

Shape Optimization of Orthopedic Fixation Plate Based on Static Stress Analysis

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Abstract: Shape optimization of orthopedic fixation plate is of great importance in the treatment of complex fracture. Therefore, a method in this paper to automatically optimize the complex shape of anatomical plate according to static analysis. Based on the theory of finite element analysis (FEA), our approach is processed as follows. First, the three-dimensional finite element model of the fracture fixation is constructed. Next, according to the type and feature of fracture, the anatomical plate was parameterized in two levels (the bounding surface and plate model). Then, parameter constraints are set up to meet the needs of surgical fracture treatment. Finally, by using the theories combined with the method of moving asymptote (MMA) and gradient projection (GP), the plate model is modified automatically based on the principle of plate stress and segment offset minimization. Experimental results show that the displacement of femur segments and the stress of fracture site were decreased slightly and can improve the biomechanical environment around the fracture.

Keywords: Shape optimization, fixation plate, static stress, feature parameterization.

1 Introduction

With the extensive application of fixation plates in the field of fracture surgery, orthopedic trauma infection, plate fracture, secondary fracture after plate removing and osteoporosis have been reported in clinical treatments [Toro, Calabrò, Toro et al. (2015)]. Notably, the excessive displacement between adjacent fragments and stress shielding at fracture have been regarded as the major causes of reduction malformation and secondary fracture in surgical treatments. In addition to incorrect fixed position, improper plate selection and premature weight of patients, the operation failure of treatment with internal fixation is related to three factors. (1) The displacement of fracture is too large to cause reduction deformity such as bending of long bones. (2) Normal blood supply of bone surface is usually oppressed and even destroyed because of the direct contact between plate and bone. (3) Original normal growth mechanical environment of fractured bone changed by stress shielding commonly causes to the poor quality of reconstruction after fracture healing [Harith, Schmutz, Malekani et al. (2016)].

As we all know, the actual biomechanical behaviors of both hip joint and knee joint at the end of femur are very complicated. What's more, after plate implanting, the original

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normal load of femur jointly undertaken with femur and plate may lead to change of biomechanical environment of bone in local fracture area, and serious problems such as fracture segment displacement and fixation failure are reported frequently. Therefore, biomechanical performance has been widely considered as one of important factors for performance evaluation of bone fractures, and is of great importance in the research of human fracture treatment.

Compared with the traditional experiment and analysis methods, finite element analysis (FEA) has the advantage of quick value solving of various stress, strain and displacement in the internal fracture fixation system under different complex loads [Bergmann, Deuretzbacher, Heller et al. (2001)]. More effective evaluation information can be obtained for fracture risk prediction and mechanical optimization of internal implant by using FEA. Therefore, many research works have been carried out on orthopedic biomechanics, and a series of helpful suggestions for fracture fixation treatment were proposed [Zhang, Ebraheim, Ming et al. (2015)]. For example, interior screws must be far away from segment ends in simple type of fractures and screws should be close to segments in the treatment of comminuted fractures. Accordingly, maximum stress found at screw holes near the fracture site has been widely regarded as one of the most common factors of fatigue fracture [Cegoñino, García, Doblaré et al. (2004)]. Another interesting finding is that the risk of fracture fixation failure is decreased effectively with the use of long fixation plates [Ricci, Streubel, Morshed et al. (2014)]. In summary, a lot of important prior knowledge and clinical experiences have been provided for orthopedic treatment, decision-making, biomechanics evaluation of fracture, the selection of plate and screw fixation from recent researches of FEA.

On the other hand, many researchers have make deep study on mechanical environment and shape optimization, and promote the development of mechanical properties of plate design. Mechanical environment of fracture position is determined by various attributes, such as fracture space, plate length, screw number and position, the distance between plate and bone. Experimental results show that the mechanics of fixation plate could be optimized [Stoffel, Dieter, Stachowiak et al. (2003)]. Based on that, optimization algorithms, and optimal size, shape and position of proximal radius fracture plate under physiological load conditions were proposed to improve the optimization efficiency [Grujicic, Xie, Arakere et al. (2010)]. Recently, a plate optimization method based on the material removal method (ERM) was proposed [Akif and Ibrahim (2013)], in which plate material was recursively reduced by eliminating the lower region in FEA to optimize the topology of tibia plate. Therefore, the contribution of this work is the effective reducing of material.

However, previous methods mentioned above pay little attention in shape optimization studies of fixation plate. On one hand, it is difficult to ensure the effectiveness of final optimization results in the optimization process, and it is hard to ensure the effectiveness of final optimization results. On the other hand, existing optimizations of plate shape are too single, and clinical medical knowledge is not considered, and the plate shape optimization without constraint maybe not expectant. As a result, these methods are still far from being completely satisfactory for the patients. Therefore, combined with the experience of femoral fracture medical treatment, how to rapidly optimize the bone plate to meet the requirement of specific patients based on static load analysis has to be researched.

2 Methods

2.1 An overview of the optimization approach

Based on our previous work [Chen, He, Chen, et al. (2016)], the initial plate was pre-designed. The proposed algorithm for plate optimization from an initial plate and fracture model consists of following major steps:

Step 1. Per-design initial plate according to the parameters of fractured model based on our previous work.

Step 2. Create assembly model with fracture bone, plate and screws.

Step 3. Construct the FEA model of static stress based on the assembly model.

Step 4. Parameterize the shape of anatomic fixation plate in two levels, that is bounding surface and solid model.

Step 5. Set up hierarchical parameter constraints.

Step 6. Optimize the plate shape by using the theories combined with the method of moving asymptote (MMA) and gradient projection (GP) based on static FEA.

The complete flow of optimizing an anatomic fixation plate based on specific fracture type is shown in Fig. 1. Steps 2-6 are the most important of above six steps, which will be expounded in the following sections of this paper.

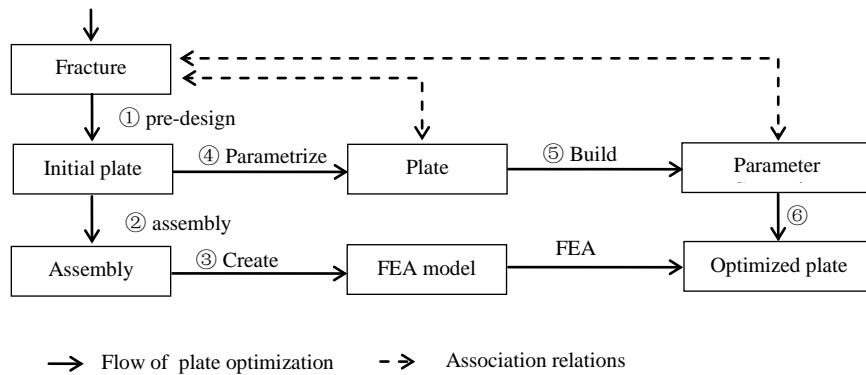


Figure 1: Overall flow of the optimization algorithm

2.2 Construction of assembly model

2.2.1 Solid fracture model reconstruction

For the difference of individual structure and bone mass of femur, solid models of human skeleton are significantly different, and the internal structure of the overall model are not the same even if one shape was close to another one. Therefore, reconstruction of solid model of individual femur is very important for the quality evaluation of femur and mechanical analyzation of plate. In this work, the fixation system of the comminuted fracture located at femur condyle was researched, and the shape optimization of anatomic plate was studied to improve biomechanical performance of the fracture position.

With individual medical CT images, a three-dimensional model of femur can be

previously reconstructed by using a commercial medical image processing software (Materialise Mimics 10). Firstly, the inner and outer contour of femoral cortical bones were extracted based on gray threshold of each CT image. Secondly, the inner and outer surface models of cortical bone were constructed from the inner and outer contours (see in Fig. 2(a)). Thirdly, the proximal and distal cancellous bone models were created to construct whole solid model of femur by adopting the method reported in recent study [Arnone (2011)], as shown in Fig. 2(b). At last, the model with AO/OTA33-A3 type fracture was generated by Boolean subtraction algorithm on the upper part of condyle, as shown in Fig. 2(c).

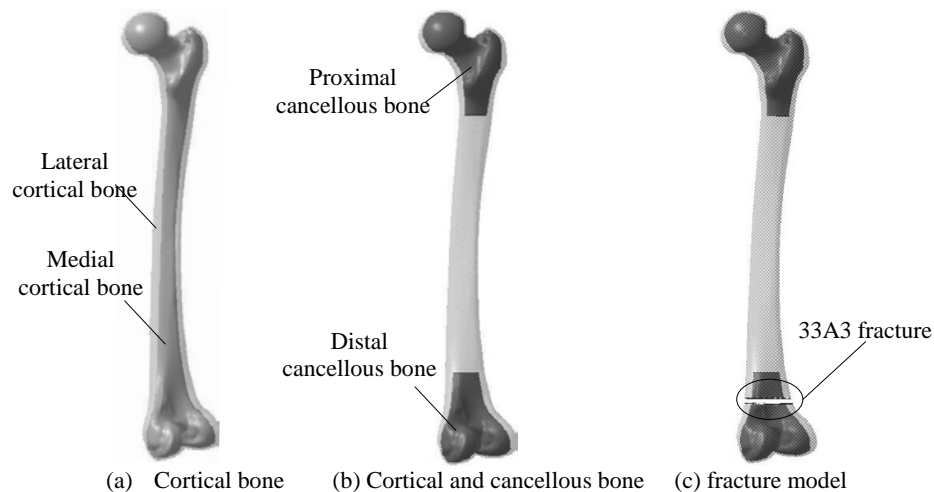


Figure 2: Construction of simulated fracture model of femur

2.2.2 Fixation model assembly

Maximum stress after plate implanting was commonly found at screw holes around the fracture. Recent researches show that the filling of fracture position corresponding to plate screw hole archives the improvement of plate strength and reduction of stress concentration of the plate. Therefore, 6 screw holes were developed in the distal part to enhance the fixation effect of cancellous bone of condylar in this work.

In our study, thread design of screws and holes is ignored for the calculation simplification of subsequent workload in finite element analysis. So, the screws are represented with smooth cylinders with a diameter of 5 mm, and the inner diameter of plate screw hole is consistent with the size of the inner diameter of the screw.

The assembly process of screw fixation system is fairly simple. Firstly, corresponding screw holes in femoral fracture mode were created by the Boolean subtraction. Then the plate, screw and femur fracture model were introduced into the same coordinate system to achieve multi-component assembly. In order to protect soft tissues and blood supplies on the surface of cortical bone, the space between plate and femur is set to 3 mm as shown in Fig. 3.

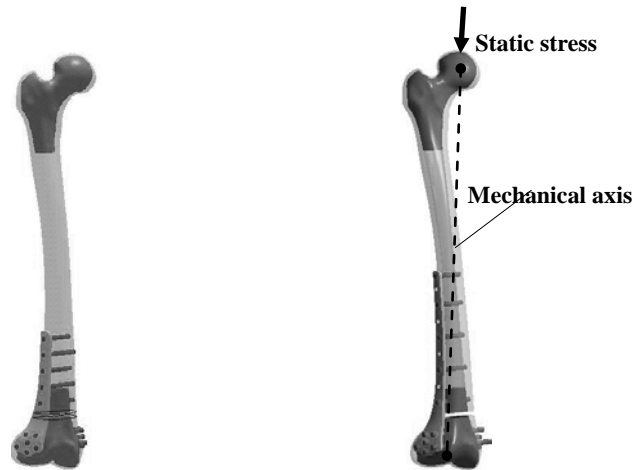


Figure 3: Plate assembly system **Figure 4:** FEA model of the plate system

2.3 FEA model construction

To obtain performance parameters of plate stress, strain and offset under normal human body load, a static stress was applied to above assembly system, and the finite element model of femoral fracture was constructed.

As we all known, femur solid mode comprised of a large number of non-uniform and anisotropic materials, and its internal structure and material configuration was essential to subsequent biomechanical analysis. Referred to the recent simplified method and subdivision method [JiangJun, Min, YaBo et al. (2014)], materials of the femur, screws, and the bone plate was all defined as linear, elastic and isotropic. Young's modulus of cortical and cancellous bone were defined as 17 Gpa and 700 Mpa, respectively, and the Poisson's ratios were uniformly set to 0.3 [Reina-Romo, Giráldez-Sánchez, Mora-Macías et al. (2014)]. Moreover, the materials of the bone plate and screws were described as titanium alloy Ti-6Al-7Nb, and their corresponding Young's modulus and Poisson's ratios were set to 123 Gpa and 0.31.

To avoid relative movement of component overlap points in the assembly model, proximal physiological boundary constraints of femur were built up (See in Fig. 3). On one hand, translational degrees of freedom in three directions were limited by fixing the center point of knee joint (the center of femoral head); on other hand, the freedom of hip joints was restricted by two directions, and only movement along the mechanical axis was allowed. Therefore, the distal outer lateral condyle was constrained at any point, and the rigid body was prevented to rotate.

In the daily activities of the human body, the femur was mainly subjected to the torsional and axial loads generated by the individual's weight load and related tendon traction, and the physiological and mechanical environment was extremely complicated. In order to simplify the structure of the finite element model of the femur, this study only focused on the axial load of the femur in the normal state of standing. However, the finite element

analysis of the static mechanics of the femoral fracture fixation system provided an intuitive reference for the shape optimization of the anatomical plate.

2.4 Shape parameterization of anatomic plate

It is noteworthy that comminuted femoral fractures are difficult to heal quickly and completely. In the early stages of surgical treatment of fractures, doctors need to rigorously evaluate multiple performance indicators related to the healing of bone fractures. Before shape optimization of complex fixed plates, it is necessary to comprehensively consider the typical medical needs of various aspects, so as to ensure that the final designed product meet the requirements of fracture internal fixation as much as possible.

In view of the importance of comminuted fracture fixation and the condition of bone growth, the objective of optimal design of fracture plate is divided into two parts. One is to enhance the initial stability of fractured segments; the other is to reduce the stress of bone plate after surgical implantation and fixation. Accordingly, tangential displacement and static stress near the fracture site are key factors to optimize the plate shape of femoral bone in this work.

Shape optimization of anatomic plate is described as the minimization of objective function, that is $\min_d f(d)$. To ensure that the optimized results meet the medical needs, constraints between the plate shape and surgical requirements are defined as Eq. (1) and Eq. (2):

$$(d_i)_{\min} \leq d_i \leq (d_i)_{\max} \quad i = 1, 2, \dots, n \quad (1)$$

$$c_j(d) \leq 0, \quad j = 1, 2, \dots, m \quad (2)$$

In which, d is the plate design parameter, $(d_i)_{\min}$ and $(d_i)_{\max}$ are the minimum and maximum values of d_i , respectively, and c_j is the constraints for clinical surgery and implant fixation.

2.4.1 Parametrization of bounding surface

To facilitate the description of plate shape and mechanical property in the fixation system, the length (plate width) of cross-sectional profile is defined to optimization parameters based on special shape of fixation plate surface. A new coordinate system is reconstructed for the convenience of defining the shape parameters of plate. As shown in Fig. 4, the profile section curve is described with an arc fitted by LSM (least squares method) in XY plane, in which, P is the center of the fitted circle, r is the radius of the arc, O is the point with coordinates $(0, 0, 0)$. The whole arc is divided into two parts by the coronal plane (XZ). Corresponding to the angles α_1 and α_2 , the distance between two end points of the arc is defined as l according to Eq.3. For each profile arc, P and r are constants, and α_1 , α_2 , and l are variables.

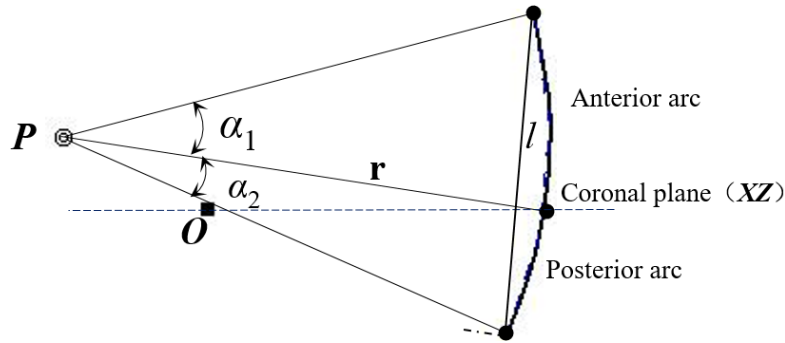


Figure 5: Parameter definition of section curve of bounding surface

$$l = r(\sin \alpha_1 + \sin \alpha_2) / \cos\left(\frac{\pi + \alpha_1 - \alpha_2}{2}\right) \quad (3)$$

2.4.2 Parametrization of plate model

After plate implantation, the stress is commonly concentrated at the surrounding area near the fracture. Therefore, the mechanical property of plate is directly determined by the shape of corresponding areas in this work. Shape optimization of plate model is defined as three corresponding section shapes, namely the shapes of fracture position, the upper and lower ends. To quantify the sectional shape characteristics of plate accurately, twelve key geometric parameters are defined based on the sectional profile and thickness characteristics of the bonding surface, as shown in Fig. 6.

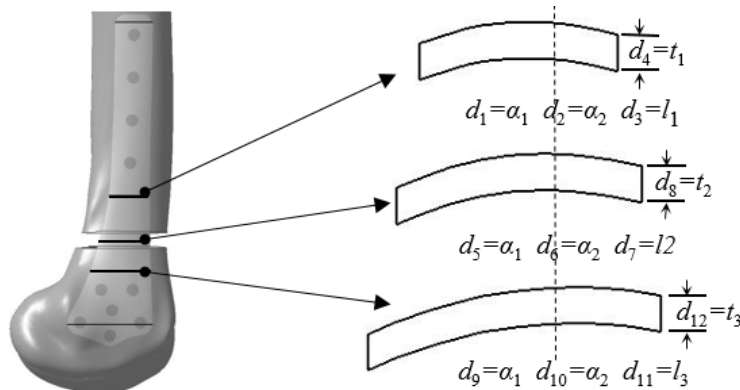


Figure 6: Parameter definition of plate model

2.5 Hierarchical parameter constraints

Suitable constraints between geometric objects are the prerequisite for optimization of three-dimensional models. Unreasonable constraint or even lack of parameter relations may lead to the failure of optimization results. For shape optimization of fixation plate, the improper optimization results usually increases the difficulty of implantation and

removal of internal plate, and even cannot meet the need of clinical fracture fixation. Combined with the needs of clinical treatment and local bone fixation, seven linear constraints are defined as Eq. (4), in which, c_1 , c_2 and c_3 , limit the local width of cross sections, c_4 and c_5 are set up to limit the local width, c_6 and c_7 constrain local thickness.

$$\begin{cases} c_1 = d_{10} - d_9 \leq 0, \\ c_2 = d_6 - d_5 \leq 0, \\ c_3 = d_2 - d_1 \leq 0, \\ c_4 = d_3 - d_7 \leq 0, \\ c_5 = d_7 - d_{11} \leq 0, \\ c_6 = d_{12} - d_8 \leq 0, \\ c_7 = d_8 - d_4 \leq 0 \end{cases} \quad (4)$$

2.6 Shape optimization of fixation plate

2.6.1 Objective function definition

For the stable fixation of femoral bone plate, the ideal goal is to firmly fix the fracture and prevent any displacements. However, due to the fact that the plate is fixed in an eccentric manner, even if bilateral fixation was used, the problem of bone fracture under physiological loading of the femur could not be avoided. In recent orthopedic surgeries, the key requirements for stable fixation of plate are the minimization of relative displacement between fractured segments after fixation. Therefore, the offset function F_d is defined in Eq. (5).

$$F_d = \frac{C}{\Gamma_C} \int_{\Gamma_C} |(u_t^{rel})|^2 d\Gamma \quad (5)$$

Because of the difference of mechanical properties between plate and bone, the stress of plate fracture is generally too concentrated after plate surgery, and it not only reduces the fixation durability of plate, but also leads to the poor quality of bone growth and osteoporosis. In the process of fracture healing, it is necessary to avoid stress occlusion caused by excessive stress. Moreover, the fracture block has to keep normal load on the stress stimulation, and the bone would restore with the normal growth mechanical environment as possible to get the better quality of new bones. Obviously, the stress assessment of the plate is another important problem in the optimization of mechanical properties of plate. Therefore, the stress function F_t is defined as shown in Eq. (6).

$$F_t = \frac{1}{\Gamma_C} \int_{\Gamma_C} |(\tau_n)|^2 d\Gamma \quad (6)$$

To obtain the global optimization effect of fixation plate, based on the above two objective functions, the compound objective function F is defined as shown in Eq. (7).

$$F = \beta_d \frac{F_d - F_d^0}{F_d^i - F_d^0} + \beta_t \frac{F_t - F_t^0}{F_t^i - F_t^0} \quad (7)$$

2.6.2 Contour optimization algorithm

In view of shape parameters of plate and objective optimization function, the combination of the method of moving asymptote (MMA) and gradient projection (GP) is applied to optimize the contour of femur plate. Firstly, the initial plate offset, stress and comprehensive objective function are calculated. Secondly, the forward finite difference method is used to solve the sensitive derivative [Chanda, Gupta, Pratihari (2016)], and the oscillation is optimized with the MMA. Finally, the GP recursive optimization is automatically processed until the convergence.

3 Experimental result and discussion

In order to evaluate the effectiveness of the proposed optimization algorithm, an anatomical bone plate for the AO/OTA-33A3 type comminuted (6mm gap) fracture fixation system is used in the experiment. The axial static finite element analysis of the femur was implemented with the i5-3470 CPU which main frequency is 3.20 GHz and 4 GB memory; the software development environment is the Visual Studio C++ 2008, the CAA V5 RADE integrated into CATIA R21, and ANSYS workbench 14 was used to finite element analysis.

3.1 Experimental results

A distal anatomic bone plate pre-constructed in our previous works [Chen, He, Chen (2017), Chen, He, Chen et al. (2016)] was used in the experiment. The static load model of the fracture fixation system was constructed with an average static load (450N). The results of objective functions of initial and optimized statuses were calculated and listed in Table 1, and the objective function values F_d and F_t were reduced to 50.08% and 49.72% respectively after optimization.

Table 1: Comparison of object functions

	F_d	F_t
Initial	65.01	55.66
Optimized	32.56	27.67

In the experiment, the weight coefficients β_d and β_t were both defined as 0.5, and the offset and stress global optimization performance were assessed according to function minimization. Optimization results of the plate were shown in Fig. 7. Compared with the results of the bone plate deflection and stress distribution before and after F_d and F_t optimization alone, the optimization profile of the plate was slightly reduced based on the composite function F , and the displacement and stress balance and global optimization were shown in Fig. 8.

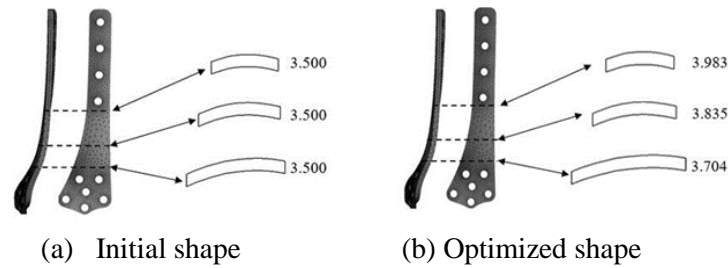


Figure 7: Result comparison of shape between the initial and optimized

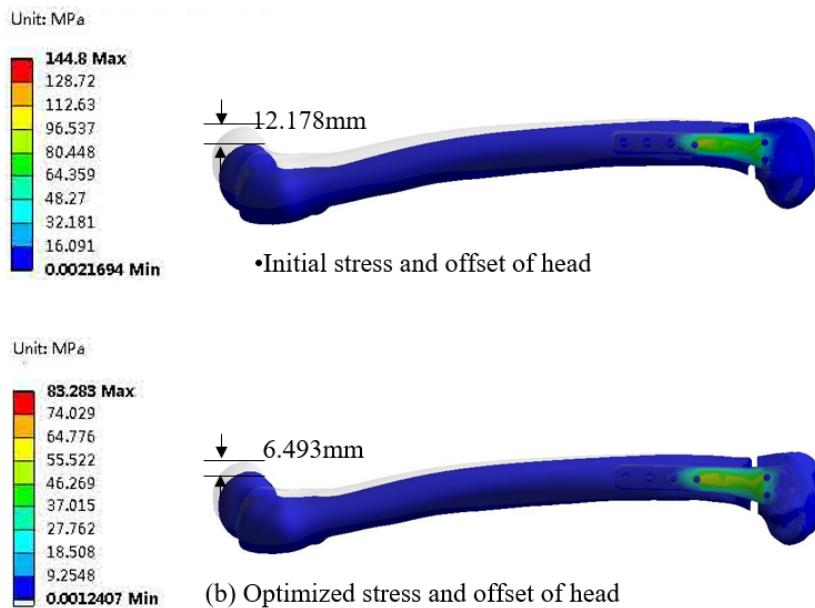


Figure 8: Result comparison of stress and offset between the initial and optimized

3.2 Discussions

The effect of femoral fractures is related to many factors, such as bone quality, bone geometry, physiological responses, surgical techniques and implant selection. For the treatment of human femur and other long bones, mechanical line reduction and functional recovery are very important. The stable fixation of femoral fracture can effectively prevent the recovery deformity or even loss of function caused by the over displacement of the fracture segment. Although the doctor's personal level and surgical skill were very important to ensure the initial implantation stability, the implant shape and mechanical properties have a direct effect on the postoperative fracture fixation and ultimately affect the outcome of patient's fracture treatment. Optimization of fracture segment displacement plays an important role in enhancing fracture fixation stability and ensuring fracture reduction function [Chanda, Gupta and Pratihari (2016)].

Wolff's law pointed out that the stress was sustained during fractured bone growth, and

the magnitude of stress was sustained by fracture position directly determines the quality of new bone growth. Because the strength of plate is higher than that of the cortical bone and the cancellous bone, the load of femur in fracture fixation system is mainly supported by the plate, and it is very easy to produce the stress occlusion of fracture position [Saravana and George (2017)], which eventually leads to the bone fracture and even the fracture of the fracture. Therefore, effective control of stress on the plate is very important for the treatment of femoral fractures.

The existing plate design studies show that the geometric shape of plate was the most important factor affecting the effect of fracture fixation, except for the material feature. Local thickness and width of plate model determine the stability of fixation system of plate and the biomechanical environment of fracture position [Colic and Sedmak (2017)]. Success of fracture surgery is closely related to the relationship between the success of clinical treatment of fracture surgery and the individual bone quality and fracture damage characteristics. The single index optimization can certainly improve a certain local performance, but it may not improve the global mechanical environment after the plate implantation, and it is often difficult to meet individual actual fixed needs. Therefore, in the optimization of plate design, in view of the actual information of individual fracture treatment, it is necessary to comprehensively evaluate the multiple optimization indexes and their optimal weights, supplemented with the necessary medical constraints.

Experiment results show that the proposed plate optimization method can improve the stability and biomechanical properties of fracture segments, both in the aspect of fracture displacement and in the static stress of plate. Compared with the existing method [Grujicic, Xie, Arakere et al. (2010), Akif and Ibrahim (2013), Zhang, Ebraheim, Ming et al. (2015), Manić, Stamenković, Mitković et al. (2015)], the proposed method has two technical advantages. (1) The optimization algorithm of the femur plate shape based on multi index can effectively reduce the workload in the manual adjustment of the shape of the plate, and then improve the efficiency of the shape of the plate significantly. (2) Optimization constraints and objective functions are defined and achieve the reasonable optimization of the plate displacement and stress performance based on clinical needs. Therefore, it has important theoretical significance and practical application value to shorten the planning period of long bone fracture, and to reduce the manual work, then improve the optimization efficiency of plate shape and promote successful healing.

The mechanical environment of the human femur and the fracture fixation system are very complex, there are still two following limitations in this work. Firstly, the optimization of the shape optimization under the static stress under a single load was tested, and the optimization of the other indexes such as torsion in the multi-load dynamic environment was not fully realized. Secondly, the complex attribute of femur has not been fully described in the construction of femur entity model. If the modeling precision was improved, the optimization of plate shape will be closer to the need of individual fracture treatment. The above problems will be studied in our future works.

4 Conclusions

A novel optimization method for orthopedic plate shape of femur based on static load analysis was proposed in this work. The static finite element analysis model of fracture

load was established based on the solid model of femoral fracture. By constraining mechanical properties to the shape parameters of plate, the plate shape can be optimized recursively to reduce the stress and fracture offset of the plate. Therefore, the proposed method can be utilized the shape optimization technology of bone plate to effectively enhance the biomechanical environment of fracture block after implantation.

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