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

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Research

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Finite element analysis of elbow joint stability by different flexion angles of the annular ligament

Guangming Xu[1*], Zhengzhong Yang[1], Jiyong Yang[1], Ziyang Liang[2✉], Wei Li [1✉]

Abstract

Objective: To investigate the biomechanical effects of different flexion angles of the annular ligament on elbow joint stability.

Methods: Left elbow CT and MRI scans were chosen from a healthy volunteer, according to a previous research model. A cartilage and ligament model was constructed with SolidWorks software according to the MRI results to simulate the annular ligament during normal, loosen, and rupture conditions at different buckling angles (0, 30, 60, 90, 120). In 15 elbow models, boundary conditions were set according to the literature. The different elbow 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: 1. According to the analysis results, olecranon cartilage stress values when the annular ligament under different conditions（normal、loosened、ruptured）with elbow extension, were 2.1 ± 0.18, 2.4 ± 0.75, and 2.9 ± 0.94 MPa. As the buckling angle increased, the stress value decreased; with 120 degrees of elbow flexion, the minimum stress values were 0.9 ± 0.12, 1.1 ± 0.38, and 1.2 ± 0.29 MPa. 2. When the contact surface of the olecranon cartilage was flexed from 0 to 30 degrees, the olecranon cartilage contact area significantly increased, reaching a maximum value of 254±5.35 mm, and then the contact area gradually decreased, reaching a minimum value of 176±2.62 mm when the elbow joint was flexed to 120 degrees. The results when the annular ligament was loosened and ruptured were different from those of the normal annular ligament. The maximum values were 283±4.74and 312±5.49mm at 60 degrees of elbow flexion. The contact area gradually decreased with an increase in the angle, and the minimum values were 210±3.82 and 236±6.59 mm at 120 degrees of elbow flexion. 3. When the elbow joint was extended, the maximum stress of the medial collateral ligament was 6.5±0.23, 11.5±0.78 and 18.7±0.94 MPa under different states; as the stress decreased with an increase in the angle, the corresponding values were 2.8±0.18, 4.8±0.56 and 6.2±0.72 MPa at 120 degrees of elbow flexion.

Conclusion: The annular ligament plays an important role in maintaining elbow joint stability. 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 on the annular cartilage, which may cause clinical symptoms.

Key words: Annular ligament; Elbow joint; Finite element analysis

Background

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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, resulting in elbow instability. On the medial side of the elbow, the lateral collateral ligament and the annular ligament are the basic structures that maintain the stability of the medial side of the elbow(3-5). In the case of elbow dislocation or fracture, such as Montages fracture, radial head fracture, and radial head dislocation, the annular ligament is vulnerable to injury, especially in severe cases. Currently, there is great controversy surrounding the treatment of the annular ligament. Some scholars believe that the elbow joint can function well without annular ligament repair(6-8). Other scholars believe that annular ligament repair can make the elbow joint more stable and reduce the pain and injury caused by elbow joint instability in later periods(9-13).Therefore, further understanding of the role of the annular ligament in elbow joint stability is particularly important. At present, there are few studies on the biomechanics of the annular ligament(14) , and most of them focus on the influence of elbow joint dislocation, deformity and fracture on elbow joint stability, while the role of the annular ligament in maintaining elbow joint stability has been ignored. As a result, a considerable number of patients cannot receive effective and timely treatment, and late elbow joint instability occurs. Based on the level of organization around the elbow joint, the analysis of ligament biomechanics, and real elbow CT images, in this paper, the bones of the elbow and articular cartilage of the lateral collateral ligament were reconstructed to create a three-dimensional (3D) finite element model. With the use of finite element simulation of annular ligament injury biomechanics, elbow flexion within the context of the lateral collateral ligament and the size of the cartilage surface stress in each part of the elbow were observed. Furthermore, the role of the annular ligament in maintaining elbow joint stability after annular ligament injury was analyzed to provide a biomechanical theoretical basis for the clinical diagnosis and treatment of elbow flexion instability.

Results

Validation of the finite element model

According to Sergey Strafun et al(15) , the mechanical experiment of the elbow joint was carried out. The neutral position of the forearm was selected for flexion at different angles, the humerus was fixed, five loads were applied in the model, and the contact area of the cartilage surface of the olecranon under different loads was recorded in the experiment. Based on the experimental data, the boundary and load of the finite element model were defined, and the contact area of the olecranon cartilage was simulated and extracted, as shown in Figure 1. Figure 1 shows that the results are basically consistent with the variation trend in the experimental data, thus verifying the validity of the model.

The elbow joint was flexed at 0, 30, 60, 90 and 120 degrees and was subjected to the corresponding load. The stress value of the olecranon cartilage surface is shown in Figure 2. The values of olecranon cartilage surface contact stress when the annular ligament under different conditions（normal、loosened、ruptured）with elbow extension were 2.1 ± 0.18, 2.4 ± 0.75 and 2.9 ± 0.94 Mpa. Then, as the angle increased, the stress value decreased; with 120 degrees of elbow flexion, the minimum stress values were 0.9 ± 0.12, 1.1 ± 0.38 and 1.2 ± 0.29 Mpa. Therefore, when the elbow was extended, the olecranon cartilage reached a maximum stress value of 3 Mpa. This result suggests that the annular ligament plays a role in maintaining elbow stability. In the case of annular ligament rupture, the radial head is prone to instability, leading to increased ulnar pressure and thus overload.

Figure 3 shows that when the contact surface of the olecranon was flexed from 0 to 30 degrees, the contact area of the olecranon cartilage significantly increased, reaching a maximum value of 254±5.35 mm. Then, the contact area gradually decreased, reaching a minimum value of 176±2.62 mm when the elbow was flexed to 120 degrees. The results when the annular ligament was loosened and ruptured were different from those of the normal annular ligament; the maximum values were reached at 60 degrees of elbow flexion and were 283±4.74 and 312±5.49 mm, respectively. Then, the contact area gradually decreased as the angle increased. The results show that when the annular ligament is completely ruptured, the contact area of the olecranon reaches a maximum value. This is because after annular ligament fracture, movement of the radial head leads to stress migration, and the load is transferred through the olecranon, leading to overload. This also suggests that the radial head plays an important role in maintaining elbow stability.

Figure 4 shows the changes in the stress value of the medial collateral ligament with the changes in the angle of the elbow joint. In elbow extension, because the medial collateral ligament is under a tensed condition and the annular ligament is under a different condition, the maximum stress values were 6.5 ± 0.23, 11.5± 0.78 and 18.7±0.94 Mpa. Then, with the increase in the angle, the ligament state changed from tension to relaxation, there was a decline in the different degrees of stress, and the different states of the annular ligament corresponded to stress values of 2.8± 0.18, 4.8 ± 0.56 and 6.2 ± 0.72 MPa at 120 degrees of elbow flexion. As shown in Figure 4, with annular ligament relaxation or fracture, stress significantly increases and the medial ligament and extended annular ligament rupture. The maximum value was 26.42 MPa due to the hyperelastic material of the ligament. Ligament stress and ultimate tensile strength are still relatively unclear, but a long period of stress may also occur in clinical pain and other clinical symptoms.

Discussion

Elbow instability caused by elbow injury is a hot topic in medical discussion and research. Previous studies have focused mainly on the ulna, radial head, cartilage, and collateral ligament(16-18) , and few biomechanical studies have been conducted on elbow instability caused by annular ligament injury. Naoki Hayami(19) conducted biomechanical studies on the rupture and reconstruction of the annular ligament in 5 cadavers and found that anatomical reconstruction of the annular ligament could provide multidirectional stability to the radial head. However, due to individual differences in cadavers, it is difficult to achieve sample uniformity and diversity in biomechanical research. There have been no reports in the previous literature on the effects of annular ligament fracture on the annular ligament and cartilage by finite element analysis. To study the influence of annular ligament stability in the elbow joint and to reduce the interference of other factors, this study adopted a reverse computer reconstruction method, established a digital model of the normal human elbow joint, and used the finite element analysis method to carry out the study. The finite element method can effectively simulate and analyze models under different conditions for the mechanical analysis of problems that cannot be solved by traditional biomechanics or in cases where the structure is complex or a biological experiment cannot be carried out(20, 21).

In this study, we established a 3D elbow finite element model that included the humerus, ulna, radius, articular cartilage, medial collateral ligament and other relevant structures and a buckling process simulation model to study the effects of different states of the annular ligament and other anatomic parameters. The variation trend of stress and strain on the cartilage surface of the medial collateral ligament and lateral collateral ligament with different flexion angles of the olecranon was analyzed. The results showed that with annular ligament rupture, the stability of the radial head was damaged, and dislocation was more likely to occur, resulting in poor contact of the ulnar and radial joints and stability damage and leading 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 2.9 ± 0.94 MPa. According to previous literature results(22) , when stress reaches 3-5 MPa, the cartilage matrix may be damaged. Compared with the results of this study, the olecranon cartilage surface was more prone to cartilage damage. Emilie Sandman(23) pointed out through biomechanical studies that reconstruction of the anatomical structure between bones alone is not sufficient to maintain the corresponding relationship of the ulnar and radial joints, while reconstruction of the annular ligament is of great significance for the long-term stability of the ulnar and radial joints, which can effectively reduce the instability of the elbow joint and the excessive stress on the ulna. Naoki Hayami et al (19) found that anatomical reconstruction of the annular ligament provided multidirectional stability of the radial head. If the annular ligament was fractured, radial head instability likely resulted, leading to a significant increase in the probability of radial head dislocation.

The annular ligament is a strong fibrous band around the radial head that contacts the radial notch of the ulna. Murat Bozkur(24) found that the annular ligament is an important component of the proximal radial joint and the radial humeral joint, as well as an important component of adjacent muscles and ligaments. When the annular ligament was loosened, the stress of the medial collateral ligament increased, while when the annular ligament was ruptured, the maximum stress value was 18.7±0.94 MPa. The table shows that elbow joint instability will significantly increase at this time, indicating that the medial collateral ligament plays an important role in maintaining elbow joint stability, similar to the study in the literature.

Morrey et al believe that the medial collateral ligament plays a crucial role in elbow joint stability. Munsar Rahman M(25) studied the effect of different degrees of medial collateral ligament deficiency on elbow joint stability through biomechanics, leading to elbow joint instability when the medial collateral ligament was completely removed. Kennith Sibber(26)showed with cadaver studies that compared to the lateral collateral ligament, the anterior fasciculus varus of the elbow joint had more than twice the effect on stability. The medial muscle tissue of the elbow joint mainly affects elbow joint stability, emphasizing its role as a secondary stabilizer, which is also consistent with our results.

From a clinical point of view, simple annular ligament rupture is relatively rare. It is usually caused by trauma and is often accompanied by fracture and dislocation. It is more common in Montsillar fractures and radial head dislocation. Whether the annular ligament should be repaired is still controversial. Altaf A Kawoosa and Hsuan-Yu Chen(6, 7) concluded that reducing the radial height effectively achieved reduction without open reduction, and annular ligament reconstruction could restore elbow function and improve elbow pain and stability. G. Canton et al(27) indicated that annular ligament rupture affected elbow joint biomechanics and resulted in radial head dislocation. Studies have indicated the importance of anatomical reconstruction of the annular ligament, indicating that the annular ligament plays a crucial role in radial head stability. According to research results, annular ligament loosen or rupture has a great impact on elbow joint stability, significantly increasing the stress of the medial collateral ligament and leading 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.

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, so the dynamic flexion of the elbow joint is not reflected.

Conclusion

In this study, a successful 3D finite element model of the normal structures of the elbow joint was established and included the MCL, LCL, annular ligament, and cartilage surface. Through data analysis, annular ligament loosen or rupture was found to lead to an increase in lateral collateral ligament and ulna olecranon articular cartilage surface stress, proving that the annular ligament plays an important role in maintaining elbow joint stability. Upon annular ligament rupture, the annular ligament should be reconstructed as much as possible to avoid the elevation of surface stress on the medial collateral ligament of the elbow and on the annular surface cartilage, which may cause clinical symptoms.

Methods

3D elbow joint model establishment

This study was approved by the ethics committee of the local institution, and written informed consent was obtained from the participants. This model was validated in our previous research(28). The surface grid editing tool in Geomagic 2013 software was used to analyze the 3D models of each part of the elbow. In particular, necessary editing and modifications were made to the 3D model reconstructed from MRI scan data to make the model more smooth and compliant. A high-quality surface model was achieved. Finally, closed-space NURBS was simulated and exported in step format. In SolidWorks 2012 software, 3D soft-tissue surface models based on two different modal data sets were registered for alignment. The positions of the medial collateral ligament (MCL), lateral collateral ligament (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 by using the direct modeling method. Then, 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 and the internal definition, and the material parameters and attributes were assigned appropriately. Then, the finite element mesh was divided into the model, and the finite element model was established. All the structures were simulated by using tetrahedral elements.By simplifying the bone tissue and articular surface cartilage in the model to homogeneous and isotropic elastomer material, the modeling period can be greatly shortened, and a large number of studies on finite element analysis have proven that finite element analysis with isotropic characteristics can also obtain more accurate analysis results(29). To better reflect the biomechanical response of ligaments, ligaments are defined as linear elastic materials that are studied according to relevant literature(15). The material parameters are shown in Table 1.

Boundary and loading conditions

According to the previous literature, the interaction between the cartilage and cartilage surface occurs via "face-to-face contact". The MCL, LCL and annular ligaments of the elbow joint play an important role in maintaining stability during joint movement by connecting bones and restricting joint movement to make the model closer to that in 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. In the stress-strain analysis and estimation, to meet the needs of the stress-strain state study, the normal, loosened, and ruptured models of the annular ligament were established. The geometric models were simulated from 0 to 120 degrees of flexion, with a 30 degree curve at intervals, and the position of the humerus was assumed to remain unchanged during flexion and extension of the elbow joint(15).Mechanical analysis was performed according to previous literature（15, 30-32）. 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 5 below).

Grid convergence test

To verify the sufficiency of the mesh, we tested the convergence of the mesh in the elbow joint model. The mesh sizes in the extended elbow joint model were set as 0.5, 1.0, 1.5 and 2.0 mm, and the mesh numbers were 132532, 257639, 361487 and 575432, respectively. Six degrees of freedom on the lower surface of the humerus were completely constrained, and 20 N was applied at the base of the MCL and LCL. The maximum von Mises stresses of the different MCL in the finite element models were calculated and compared. When the predicted results of the two schemes had a difference of less than 5%, the grid was considered to be convergent(33). When the mesh size was 1.0 mm, a further increase in the number of later meshes did not lead to any change in the results, and mesh refinement was stopped. Thus, the finite element mesh of the elbow joint consisted of approximately 361,487 units over a linear tetrahedra (see Figure 6 below).

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.

Appendix

Acknowledgements

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Abbreviations

MCL: medial collateral ligament; LCL: lateral collateral ligament;

Availability of data and materials

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

Ethics approval and consent to participate

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

Competing interests

The authors declare that they have no competing interests.

Consent for publication

All of authors consents to make the submission.

Authors' contributions

WL, ZZ and JY conceived and designed the study. GM built the finite element model and was responsible for the data acquisition. ZY were responsible for the statistical analysis part. Each author has participated sufficiently in the work to take public responsibility for appropriate portions of the content.

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Figures

Fig 1

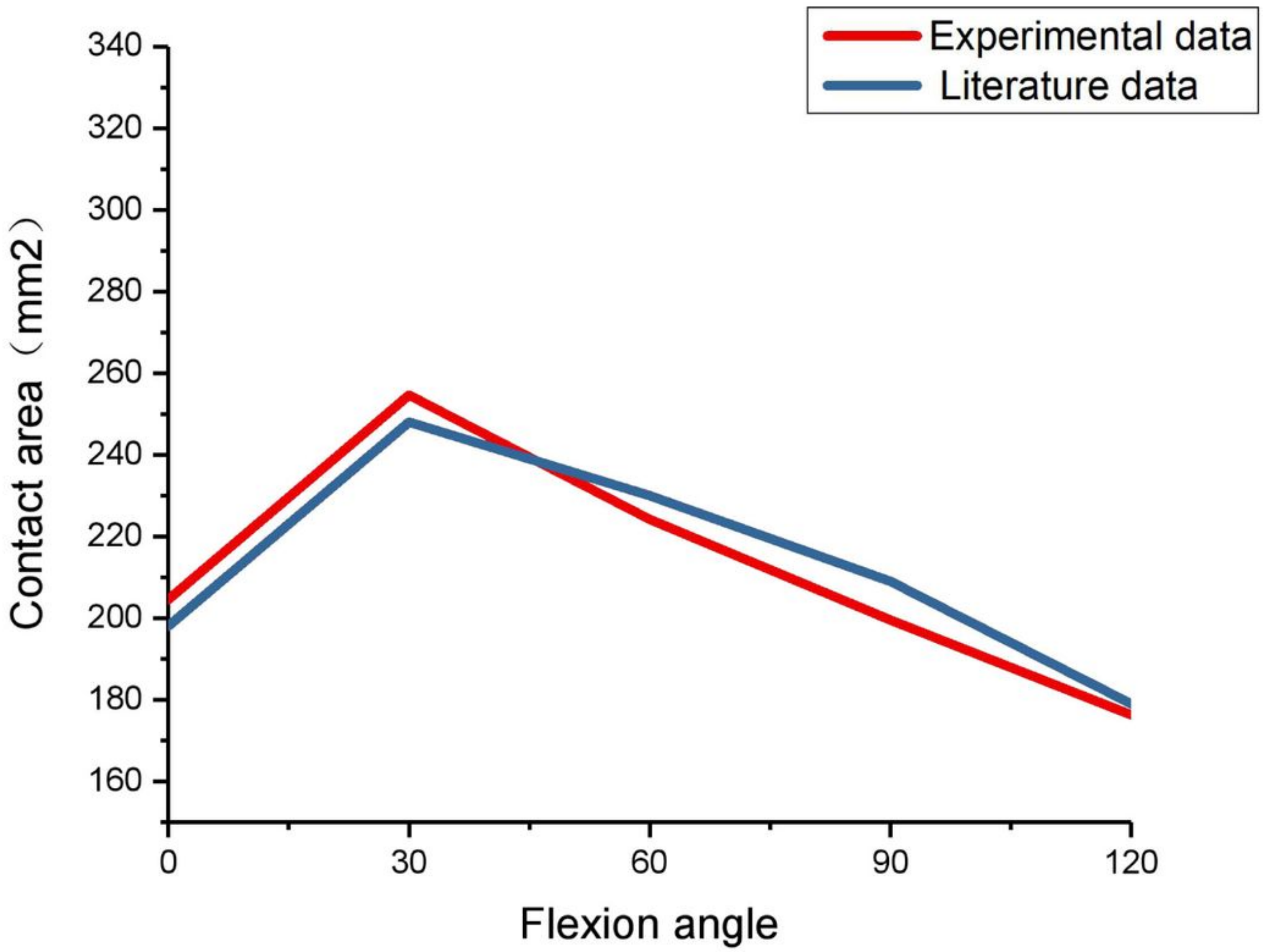

Figure 1

Data contrast diagram of the contact surface of the olecranon cartilage

Fig 1

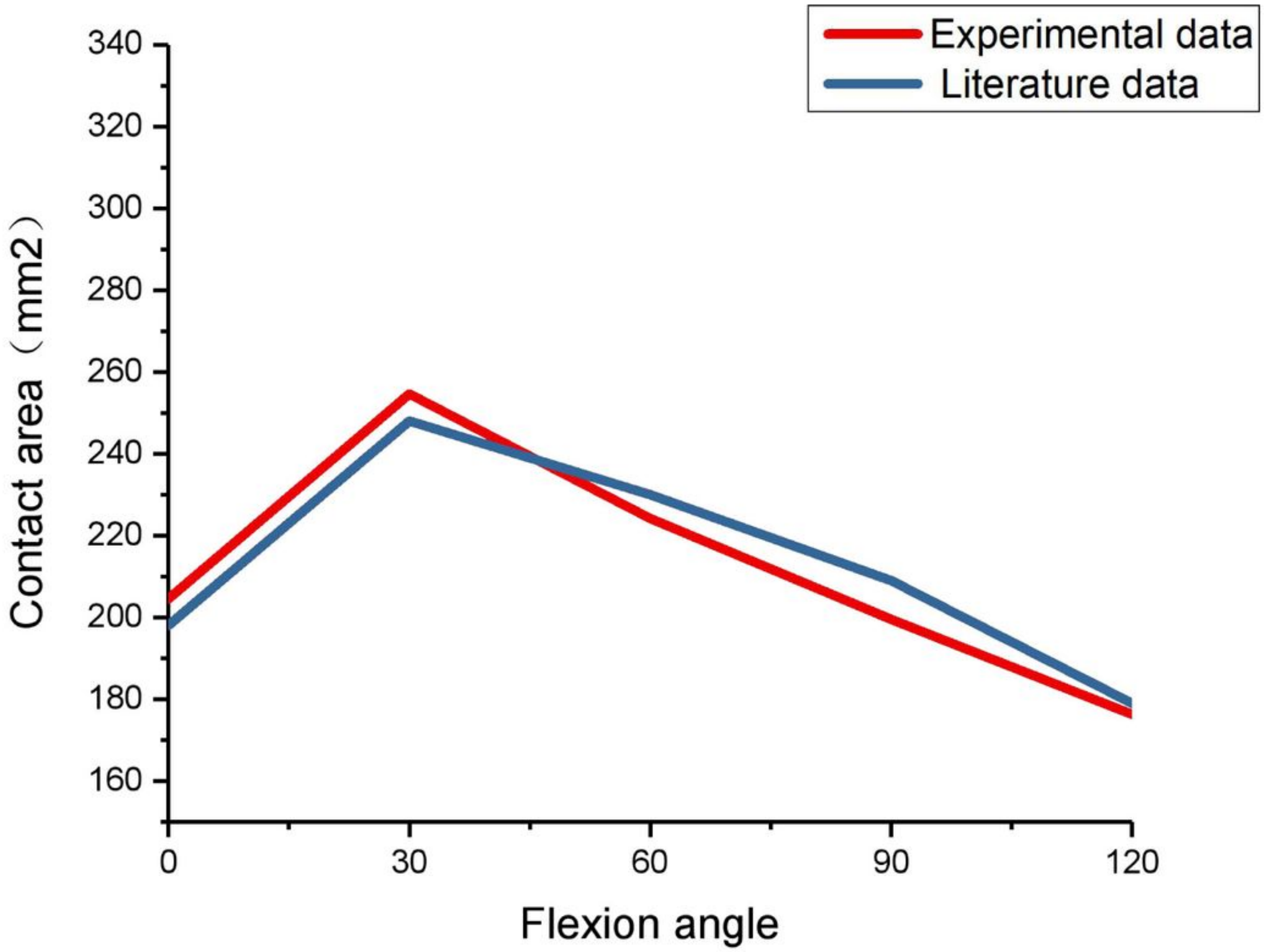

Figure 1

Data contrast diagram of the contact surface of the olecranon cartilage

Fig 2

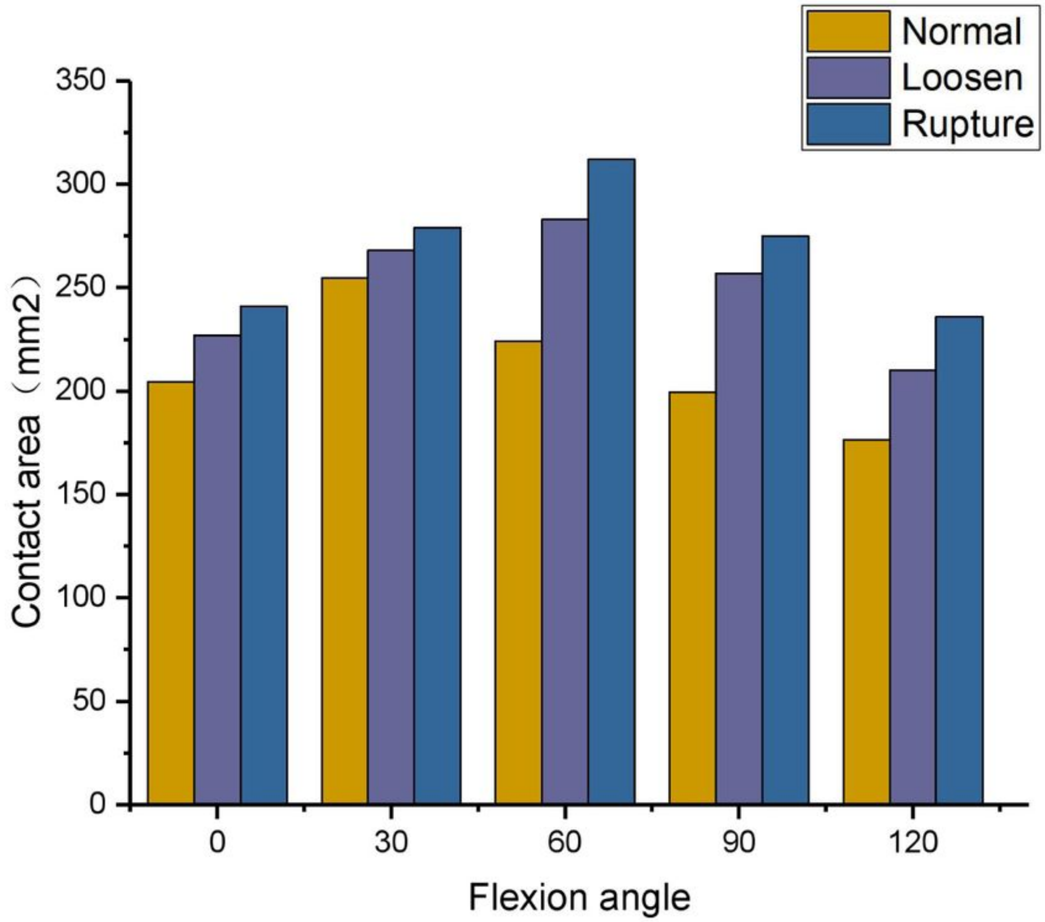

Figure 2

Different stress values of olecranon cartilage when the annular ligament under different conditions (normal、loosened、ruptured) as the buckling angle increased

Fig 2

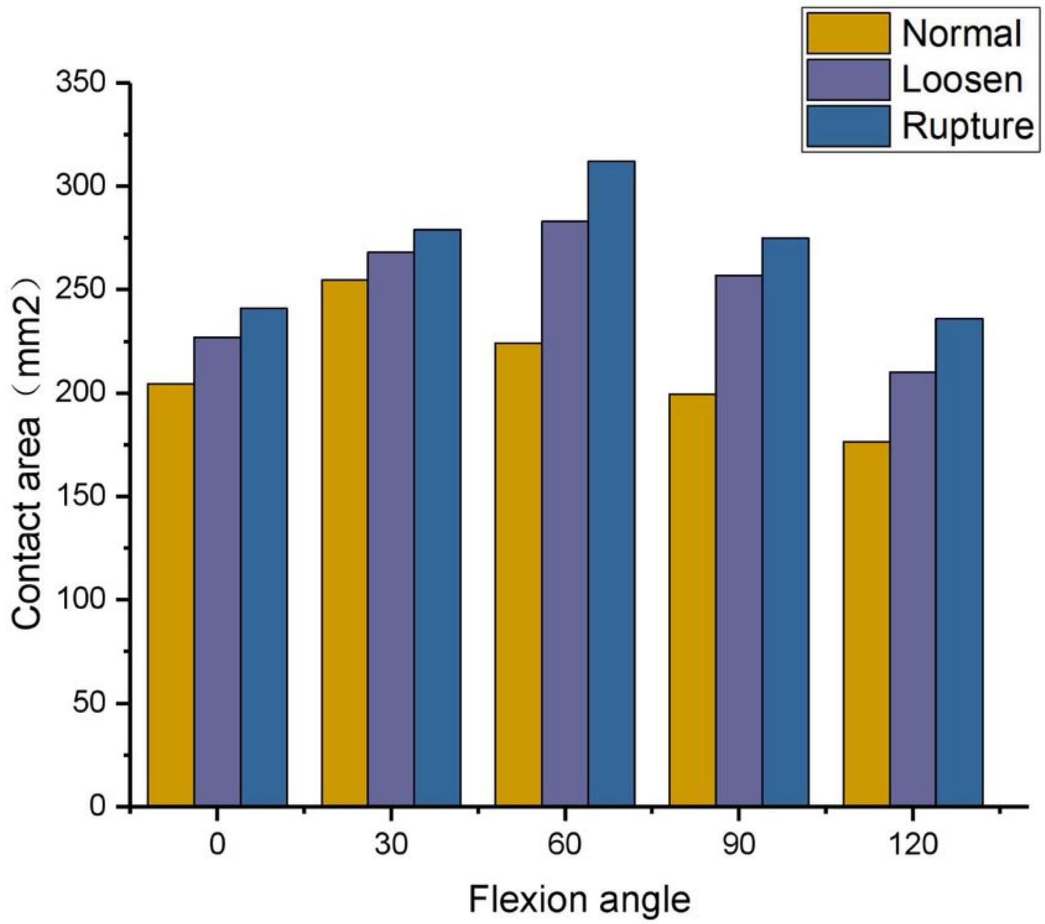

Figure 2

Different stress values of olecranon cartilage when the annular ligament under different conditions (normal□loosened□ruptured) as the buckling angle increased

Fig 3

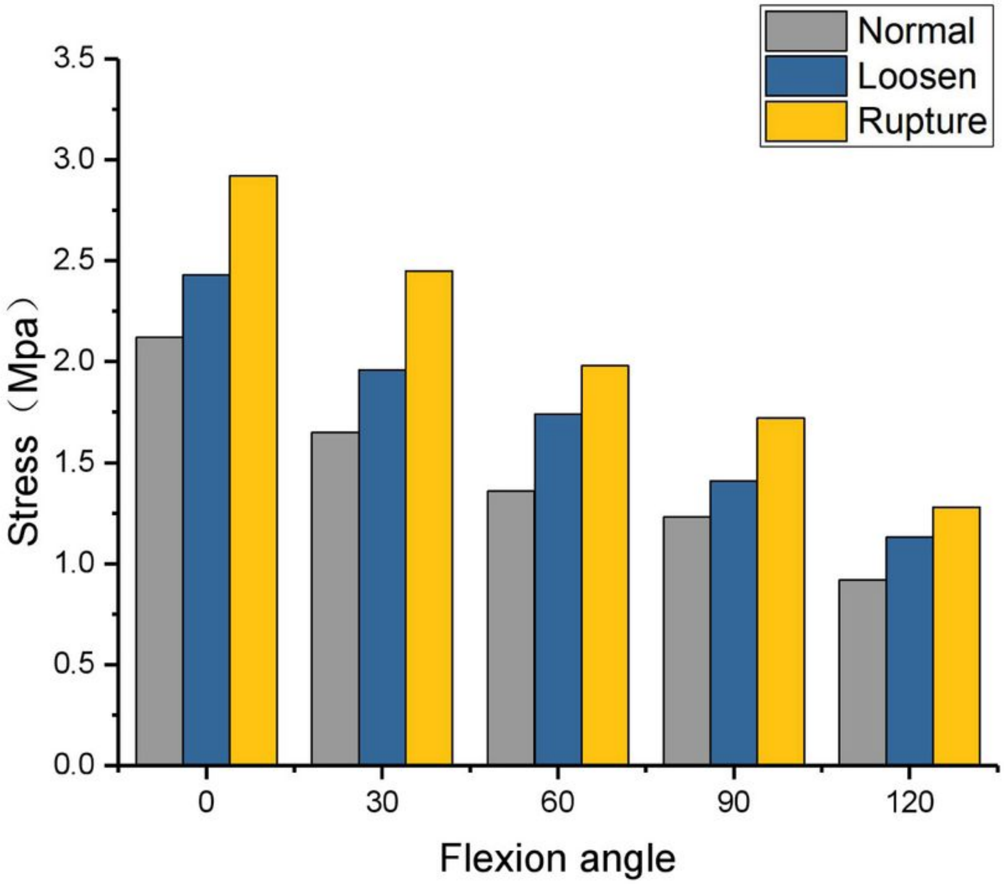

Figure 3

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

Fig 3

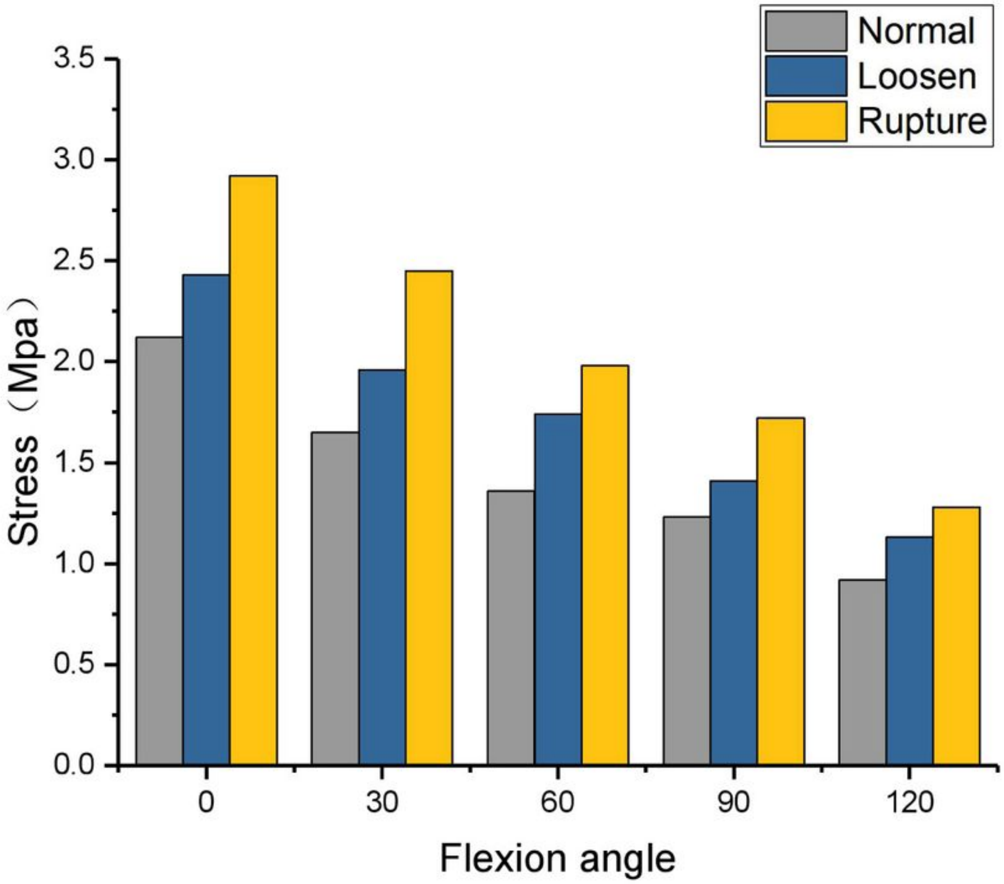

Figure 3

Different contact surface values of olecranon cartilage when the annular ligament under different conditions (normal、loosened、ruptured) as the buckling angle increased

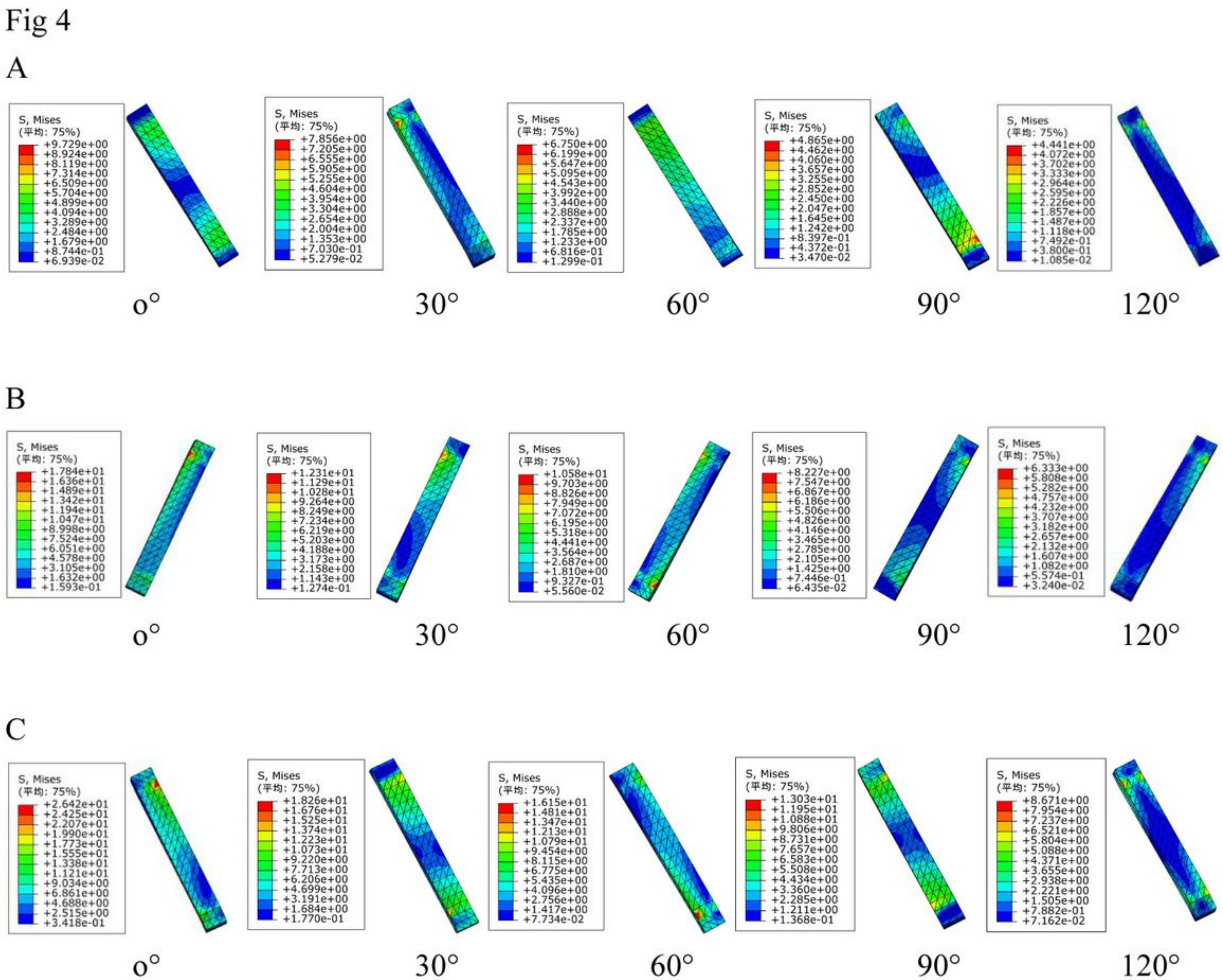

Figure 4

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

Fig 4

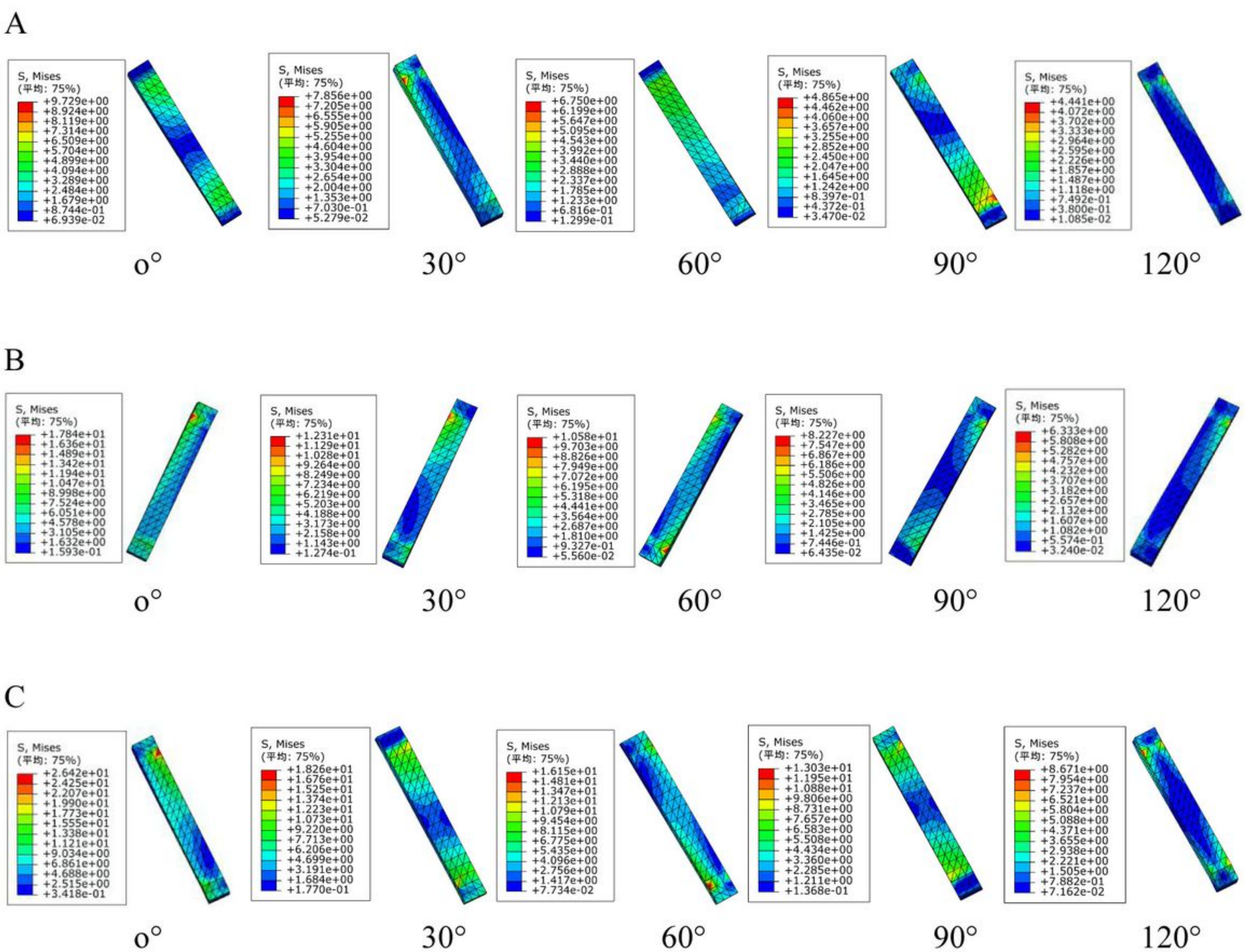

Figure 4

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

Fig 5

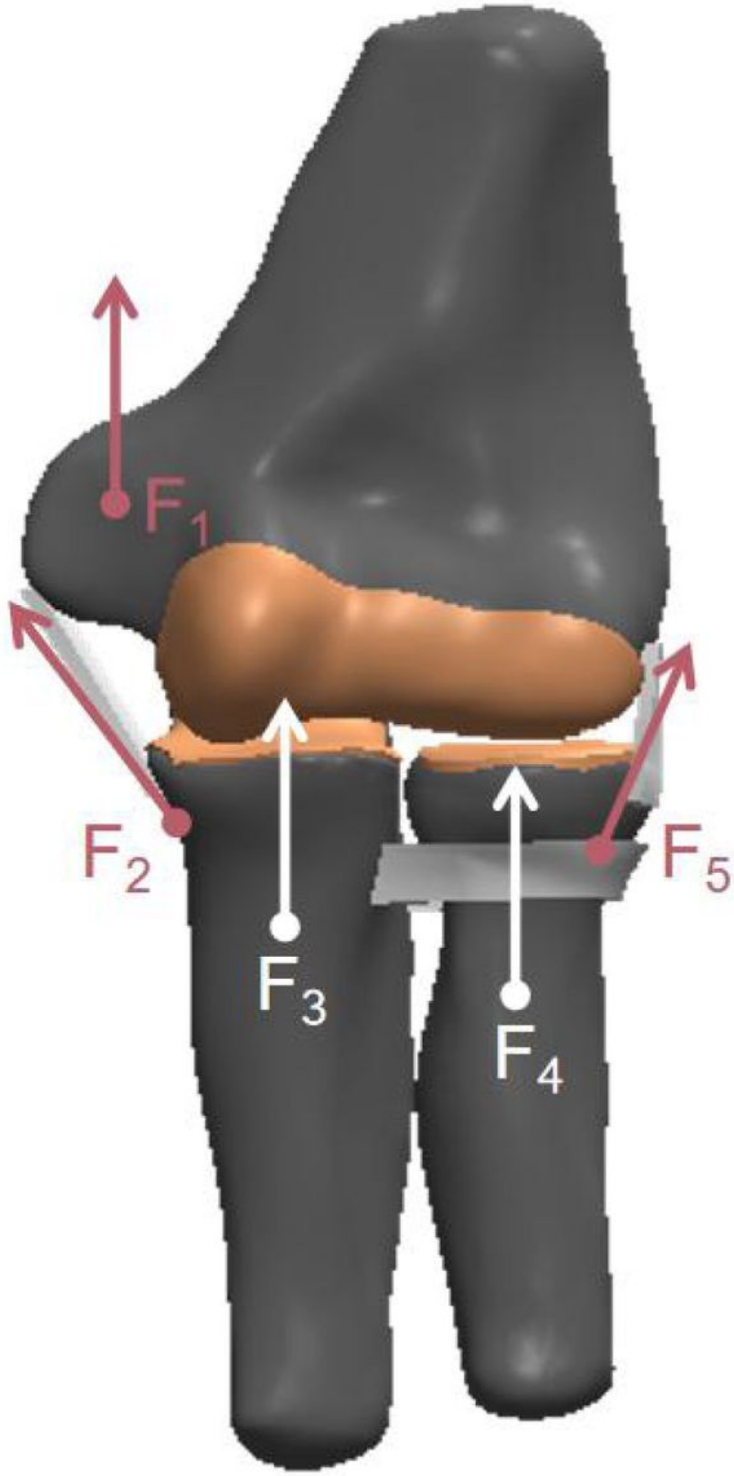

Figure 5

Loads condition are applied to the elbow model

Fig 5

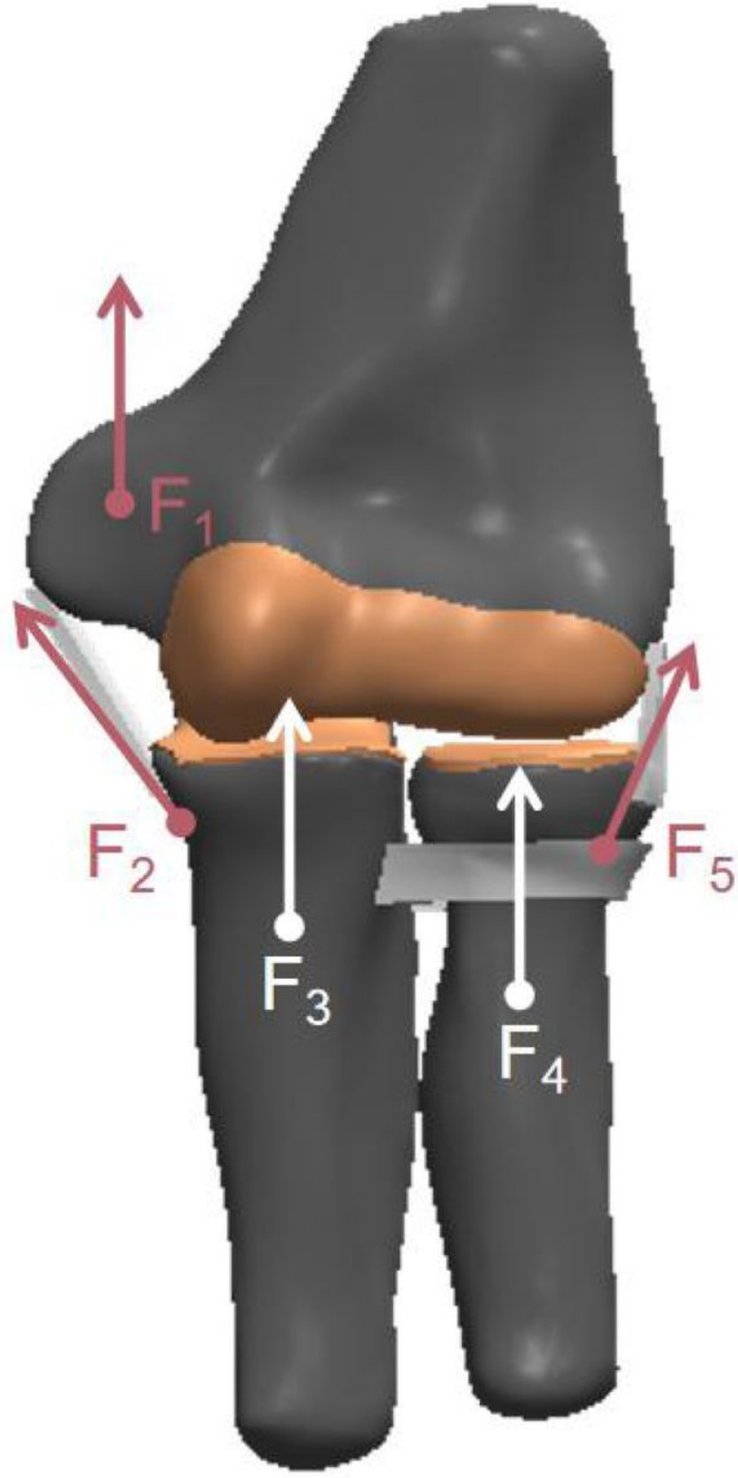

Figure 5

Loads condition are applied to the elbow model

Fig 6

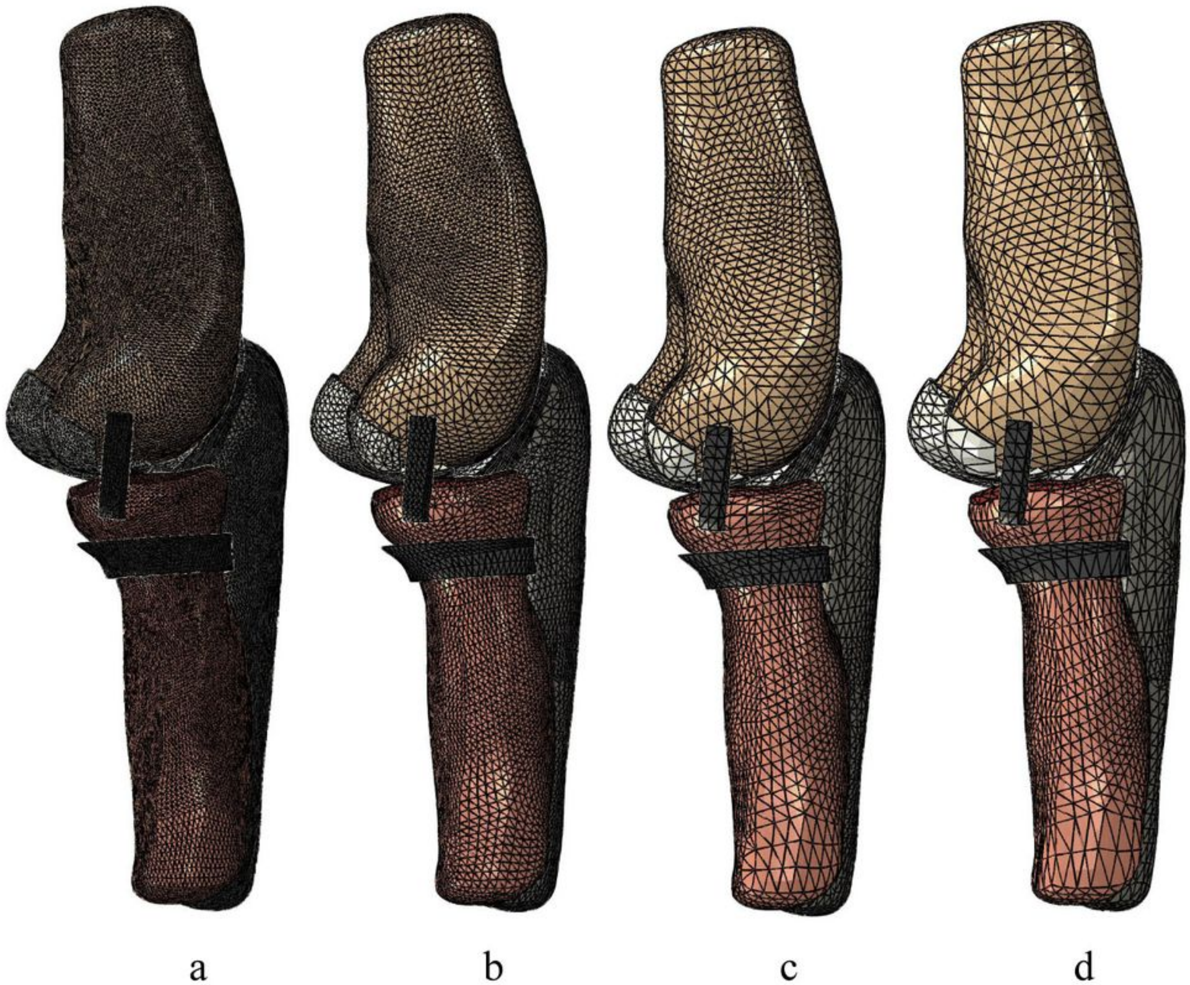

Figure 6

Result of Grid convergence test (a. Mesh sizes was set as 0.5mm; b. Mesh sizes was set as 1.0mm; c. Mesh sizes was set as 1.5mm; d. Mesh sizes was set as 2.0mm)

Fig 6

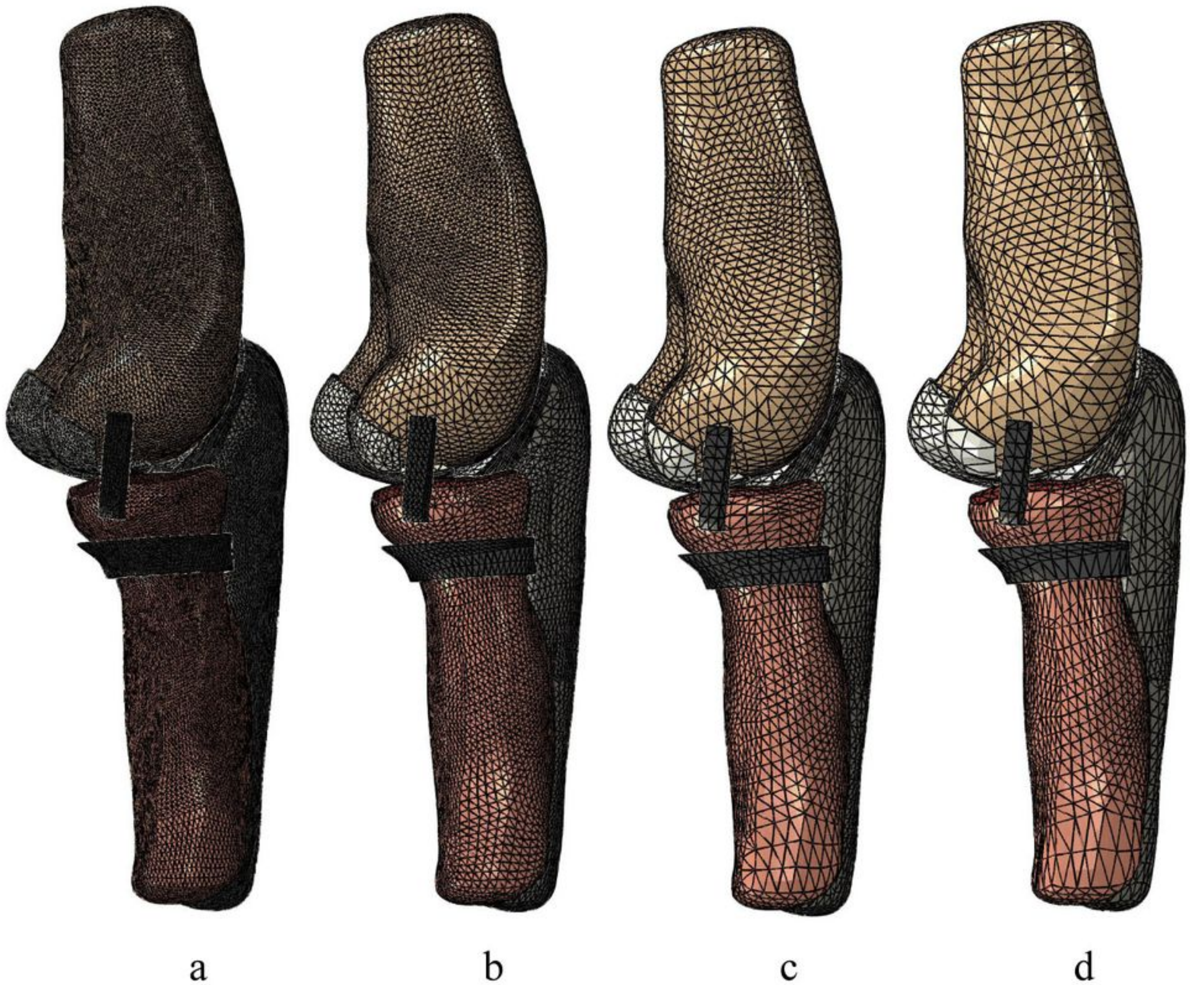

Figure 6

Result of Grid convergence test (a. Mesh sizes was set as 0.5mm; b. Mesh sizes was set as 1.0mm; c. Mesh sizes was set as 1.5mm; d. Mesh sizes was set as 2.0mm)

Supplementary Files

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- Titlepage.pdf
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