Comparison of Spiral Versus Lateral Plate Fixations in Treatment of Multiple Humeral Fractures: A Finite Element Analysis

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Abstract: Open reduction internal fixation technique has been generally accepted for treatment of complex humeral fractures. Traditional proximal humeral locking plate design (PHILOS) have been reported in clinical or biomechanical researches, while presently the spiral plate design has been introduced improved biomechanical behavior over conventional designs. In order to objectively realize the multi-directional biomechanical performances and minimally invasive surgery for humeral plate designs, a current conceptual finite element analysis has been conducted with identical cross-sectional features for humeral plates. The conceptual lateral, and spiral humeral plate models were constructed for virtual reduction and fixation to the multiple fractures of the humerus. Mechanical load cases including axial compression, counterclockwise torsion and anterior bending have been applied for confirming the multi-directional structural stability and implant safety in biomechanical perspective. Results revealed that the lateral humeral plate model showed lower equivalent (von-Mises) stress under counterclockwise torsion, while the spiral humeral plate model performed greater rigidity and lower equivalent (von-Mises) stress under other loading cases. Four models represented similar structural stiffness under bending load. Under the different mechanical load cases, the spiral humeral plate model revealed comparable results with acceptable multi-directional biomechanical behavior. The concept of spiral humeral plate design is worth considering in practical application in clinics. Implant safety and stability should be further investigated by evidences in future mechanical tests and clinical observations.

Keywords: Multi-directional, Minimally invasive surgery, Plate fixations, Structural stability.

1. INTRODUCTION

Humeral shaft fractures account for 3%–5% of all skeletal fractures and 20% of all humeral fractures [1]. Humeral fractures often occurs in ball games, such as throwing or arm-wrestling movement, can also be found in a car accident injury, machine and scratches. Currently, the clinical treatment of middle and proximal humeral fractures is conventionally performed by interlocking intramedullary nail or locking plate percutaneous internal fixation [2-3]. Although some scholars think that these fractures can be treated without surgery [4], a recent study, involving a randomized controlled trial, concluded that surgical plating has a statistically significant advantage with a greater function, more rapid bone union, and lower deformity rate [5]. Using intramedullary interlocking nail had more complications and higher technical requirements compared with bridge plate, so some scholars preferred to use the lateral long PHILOS plate for treatment, and achieved satisfactory results [6]. However, in the operation, not only is the part of deltoid insertion needed to be cut, but the radial nerve is more likely to be damaged at the distal end of the plate [7]. Conventionally, a long locking plate is generally utilized for complicated fracture fixation including multiple fracture and oblique-type fracture. There are several experimental and clinical studies describing the use of the long PHILOS plate for minimally invasive percutaneous plate osteosynthesis (MIPPO) in fractures of the proximal and diaphyseal humerus [8]. Because it can distribute pressure over a wide area, providing more stable fixation. While stronger plates having improved anatomical features have been designed to match the curvature of the surface of the humerus, these designs are reported to be subject to complications such as screw loosening, screw breakage, plate breakage or severe deformation. Lateral humerus locking anatomical plates were subsequently introduced having advantages such as a less compression of the periosteum and adequate alignment. Previous studies have reported that locking plates possess superior biomechanical stability [9].

Recently, there have been several publications addressing feasibility and clinical benefit of MIPPO techniques in fractures of the humeral shaft. To our

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best knowledge only few publications reported on MIPPO of humeral shaft fractures through a lateral deltoid-split approach particularly focusing on radial nerve damage, which is regarded as a main specific complication during this procedure. Mario *et al* reported that minimal invasive long PHILOS plate osteosynthesis using a combined lateral deltoid-split and brachialis/brachioradialis intermuscular approach was a safe procedure for the treatment of metadiaphyseal fractures of the proximal humerus with low morbidity and full restoration of quality of life in these elderly patients [10]. However, regarding the distal incision, radial nerve is always explored during the procedure which MIPPO is for humeral fractures and lateral positioning of the plate, when radial nerve is directly visualized rather than protected simply by gentle retraction. In this study, we hypothesize that the iatrogenic radial nerve damage can be avoided during the procedure of long PHILOS plate fixation via MIPPO method for proximal humeral fractures associated with distal shaft extension, in which the distal end of straight long PHILOS plate was pre-contoured helically and attached the anterior side of the distal humerus, and inserted through the brachialis muscle belly.

The first clinical use of helical implants for bone fixation is presented by Fernández *et al*. [11] and the options have been proven to be particularly useful when attempting to avoid damage to the vascular system of the femoral head and when performing MIPPO bridge plating of humeral shaft fractures. The structure of the helical humeral plates is twisted approximately 90°to lie on the lateral aspect of the greater tuberosity proximally and the anterior or anteromedial aspect of the humeral shaft distally. This technique was developed and successfully used to treat proximal humeral shaft fractures. The helical-shaped design is principally direct at reducing the risk of radial nerve injury, because the plate approximately parallels the nerve from the proximal to the distal humerus. So that's another advantage, most of the deltoid muscle attachment can be preserved by using the minimally invasive plate osteosynthesis (MIPPO) technique. In previous study, its safety and efficacy have been proven. It demonstrated that using a helical humeral plate could reduce the technical challenge, shorten the duration of surgery, and reduce blood loss volume.

Since the helical plating technique was introduced for the treatment of humeral fractures, some studies have shown that this technique resulted in increased stiffness compared to fixation with a straight plate and produced satisfactory clinical outcomes. Krishna *et al*. evaluated the biomechanical properties of the spiral plate and concluded that the twisted plate could be approximately vertically intersected with the spiral fracture line and the fixation effect was more stable [12].

In order to compare the biomechanical properties of internal fixation and provide further theoretical basis for the clinical application of this technique, we compared the spiral PHILOS plate design with the conventional long PHILOS plate design. The purpose of this study was to investigate the benefit of pre-contouring long spiral PHILOS plates on biomechanical analysis models. We analyzed the models by using finite element analysis.

2. METHODS

2.1. Construction of Bone Humerus Model and Internal Fixation Models

A series of computed tomography images (Light Speed VCT, GE Medical System, General Electric Company, USA) of a healthy subject (Female, 35 y/o, left humerus, slice thickness: 1.25 mm, 512 × 512 pixels per image) was utilized for three-dimensional humeral model reconstruction with Mimics (Materialise, Belgium: http://biomedical.materialise.com/mimics).A simulated midshaft transverse fracture with a fracture gap of 2.5 mm left between the fractured segments was made referring to the assignment in a previous finite element study by Partal *et al*. [13]. Subsequently, the models were imported into ANSYS software (ANSYS R15.0, Ansys Inc., Houston, PA, USA) for meshing (Figure **1**). Each assembly was meshed by tetrahedral 10-node elements. Four conceptual humeral plate models – the transverse fracture with lateral plate (Figure **1**(**A**)), the transverse fracture with spiral plate (Figure **1**(**B**)), the oblique fracture with lateral plate (Figure **1**(**C**)), and the oblique fracture with spiral plate (Figure **1**(**D**)) were constructed by a 3D scanner. All plates were fixed on the humerus with locking screws (nine screws inserted proximally). According to AO principles, at least two or three screw holes should be left open over the fracture to decrease stress concentration. Fifteen 2.4 mm (in diameter) locking screws were inserted into the screw holes and left the 2 screw holes which near to fracture site empty in each model. All screws were assigned as bicortex fixation to eliminate possible error from different simulated conditions.

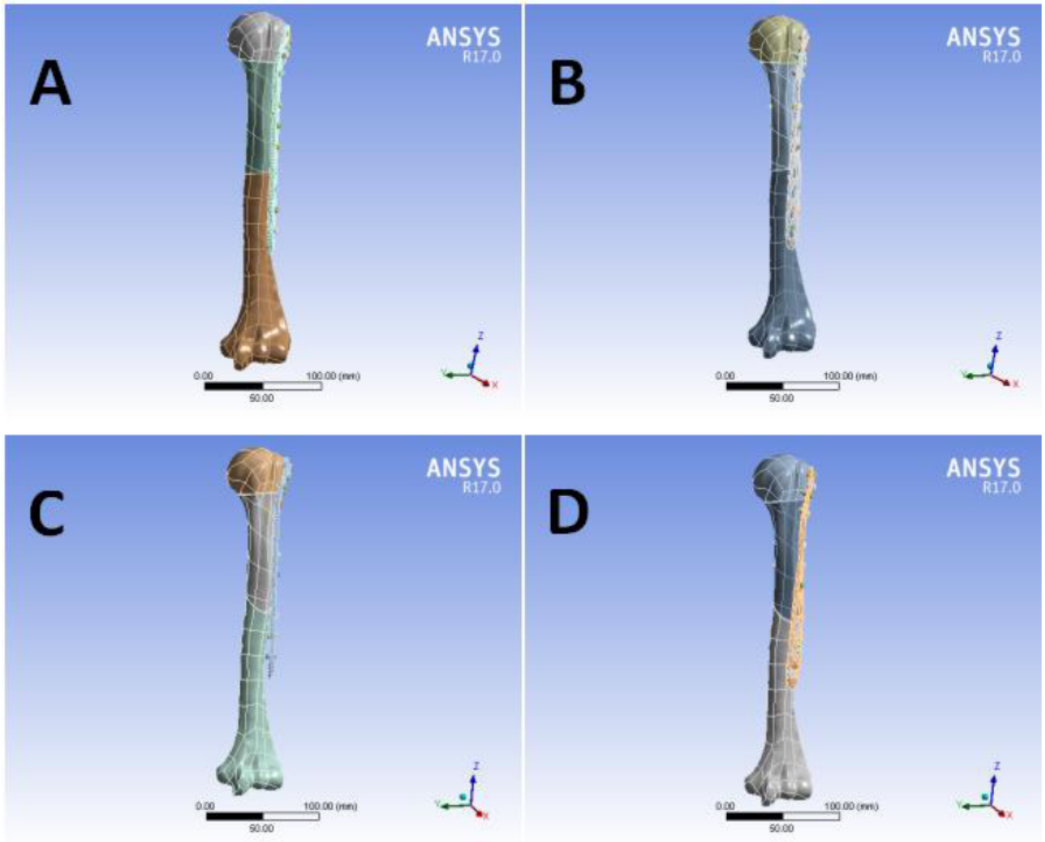

Figure 1: Finite element models applied in current study. (**A**) The transverse fracture model with lateral plate;(**B**) The transverse fracture model with spiral plate;(**C**) The oblique fracture model with lateral plate; (**D**)The oblique fracture model with spiral plate.

2.2. Finite Element Analysis

For simplifying the locking mechanism between both the bone/screw and screw/plate interfaces, all screw threads were removed and the boundary conditions between the bone/screw and screw/plate interfaces were assigned as bonded. Referring to relevant literature [14], the contact relationship between the fractured segments is set as friction, and the friction coefficient is 1. The steel plate is pre-bent to make the steel plate fully fit to the bone surface. To avoid bone plate penetration into the humerus, the contact relationship is set as friction and the friction coefficient is 0.37. The material properties for each solid component in the finite element models Table **1** [15]. The number of nodes and elements of the four models are listed in Table **2**. By fully constraining the end of the humerus, three loading modes were respectively applied for determining the multi-directional biomechanical behavior of the humeral plate models:(1) 200 N axial compressive load: The proximal humerus was defined as fixed, 200 N axial pressure was applied along the long axis of the humerus, and the application point was the distal humerus. (2) 30 Nm axial torque: Fix the proximal humerus, apply 30 Nm of torque along the long axis, and twist direction is counterclockwise. (3) 30 N bending load: The proximal and distal articular surfaces of the humerus were fixed respectively;30 N pressure was applied to the front of the broken end of the fracture. The tetrahedral elements contained were respectively 232,258 for the transverse fracture model with lateral plate, 219,079 for the transverse fracture model with spiral plate, 232,45 for the oblique fracture model with lateral plate, and 220,466 for the oblique fracture model with spiral plate, determined according to convergence tests of total strain energy.

Table 1: Material Properties Utilized in Finite Element Models

Materials	Young's Modulus (MPa)	Poisson's Ratio
Cortical bone	11,000	0.3
Cancellous bone	500	0.1
Titanium alloy	110,000	0.3

Movement of the fracture end in each model was applied for determining the stability of internal fixation. In consideration of implant safety, the von Mises stresses on humeral plate and screw models were compared.

Table 2: Details of the Three Assembly Units and the Total Number of Nodes

Case Group	Nodes	Elements
The transverse fracture model with lateral plate	369357	232258
The transverse fracture model with spiral plate	350911	219079
The oblique fracture model with lateral plate	369878	232450
The oblique fracture model with spiral plate	352759	220466

3. RESULTS

3.1. Stress on Humeral Plates

For all simulated models in various loading conditions, stress concentration on the humeral plates were observed around the center 2 screw holes adjacent to the fracture site (where the screw hole was left empty). In axial compression load cases, the lateral long locking plate models exhibited a comparative larger von Mises tress(respectively 149.310MPa in transverse fracture and 51.913MPa in oblique fracture), compared to spiral plate models(respectively 57.383MPa in transverse fracture and 30.512MPa in oblique fracture). In three-point bending load cases, larger von Mises stress was showed in the lateral long locking plate models(respectively 15.630MPa in transverse fracture and 8.278MPa in oblique fracture), than the spiral plate models(respectively 12.392MPa in transverse fracture and 7.961MPa in oblique fracture). As for the axial torsion cases, the spiral plate models represented the larger stress(respectively 4031.2MPa in transverse fracture and 3445.9MPa in oblique fracture), however the lateral long locking plate models(separately 2936.1MPa in transverse fracture and 2554.1MPa in oblique fracture). Overall, greatest stresses were found on the part of the plate adjacent to the fracture gap in each model (Figure **2**).

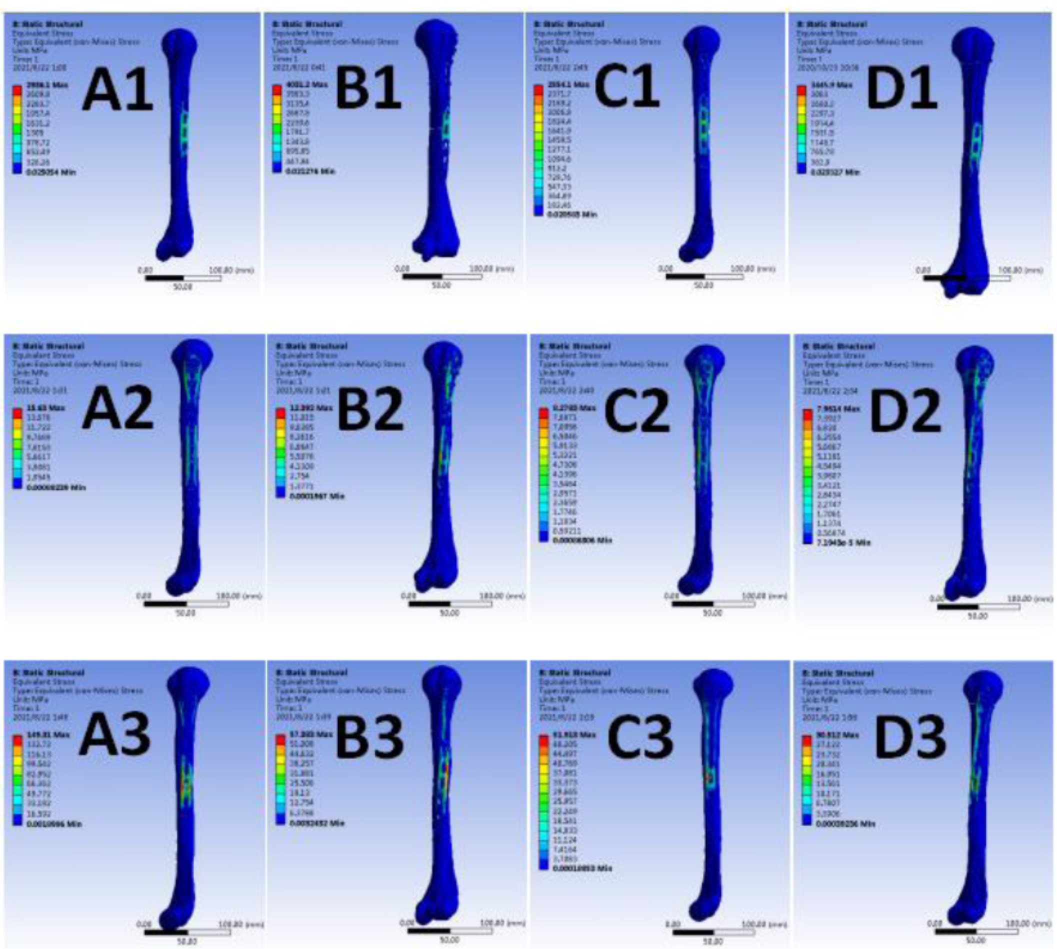

Figure 2: Von Mises stress (VMS) values of the internal fixation components. (**A1**-**D1**) 30 Nm axial torque group; (**A2**-**D2**) 30 N bending load group; (**A3**-**D3**) 200 N axial compressive load group.

3.2. Deformation on Fracture Ends

According to the displacement contours of the humerus with transverse and oblique fractures with lateral and spiral plate, the maximum displacement occurs at the end of the humerus and is shown in Figure **3**. In 30 N bending load cases, the displacement value of fracture ends was smaller in the spiral plate model relative to in the lateral long locking plate model. The displacement values of fracture ends were 0.052mm for the transverse fracture model with lateral plate, 0.041mm for the transverse fracture model with spiral plate, 0.027mm for the oblique fracture model with lateral plate and 0.022mm for the oblique fracture model with spiral plate.

Nevertheless, no noticeable differences were found between the two plates in all other models. What is more, in the other loading conditions, displacement value of fracture ends in the spiral plate model compared to the lateral long locking plate model were smaller.

4. DISCUSSION

Finite element analysis is mainly used to analyze the biomechanics of bone and its relationship with structure, to study the selection and improvement of internal and external fixation devices, to analyze the mechanism of injury, and to compare various surgical methods [16]. Krishna performed a finite element analysis of the hemi-helical plate to elucidate the efficacy of fracture gap movement and closure, as well as the flexibility of fixation under compressive, moment, and torsional loads [12]. The major finding from the computational simulations has confirmed the spiral humeral plate design delivers comparable performance in structural stability and implant safety in multidirectional loads. The results reported in the current study may enhance the confidence of orthopedic surgeons in application of spiral humeral plates in clinical practice.

In our study, we discussed the biomechanical effect of a new type of spiral internal fixation system in the

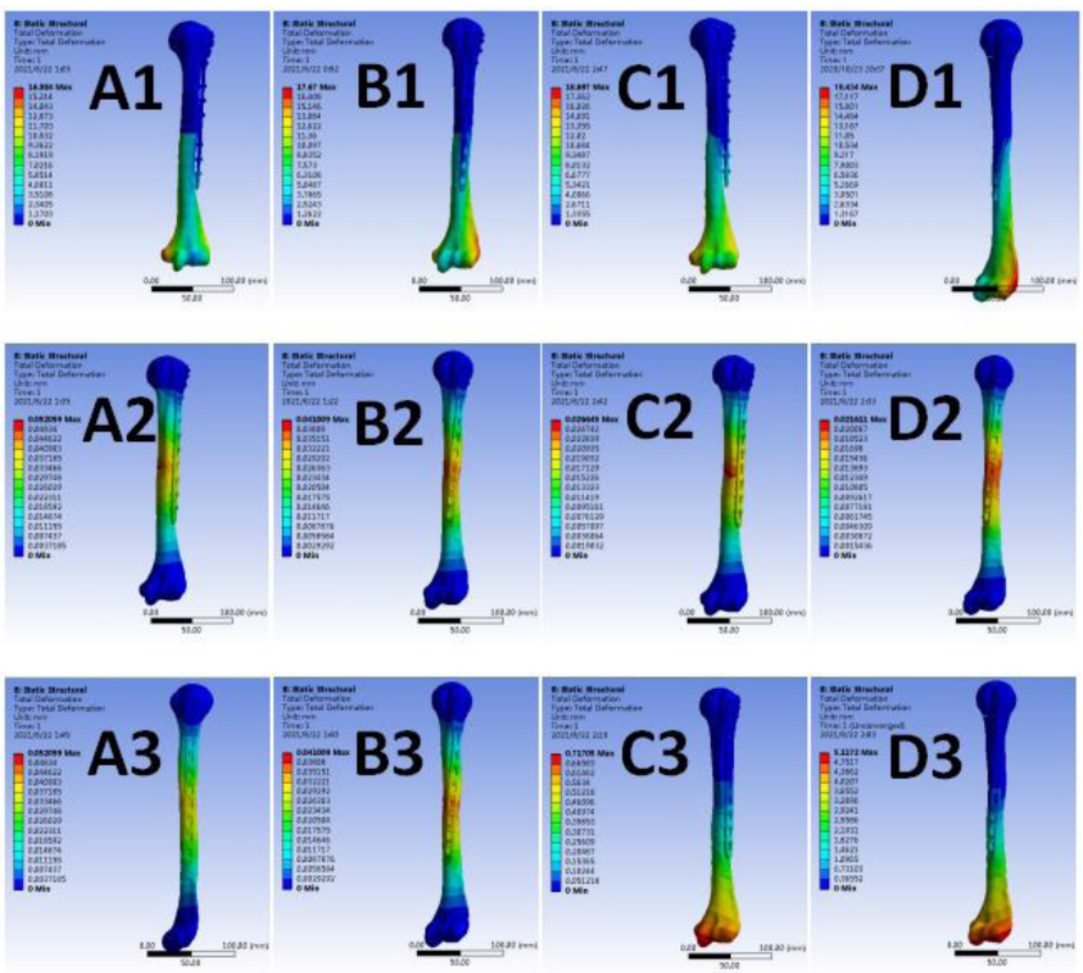

Figure 3: The displacement of the end of the humerus fracture. (**A1**-**D1**) 30 Nm axial torque group;(**A2**-**D2**) 30 N bending load group;(**A3**-**D3**) 200 N axial compressive load group.

treatment of multiple fractures of the humerus through finite element analysis. The maximum equivalent stress distribution of the internal fixation is an important criterion to measure the quality of the internal fixation. The ideal internal fixation should have a uniform stress distribution and a small maximum equivalent stress value [2]. Under the three working conditions, the maximum Von Mises stress on the internal fixation is mainly distributed near the broken end of the fracture. In compression and bending conditions, the maximum Von Mises stress value of the spiral fixator is smaller than that of the lateral internal fixator, which indicates that the spiral plate has better compression and bending resistance than lateral straight plate. However, in torsion condition, the maximum equivalent stress value of the spiral plate is larger than that of the lateral plate. We think that the steel plate is spirally processed, the rigidity of the torsion is reduced. So, it indicates that we can thicken the spiral part of the steel plate to improve the safety.

In this study, both two kinds of fractures (the transverse fracture and the oblique fracture) were fixed by spiral plate and lateral straight plate. The results show that under the axial load about the physiological load range of 200N, the displacement of the fracture end could still be within the reasonable fretting range of about 2mm, which interference to fracture healing is not obvious. What is more, the spiral plate model has shown that the deformation was smaller than the lateral straight plate model, which demonstrated that the fixed effect was more stable. Under the forward and backward three-point bending load, the equivalent stress (von Mises stress) results of the FE models have shown that the maximum equivalent stress value in the spiral plate are smaller than the lateral straight plate.

However, several limitations still exist in this study: There are various treatment methods for the spiral fracture of the middle and upper segment of the humerus. In this experiment, the commonly used PHILOS plate internal fixation method was selected for analysis, and other internal fixation methods were not considered. Due to the limitation of experimental conditions and techniques, the model was simplified in this study, and the influence of soft tissues such as muscle and joint capsule on the experimental results was not considered. The mechanical properties of bone materials were regarded as homogeneous, linear and isotropic elastic materials, and the preload force of lag screw and screw thread were ignored. But in fact, human bone is an isotropic heterogeneous material; thus, the material properties in the finite element experiment may affect the final results.

In this experiment, it is assumed that the fracture end and the plate is fully fitted to the bone surface, but it is difficult to achieve in practice. In addition, the experiment applied a single load to simulate the specific action, but the humerus stress is often the superposition of a variety of loads, the actual stress condition is more complex, using the finite element method for mechanical analysis, the results may be wrong with the clinical expectations.

5. CONCLUSION

Our results demonstrated that though the mechanical properties of the spiral long PHILOS have changed, which was generally superior to the lateral straight plate and able to meet the needs of early postoperative functional exercise. Additionally, combined with minimally invasive technique and the spiral plating technique for clinical operation, radial nerve injury can be avoided. Finally, the future design of the locking plate can be further improved to strengthen the stress concentration area on the bone plate to reduce the chance of metal fatigue fracture, and the screw position should be adjusted according to the stress concentration trend of the humerus.

DATA AVAILABILITY

The datasets generated and analyzed during the current study are not publicly available due to the respect and protection of privacy of the patients but are available from the corresponding author upon reasonable request.

CONFLICTS OF INTEREST

All authors state that they have nothing to disclose and no conflict of interests.

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AUTHORS' CONTRIBUTION

Ya Chen, Chang-Peng Xu and Yong Qi conceived the study and wrote the manuscript. Shuan-Ji Ou and

Yang Yang reconstructed the models and performed the finite element analysis. Wei Zhang and Chang-Liang Xia contributed to the data collection and interpretation of the results. All authors read and approved the final manuscript and consented to publish this manuscript.

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