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Stress-deformed state of the acromioclavicular joint in case of damage to the upper *acromioclavicular ligament superior* and various methods of fixation

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During the operative stabilization of the acromial end of the clavicle (AEC) for its dislocation, there are two ways: clavicle – beak-like process, clavicle – acromial process. Fixation of the AEC to the acromial process of the scapula is a priority. Competing metal structures are the hook plate and the Weber method. The significant disadvantages of using the Weber method of fixation are the migration of the tips and the violation of their integrity and the wire. Objective. To conduct a comparative analysis of the fixation of the acromial end of the clavicle according to Weber, hook plate and the proposed construction, by studying the stressed-deformed state of the clavicular-acromial joint in case of damage to the lig. acromioclavicular superior and various methods of fixation. Methods. A finite-element model of the clavicular-acromial joint was constructed. Damage to the ligaments was modeled. claviculo-acoacromiale superior, as well as fixation of AEC in three ways: according to Weber, hook plate and the proposed construction. Results. The best results, from the point of view of reducing the level of stresses in intact ligaments, are provided by fixation of the AEC according to Weber, but its use leads to an increase in the level of stresses on the AEC and the acromial process of the scapula, which can cause destruction of the latter. The hinge-type fixator provides the best stress distribution, both in the bony elements of the model and in intact ligaments. The hook plate holder occupies an average position, both in terms of the level of stress and the magnitude of the relative deformations in the ligaments. Conclusions. Weber fixation provides the best results for reducing the level of stresses and relative strains in the intact ligaments, but leads to a several-fold increase in the level of stresses on the AEC and acromial process of the scapula. The hook plate holder occupies an average position, both in terms of the stress level and the magnitude of the relative deformations in the ligaments. The proposed design provides the best stress distribution, both in the bony elements of the model and in the intact ligaments.

За оперативної стабілізації акроміального кінця ключиці (АКК) у разі його вивиху діють двома шляхами: ключиця – дзьобоподібний відросток, ключиця – акроміальний відросток. Фіксація АКК до акроміального відростка лопатки є пріоритетною. Конкуруючими металевими конструкціями є гачкоподібна пластина — hook plate та спосіб Вебера. Суттєвими недоліками застосування способу фіксації за Вебером є міграція шпиць і порушення їхньої цілісності й дроту. Мета. Провести порівняльний аналіз фіксації акроміального кінця ключиці за Вебером, hook plate та запропонованою конструкцією шляхом вивчення напружено-деформованого стану ключично-акроміального суглоба в разі ушкодження lig. acromioclavicular superior і різних способів фіксації. Методи. Побудовано скінчено-елементну модель ключично-акроміального суглоба. Моделювали ушкодження lig. claviculo-acoacromiale superior, а також фіксацію АКК трьома способами: за Вебером, hook plate та запропонованою конструкцією. Результати. Найкращі результати, із точки зору зниження рівня напружень у неушкоджених зв'язках, забезпечує фіксація АКК за Вебером, але його використання призводить до підвищення рівня напружень на АКК й акроміальному відростку лопатки, що може спричинити руйнування останньої. Фіксатор шарнірного типу забезпечує найкращий розподіл напружень як у кісткових елементах моделі, так і в неушкоджених зв'язках. Тримач hook plate посідає середню позицію як за рівнем напружень, так і за величиною відносних деформацій у зв'язках. Висновки. Фіксація за Вебером забезпечує найкращі результати для зниження рівня напружень і відносних деформацій в неушкоджених зв'язках, але призводить до підвищення в кілька разів рівня напружень на АКК й акроміальному відростку лопатки. Тримач hook plate займає середню позицію, як за рівнем напружень, так і за величиною відносних деформацій у зв'язках. Запропонована конструкція забезпечує найкращий розподіл напружень як у кісткових елементах моделі, так і в неушкоджених зв'язках. Ключові слова. Ключично-акроміальний суглоб, зв'язки, фіксація.

Keywords. Acromioclavicular joint, ligaments, fixation

Introduction

Dislocations of the acromial end of the clavicle (AEC) are a fairly common traumatic injury of the movement and support apparatus and, according to various authors, make up from 3 to 26.1 % of dislocations of other locations, and almost 10 % in the structure of acute injuries of the shoulder girdle, ranking third after dislocations shoulder and forearm [1].

Under the conditions of surgical intervention to stabilize the clavicle during dislocations, AEC is implemented in two ways: clavicle – coracoid process, clavicle — acromial process. Fixation of the acromial end of the clavicle to the acromial process of the scapula is a priority. Competing metal structures for securing are the hook plate [2] and Weber's method [3].

Among the disadvantages of using a hook plate are the following: pain in the shoulder; post-traumatic arthritis caused by fragmented tissues (fragmented bones, articular discs, cartilage and ligaments); destruction of tissues, which continues for the period of presence of the structure and irritation of peripheral nerves in the soft tissues between the hook of the plate and the acromion; “subacromial impingement syndrome”, which leads to rotator cuff injury; destruction of bone tissue, especially in the area of the acromial process of the scapula with the formation of subacromial erosions [4]. The significant disadvantages of using the Weber method of fixation are the migration of the tips and the violation of their integrity and the wire [5].

All this leads to the further study of the design features of the most used fasteners and the development of the latest tools.

Purpose: to conduct a comparative analysis of the fixation of the acromial end of the clavicle according to Weber, hook plate and the proposed construction, by studying the stressed-deformed state of the clavicular-acromial joint in case of damage to the *acromioclavicular superior ligament* and various methods of fixation.

Material and methods

In the biomechanics laboratory of the State Establishment “Professor M. I. Sytenko Institute of Spine and Joint Pathology of the National Academy of Sciences of Ukraine” we built a finite element model of the clavicular-acromial joint (CAJ), comprised of the scapula, the clavicle and the ligaments of the clavicular-acromial and clavicular-coracoid complexes (Fig. 1).

In this study, we modeled damage to the ligaments of the clavicular-acromial complex, namely *lig. acromioclavicular superior* (Fig. 2).

For each variant of damage to the ligaments of the clavicle-acromial complex, a model of fixation of the acromial end of the clavicle was built in three ways: according to Weber, hook plate and the proposed design [6] (Fig. 3).

During simulation, the material was assumed to be homogeneous and isotropic. A 10-node tetrahedron with a quadratic approximation is chosen as a finite element. The mechanical properties of the materials were selected from literature sources [7–11]. The used characteristics (E — Young's modulus of elasticity, ν — Poisson's ratio) are listed in Table 1.

During the study, the loads acting on the CAJ were simulated under conditions of abduction of the upper extremity at an angle of 90°.

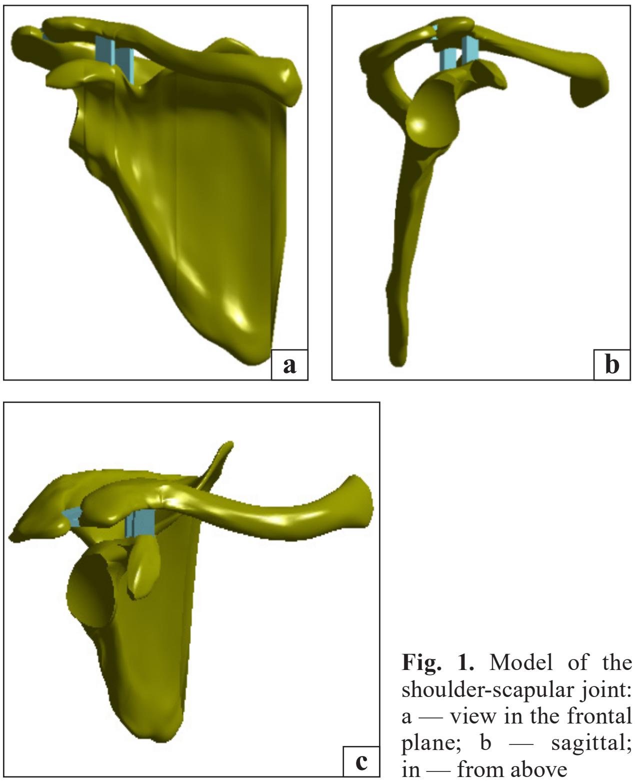

Fig. 1. Model of the shoulder-scapular joint: a — view in the frontal plane; b — sagittal; in — from above

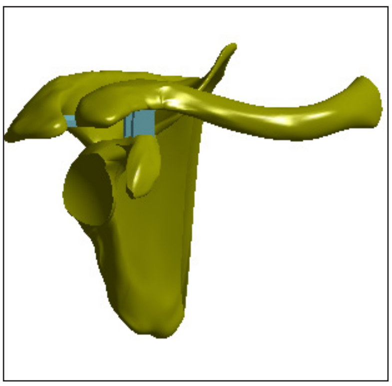

Fig. 2. Variants of the model with missing *lig. acromioclavicular superior*

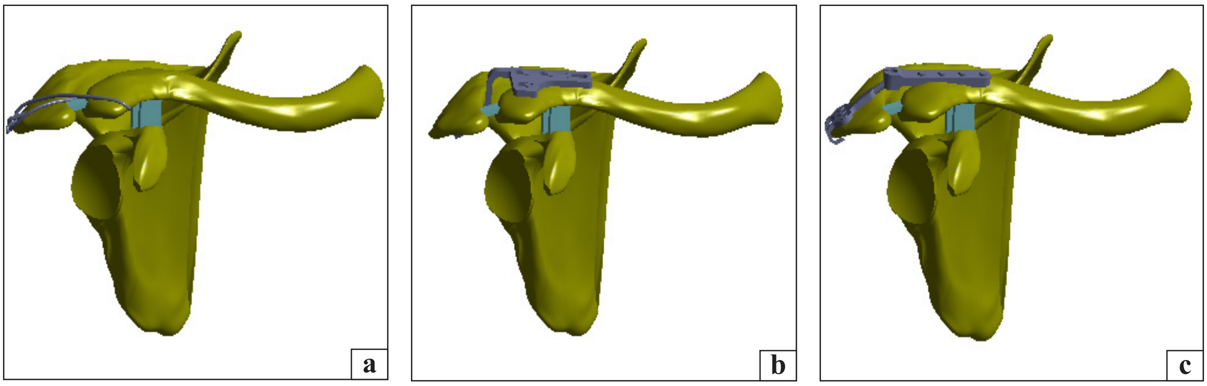

Fig. 3. Models with fixation of the acromial end of the clavicle: a — according to Weber; b — hook plate fixator; c — the proposed design

Table 1

Mechanical characteristics of the materials used

Material	Young's modulus of elasticity (E), MPa	Poisson's ratio, ν	Strength limit, MPa
Cortical bone	18350.00	0.30	170.00
Spongy bone	1040.00	0.30	10.00
Ligaments	330.00	0.40	—
Cartilage	5.58	0.44	—
Surgical steel AISI 316L	200000	0.30	505.00

Fig. 4. Scheme of loading the model

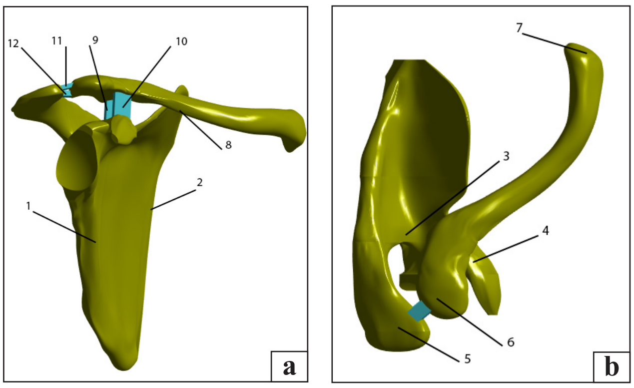

Fig. 5. The layout of control points: a — front; b — from above

Table 2

Control points

Control point	Anatomical area	Model element
1	lateral edge	scapula
2	medial edge	
3	notch of the scapula	
4	coracoid process	
5	acromial process	
6	acromial end	clavicle
7	sternal end	
8	body	
9	*conoideum*	ligaments
10	*trapezoideum*	
11	*acromioclavicular superior*	
12	*acromioclavicular inferior*	

Forces were applied to the models that simulated the action of muscles: *middle deltoid* — 173.4 N; *anterior deltoid* — 121.9 N; *posterior deltoid* — 371.3 N; *supraspinatus* — 190.7 N; *subscapularis* — 1029.8 N; *infraspinatus combined* — 55.6 N [11]. The load diagram of the model is shown in Figure 4.

Control points were selected to compare stress values in model elements with different damage and fixing options. The layout of control points is shown in Figure 5 and Table 2.

The maximum level of stress in ligaments, bone elements and metal structures was registered. In addition, the values of relative deformations in ligaments were studied. The model was built in the SolidWorks software [12]. Calculations of the stress-strain state of the models were performed using the ANSYS program [13].

Results

At the first stage of the study, the stress-strain state of the model without damage to the ligamentous apparatus was analyzed. The stress distribution in the bone elements of the model is normally shown in Fig. 6.

The conducted research made it possible to determine that, in conditions of intact ligaments of the CAJ, the abduction of the upper limb causes the stress of the model elements, which acquire a maximum value of 81.8 MPa in the middle part of the clavicle, and the minimum stress level of 3.0 MPa is observed at its sternal end. On the scapula, the most stressed 32.5 MPa is found at the edge of its notch, the minimum stresses of 11.2 MPa occur along its medial edge. Among the ligaments, the highest stress level was recorded at *lig. trapezoideum* — 50.6 MPa, the lowest on *lig. acromioclavicular superior* — 39.5 MPa.

The second stage of the study was to assess changes in the stress-strain state of the model as a result of ligament injuries of the clavicle-acromial complex. The pattern of stress distribution in the model with damage to *lig. acromioclavicular superior* is shown in Figure 7.

Rupture of *lig. acromioclavicular superior* in abduction of the limb leads to an increase in the level of stress at the ends of the clavicle to 4.0 MPa on the sternum and up to 36.5 MPa on the acromial. In the middle part, the amount of stress does not change. On the blade, changes in the stress-strain state are multidirectional in nature. Thus, the stresses increase along the lateral edge and edge of the notch to 20.6 and 35.0 MPa, respectively, and decrease along its medial edge to 10.9 MPa and on the coracoid and acromial processes to 25.7 and 25.5 MPa, respectively. At the same time, the stresses on all intact ligaments increase and reach a maximum of 73.0 MPa per *lig. acromioclavicular inferior.*

Stress distribution in the bone elements of the model in damage to *lig. acromioclavicular superior* with fixation of AEC according to Weber is shown in Fig. 8.

Compared to the model without fixation of the clavicle, the Weber wire fixation causes a 5-fold increase in the level of stress on the AEC — up to 175.5 MPa and on the acromial process of the scapula — up to 218.4 MPa. At the same time, the stresses in the ligaments are significantly reduced and do not exceed 53.4 MPa.

A decrease in the amount of stress in the ligaments occurs due to the distribution of the load on the elements of the metal structure. At the peaks, they are determined at the level of 119.1 and 241.5 MPa at the front and rear, respectively. The situation looks much worse with the wire, in which the stresses reach 489.6 MPa, which critically approaches the strength limit of surgical steel — 505.0 MPa. This indicates that a small additional load can lead to wire breakage and loss of stability of the CAJ.

Fig. 9 shows the distribution of stresses in the bone elements of the model with damage to *lig. acromioclavicular superior* in hook plate fixation of the AEC.

The conducted studies showed that the use of a hook plate in case of damage to the *lig. acromioclavicular superior* provides for a reduction in the level of stress in all intact ligaments of the model, as well as in almost all control points of bone elements. The exception is the medial edge of the scapula and the edge of its notch, where there is a slight increase in the stress level to 11.1 and 25.6 MPa, respectively, compared to the model without fixation. Regarding the metal structure, the stresses in its sections do not acquire critical values and reach a maximum of 355.5 MPa. They are fixed at 223.4 MPa on the lateral screw, 141.9 MPa on the medial screw.

The stress-strain state of the model with damage to the *lig. acromioclavicular superior* with fixation of the acromial end of the clavicle by the proposed design is shown in Figure 10.

Compared to the model without fixation, the hinge-type holder allows to reduce the level of stresses in all control points of the model, except for the edge of the scapular notch and its acromial process, where they increase to 35.7 and 28.2 MPa, respectively. Among the elements of the metal structure, the plates are the most stressed — 356.6 and 277.6 MPa on the scapula and clavicle, respectively. The stresses on the fixing screws do not exceed the marks of 99.5 MPa on the clavicle and 53.8 MPa on the acromial process. In ligaments, they reach a maximum value of 53.0 MPa in *lig. acromioclavicular inferior.*

Indicators of maximum stress values at control points of models with damage to the *lig. acromioclavicular superior* according to various options for fixation of the acromial end of the clavicle are shown in Table 3.

Comparative stress values at the control points of the model with damage to the *lig. acromioclavicular superior* with various options for fixation of the AEC is presented in Figure 11.

All options for fixation of the acromial end of the clavicle for damage to the *lig. acromioclavicular superior* allow to reduce the stress level both

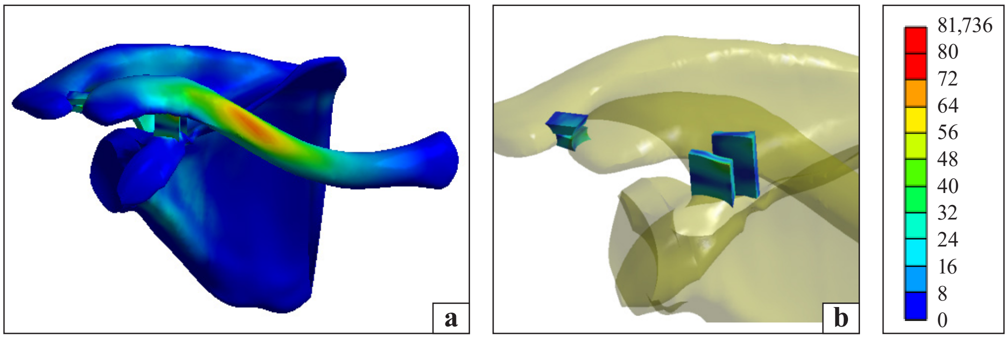

Fig. 6. Distribution of stresses in the elements of the model in norm: a — bone elements; b — ligaments

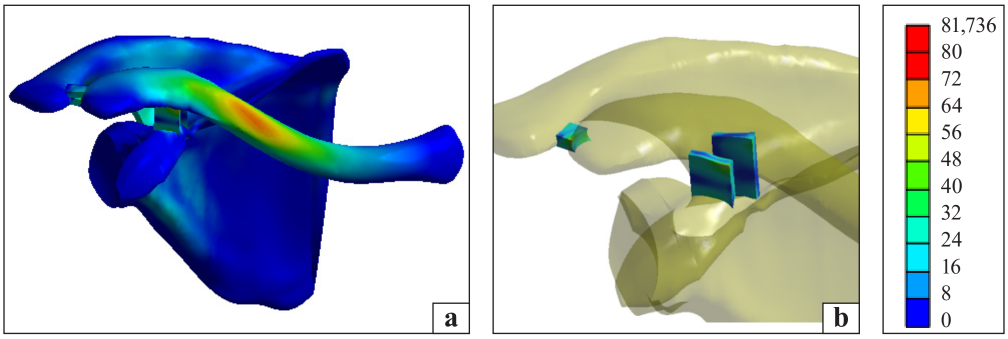

Fig. 7. Stress distribution in the elements of the model with damage to the *lig. acromioclavicular superior*: a — bone elements; b — ligaments

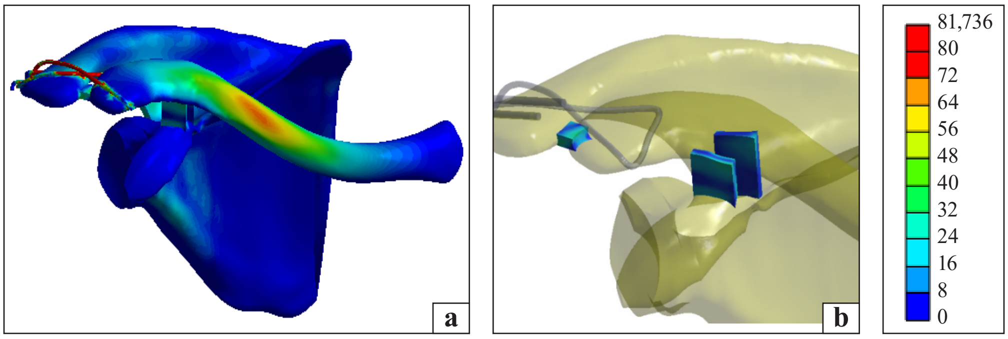

Fig. 8. Stress distribution in the elements of the model with damage to the *lig. acromioclavicular superior* in fixation of the acromial end of the clavicle according to Weber: a — bone elements; b — ligaments

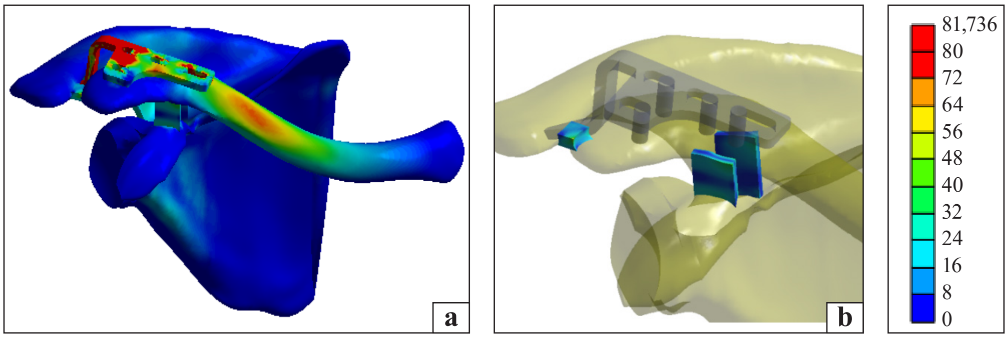

Fig. 9. Stress distribution in the elements of the model with damage to the *lig. acromioclavicular superior* in fixation of the acromial end of the clavicle with a hook plate fixator: a — bone elements; b — ligaments

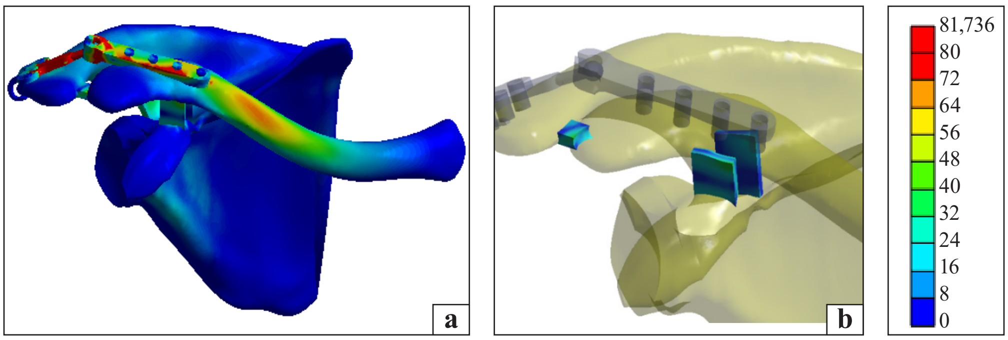

Fig. 10. Stress distribution in the elements of the model with damage to the *lig. acromioclavicular superior* in fixation of the acromial end of the clavicle by the proposed construction: a — bone elements; b — ligaments

Table 3

Stress values at the control points of the model with damage to the *lig. acromioclavicular superior* in various options for fixing the acromial end of the clavicle

Anatomical area	Control point	Stress, MPa				
		norm	without fixation	according to Weber	hook plate	hinge
Scapula	1	19.3	20.6	21.2	20.5	20.2
	2	11.2	10.9	9.7	11.1	9.0
	3	32.5	35.0	30.2	32.3	35.7
	4	28.2	25.7	20.9	22.3	25.8
	5	27.9	25.5	218.4	27.6	28.2
Clavicle	6	21.2	36.5	175.5	26.9	29.1
	7	3.0	4.2	3.7	3.4	3.8
	8	81.8	81.8	81.8	81.2	81.0
Ligaments	9	44.0	46.4	28.4	40.1	37.9
	10	50.6	67.3	36.9	44.0	49.5
	11	39.5	—	—	—	—
	12	48.2	73.0	53.4	64.3	53.0

Table 4

Values of stresses in the elements of metal structures of the model in damage to the *lig. acromioclavicular superior* in various options for fixing the acromial end of the clavicle

Fixation option	Stress, MPa									
	wire	anterior spit	posterior spit	plate	lateral screws	medial screws	scapula plate	clavicle plate	scapula screws	slavicle screws
According to Weber	489.6	119.1	241.5	—	—	—	—	—	—	—
hook plate	—	—	—	355.5	223.9	141.9	—	—	—	—
Hinge	—	—	—	—	—	—	356.6	277.6	53.8	99.5

in the bony elements of the model and in intact ligaments. An exception is fixation according to Weber, which leads to a 5-fold increase in the level of stress on the AEC and the acromial condyle of the scapula since the load between these departments is transferred due to the wire, which has a small diameter and, as a result, a small contact area with the bone tissue.

Data on stress values in the elements of metal structures of the model with damage to the *lig. acromioclavicular superior* under various options for fixation of the ACC are shown in Table 4.

Thus, the maximum stresses on the cerclage wire for damage to the *lig. acromioclavicular superior* occur during abduction of the limb, which is due to its small cross-sectional area.

The last stage of the work was to study the values of relative deformations in the ligaments of the models in normal conditions and with damage to the *lig. acromioclavicular superior*, as well as in all variants of AEC fixation. The pattern of the distribution of relative deformations in the ligaments on the model in normal conditions and with damage to the *lig. acromioclavicular superior* without fixation of the AEC is shown in Fig. 12.

The conducted study showed that, normally, during abduction of the upper limb, the maximum relative deformations of 19 % will be experienced by the *lig. trapezoideum*, minimum 12 % by the *lig. acromioclavicular superior*. Relative deformations of *lig. conoideum* and *lig. acromioclavicular inferior* are determined at the level of 13 and 14 %, respectively. In case of damage to the *lig. acromioclavicular superior* all the loads that arise in the clavicular-acromial articulation are taken over by the *lig. acromioclavicular inferior*, which leads to a significant increase in its relative deformation, up to 22 %. Deformations of the ligaments of the clavicular joint increase slightly — up to 13 % *lig.conoideum* and up to 20 % *lig. trapezoidum*.

Let us consider how fixation of the AEC affects the relative deformations of intact ligaments. Distribution of relative deformations in models with different options for fixation of the AEC in damage to the *lig. acromioclavicular superior* is shown in Fig. 13.

The use of the Weber method of fixation allows to reduce the relative deformations of all intact ligaments.

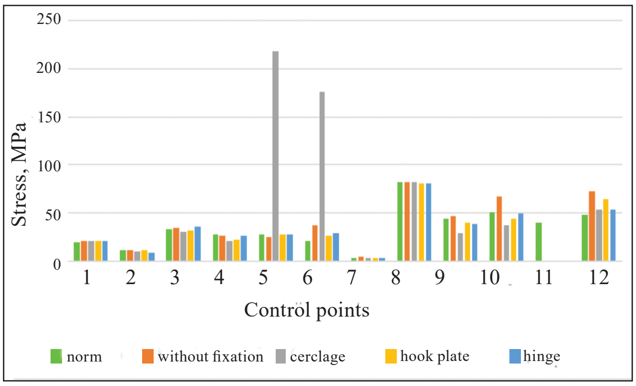

Fig. 11. Diagram of stress values at the control points of the model with damage to the *lig. acromioclavicular superior* for various options for fixing the acromial end of the clavicle

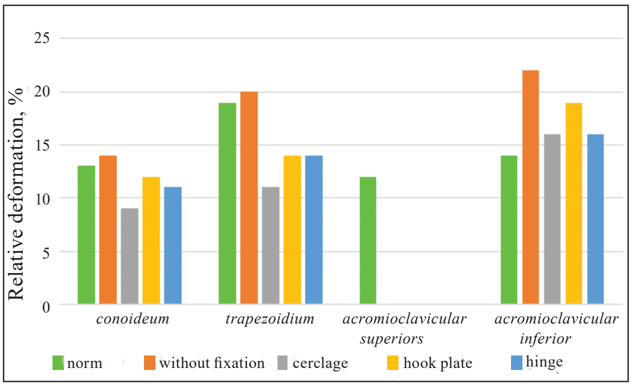

Fig. 14. Diagram of relative deformations in ligaments of models in damage to the *lig. acromioclavicular superior*

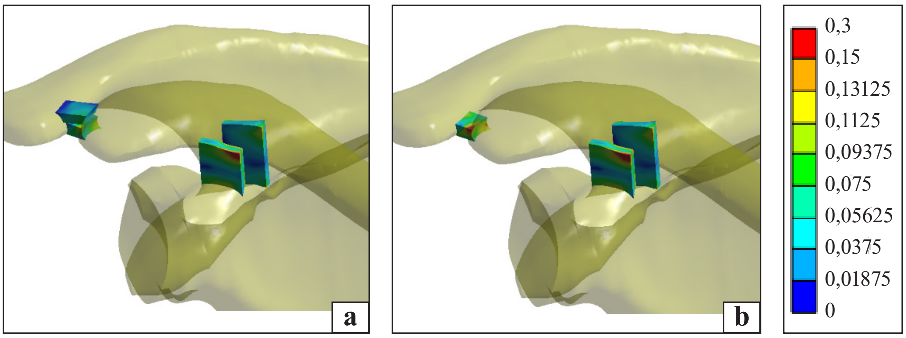

Fig. 12. Distribution of relative deformations in the links of the model: a — norm; b — damage to the *lig. acromioclavicular superior* without fixation

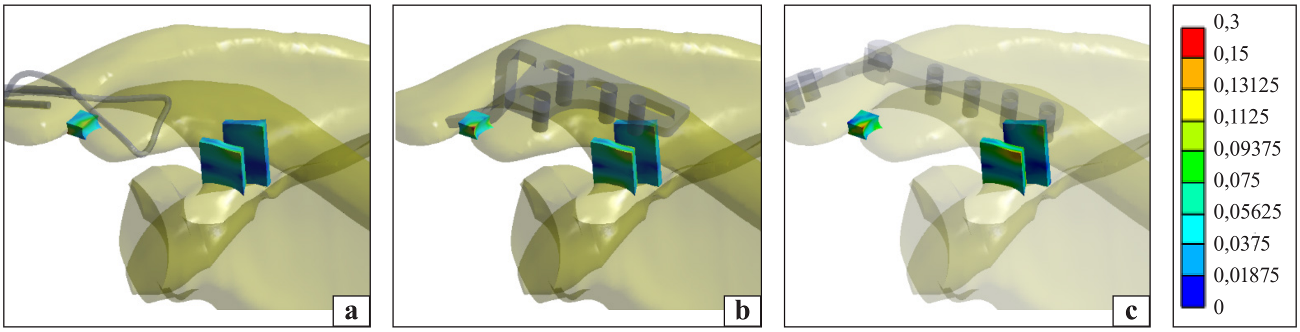

Fig. 13. Distribution of relative deformations in models with damage to the lig. acromioclavicular superior: a — according to Weber; b — hook plate; c – proposed construction

At the same time, deformations of the ligaments of the clavicular joint acquire indicators below the normal model and are determined at the level of 9 and 11 % for *lig. conoideum* and *lig. trapezoideum* respectively. Relative deformations of *lig. acromioclavicular inferior*, although not reaching the norm, but also significantly decrease and are determined at the mark of 16 %. The values of the maximum values of the relative deformations in the ligaments of the models are given in the Table 5.

A visual representation of the ratio of the values of relative deformations in the ligaments of models due to damage to the *lig. acromioclavicular superior* can be seen using the diagram shown in Fig. 14.

Summarizing, we note that according to the criterion of minimizing the magnitude of relative deformations in the ligaments of the clavicle-scapular articulation due to damage to the *lig. acromioclavicular superior*, the best results were shown by the Weber method of fixing the acromial end of the clavicle. The largest deformations in ligaments occur during fixation with a hook plate, although they are below the level of the model without fixation.

Discussion

The study showed that when the ligaments of the clavicle-acromial complex are injured, the best results, from the point of view of reducing the level

Table 5

Maximum values of relative deformations in the ligaments of the models in damage to the *lig. acromioclavicular superior*

Control point	Relative deformation, %				
	norm	without fixation	according to Weber	hook plate	hinge
lig.conoideum	13	14	9	12	11
lig.trapezoideum	19	20	11	14	14
lig. acromioclavicular superior	12	—	—	—	—
lig. acromioclavicular inferior	14	22	16	19	16

of stress in intact ligaments, are provided by the fixation of the AEC according to Weber. However, this method leads to a several-fold increase in the level of stress on the AEC and the acromial process of the scapula. This is because the load between these departments is transferred due to the wire, which has a small diameter and, as a result, a small contact area with the bone tissue. This level of tension in the contact zone of the wire and bone tissue can cause the destruction of the latter. The second negative factor that speaks against the use of this method of fixation is that the level of tension in the wire during abduction of the limb under conditions of damage to individual ligaments approaches the strength limit of the surgical steel from which it is made. This can be the cause of wire breakage and, as a result, loss of stability of the CAJ.

The hinge type holder provides the best stress distribution both in the bony elements of the model, and quite low in the intact ligaments for all types of injuries. The hook plate retainer occupies an average position both in terms of the level of stress and the amount of relative deformations in the ligaments.

According to the criterion of minimizing the amount of relative deformations in the ligaments of the clavicle-scapular joint due to damage to the *lig. acromioclavicular superior*, the best results were shown by the method of fixing the acromial end of the clavicle according to Weber, but the worst indicators of stress values in bone tissue and cerclage wire nullify all the advantages of this method. The largest deformations in ligaments occur after fixation with a hook plate, although they are below the level of indicators of the model without fixation. The holder of the hinged type of the proposed design has the most balanced indicators of stresses and relative deformations for abduction of the upper limb in damage to the *lig. acromioclavicular superior*.

Conclusions

Fixation of the acromial end of the clavicle according to Weber provides the best results in terms of reducing the level of stresses and relative deformations in intact ligaments but leads to a several fold increase in the level of stresses on the AEC and the acromial process of the scapula. The level of tension in the wire during abduction of the limb due to injury of individual ligaments approaches the strength limit of the surgical steel from which it is made, which may cause the wire to break and, as a result, lose the stability of the CAJ.

The hook plate holder occupies an intermediate position, both in terms of the level of stress and the magnitude of the relative deformations in the ligaments.

The proposed design provides the best distribution of stresses both in the bony elements of the model, as well as a fairly low level of stresses and relative deformations in intact ligaments.

Conflict of interest. The authors declare no conflict of interest.

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STRESS-DEFORMED STATE OF THE ACROMIOCLAVICULAR JOINT IN CASE OF DAMAGE TO THE UPPER ACROMIOCLAVICULAR LIGAMENT SUPERIOR AND VARIOUS METHODS OF FIXATION

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