

CLINICAL ARTICLE

Finite Element Analysis of Elbow Joint Stability by Different Flexion Angles of the Annular Ligament

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Objective: The injury of the annular ligament can change the stress distribution and affect the stability of the elbow joint, but its biomechanical mechanism is unclear. The present study investigated the biomechanical effects of different flexion angles of the annular ligament on elbow joint stability.

Methods: A cartilage and ligament model was constructed using SolidWorks software according to the magnetic resonance imaging results to simulate the annular ligament during normal, loosened, and ruptured conditions at different buckling angles (0°, 30°, 60°, 90°, and 120°). The fixed muscle strengths were 40 N (F1), 20 N (F2), 20 N (F3), 20 N (F4), and 20 N (F5) for the triceps, biceps, and brachial tendons and the base of the medial collateral ligament and lateral collateral ligament. The different elbow three-dimensional (3D) finite element models were imported into ABAQUS software to calculate and analyze the load, contact area, contact stress, and stress of the medial collateral ligament of the olecranon cartilage.

Results: The results showed that the stress value of olecranon cartilage increased under different conditions (normal, loosened, and ruptured annular ligament) with elbow extension, and the maximum stress value of olecranon cartilage was 2.91 ± 0.24 MPa when the annular ligament was ruptured. The maximum contact area of olecranon cartilage was 254 mm² with normal annular ligament when the elbow joint was flexed to 30°, while the maximum contact area of loosened and ruptured annular ligament was 283 and 312 mm² at 60° of elbow flexion, and then decreased gradually. The maximum stress of the medial collateral ligament was 6.52 ± 0.23 , 11.51 ± 0.78 , and 18.74 ± 0.94 MPa under the different conditions, respectively.

Conclusion: When the annular ligament ruptures, it should be reconstructed as much as possible to avoid the elevation of stress on the surface of the medial collateral ligament of the elbow and the annular cartilage, which may cause clinical symptoms.

Key words: annular ligament; contact stress; elbow joint; finite element analysis; olecranon cartilage

Introduction

The elbow is a complex joint, and its stability plays an important role in maintaining daily activities. Elbow instability is caused by damage to the bone joint surface and the ligament structure of the elbow joint. It is a common disease secondary to acute fracture dislocation and chronic exercise strain^{1,2}. Elbow dysfunction is often accompanied by

ligament damage, which results in elbow instability. The medial collateral, lateral collateral, and annular ligaments maintain the stability of the elbow³⁻⁵. Frangiamore *et al.*³ found that the ulnar collateral ligament was the primary stabilizer of valgus stress in the elbow and provided a clear understanding of the anatomical relationships of the static and dynamic stabilizers of the elbow. Wang *et al.*⁴ demonstrated that surgical

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reattachment of the lateral collateral ligament (LCL) complex to the lateral epicondyle was helpful for elbow stability using relevant biomechanical studies. Anderson *et al.*⁵ demonstrated the role of the annular ligament in providing proximal radial head stability based on knowledge of forearm biomechanics. The annular ligament is vulnerable to injury in cases of elbow dislocation or fracture, such as Monteggia's fracture, radial head fracture, and radial head dislocation, especially in severe cases. There is great controversy surrounding the treatment of the annular ligament. Some scholars believe that the elbow joint functions well without annular ligament repair⁶⁻⁸. Chen *et al.*⁶ concluded that patients maintained elbow stability using a surgical strategy to reduce the radial head without annular ligament reconstruction for neglected radial head dislocation following Monteggia fracture dislocation. Han *et al.*⁸ found that annular ligament repair was not essential in the operative treatment of isolated radial head fractures when the lateral collateral ligament was intact. Other scholars believe that annular ligament repair makes the elbow joint more stable and reduces the pain and injury caused by elbow joint instability in later periods⁹⁻¹³. Bhaskar¹⁰ found that the need for annular ligament reconstruction was based on intraoperative findings of radial head instability for missed Monteggia fractures. Nwoko *et al.*¹¹ showed that incompetence of the annular ligament caused persistent instability of the proximal radius requiring ligament reconstruction. Therefore, further understanding of the role of the annular ligament in elbow joint stability is particularly important. Most biomechanical studies focused on the influence of elbow joint dislocation, deformity, and fracture on elbow joint stability, but the role of the annular ligament in maintaining elbow joint stability has been ignored, and there are few studies on the biomechanics of the annular ligament¹⁴. Tan *et al.*¹⁴ constructed a finite element analysis (FEA) model of the ulna and radius with the annular ligament to simulate Monteggia fracture and explain the annular ligament pathology. Therefore, a considerable number of patients do not receive effective and timely

treatment, and the late elbow joint instability that occurs due to the annular ligament injury is not given sufficient attention.

The present study intends to establish finite element models of elbow bone, medial and lateral collateral ligaments, and annular ligaments through CT and magnetic resonance imaging (MRI) images of elbow joint to simulate the mechanical effects of different states of annular ligaments (normal, loosened, and ruptured) on elbow joint tissues in the process of flexion, and to analyze the stress distribution among different tissues.

Materials and Methods

3D Elbow Joint Model Establishment

The ethics committee of the local institution approved this study, and all protocols were performed in accordance with relevant guidelines and regulations. Written informed consent was obtained from the participants. This model was validated in our previous research¹⁵. The surface grid editing tool in Geomagic 2013 software was used to analyze the 3D models of each part of the elbow. Necessary editing and modifications were made to the 3D model reconstructed from MRI scan data to make the model smoother and more compliant. A high-quality surface model was achieved. Closed-space non-uniform rational B-spline (NURBS) was simulated and exported in step format. 3D soft-tissue surface models based on two different modal data sets were registered for alignment in SolidWorks 2012 software. The positions of the medial collateral ligament (MCL), LCL, annular ligaments, and other 3D models reconstructed from the MRI scan data were converted to the CT scan data space, and the MCL and LCL, annular ligaments, articular surface cartilage, and other tissues were constructed using the direct modeling method. The model was imported into ABAQUS, and the ranges of bones, ligaments, and cartilage were defined differently based on the difference between the surface definition

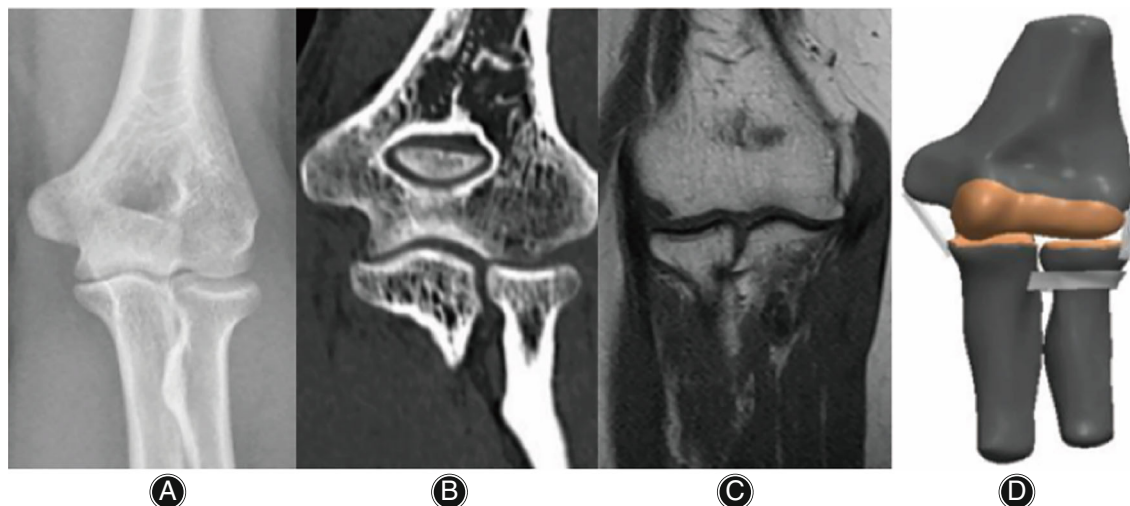


Fig. 1 (A) X-ray image of elbow; (B) CT image of elbow; (C) MRI image of elbow; (D) Finite element model of elbow joint

TABLE 1 Mechanical properties of materials

Material name	Young's modulus (MPa)	Poisson's ratio
Cortical bone	18,000	0.3
Cancellous bone	400	0.26
Ligament	366	0.499
Cartilage	1000	0.07

and the internal definition. The material parameters and attributes were assigned appropriately. The finite element mesh was divided into the model, and the finite element model was established, as shown in Figure 1. All of the structures were simulated using tetrahedral elements. The modeling period was greatly shortened by simplifying the bone tissue and articular surface cartilage in the model to homogeneous and isotropic elastomer material. To better reflect the biomechanical response of ligaments, ligaments were defined as linear elastic materials and used 3D solid elements according to relevant literature¹⁶. The material parameters are shown in Table 1.

Boundary and Loading Conditions

According to the previous literature^{16,17}, the interaction between the cartilage surfaces was simulated using the penalty function method with implementation of "surface-to-surface contact." The cartilage thickness was assumed to be a constant 1 mm on all surfaces. The contact between cartilage and subchondral bone was also modeled. The coefficient of friction between the contact pairs was set to $\mu = 0.1$. The contact area between the cartilage surface of the distal humerus and the olecranon was calculated in this paper. The MCL, LCL, and annular ligaments of the elbow joint played an important role in maintaining stability during joint movement, which made the model closer to SolidWorks. The two ends of each major ligament and its anatomical attachment point were set as the common node contact connection. The internal surface of the articular cartilage was set to be fixed with the surface of bone tissue. Mechanical analysis was performed according to previous literature¹⁶. Mechanical values were assigned to ligaments, bones, and cartilage to simulate natural flexion of the elbow joint. The values and positions of these loads were selected in accordance with previously published studies. The fixed muscle strengths were 40 N (F1), 20 N (F2), 20 N (F3), 20 N (F4), and 20 N (F5) for the triceps, biceps, and brachial tendons and the base of the MCL and LCL, respectively (see Figure 2 below).

Constructed Different Condition Models

To meet the needs of the stress-strain state study, normal, loosened, and ruptured models of the annular ligament were established. According to the anatomical structure and previous literature¹⁷, the normal MCL, LCL, and annular ligament were established using computer-aided design (CAD)

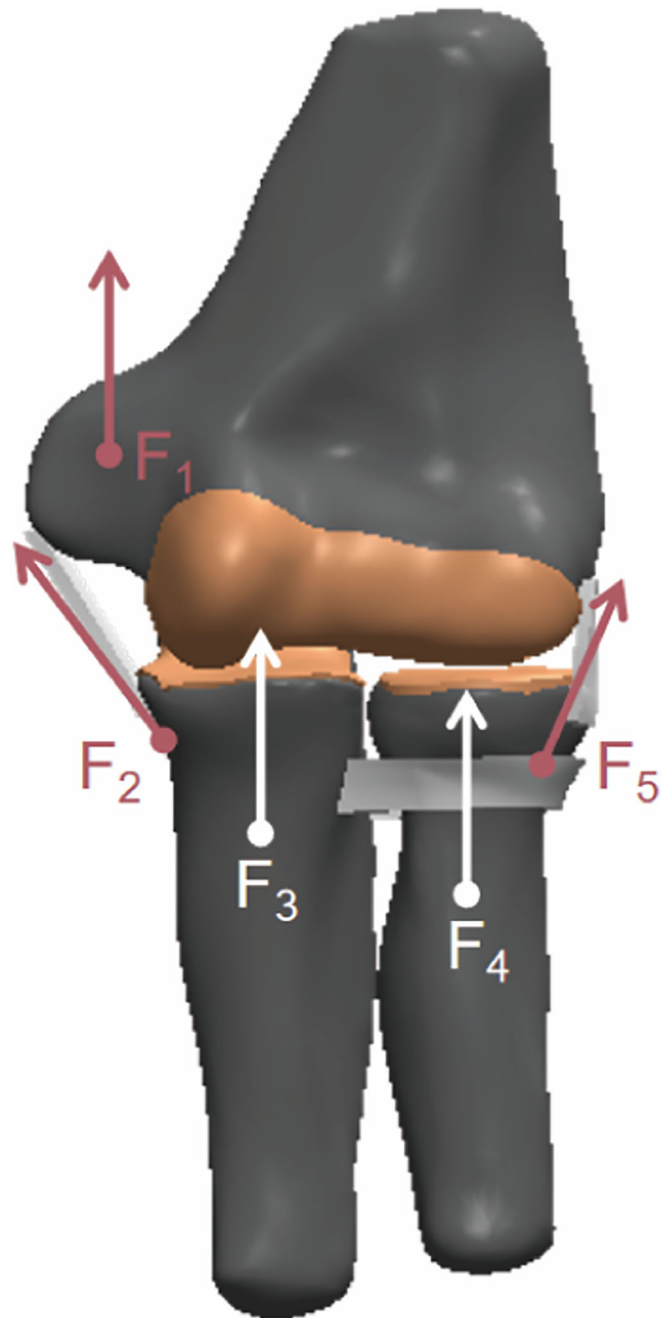


Fig. 2 Loads condition are applied to the elbow model

modeling. The contact area between the annular ligament and the proximal radius was moved 2 mm outward in the loosened annular ligament model; otherwise, it was unchanged. The ruptured annular ligament model was constructed by removing the annular ligament. The geometric models were simulated from 0° to 120° of flexion, with a 30° at intervals, and the position of the humerus was assumed to remain unchanged during flexion and extension of the elbow joint¹⁶.

Grid Convergence

To verify the sufficiency of the mesh, we tested the convergence of the mesh in the elbow joint model. Mesh sizes with different buckling angles were set as 0.5, 1.0, 1.5, and 2.0 mm, as shown in Figure 3. The boundary and loading conditions are shown in Figure 2. To evaluate the predictive capacity of the finite element (FE) models, a few criteria were used, including the multiple correlation coefficients (R^2), the root mean squared error (RMSE), and the mean absolute error (MAE)¹⁸. \hat{R}^2 is a measure of the variation around the mean that the regression model produced, and RMSE and MAE are methods that attempt to determine the relationships between input variables and one or more response variables. The criteria were defined as follows.

$$\text{MAE} = \frac{\sum_{i=1}^n |y_i - x_i|}{n} \quad (1)$$

$$\text{RMSE} = \sqrt{\frac{1}{n} \sum_{k=1}^n |y_i - x_i|^2} \quad (2)$$

$$\text{SS}_{\text{res}} = \sum_i (x_i - y_i)^2 = \sum_i e_i^2 \quad (3)$$

$$\text{SS}_{\text{tot}} = \sum_{i=1} (x_i - \bar{x})^2 \quad (4)$$

$$R^2 = 1 - \frac{\text{SS}_{\text{res}}}{\text{SS}_{\text{tot}}} \quad (5)$$

where y_i are the predicted values obtained from the finite element model, x_i are actual values, and n is the number of data points that were analyzed, as shown in Equations (1) and (2). e_i are the residual sum, and SS_{res} and SS_{tot} are called the residual sum of squares and total sum of squares, respectively, as shown in Equations (3–5). To compare the various errors in predicting outputs in this case, MAE, RMSE, and R^2 were calculated from the normalized data (0–1).

A mesh quality assessment in ABAQUS showed that 0.94% of the elements had an aspect ratio of less than 5.0 (maximum 10.0), and 96% and 97% of all shell and solid elements had Jacobian values larger than 0.6 (minimum 0.24).

Observational Factors

The loading conditions and boundary conditions were the same in the 15 elbow joint models. The mean and standard deviation of the contact stress in the olecranon cartilage, the contact area of olecranon cartilage, and the medial collateral ligament were calculated.

Results**Grid Convergence**

The maximum contact stress value of the olecranon cartilage surface was calculated and compared, as shown in Table 2. When the 0.5 mm mesh was compared with the 1.0 mm mesh, the resulting values of MAE and RMSE were 0.096 and 0.098, respectively. The resulting values of MAE and

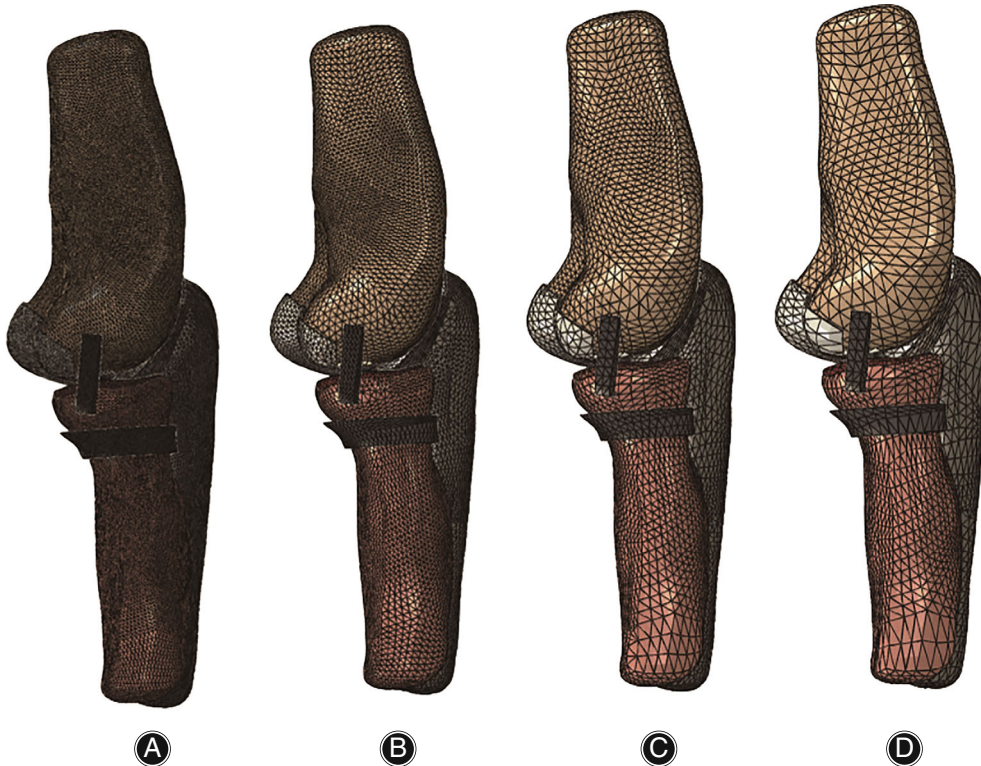


Fig. 3 Model of Grid convergence test; (A) Mesh sizes was set as 0.5 mm; (B) Mesh sizes were set as 1.0 mm; (C) Mesh sizes were set as 1.5 mm; (D) Mesh sizes were set as 2.0 mm

TABLE 2 Mesh sizes with different buckling angles were set as 0.5, 1.0, 1.5, and 2.0 mm

Angles (°)	Sizes (mm)			
	0.5	1.0	1.5	2.0
0	2.06	2.12	2.55	2.73
30	1.53	1.65	2.02	2.39
60	1.45	1.36	1.75	1.95
90	1.11	1.23	1.61	1.79
120	1.01	0.92	1.41	1.58

RMSE were 0.412 and 0.414 in the comparison of the 1.5 mm mesh and the 1.0 mm mesh, respectively. Between the 2.0 mm mesh and the 1.0 mm mesh, the resulting values of MAE and RMSE were 0.632 and 0.710, respectively. These results showed that the comparison of the 0.5 mm mesh and the 1.0 mm mesh was minor (the maximum MAE was approximately 10%). These results indicated that the 1.0 mm mesh possessed a good predictive capacity.

Validation of the Finite Element Model

The contact area of the olecranon cartilage was simulated and extracted, as shown in Table 3.

The resulting values of R^2 (0.973) were close to 1, which indicated that these models had good predictive capacity. Relative to the experimental and FE values, the MAE (4.800) and RMSE (4.939) values were minor, which indicated that the present FE model possessed good predictive capacity.

The elbow joint was flexed at 0,30,60,90 and 120 degrees and subjected to the corresponding load. The stress values of the olecranon cartilage surface are shown in Fig. 4 and 5. The values of olecranon cartilage surface contact stress when the annular ligament was under different conditions (normal, loosened, and ruptured) with elbow extension were 2.13 ± 0.18 , 2.41 ± 0.35 , 2.91 ± 0.24 MPa, respectively. The stress value decreased as the angle increased. With 120 degrees of elbow flexion, the minimum stress values were 0.92 ± 0.12 , 1.15 ± 0.38 and 1.23 ± 0.29 MPa under normal, loosened and ruptured, respectively. This result suggests that the annular ligament plays a role in maintaining elbow stability. The radial head is prone to instability in cases of annular ligament rupture, which led to increased ulnar pressure and overload.

The contact area of the olecranon cartilage significantly increased and reached a maximum value of 254 mm² in Figure 6 when the contact surface of the olecranon was flexed

TABLE 3 Changes in the contact area (mm²) of the olecranon cartilage based on elbow flexion angles (°) and the constant muscle strength values

Strength values	0°	30°	60°	90°	120°
Experimental data	198	248	227	202	178
FE model data	204	254	224	199	174

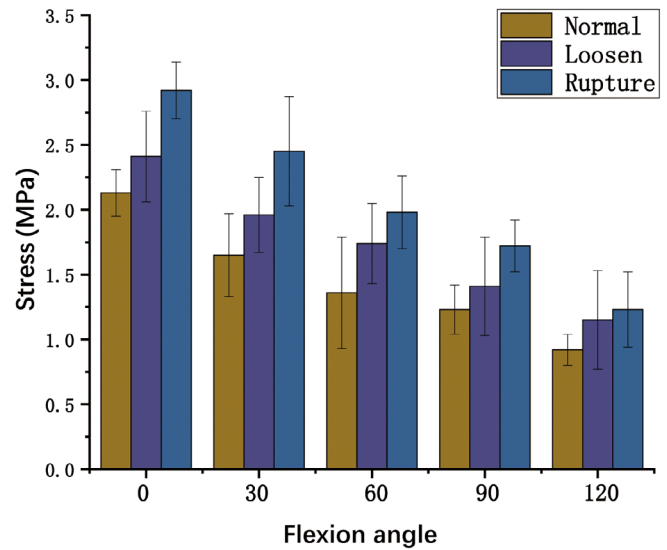


Fig. 4 Different stress values of the olecranon cartilage surface when the annular ligament was under different conditions (normal, loosened, ruptured) as the buckling angle increased

from 0 to 30 degrees. The results when the annular ligament was loosened and ruptured were different from the normal annular ligament. The maximum values for loosened and ruptured were reached at 60° of elbow flexion and were 283 and 312 mm², respectively. The contact area gradually decreased as the angle increased. These results showed that the contact area of the olecranon reached a maximum value when the annular ligament was completely ruptured. This result occurred because movement of the radial head led to stress migration after annular ligament fracture, and the load was transferred through the olecranon, which led to

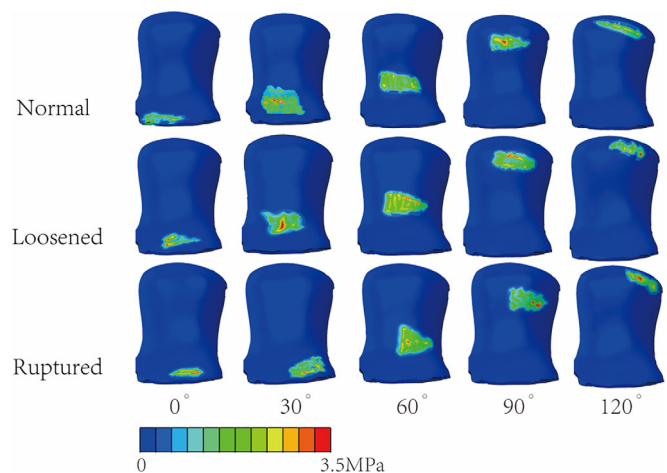


Fig. 5 Different stress values of the olecranon cartilage surface when the annular ligament was under different conditions (normal, loosened, ruptured) as the buckling angle increased (Nephogram)

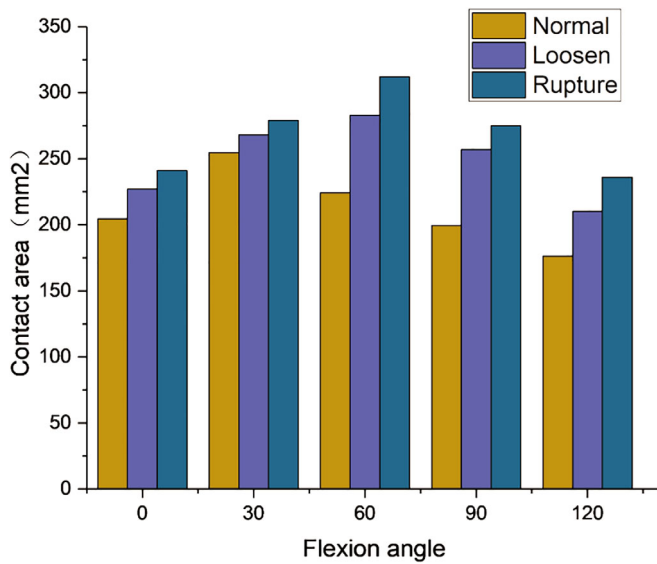


Fig. 6 Different contact surface values of olecranon cartilage when the annular ligament was under different conditions (normal, loosened, ruptured) as the buckling angle increased

overload. This result also suggests that the radial head plays an important role in maintaining elbow stability.

The changes in the stress value of the medial collateral ligament with the changes in the angle of the elbow joint are shown in Figure 7. Because the medial collateral ligament is under a tensed condition in elbow extension and the annular ligament is under a different condition, the maximum stress values were 6.52 ± 0.23 , 11.51 ± 0.78 and 18.74 ± 0.94 MPa

under normal, loosened, and ruptured conditions, respectively. The ligament state changed from tension to relaxation with the increase in the angle, and there was a decline in the different degrees of stress. The different states of the annular ligament corresponded to stress values of 2.81 ± 0.18 , 4.83 ± 0.56 and 6.22 ± 0.72 MPa, respectively, at 120° of elbow flexion. As shown in Figure 7, stress significantly increased with annular ligament relaxation or fracture, and the medial ligament and extended annular ligament rupture. The maximum value was 26.42 MPa. Ligament stress and ultimate tensile strength were relatively unclear, but a long period of stress may occur in clinical pain and other clinical symptoms.

Discussion

In this study, the bone, articular cartilage, and lateral collateral ligament were constructed by the elbow CT and MRI images, and the finite element model was established to simulate the biomechanics of annular ligament injury and analyze the stability of the elbow joint after annular ligament injury. Based on the above results, we found that the stress of cartilage and collateral ligament increased significantly after annular ligament injury, which had a significant impact on the stability of elbow joint.

Advantages of the FE Method at the Annular Ligament

The densely packed parallel fiber arrangement and few elastic fibers of the AUCL, RCL, and AL indicate a strong biomechanically stabilizing function¹⁹. Hayami *et al.*²⁰ performed biomechanical studies on the rupture and reconstruction of the annular ligament in five cadavers and found that anatomical reconstruction of the annular ligament provided

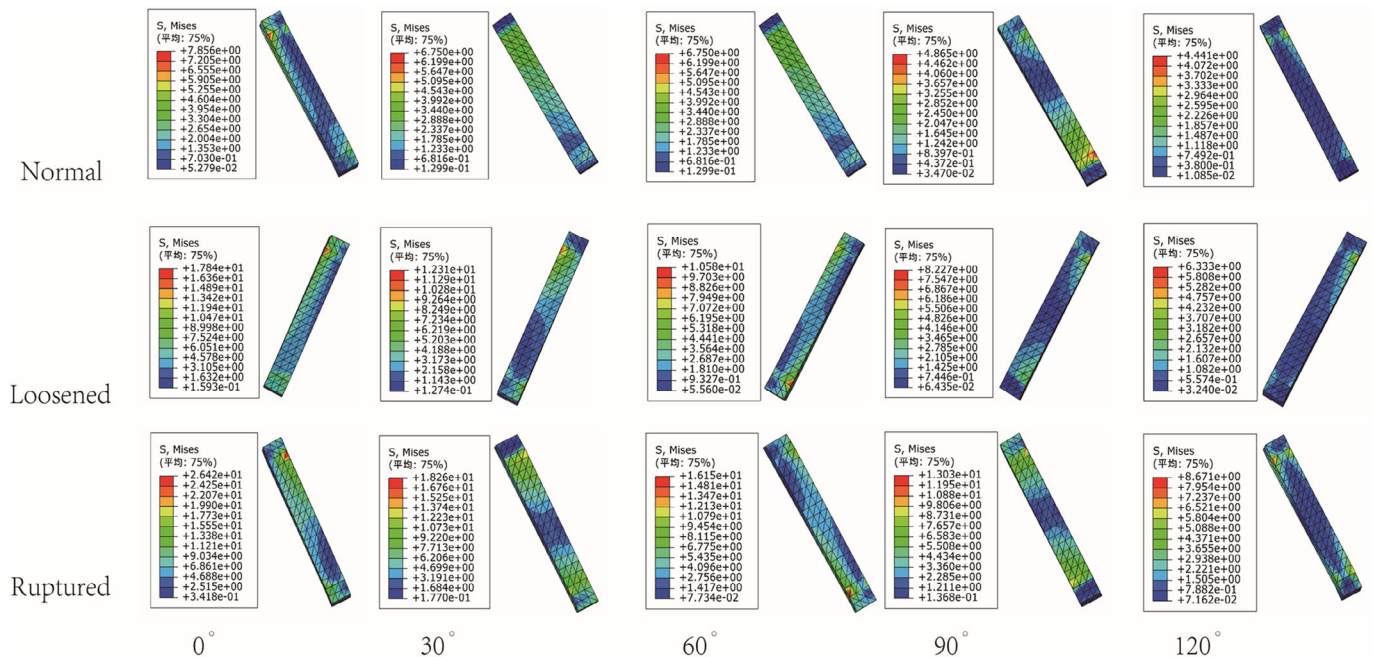


Fig. 7 Stress distribution of the MCL. (A) The annular ligament under normal condition; (B) The annular ligament under loosened condition; (C) The annular ligament under ruptured condition

multidirectional stability to the radial head. However, due to the individual differences of cadavers, it is difficult to obtain the uniformity and diversity of samples through cadaver biomechanical experiments with the loosened and ruptured annular ligaments. The repeatability of finite element analysis is one of the common mechanical analysis methods.

Previous studies primarily focused on the ulna, radial head, cartilage, and collateral ligament^{21–23}, and few biomechanical studies were performed on elbow instability caused by annular ligament injury. There are no reports on the effects of annular ligament fracture on the annular ligament and cartilage using FEA. The FE method effectively simulates and analyzes models under different conditions for the mechanical analysis of problems that cannot be solved using traditional biomechanics or in cases where the structure is complex or a biological experiment cannot be performed^{24,25}.

Role of the Annular Ligament in Maintaining Elbow Stability

The present study established a 3D elbow finite element model that included the humerus, ulna, radius, articular cartilage, MCL, and other relevant structures and a buckling process simulation model to study the effects of different states of the annular ligament and other anatomical parameters. The variation trends of stress and strain on the cartilage surface of the MCL and LCL with different flexion angles of the olecranon were analyzed. The results showed that the stability of the radial head was damaged, with annular ligament rupture, and dislocation was more likely to occur, which resulted in poor contact of the ulnar and radial joints and stability damage and led to an increase in the maximum contact stress of the articular cartilage of the olecranon. When the annular ligament ruptured in an extended position, the maximum stress of the articular surface of the olecranon was up to 2.91 ± 0.24 MPa. According to previous literature results²⁶, the cartilage matrix may be damaged when stress reaches 3–5 MPa. Compared to the results of this study, the olecranon cartilage surface was more prone to cartilage damage. Sandman *et al.*²⁷ used biomechanical studies and showed that reconstruction of the anatomical structure between bones alone was not sufficient to maintain the corresponding relationship of the ulnar and radial joints, and reconstruction of the annular ligament was of great significance for the long-term stability of the ulnar and radial joints, which effectively reduced the instability of the elbow joint and the excessive stress on the ulna. Hayami *et al.*²⁰ found that anatomical reconstruction of the annular ligament provided multidirectional stability of the radial head. Radial head instability likely resulted when the annular ligament was fractured, which led to a significant increase in the probability of radial head dislocation.

Role of the MCL to the Elbow

The annular ligament is a strong fibrous band around the radial head that contacts the radial notch of the ulna. Lapner

*et al.*²⁸ found that the annular ligament was an important component of the proximal radial joint, the radial humeral joint, and adjacent muscles and ligaments. When the annular ligament was loosened, the stress of the medial collateral ligament increased, and the maximum stress value was 18.74 ± 0.94 MPa when the annular ligament was ruptured. The table shows that elbow joint instability significantly increases at this time, which indicates that the MCL plays an important role in maintaining elbow joint stability, similar to a previous study.

Morrey *et al.* demonstrated that the MCL played a crucial role in elbow joint stability. Rahman *et al.*²⁹ studied the effect of different degrees of MCL deficiency on elbow joint stability using biomechanics, which led to elbow joint instability when the medial collateral ligament was completely removed. Seiber *et al.*³⁰ showed that the anterior fasciculus varus of the elbow joint had more than twice the effect on stability compared to the LCL in cadaver studies. The medial muscle tissue of the elbow joint primarily affected elbow joint stability, which emphasizes its role as a secondary stabilizer and is consistent with our results.

Simple annular ligament rupture is relatively rare clinically. It is generally caused by trauma and often accompanied by fracture and dislocation. It is more common in Montsillar fractures and radial head dislocation. Whether the annular ligament should be repaired remains controversial. Chen *et al.* and Kawoosa *et al.*^{6,7} concluded that reducing the radial height effectively achieved reduction without open reduction, and annular ligament reconstruction restored elbow function and improved elbow pain and stability. Canton *et al.*³¹ indicated that annular ligament rupture affected elbow joint biomechanics and resulted in radial head dislocation. Previous studies indicated the importance of anatomical reconstruction of the annular ligament, which indicates that the annular ligament plays a crucial role in radial head stability. Previous research results showed that annular ligament loosening or rupture had a great impact on elbow joint stability, which significantly increased the stress of the medial collateral ligament and led to pain and other symptoms in later stages. Due to the increased stress on the annular cartilage surface, osteoarthritis may occur in severe cases. Therefore, the integrity of the annular ligament plays an important role in elbow joint stability.

Limitations

There are other limitations in this study. First, it is necessary to further simulate the joint capsule, muscle, skin, and other tissues, and the model is limited to flexion. Second, when the finite element model of the elbow joint was established, the bone, soft tissues, and ligaments were assumed to be isotropic linear elastic materials, which has certain limitations in terms of physiological conditions. Third, the model simulates only the static mechanics of the elbow joint at different flexion angles, and the dynamic flexion of the elbow joint is not reflected.

Conclusion

The present study established a successful 3D FE model of the normal structures of the elbow joint and included the MCL, LCL, annular ligament, and cartilage surface. Data analysis revealed that annular ligament loosening or rupture led to an increase in lateral collateral ligament and ulna olecranon articular cartilage surface stress, which demonstrates that the annular ligament plays an important role in maintaining elbow joint stability. The annular ligament should be reconstructed upon rupture as much as possible to avoid the elevation of surface stress on the MCL of the elbow and the annular surface cartilage, which may cause clinical symptoms.

Acknowledgements

None.

Authors Contributions

Guangming Xu built the finite element model and was responsible for the data acquisition. Wenzhao Chen revised the manuscript of the article. Zhengzhong Yang and

Jiyong Yang were responsible for the statistical analysis part. Ziyang Liang and Wei Li conceived and designed the study. Each author has participated sufficiently in the work to take public responsibility for appropriate portions of the content.

Conflict of Interest

The authors declare that they have no conflict of interest.

Consent for Publication

Not applicable.

Ethics Approval

This study was approved by the ethics community of Shenzhen Pingle Orthopaedic Hospital. The proper informed consent was obtained before the experiment.

Data Availability Statement

The datasets used and analyzed during the current study are available from the corresponding author on reasonable request.

References

- Edelman D, Ilyas AM. Temporary bridge plate stabilization of unstable elbow fractures and dislocations. *Tech Hand Up Extrem Surg.* 2018;22:46–50.
- Heijink A, Vanhees M, van den Ende K, van den Bekerom MP, van Riet RP, van Dijk CN, et al. Biomechanical considerations in the pathogenesis of osteoarthritis of the elbow. *Knee Surg Sports Traumatol Arthrosc.* 2016;24:2313–8.
- Frangiamore SJ, Moatshe G, Kruckeberg BM, Civitaresse DM, Muckenhirn KJ, Chahla J, et al. Qualitative and quantitative analyses of the dynamic and static stabilizers of the medial elbow: an anatomic study. *Am J Sports Med.* 2018;46:687–94.
- Wang Y-x, Huang L-x, Ma S-h. Surgical treatment of “terrible triad of the elbow”: technique and outcome. *Orthop Surg.* 2010;2:141–8.
- Anderson A, Werner FW, Tucci ER, Harley BJ. Role of the interosseous membrane and annular ligament in stabilizing the proximal radial head. *J Shoulder Elb Surg.* 2015;24:1926–33.
- Chen H-Y, Wu K-E, Dong Z-R, Huang S-C, Kuo KN, Wang T-M. The treatment of chronic radial head dislocation in Monteggia fracture without annular ligament reconstruction. *Int Orthop.* 2018;42:2165–72.
- Kawoosa AA, Dhar SA, Butt MF, Wani SA, Mir MR, Dar TA. Stable relocation of the radial head without annular ligament reconstruction using the Ilizarov technique to treat neglected Monteggia fracture: two case reports. *J Med Case Rep.* 2010;4:344–9.
- Han SH, Lee SC, Ryu KJ, Lee JH. Repairing the annular ligament is not necessary in the operation of Mason type 2, 3 isolated radial head fractures if the lateral collateral ligament is intact: minimum 5 years follow-up. *Injury.* 2013;44:1851–4.
- Hackl M, Wegmann K, Ries C, Lappen S, Scaal M, Müller LP. Annular ligament reconstruction with the superficial head of the brachialis: surgical technique and biomechanical evaluation. *Surg Radiol Anat.* 2017;39:585–91.
- Bhaskar A. Missed Monteggia fracture in children: is annular ligament reconstruction always required? *Indian J Orthop.* 2009;43:389–95.
- Nwoko OE, Patel PP, Richard MJ, Leversedge FJ. Annular ligament reconstruction using the distal tendon of the superficial head of the brachialis muscle: an anatomical feasibility study. *J Hand Surg Am.* 2013;38:1315–9.
- Wang MN, Chang WN. Chronic posttraumatic anterior dislocation of the radial head in children: thirteen cases treated by open reduction, ulnar osteotomy, and annular ligament reconstruction through a Boyd incision. *J Orthop Trauma.* 2006;20:1–5.
- Hatta T, Shinagawa K, Hayashi K, Hasegawa K, Miyasaka Y, Yamamoto N, et al. Ligament reconstruction for recurrent anterior dislocation of the radial head. *Case Rep Orthop.* 2019;2019:6067312.
- Tan J, Mu M, Liao G, Zhao Y, Li J. Biomechanical analysis of the annular ligament in Monteggia fractures using finite element models. *J Orthop Surg Res.* 2015;10:30–5.
- Xu GM, Liang ZY, Li W, Yang ZZ, Chen ZB, Zhang J. Finite element analysis of insertion angle of absorbable screws for the fixation of radial head fractures. *Orthop Surg.* 2020;12:1710–7.
- Strafun S, Levadnyi I, Makarov V, Awrejcewicz J. Comparative biomechanical analysis of stress-strain state of the elbow joint after displaced radial head fractures. *J Med Biol Eng.* 2018;38:618–24.
- McCartney W, MacDonald B, Ober CA, Lostado-Lorza R, Gómez FS. Pelvic modelling and the comparison between plate position for double pelvic osteotomy using artificial cancellous bone and finite element analysis. *BMC Vet Res.* 2018;14:100.
- Somovilla-Gómez F, Lostado-Lorza R, Corral-Bobadilla M, Escribano-García R. Improvement in determining the risk of damage to the human lumbar functional spinal unit considering age, height, weight and sex using a combination of FEM and RSM. *Biomech Model Mechanobiol.* 2020;19:351–87.
- Lühmann P, Kremer T, Siemers F, Rein S. Comparative histomorphological analysis of elbow ligaments and capsule. *Clin Anat.* 2022. <https://doi.org/10.1002/ca.23913>
- Hayami N, Omokawa S, Iida A, Kraisarin J, Moritomo H, Mahakkanukrauh P, et al. Biomechanical study of isolated radial head dislocation. *BMC Musculoskelet Disord.* 2017;18:470–6.
- Willing RT, Lalone EA, Shannon H, Johnson JA, King GJW. Validation of a finite element model of the human elbow for determining cartilage contact mechanics. *J Biomech.* 2013;46:1767–71.
- Matsuura Y, Takamura T, Sugiura S, Matsuyama Y, Suzuki T, Mori C, et al. Evaluation of anterior oblique ligament tension at the elbow joint angle—a cadaver study. *J Shoulder Elb Surg.* 2021;30:359–64.
- Panero E, Gastaldi L, Terzini M, Bignardi C, Sard A, Pastorelli S. Biomechanical role and motion contribution of ligaments and bony constraints in the elbow stability: a preliminary study. *Bioengineering (Basel).* 2019;6:68.
- Yan L, Lim JL, Lee JW, Tia CSH, O'Neill GK, Chong DYR. Finite element analysis of bone and implant stresses for customized 3D-printed orthopaedic implants in fracture fixation. *Med Biol Eng Comput.* 2020;58:921–31.
- Li L, Yang L, Zhang K, Zhu L, Wang X, Jiang Q. Three-dimensional finite-element analysis of aggravating medial meniscus tears on knee osteoarthritis. *J Orthop Translat.* 2020;20:47–55.
- Loening AM, James IE, Levenston ME, Badger AM, Frank EH, Kurz B, et al. Injurious mechanical compression of bovine articular cartilage induces chondrocyte apoptosis. *Arch Biochem Biophys.* 2000;381:205–12.
- Sandman E, Canet F, Petit Y, Lafamme GY, Athwal GS, Rouleau DM. Radial head subluxation after malalignment of the proximal ulna: a biomechanical study. *J Orthop Trauma.* 2014;28:464–9.
- Lapner M, Willing R, Johnson JA, King GJ. The effect of distal humeral hemiarthroplasty on articular contact of the elbow. *Clin Biomech (Bristol, Avon).* 2014;29:537–44.
- Rahman M, Cil A, Stylianou AP. Medial collateral ligament deficiency of the elbow joint: a computational approach. *Bioengineering (Basel).* 2018;5:84.
- Seiber K, Gupta R, McGarry MH, Safran MR, Lee TQ. The role of the elbow musculature, forearm rotation, and elbow flexion in elbow stability: an in vitro study. *J Shoulder Elb Surg.* 2009;18:260–8.
- Canton G, Hoxhaj B, Fattori R, Murena L. Annular ligament reconstruction in chronic Monteggia fracture-dislocations in the adult population: indications and surgical technique. *Musculoskelet Surg.* 2018;102:93–102.