

Original Article

Establishment of a three-dimensional finite element model and biomechanical analysis of three different internal fixation methods for humeral greater tuberosity fracture

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Abstract: *Objective:* The aim of this study was to provide the basis for implanting selection by comparing the biomechanical performances of three fixation techniques used in the treatment of greater tuberosity fracture: screws, a tension band, or the locking plate which were specifically designed through the establishment of a three-dimensional finite element model. *Methods:* Three-dimensional reconstructions of the scapula and proximal humerus were assembled and a finite element model was established. Loading force and traction testing was carried out using the maximal contraction force of the rotator cuff muscle. The maximum displacement, maximum Von Mises stress, and the displacement and stress distribution diagram of the three fixation models were compared. *Results:* The stress applied to the greater tuberosity of the locking plate and screw was lower than the yield strength of titanium alloy. The greater tuberosity locking plate demonstrated homogeneous stress distribution, and the stress was dispersed and transmitted rapidly, closer to the physiological state. The biomechanical stability was also greater than that of the screw fixation or tension band fixation. *Conclusion:* The locking plate demonstrated significant biomechanical advantages of stress dispersion and transmission compared to screw or tension band fixation in the treatment of greater tuberosity fracture.

Keywords: Humeral greater tuberosity fracture, three-dimensional finite element model, screw fixation, tension band fixation, greater tuberosity locking plate

Introduction

Greater tuberosity fracture of the humerus is classified as a part 2 fracture according to the Neer classification of proximal humeral fractures. Displacement of a greater tuberosity fracture of the humerus by 3-5 mm can influence the biomechanical function of the rotator cuff and lead to the occurrence of subacromial impingement, in which the surgical internal fixation needs to be employed [1]. The commonly-used surgical treatment methods are suture fixation, screw fixation, and tension band fixation. These fixation methods have different advantages and disadvantages. Suture fixation is simple and inexpensive, and the clinical results are often satisfactory [2]. However, if

greater tuberosity fracture of the humerus is comminuted, suture fixation may further reduce the stability among the fracture fragments [3], making it difficult to maintain the location of the fracture fragments. Simple screw fixation can be performed by percutaneous implantation with minimal surgical trauma, but screw fixation may lead to further comminution of the fracture fragments, while the use of gaskets increases the possibility of shoulder impingement [4-6]. Tension band fixation could convert tension into fracture pressure, which has strong fixation strength, but is likely to cause iatrogenic fracture of the surgical neck of the humerus when treating greater tuberosity fracture [7]. On the other hand, as the tension band inserts from the posterior supraspinatus tendon, although

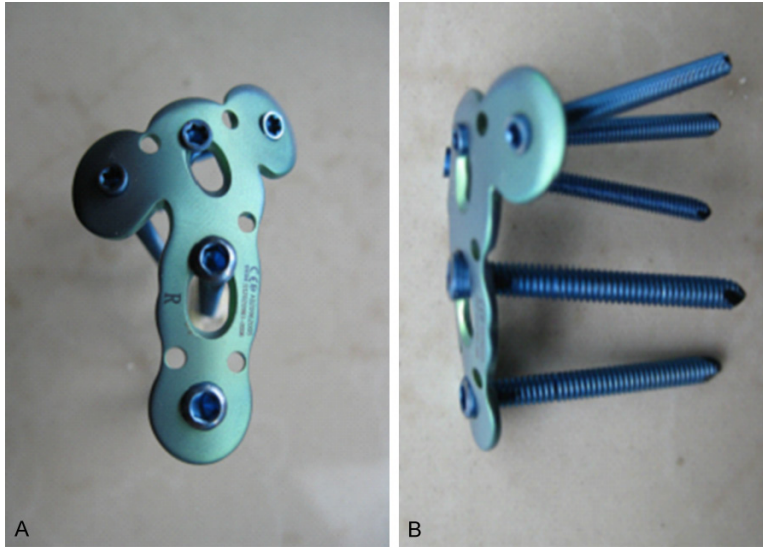


Figure 1. Image of greater tuberosity locking plate. A. Anterior; B. Lateral.

elastic tendon tissue can resist tension band cutting to a certain extent, the long tensile force of the tension band steel wire could still potentially damage the supraspinatus tendon. Therefore, we designed a locking plate [8] for the fixation of humeral greater tuberosity fractures (**Figure 1**). In this paper we established a three-dimensional finite element model for different methods of internal fixation for greater tuberosity fractures: screw, tension band, and locking plate of the greater tuberosity, and compared the biomechanical performance of these three methods in fixing a greater tuberosity fracture, providing the basis for the choice of implants in clinical treatment of greater tuberosity fracture of the humerus.

Materials and methods

Solid modeling establishment

The solid modeling data was provided by the Orthopedics Research Institute of Ruijin Hospital Affiliated to Shanghai Jiao Tong University. Data were collected from a 29-year-old healthy male volunteer, height 175 cm and weight 80 kg. X-ray examination was carried out to exclude shoulder joint injuries, tumors, and abnormalities. Thirty-two-slice spiral computed tomography (CT) (Siemens Somatom Sensation 32, Forchheim, Germany) was employed to scan from the upper cervical spine to the middle of the thoracic spine with 2 mm layer depth. Three-dimensional geometric reconstruction of the scapula, humerus sur-

face, and internal medullary cavity was conducted using Mimics10.1 (Materialise, Leuven, Belgium). The cortical bone and cancellous bone [9] were differentiated by 600 gray values. Cartilage was not included due to the lack of cartilage imaging. The surface/solid model reconstructed by Mimics10.1 (STL/SLA) was introduced into Geomagic (Geomagic Inc., Morrisville, NC, USA) for surface reconstruction, establishing the three-dimensional finite element model. The constructed bones were reassembled in the finite element pre-processing software HyperMesh 10 (Altair,

Troy, MI, USA), with mesh defined using a two-order 10-node, tetrahedral unit. The material property was set as a linear elastic material, and the contact interface was all closely connected, with C3D4 units utilized for humeral cortical bone, cancellous bone, and scapula [9, 10]. Ligament [11] was reconstructed using a one-dimensional elastic truss element, and the five main ligaments of the shoulder joint (superior glenohumeral ligament, middle glenohumeral ligament, inferior glenohumeral ligament, posterior glenohumeral ligament and rotator cuff ligament) employed quadrilateral shell elements. Specific values were assigned for humeral cortical bone, humeral cancellous bone, ligament, scapula, and internal fixation as shown in **Table 1**.

Establishment of the finite element analysis model

The model was established based on the anatomical structure of the proximal humerus of cadaveric specimens in our previous study [13]. The proximal end of the greater tubercle of the humerus was drawn according to the relevant anatomical data, and a standard fracture model of the greater tuberosity of the humerus was established, including fracture models of the scapula, humerus, and greater tuberosity of the humerus, a screw model, a tension band model, and a greater tuberosity locking plate model, as well as three internal fixation methods used for the fixation of proximal humerus greater tuberosity fracture, simulating the func-

Table 1. Mechanical properties of the materials

Structure	Modulus of elasticity/GPa	Poisson's ratio	Element number	Node number
Cortical bone of humerus [10]	20	0.30	121,366	32,116
Humeral cancellous bone [10]	0.1	0.26	69,671	15,653
Scapula [11]	9	0.30	98,215	24,536
Ligament [12]	0.15	0.30	315	534
Locking plate [13]	120	0.30	17,633	5,705

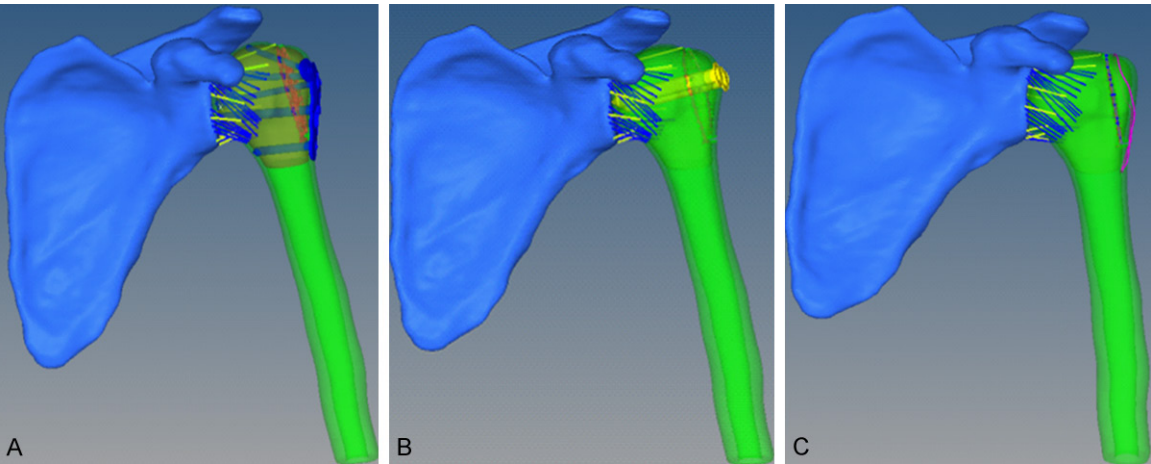


Figure 2. Finite element analysis models. A. Novel locking plate fixation model; B. Screw fixation model; C. Tension band fixation model.

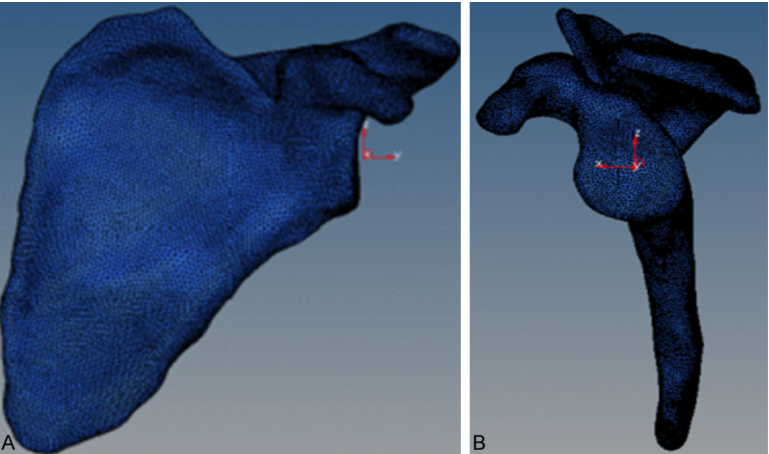


Figure 3. Loading directions of the rotator cuff muscles. A. Anterior; B. Lateral.

tional position of the three fracture internal fixation models in four-direction adduction of the shoulder joint in the neutral position (Figure 2).

Calculation

Load and boundary conditions: The same constraints and loading conditions were applied

to each model in ABAQUS 6.9 (Dassault, Systems, MA, USA) and finite element analysis was carried out. With the shoulder blades and the humerus restricted, a local coordinate system was established in the glenoid cavity as shown in Figure 3, with the X-axis indicating the coronal section of the shoulder blade, the Y-axis indicating the shoulder blade level, and the Z-axis indicating the sagittal plane of the scapula. The contraction force of rotator cuff muscle was simulated by establishing a coupling element to couple the surface of the greater and smaller tubercles of the humerus, and applying loading force in three directions.

Parameter design and loading direction of rotator cuff muscle strength: Through the simulation of pulling rotator cuff muscles (supraspinatus, subscapularis, infraspinatus, teres minor), force was applied from different anatomical

Finite element model for humeral greater tuberosity fracture

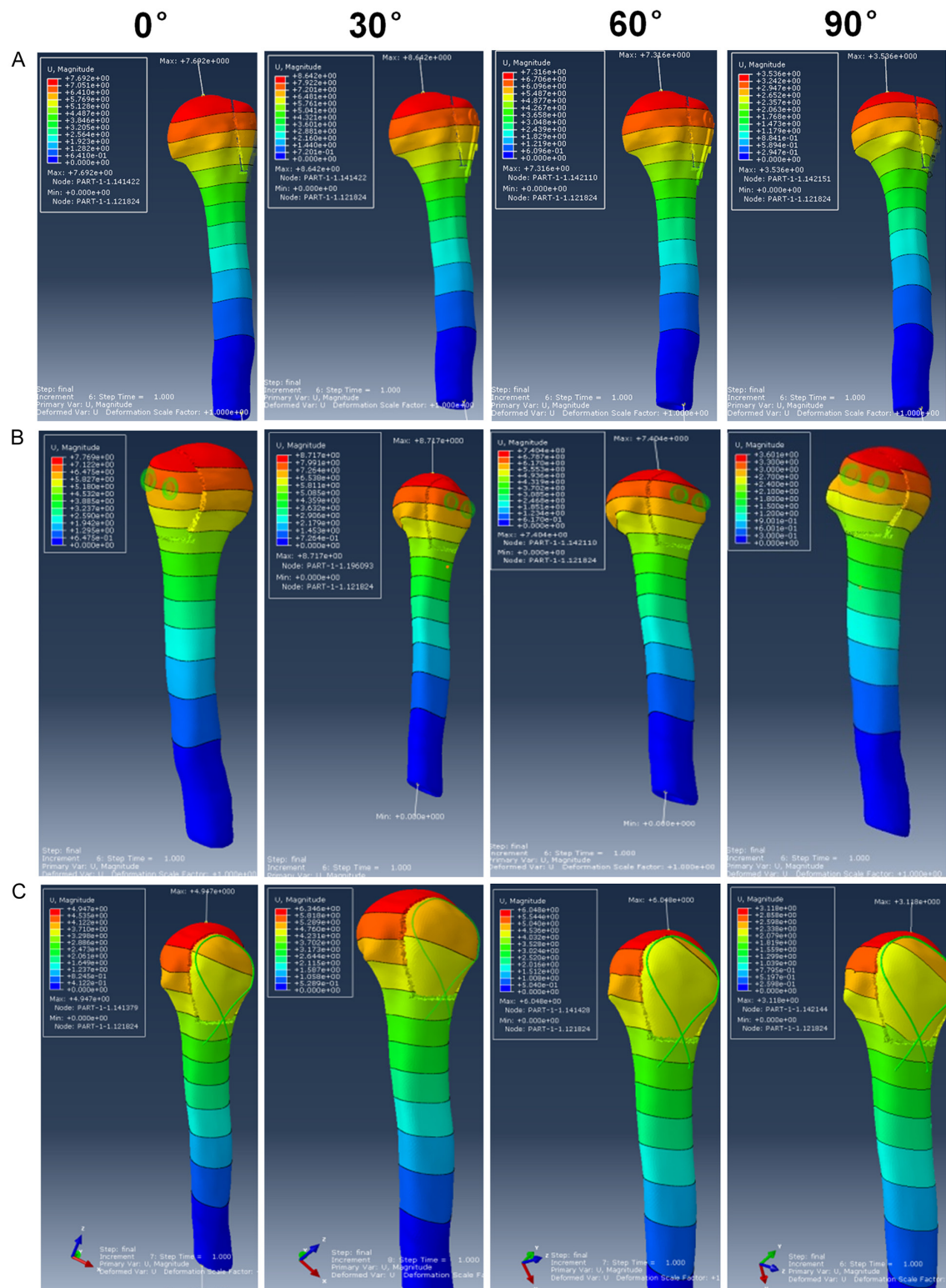


Figure 4. The maximum displacement diagram of the three fracture fixation models with different shoulder abduction angles. A. Greater tuberosity locking plate fixation model; B. Screw fixation model; C. Tension band fixation model.

directions to determine the maximum contraction produced by the rotator cuff muscle under

physiological conditions. A study by Keating et al. [14] showed that the contractile force pro-

duced by the supraspinatus and teres minor could reach 97 and 40 N, respectively, therefore the approximate sum value of 150 N was used. A study by Hughes et al. [15] showed that the maximum contractile force of the supraspinatus muscle was 117 N during abduction of the shoulder joint, while a study by Heckman et al. [16] showed that the maximum contraction force of the shoulder muscles was 225 N. According to the methods reported by Apreleva et al. [17], loading was applied to the rotator cuff muscle from different directions to simulate the maximum contraction force in three directions. According to our previous study [18], the function direction of the supraspinatus muscle was 172° clockwise to the Y-axis, the function direction of the subscapularis was 122 degrees clockwise to the Y-axis, and the function direction of the infraspinatus and teres minor muscles was 129° clockwise to the Y-axis. Coupling elements were used to connect the three groups of muscles at the midpoint between the end of the humerus and the shoulder blade, with loading force applied to the midpoint. The maximum displacement, maximum Von Mises stress, displacement and stress distribution diagram of the three methods of fracture internal fixation were obtained and compared.

Results

Comparisons of maximum displacements of the three internal fixation models

Figure 4 shows the maximum displacement of the three models of internal fracture fixation. The maximum displacements of 0°, 30°, 60° and 90° of the shoulder abduction model with a locking plate were 7.692, 8.642, 7.316 and 3.536 mm, respectively; the maximum displacements of screws were 7.769, 8.717, 7.404 and 3.536 mm, respectively, and the maximum displacements of the tension band were 4.947, 6.346, 6.048 and 3.118 mm, respectively. In the process of shoulder abduction, with traction of the rotator cuff muscle, maximum displacement of the new humeral greater tuberosity locking plate was close to that of the screw. The differences of maximal displacement between tension band fixation and the other two types of internal fixation in fixing shoulder abduction of 0°, 30° and 60° were significant.

Comparisons of maximum Von Mises stress of the three models of internal fixation

The maximum Von Mises stress of the three models of internal fixation shown in **Figure 5** demonstrated that, at shoulder abduction of 0°, 30°, 60° and 90°, the maximum Von Mises stresses were 298.9, 291.1, 282.5 and 247.8 MPa, respectively for the locking plate, and 568.4, 886.3, 817.0 and 593.4 MPa for the tension band. In the process of shoulder abduction, the stress in the greater tuberosity locking plate model is concentrated in the posterolateral side and disperses along the screw. The stress in the tension band model is concentrated at the mid-point of the “8”, leading to concentrated stress and insignificant stress dispersion due to the small contact area. The contact area in the screw fixation model is also small, leading to concentrated stress and insignificant stress dispersion.

Von Mises stress comparison of the three models of internal fracture fixation

As shown in **Figure 6**, based on the maximum Von Mises stress of the three fracture fixation models as illustrated by the different angles of abduction at different shoulder joints demonstrated in **Figure 4**, the overall stress of the tension band is most significantly concentrated, with slow dispersion of stress, followed by screw fixation. Locking plate fixation of the greater tuberosity could also achieve homogeneous stress distribution at the proximal humeral surface, with dispersed stress distribution, which is consistent with the normal physiological characteristics of the human body. Therefore, all three types of internal fixation for fracture of the greater tuberosity of the humerus can stabilize the fracture, but the stress is concentrated in the tension band and screw models. The new locking plate model showed a significant mechanical advantage, making it more suitable for fracture fixation of the humeral greater tuberosity.

Discussion

Even a slight displacement of the greater tuberosity of the humerus can lead to acromion impingement [19]. Meanwhile, delayed healing, malunion and even nonunion of greater tuberosity fracture of the humerus will eventually

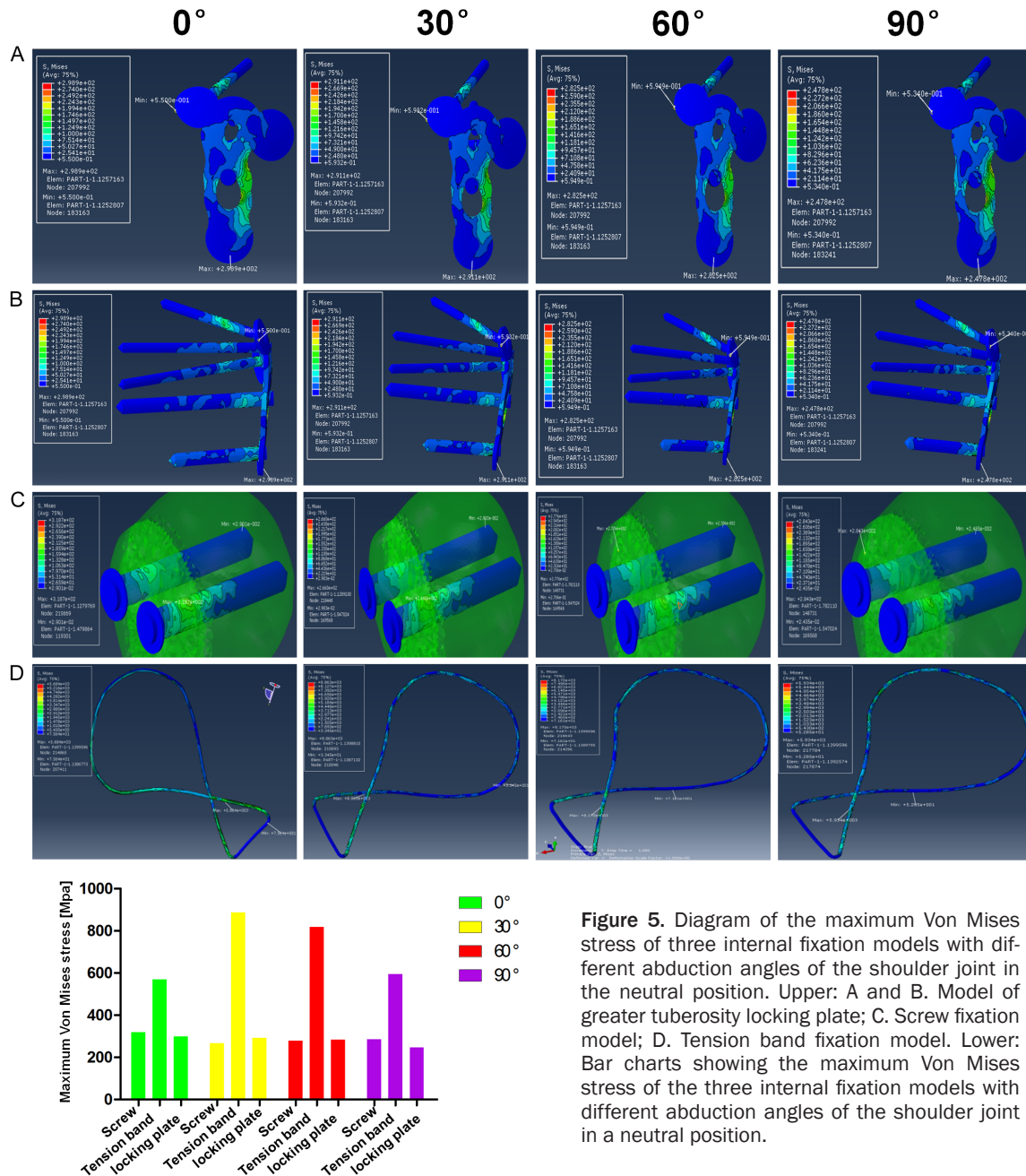
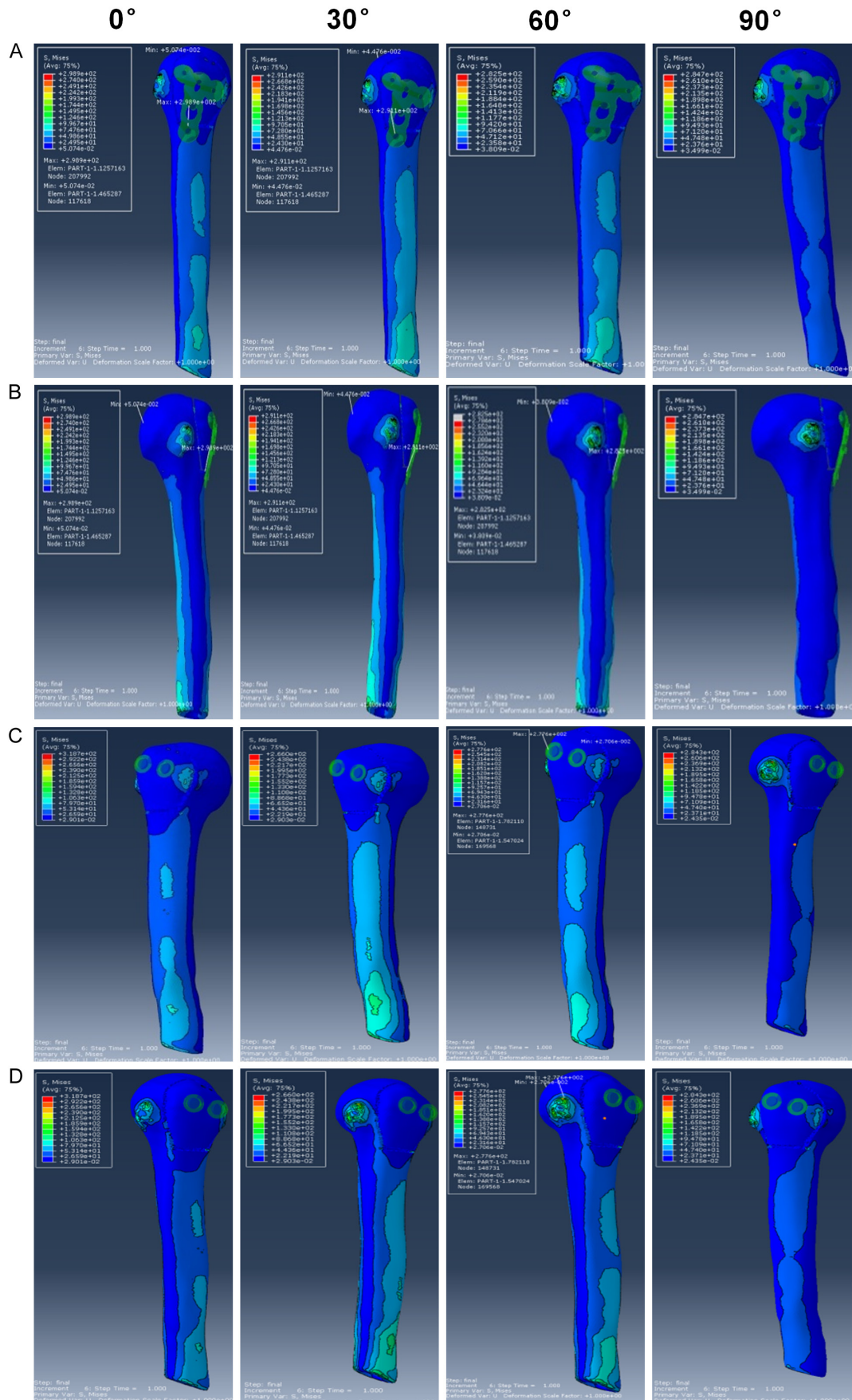


Figure 5. Diagram of the maximum Von Mises stress of three internal fixation models with different abduction angles of the shoulder joint in the neutral position. Upper: A and B. Model of greater tuberosity locking plate; C. Screw fixation model; D. Tension band fixation model. Lower: Bar charts showing the maximum Von Mises stress of the three internal fixation models with different abduction angles of the shoulder joint in a neutral position.

impair rotator cuff function, resulting in complications such as limited shoulder movement and pain, and eventually leading to shoulder dysfunction [20]. Although it has been reported that proximal humeral locking plate fixation for the treatment of greater tuberosity fractures of the humerus can achieve accurate anatomical reduction and good function [21], the midleg X-shape locking plate used in our study for fixation of the greater tuberosity of the humerus also obtained the same excellent clinical results

[22]. Recently, Bogdan et al. [23] reported a mesh locking plate treatment of 10 cases of humeral greater tuberosity fracture, with 8-month follow-up, in which all fractures were healed with good shoulder joint function. However, steel plates specifically designed for fixation of greater tuberosity fractures of the humerus have not yet been developed for clinical use. We previously [13] determined the location of the anterior humeral circumflex artery and axillary nerve based on bony land-

Finite element model for humeral greater tuberosity fracture



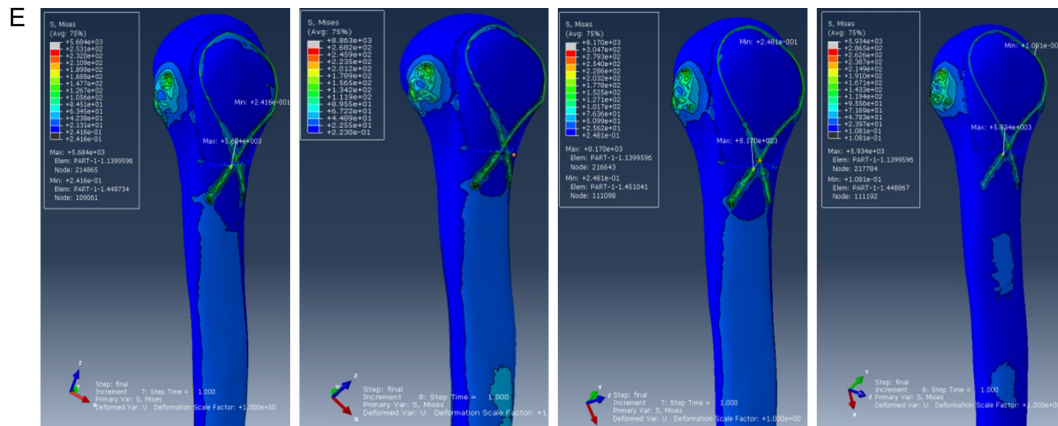


Figure 6. Von Mises stress diagram of the three internal fixation models with different abduction angles of the shoulder joint in the neutral position. A and B. Locking plate model of the greater tuberosity of the humerus; C and D. Screw fixation model; E. Tension band fixation model.

marks, and provided anatomical information to enable a safe approach when treating a proximal humeral fracture. We then developed a greater tuberosity of the humerus locking plate based on these anatomical characteristics [8]. To further improve the design of the steel plate, it is necessary to further test and verify the locking plate for the greater tuberosity of the humerus.

Finite element analysis shows that in the process of shoulder joint abduction in a neutral position from four different angles, stress exerted on the new locking plate and screw with loading is smaller than the yield strength of titanium alloy which is 931 MPa [24]. By contrast, the maximum stress of a tension band is far greater than 259 MPa, the yield strength of the material, and thus could easily lead to failure of internal fixation. Moreover, the fracture fragments stress in the tension band fixation model is relatively concentrated, with insignificant stress dispersion and transmission, and this may increase the risk of re-fracture. The entire fixation area of a screw is smaller, with more significant stress concentrations, and the stress dispersion and transmission is also relatively significant. The new locking plate fixation method for fracture of the greater tuberosity of the humerus has significant biomechanical advantages of stress dispersion and transmission. The biomechanical study by Gaudelli et al. [25] is consistent with the results of our finite element analysis. Using a pig greater tuberosity fracture model, they found that, compared with fixation using a tension band and double Bianca screw, fixation of a dis-

placed greater tuberosity fracture of the humerus using a locking plate (trimmed and shaped from a calcaneus locking plate) provided the strongest and stiffest biomechanical fixation. Our biomechanical tests based on human cadaveric humeral tuberosity fracture models are also consistent with the current study. The results showed that compared with screw and tension band fixation, the maximum force required for 5 mm displacement of locking plate fixation is the greatest, making it the failure loading force [8].

According to the results of our finite element model analysis, the stress distribution when using the designed locking plate in fracture fixation of the greater tuberosity of the humerus is relatively homogeneous, with significantly dispersed stress transmission. Due to its small size and locking design, compared with other types of steel plate for fixation of the greater tubercle of the humerus fracture [1, 23, 26], the locking plate we designed is shaped according to the local anatomical structure of the greater tuberosity, and thus could achieve less soft tissue dissection and interference, protecting the blood supply to the fracture area. In addition, in cases of comminuted fracture of the greater tuberosity of the humerus or osteoporosis, the locking plate has advantages such as providing a stable angle design and suture fixation hole (Figure 1), which make it more suitable for clinical use.

However, there are some limitations in this study. Any digital model is a simulation of the real situation. In the process of shoulder joint

activity, the greater tuberosity is exposed to various forces. The current study only involved finite element analysis of the loading force of the greater tuberosity of the humerus during abduction of the shoulder joint in a neutral position. Secondly, this study did not include all surrounding soft tissues and adjacent anatomic structures in the finite element analysis, and thus cannot completely simulate the complex stress environment of the bone under physiological conditions, but can only take into account the effect of the rotator cuff muscle on the greater tuberosity, without the humerus, soft tissue attachment and other muscle groups. Therefore, there are still some gaps compared with the actual physiological state.

In summary, the locking plate of the greater tuberosity of the humerus demonstrates homogeneous stress distribution and faster dispersion, which is closer to the physiological state, and also demonstrates higher biomechanical stability compared with fixation using screws or a tension band. Further clinical trials are recommended to validate these findings.

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Disclosure of conflict of interest

None.

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