ORIGINAL ARTICLE

ANATOMICAL AND BIOMECHANICAL ROLE OF STATIC STABILIZERS OF THE ACROMIOCLAVICULAR JOINT

DOI: 10.36740/WLek202312109

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ABSTRACT

The aim: To determine the anatomical and biomechanical significance of the static stabilizers of the acromioclavicular joint by conducting numerical modeling using the finite element method and experimental investigation

Materials and methods: To ensure the study, modeling of the deformation processes of the clavicle and scapula systems with various combinations of ligament damage was conducted. The COMPAS-3D software package was used to build the simulation model, which allowed obtaining models that are closest to reality. To verify the results of the numerical modeling, corresponding studies of the mechanical characteristics and determination of the stiffness of the investigated systems were carried out using the upgraded TIRAtest-2151 testing stand

Results: The stiffest system is the system in which all ligaments are intact, and the sequence of decreasing stiffness of the system is presented in the following order: damage to lig. trapezoideum; lig. conoideum; lig. claviculo-acoacromiale inferior; lig. claviculo-acoacromiale superior; the coracoclavicular ligament complex; the acromioclavicular ligament complex

Conclusions: Static stabilizers in general, and their components in particular, are characterized by significant anatomical and functional features. The natural stabilization of the acromioclavicular joint is provided by their synergistic interaction, which is the basis for the development and implementation of surgical interventions, the scope of which includes the restoration of both ligament complexes. The loss of stiffness in the «clavicle-scapula» system is significantly more pronounced when lig. acromioclaviculare superior and inferior are damaged (8.5 N/mm) than when lig. conoideum and lig. trapezoideum are damaged (11.6 N/mm)

KEY WORDS: Acromioclavicular joint, static stabilizers, biomechanical

Wiad Lek. 2023;76(12):2607-2613

INTRODUCTION

Acromial end of the clavicle dislocations (AEC) make up from 6.8% to 26.1% of all dislocations, and rank third after shoulder and forearm dislocations. In the context of acute traumatic injuries affecting the shoulder girdle region, it is noteworthy that the incidence of AEC dislocations exceeds 12%. These injuries are more common in working-age men (30 to 40 years old) and athletes who engage in contact sports [1].

The acromioclavicular joint (ACJ) possesses six degrees of freedom in the anterior-posterior and superior-inferior planes. The rotational range of motion is approximately 45º, with vertical motion up to 15°, sagittal motion up to 19°, and frontal motion up to 29°. The proper anatomical relationship between the flat and small joint ends of the clavicle and the acromion process of the scapula, as well as the primary stabilization of the joint during movement, is ensured through the dynamic and static stabilizers. Crucial anatomical structures that contribute to the static stabilization of the joint include the joint capsule, acromioclavicular and coracoclavicular ligaments [2].

An examination of the relevant literature reveals an ongoing debate spanning nearly a century regarding the primary stabilizer of the acromioclavicular joint (ACJ), which is commonly referred to as the "key" component in this regard. At present, two primary positions have been established: (1) the claviculo-acromial ligament serves as the primary stabilizing structure, and (2) the coracoclavicular ligament assumes the dominant role in joint stabilization.

The aforementioned debate has paved the way for a multitude of surgical approaches to the restoration of damaged ligamentous complexes, with over 150 methods currently proposed. The sheer volume of suggested techniques was intended to promote an individualized approach to the treatment of AEC dislocations. Nevertheless, the lack of clear indications

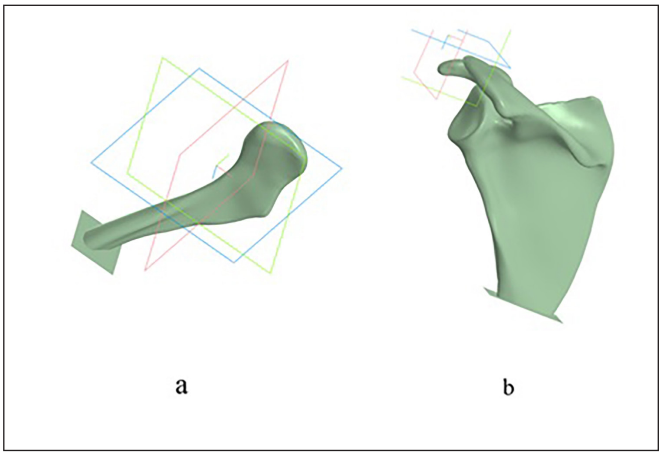

Fig. 1. Simplified models of the studied system: a) - clavicle, b) – scapula

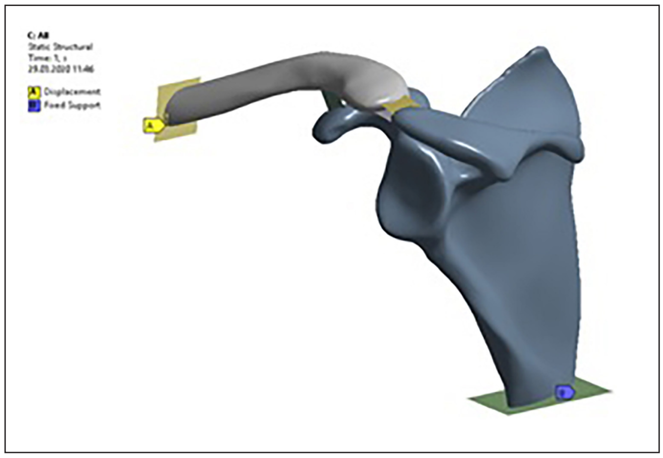

Fig. 2. Investigated system

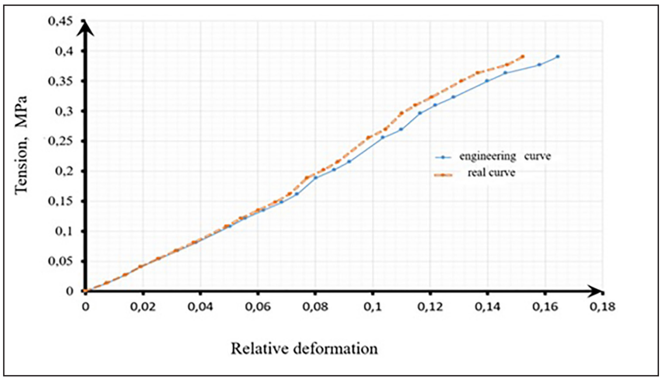

Fig. 3. Experimental deformation curves of the rubber bands.

for their employment has compromised this direction.

The use of different surgical techniques for treating AEC dislocations allows for an average of final outcome measures, among which negative results account for 9 to 12%. The relatively high rate of unsatisfactory outcomes is due to several main factors, such as horizontal instability of the AEC, loss of congruency within the joint, heterotopic ossification, and post-traumatic ACJ osteoarthritis [3].

Given the current challenges and inconsistencies in treating ACJ dislocations, further research, improvement, and development of novel treatment approaches are objectively warranted.

THE AIM

To determine the anatomical and biomechanical significance of the static stabilizers of the acromioclavicular joint by conducting numerical modeling using the finite element method and experimental investigation.

MATERIALS AND METHODS

The feasibility of determining and comparing the stiffness of the clavicle-scapula connection systems depending on the combination of damaged ligaments investigated by this method is justified due to the fact that conducting in-vivo experimental studies to determine the stiffness of such systems is not always possible due to their complexity, ethical considerations, and labor-intensive nature. It is also important to consider that the characteristics of the ligamentous apparatus depend on the time since death.

In order to facilitate the investigation, computer-based simulations of the deformation processes of the clavicle (C) and scapula (S) systems with varying damage combinations were conducted.

The software package KOMPAS-3D was utilized to construct an accurate simulation model of C and S, taking into consideration their anatomical peculiarities. Subsequently, the presented models of the clavicle and scapula were incorporated into a final model, taking into account the actual experimental studies' method of fixation and loading (Fig 1a, b).

We made a numerical simulation of the deformation process of the C and S systems with different combinations of damaged ligaments, using the Ansys Workbench numerical package and the static structural module. The investigated system with all intact ligaments is presented in Fig 2.

Table I. Stiffness of systems with different combinations of damaged ligaments, obtained through numerical modeling.

Case	a	b	c	d	e	f	g
Stiffness, N/mm	19.5	15.1	16	13	14.8	8.5	11.6

Note: a - intact ligamentous apparatus; b - damage to lig. conoideum; c - damage to lig. trapezoideum; d - damage to lig. claviculo-acromiale superior; e - damage to lig. claviculo-acromiale inferior; f - damage to the acromioclavicular ligament complex; g - damage to the coracoclavicular ligament complex.

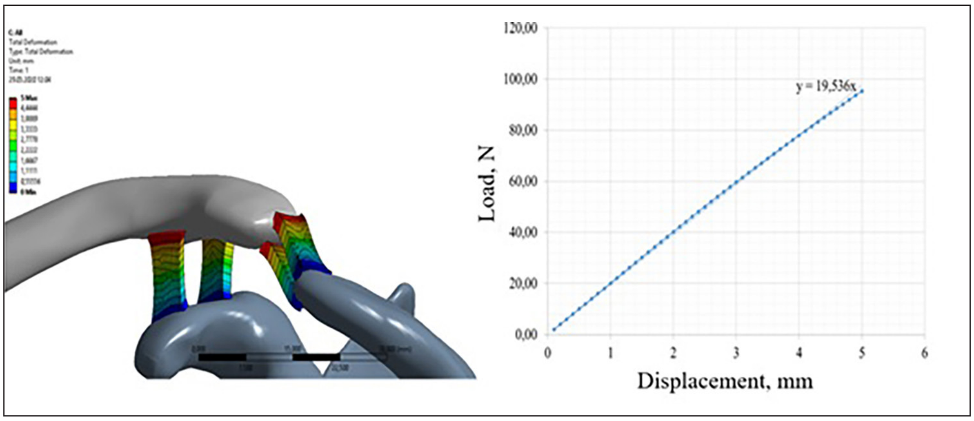

Fig. 4. The model of static ASJ stabilizers and the relationship between the applied force and displacement under standard conditions

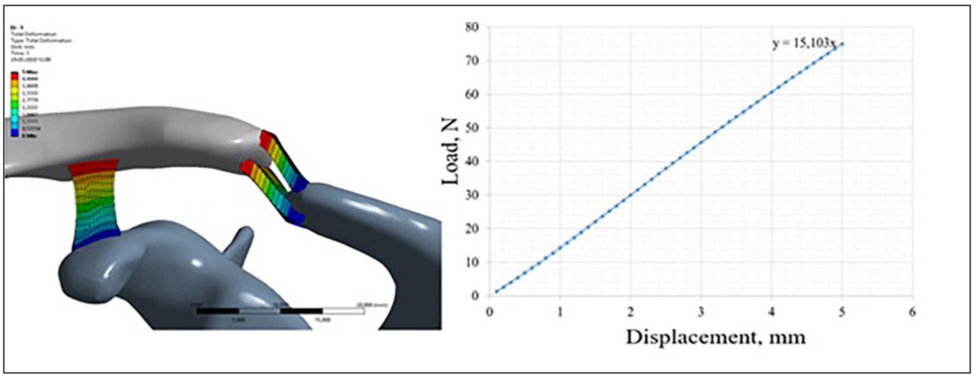

Fig. 5. The model of static stabilizers of the ACJ and the relationship between the applied force and displacement under damage to the lig. Conoideum

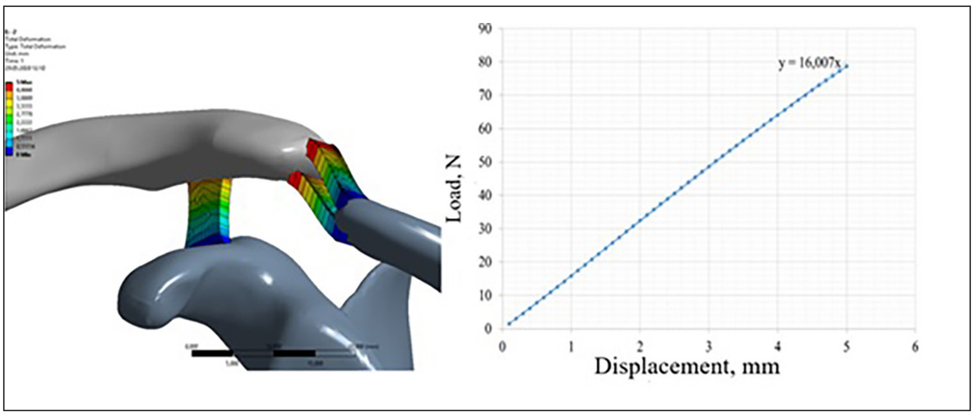

Fig. 6. Model of static stabilizers of the ACJ and the relationship between the applied force and displacement under damage to the ligament trapezoideum

In the analysis, the clavicle (C) and scapula (S) were treated as rigid bodies with infinite stiffness, which simplified the computations. This assumption was based on the observation that the stiffness of C and S is significantly greater than that of the ligaments, and, therefore, the impact of the ligaments on the system's behavior could be neglected under relatively low loads.

Medical rubber bands were used as ligaments in the experimental investigations. This material was selected due to the Neo-Hookean model, which is based on the stress-strain curve obtained from experimental research (Fig 3). This material is highly elastic and appropriate for use as ligaments in the investigated system.

To verify the results of numerical modeling, relevant investigations of mechanical characteristics and determination of the stiffness of the studied systems were conducted, using the modernized testing stand TIRAtest-2151.

The boundary conditions were selected according to real experimental studies, so that the lower part of S was rigidly fixed, similar to fixing the sample to the frame of the testing machine. Displacements of 5, 10, and 12 mm were applied to part C in the corresponding plane, according to the load applied during the experiment.

RESULTS

The model of the static ASJ stabilizers and the numerical simulation results, with the relationship between applied force and displacement under standard conditions are presented in Fig 4.

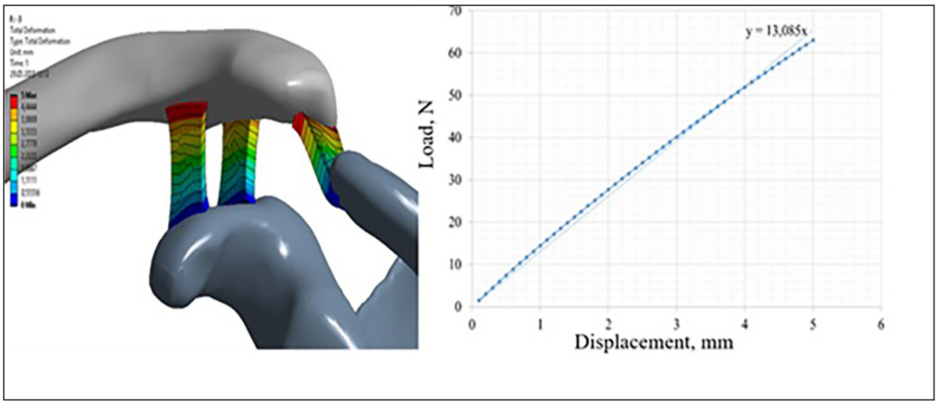

Fig. 7. The model of static stabilizers of the AC joint and the relationship between the applied force and displacement under damage to the superior acromioclavicular ligament.

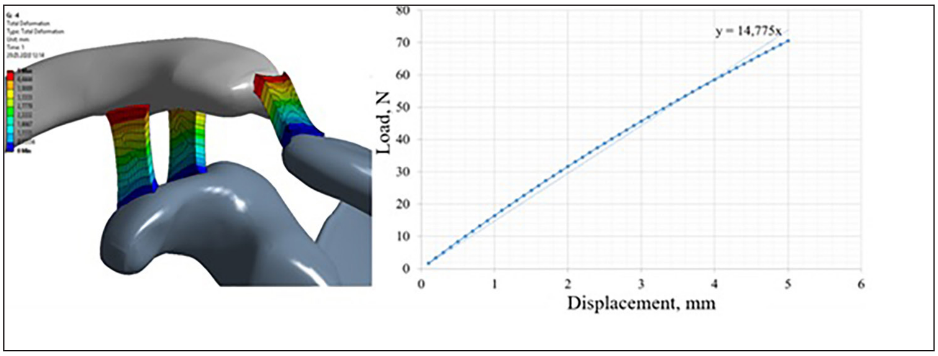

Fig. 8. The model of static stabilizers of the ACJ and the relationship between the applied force and displacement under damage to the ligamentum claviculo-acromiale inferius

Numerical modeling was carried out for the presented research system to obtain displacement distribution fields with different combinations of damaged connections.

The model of static stabilizers of the ACJ and the results of the dependence of the applied force on the displacement in the case of damage to the ligamentum conoideum are presented in Fig 5.

The model of the static stabilizers of the AC joint and the dependence of the applied force on displacement with ligamentum trapezoideum damage is shown in Fig 6.

The model of the static stabilizers of the ACJ and the relationship between the applied force and displacement under damage to the lig. claviculo-acoacromiale superior is presented in Fig 7.

The model of static stabilizers of the ACJ and the relationship between the applied force and displacement under damage to the ligament claviculo-acromiale inferior is presented in Fig 8.

The model and the relationship between the applied force and displacement under complete damage of the acromioclavicular ligament complex are presented in Fig 9.

Model and relationship between the applied force and displacement under complete damage of the clavicular coracoid ligament complex is shown in Fig 10.

Considering the presented results and obtained dependencies, the stiffness values for the respective systems are presented in the form of Table I.

Based on the results presented in Table I, it can be concluded that the stiffest system is the system in case (a), where all ligaments are intact. The decreasing order of system stiffness is as follows: a, c, b, e, d, g, f.

Therefore, the results indicate that the loss of stiffness in the "clavicle-scapula" system is significantly more pronounced in case of damage to the ligaments lig. acromioclaviculare superior and inferior (8.5 N/mm) compared to lig. conoideum and lig. trapezoideum damage (11.6 N/mm).

DISCUSSION

An examination of the relevant literature reveals an ongoing debate spanning nearly a century regarding the main stabilizer of the AC joint: is it the coracoclavicular ligament (CCL) or the acromioclavicular ligament (CAL)?

Volkovich N.M. (1928), as well as Buason and Ader (1930), were among the first to conduct experimental research on cadavers to determine the role of the ACJ ligamentous complex in maintaining congruity. When the CAL was severed, the researchers noted vertical instability, whereas when the CCL was incised, there was a significant displacement of the clavicle relative to the acromial process of the scapula (greater than 2 cm). The results led to the conclusion that isolated CAL damage leads to subluxation, while combined damage involving both CAL and CCL results in ACJ dislocation [4, 5].

D. Muscolo conducted an experiment on cadavers where he damaged ligaments and conducted radiographic studies to assess the relationship in the ACJ.

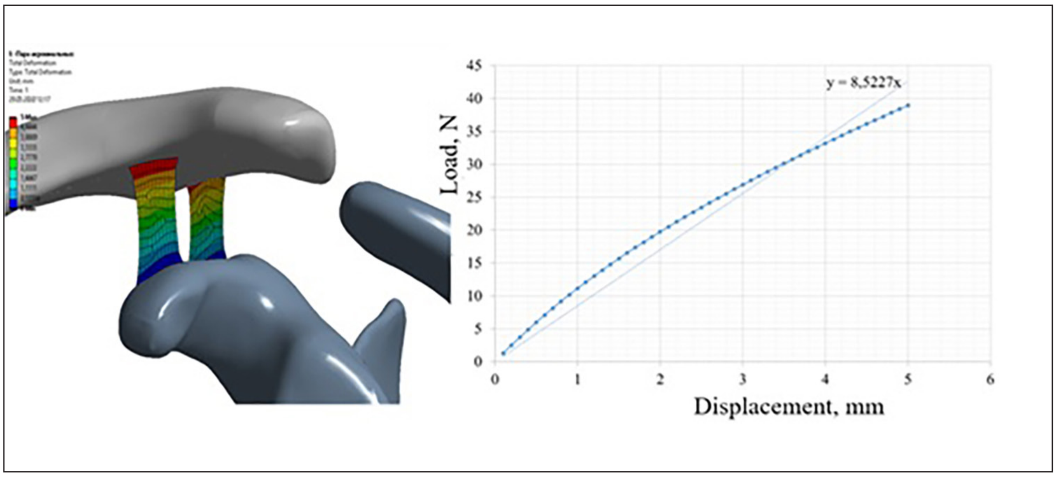

Fig. 9. Model and relationship between the applied force and displacement under complete damage to the acromioclavicular ligament complex

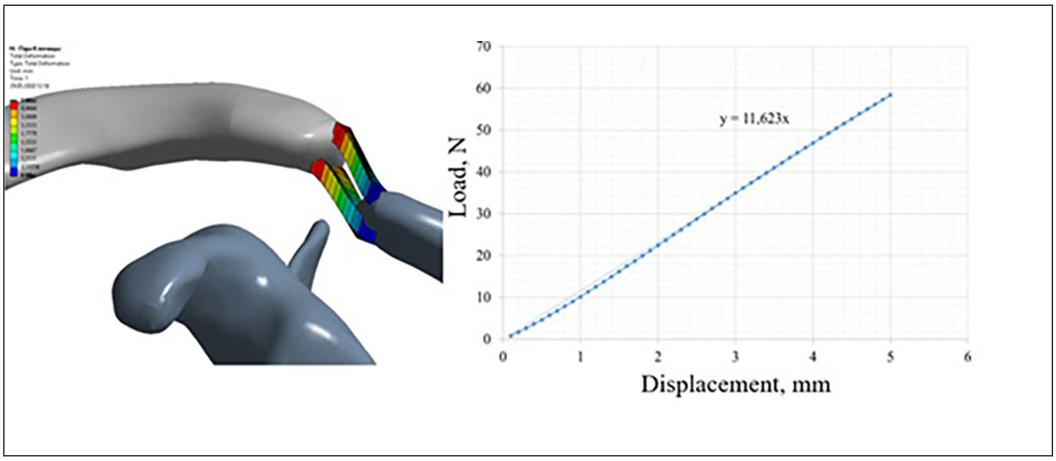

Fig. 10. Model and relationship between the applied force and displacement under complete damage to the acromioclavicular ligament complex

He observed only minor congruity disturbance on the radiograph with loading after severing the CCL, whereas cutting the CAL resulted in a dislocation. This led him to conclude that the CAL plays a leading role in stabilizing the ACJ [6].

R. Urist (1963) and M. Rosenorn and V. Pedersen (1974) also found that severing the CCL does not cause dislocation of the ACJ [7].

On the other hand, an opposing view highlights the crucial role of the coracoclavicular complex.

K. Dohn (1956) found that the strength of CAL is 36-46 kgf, whereas CCL exceeds 80 kgf, and its restoration is an essential component in stabilizing the ACJ [8].

Other researchers have also emphasized the significance of the coracoclavicular ligament in ACJ stabilization [9].

The desire to determine the primary ligamentous complex responsible for stabilizing the ACJ not only serves as the basis for an ongoing debate, but also forms the groundwork for the development and implementation of surgical techniques aimed at restoring the ACJ ligamentous apparatus. Two approaches are currently used for this purpose: restoration of the CC ligament complex [10-12], or the CA ligament complex [13,14].

Anatomical and biomechanical research continues to deepen our understanding of these structures.

Nakazawa detailed the morphology of the acromioclavicular ligament, specifically its bipartite arrangement, through histological and anatomical studies. In addition, a clear structural advantage of the superoposterior bundle (SPB) over the less consistent anteroinferior bundle (AIB) was also found. The SPB is a well-defined capsular thickening that is consistently present in all samples at a 30° orientation. Its attachments originate from the upper, posterior, and lower portions of the clavicle [15].

Ausberto Velasquez Garcia et al. conducted thorough research on the functional role of these components and concluded that although the two bundles of the ACJ ligament function in a complementary mode to maintain the kinematics, the AIB plays the primary role in joint constraint throughout the shoulder motion examined. Furthermore, the SPB appears to help avoid excessive anterior and superior translation, particularly during horizontal adduction [16].

Modern anatomical studies have revealed a unique orientation of the CAL portions, the attachments of the lig. conoideum and lig. trapezoideum on the procesus coracoideus and C, indicating their diverse function.

However, these structures only provide natural stabilization of the ACJ through their combined action [17].

Practice confirms this important concept. An anatomical reconstruction of the CCL demonstrates better primary stability similar to native ligaments compared to non-anatomical reconstruction. However, in 42% of cases, persistent dynamic posterior instability, which is considered as a postoperative deficit of the ACL, was detected [18-20].

Further clinical and anatomo-biomechanical studies indicate that isolated restoration of the acromioclavicular or coracoclavicular ligament complex does not provide complete stability of the ACJ and demonstrate the necessity of ligament reconstruction of both locations [21,22].

CONCLUSIONS

1. Static stabilizers in general and their components in particular are characterized by significant anatomical and functional peculiarities. Natural stabilization of the acromioclavicular joint is provided by their synergistic interaction, which is the basis for the development and implementation of surgical interventions, the scope of which includes the restoration of both ligament complexes.
2. Loss of stiffness in the "clavicle - scapula" system is significantly more pronounced in case of damage to the superior and inferior acromioclavicular ligaments (8.5 N/mm) than in case of damage to the conoid and trapezoid ligaments (11.6 N/mm).

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Conflict of interest:
The Authors declare no conflict of interest.

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Received: 03.05.2023
Accepted: 04.10.2023

A - Work concept and design, **B** – Data collection and analysis, **C** – Responsibility for statistical analysis, **D** – Writing the article, **E** – Critical review, **F** – Final approval of the article

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