Construction and Optimization of Orthopedic Plates Based on Average Bone Model

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Abstract. Serial plates are not reasonable in material saving and stress dispersion. To design orthopedic plates ideally and conveniently, this paper proposes a method to optimize plates through editing semantic parameters based on average bone model. Firstly, for the reasonable distribution of serial plates in number and size, an average bone model is created from the existing bones, among which each bone has a contribution to the average model. Secondly, a common orthopedic plate with semantic parameters is constructed on average bone model and it can be conveniently modified. Lastly, optimizing the thickness of the plate through finite element analysis and genetic algorithm to meet the stress condition and use as little material as possible. The simulation results indicate that the method can save material and disperse the stress of the plates so that it can effectively optimize the orthopedic plates.

Keywords: Orthopedic plate; Average model; Optimization; Genetic algorithm
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1 INTRODUCTION

The aggravating trend of an aging population and the frequent occurrence of various types of traffic accidents have led to a significant increase in the demand for orthopedic implants. Currently, in an orthopedic operation, patients of bone defects and traumatic fracture need such fixed implant as internal fixation plate (orthopedic plate), bone nail, bone needle and so on. Among them, the design of internal fixation plate is the core of implant design [1,2]. Orthopedic plates include customized plates and serial plates [3]. Compared with the customized plates, the universal serial plates are used more widely, for they have been manufactured before operation and doctors can choose the appropriate plate and shape it when performing an operation. However, there are some problems with serial plates. In terms of size design, the technical level limits our existing serial plates are mainly referring to foreign parameters in production. The considerable differences in bone shape lead to the plates which are imported from abroad are difficult to meet the needs of the Chinese people in shape and size. Besides, in the aspect of material and stress, titanium alloy which is the principal manufacturing material is expensive, and the plates are easily fractured due to the stress concentration.

Recent years, digital orthopedics [4] has become a hot research issue and developed rapidly. Shen et al. [5] summed up the research achievements of rapid prototyping technology applied to artificial prostheses and other manufacturing technology from the angle of engineering processing. This research established the foundation for future study in digital orthopedic field. Ren et al.[6] uses CT initial data to actualize the simulated reduction of fractures and the creation of three-dimensional model of customized plates. Neto et al. [7] put forward a method from the design angle, which first generates an approximate shape of the plate abutted surface based on the surface of bone model, and then trim the surface to match the needed shape for the patient. Koen et al [8] concluded that population "average model" can be used for design, enabling the engineer to design implants that should fit significantly. Yumer et al. [9,10] propose editing a shape with a set of semantic attributes. This method provides a handle for non-experts to produce semantically-guided shape variations. This issue is to create the mapping between high-level semantic attributes and low-level geometrical elements to enable simple and intuitive shape manipulations. Ching et al. [11] studied the finite element parameters of cervical plate and pointed out that changing the screw orientation in a superior-inferior direction could significantly improve the fixation stability. Dalibor M et al [12] proposed a method for the creation of geometrical models of internal fixator with parameters. Method enables the fixator customized for the specific patient or optimized for the group of patients. Kaman et al. [13] conduct a numerical simulation based on the finite element methodology, to estimate the von Mises stress subjected to the plate and screw which is used in the tibia fracture treatment. Pendergast et al. [14] studied the finite element parameters of clavicle plate and pointed out that the thickness of the plate had a great influence on its structural stiffness. The results of the above research have promoted the development of orthopedic implants to a certain extent. However, few articles have been reported on material saving and stress dispersion of the bone plates by adjusting the thickness parameters.

Based on the research achievements of our group [15,16], this paper focuses on the construction and optimization of general plates based on the average bone model. The key issue is optimizing the thickness of the plate quickly and efficiently. In this paper, an average bone model with weight is utilized to design the specified type of plate. And semantic parameters are defined on the plate in order to be revised in the subsequent period of optimization. Then genetic algorithm is utilized to modify the thickness parameters to meet the stress condition and save material.

2 OVERVIEW OF METHOD

In this paper, the construction and optimization of plates include three parts. Firstly, constructing the average bone model. Secondly, designing the specific plate on the average model and defining semantic parameters on plate. Thirdly, optimizing the thickness of the plate through the genetic algorithm. To state succinctly, the whole process of the method is shown in Fig.1.

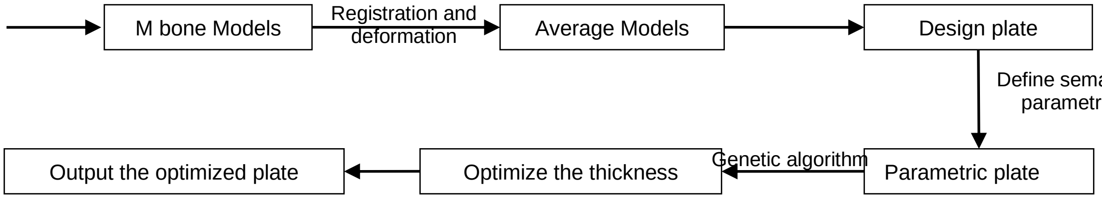


Figure 1: The flowchart of the method.

Details of the steps are as follows.

Step 1: Construct the average bone model. Construction of orthopedic plates relies on the features of bone model [17]. The average bone model provides a scientific basis for the reasonable distribution of serial plates in number and size.

Step 2: Design plate on the average bone model and define semantic parameters on the plate so that it can be conveniently modified.

Step 3: Optimize the thickness of the plate through the genetic algorithm. The best thickness distribution will be calculated with the aim of saving material and dispersing stress.

3 CONSTRUCTION OF ORTHOPEDIC PLATE BASED ON AVERAGE MODEL

The construction of orthopedic plates rely on the features of bone model. The average bone model provides a scientific basis for the reasonable distribution of serial plates in number and size.

3.1 Generation of an Average Bone Model

The part of constructing average bone model in this paper will be described briefly because relative work has been reported [15]. The method of generating a weighted average bone model is constructed, as shown in Eq.1.

$$\begin{aligned}\overline{\mathrm{M}} &= f(m_1, M_1, m_2, M_2, \cdots, m_n, M_n)\\ &= f(\sum_{i=1}^{k} m_i, f(m_1, M_1, m_2, M_2, \cdots, m_k, M_k), \sum_{i=k+1}^{n} m_i, f(m_{k+1}, M_{k+1}, m_{k+2}, M_{k+2}, \cdots, m_n, M_n))\\ &= (\sum_{i=1}^{k} m_i * (m_1 * M_1 + \cdots + m_k * M_k) / \sum_{i=1}^{k} m_i + \sum_{i=k+1}^{n} m_i * (m_{k+1} * M_{k+1} + \cdots + m_n * M_n) / \sum_{i=k+1}^{n} m_i) / \sum_{i=1}^{n} m_i \quad (1)\\ &= \frac{1}{\sum_{i=1}^{n} m_i}(\sum_{i=1}^{k} m_i M_i + \sum_{i=k+1}^{n} m_i M_i) = \frac{1}{\sum_{i=1}^{n} m_i}(\sum_{i=1}^{n} m_i M_i\end{aligned}$$

$\overline{\mathrm{M}}$ represents the average bone model, M_i represents individual bone model, m_i represents the corresponding weight value. In general, considering that the contribution of the individual model to the average model is equal, the initial weight is set to 1($m_i = 1$). In our previous work, we take 100 Asian adult fumer models as examples.

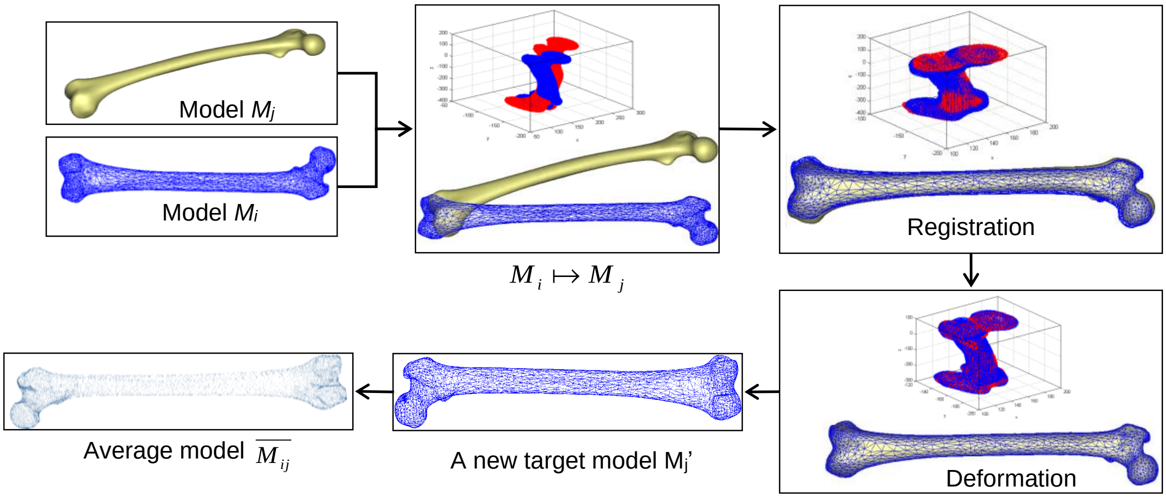


Figure 2: Generate a new target model from the model M_i (blue) to the model M_j (yellow, red) by registration and deformation, and finally generate average model between source model.

Main steps are as follows.

Step1: Consider the same type of N point cloud or mesh models as a set of N nodes, and each node is under a weight.

Step2: Select any two nodes in the set of nodes, using rigid registration and non-rigid deformation [18], as shown in Fig.2, to generate a new average node whose weight is the sum of the weights of the selected two nodes.

Step3: Delete the selected two nodes from the node set and add the generated new average node to the set.

Step4: Repeat Step2 until the last node left in the set, which is the average bone model and its weight is the sum of the weights of N nodes.

3.2 Construction of Orthopedic Plate with ROI

A general plate can be designed based on average bone model. Taking femur clover plate for example, the design method is as follows: First, the boundary curve of ROI(region of interest) is selected and defined on average bone model, as shown in Fig.3(a, b); Then, the interior constraint curves are defined on the region, as shown in Fig.3 (c); Last, a new and independent CAD surface is reconstructed with surface generation method, such as the filled method, the new surface is regarded as the abutted surface of plate, as shown in Fig.3 (d).

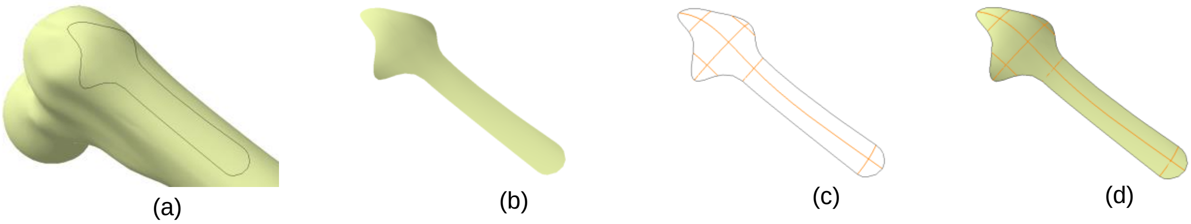


Figure 3: Select the region of interest and reconstruct it as the abutted surface of plate.

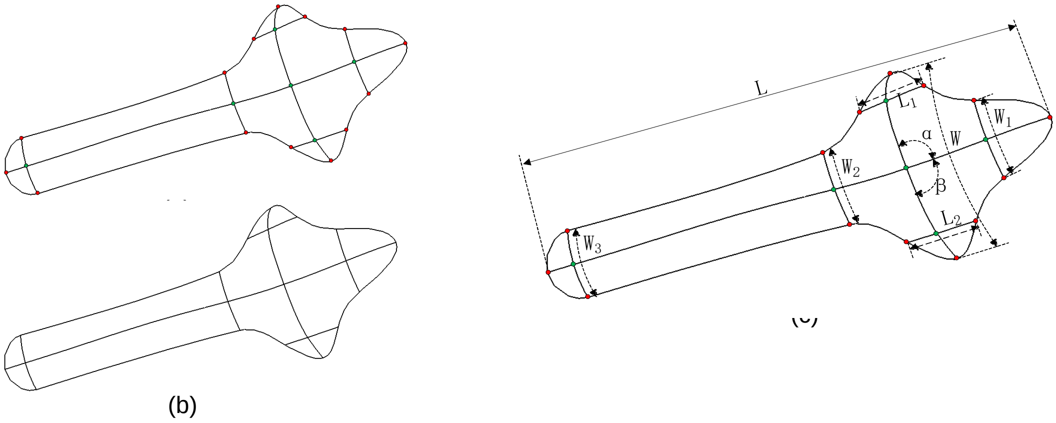


Figure 4: Parameterization of the abutted surface.

To modify the shape and size of plates, it is necessary to parameterize the abutted surface. The emphasis is how to realize the deformation of the abutted surface of the plate by modifying a small number of semantic parameters. Abutted surface of the plate is a free surface, and its parameterization definition is more complicated. In this paper, a hierarchical parameterization method based on feature points and feature curves is adopted [19,20]: Low-level parameters describe the characteristic curves and the points on the surface, as shown in Fig. 4(a); Middle-level parameters describe the shape of feature curve, including boundary curve and interior constraint curves, as shown in Fig.4(b); High-level semantic parameters describe the global shape of surface features, as shown in Fig.4(c). There is a constraint relationship between the parameters of each level [21,22] and the modification of surface features can be achieved by a small number of high-level semantic parameters.

Surface parameters are used to describe the shape of the abutted surface. Volumetric parameters are regarded as higher-level parameters used to describe the different thicknesses at different locations. In this study, the construction of volumetric plate is a key issue. Generally, the thickness parameters are defined on between the abutted surface and the outside surface. When the abutted surface was generated, we used the following Eq.2 to construct the outside surface.

$$E(u,v) = A(u,v) + d(u,v) * I(u,v) \tag{2}$$

Where, A(u,v) is the abutted surface, and E(u,v) is the outside surface, d(u,v) is the thicknesses at different locations between abutted surface and outside surface, and I(u,v) is unit normal vector at different locations of abutted surface. The corresponding key point of the outside surface can be calculated from the Eq. 3:

$$P_i' = P_i + d_i * I_i \tag{3}$$

Where, P_i' is the corresponding key point of the outside surface, P_i is the key point of abutted surface, d_i is the thickness, and I_i is the unit normal vector at the P_i location.

Combining with the Eq. 2 and Eq. 3, the construction of orthopedic plate consists of the following main steps:

Step1: The selected region is reconstructed as the abutted surface, as shown in Fig. 5(a, b);

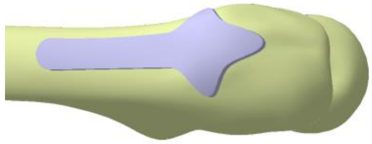
Step2: The key points, interior constraint curves and some semantic parameters are defined on the abutted surface, and constraint relationships between each level are built. Shape of abutted surface can be edited through adjusting semantic parameters, as shown in Fig. 5(c, d);

Step3: The thickness parameters are defined on some key points of abutted surface and the corresponding outside points are created, as shown in Fig. 5(e);

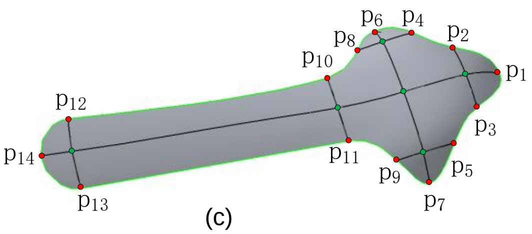
Step4: A new and outside surface is constructed based on step 3, as shown in Fig. 5(f);

Step5: A volumetric plate is created based on abutted surface and outside surface, as shown in Fig. 4(b).

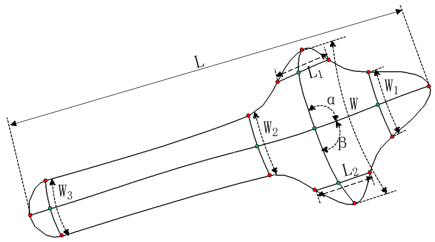
(a)



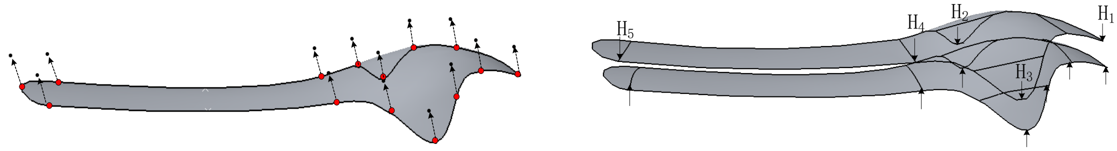
(b)



(c)



(d)



(e) (f)

Figure 5: Construction of volumetric plate :(a) Abutted surface, (b) Volumetric plate (c)Abutted surface and key points, (d)Characteristic curves and semantic parameters, (e) Corresponding outside key points, (f) Outside surface and thickness parameters.

4 OPTIMIZATION OF ORTHOPEDIC PLATE

Based on the plates with parameters in section 3.2, serial plates with different shape and sizes can be conveniently deformed with semantic parameters. Optimizing the plates to save material and disperse stress, this paper focuses on the modification of the thickness parameters in the premise that the appropriate plate has been selected.

4.1 Plate Deformations and Analysis

The volumetric plate can be configured with some thickness parameters at different locations. Plates with different thickness have different rigidities. For example, the clover plate which designed based on average femur model is configured with 5 thickness parameters H_1, H_2, H_3, H_4, H_5, as shown in Fig.6 and some new plates are created by adjusting values of thickness parameters as shown in Fig.7.

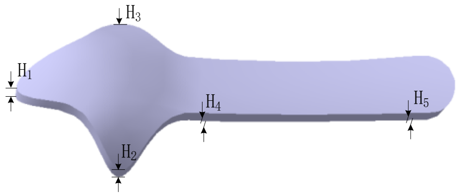
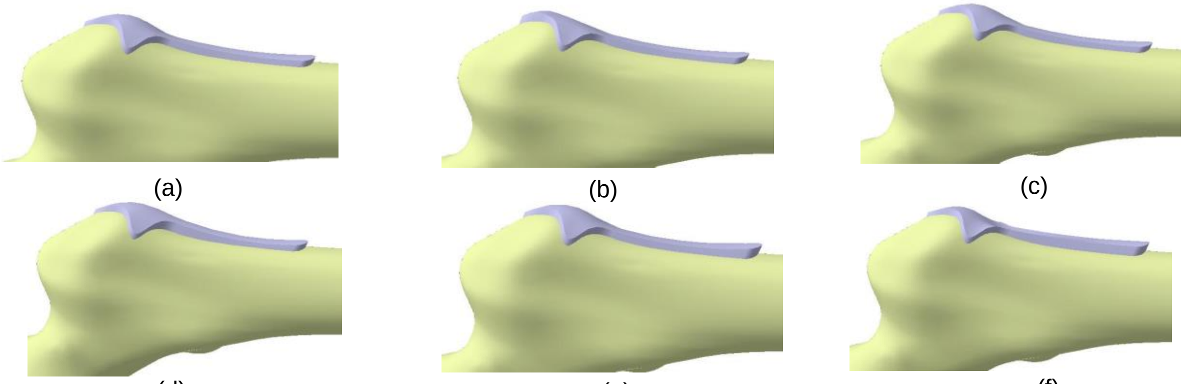


Figure 6: Defining thickness parameters on plate.



(a) (b) (c)

(d) (e) (f)

Figure 7: Plates with different thickness: (a) H_1=2mm H_2=2mm H_3=2mm H_4=2mm H_5=2mm, (b)H_1=3mm H_2=2mm H_3=2mm H_4=2mm H_5=2mm, (c) H_1=2mm H_2=3mm H_3=2mm H_4=2mm H_5=2mm, (d) H_1=2mm H_2=2mm H_3=2mm H_4=3mm H_5=2mm, (e) H_1=2mm H_2=2mm H_3=2mm H_4=2mm H_5=3mm, (f) H_1=2mm H_2=3mm H_3=3mm H_4=3mm H_5=3mm.

The load of plates in the human body is affected by various factors, including muscle, ligament, screw friction and impact load [23]. In this paper, the axial compression force of the plate under normal standing of the 60kg adult male is considered only, and the other factors are neglected. The axial compressive force of the plate is set to 600N, and the direction is set to 15 angles with the parallel line of the plate, which is consistent with the weight-bearing line of a person when standing upright [24]. The plate material is medical titanium alloy with an elastic modulus of 105GPa and a Poisson's ratio of 0.3. The stress distribution of the plates with different thickness is analyzed by the finite element method, as shown in Fig.8. The results of experiment show that the stress distribution in the plate is different at different thickness. In order to design a plate meeting stress demand and using the least material reasonably, an optimization method is proposed in Section 4.2.

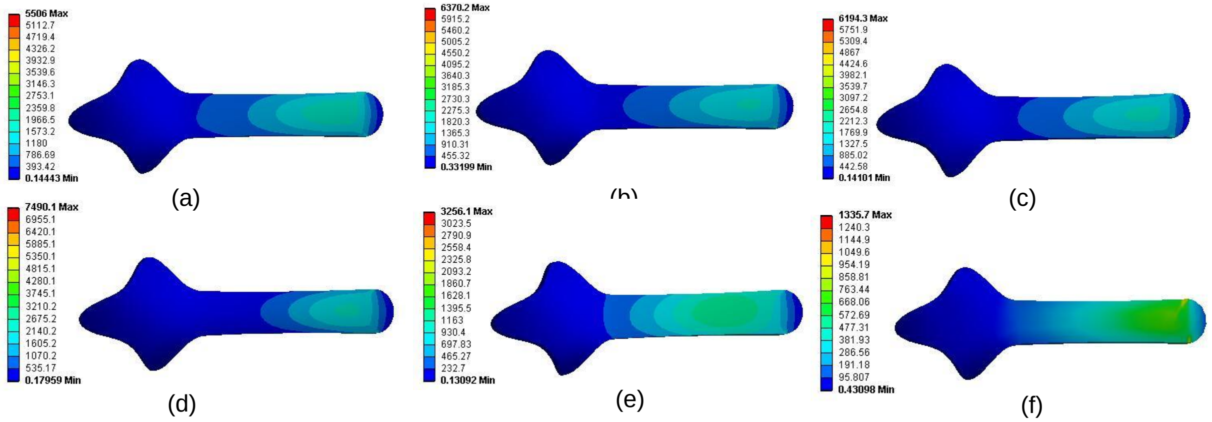


Figure 8: Analysis of plates with different thickness: (a) H_1=2mm H_2=2mm H_3=2mm H_4=2mm H_5=2mm, (b)H_1=3mm H_2=2mm H_3=2mm H_4=2mm H_5=2mm, (c) H_1=2mm H_2=3mm H_3=2mm H_4=2mm H_5=2mm, (d) H_1=2mm H_2=2mm H_3=2mm H_4=3mm H_5=2mm, (e) H_1=2mm H_2=2mm H_3=2mm H_4=2mm H_5=3mm, (f) H_1=2mm H_2=3mm H_3=3mm H_4=3mm H_5=3mm.

4.2 Optimization of Plate

There are two main materials to manufacture the plates: titanium alloy and stainless steel. Generally, titanium alloy plate is lightweight, high tensile strength and toughness, so it is commonly used in the plates. But the titanium alloy is expensive and the fracture of the plate is easily occurred because of the stress concentration. Therefore, it is necessary to optimize the design of the plates in order to reduce the weight and disperse stress as much as possible. Andrade-Campos and Kutuk propose an approach for obtaining fixation plates with possible minimum mass based on topology optimizations [25,26]. Arnone developed computer-aided engineering approach for minimizing implant mass to meet the design constraints associated with the factor of safety [27]. However, their methods are utilized to design and analyze the plates with equal thickness. Our approach is how to optimize the plate by varying the thickness of the plate on condition that the abutted surface is fixed.

Eq. 4 gives an equation for calculating the volume of the plate. Where M is the volume of the plate, Δs is the differential area of abutted surface and d_i is its thickness parameter in different locations. A(u, v) is the abutted surface and E(u, v) is the outside surface, as shown in Fig. 9. M is approximately equal to $\sum \Delta s * d_i$.

$$\mathrm{M} = \iint \mathrm{d}(u,v) d\sigma = \iint \left| E(u,v) - A(u,v) \right| d\sigma \approx \sum \Delta s * d_i \tag{4}$$

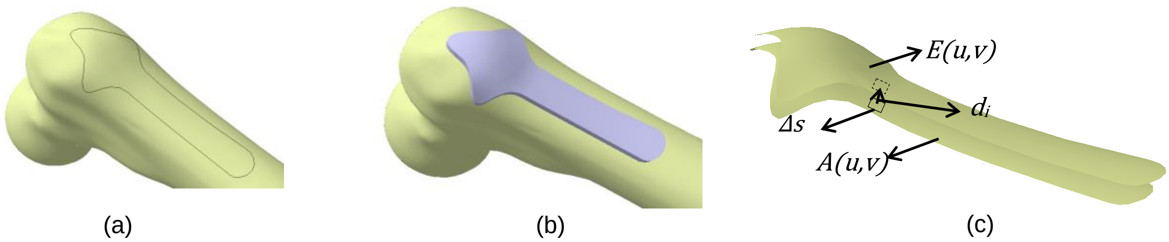


Figure 9: Volume of plate and its calculation: (a) Abutted surface, (b) Volumetric plate, (c) A represents abutted surface and E represents outside surface.

To optimize the thicknesses of plate, a genetic algorithm [28] is used to arrive at the minimum material. In recent years, genetic algorithm has been used in the study of freeform surface [29,30]. In this paper, the procedure is shown in Fig. 10.

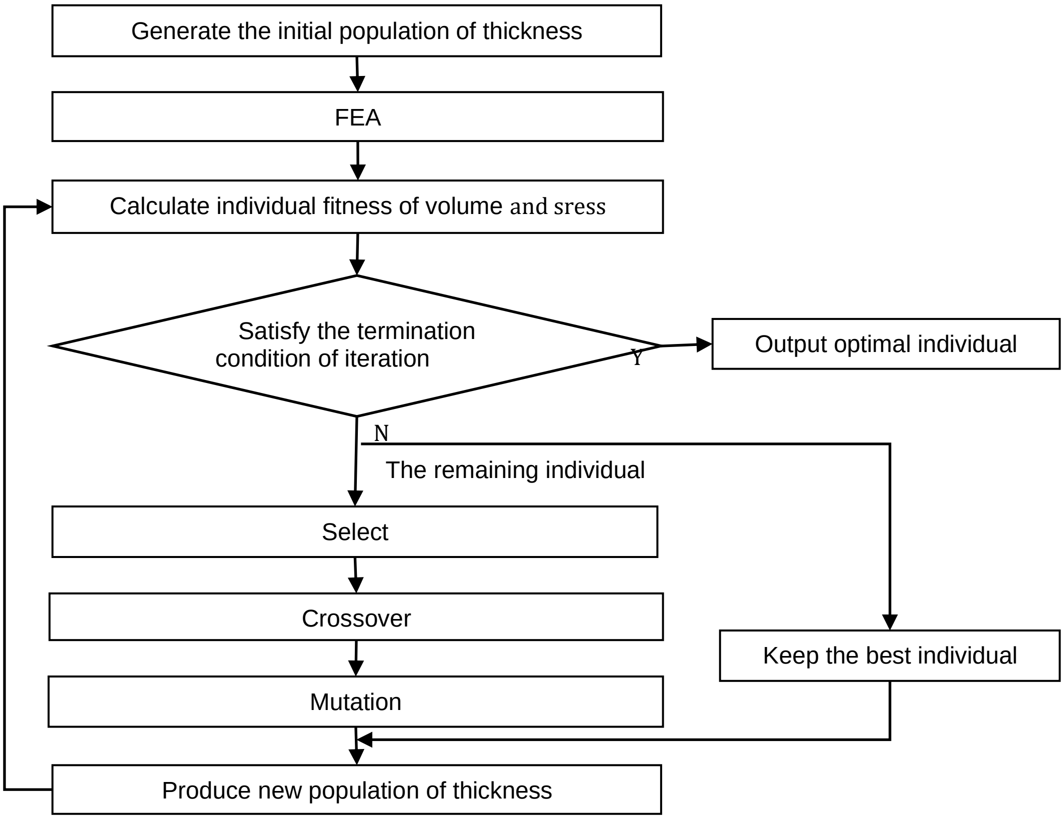


Figure 10: Procedure of optimizing the plate with genetic algorithm.

Main steps are as follows.

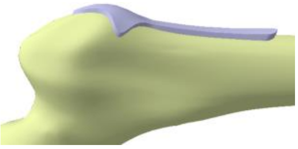
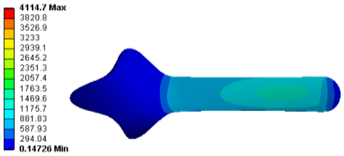
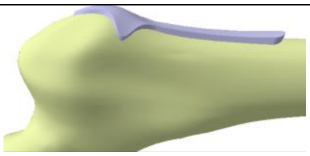
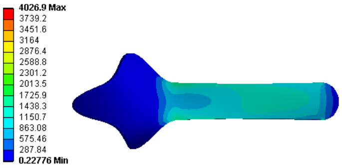
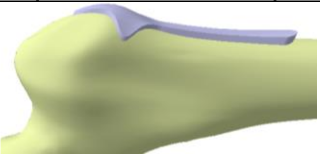
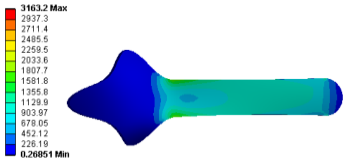
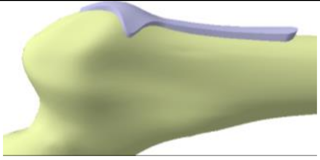
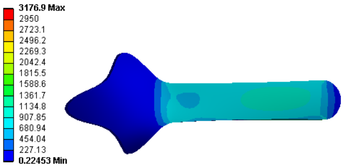
Step1: Generate initial population of thickness. The optimization variables are represented by a fixed length of binary characters by encoding. And then the initial population is generated randomly.

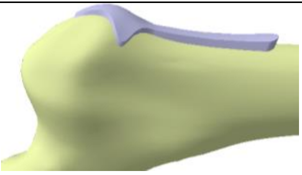
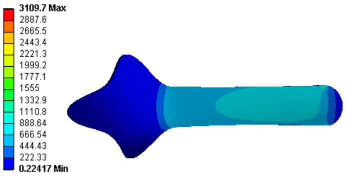
Step2: Calculate individual fitness of volume and stress. According to the optimization goal, the fitness value of each individual in the population is calculated.

Step3: Determine if the termination condition of iteration is satisfied. If the condition is met, the optimal individual is output.

Step4: Produce new population of thickness. New populations are created by selection, crossover, and mutation and then repeating Step2.

Taking femur clover plate as example. Optimized variables are thickness parameters. They are defined between 1.5mm and 3.5mm and the figure is account to one decimal place. Therefore, all the variables can be represented by 5-bit binary code and each binary code is called a gene. Five thickness parameters are defined on the plate, so the a chromosome that describes all the features of an individual is represented by 25-bit binary code. Firstly, a set of chromosomes is randomly generated as initial populations. Secondly, taking the stress and volume of the plate as the optimization target and calculating the fitness of the individual. Then, judging whether the plate meets the stress condition. Since the titanium alloy is an isotropic elastomeric material, only a single point or a small range of high stress does not cause any yield impact on the material as a whole. Therefore, when most of the elements in the bone plate stress are lower than the yield strength which is set to 817MPa[31], the stress condition is met and the optimal individual can be output. If the condition is not satisfied, new populations are generated by selection, crossover and mutation. Here, we use the roulette wheel selection, and the crossover rate and mutation rate are set to 0.6 and 0.02. In order to ensure that the optimal individual in the previous generation can be inherited to the next generation, the elite retention strategy is used, that is, the best individual in the population is directly inherited to the next population without crossover and mutation. The best individuals of some generations are shown in Fig. 11.

Generation	Best individual (H_1,H_2,H_3,H_4,H_5)	FEA result	Volume （ mm^3）	Satisfy stress rate
5	 (1.8,1.7,1.5,1.5,2.6)		1272	85.1%
10	 (1.6,1.5,1.6,1.6,2.6)		1124	78.7%
15	 (1.6,1.5,1.6,1.6,2.9)		1176	82.3%
20	 (1.6,1.5,1.5,1.6,2.9)		1297	89.5%

25	 (1.6,1.5,1.5,1.6,3.1)		1400	94.5%
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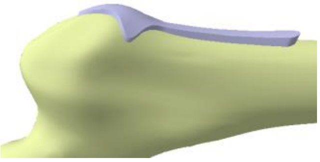
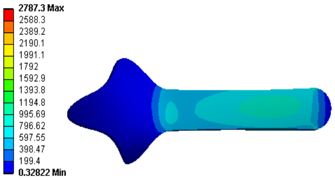
50	 (1.5,1.5,1.5,1.6,3.1)		1369	97.2%

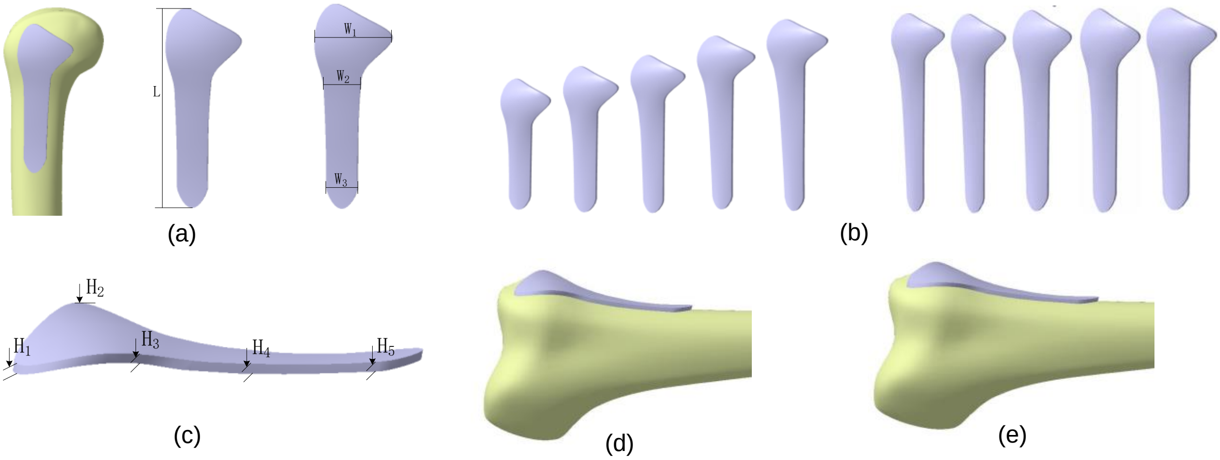
Figure11: The best individuals of some generations.

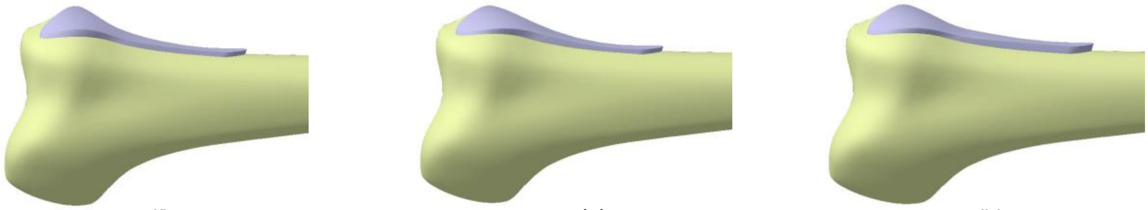
After 50 iterations, the optimal thickness of the femur clover plate can be obtained. In this example, the plate is small in volume and the stress is relative disperse when H_1,H_2,H_3,H_4 and H_5 are 1.5mm, 1.5mm, 1.5mm, 1.6mm and 3.1mm, as shown in the last column in Fig.11.

4.3 Implementation and Tests

The above-mentioned methodology and algorithms are implemented by using VC++ 2015, Geometric Modeling Engine CATIA V5R21, MATLAB and ANSYS with experimental cases. Experiments show that the method is effective.

Taking III type and Y type of the plate for the distal femur as example, firstly, the abutted surface is constructed and parameterized on the average femur model, as shown in Fig.12(a) and Fig.14(a). The parameterization of abutted surface is designed for modifying the shape of the plate, different size of plates can be constructed by editing the parameters, as shown in Fig.12(b) and Fig.14(b). Then, defining the thickness parameters at the key points, as shown in Fig.12(c)and Fig.14(c). The thickness parameters are used to describe the thickness of the plate at different locations as shown in Fig.12(d, e, f, g, h) and Fig.14(d, e, f, g, h). Lastly, the thickness is optimized by the genetic algorithm and the finite element analysis. Fig.13 and Fig.15 show the procedure of optimizing the thickness of the plate through this method.





(f) (g) (h)

Figure12: Parameterization of III type of plate and plates with different thickness: (d) H_1=2mm H_2=2mm H_3=2mm H_4=2mm H_5=2mm, (e)H_1=3mm H_2=2mm H_3=2mm H_4=2mm H_5=2mm, (f) H_1=2mm H_2=3mm H_3=2mm H_4=2mm H_5=2mm, (g) H_1=2mm H_2=2mm H_3=3mm H_4=2mm H_5=2mm, (h) H_1=2mm H_2=2mm H_3=2mm H_4=3mm H_5=3mm.

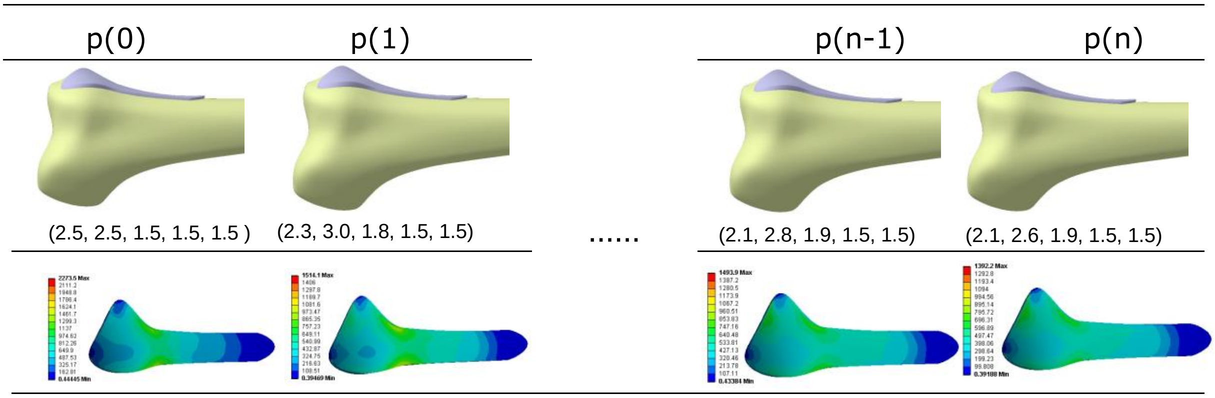


Figure 13: Optimizing the III type of plate by modifying thickness parameters.

In this paper, we compared the volume and stress between the equal thickness plate before optimizing which thickness is set to 2mm and the optimized unequal thickness plate. The results are shown in Table 1, the volume of the optimized clover plate was decreased by 3.7% and its elements which satisfying stress condition is increased by 13.6%. Volume of the optimized III type of the plate for the distal femur is decreased by 12.2% and its elements which satisfying stress condition is increased by 1.4%. And the volume of the optimized Y type of the plate is decreased by 26.5%. Experiments show that using this method to optimize the plate can reduce the volume and achieve the purpose of saving materials. At the same time, the stress distribution of the optimized plate is more uniform, and the fracture risk of the plate is reduced.

5 CONCLUSION

In this paper, a method of construction and optimization of orthopedic plates based on average bone model is proposed in order to disperse the stress of the plate and save material. The paper mainly includes: constructing an average bone model by using several bone models of the same type, designing the plate in the specified area of the average bone model and defining the semantic parameters, and modifying the thickness of the plate through genetic algorithm making the plate to meet the stress condition and using as little material as possible. The main advantages of our method are as following: (1)A weighted average bone model generation method is constructed which is favorable for the later extension of average model when a new bone is added; (2) Defining the semantic parameters on the plate so it is easy to construct a new plate by modifying the high-level parameters;(3) The genetic algorithm is applied to the optimization of plate, an ideal bone plate can be quickly constructed to meet the stress condition and save material. Our future work will focus on the design of personalized plates for different individuals combining with medical needs and optimizing the topology of the plate.

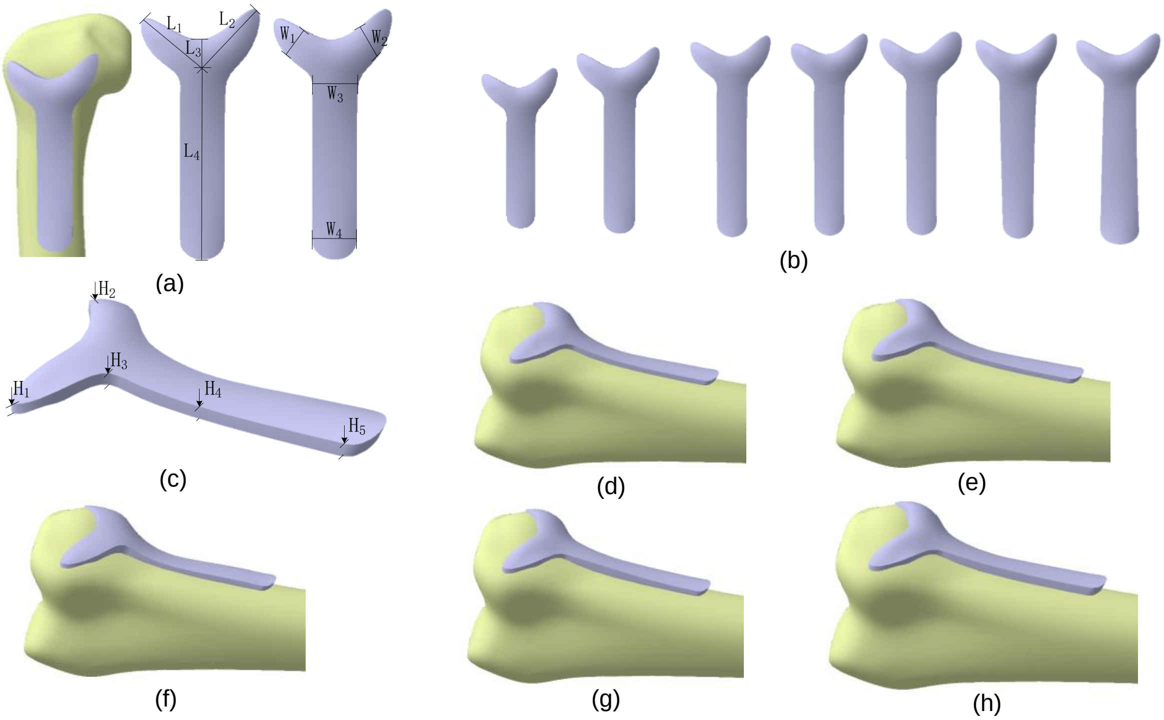


Figure14: Parameterization of Y type of plate and plates with different thickness: (d) H_1=2mm H_2=2mm H_3=2mm H_4=2mm H_5=2mm, (e)H_1=3mm H_2=2mm H_3=2mm H_4=2mm H_5=2mm, (f) H_1=2mm H_2=2mm H_3=3mm H_4=2mm H_5=2mm, (g) H_1=2mm H_2=2mm H_3=2mm H_4=3mm H_5=2mm, (h) H_1=2mm H_2=2mm H_3=2mm H_4=3mm H_5=3mm.

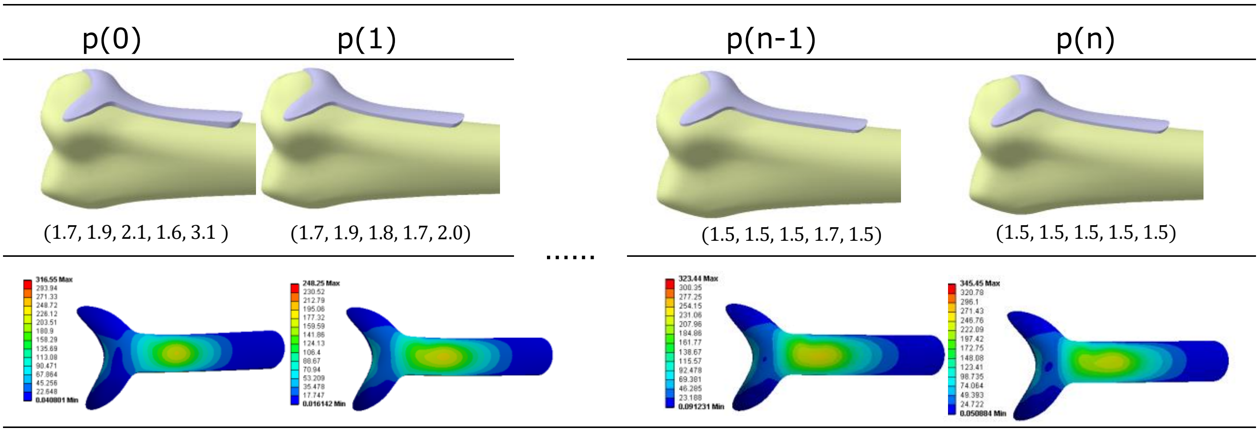


Figure 15: Optimizing the Y type of plate by modifying thickness parameters.

Type	*Thickness (mm)*	*Volume (mm3)*	*Satisfy stress rate*	*Volume decrease rate*	*Stress increase rate*

Clover plate	H_1=2 H_2=2 H_3=2 H_4=2 H_5=2	1422	83.6%	3.7%	13.6%
	H_1=1.5 H_2=1.5 H_3=1.5 H_4=1.6 H_5=3.1	1369	97.2%		
Ⅲ type plate	H_1=2 H_2=2 H_3=2 H_4=2 H_5=2	1645	97.9%	12.2%	1.4%
	H_1=2.1 H_2=2.6 H_3=1.9 H_4=1.5 H_5=1.5	1444	99.3%		
Y type plate	H_1=2 H_2=2 H_3=2 H_4=2 H_5=2	2366	100%	26.5%	0
	H_1=1.5 H_2=1.5 H_3=1.5 H_4=1.5 H_5=1.5	1738	100%		

Table 1: Comparison of volume and stress of plate before and after optimization.

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