

1 Finite element analysis of elbow joint stability by different flexion angles of the annular 2 ligament

3 Guangming Xu^{1*}, Zhengzhong Yang¹, Jiyong Yang¹, Ziyang Liang^{2✉}, Wei Li ^{1✉}

4 5 Abstract

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

8 **Methods:** Left elbow CT and MRI scans were chosen from a healthy volunteer, according to a
9 previous research model. A cartilage and ligament model was constructed with SolidWorks
10 software according to the MRI results to simulate the annular ligament during normal, loosen, and
11 rupture conditions at different buckling angles (0, 30, 60, 90, 120). In 15 elbow models, boundary
12 conditions were set according to the literature. The different elbow 3D finite element models were
13 imported into ABAQUS software to calculate and analyze the load, contact area, contact stress and
14 stress of the medial collateral ligament of the olecranon cartilage.

15 **Results:** 1. According to the analysis results, olecranon cartilage stress values when the annular
16 ligament under different conditions (normal, loosened, ruptured) with elbow extension, were 2.1
17 ± 0.18 , 2.4 ± 0.75 , and 2.9 ± 0.94 MPa. As the buckling angle increased, the stress value decreased;
18 with 120 degrees of elbow flexion, the minimum stress values were 0.9 ± 0.12 , 1.1 ± 0.38 , and 1.2
19 ± 0.29 MPa. 2. When the contact surface of the olecranon cartilage was flexed from 0 to 30
20 degrees, the olecranon cartilage contact area significantly increased, reaching a maximum value of
21 254 ± 5.35 mm, and then the contact area gradually decreased, reaching a minimum value of
22 176 ± 2.62 mm when the elbow joint was flexed to 120 degrees. The results when the annular
23 ligament was loosened and ruptured were different from those of the normal annular ligament. The
24 maximum values were 283 ± 4.74 and 312 ± 5.49 mm at 60 degrees of elbow flexion. The contact
25 area gradually decreased with an increase in the angle, and the minimum values were 210 ± 3.82
26 and 236 ± 6.59 mm at 120 degrees of elbow flexion. 3. When the elbow joint was extended, the
27 maximum stress of the medial collateral ligament was 6.5 ± 0.23 , 11.5 ± 0.78 and 18.7 ± 0.94 MPa
28 under different states; as the stress decreased with an increase in the angle, the corresponding
29 values were 2.8 ± 0.18 , 4.8 ± 0.56 and 6.2 ± 0.72 MPa at 120 degrees of elbow flexion.

30 **Conclusion:** The annular ligament plays an important role in maintaining elbow joint stability.
31 When the annular ligament ruptures, it should be reconstructed as much as possible to avoid the
32 elevation of stress on the surface of the medial collateral ligament of the elbow and on the annular
33 cartilage, which may cause clinical symptoms.

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

35 36 Background

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1 Elbow instability is caused by damage to the bone joint surface and the ligament structure of the
2 elbow joint. It is a common disease secondary to acute fracture dislocation and chronic exercise
3 strain(1, 2). Elbow dysfunction is often accompanied by ligament damage, resulting in elbow
4 instability. On the medial side of the elbow, the lateral collateral ligament and the annular ligament
5 are the basic structures that maintain the stability of the medial side of the elbow(3-5). In the case
6 of elbow dislocation or fracture, such as Montages fracture, radial head fracture, and radial head
7 dislocation, the annular ligament is vulnerable to injury, especially in severe cases. Currently, there
8 is great controversy surrounding the treatment of the annular ligament. Some scholars believe that
9 the elbow joint can function well without annular ligament repair(6-8). Other scholars believe that
10 annular ligament repair can make the elbow joint more stable and reduce the pain and injury
11 caused by elbow joint instability in later periods(9-13).Therefore, further understanding of the role
12 of the annular ligament in elbow joint stability is particularly important. At present, there are few
13 studies on the biomechanics of the annular ligament(14) , and most of them focus on the influence
14 of elbow joint dislocation, deformity and fracture on elbow joint stability, while the role of the
15 annular ligament in maintaining elbow joint stability has been ignored. As a result, a considerable
16 number of patients cannot receive effective and timely treatment, and late elbow joint instability
17 occurs. Based on the level of organization around the elbow joint, the analysis of ligament
18 biomechanics, and real elbow CT images, in this paper, the bones of the elbow and articular
19 cartilage of the lateral collateral ligament were reconstructed to create a three-dimensional (3D)
20 finite element model. With the use of finite element simulation of annular ligament injury
21 biomechanics, elbow flexion within the context of the lateral collateral ligament and the size of the
22 cartilage surface stress in each part of the elbow were observed. Furthermore, the role of the
23 annular ligament in maintaining elbow joint stability after annular ligament injury was analyzed to
24 provide a biomechanical theoretical basis for the clinical diagnosis and treatment of elbow flexion
25 instability.

26 **Results**

27 **Validation of the finite element model**

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

36
37 The elbow joint was flexed at 0, 30, 60, 90 and 120 degrees and was subjected to the
38 corresponding load. The stress value of the olecranon cartilage surface is shown in Figure 2. The
39 values of olecranon cartilage surface contact stress when the annular ligament under different
40 conditions (normal、loosened、ruptured) with elbow extension were 2.1 ± 0.18 , 2.4 ± 0.75 and 2.9
41 ± 0.94 Mpa. Then, as the angle increased, the stress value decreased; with 120 degrees of elbow
42 flexion, the minimum stress values were 0.9 ± 0.12 , 1.1 ± 0.38 and 1.2 ± 0.29 Mpa. Therefore,
43 when the elbow was extended, the olecranon cartilage reached a maximum stress value of 3 Mpa.
44 This result suggests that the annular ligament plays a role in maintaining elbow stability. In the

1 case of annular ligament rupture, the radial head is prone to instability, leading to increased ulnar
2 pressure and thus overload.

3 Figure 3 shows that when the contact surface of the olecranon was flexed from 0 to 30
4 degrees, the contact area of the olecranon cartilage significantly increased, reaching a maximum
5 value of 254 ± 5.35 mm. Then, the contact area gradually decreased, reaching a minimum value of
6 176 ± 2.62 mm when the elbow was flexed to 120 degrees. The results when the annular ligament
7 was loosened and ruptured were different from those of the normal annular ligament; the
8 maximum values were reached at 60 degrees of elbow flexion and were 283 ± 4.74 and $312 \pm$
9 5.49 mm, respectively. Then, the contact area gradually decreased as the angle increased. The
10 results show that when the annular ligament is completely ruptured, the contact area of the
11 olecranon reaches a maximum value. This is because after annular ligament fracture, movement of
12 the radial head leads to stress migration, and the load is transferred through the olecranon, leading
13 to overload. This also suggests that the radial head plays an important role in maintaining elbow
14 stability.

15 Figure 4 shows the changes in the stress value of the medial collateral ligament with the
16 changes in the angle of the elbow joint. In elbow extension, because the medial collateral ligament
17 is under a tensed condition and the annular ligament is under a different condition, the maximum
18 stress values were 6.5 ± 0.23 , 11.5 ± 0.78 and 18.7 ± 0.94 Mpa. Then, with the increase in the angle,
19 the ligament state changed from tension to relaxation, there was a decline in the different degrees
20 of stress, and the different states of the annular ligament corresponded to stress values of 2.8 ± 0.18 ,
21 4.8 ± 0.56 and 6.2 ± 0.72 MPa at 120 degrees of elbow flexion. As shown in Figure 4, with
22 annular ligament relaxation or fracture, stress significantly increases and the medial ligament and
23 extended annular ligament rupture. The maximum value was 26.42 MPa due to the hyperelastic
24 material of the ligament. Ligament stress and ultimate tensile strength are still relatively unclear,
25 but a long period of stress may also occur in clinical pain and other clinical symptoms.

26 **Discussion**

27 Elbow instability caused by elbow injury is a hot topic in medical discussion and research.
28 Previous studies have focused mainly on the ulna, radial head, cartilage, and collateral
29 ligament(16-18) , and few biomechanical studies have been conducted on elbow instability caused
30 by annular ligament injury. Naoki Hayami(19) conducted biomechanical studies on the rupture
31 and reconstruction of the annular ligament in 5 cadavers and found that anatomical reconstruction
32 of the annular ligament could provide multidirectional stability to the radial head. However, due to
33 individual differences in cadavers, it is difficult to achieve sample uniformity and diversity in
34 biomechanical research. There have been no reports in the previous literature on the effects of
35 annular ligament fracture on the annular ligament and cartilage by finite element analysis. To
36 study the influence of annular ligament stability in the elbow joint and to reduce the interference
37 of other factors, this study adopted a reverse computer reconstruction method, established a digital
38 model of the normal human elbow joint, and used the finite element analysis method to carry out
39 the study. The finite element method can effectively simulate and analyze models under different
40 conditions for the mechanical analysis of problems that cannot be solved by traditional
41 biomechanics or in cases where the structure is complex or a biological experiment cannot be
42 carried out(20, 21).
43

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

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

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

38 From a clinical point of view, simple annular ligament rupture is relatively rare. It is usually
39 caused by trauma and is often accompanied by fracture and dislocation. It is more common in
40 Montsillar fractures and radial head dislocation. Whether the annular ligament should be repaired
41 is still controversial. Altaf A Kawoosa and Hsuan-Yu Chen(6, 7) concluded that reducing the radial
42 height effectively achieved reduction without open reduction, and annular ligament reconstruction
43 could restore elbow function and improve elbow pain and stability. G. Canton et al(27) indicated
44 that annular ligament rupture affected elbow joint biomechanics and resulted in radial head

1 dislocation. Studies have indicated the importance of anatomical reconstruction of the annular
2 ligament, indicating that the annular ligament plays a crucial role in radial head stability.
3 According to research results, annular ligament loosen or rupture has a great impact on elbow joint
4 stability, significantly increasing the stress of the medial collateral ligament and leading to pain
5 and other symptoms in later stages. Due to the increased stress on the annular cartilage surface,
6 osteoarthritis may occur in severe cases. Therefore, the integrity of the annular ligament plays an
7 important role in elbow joint stability.

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

15 **Conclusion**

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

25 **Methods**

27 **3D elbow joint model establishment**

28 This study was approved by the ethics committee of the local institution, and written informed
29 consent was obtained from the participants. This model was validated in our previous research(28).
30 The surface grid editing tool in Geomagic 2013 software was used to analyze the 3D models of
31 each part of the elbow. In particular, necessary editing and modifications were made to the 3D
32 model reconstructed from MRI scan data to make the model more smooth and compliant. A
33 high-quality surface model was achieved. Finally, closed-space NURBS was simulated and
34 exported in step format. In SolidWorks 2012 software, 3D soft-tissue surface models based on two
35 different modal data sets were registered for alignment. The positions of the medial collateral
36 ligament (MCL), lateral collateral ligament (LCL), annular ligaments and other 3D models
37 reconstructed from the MRI scan data were converted to the CT scan data space, and the MCL and
38 LCL, annular ligaments, articular surface cartilage and other tissues were constructed by using the
39 direct modeling method. Then, the model was imported into ABAQUS, and the ranges of bones,
40 ligaments and cartilage were defined differently based on the difference between the surface
41 definition and the internal definition, and the material parameters and attributes were assigned
42 appropriately. Then, the finite element mesh was divided into the model, and the finite element
43 model was established. All the structures were simulated by using tetrahedral elements. By
44 simplifying the bone tissue and articular surface cartilage in the model to homogeneous and

1 isotropic elastomer material, the modeling period can be greatly shortened, and a large number of
2 studies on finite element analysis have proven that finite element analysis with isotropic
3 characteristics can also obtain more accurate analysis results(29). To better reflect the
4 biomechanical response of ligaments, ligaments are defined as linear elastic materials that are
5 studied according to relevant literature(15). The material parameters are shown in Table 1.

7 **Boundary and loading conditions**

8 According to the previous literature, the interaction between the cartilage and cartilage surface
9 occurs via "face-to-face contact". The MCL, LCL and annular ligaments of the elbow joint play an
10 important role in maintaining stability during joint movement by connecting bones and restricting
11 joint movement to make the model closer to that in SolidWorks. The two ends of each major
12 ligament and its anatomical attachment point were set as the common node contact connection: the
13 internal surface of the articular cartilage was set to be fixed with the surface of bone tissue. In the
14 stress-strain analysis and estimation, to meet the needs of the stress-strain state study, the normal,
15 loosened, and ruptured models of the annular ligament were established. The geometric models
16 were simulated from 0 to 120 degrees of flexion, with a 30 degree curve at intervals, and the
17 position of the humerus was assumed to remain unchanged during flexion and extension of the
18 elbow joint(15).Mechanical analysis was performed according to previous literature (15, 30–32) .
19 Mechanical values were assigned to ligaments, bones, and cartilage to simulate natural flexion of
20 the elbow joint. The values and positions of these loads were selected in accordance with
21 previously published studies. The fixed muscle strengths were 40 N (F1), 20 N (F2), 20 N (F3), 20
22 N (F4), and 20 N (F5) for the triceps, biceps and brachial tendons and the base of the MCL and
23 LCL, respectively (see Figure 5 below).

25 **Grid convergence test**

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

37 **Observational factors**

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

1 **Appendix**

2

3 **Acknowledgements**

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7 **Abbreviations**

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

9 **Availability of data and materials**

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

12 **Ethics approval and consent to participate**

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

15 **Competing interests**

16 The authors declare that they have no competing interests.

17 **Consent for publication**

18 All of authors consents to make the submission.

19 **Authors' contributions**

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

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33 **References**

34 1. Edelman D, Ilyas AM. Temporary Bridge Plate Stabilization of Unstable Elbow Fractures
35 and Dislocations. *Techniques in hand & upper extremity surgery*. 2018;22(2):46-50.

36 2. Heijink A, Vanhees M, van den Ende K, van den Bekerom MP, van Riet RP, Van Dijk CN, et al.
37 Biomechanical considerations in the pathogenesis of osteoarthritis of the elbow. *Knee surgery, sports
38 traumatology, arthroscopy : official journal of the ESSKA*. 2016;24(7):2313-8.

39 3. Frangiamore SJ, Moatshe G, Kruckeberg BM, Civitarese DM, Muckenhirn KJ, Chahla J, et al.
40 Qualitative and Quantitative Analyses of the Dynamic and Static Stabilizers of the Medial Elbow: An
41 Anatomic Study. *Am J Sports Med*. 2018;46(3):687-94.

42 4. Terzini M, Zanetti EM, Audenino AL, Putame G, Gastaldi L, Pastorelli S, et al. Multibody
43 modelling of ligamentous and bony stabilizers in the human elbow. *Muscles, ligaments and tendons*

- 1 journal. 2017;7(4):493-502.
- 2 5. Anderson A, Werner FW, Tucci ER, Harley BJ. Role of the interosseous membrane and annular
3 ligament in stabilizing the proximal radial head. *J Shoulder Elbow Surg.* 2015;24(12):1926-33.
- 4 6. Chen HY, Wu KW, Dong ZR, Huang SC, Kuo KN, Wang TM. The treatment of chronic radial
5 head dislocation in Monteggia fracture without annular ligament reconstruction. *International*
6 *orthopaedics.* 2018;42(9):2165-72.
- 7 7. Kawoosa AA, Dhar SA, Butt MF, Wani SA, Mir MR, Dar TA. Stable relocation of the radial head
8 without annular ligament reconstruction using the Ilizarov technique to treat neglected Monteggia
9 fracture: two case reports. *Journal of medical case reports.* 2010;4:344.
- 10 8. Han SH, Lee SC, Ryu KJ, Lee JH. Repairing the annular ligament is not necessary in the
11 operation of Mason type 2, 3 isolated radial head fractures if the lateral collateral ligament is intact:
12 Minimum 5 years follow-up. *Injury.* 2013;44(12):1851-4.
- 13 9. Hackl M, Wegmann K, Ries C, Lappen S, Scaal M, Müller LP. Annular ligament reconstruction
14 with the superficial head of the brachialis: surgical technique and biomechanical evaluation. *Surgical*
15 *and radiologic anatomy : SRA.* 2017;39(6):585-91.
- 16 10. Bhaskar A. Missed Monteggia fracture in children: Is annular ligament reconstruction always
17 required? *Indian journal of orthopaedics.* 2009;43(4):389-95.
- 18 11. Nwoko OE, Patel PP, Richard MJ, Leversedge FJ. Annular ligament reconstruction using the
19 distal tendon of the superficial head of the brachialis muscle: an anatomical feasibility study. *The*
20 *Journal of hand surgery.* 2013;38(7):1315-9.
- 21 12. Wang MN, Chang WN. Chronic posttraumatic anterior dislocation of the radial head in children:
22 thirteen cases treated by open reduction, ulnar osteotomy, and annular ligament reconstruction through
23 a Boyd incision. *Journal of orthopaedic trauma.* 2006;20(1):1-5.
- 24 13. Hatta T, Shinagawa K, Hayashi K, Hasegawa K, Miyasaka Y, Yamamoto N, et al. Ligament
25 Reconstruction for Recurrent Anterior Dislocation of the Radial Head. *Case reports in orthopedics.*
26 2019;2019:6067312.
- 27 14. Tan J, Mu M, Liao G, Zhao Y, Li J. Biomechanical analysis of the annular ligament in Monteggia
28 fractures using finite element models. *Journal of orthopaedic surgery and research.* 2015;10:30.
- 29 15. Strafun S, Levadnyi I, Makarov V, Awrejcewicz J. Comparative Biomechanical Analysis of
30 Stress-Strain State of the Elbow Joint After Displaced Radial Head Fractures. *Journal of medical and*
31 *biological engineering.* 2018;38(4):618-24.
- 32 16. Willing RT, Lalone EA, Shannon H, Johnson JA, King GJ. Validation of a finite element model of
33 the human elbow for determining cartilage contact mechanics. *Journal of biomechanics.*
34 2013;46(10):1767-71.
- 35 17. Matsuura Y, Takamura T, Sugiura S, Matsuyama Y, Suzuki T, Mori C, et al. Evaluation of anterior
36 oblique ligament tension at the elbow joint angle—a cadaver study. *J Shoulder Elbow Surg.* 2020.
- 37 18. Panero E, Gastaldi L, Terzini M, Bignardi C, Sard A, Pastorelli S. Biomechanical Role and
38 Motion Contribution of Ligaments and Bony Constraints in the Elbow Stability: A Preliminary Study.
39 *Bioengineering (Basel, Switzerland).* 2019;6(3).
- 40 19. Hayami N, Omokawa S, Iida A, Kraissarin J, Moritomo H, Mahakkanukrauh P, et al.
41 Biomechanical study of isolated radial head dislocation. *BMC musculoskeletal disorders.*
42 2017;18(1):470.
- 43 20. Yan L, Lim JL, Lee JW, Tia CSH, O'Neill GK, Chong DYR. Finite element analysis of bone and
44 implant stresses for customized 3D-printed orthopaedic implants in fracture fixation. *Medical &*

1 biological engineering & computing. 2020;58(5):921-31.

2 21. Li L, Yang L, Zhang K, Zhu L, Wang X, Jiang Q. Three-dimensional finite-element analysis of
3 aggravating medial meniscus tears on knee osteoarthritis. *Journal of orthopaedic translation*.
4 2020;20:47-55.

5 22. 2020.Loening AM, James IE, Levenston ME, Badger AM, Frank EH, Kurz B, et al. Injurious
6 mechanical compression of bovine articular cartilage induces chondrocyte apoptosis. *Archives of*
7 *biochemistry and biophysics*. 2000;381(2):205-12.

8 23. Sandman E, Canet F, Petit Y, Laflamme GY, Athwal GS, Rouleau DM. Radial Head Subluxation
9 After Malalignment of the Proximal Ulna: A Biomechanical Study. *Journal of orthopaedic trauma*.
10 2014;28(8):464-9.

11 24. Lapner M, Willing R, Johnson JA, King GJ. The effect of distal humeral hemiarthroplasty on
12 articular contact of the elbow. *Clinical biomechanics (Bristol, Avon)*. 2014;29(5):537-44.

13 25. Rahman M, Cil A, Stylianou AP. Medial Collateral Ligament Deficiency of the Elbow Joint: A
14 Computational Approach. *Bioengineering (Basel, Switzerland)*. 2018;5(4).

15 26. Seiber K, Gupta R, McGarry MH, Safran MR, Lee TQ. The role of the elbow musculature,
16 forearm rotation, and elbow flexion in elbow stability: an in vitro study. *J Shoulder Elbow Surg*.
17 2009;18(2):260-8.

18 27. Canton G, Hoxhaj B, Fattori R, Murena L. Annular ligament reconstruction in chronic Monteggia
19 fracture-dislocations in the adult population: indications and surgical technique. *Musculoskeletal*
20 *surgery*. 2018;102(Suppl 1):93-102.

21 28. Xu GM, Liang ZY, Li W, Yang ZZ, Chen ZB, Zhang J. Finite Element Analysis of Insertion Angle
22 of Absorbable Screws for the Fixation of Radial Head Fractures. *Orthopaedic surgery*..

23 29. Ramaniraka NA, Saunier P, Siegrist O, Pioletti DP. Biomechanical evaluation of intra-articular
24 and extra-articular procedures in anterior cruciate ligament reconstruction: a finite element analysis.
25 *Clinical biomechanics (Bristol, Avon)*. 2007;22(3):336-43.

26 30. Bozkurt M, Acar HI, Apaydin N, Leblebicioglu G, Elhan A, Tekdemir I, et al. The annular
27 ligament: an anatomical study. *Am J Sports Med*. 2005;33(1):114-8.

28 31. Pichora JE, Fraser GS, Ferreira LF, Brownhill JR, Johnson JA, King GJ. The effect of medial
29 collateral ligament repair tension on elbow joint kinematics and stability. *The Journal of hand surgery*.
30 2007;32(8):1210-7.

31 32. Willing R, Lapner M, King GJ, Johnson JA. In vitro assessment of the contact mechanics of
32 reverse-engineered distal humeral hemiarthroplasty prostheses. *Clinical biomechanics (Bristol, Avon)*.
33 2014;29(9):990-6.

34 33. Jones AC, Wilcox RK. Finite element analysis of the spine: towards a framework of verification,
35 validation and sensitivity analysis. *Medical engineering & physics*. 2008;30(10):1287-304.

36