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«TERRIBLE TRIAD» OF THE SHOULDER. BIOMECHANICAL SEMI-NATURAL MODELING AND JUSTIFICATION TO ROTATOR CUFF RESTORATION

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Abstract

The aim of this study: was determine the force of tension and deformation of axillary nerve in rupture rotator cuff and paresis of deltoid muscle of the shoulder joint.

Material and methods: Semi-natural modelling based on the axial scans spiral computed tomography of the intact shoulder joint was performed to determine the degree of traction load on the axillary nerve with distal displacement shoulder head and tendon rupture which paresis of the deltoid muscle.

Result: The values of deformations for axillary nerve being at the limit of tissue strength at distal displacement of humeral head of the model by 50 %, progressively increased with increasing distal displacement of humeral head to 100 % of its diameter, reaching values 1.7 times higher than the strength nervous tissue.

Conclusion: The progressive changes occurring in the axillary nerve under the action of traction loads, and as a consequence of its ischemia, over time can lead not only to demyelination, but also to the defeat of the axons themselves atrophy of its fibers. In turn, deltoid muscle atrophy increases the traction load on the affected axillary nerve, which forms a vicious circle. The only possible option to «break» the vicious circle is restore the stabilizing structures damaged during the injury, among which one of the most important is the tendons of the rotator cuff of the shoulder. Surgical restoration of the integrity rotator cuff of the shoulder reduces the traction load acting on the axillary nerve, which in turn significantly improves the conditions for reinnervation of the deltoid muscle.

Keywords: axillary nerve, «terrible triad» of the shoulder, m. supraspinatus, rotator cuff tears.

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1. Introduction

According to the literature, shoulder dislocations occur in 2 % of all types of traumas worldwide [1]. Anterior traumatic shoulder dislocation is a common pathology of the shoulder joint and occurs in 95 % of all shoulder dislocations, and combination with rotator cuff tendon rupture in 54 % of all anterior shoulder dislocations [2–6]. According to the literature, anterior traumatic dislocation of the shoulder is complicated by rupture of the rotator cuff or fracture tubercles of the humerus with paresis of the deltoid muscle. The primary function of the rotator cuff is to keep the head of the humerus depressed and centred into the glenoid fossa permitting a single centre of rotation, while allowing efficient abduction or forward elevation of the arm [7]. Shoulders with an intact cuff required 193.8 N (95 % CI, 125.5 to 262.1) total deltoid force to achieve 79.8° (95 % CI, 66.4° to 93.2°) of maximum glenohumeral abduction. Axillary nerve injury is a relatively common injury after anterior glenohumeral joint dislocation [8–12], as a result of axillary nerve injury occurs in 9–18 % of all anterior dislocations of the shoulder [12–14]. Neurological complications were found in 5.4–55 % of all dislocations, with the two most commonly affected patient groups being elderly women sustaining dislocation as a result of a simple fall and young men after high-energy injuries, often multitrauma victims. Infraclavicular part of the brachial plexus was most often affected [9–11, 13, 14]. Such a severe injury to the shoulder joint is called «terrible triad» [2, 6, 12, 13].

The deltoid and supraspinatus muscles act as the coronal force couple, compressing the humeral head to the glenoid in abduction [15]. Rupture of the rotator cuff and paresis of the deltoid muscle result in muscle imbalance and instability of the shoulder joint, which causes displacement the head of the shoulder distally. This leads to a constant traction load on the axillary nerve, and the impossibility of reinnervation of the deltoid muscle. The purpose of our study was to determine the parameters of the forces acting on the axillary nerve in the aftermath of the «terrible triad» of the shoulder.

The aim of this study is determining the force of tension and deformation axillary nerve in rupture rotator cuff and paresis of the deltoid muscle of the shoulder joint.

2. Materials and methods

A study was conducted between 2017 and 2021 in SI «Institute of Traumatology and Orthopedics of the National Academy of Medical Sciences of Ukraine» in the department of «Microsurgery and Reconstructive-Recovery Surgery of Upper Limb» and department of «Biomechanics» a semi-natural modelling of the shoulder joint was performed to determine the degree of traction load on the axillary nerve with distal displacement shoulder head and tendon rupture which paresis of the deltoid muscle. Based on the axial scans spiral computed tomography of the intact shoulder joint obtained on the computed tomography «Toshiba Activion 16» (Japan), the spatial geometry of the structures of the shoulder joint was reproduced in automatic and semi-automatic modes using the software package «Mimics» (**Fig. 1**). SolidWorks software package creates a simulation 3-D model of the shoulder joint. Soft-tissue elements are added to the model – deltoid and supraspinatus muscles, vessels and nerves, morphometric and topographic data of which are obtained from cadaveric material (**Fig. 2**).

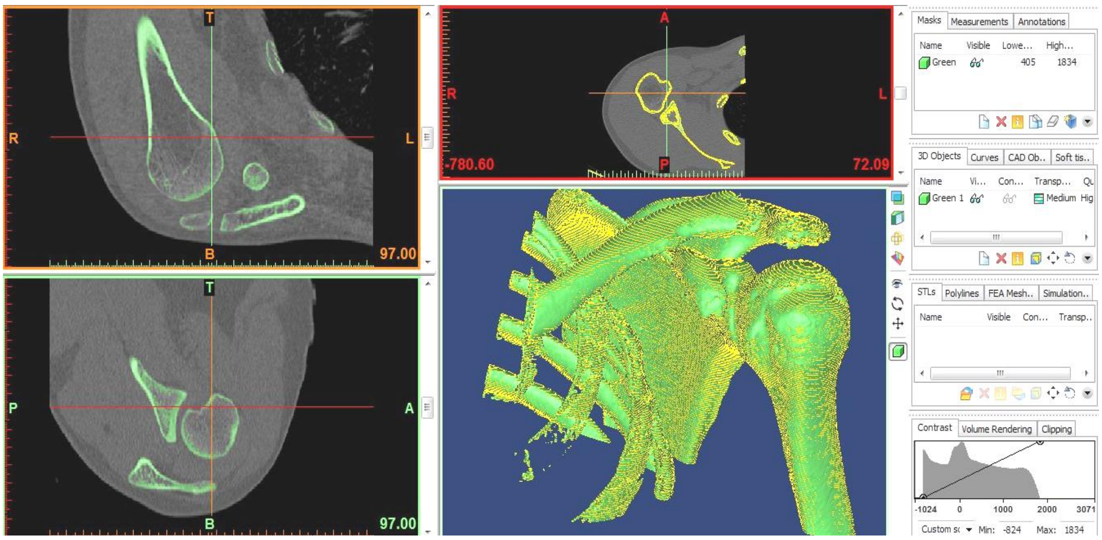

Fig. 1. Reproduction of the spatial geometry of the shoulder joint

The location and ratio of elements (LR) of the model are as close as possible to real conditions. The existing deviations did not make fundamental differences and did not affect the results of the calculations. The averaged mechanical properties of biological tissues such as cortical bone, cartilage, tendon, nerve, and artery used for calculations were obtained from the literature [15, 16].

Further calculations were performed by the LR method, which allows us to study the evolution of the process of deformation under load of elements of the simulation model of the shoulder, namely bone, muscle, and nerve, with large geometric and physically nonlinear properties of materials and time-varying external influences. Simulations were imported into the ANSYS program for stress and strain (CSS) calculations using the LR method. The calculations used the average physical properties of biological tissues obtained from literature sources [16, 17]. For comparative analysis, the lowest value of the tissue strength limit was chosen.

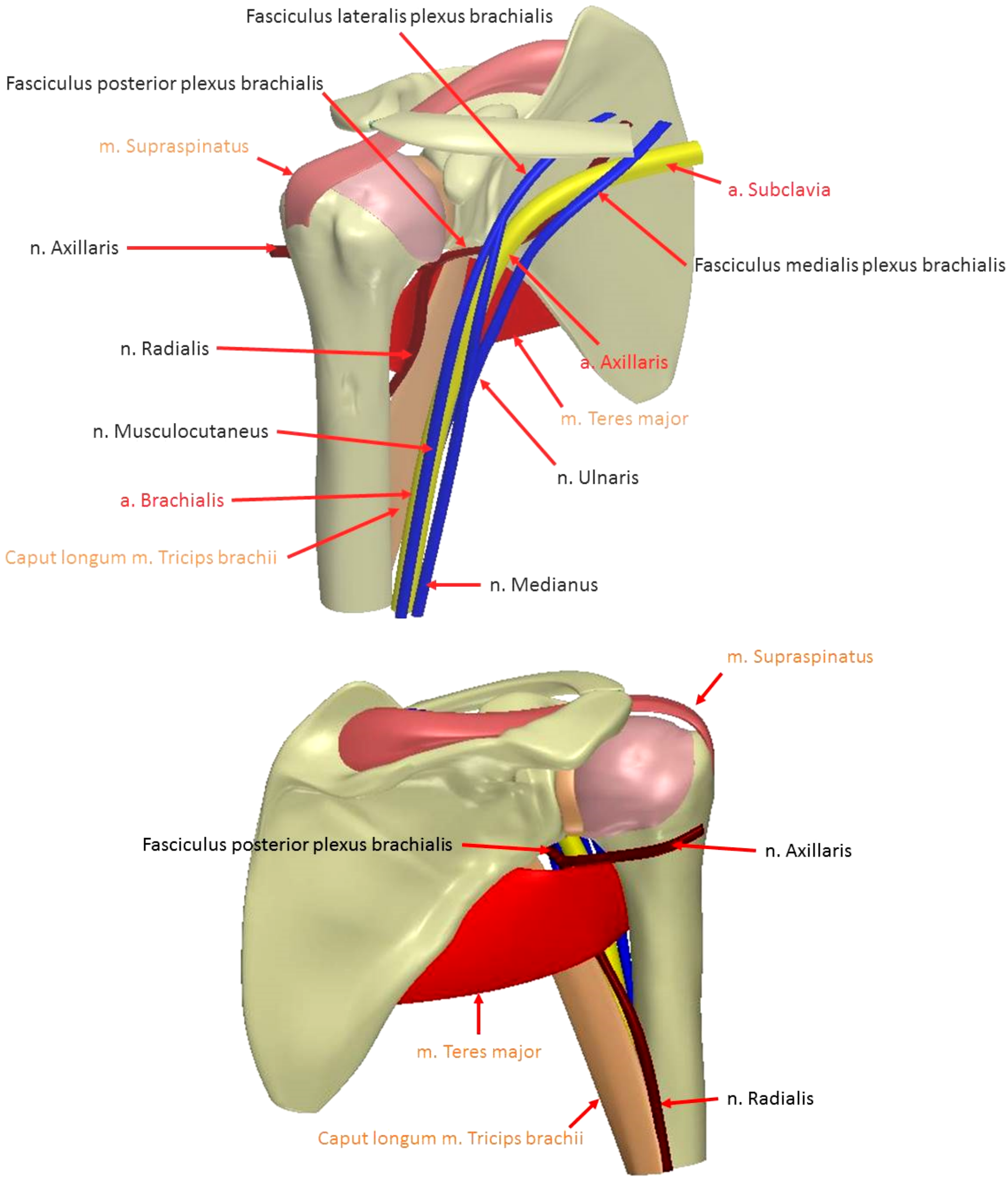

Fig. 2. Simulation 3-D model of intact shoulder joint with soft tissue structures

In the semi-automatic mode, 3 variants of the LR model were generated (**Fig. 3**) with distal displacement of the humeral head by 25 %, 50 % and 100 % of its diameter, under the action of the mass of the upper limb, which simulates the exclusion of deltoid muscle function. The load of the model is the effect of the above mass of the upper limb for the average person weighing 75 kg in a standing position, taking into account the mass-inertial characteristics: shoulder – 2.7 %, forearm – 1.6 %, hand – 0.6 %, total – 4.9 % of the total human body weight [18]. Therefore, a force of 750 H×0.049 = 36.75 N was applied to the distal end of the humerus of the model (**Fig. 4**).

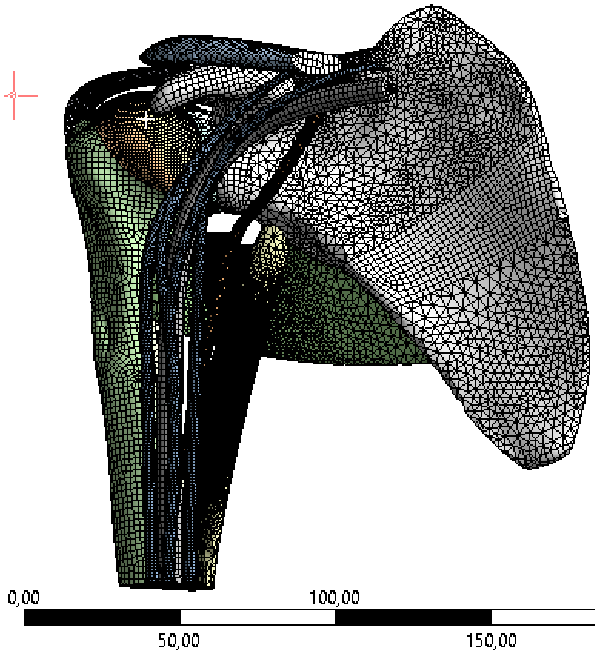

Fig. 3. Finish element model

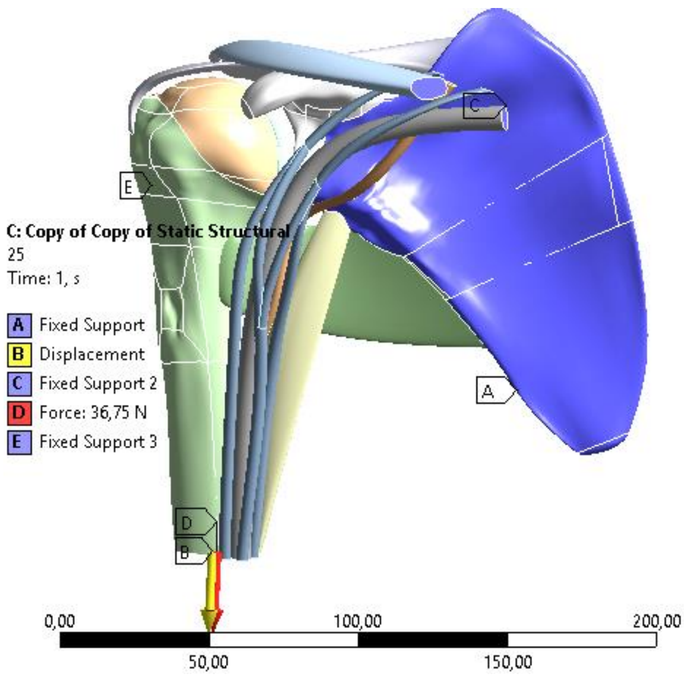

Fig. 4. Boundary conditions (calculated scheme of fastening and loading)

The key indicators for comparative analysis are the data obtained by calculating the values of the intensity of stresses and strains (according to Misis), as well as the total displacements (Total Deformations). The behaviour of the vascular-nervous bundle of the model at the distal movement of the humerus in the shoulder joint by 25 %, 50 % and 100 % of the diameter of its head was studied.

3. Results

Distal movement of the humeral head of the model by 25–100 % of its diameter is accompanied by joint movements of the structures vascular-nervous bundle. However, all elements of the plexus due to the anatomical location, interstitial junction and their own mechanical properties do not move evenly. Axillary nerve stress data for different variants of distal displacement of the humeral head (25, 50 and 100 % of the diameter) are presented in **Table 1**.

Table 1

Axillary nerve stress data for different variants of distal displacement of the humeral head

Distal displacement of head of humeral bone	Tension, MPa
25 %	0.058
50 %	0.101
100 %	0.173

The values of deformations for axillary nerve being at the limit of tissue strength at distal displacement of the humeral head of the model by 50 % progressively increased with increasing distal displacement of the humeral head to 100 % of its diameter, reaching values 1.7 times higher than the strength nervous tissue. The combined data of deformation indices on the model elements for different variants of distal displacement of the humeral head (25, 50 and 100 % of the diameter) are presented in **Table 2**.

Table 2

Deformation indices on the model elements for different variants of distal displacement of the humeral head

Distal displacement of head of humeral bone	Deformations, mm
25 %	0.102
50 %	0.178
100 %	0.303

4. Discussion

With an increase in the distal displacement of the humeral head to 100 %, a progressive increase in the maximum values of stress on n. axillaris with σ_{max}=0.058 MPa to σ_{max}=0.173 MPa, and deformation rates with ε_{max}=0.102 mm to ε_{max}=0.303 mm, which exceeds the allowable by 25 %, and is accompanied by traction load on the nerve causing its ischemia, except for function m. in the area of innervation and progression of the distal displacement of the head of the shoulder. The only anatomical structure that can limit further distal displacement of the humeral head in these conditions is the m. supraspinatus. However, the very nature of the injury and suggests its damage.

The progressive changes occurring in the axillary nerve under the action of traction loads, and as a consequence of its ischemia, over time can lead not only to demyelination, but also to the defeat of the axons themselves atrophy of its fibers. In turn, deltoid muscle atrophy increases the traction load on the affected axillary nerve, which forms a vicious circle.

The authors of biomechanical studies there looked at the mechanism of injury for the upper region of brachial plexus based on stress analysis of its by using 3D-FEM of the spine, dura mater, root, and the brachial plexus all in one model. Retroflexion and lateroflexion of the cervical spine, simulating a clinical situation of moving the head and neck away from the shoulder and 30 degrees abduction of the upper limb resulted in the focus of strain in the upper trunk and the roots of C5 and C6 [15].

Another investigation based on computational framework integrating finite element analysis and musculoskeletal modelling of 8 weeks of glenohumeral growth in a rat model to examine the mechanical factors contributing to changes in bone growth and morphometry following brachial plexus. Our study aimed to FE biomechanical analysis of the brachial plexus' infraclavicular region and m. supraspinatus structures' behaviour within the Terrible Triad of the Shoulder, resulting from the distal displacement of the humeral head under the gravity action of the upper extremity. Understanding the behaviour of each structure of the brachial plexus will help to choose the optimal surgical repair strategies for to avoid serious complications in this type of injury [19].

The only possible option to «break» the vicious circle is restore the stabilizing structures damaged during the injury, among which one of the most important is the tendons of the rotator cuff of the shoulder. Surgical restoration of the integrity rotator cuff of the shoulder reduces the traction load acting on the axillary nerve, which in turn significantly improves the conditions for reinnervation of the deltoid muscle.

But some authors of studies indicate that a repaired rotator cuff tendon in rats does not heal as well as a repaired tendon without accompanying brachial plexus injury. This suggests that more proximal neuropathy is one of the risk factors for re-rupture of the repaired rotator cuff tendon [20].

Study limitations. The mechanical behaviour of the tissues was assumed isotropic using linear elastic model. This is quite simplistic because the mechanical response of soft tissue is visco-hyperelastic. The elastic properties used in the article widely used in most scientific literature and characterize only the stiffness properties in the short terms loads. Visco-elastic properties were not the subject of study in this work. In order to use anisotropic properties or take into account the hyperelasticity of tissues, we need to know a lot of parameters of tissue properties, such as yield strength/modulus of elasticity 1st and 2nd, etc. For biological tissues, they are either absent or vary in large ranges, so their use can cause much greater error in calculations than the use of conservative/linear model.

Prospects for further research. In the future, we plan to conduct research that can indicate critical damage to the brachial plexus or axillary nerve, depending on the time under which the nerves remain in tension, as well as research that can show us the exact fate of restoring conduction along the nerve.

5. Conclusions

Distal movement of the humerus in the shoulder joint by 25 %, 50 % and 100 % of the diameter of its head is accompanied by an increase in the values of stress at 0.058, 0.101, 0.173 and deformation at 0.102, 0.178, 0.303, respectively acting on the axillary nerve.

With an increase in the distal displacement of the humeral head from 25 %, a progressive increase in the values of stress and deformation of the axillary nerve state is accompanied by traction load on the nerve causing its ischemia, followed by progressive exclusion of m.deltoideus function.

Prompt restoration the integrity of rotator cuff of the shoulder reduces a traction load acting on the axillary nerve, which in turn significantly improves the conditions for reinnervation of the deltoid muscle.

Conflict of interest statement

The authors declare that they have no conflicts of interest.

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