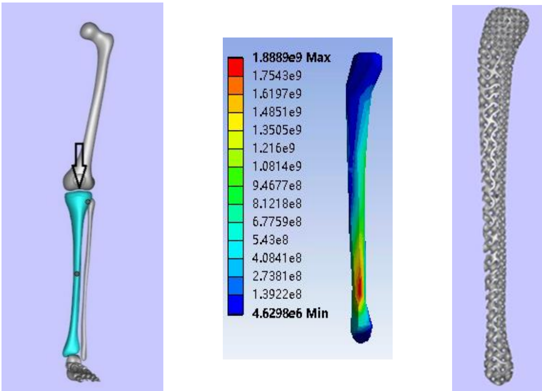
Figure 8. The structure of human native bone (bone trabecular of femoral head)

4.2. The Results of Proposed Lightweight Methods

In this part, we chose bone models of lower leg and foot with the constraints (specified applied force and porosity: 70%). As shown in Figure 9, (a) is the specified bone of lower leg and the applied force (blue part: length 20 cm, applied vertical force: 300 N); (b) is the stress analysis of the original model (the red colour indicates the larger stress); (c) is the final lightweight of bone model. Similarly, Figure 10 shows the lightweight result of foot talus (red part: length 4.6 cm, applied vertical force: 400 N). Figure 11 shows the lightweight result of foot metatarsus (yellow part: length 4.4 cm, applied vertical force: 100 N). From the above results, we can see that the proposed framework can achieve the lightweight of arbitrary given bone models using non-uniform porous structures under the given constraints. It should be noted that there are also some shortcomings in the current method, such as that lightweight models are the results of approximation but not the optimized ones. In addition, the efficiency of storage and stress analysis needs to be accelerated, especially for large models. To solve this problem, we currently make a tradeoff between the accuracy and the efficiency.

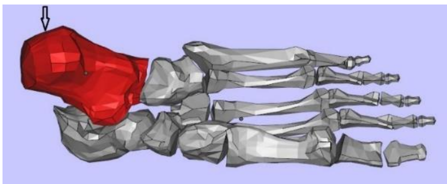
5. **Conclusions**

In this approach, we proposed a complete lightweight framework of artificial bones, and provided a feasible solution for the lightweight. Specifically, the triply periodic minimal surface was exploited to design the porous structures, which was used to model the problem of lightweight. The finite element method was utilized to optimize the modeling, and 3D printing was also employed to print models for practical verification and feedback correction. The experimental results illustrated the effectiveness and efficiency of the proposed framework. In the near future, we would like to extend the proposed method to bionics design of more general models. Moreover, how to achieve better biological compatibility also deserves further investigation.

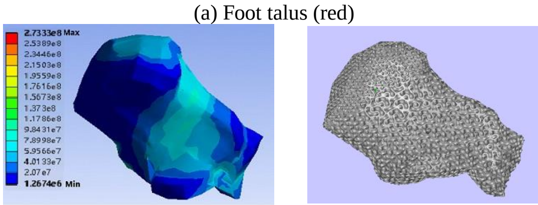


(a) Low leg bone (blue) (b) The stress analysis (c) The lightweight model

Figure 9. The lightweight of lower-leg bone

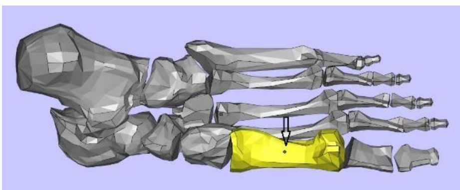


(a) Foot talus (red)

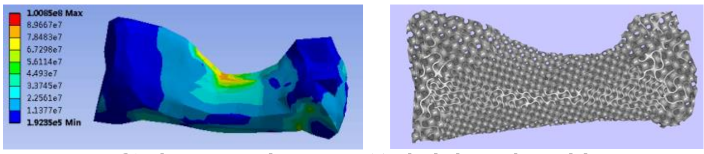


(b) The stress analysis (c) The lightweight model

Figure 10. The lightweight of foot talus



(a) Foot metatarsus (yellow)



(b) The stress analysis (c) The lightweight model

Figure 11. The lightweight of foot metatarsus

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