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Analysis of the stress-strain state three-dimensional model of a healthy shoulder joint

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Objective. To work out as close as possible to normal human anatomy three-dimensional finite element model of the shoulder joint with elastic ligaments as well as with muscles and the spatial location of their attachment points, to analyze the stress-strain state of the element proximal humerus and scapula. Methods. A geometric model of the humerus and scapulae are constructed. The three-dimensional modeling of the shoulder join based on the geometric models was used with software SolidWorks with mathematical modeling method finite elements and the stress-strain state analysis in the application package Ansys software. To approach the real conditions of the model we have added the elastic elements that mimic muscles. Model loaded with forces that reproduce the effort in the muscles, applied to the respective contact planes on the humerus head of the human bone. The stress-strain state of proximal elements is calculated in the humerus and scapula for the angles of the abduction — 0°, 30°, 60° and 90° in neutral rotation of the humerus. Results. The tensile stresses in the scapula are distributed in such a way that at an angle of 0 ° the limb is not raised +5.67 MPa in the area below the joint depressions. The minimum values of the compressive stress have been reached 18.5 MPa. Maximum stresses are in 1.5–2 times higher area of the articular cartilage of the humerus head compared to the cartilage of the glenoid cavity of the scapula. It is established that the dependence of the values of the area of the contact zone in the range of change limb abduction angle (0° ... 90°) can be approximated section of a cubic parabola, with changes in area insignificant and are equal to +2.26% — 7.3 % of the value in neutral position at an angle of 0°. Minor differences with the results of similar studies indicate that the validity of the developed mathematical model. Conclusions. The proposed model would allow performing more correct mathematical modeling and comparative analysis of the stress-strain state for various methods of surgical treatment of pathology shoulder joint, in particular arthroplasty. Key words. Shoulder joint, humerus, articular cartilage, contact area of the scapula,three-dimensional model, finite element method, stress-strain state.

Мета. Розробити максимально наближену до нормальної анатомії людини тривимірну скінченно-елементну модель плечового суглоба з урахуванням пружних зв'язків (м'язів) і просторового розташування точок їхнього кріплення, проаналізувати напружено-деформований стан (НДС) елементів проксимального відділу плечової кістки та лопатки. Методи. Побудовано геометричну модель плечової кістки та лопатки. Для тривимірного моделювання плечового суглоба на основі геометричних моделей використано програму SolidWorks із математичним моделюванням методом скінченних елементів й аналізом НДС у пакеті прикладних програм Ansys. Для наближення до реальних умов у модель додані пружні елементи, які імітують м'язи. Модель навантажували силами, які відтворюють зусилля в м'язах, прикладеними до відповідних площин контакту на головці плечової кістки. Розраховано НДС елементів проксимального відділу плечової кістки та лопатки для кутів відведення кінцівки 0°, 30°, 60° і 90° у нейтральній ротації плечової кістки. Результати. Напруження розтягнення в лопатці розподілені в такий спосіб, що за кута 0° відведення кінцівки не перевищували +5,67 МПа в зоні, розташованій нижче суглобової западини. Мінімальні значення напруження стискання досягли 18,5 МПа. Максимальні напруження більші в 1,5–2 разу в зоні суглобового хряща головки плечової кістки порівняно з хрящем гленоїдальної западини лопатки. Установлено, що залежність значень площі контактної зони в діапазоні зміни кута відведення кінцівки (0°... 90°) може бути апроксимована ділянкою кубічної параболи, при цьому зміни площі незначні та дорівнюють +2,26 % ...–7,3 % від значення в нейтральному положенні за кута відведення 0°. Розбіжності з результатами аналогічних досліджень указують на достовірність розробленої математичної моделі. Висновки. Використання запропонованої моделі дозволить коректніше проводити математичне моделювання та порівняльний аналіз НДС за різних методів хірургічного лікування патології плечового суглоба, зокрема ендопротезування.

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Key words. Shoulder joint, humerus, articular cartilage, contact area of the scapula,three-dimensional model, finite element method, stress-strain state

Introduction

A healthy human shoulder joint is a complex anatomical formation ensuring both maximum range of motion and stability of the position of the upper limb in the three-dimensional coordinate system [1]. Three-dimensional modeling and finite element method (FEM) in the biomechanics of the shoulder joint are used for comparative assessment both in norm and abnormalities, for example, in instability of the shoulder joint, ruptures of the rotator cuff, during various types of osteosynthesis and endoprosthesis [2, 3]. The main problem in the development of a three-dimensional finite-element model of the shoulder joint and the study of its stress-strain state (SSS) is the difficulty of modeling anisotropic inhomogeneous material under conditions of comparative evaluation with experimental parameters. A number of difficulties in creating models are the variety of individual physiological characteristics of bone, cartilage, muscle and connective tissue of the shoulder joint [4]. It should be noted that most experimental studies to study the stresses that occur in the area of the shoulder joint are limited by in vitro conditions [5, 6]. Significant simplification of three-dimensional models of the shoulder joint [2] leads to difficulties in conducting a comparative analysis of stress distribution and interaction of different components of musculoskeletal structures of the shoulder joint, which, in turn, does not allow to obtain any clinically useful conclusions. Although articular surface of the glenoid cavity is known to be smaller than the humerus, it provides a range of motion greater than in other human joints, while the stability of the shoulder joint is achieved by soft tissues, which necessitates the modeling of muscles and other structures when calculating the SSS to obtain indicators close to experimental [2, 4]. FEM-based mathematical models of solid medium mechanics are a powerful tool for analytical assessment of SSS conditions of musculoskeletal system models [4, 5], which are usually impossible to measure in vivo. Thus, elaboration of a three-dimensional mathematical model of the shoulder joint, as close as possible to normal human anatomy, consisting of a soft tissue structure that stabilizes the shoulder joint, is relevant and deserves further study.

The purpose of the study: to develop three-dimensional finite element model of the shoulder joint as close as possible to normal human anatomy, taking into account the elastic connections (muscles) and the spatial location of their attachment points, to analyze the stress-strain state of the proximal humerus and scapula.

Material and methods

FEM-based software was used to calculate the SSS of the elements of the proximal humerus and scapula, as well as to determine the stress distribution [11, 12]. FEM is an effective tool for solving problems of static loading of various structures. We employed matrix equation, which can determine displacement of the nodes of the model (1) [12, 13]:

$$[K]_e\{U\}_e = \{F\}_e + \{P\}_{eg} + \{P\}_{eq} + \{P\}_{e\varepsilon_0} + \{P\}_{e\sigma_0} \quad (1),$$

where $[K]_e$ — is the element stiffness matrix; $\{U\}_e$ — is the vector of nodal displacements of the element; $\{F\}_e$ — is the vector of nodal forces of the element; $\{P\}_{eg}$, $\{P\}_{eq}$ — are vectors of nodal forces, statically equivalent to mass and surface forces; $\{P\}_{e\varepsilon 0}$, $\{P\}_{e\sigma 0}$ — are vectors of nodal forces, statically equivalent to the initial deformations and stresses.

The general system of equilibrium equations of the whole finite-element model of the studied deformed solid body is formed from the conditions of equilibrium of nodes or by means of variational principles, as well as methods of residuals. For statics tasks, it has the form (2) [11–13]:

$$[K]\{U\} = \{P\} + \{P\}^q + \{P\}^g + \{P\}^{\varepsilon_0} + \{P\}^{\sigma_0} \quad (2),$$

where $[K]$ — is the global stiffness matrix of the finite element model; $\{P\}$ — is the global vector of given external nodal forces; $\{P\}^q$, $\{P\}^g$, $\{P\}^{\varepsilon_0}$, $\{P\}^{\sigma_0}$ — are, respectively, global vectors of nodal forces equivalent to distributed surface and mass forces, initial deformations and stresses.

The general system of equations obtained by the FEM for a static linear-elastic model of a body is mathematically a system of linear algebraic equations. The global vector of nodal displacements {U} becomes a solution of equation (1) following the assessment of the superimposed connections that do not allow the model to move as a solid body. After its determination, the vectors of nodal displacements of the elements $\{U\}_e$ are calculated. Next, displacement of any points of the elements is calculated by interpolation using the shape function.

Differentiating the approximating functions of displacements inside the elements, we can determine the deformation and Hooke's law to calculate the stress (3):

$$\{\sigma\} = [D]\{\varepsilon^{el}\} \qquad (3),$$

where $\{\sigma\} = \{\sigma_x\ \sigma_y\ \sigma_z\ \sigma_{xy}\ \sigma_{yz}\ \sigma_{xz}\}^T$ — is the stress vector; $\{\varepsilon^{el}\} = \{\varepsilon_x\ \varepsilon_y\ \varepsilon_z\ \varepsilon_{xy}\ \varepsilon_{yz}\ \varepsilon_{xz}\}^T$ — is the strain vector.

A geometric model of the humerus and scapula is constructed. Three-dimensional modeling of the shoulder joint based on geometric models was performed using SolidWorks 2019 SP 1.0 software with mathematical modeling of FEM and SSS analysis in the application package Ansys, 2019. The applied software automatically calculates all stages of FEM.

To approximate the physical and strength characteristics of the calculation model to the real human humerus, the computer model is divided into layers. The general view of the model of the humerus and scapula is shown in Fig. 1. The calculated model of the shoulder joint includes the cartilaginous articular surfaces on the humerus and the glenoid cavity of the scapula.

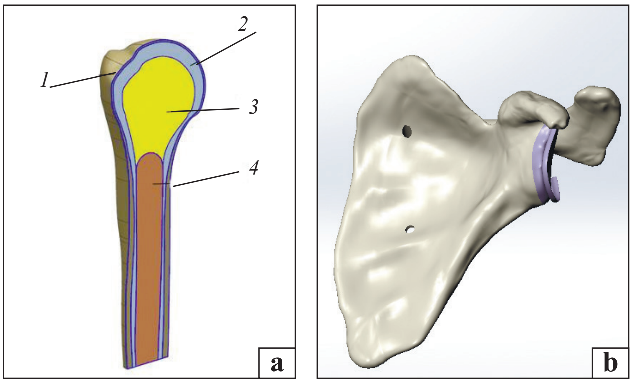


Fig. 1. Model of the proximal humerus (a) and scapula (b). Cortical (*1*), subchondral (*2*) and spongy (*3*) layers; bone marrow canal (*4*)

Physico-mechanical properties of the layers of the model (Table 1), as well as the nature of the model load for all calculations were assumed to be constant [3, 14–18]. We analyzed the options for loading the humerus in the position of neutral rotation with angles of abduction in the shoulder joint 0°, 30°, 60° and 90°.

To the geometric models of the humerus and scapula, according to normal human anatomy, were added elastic elements that mimic muscles: supraspinatus, infraspinatus, subscapular, minor and major teres, latissimus dorsi, minor and major rhomboid, trapezius, minor and major pectoral, deltoid. Fig. 2 schematically shows the sites of attachment of the supraspinatus muscle as an example of modeling.

A kinematic model in the Rigid Dynamics module was created to determine the effort in the muscles at different positions of the elements of the shoulder joint. The humerus is connected to the scapula by elastic elements that mimic muscles at the attachment points, as described above. Muscle characteristics are given in Table 2, kinematic model and load conditions in Fig. 3. The load on the humerus and scapula occurred by moving and turning in the appropriate positions (Fig. 4).

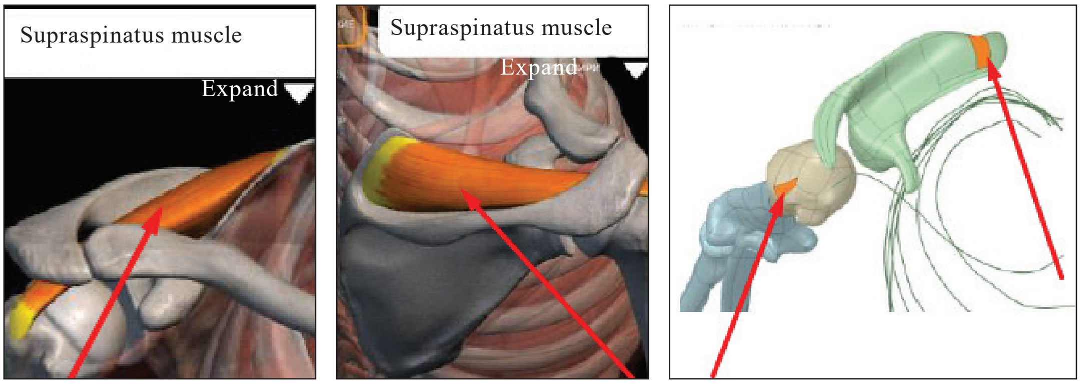


Fig. 2. Anatomical location of the supraspinatus muscle and the place of attachment on the model of the shoulder joint (top view)

Table 1

Physico-mechanical properties of bone and cartilage tissues in the model

Tissue type	Density, kg/m³	Young's modulus, E, GPa	Poisson's ratio, ν	Tensile strength, σ+, МПа	Compressive strength, σ–, МПа
Cortical	1640	12.65	0.30	157.0	200.0
Subchondral	900	2.20	0.30	300.0	100.0
Spongy	200	0.47	0.48	3.9	28.6
Cartilage	1300	9.00	0.30	12.0	50.0

The calculation of contact stresses in the shoulder joint for all considered positions of the upper limb was performed taking into account findings of the studies [1, 3]. The following initial parameters were employed during the calculation [3]: human weight 76 kg, upper limb weight 3.8 kg (5 % of body weight), distance from the shoulder joint to the center of the upper limb mass 32 cm; to the center of hand mass 74 cm.

In all calculated cases, the vertical external force was applied to the hand and was equal to 200 N. Elaboration of a new three-dimensional model of the shoulder joint involved taking into account muscles, considered the most important for this load: middle (MM), anterior (AM) and posterior (PM) parts of the deltoid, supraspinatus (SM), infraspinatus together with minor teres (IM), subscapular (SSM).

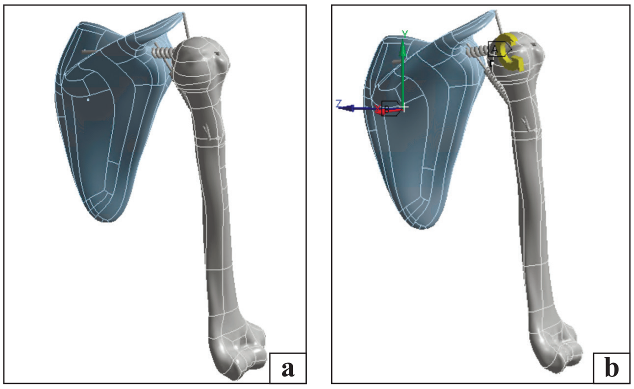


Fig. 3. Shoulder joint: kinematic model (a) and load diagram (b)

Muscles were modeled as three-dimensional and one-dimensional elastic elements (springs) along the main directions of their action (for example, from the starting point on the humerus to the point of attachment on the shoulder blade), depending on the calculated case. The cross-sectional area of the three-dimensional elements was chosen based on the conditions of ensuring the required rigidity. The middle deltoid muscle with a longitudinal stiffness of 52.2 N/mm was chosen as the main one [7]. The stiffness of other muscles was determined in proportion to the stiffness of the MM by multiplying it by the appropriate factor (this technique is described in [3]).

Schemes with applied forces for the calculated cases of the angles of the limb at 30°, 60° and 90° are shown in Fig. 4.

Calculation of the used kinematic model of a shoulder joint yielded the value of efforts in muscles (Table 3) depending on an angle of abduction of an extremity.

The finite element model (FEM) of the humerus, built on the basis of a three-dimensional geometric model, is shown in Fig. 5. Second-order solid dimensional elements are used. The constructed FEM contains 425 thousand Tetra10 elements (tetrahedron with 10 nodes) and 285 thousand nodes. The mean linear size of the elements is 2 mm. The scapula is connected to the ribs and spine by connections

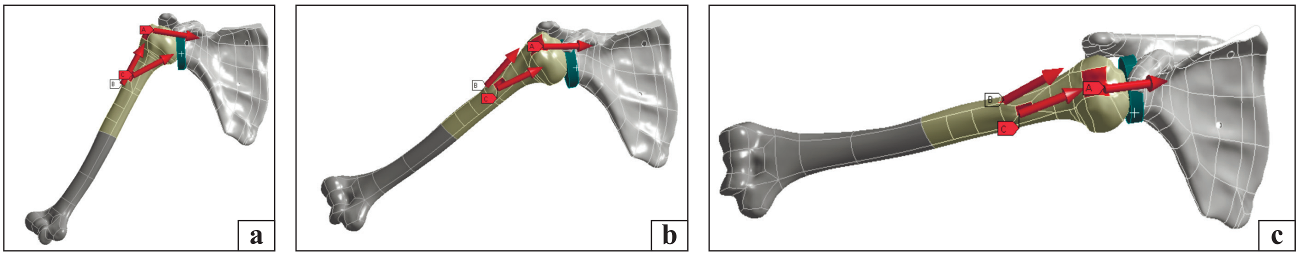


Fig. 4. Three-dimensional model of the shoulder joint for the calculated cases of the angle of humerus abduction by: a) 30°; b) 60°; c) 90°

Table 2

Characteristics of the muscles used in the three-dimensional model of the shoulder joint

Muscle characteristics	Muscle					
	MM	AM	PM	SM	SSM	IM
Length L_i, mm	110.8	129.1	129.1	80.9	99.2	99.2
Section plane A_i, mm^2	10	10	10	10	10	10
Calculation of the coefficient (according to the method [3]), $r_i = F_i/F_{MD}$	1.0	0.8	0.2	0.5	0.5	0.5
Stiffness K_i, $K_i = KC_{MM} \cdot r_i$ N/mm	52.20	41.76	10.44	26.10	26.10	26.10
Module E_i, $E_i = K_i \cdot L_i/A_i$, MPa	578.5	539.4	134.8	211.3	258.9	258.9

of «joint» type. The spine is rigidly fixed in the upper and lower parts (zones C and D), and the sternum to it (zone E) (Fig. 5). The humerus is in contact with the scapula of the «bonded» type, attached to the spine and sternum. The model was loaded with forces that mimic the forces in the muscles applied to the respective planes of contact on the head of the humerus.

During the calculation, the fact that all the constituent elements of the shoulder joint consist of brittle materials is taken as a basis, therefore, in order to analyze their strength, the first theory of strength was used [8–10]. It is based on the hypothesis that the material acquires a dangerous state when the maximum in absolute value of the main stress reaches a value corresponding to the dangerous state in the case of simple stretching or compression [11–14]. The main are the normal stresses on the planes of the selected element of the body with zero tangential stresses, there are three values, namely the first, second and third main stresses, of which the first in its indicator are the maximum, and the third are the minimum ones. Within this theory, the first and third principal stresses are, for the most part, compared to the tensile strength of the material during tensile and compressive pressure, respectively.

Thus for each element two values of a safety margin from which the minimum is chosen are calculated.

To visualize the distribution of stresses in the articular cartilage of the humeral head, glenoid cavity, cortical, subchondral and spongy layers, two cross-sectional planes of the proximal humerus were used (Fig. 6).

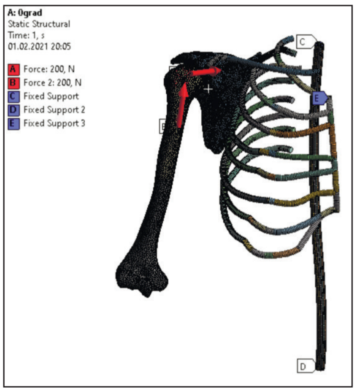


Fig. 5. Model of the shoulder joint in the form of a network of finite elements with added forces mimicking the forces in the muscles, in a position with an angle of shoulder joint abduction of 0°

Results and their discussion

SSS calculations of the elements of the proximal humerus and scapula for the four angles of limb abduction (0°, 30°, 60° and 90°) in the neutral rotation of the humerus were performed (Fig. 7–14). Calculations established that depending on the angle of the limb, the distribution of maximum and minimum main stresses for the cortical layer of the humerus (Fig. 7, a, c) in the articular cartilage of the humeral head (Fig. 7, b, d) is nonlinear. This is due to the complex contact surface, changing the directions of the resulting vectors of reactions that mimic muscle elements, moving the points of attachment of elastic ligaments.

The maximum stresses in the scapula with an angle of 0° of the humerus are given in Fig. 8. The tensile stresses in the scapula are distributed in such a way that in the position with an angle of 0° of the limb does not exceed +5.67 MPa in the area below the joint cavity. The minimum values of the compressive stress reach 18.5 MPa.

Table 4, 5 shows the minimum and maximum main stresses in the shoulder joint, obtained after modeling

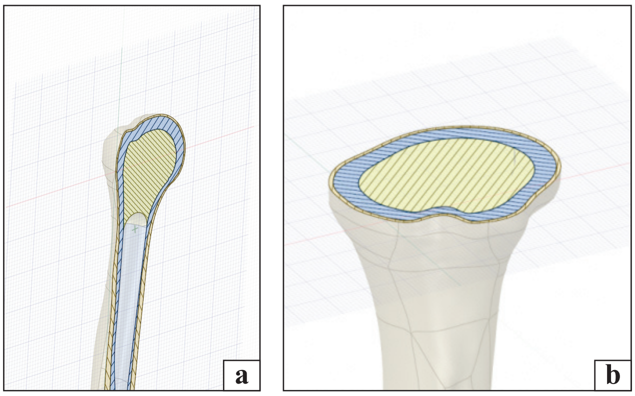


Fig. 6. View of the cross-sectional planes of the head of the humerus: a) sagittal passes through the geometric middle of the great tubercle, head and diaphysis of the humerus; b) axial perpendicular to the vertical axis of the diaphysis of the humerus at the level of the lower third of the head

Таблиця 3

Зусилля в м’язах залежно від кута відведення плечової кістки під час моделювання

Muscle (indicated in Fig. 5)	Muscle effort (N) depending on the angle of abduction		
	30°	60°	90°
SM (a)	102	267	364
AM (b)	112	245	505
MM (c)	463	808	1417

the SSS using Ansys software. The values of stresses were much lower than the stress limits for the materials of the elements of the shoulder joint (Table 1).

There are studies of SSS of the shoulder joint with various injuries of the articular lip, where an increase in stress in the head of the humerus is set by 1.22 ... 2.65 times [2–4].

Table 4

Maximum and minimum main stresses in the elements of the joint in a position with an angle of 0° of humerus abduction

Element of the shoulder joint	Main stresses, MPa	
	minimum	maximum
Cortical layer of the humerus	–13.70	+12.90
Cortical layer of the scapula	–18.50	+5.67
Articular cartilage of the head of the humerus	–1.37	+1.28
Articular cartilage of the glenoid cavity of the scapula	–3.58	+3.60
Spongy bone of the head of the humerus (sagittal section)	–0.24	+8.86
Subchondral bone of the humeral head (axial section)	–3.24	+6.78

Our study showed that the maximum stresses are 1.5–2 times higher in the area of the articular cartilage of the humeral head in comparison with the cartilage of the glenoid cavity of the scapula (Table 5). Assessment of the obtained data showed that the dependence of the values of the area of the contact zone (Table 6) in the range of changes in the angle of the limb (0° ... 90°) can be approximated by the area of the cubic parabola, with changes in area insignificant and equal to +2.26% ...– 7.3% of the value in the neutral position at an abduction angle of 0°.

The use of FEM to study the shoulder joint is a tool that can improve the understanding of biomechanics in norm and abnormalities (various types of instability, deficiency of the rotational cuff of the shoulder, osteoarthritis). Many models of the shoulder joint have now been proposed and discussions continue about their features, advantages and disadvantages [2–4].

Recently, FEM-based studies of the shoulder joint have tended to build models taking into account data on muscle strength and/or bone movement proceeding from dynamic measurements and complex simulations of several bodies with different properties. Despite the complexity of modeling multiple bodies, this integration provides more precise

Table 5

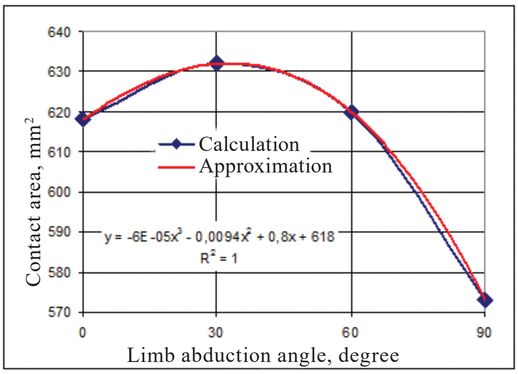
Maximum and minimum main stresses in the articular cartilage and the contact zone of the scapula in positions with an abduction angle of 30°, 60° and 90°

Element of the shoulder joint	The angle of the humerus, degree	Main stresses, MPa	
		minimum	maximum
Articular cartilage of the head of the humerus	30°	–13.70	+2.40
	60°	–18.50	+10.40
	90°	–3.58	+13.80
Articular cartilage of the glenoid cavity of the scapula	30°	—	+1.66
	60°	—	+4.08
	90°	—	+3.62

Table 6

Value of the contact zone area at different angles of the limb

Limb abduction angle, degree	Contact area, mm^2
0°	618
30°	632
60°	620
90°	573



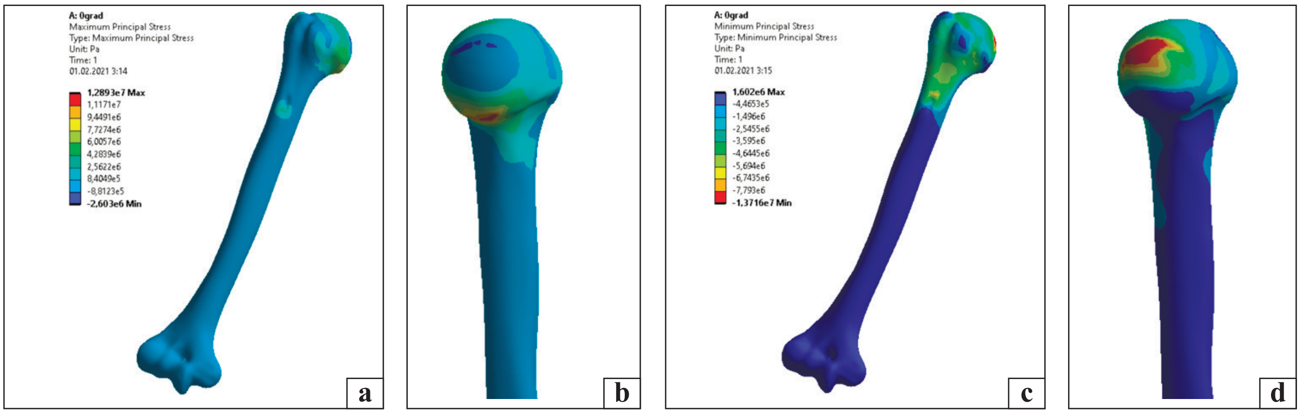


Fig. 7. Maximum (a, b) and minimum (c, d) main stresses (Pa) in the position with 0° angle of the humerus abduction in the cortical layer (a, c) and articular cartilage of the head (b, c) of the humerus

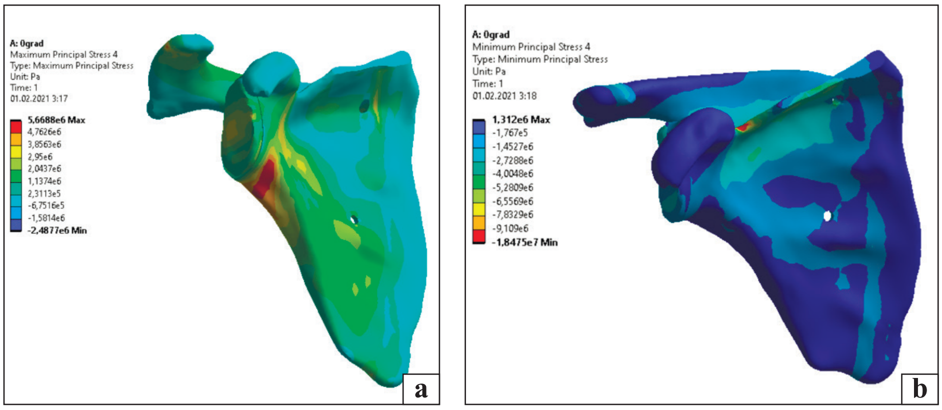


Fig. 8. Maximum (a) and minimum (b) main stresses (Pa) in the scapula in the position of 0° angle of the limb abduction

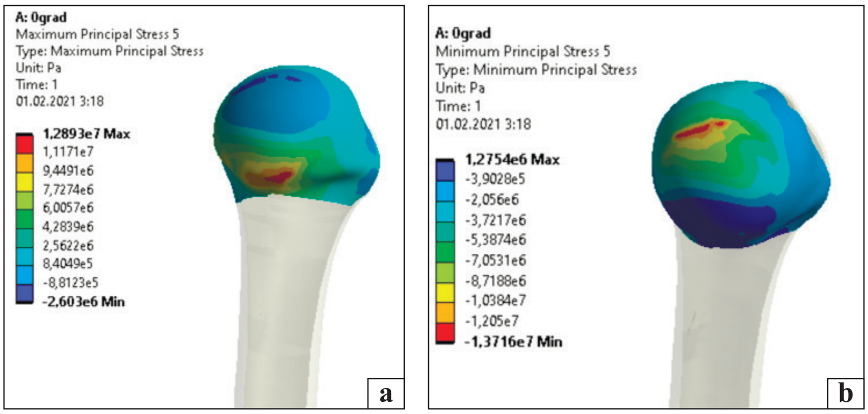


Fig. 9. Maximum (a) and minimum (b) main contact stresses (Pa) in the articular cartilage of the head of the humerus in the position of 0° angle of the limb abduction

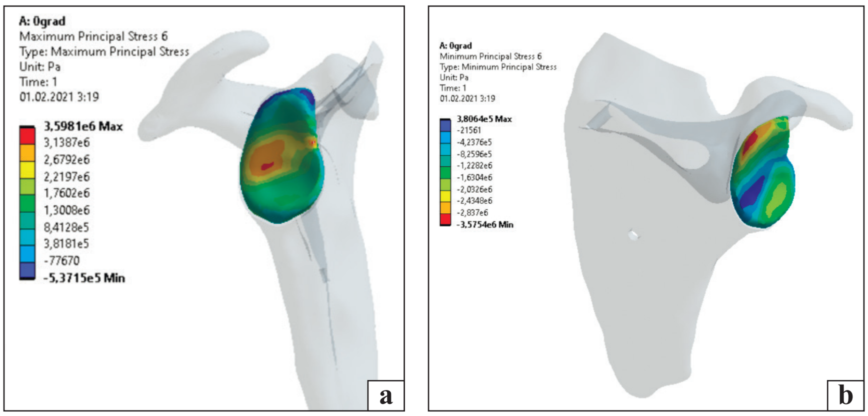


Fig. 10. Maximum (a) and minimum (b) main stresses (Pa) in the scapula in the contact zone in the position of 0° angle of the limb abduction

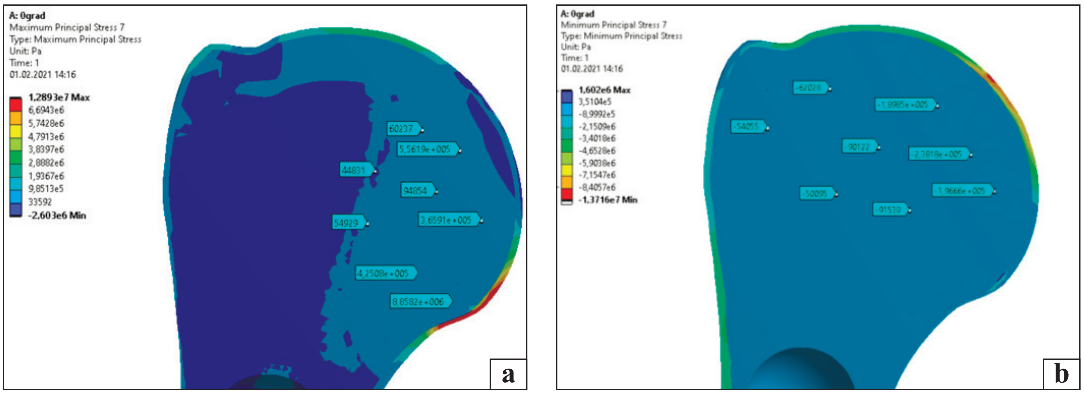


Fig. 11. Maximum (a) and minimum (b) main stresses (Pa) in the sagittal section in the position 0° angle of the limb abduction

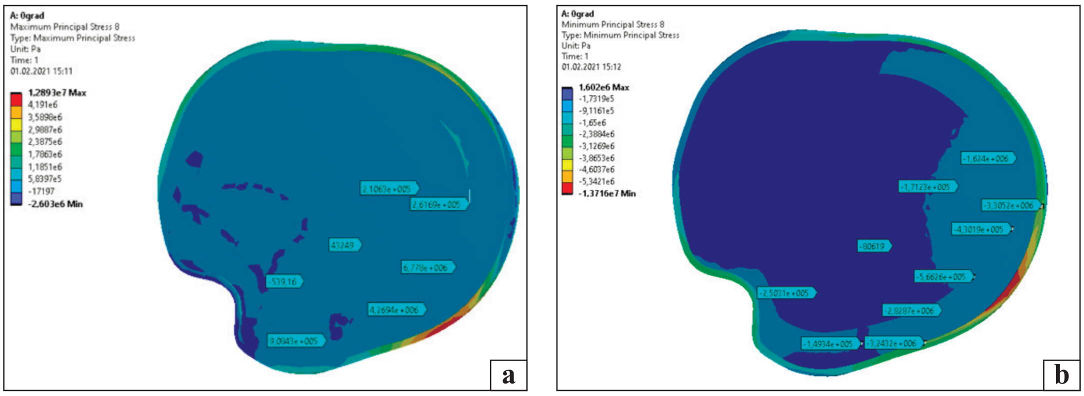


Fig. 12. Maximum (a) and minimum (b) main stresses (Pa) in the axial section in the position of 0° angle of the limb abduction

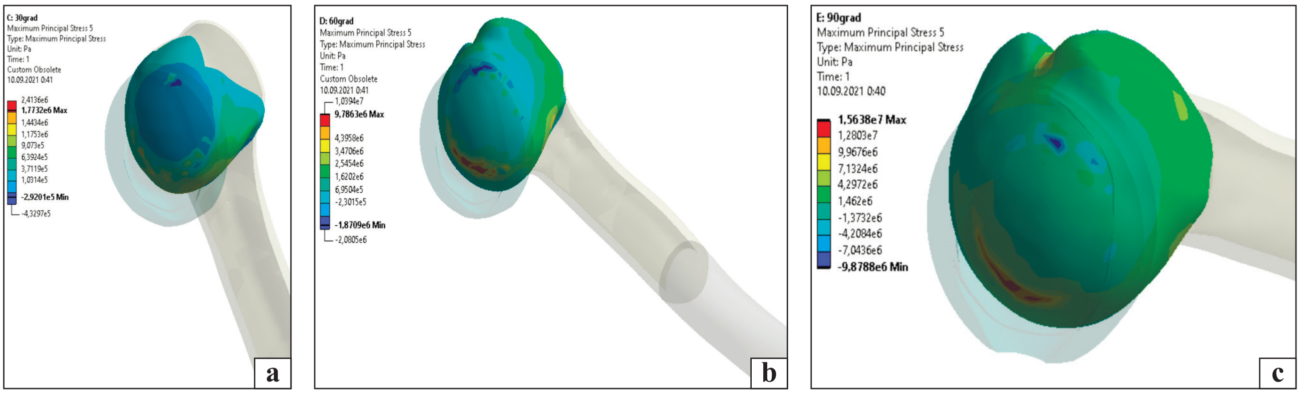


Fig. 13. Maximum main stresses (Pa) in the articular cartilage of the humeral head in the contact zone with the abduction angle of: a) 30°; b) 60°; c) 90°

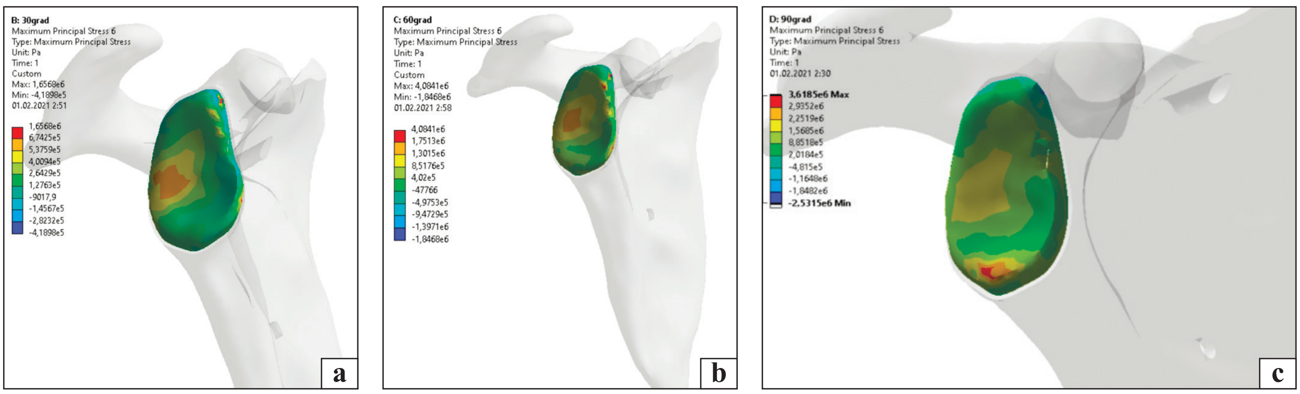


Fig. 14. Maximum main stresses in the scapula in the contact zone, in the position with the humerus abduction angle of: a) 30°; b) 60°; c) 90°

boundary conditions and loads. The complete three-dimensional model developed by the authors taking into account the muscles and their interaction with the shoulder girdle bones is very important and necessary for a better understanding of the biomechanics of the shoulder joint and further comparative analysis of stresses in bone and contact surfaces under different implants. justify their advantages. For the first time, the dynamic modeling of the FEM based on physiologically realistic boundary conditions and load conditions, applied by the authors, made it possible to better stabilize the model and estimate the deformations and stress distribution in soft and hard tissues. Thus, the developed three-dimensional model of the humerus and SSS assessment findings can be used in the future to develop more effective surgical interventions and treatments, including humeral arthroplasty.

Conclusions

The developed three-dimensional model of the shoulder joint, which differs in the administration of elastic connections (muscles) and the spatial location of their attachment points, allowed to more accurately stabilize the model and assess the deformation and stress distribution in soft and hard tissues.

Assessment of SSS for modeling the load on the shoulder joint with different angles of the limb showed that the greatest stresses occur in the contact areas on the humerus, as well as in the upper and middle parts of the head, depending on the applied external influences.

The obtained results of numerical simulation of SSS in the elements of the shoulder joint are compared with the allowable stresses for materials. It is determined that in case of lip damage contact stresses approach the maximum allowable ones. Slight discrepancies with the results of similar studies indicate the reliability of the proposed mathematical model.

With the help of the developed simulation computer 3D-model of the shoulder joint, it will be possible to perform a comparative analysis of stresses occurring in the bone and contact surfaces under the conditions of using different implants.

Conflict of interest. The authors declare the absence of conflict of interest.

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ANALYSIS OF THE STRESS-STRAIN STATE THREE-DIMENSIONAL MODEL OF A HEALTHY SHOULDER JOINT

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