STRESS-STRAIN STATE OF ARTICULAR SURFACES OF THE SHOULDER JOINT UNDER VARIOUS OPTIONS OF ITS ARTHROGENIC CONTRACTURE

[a]SERHII STRAFUN, [b]SERHII BOHDAN, [c]LIUBOMYR YURIICHUK, [d]OLEKSANDR STRAFUN, [e]RUSLAN SERGIENKO

[a,b,d]SI "Institute of Traumatology and Orthopedics of the National Academy of Medical Sciences of Ukraine", 27, Bulvarno-Kudryavska Str., 01061, Kyiv, Ukraine
[c]Ivano-Frankivsk Regional Clinical Hospital, 91, Fedkovicha Str., 76008, Ivano-Frankivsk, Ukraine
[e]SPE Company "Rehabilitation", 17, Lobanovsky Ave., 03037, Kyiv, Ukraine
email: [a]strafun_s@ukr.net, [b]sergey_mena@ukr.net, [c]traumaokl@gmail.com, [d]ostrafun@ukr.net, [e]anna_vovchenko.md@gmail.com

Abstract: The basis of conservative treatment is the performance of a set of exercises aimed at increasing the volume of the shoulder joint by stretching its capsule. However, stretching of the capsule occurs due to overloading of certain areas of the articular cartilage of both the scapula and the head of the humerus. The purpose of the work is to determine the changes in the stress-strained state of the articular surfaces of the humerus and the articular cavity of the scapula when attempting movements in the shoulder joint (SJ) in the conditions of various options of arthrogenic contracture. The constructed 3D model of the shoulder joint was imported into the ANSYS environment for further calculations. For calculations, a model with a SE grid was chosen, which included 1,401,723 nodes and 250,397 elements. To optimize and simplify the calculations, the connective tissue structures of the shoulder joint area (capsule, tendons of the RMP, muscles) were replaced with standard ANSYS elements, which were modeled as 4 springs, with the corresponding stiffness of 0.8 N/mm, and anterior, posterior, superior, and inferior location. Tissue changes that mimic the phenomena of contracture (arthrofibrosis) were modeled by increasing the stiffness of the corresponding spring by 10 times. As can be seen from the results of the simulated modeling, when trying to extend from an angle of 30^0 in conditions of arthrofibrosis of the anterior parts of the shoulder joint capsule and combined arthrofibrosis of the front and lower parts of the capsule of the shoulder joint, as well as when trying to bend from an angle of 30^0 in conditions of arthrofibrosis of the posterior parts of the shoulder joint capsule, there is a critical increase in stress indicators on the elements of the model, mainly on the articular cartilage and subchondral bone of the head of the humerus, the articular cartilage lip and the subchondral bone of the glenoid cavity. Thus, passive movements with resistance to extension from an angle of 30^0 in conditions of arthrofibrosis of the front parts of the shoulder joint capsule and combined arthrofibrosis of the front and lower parts of the shoulder joint capsule, as well as bending from an angle of 30^0 in conditions of arthrofibrosis of the back parts of the shoulder joint capsule, should be excluded from rehabilitation programs during the functional restoration of mobility of the shoulder joint in the conditions of its contracture.

Keywords: shoulder joint; articular cartilage; joint capsule; arthrogenic contracture; stress-deformed state; biomechanical modeling.

1 Introduction

Arthrogenic contracture is a limitation of movements in a joint, which is associated with a violation of the properties of its capsule [10; 18; 20]. Adhesive capsulitis in the stage of formed contracture is a classic example of arthrogenic contracture. The tension and relaxation of certain parts of the capsule of the SJ, depending on the position of the head of the shoulder, provides up to 20% of the stability of the joint, and the same mechanism also ensures the mobility of SJ [6; 10; 18; 20].

Among the main causes of acquired SJ contracture, post-operative and post-traumatic are distinguished [10; 20]. Any damage to the SJ (traumatic rupture of the RMP, separation of the articular lip of the scapula, fracture of the proximal epimetaphysis of the shoulder, etc.) leads to the appearance of inflammatory processes in the capsule, its thickening, which, in turn, often leads to contracture of the SJ or secondary adhesive capsulitis [6; 10; 18; 20].

The goal of treatment of any SJ contracture is to fully or partially restore the range of motion in the SJ, which is achieved both surgically (restoration of damaged structures of the SJ and partial or complete dissection of the SJ capsule) and conservative methods (physical therapy, massage, physical methods) [1; 4; 6; 18]. The basis of conservative treatment is the performance of a set of exercises aimed at increasing the volume of the SJ by stretching its capsule. However, stretching of the capsule occurs due to overloading of certain areas of the articular cartilage of both the scapula and the head of the humerus [5; 12; 19].

In practice, we often encounter the appearance of "acoustic phenomena" and pain syndrome in the area of the clavicular-acromial joint in patients who, for various reasons, develop movements in the SJ for a long time. In our opinion, this is related to the overload of the articular cartilage and the progression of arthrosis of the clavicular-acromial joint. Revealed with the help of arthroscopy changes in articular cartilage in patients with SJ adhesive capsulitis lead us to believe that a similar situation occurs in SJ, which requires a detailed study. It is possible that some movements in SJ cause a significant overload of the articular cartilage in the SJ and must be excluded or limited in patients with contracture of the SJ.

The purpose of the work is to determine the changes in the stress-deformed state of the articular surfaces of the humerus and the articular cavity of the scapula when attempting movements in the SJ in the conditions of various options of arthrogenic contracture.

2 Materials and Method

Biomechanical studies were performed on the basis of the biomechanics laboratory of the State University "Institute of Traumatology and Orthopedics of the National Academy of Medical Sciences of Ukraine", which is certified by the State Enterprise "Ukrmetrteststandard" for conducting relevant measurements (certificate PT-№107/215 dated 09.03.2021).

Using the SolidWorks software package, a simulated 3D model of the shoulder joint was constructed using anatomical and anthropometric data as close as possible to real ones. The model consisted of elements - the scapula, the cartilage of the articular cavity with a cartilaginous lip, the humerus, the cartilage of the head of the humerus (Figure 1). The constructed 3D model of the shoulder joint was imported into the ANSYS environment for further calculations.

Figure 1. Simulation 3D model (SolidWorks) of the shoulder joint

Calculations of the stress-strain state (SSS) of the model were carried out in the ANSYS software package using the finite element method (FE), which has become widespread as a numerical method for solving boundary value problems of the mechanics of continuous media, oriented to the use of a software-computer complex [17; 22].

The calculations used the physical properties of healthy bone and cartilage tissue of middle-aged people, which were obtained from literary sources [2; 8; 13; 21] (Table 1). Due to age and other reasons that can cause bone tissue degradation, the mechanical properties can vary [2; 13].

Table 1: Physical properties of bone and cartilage tissue

Tissue type	Young's modulus, MRa	Poisson's ratio
Cortical layer	17.62	0.3
Spongy layer	500	0.2
Articular cartilage	50	0..45

Bone tissue in calculations is considered as isotropic and linearly elastic. The cortical layer was modeled as a solid body with a constant thickness by shifting the outer surface inward by 1 mm [2; 8; 13].

For articular cartilage, properties were chosen that correspond to a material containing a large amount of liquid, where the modulus of elasticity increases under conditions of rapid deformation. The model includes the properties of cartilage precisely in the dense phase of its work under the influence of load, where it is presented as an incompressible elastic material. Artificial increasing of the density to the Young's modulus E=50 MPa allows observing exactly the behavior of the cartilage during processing of the main load and determining the places and conditions of its damage [13].

The finite element model (Figure 2) is created in semi-automatic mode; the size of the finite element for the bone tissue of the scapula and humerus does not exceed 1 mm; it consists mainly of tetrahedral elements; the grid is thickened in the contact points and the element sizes do not exceed 0.1 mm. Reducing the dimensions of the finite element to an acceptable level ensures the necessary detailing of the calculation model and obtaining more reliable results.

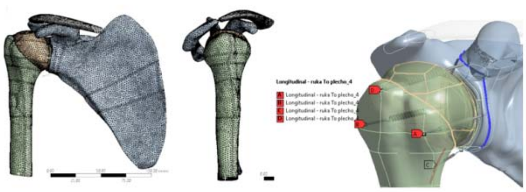
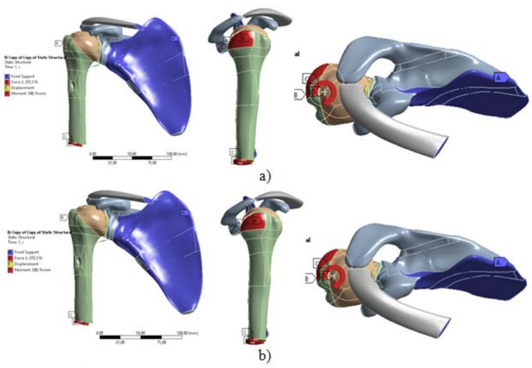


Figure 2. Finite element and calculation model

For further calculations, a model with a SE grid was chosen, which included 1,401,723 nodes and 250,397 elements (Figure 2). To optimize and simplify the calculations, the connective tissue structures of the shoulder joint area (capsule, tendons of the RMP, muscles) were replaced with standard ANSYS elements, which were modeled as 4 springs, with the corresponding stiffness of 0.8 N/mm, and the location - anterior, posterior, superior, inferior. Tissue changes that mimic the phenomena of contracture (arthrofibrosis) were modeled by increasing the stiffness of the corresponding spring by 10 times.

In order to solve the set tasks, the models underwent reconstruction for the appropriate position of the humerus relative to the scapula. SSS on elements of the shoulder joint was studied for 8 variants of tasks, for which corresponding calculation models were built (Figure 3):



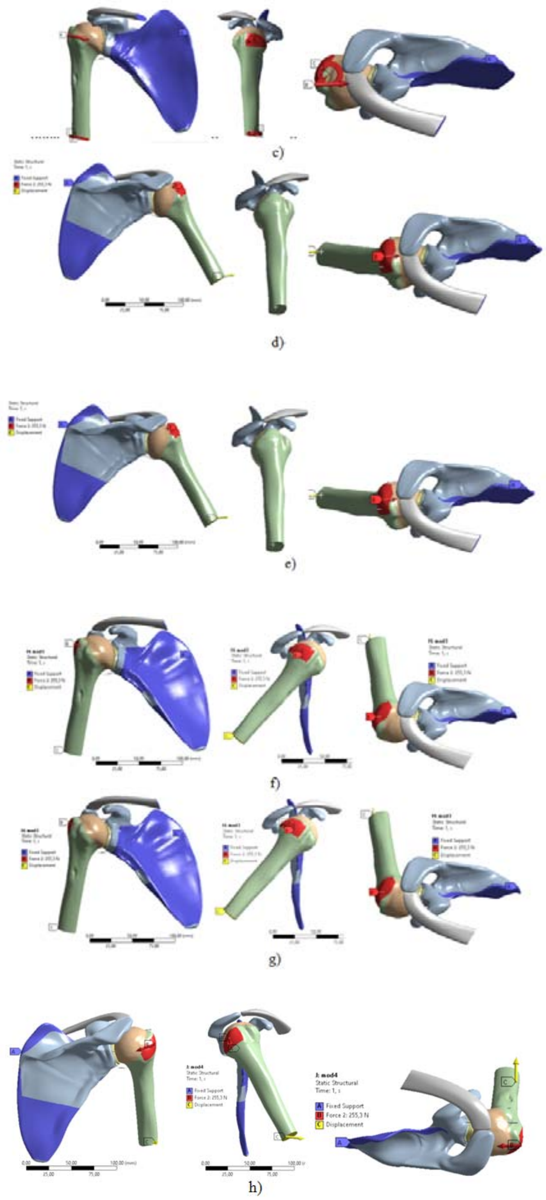


Figure 3. Simulation models of the shoulder joint for calculating SSS in case of arthrofibrosis of the joint capsule of different localization:

a) *An attempt of external rotation from an angle of 0 in conditions of arthrofibrosis of the front parts of the capsule of the shoulder joint;*
b) *An attempt of external rotation from an angle of 0 in conditions of arthrofibrosis of the front and lower parts of the capsule of the shoulder joint in combination;*
c) *An attempt of internal rotation from an angle of 0 in conditions of arthrofibrosis of the posterior parts of the capsule of the shoulder joint;*
d) *Abduction attempt in conditions of arthrofibrosis of the lower parts of the capsule of the shoulder joint (humerus is in neutral rotation and abduction 30º);*
e) *Attempted abduction in conditions of arthrofibrosis of the front and lower parts of the capsule of the shoulder joint in combination (the humerus is in neutral rotation and abduction 30º);*
f) *An attempt to extend in conditions of arthrofibrosis of the anterior parts of the capsule of the shoulder joint (the humerus is in neutral rotation and abduction of 30º);*
g) *An attempt to extend in conditions of arthrofibrosis of the front and lower parts of the capsule of the shoulder joint in*

combination (the humerus is in neutral rotation and abduction 30º);

h) *Bending attempt in conditions of arthrofibrosis of the posterior parts of the capsule of the shoulder joint (the humerus is in neutral rotation and abduction 30º).*

With the help of ANSYS tools, the limit conditions of fixation and loading (compressive force in the shoulder joint – 255.3 N), as well as additional restrictions on the movement of the scapula, are set for each position (Figure 3).

To the distal end of the humerus, additional movements were applied up to the tension of the springs, simulating the area of arthrofibrosis of the SJ capsule, respectively, for each task:

1. External rotation around the vertical axis Z by 5º;
2. External rotation around the vertical axis Z by 5º;
3. Internal rotation around the vertical Z axis by 5º;
4. Abduction along the X axis by 30 mm (rotation in the joint about 5º);
5. Abduction along the X axis by 30 mm (rotation in the joint about 5º);
6. Extension along the Y axis by 30 mm (rotation in the joint about 5º);
7. Extension along the Y axis by 30 mm (rotation in the joint about 5º);
8. Bending along the Y axis by 30 mm, rotation in the joint about 5º);

The calculation of contact stresses in the shoulder joint for all considered positions of the upper limb was performed taking into account the mass-inertial characteristics of the segments of the human musculoskeletal system [1]. The input parameters [1] were used for the calculation: human mass 75 kg, mass of the upper limb — 3.75 kg (5% of body mass P=37.5N), distance from the shoulder joint to the center of mass of the upper limb — 32 cm (Lr); the distance from the place of muscle attachment to the center of rotation in the shoulder joint is 6 cm on average (L_V). Calculation of muscle loads was carried out from the mass of the upper limb, without additional load. The total load on the muscles is equal to:

$$\sum F_M = (P \cdot Lr)/L_V = (38.5 \cdot 32)/6 = 205.3 \text{ N} \qquad (1)$$

An additional compression load on the glenoid cavity due to the intra-articular vacuum effect is also taken into account - 50 N.

$$\sum FM = 205.3+50 = 255.3 \text{ N} \qquad (2)$$

3 Results

Indicators of stress values at the corresponding areas in the contact zone of the SJ model when attempting external rotation from an angle of 0^0, in conditions of arthrofibrosis of the anterior parts of the SJ capsule are presented in Figure 4a. The fields of maximum stress values on the cavity and its cartilage are shifted to the posterior-lower sector, on the cartilaginous lip - localized in the upper sector, on the cartilage and bone surface of the humeral head - located centrally with a slight shift to the rear.

Indicators of stress values at the corresponding areas in the contact zone of the SJ model when attempting external rotation from an angle of 0^0, in conditions of arthrofibrosis of the front and lower parts of the SJ capsule in combination are presented in Figure 4b. The fields of maximum stress values on the cavity and its cartilage are shifted to the posterior-lower sector, on the cartilaginous lip - localized in the upper sector, on the cartilage and bone surface of the head of the humerus - are centrally located with a slight shift to the rear.

Indicators of stress values at the corresponding areas in the contact zone of the SJ model when attempting internal rotation from an angle of 0^0, in conditions of arthrofibrosis of the posterior parts of the SJ capsule are presented in Figure 4c. The fields of maximum stress values on the cavity and on the cartilage lip are shifted to the anterior-upper sector, on the cartilage of the cavity - to the anterior-lower sector, on the cartilage and bone surface of the head of the humerus - they are located centrally, with a downward shift.

Indicators of stress values at the corresponding areas in the contact zone of the SJ model when attempting to abduct from an angle of 30^0, in conditions of arthrofibrosis of the lower parts of the SJ capsule are presented in Figure 4d. The fields of maximum stress values on the cavity and its cartilage are shifted to the lower sector, on the cartilage lip - shifted to the back, on the cartilage and bone surface of the humeral head - localized centrally with a shift to the front-upper sector.

Indicators of stress values at the corresponding areas in the contact zone of the SJ model when attempting to abduct from an angle of 30^0 in conditions of arthrofibrosis of the front and lower parts of the SJ capsule in combination are presented in Figure 4d. The fields of maximum stress values on the cavity and its cartilage are shifted to the lower sector, on the cartilage lip - shifted to the rear, on the cartilage and bone surface of the head of the humerus - are located centrally, with a shift to the front-upper sector.

Indicators of stress values at the corresponding areas in the contact zone of the SJ model when trying to extend from an angle of 30^0 in conditions of arthrofibrosis of the anterior parts of the SJ capsule are presented in Figure 4e. The fields of maximum stress values on the cavity and its cartilages are shifted to the lower sector, on the cartilaginous lip - shifted to the anterior-upper sector, on the cartilaginous surface of the humeral head - located centrally, with a shift to the posterior-upper sector and the bony surface of the humeral head - with shifting to the lower sector.

Indicators of stress values at the corresponding areas in the contact zone of the SJ model when trying to extend from an angle of 30^0 in the conditions of arthrofibrosis of the front and lower parts of the SJ capsule in combination are presented in Figure 4f. The fields of maximum stress values on the cavity and its cartilage are shifted to the lower sector, on the cartilage lip - shifted to the front-upper sector, on the cartilaginous surface of the humeral head - located centrally, with a shift to the front and the bony surface of the humeral head - located centrally, with shifting to the lower sector.

Indicators of the stress values at the corresponding areas in the contact zone of the SJ model when attempting to bend from an angle of 30^0 in conditions of arthrofibrosis of the posterior parts of the SJ capsule are presented in Figure 4g. The fields of maximum stress values on the cavity and its cartilage are shifted to the front and antero-inferior sectors, on the cartilaginous lip - localized in the upper sector, on the cartilaginous surface of the humeral head - located centrally, with a shift to the front-upper sector, on the bony surface of the humeral head bones - with a shift to the front-upper and lower sectors.

Stress indicators on the elements of the model in the contact zone, according to the results of SSS calculations in the conditions of arthrofibrosis, in its different localization and according to each task, are presented in Table 2 and on the graphs (Figure 5).

Table 2: Stress indicators on model elements in the contact zone (MPa) according to the task

	1	2	3	4	5	6	7	8
bone tissue of the glenoid cavity	1.83	3.82	3.95	3.22	3,21	5.01	4.98	11.26
cartilage of the glenoid cavity	1.02	0.99	2.49	2.83	2,82	4.57	4.49	0.13
cartilaginous lip	2.78	2.97	10.05	3.89	3,85	6.72	6.65	17.86
humeral head cartilage	1.68	1.69	8.46	4.63	4,57	28.09	27.75	9.20

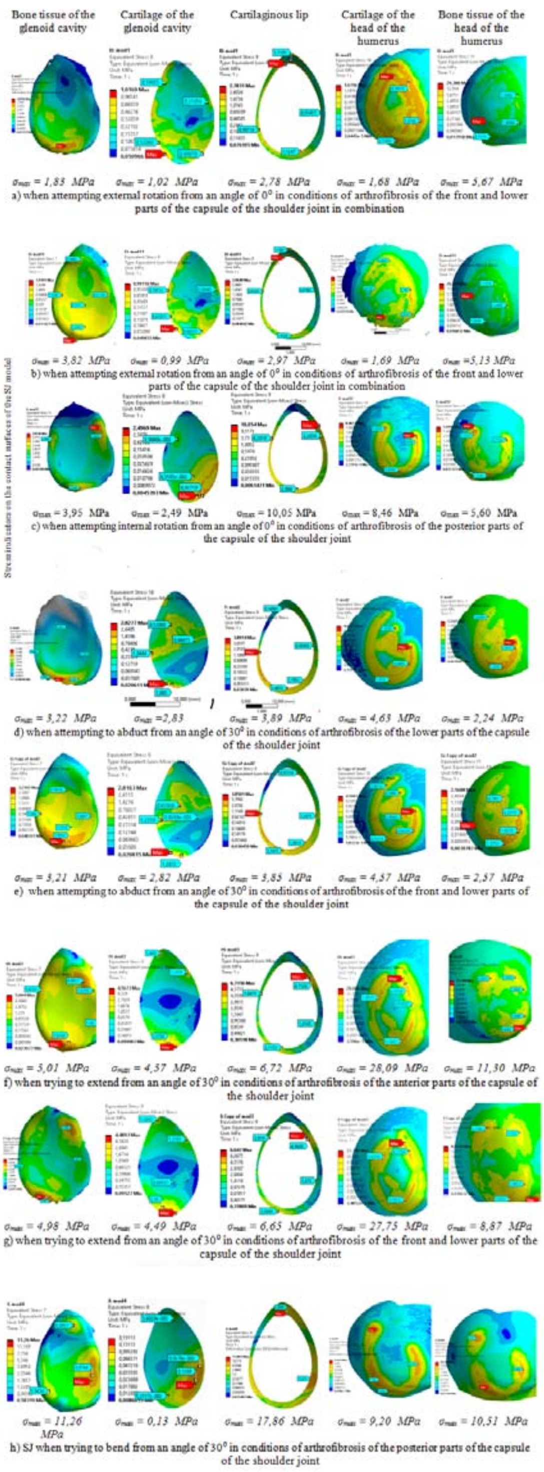


Figure 4. Indicators of stress values at the corresponding sections in the contact zone of the SJ model

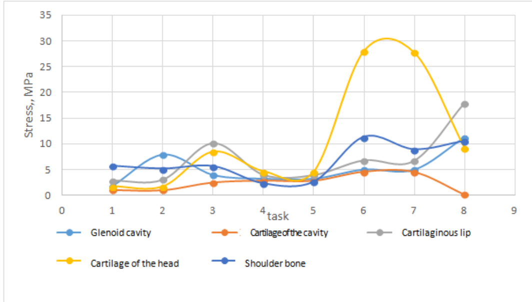


Figure 5. Stress indicators on the elements of the model in the contact zone depending on the localization of the arthrofibrosis area

The results of a comparative analysis of stress indicators on model elements in the contact zone, depending on the location of the arthrofibrosis area, are presented in Figure 6.

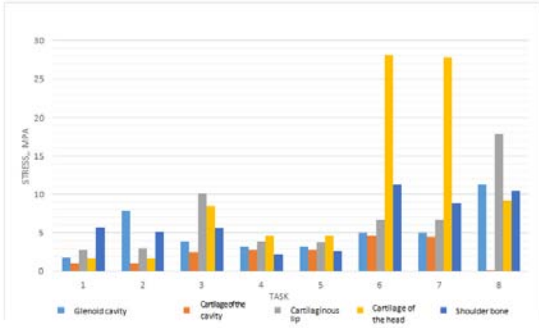


Figure 6. Comparative analysis of stress indicators on model elements in the contact zone depending on the localization of the arthrofibrosis area

Thus, an attempt at external rotation from an angle of 0^0 in conditions of arthrofibrosis of the anterior and anterior-inferior parts of the SJ capsule does not cause a significant increase in stress indicators on all elements of the model.

An attempt to abduct from an angle of 30^0 in conditions of arthrofibrosis of the lower and antero-inferior parts of the SJ capsule slightly increases the stress indicators on the cartilage of the humeral head to 4.63 MPa and 4.57 MPa, respectively.

An attempt of internal rotation from an angle of 0^0 in conditions of arthrofibrosis of the posterior parts of the capsule of the shoulder joint is accompanied by an increase in stress indicators on the cartilage lip and cartilage head of the humerus to 10.05 MPa and 8.46 MPa, respectively.

An attempt to extend from an angle of 30^0 in conditions of arthrofibrosis of the anterior parts of the shoulder joint capsule is accompanied by a significant increase in stress indicators on the cartilage of the humeral head and subchondral bone of the head to 28.09 MPa and 11.3 MPa, respectively, as well as an increase in stress on the cartilage of the glenoid cavity to 4, 57 MPa, the subchondral bone of the cavity - up to 5.01 MPa and the cartilaginous lip - up to 6.72 MPa.

An attempt to extend from an angle of 30^0 in conditions of combined arthrofibrosis of the anterior and lower parts of the SJ capsule is accompanied by a significant increase in stress indicators on the cartilage of the humeral head to 27.75 MPa, as well as an increase in stress on the subchondral bone of the head to 8.87 MPa, cartilage of the glenoid cavity - to 4.49 MPa, the subchondral bone of the cavity - up to 4.98 MPa and the cartilaginous lip - up to 6.65 MPa.

An attempt to bend from an angle of 30^0 in the conditions of arthrofibrosis of the posterior parts of the SJ capsule is accompanied by a significant increase in stress indicators on the cartilage lip and subchondral bone of the glenoid cavity - up to 17.86 MPa and 11.26 MPa, respectively, on the subchondral bone of the humeral head - up to 10.51 MPa, as well as an increase in stress on the humeral head cartilage - up to 9.2 MPa.

As can be seen from the results of the simulated modeling, when trying to extend from an angle of 30^0 in conditions of arthrofibrosis of the anterior parts of the shoulder joint capsule and combined arthrofibrosis of the front and lower parts of the capsule of the shoulder joint, as well as when trying to bend from an angle of 30^0 in conditions of arthrofibrosis of the posterior parts of the shoulder joint capsule, there is a critical increase in stress indicators on the elements of the model, mainly on the articular cartilage and subchondral bone of the humeral head, the articular cartilage lip and the subchondral bone of the glenoid cavity. Such an increase in stress indicators, especially during cyclic loads, can be the cause of the destruction and exfoliation of articular cartilage, deformation and damage of the subchondral bone, rupture of the articular lip of the scapula - as a basis for the development of osteoarthritis of the knee joint.

4 Discussion

Finite element modeling and research of SSS of articular surfaces or bone tissue have long been used by scientists for the purpose of deeper understanding of biomechanical processes in the human body when using certain fixators or implants [2; 17; 22]. The vast majority of modern English-language journals promote biomechanical research of various soft tissue injuries of the SJ on cadaveric material [3; 8; 13; 21]. In these cases, the load or stretching of certain sections of the aircraft is assessed using strain gauges or other measuring equipment. Such studies, in our opinion, do not take into account the influence of all elements of the SJ (muscles of the RMP, thickness of articular cartilage, capsule of the shoulder joint, etc.) on the biomechanical processes that take place in the joint and are quite rough, since the tissues of the human body change their properties when long-term storage or freezing. These factors are leveled when we perform computer modeling, entering the data of all joint elements into the program.

An important element of any surgical intervention is the implementation of a rehabilitation program, which has its own characteristics for any joint [10; 14; 18; 20]. The development of movements in any joint leads to overloading of the articular cartilage to one degree or another [1; 6; 7; 10; 20]. Thus, applying excessive effort to increase the range of motion in any joint can inevitably lead to damage to the articular cartilage and, sometimes, to bone fractures or damage to other joint structures. This fact must be remembered by both physical therapy specialists and rehabilitation specialists, as well as orthopedists who try to perform SJ redress under local anesthesia, without performing selective capsulotomy (Figure 7).

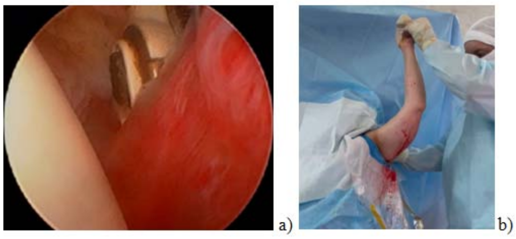


Figure 7. Stages of surgical intervention in adhesive capsulitis: a) selective capsulotomy; b) redress

Performing SSS redressing without prior selective capsulotomy is a rather difficult procedure, even under anesthesia, provided that the doctor needs to tear the capsule, the thickness of which ranges from 3 to 5 mm. In these cases, complications are almost inevitable. Among the main complications, there are: separation of the articular lip of the scapula, fracture of the head of the humerus, damage to the n. axillaris, as well as the articular cartilage of the SJ [9; 10; 15; 20]. Our Western colleagues have even developed a sequence of movements during SJ redress [9; 11; 20], which will significantly reduce the risks of a humerus fracture. The essence of these manipulations under anesthesia is that the main effort is applied to the scapula, which is displaced during flexion or elevation in the SJ, and not to the distal third of the humerus. In addition, rotational movements in the SJ, which can lead to a helical fracture of the humerus, are prohibited.

Interesting ones, in our opinion, are studies of biomechanics of bone tissue in which the authors show the influence of such factors as load or limitation of movements in the joint on the development of osteoporosis [16; 23; 25]. However, we could not find an analysis of the influence of these factors on the articular cartilage of the SJ in the available literature.

An increase in the range of motion in the SJ, which is the most mobile joint of our body, is inextricably linked to exercise of heeling fitness. Our study, in the conditions of SJ contracture, gives us the opportunity to determine and predict overloading of certain areas of the articular cartilage during the development of movements in the SJ and to exclude from the physical therapy program those exercises that cause damage to the articular cartilage.

During numerous surgical interventions in patients with idiopathic or secondary adhesive capsulitis of the SJ, we often encounter areas of articular cartilage with injuries of various degrees according to Otterbridge (Figure 8).

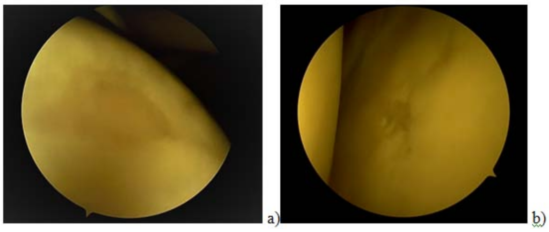


Figure 8. Arthroscopy of the shoulder joint: a) damage to the articular cartilage of the shoulder head, b) damage to the articular cartilage of the articular surface of the scapula

And while in patients with secondary adhesive capsulitis, damage to the articular cartilage can be associated with various soft tissue pathologies of the SJ (rupture of the articular lip of the scapula, tendons of the rotator cuff of the shoulder, etc.), in patients with idiopathic adhesive capsulitis, we usually report that damages to the articular cartilage were related with the irrational use of hormonal drugs. However, the damage to the articular cartilage of the SJ in patients who did not undergo distensive intra-articular injections with hormonal drugs led us to believe that there are other causes of this pathology.

Thus, our study expands the indications for performing selective capsulotomy in patients with SJ contracture on the background of both idiopathic and secondary adhesive capsulitis, especially in cases where there is no progress in rehabilitation. At the same time, it should not be forgotten that the performance of selective capsulotomy in patients with idiopathic adhesive capsulitis gives good results when the surgical intervention is performed at the stage of the formed contracture. Our Western colleagues recommend performing arthroscopy even for patients after SJ prosthetics, justifying this by the presence of scars in the SJ. Probably, the components of the endoprosthesis are overloaded and damaged in the presence of long-term contracture of the SJ.

What is interesting, in our opinion, is the fact that namely the presence of combined arthrofibrosis of the front and lower parts of the SJ capsule causes a critical increase in stress indicators on the model elements. Dissecting the front and lower parts of the SJ capsule significantly reduces the force used by the surgeon to elevate the SJ during its redress.

The results obtained during this study may also expand the indications for the use of injectable chondroprotectors in patients with SJ contracture.

5 Conclusion

Thus, passive movements with resistance to extension from an angle of 30^0 in conditions of arthrofibrosis of the front parts of the shoulder joint capsule and combined arthrofibrosis of the front and lower parts of the shoulder joint capsule, as well as bending from an angle of 30^0 in conditions of arthrofibrosis of the back parts of the shoulder joint capsule, should be excluded from rehabilitation programs during the functional restoration of mobility of the shoulder joint in the conditions of its contracture. Also, passive movements with resistance to internal rotation from an angle of 0^0 in conditions of arthrofibrosis of the posterior parts of the capsule of the shoulder joint, as well as abduction from an angle of 30^0 in conditions of arthrofibrosis of the lower and front-lower parts, should be treated with caution and a clear dosage of the load. Age-related changes and the presence of osteoporosis can aggravate the process with the destruction of bone tissue, both in the glenoid cavity and the head of the humerus. Wrinkling of the cancellous layer of the bone tissue of the glenoid cavity of the humeral head in the areas of articular contact happens under the influence of load in conditions of contracture of the shoulder joint.

Literature:

1. Ando, A., Sugaya, H., Hagiwara, Y. et al. (2013). Identification of prognostic factors for the nonoperative treatment of stiff shoulder. *International Orthopaedics, 37,* 859-864. doi: 10.1007/s00264-013-1859-8
2. Ciarelli, M. J., Goldstein, S. A., Dickie, D., Ku, J. L., Kapper, M., Stanley, J., Flynn, M. J., Matthews, L. S. (1986). Experimental determination of the orthogonal mechanical properties, density, and distribution of human trabecular bone from the major metaphysical regions utilizing materials testing and computed tomography. Transactions of the Orthopedic Research Society, (1986) p. 42. doi.org/10.1016/0021-9290(87)90023-6
3. Dashottar, A., & Borstad, J. (2016). Quantifying Range-of-Motion Changes Across 4 Simulated Measurements of the Glenohumeral Joint Posterior Capsule: An Exploratory Cadaver Study. *Journal of Orthopaedics & Sports Physical Therapy, 46(*12), 1080-1085. doi:10.2519/jospt.2016.6440.
4. Ebrahimzadeh, M.H., Moradi, A., Bidgoli, H.F., Zarei, B. (2019). The relationship between depression or anxiety symptoms and objective and subjective symptoms of patients with frozen shoulder. International *Journal of Preventive Medicine, 10*, 38. doi: 10.4103/ijpvm.IJPVM_212_17
5. Elhassan, B., Ozbaydar, M., Massimini, D. et al. (2009). Arthroscopic capsular release for refractory shoulder stiffness: a critical analysis of effectiveness in specific etiologies. *Journal of Shoulder and Elbow Surgery, 19*, 580-587. doi: 10.1016/j.jse.20 09.08.004.
6. Fields, B., Skalski, M.R., Patel, D.B. et al. (2019). Adhesive capsulitis: review of imaging findings, pathophysiology, clinical presentation, and treatment options. *Skeletal Radiology, 48*(8), 1171-1184. doi: 10.1007/s00256-018-3139-6.
7. Goldstein, S.A. (1987). The mechanical properties of trabecular bone: Dependence on anatomic location and function. *Journal of Biomechanics, 20*(11-12), 1055-1061. doi: 10.1016/ j.jbiomech.2012.07.023
8. Han, F., Kong, C.-H., Hasan, M., Ramruttun, A., Prem Kumar, V. (2019). Superior capsular reconstruction for irreparable supraspinatus tendon tears using the long head of biceps: A biomechanical study on cadavers. *Orthopaedics & Traumatology: Surgery & Research, 105*(2), 257-263. : 10.1016/j.otsr.2018.10.023.
9. Huang, C.Y., Stankiewicz, A., Ateshian, G.A., Mow, V.C. (2005). Anisotropy, inhomogeneity, and tension–compression nonlinearity of human glenohumeral cartilage in finite deformation. *Journal of Biomechanics, 38*(4), 799–809. doi:10.1016/j.jbiomech.2004.05.006
10. Itoi, E., Arce, G., Bain, G.I. et al. (2016). Shoulder stiffness: Current concepts and concerns. *Arthroscopy, 32*, 1402-1414. doi: 10.1016/j.arthro.2016.03.024
11. Johnson, D. H., Amendola, A., Barber, F. A. et al. (2012). *Operative Arthroscopy*. (4th ed.). Lippincott Williams & Wilkins.
12. Kim, J., Ha, D., Kim, S. et al. (2019). Does arthroscopic preemptive extensive rotator interval release reduce postoperative stiffness after arthroscopic rotator cuff repair? A prospective randomized clinical trial. *Journal of Shoulder and Elbow Surgery, 28*, 1639-1646. doi: 10.1016/j.jse.2019.05.021
13. Kwak, J.-M., Lee, K., Jung, G.-H., Kholinne, E., Hwang, S., Koh, K., Jeon, I.-H. (2023). Biomechanical impact of elbow motion in elbow stiffness *International Orthopaedics, 47*(7), 1779-1786.doi: 10.1007/s00264-023-05781-2.
14. Manocha, R., Banayan, S., Johnson, J.A., King, G. (2022). Overhead arm positioning in the rehabilitation of elbow dislocations: An in vitro biomechanical study. *Journal of Hand Therapy, 35*(2), 245-253. doi: 10.1016/j.jht.2022.01.008.
15. Mansat, P., Barea, C., Hobatho, M.-C., Darmana, R., Mansat, M. (1998). Anatomic variation of the mechanical properties of the glenoid. *Journal of Shoulder and Elbow Surgery, 7*, 109-115. https://doi.org/10.1016/S1058-2746(98)90 219-1
16. Morgan, E. F et al. (2018). Bone Mechanical Properties in Healthy and Diseased States. *Annual Review of Biomedical Engineering, 20*, 119-143. doi:10.1146/annurev-bioeng-062117-121139
17. Natali, A. N., & Meroi, E. A. (1988). A review of the biomechanic properties of bone as a material. *Journal of Biomechanical Engineering*, *11*, 266-275. DOI: 10.1016/0141-5425(89)90058-7.
18. Ramirez, J. (2019). Adhesive capsulitis: Diagnosis and management. *American Family Physician, 99*(5), 297-300.
19. Ricchetti, E.T. (2019). Editorial commentary: in search of the optimal diagnostic tool for periprosthetic joint infections of the shoulder. *Arthroscopy, 35*, 2578-2580. doi: 10.1016/j.arthro .2019.05.004
20. Rockwood, Ch., & Matsen, F. (2022). *The Shoulder* (6th ed.) Elsevier.
21. Shiota, Y., Yamamoto, N., Kawakami, J., Nagamoto, H., Muraki, T., Kaneko, K., Itoi, E. (2017). Contact pressure of the coracoacromial arch in shoulders with joint contracture: A cadaveric study. *Journal of Orthopaedic Science, 22*(6), 1031-1041. doi:10.1016/j.jos.2017.06.018
22. Simpson, H., & Augat, P. (2015). *Experimental research methods in orthopedics and trauma*. Thieme Verlag.
23. Tamimi, I., Cortes, A., Sánchez-Siles, J. M., Ackerman, J. L., González-Quevedo, D., García, Á., Yaghoubi, F., Abdallah, M. N., Eimar, H., Alsheghri, A., Laurenti, M., Al-Subaei, A., Guerado, E., García-de-Quevedo, D., & Tamimi, F. (2020). Composition and characteristics of trabecular bone in osteoporosis and osteoarthritis. *Bone, 140*, 115558. https://doi.org/10.1016/j.bone.2020.115558.
24. Voight, M.L. (2017). Shoulder Instability. In: *Orthopedics Physical Therapy secrets*. Hanley & Belfus, Philadelphia.
25. Zhen, G., Guo, Q., Li, Y., Wu, C.,] Zhu, Sh., Wang, R., Guo, H., Kim, B., Huang, J., Hu, Y., Dan, Y., Wan, M., Ha, T., An, S., Cao, X. (2021). Mechanical stress determines the configuration of TGFβ activation in articular cartilage. *Nature Communications, 12*(1), 1706. doi:10.1038/s41467-021-21948-0.

Primary Paper Section: F

Secondary Paper Section: FJ