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Mathematical modeling of the muscles responsible for shoulder joint flexion in upper obstetric paralysis

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Objective. To determine the degree of change in muscle length and torque of the shoulder joint during flexion in conditions of the pathological position of the upper limb in Erb-Duchen syndrome. Methods. The analysis of the change in muscle length and torque of the shoulder joint was performed at flexion within 50°–60°. In the Erb syndrome clinic, the torque value of the joint is reduced due to weakness or paralysis of the muscles that provide stability and mobility of the shoulder joint. Verification of the appearance of the model was carried out according to the 3D-model obtained from the CT scan of the patient. Results. After analyzing the work of the muscles responsible for the flexion of the shoulder joint, it was determined that a decrease in muscle strength leads to a decrease in the moment of force acting on the joint, a change in the length of the force lever affects the moment of force, a change in the angle between the force and the arm of the force leads to a decrease in the muscle's efficiency. Internal rotation of the humerus reduces the length of the muscle, which is demonstrated in the models. When lifting the arm with a load, the muscle shortens and its length decreases accordingly. Other muscles not represented in the model do not contribute to the generation of torque of the shoulder joint due to their lack of direct connection to the humerus, but they are responsible for the movement of the scapula and clavicle. A decrease in their strength, a change in the direction of the force vector leads to significant changes in the ratio of the anatomical structures of the shoulder girdle with high individual variability. Conclusions. A change in the direction of the force vector of a muscle and its length during bending lead to changes in motor activity: a decrease in the moment of the joint leads to a limitation of the amplitude of movements in the joint, the balance between different muscles acting on the joint is disturbed, it can lead to its instability and deformates. Biomechanical changes limit the functionality of the joint and cause pain syndrome. The identified biomechanical changes indicate the need to correct the specified pathological conditions.

Мета. Визначити ступінь зміни довжини м'язів та крутного моменту плечового суглоба під час згинання в умовах патологічного положення верхньої кінцівки в разі синдрому Ерба-Дюшена. Методи. Проаналізували зміни довжини м'язів і крутного моменту плечового суглоба за флексії в межах 50°–60°. За умов синдрому Ерба величина крутного моменту суглоба знижується через слабкість або параліч м'язів, які забезпечують стабільність і рухливість плечового суглоба. Верифікацію вигляду моделі проводили відповідно до 3D-моделі, яку отримали з КТ пацієнта. Результати. Розглянувши роботу м'язів, відповідальних за флексію плечового суглоба визначили, що зменшення сили м'яза призводить до зниження моменту сили, яка діє на суглоб, зміна довжини важеля сили впливає на момент сили, зміна кута між силою і плечем сили спричинює зменшення ефективності м'яза. Внутрішня ротація плечової кістки зменшує довжину м'яза, що продемонстровано на моделях. У разі згинання плечового суглоба довжина м'яза зменшується, причому в базовій і деформованій моделях однаково, хоча початкова довжина м'яза деформованої моделі менше, ніж у базовій. Інші м'язи, які не наведені в моделі, не впливають на створення крутного моменту плечового суглоба через відсутність їхнього прямого з'єднання з плечовою кісткою, але вони відповідають за рух лопатки та ключиці. Зменшення їхньої сили, зміна напрямку вектора дії сили призводить до значних змін співвідношення анатомічних структур плечового поясу з високою індивідуальною варіабельністю. Висновки. Зміни напрямку вектора дії сили м'яза та його довжини під час згинання спричинюють зміни в руховій активності: зменшення моменту суглоба спричинює обмеження амплітуди рухів у суглобі, порушується баланс між різними м'язами, які діють на суглоб, може призвести до його нестабільності та деформації. Біомеханічні зміни обмежують функціональність суглоба й обумовлюють больовий синдром. Виявлені біомеханічні зміни свідчать про необхідність корекції означених патологічних станів. Ключові слова. Акушерський параліч, синдром Дюшена-Ерба, плечовий суглоб, момент суглоба, сила м'яза, моделювання.

Key words. Obstetric brachial plexus palsy, Erb-Duchenne syndrome, shoulder joint, joint moment, muscle strength, modeling

Introduction

Obstetric brachial plexus palsy occurs most often as a result of nerve damage in the shoulder area during difficult vaginal birth due to excessive forces applied to the shoulder, which cause it to stretch [1, 2]. It is observed in approximately 1–4 cases per 1,000 newborns. Anatomically, it occurs on both sides, but more often on the right.

Three main types are distinguished by the level of damage:

– upper (Duchenne-Erb palsy), when the C_V–C_{VI} roots are injured. Characteristic manifestations of the syndrome are the adducted and rotated inward arm, “waiter's hand pose”, impaired abduction and external rotation of the shoulder, limited forearm flexion;

– middle (Remak's palsy) — damaged C_{VII} roots, characterized by impaired extension of the forearm, extension of the hand and fingers. It can often be combined with the previous type;

– total (Dejerine-Klumpke paralysis) — roots C_V–C_{VIII} are affected. Signs include complete paralysis of the entire arm, “hanging arm”. Damage to T_I can cause Horner syndrome (ptosis, miosis, enophthalmos).

In this study, we consider Erb-Duchenne syndrome. Erb’s point is a place in the upper trunk of the brachial plexus, located 2–3 cm above the clavicle [3], formed by the union of the C_V and C_{VI} roots, which later converge. Damage to the axillary, musculocutaneous and suprascapular nerves leads to impaired nerve transmission and muscle atrophy and, as a result, to clinical manifestations of Erb’s syndrome [4].

Surgical intervention at an early age (up to a year) increases the chances of partial or even complete restoration of limb functions. However, even with successful reconstruction, patients may have some residual movement impairment and may require long-term rehabilitation [5].

In medical practice, there are instances when conservative treatment of brachial plexus paralysis syndrome does not achieve the desired outcome, and early surgical intervention is not performed. The course of the disease for 4–10 years leads not only to the progression of muscle imbalance, but also to deformation of the bones of the upper limb with the involvement of the humeral head, often accompanied by its subluxation or dislocation. Changes in the anatomical proportions of the components of the shoulder joint cause violations of both the length of the muscles and the vector of their action, which, in turn, leads to a disorder of the movements of the upper limb.

The main goal of treatment of patients with a long course of Erb's syndrome is to restore the “hand-mouth” movement, that is, to provide basic conditions for self-service. It is the ability to perform the specified actions that allows the patient not only to eat independently, but also to perform most of the daily exercises [6].

Purpose: to determine the degree of change in muscle length and the magnitude of their torque in the shoulder joint during flexion in conditions of pathological position of the upper limb in the case of Erb-Duchenne syndrome.

Material and methods

The specificity of Erb's syndrome is the magnitude of the joint torque, which is reduced due to weakness or paralysis of the muscles that provide stability and mobility of the shoulder joint. In particular, the reduced torque affects the child's ability to abduct and externally rotate the shoulder, which limits the functionality of the hand. The joint torque is determined by muscle strength, shoulder length (perpendicular from the line of force to the axis of rotation) and the direction of force [7, 8].

The greatest force a muscle can develop when its fibers are stretched to the optimal length (individual for each). Given that the length of the lever (joint bones) does not change, the torque will be affected only by the muscle strength and the angle of its action. In the case of a long-term state of imbalance of the muscles of the joint, namely the weakening of those that abduct the shoulder back and the preservation of muscle strength from the side of the clavicle, the direction of action of the muscle force vector of the entire upper limb changes. This leads to a change in the joint torque and the direction of movement of the limb. The pathological position of the shoulder, such as pressing against the body, causes a decrease in the length of the muscles responsible for its abduction, which prevents full flexion of the joints of the arm, even if the innervation of the control muscles is intact.

The work is based on the DAS-3 model, which is part of the Dynamic Arm Simulator project for real-time modeling of the musculoskeletal system of the shoulder and arm. The main parameters of the basic model and the mathematical foundations are presented by E. Chadwick et al. [9].

The model consists of 138 muscles and 6 joints: supraclavicular, sternoclavicular, humeral, humeral-ulnar, humeral-radial and radiocarpal (Fig. 1, a).

In the modified model, the location of the humeral head in the joint was changed to the outside by 45°, and the bones of the humerus were raised, which led to a corresponding change in the location of the entire shoulder joint (Fig. 1, b, c) and rotation of the elbow joint to the outside. The wrist was flexed at 30°, the arm was pressed against the body, internally rotated in the shoulder joint, the forearm was pronated, and the elbow joint was extended. The size of the scapula was reduced by 20 %. Verification of the appearance of the model was carried out according to the 3D model obtained using a CT scan of the patient (Fig. 2).

The analysis of changes in muscle length and torque of the shoulder joint was carried out with flexion within 50°–60°.

Results

The shoulder joint (*articulatio humeri*) is the most mobile joint of the bones. Its anatomical structure allows the upper limb to perform a wide range of movements, such as external and internal rotation, flexion, extension, abduction and adduction of the arm. With the help of the joint, various actions are performed by the upper limb. The most important movement that provides the possibility of self-service is the ability to bring the palm to the mouth. Let us examine the functioning of the muscles responsible for this action.

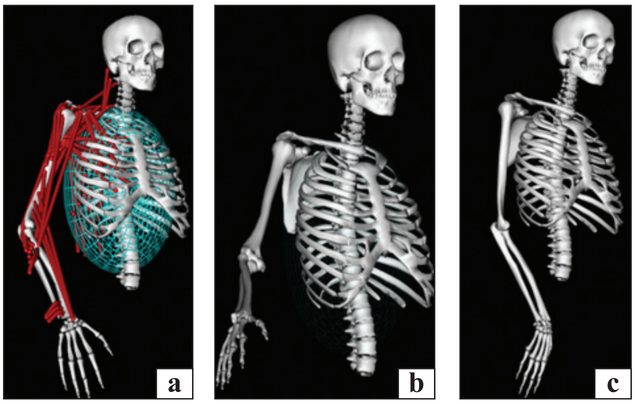

Fig. 1. DAS-3 model: basic models with muscles and contact geometry elements (a) and without muscles (standard joint arrangement) (b); c) modified model according to the description of the location of the shoulder girdle joints in Duchenne-Erb syndrome

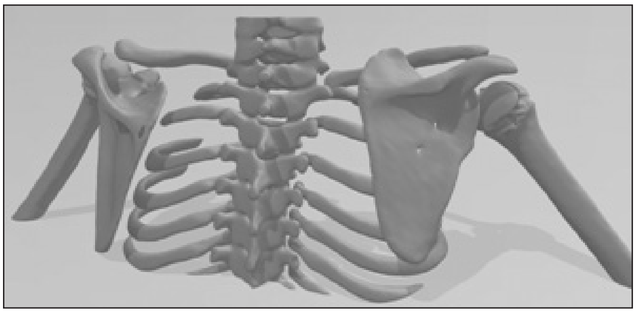

Fig. 2. 3D image obtained from the patient's CT scan

The front part of the deltoid muscle (*m. deltoideus*) raises the arm forward, facilitating shoulder joint flexion. It is located in the area of the acromial, clavicular and scapular spine. Its acromial part (middle fibers) abducts the arm, while the clavicular and scapular play a significant role in stabilization, providing a stable plane of abduction. The clavicle can act as a flexor and internal rotator of the upper limb, while the scapula (posterior fibers) can extend and rotate the arm outward.

In the model, the deltoid muscle is represented by two muscle groups: *deltoid_clavicle* (4 fibers) and *deltoid_scapula* (11 fibers). The extreme fibers of the anterior and posterior parts of the muscle are analyzed in both the basic (N) and deformed (D) models (Fig. 3, c).

Assessment of the work of the anterior part of the muscle shows that normally, during flexion in the shoulder joint, the length of the fibers located dorsally increases most significantly (*N_delt_clav 4*), i. e., when the shoulder is raised, the muscle travels a longer path than its ventral part (*N_delt-clav 1*) (Fig. 3, a). In the deformed model, we observe a completely different picture, namely: internal rotation of the shoulder joint and medial adduction of the humerus lead to a greater stretching of the dorsal part (*D_delt_clav 1*) than the anterior part (*D_delt_clav_4*) (Fig. 3, a). The change in muscle length in the deformed model is less than in the baseline model.

The dorsal and ventral fibers of the posterior part of the *m. deltoideus* (Fig. 3, b) during flexion of the shoulder joint have the opposite direction of change in length, which is preserved during deformation of the model. But in the latter, the dorsal fibers are less stretched than in the normal one due to the reduced size of the scapula, i. e. due to the reduction in the length of the muscle itself. The anterior fibers of the posterior part of the *m. deltoideus* change their length little due to their more central location.

The *biceps brachii* muscle helps to raise the arm and supinates the forearm. It consists of a short and long head. The long head is located on the lateral side of the biceps brachii muscle, and the short head is on the medial side. The biceps brachii muscle is able to generate movements in the shoulder and elbow joints.

For the execution of the "hand-mouth" movement, *m. biceps brachii* controls both the shoulder and elbow joints, while the length of both heads of the muscle decreases, i. e. during the movement the muscle shortens. Normally, when the shoulder joint is flexed, the long head of *m. biceps brachii long head* practically does not change its length. It is important to note that the observed phenomenon occurs when the arm is raised without any load, resulting in muscle shortening and a decrease in length. This scenario is not under consideration.

In the deformed model, a parallel trajectory of the reduction of the attachment points of both heads of the muscle can be observed, this is due to the fact that during internal rotation of the shoulder joint (Fig. 4, a) the long head of the muscle, which originates precisely at the head of the humerus, rotates to the middle position, i.e. becomes parallel to the short one, and the degree of contraction depends only on the initial length of the muscles.

During elbow flexion (Fig. 4, b) the trajectories of muscle length reduction are parallel, but in the deformed model they converge, for the reason already indicated.

The pectoralis major muscle (*m. pectoralis major*) is responsible for flexion and adduction of the arm and is the largest superficial muscle of the anterior chest wall. It has two heads: clavicular and sternocostal. In the model it is represented by two muscle groups *m. pectoralis major_clavicle* (2 fibers) and *m. pectoralis major_terez* (6 fibers) (Fig. 5, c). We analyze the extreme fibers of the sternocostal muscle and both clavicular fibers.

Changes in the length of the fibers of the clavicular head of *m. pectoralis major* occur unidirectionally due to their parallel arrangement, which is displayed on the graph (Fig. 5, a). A decrease in the length of the fibers during the function of flexion in the shoulder joint was recorded. The length of the corresponding muscles also changes in the deformed model.

The nature of the change in the length of the sternocostal part of the *m. pectoralis major* in the basic and deformed models is the same (Fig. 5, b). The fibers located caudal to the elevation of the shoulder increase, and in the coronary, on the contrary, decrease. In the deformed model, the process of muscle length changes is similar, but they are noticeably smaller.

It is noted that the *m. pectoralis major* is innervated by the T_I–T_{II} roots and is not injured in Erb's syndrome. Its function is preserved, unlike the muscles of the back. It is the predominance of the strength of the anterior group of muscles that leads to internal rotation and adduction of the humerus.

The coracobrachialis muscle (*m. coracobrachialis*) is involved in flexion and adduction of the arm. It starts from the beak-shaped process of the scapula, located on the supramedial part of the humerus. Its main function is to flex and adductorize the humerus, and promote internal rotation of the arm. In the model, it is represented by three parallel fibers (Fig. 6, c). Let us analyze the change in the length of the longest fiber.

Internal rotation of the humerus reduces the length of the muscle, which is demonstrated in the models. During flexion of the shoulder joint, the length of the muscle decreases, and in the basic and deformed models it is the same, although its initial size in the deformed model is smaller than in the basic one.

We have considered the main muscles that provide movements in the shoulder joint. All of them, except for the pectoralis major muscle, are innervated by the roots of the C_V–C_{VI}, that is, they change their functionality in the case of Duchenne-Erb syndrome. A decrease in innervation, depending on the degree and location of the damage, leads to a decrease in muscle strength, sometimes to complete paralysis. That is, the mobility of the joint, which is characterized by its torque, changes, because the muscle strength, length and angle of action of its force vector affect it, provided that the length of the limb is preserved. We do not consider muscle paralysis. In the model with a deformed humerus, we reduce the strength of the muscles that innervate the joint by 50 %. Of course, this is conditional, because there is a large variability in both the change in muscle strength and the angle of their action during joint rotation.

Let us consider how a change in muscle strength and the vector of its action affect the torque of the joint. Therefore, it can be influenced only by the muscles that pass through the joint, or directly by the movement of its components. Let us analyze not individual muscle fibers, but the influence of the entire array on the joint. As the modeling showed, in the deformed model we observe a significant decrease in the torque of the joint. Thus, this torque, which is created by the clavicular part of the deltoid muscle, in the basic model has a characteristic increase in the phase from 20° to 30°. With an increase in the angle of flexion of the shoulder joint, further movement is intercepted by the muscles of the humerus (*m. biceps*), in the deformed model we observe a moderate increase in the action of the deltoid muscle throughout the entire time of flexion. The torque in the deformed model is noticeably less than in the basic one (Fig. 7, a).

The action of the scapular part of the deltoid muscle on the torque of the shoulder joint continues throughout the flexion phase. In the deformed model, the action of the scapular part of the deltoid muscle is

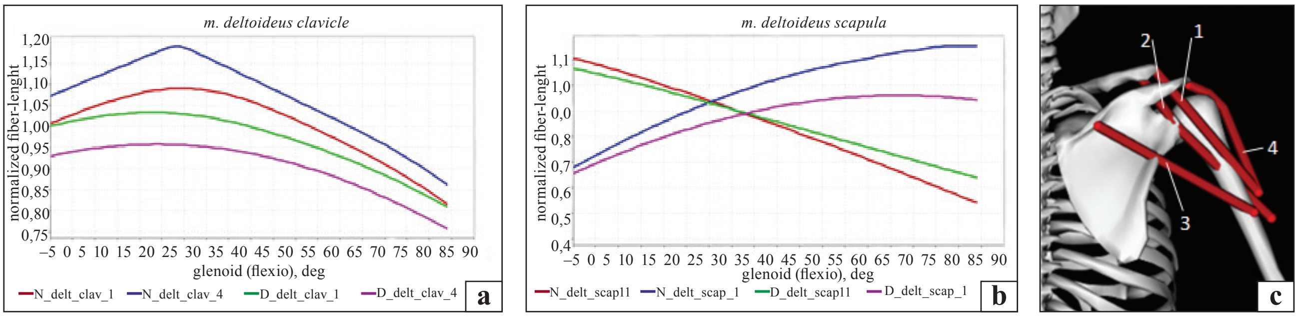

Fig. 3. Change in the normalized length of the *m. deltoideus muscle* during flexion of the shoulder joint: a) anterior section; b) posterior section; c) fibers of the *m. deltoideus muscle*: 1 — *delt_clav 1*; 2 — *delt_clav 4*; 3 — d*elt_scap 1*; 4 — *delt_scap 11*

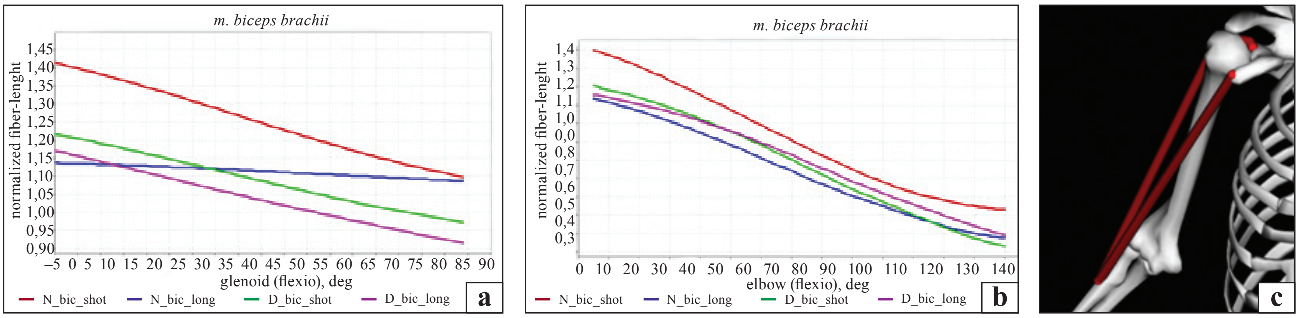

Fig. 4. Change in the normalized length of the *m. biceps brachii* muscle: a) during flexion of the shoulder joint; b) during flexion of the elbow joint; c) appearance of muscles in the model

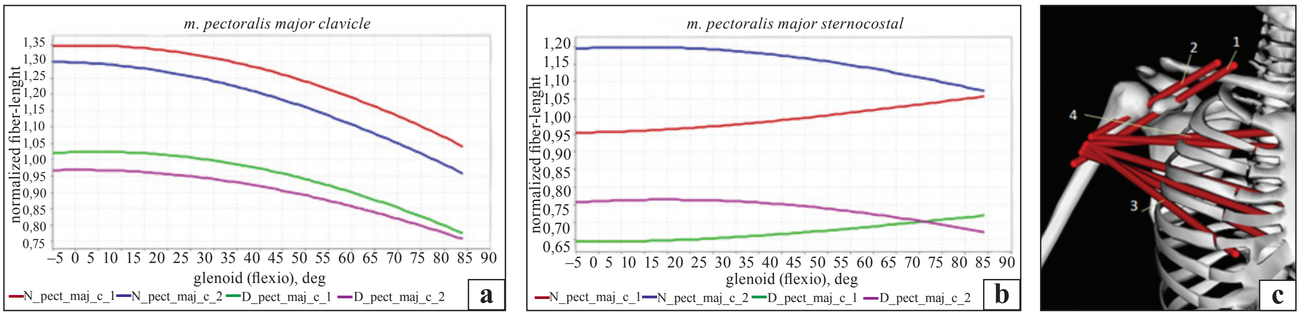

Fig. 5. Change in normalized length of *m. pectoralis major* during flexion of the shoulder joint: a) clavicular head of the muscle; b) sternocostal; c) *m. pectoralis major*: clavicular part 1 — *pect_maj_c_1*; 2 — *pect_maj_c_2*; costal part 3 — *pect_maj_t_1*; 4 — *pect_maj_t_6*

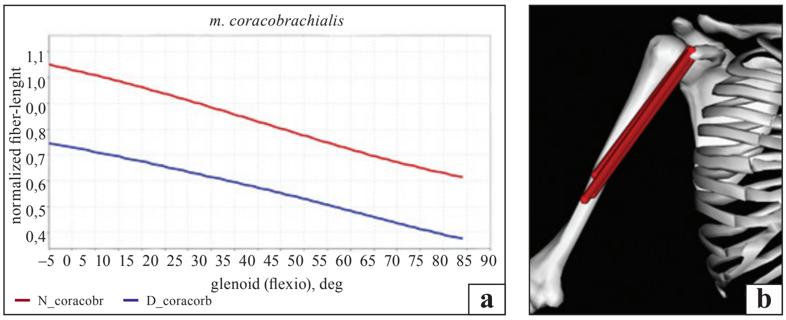

Fig. 6. Change in normalized length of *m. coracobrachialis* during flexion of the shoulder joint: a) in the basic and deformed models; b) *m. coracobrachialis*

practically constant, but at the initial stage it exceeds the corresponding torque in the basic one, which may indicate constant muscle tension (Fig. 7, b).

The pectoralis major muscle (*m. pectoralis major*) simultaneously acts from two structures of the joint, the clavicle (Fig. 7, c) and the sternum (Fig. 7, d). Even without changing the force, in the deformed model the torque of the clavicular part of the muscle is less than in the basic one. In the thoracic one, on the contrary, it increases.

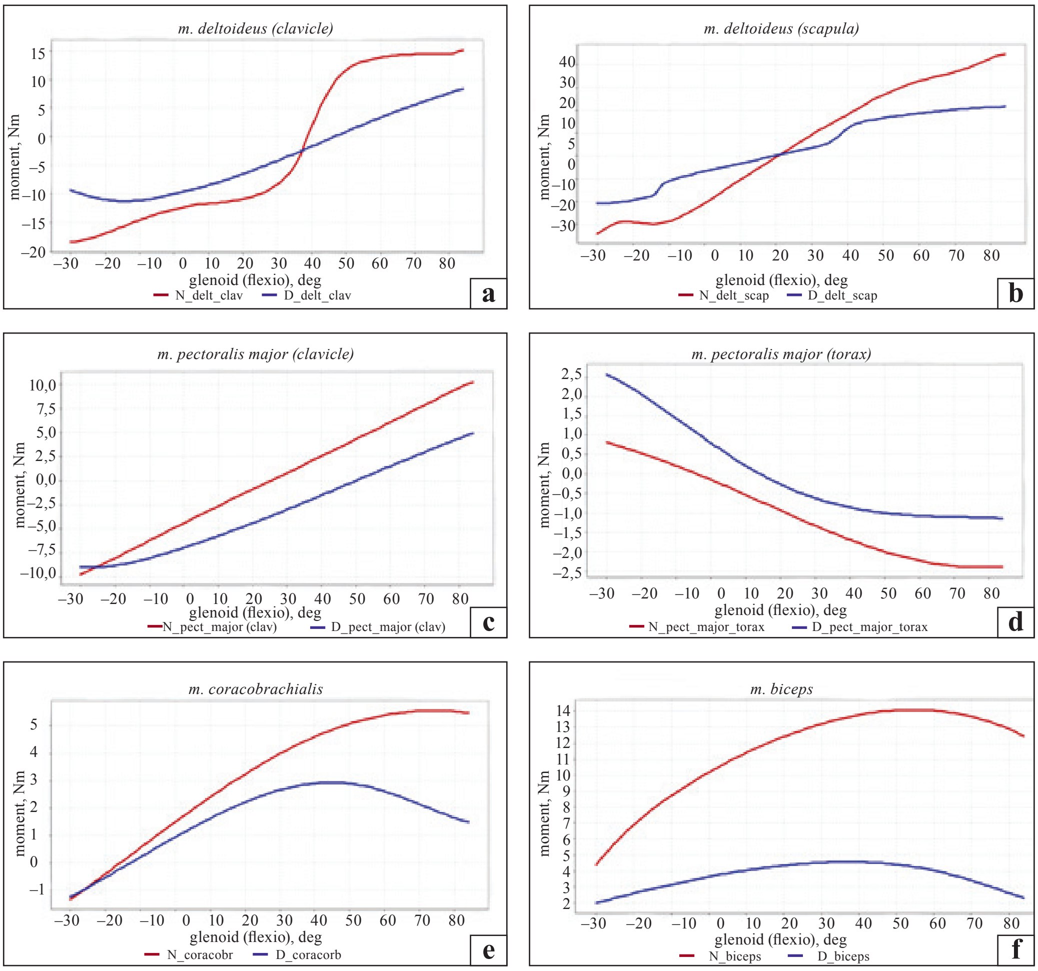

Fig. 7. Torque of the shoulder joint created by the muscles responsible for its flexion: a) *m. deltoideus (clavicle)*; b) *m. deltoideus (scapula)*; c) *m. pectoralis major (clavicle)*; d) *m. pectoralis major (thorax)*; e) *m. coracobrachialis*; f) *m. biceps*

The coracobrachialis muscle (*m. coracobrachialis*) takes an active part in raising the shoulder. In the basic model, its force is not changed. In the deformed state, the changes led to a significant decrease in the moment in the shoulder joint (Fig. 11, c) and were more gradual than in the baseline state.

The strength of both heads of the biceps is reduced, which led to a significant decrease in the moment, almost to the complete absence of muscle activation.

Other muscles do not affect the creation of the torque of the shoulder joint due to the absence of their direct connection with the humerus, but they are responsible for the movement of the scapula and clavicle. A decrease in their strength, a change in the direction of the action vector leads to significant violations of the ratio of the anatomical structures of the shoulder girdle with high individual variability.

Conclusions

Our findings allowed us to make the following generalizations: a decrease in muscle strength leads to a decrease in the moment of force acting on the joint. This means that the muscle becomes less effective in creating movement in the joint. A change in muscle length due to prolonged restriction of mobility affects the torque of force.

A change in the angle of action of the muscle force causes a disruption of the normal biomechanics of the joint and can lead to a decrease in muscle efficiency.

Disruption of the function of one muscle causes a loss of synergy: the joint work of the muscles. Injuring one can affect the work of other muscles that are part of the synergistic group and additionally reduce the torque of the joint.

The data presented indicate significant changes in the motor activity of the joint: a decrease in torque leads to a limitation of the function (amplitude) of movements, a violation of the balance between different muscles that act on the joint, causes its instability and deformation. Biomechanical changes limit functionality and cause pain syndrome. The identified biomechanical changes indicate the need to correct the indicated pathological conditions.

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

Prospects for further research. In the future, it is of interest to study the possibility of glenoid remodeling after surgical interventions for muscle transpositions of the shoulder girdle.

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Authors' contribution. Karpinska O. D. — development of the mathematical model, data calculation, writing the text; Hrytsenko A. M. — collection and processing of materials, editing the text.

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MATHEMATICAL MODELING OF THE MUSCLES RESPONSIBLE FOR SHOULDER JOINT FLEXION IN UPPER OBSTETRIC PARALYSIS

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