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Effect of changes in the length of the components of the musculotendinous element of the elbow flexor muscles on the isometric force and joint torque

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Immobilization of the joint leads to the formation of immobilization contracture, which is accompanied by a decrease in the elasticity of tendons and muscles, i.e. loss of full contraction and stretching. The torque in human joints is one of the key indicators in assessing rehabilitation. Objective. To study the effect of changes in the strength, length of muscles and tendons of the elbow joint on the torque in flexion. Methods. The basic OpenSim model arm26 was used for modeling. To determine the change in the length of the components of the muscle-tendon element (MTE), their length was determined at a 90° angle of elbow flexion. The decrease in muscle strength was considered a loss per day for elbow flexors — 1.2 %, extensors — 1.1 %. The decrease in strength was calculated for a period of immobilization of 45 days. Three models were created: Normal — a model without changes in muscle parameters; Contracture — a change in the length of muscles and tendons; Contracture + muscle (CM) — an additional decrease in muscle strength. Results. The obtained data of torques when changing the length of the MTE components showed their increase in conditions of unchanged isometric muscle strength. But this option is not possible after immobilization of the limb. Therefore, it is closer to the real model of CM, in which the torque is significantly reduced by the amount of decrease in muscle strength. These models show a tendency that the change in the components of the MTE due to immobilization increases the joint torque and, when trying to apply excessive force during joint development, can lead to traumatic consequences. During immobilization, the flexor muscles shorten, which prevents the patient from fully extending the elbow joint. Conclusions. This work on predicting the elbow joint torque generated by the muscles can be useful in studying specific clinical situations with elbow joint contractures, but cannot be fully transferred to practice due to the significant conventionality of the model parameters. However, the modeling method can show trends in changes in muscle function parameters when their geometry changes.

Знерухомлення суглоба призводить до формування іммобілізаційної контрактури, яка супроводжується зниженням еластичності сухожилків і м'язів, тобто втратою повноцінного скорочення/розтягування. Крутний момент у суглобах людини є одним із ключових показників під час оцінювання результатів реабілітації. Мета. Вивчити вплив зміни сили, довжини м'язів і сухожилків ліктьового суглоба на крутний момент за згинання. Методи. Для моделювання використано базову модель OpenSim — arm26. Зміну довжини компонентів м'язово-сухожилкового елемента (МСЕ) визначили за їхньою довжиною за кута згинання ліктьового суглоба під 90°. Зменшенням сили м'язів вважали втрати за добу для згиначів ліктьового суглоба — 1,2 %, розгиначів — 1,1 %. Розраховували зменшення сили для терміну іммобілізації 45 діб. Створено 3 моделі: Normal — без змін параметрів м'язів; Contracture — зміна довжини м'язів і сухожилків; Contracture + muscle (CM) — додатково зменшення сили м'язів. Результати. Отримані значення крутних моментів за зміни довжини компонентів МСЕ показали їхнє зростання в умовах незміненої ізометричної сили м'язів. Але такий варіант неможливий після іммобілізації кінцівки. Тому ближче до реального є модель CM, коли крутний момент помітно зменшується на величину послаблення сили м'язів. Наведені моделі демонструють, що зміна компонентів МСЕ внаслідок іммобілізації збільшує крутний момент суглоба та, в разі намагання в процесі фізіотерапії суглоба прикласти надмірне зусилля, може призвести до травматичних наслідків. За іммобілізації м'язи-згиначі вкорочуються, що заважає пацієнтові повністю розігнути ліктьовий суглоб. Висновки. Прогнозування крутного моменту ліктьового суглоба, який створюють м'язи, може бути корисним для вивчення конкретних клінічних ситуацій за контрактур цього суглоба, але його не доцільно повністю переносити в клінічну практику через значну умовність параметрів моделей. Застосований метод моделювання може показати тенденції за змін параметрів функціонування м'язів у разі модифікації їхньої геометрії. Ключові слова. Математичне моделювання, ліктьовий суглоб, крутний момент, контрактура.

Keywords. Mathematical modeling, elbow joint, torque, contracture..

Introduction

It is a well-known fact that immobilization of a joint leads to the formation of an immobilization contracture. Due to long-term immobilization, a number of changes occur both in the joint itself and in periarticular tissues. As a result of the slowing of blood circulation, there is a shortage of tissue nutrition, which triggers their physical (loss of cartilage hydration, decrease in muscle strength) and morphological (reorganization of the biochemical structure) changes. In the case of temporary immobilization (up to 6 months), changes in the joints are either mostly or completely eliminated, during longer periods of immobilization, the tissues of the joints and muscles undergo permanent irreversible restructuring [1, 2].

A decrease in the elasticity of the tendons ("hardening" of the muscles), that is, the loss of the ability to fully contract/stretch is one of the obvious changes that occur in the joint after immobilization. This is the most important cause of joint contractures.

Torque in a person's joints is one of the key indicators when evaluating the results of rehabilitation. Computer modeling has become a modern method of researching the work of muscles during movement. It helps to identify the factors that cause movement disorders, to assess the biomechanical consequences of possible treatment methods. OpenSim is software for developing, analyzing and distributing such simulations. In OpenSim, the musculoskeletal model consists of a set of rigid bodies connected by joints. Muscles cover these joints and create forces that accelerate the body according to the laws of physics.

Purpose: to study the influence of changes in the strength, length of muscles and tendons of the elbow joint on the torque during bending.

Material and methods

The basic OpenSim model — arm26 [3] was used for simulation.

Basic principles of muscle biomechanics

Let us present technical characteristics for understanding the methods of studying the effect of contracture on force and joint moment due to changes in the length of muscle fibers and tendons in the OpenSim software [4].

The most famous model of the musculotendinous element (MTE) is the Hill model. Fig. 1 shows its improved model, which is used to determine the force of muscle contraction [5]. It includes a sequential elastic element (SE), a passive elastic element (PE), a contraction element (SE), a visco-deformable element (VE) and the pentagonal angle of muscle fibers (*pars penina*) (ϕ) (Fig. 1) .

According to Hill's muscle model, the relationship between muscle length (l_{mt}), muscle fiber length (l_m) and tendon length (l_t) is described by the formula [6]:

$$l_{mt} = l_m \cdot cos\varphi + l_{t1} + l_{t2}. \quad (1)$$

Muscle strength is calculated according to the formula:

$$F_M = (F_{CE} + F_{PE} + F_{VE}) \cdot cos\varphi. \quad (2)$$

The active force produced by a muscle depends on its activation, length, and speed.

To study the effect of muscle length (l) on its force (F) according to the general Hill model, four initial parameters are used: optimal muscle fiber length (l_{m0}), maximum isometric muscle force (F_M), tendon sag length (l_{ts}), angle ϕ (pentation angle).

A muscle produces its maximum active force (F_{M0}) when the muscle fiber length (l_M) corresponds to the optimal fiber length (l_{m0}). Although the optimal fiber length is different for different muscles, the isometric force-generating capacity of any muscle can be characterized by the muscle's current fiber length relative to its optimal length. When the length of the muscle fiber exceeds its optimal length, the parallel elastic element stretches, creating a passive force that depends on the length of the muscle, regardless of activation. If the tendon is stretched beyond the sag length (l_{ts}), it also creates a passive force. Since the muscle works in series with the tendons, the force of the muscle and the force of the tendon must be in balance, given the angle of pentation (ϕ).

Torque (Nm)

To understand torque, it is important to define the concept of torque lever. It is the perpendicular distance from the axis of rotation to the line of action of the force. The moment arm determines the quality of the torque and changes depending on the angle of force application (Fig. 2, a). The torque depends on

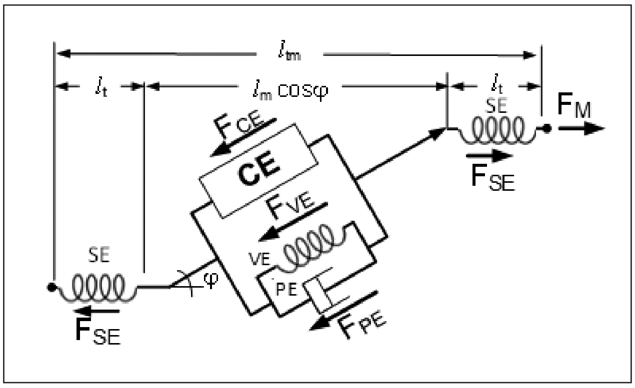

Fig. 1. Model of the musculotendinous element and the forces acting during muscle contraction

the amount of force (muscle force), the angle of application of the force and the length of the torque lever.

The torque creates a biomechanical movement, that is, the movement of the lever system (bones). Being able to maximize the torque that a muscle can generate will allow it to be optimally strengthened. The greater the torque a muscle can produce, the greater the movement is created on the limbs (lever) of the body. So, to increase the mobility of the joint, it is possible to manipulate the change in torque. The amplitude of the movement of the joint does not always correlate with the amount of torque that the muscle can create. Given that the length of the lever (the length of the forearm) does not change, the torque will only be affected by the strength of the muscle. Modifications to muscle strength in the model are described below.

The greatest torque occurs when the force is applied at an angle of 90°.

In the elbow joint, the torque (T_t) is generated by the muscle and transmitted through the tendons (F_{SE}) and the radius of the elbow joint (r_j) (Fig. 1), calculated according to the formula [8].

$$T_t = F_{SE} \cdot r_j. \tag{3}$$

Anatomical basis for changing models

In conditions of immobilization, the elbow joint is bent at 90°. That is, the flexor muscles of the joint decrease their length, and the extensors, on the contrary, increase it.

We do not consider pronation and supination movements of the forearm. In the model, only flexion of the elbow joint up to 90° is provided, therefore, in order to study the work of the extensors, the joint movement coordinate file was extended to extension.

Coordinates of flexion movements — from 0° to 90°, extension — from 90° to 0°

Changes in the model involved modification of muscle length and strength in accordance with immobilization at an angle of 90° and loss of strength of the standard duration of uncomplicated extra-articular injuries of the upper limb — 45 days.

In the case of immobilization of the elbow joint in a 90° bent position, the length of the MTE components of the flexor muscles is forcibly reduced. On the contrary, the elements of the extensor muscles are stretched. Long-term immobilization affects the condition of the musculotendinous element by "fixing" the length of its components. Immediately after removal of immobilization, joint mobility is sharply limited, even regardless of the duration of immobilization. With a decrease in the length of the muscle components, the active force of the muscles decreases, and with an increase in the length and strength of the muscles, the mobility of the joints is restored.

During the simulation, we assumed that immediately after removing the immobilization at an angle of 90°, the length of the components of the muscle-tendon element would correspond to the length at this bending angle. Based on the fact that muscles lose strength during immobilization, according to a meta-analysis [9], the loss of flexor strength of the elbow joint is 1.2 % per day, the loss of extensor strength is 1.1 % per day. Indicators of changes in muscle and tendon parameters are given in the Table.

3 models were created:

Normal (N) — basic, without changes in muscle parameters;

Contracture (C) — with a changed length of muscle and tendons (according to calculations);

Contracture + muscle (CM) — previous model with changed muscle strength (according to calculations).

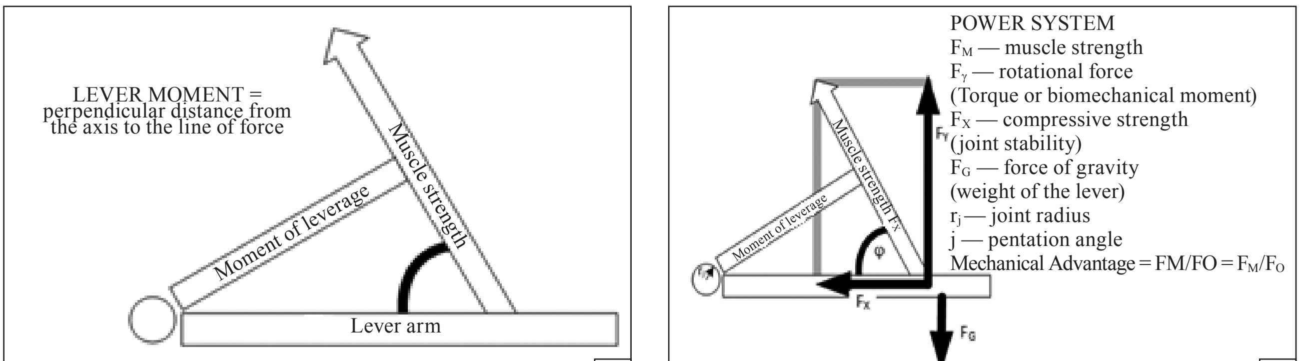

Fig. 2. Torque of the elbow joint [7]: a) moment of the lever in the power system; b) free-body force diagram of the analysis of the components of the force system (including torque)

Due to the fact that the rehabilitation of the recovery of movements in the elbow joint also involves strength exercises, the modeling of the active moment was studied with the activation of the force by 50 %. The torque is calculated relative to the modulation time, in 1 s there is 90° bending, in 2 s — full extension of the joint.

Results and their discussion

Movements in the elbow joint occur only in one plane. Flexion and extension are performed by two groups of arm muscles: anterior and posterior.

Bending in the elbow joint is provided by the muscles of the anterior group: *biceps brachii*, which has two heads (*biceps long* and *biceps short*) and *brachialis*. In the process of bending the elbow joint, a torque is created. In the case of changes in the components of MTE that occur during immobilization, the moment of the joint will also change.

The length of the muscle affects the force that the muscle can develop. In model C, the length of the components of the musculotendinous element (Table) was changed, which accordingly affected the force developed by the muscle. Because the torque depends on the force and radius of the joint, given that the dimensions of the joint remain constant, it is the strength of the muscle that will be responsible for the magnitude of the torque of the joint.

During flexion of the elbow joint, the components of the MTE change their length in different ways. The change in the length of the MTE components affects the ratio “muscle strength” ↔ “fiber length” of the muscle and, accordingly, this ratio may be violated at different angles of elbow joint flexion.

The diagrams show the *total fiber-force* of a muscle, which is equal to the sum of its passive and active forces (without / full activation of the muscle). Since the passive part of the muscle's strength is taken over by the tendon, its total strength will include the strength developed by the tendon and muscle tissue. The development of the muscle strength curve for the SM model will be parallel to the curve of the C model, but 50% smaller.

Let us consider the effect of the changed muscle strength on the torque of the joint. It will be different during flexion of the joint without load, i. e. without muscle activation, and with 50% activation.

Changes in the moment of the elbow joint by *m. Biceps Long* is shown in Fig. 3.

Normally, during bending at an angle of 90°, the long head of the biceps muscle tissue shortens by 20 %, and the length of the tendons increases by 3 % (Table). The normal muscle strength curve is shown in Fig. 3, a. The maximum occurs at a bending angle of 45°, and the minimum at 90°. The passive moment is normally 1 Nm at a bending angle of 45°. During the activation of *m. Biceps Long* is active along the entire bending trajectory [10], which corresponds to the diagram in Fig. 3, c

In model C, after changing the length of the MTE components, the force curve mirrored its direction. The muscle is in tension when the joint is fully extended, and reduces the force during flexion to 45°, and increases in the case of further movement to an angle of approximately 75°, remaining in an excited state until the moment of extension to the same angle. Excitation of the muscle is visible on the curve of the passive moment, that is, the tendons are maximally stretched when bending the angle up to 45°, and minimally — 90°. The change in passive moment during extension mirrors the flexion curve.

In the CM model, in addition to the change in the length of the MTE components, the muscle strength is reduced. The force development curve from the bending angle is parallel to the curve of model C, but reduced by 50 %. The passive moment curve, accordingly, is also similar to that of model C, but the peak values are also reduced by 50 %, with a minimum at a bending angle of 90°.

During the active moment, the curves of the N and C models are close, because the muscle strength of the C model is greater, and the moment is also by about 3–5 %. The curve of the SM model has a similar shape with a decrease in the maximum by the amount of reduction in the isometric strength of the MTE components.

Table

MTE parameters in elbow joint models

Muscle	Length of the components of the musculotendinous element (m)				Muscle strength (N)			
	optimal		in 90° bending		nominal	loss (%)		remainder
	muscle	tendon	muscle	tendon		within a day	45 days	
Biceps long	0.116	0.272	0.092	0.281	624.30	1.1	49.5	315.27
Biceps short	0.132	0.192	0.092	0.198	435.56	1.1	49.5	219.96
Brachialis	0.086	0.054	0.067	0.055	987.26	1.1	49.5	498.57

Let us consider how the force of *m. Biceps Short* changes with an alterations in the length of the MTE components (Fig. 4, a).

Isometric force of *m. Biceps Short* is less than that of *m. Biceps Long*, the strength curve is smoothed. In the interval from 0° to 45° of flexion, the strength of the muscle does not change, and from 45° to 90°, a decrease in isometric force is observed. During stretching, the curve is mirrored.

In the case of changing the components of MTE, a decrease in the length of the muscle fibers by 30 % and an increase in the tendon by 3 % was recorded in model C, the force curve is similar to *m. Biceps Long*, but smoothed and has smaller values.

Passive torque of *m. Biceps Short* normally has minor changes in torque and two maxima — at a joint flexion angle of 30° at the level of 0.215 Nm and at a 90° flexion — 0.189 Nm, so it can be assumed that the passive torque is constant. A significant change in the force curve due to changes in the length of the MTE components shows the maximum torque at a bending angle of up to 30° exceeding the norm by 90 % (up to 3.5 Nm) with a decrease at an angle of 90° to the norm. The reverse process of extension repeats the increase in torque up to 30° and its gradual decrease. For the CM model, the torque curve has a similar trajectory to the C model, with a maximum torque of 1.8 Nm at a 30° bending angle, and a minimum of 90° bending at 0.1 Nm, which is below the norm. The maximum of the C model is greater than the N model by 5 to 20 % at various bending moments, and the CM model is less than twice the norm.

In the case of muscle activation by 50 %, the curves have the same torque trajectory with a gradual increase to an angle of 90°, but the torque of the C model exceeds from 5 to 21 % depending on the bending angle, the torque of the N model, and for the CM model — the torque is 50 % less than normal.

Let us consider the change in the force of *m. Brachialis* (Fig. 5, a). Because the humerus is quite short, but the strongest of the arm muscles, the changes that occur during immobilization affect its strength, and given that it is solely responsible for elbow flexion, it is this function that suffers.

Normally *m. Brachialis* during a fully extended elbow joint is tense. That is why the most comfortable position of the hand is with slight elbow flexion. The strength of the muscle decreases after a bending angle of 40° and reaches a minimum at an angle of 90°. In the case of a change in the length of the MTE components — the length of the muscle fibers decreases by 20 % and the length of the tendons increases by 1 %, the curve of the isometric force of the muscle changes dramatically. Under the conditions of a fully extended elbow joint, only due to the increase in the length of the tendons, the isometric force of the muscle decreased by 4.5 %, and up to a bending angle of 70°, the muscle force continues to increase and remains unchanged up to 90°. That is, in model C, the force curve has an inverted trajectory relative to model N.

Passive torque of *m. Brachialis* normally has a smoothed character with a maximum of 0.375 Nm under the conditions of a fully extended joint and during bending at 90° — 0.2 Nm. As can be seen in the diagram (Fig. 5, b), model C is characterized by a significant (by 87 %) increased initial torque (up to 3 Nm) and a rapid decrease in the norm in the case of an elbow joint bent at 90°. For the CM model, the torque curve is similar to the C model, but more smoothed, with lower extreme values — 1.5 Nm for an extended joint and 0.1 Nm for an angle of 90°, which is less than the norm.

When the muscle is activated by 50 % for the C model, the reduction in the length of its components is leveled off and the torque is almost close to normal, but exceeds it. For the CM model, the torque is parallel to the normal, but reduced and more smoothed, that is, the muscle is not able to perform the normal movement of the joint.

Let us consider the torque developed by the flexor muscles in passive and active modes of operation (Fig. 6)

Simulation findings showed that normally during flexion of the elbow joint, the total force developed by the flexor muscles is 100 N with a maximum at full extension of the joint. The change in the length of the MTE components leads to an increase in force activation with a 0° joint angle in the C model to 730 N, in the CM model to 370 N. At a 90° joint angle, the total muscle force for all models is almost 10 N. The passive moment in the norm has a maximum at a bending angle of 30° — 1.8 Nm, at an angle of 90° the torque is 1.2 Nm. The torque of the C model increased sharply to 9.5 Nm at the joint angle in the range from 20° to 30° with a minimum at 90° — 1.2 Nm. In the SM model, the torque also has a maximum in the range from 20° to 30° — 5 Nm with a minimum of 0.6 N at an angle of 90°.

The active torque normally has a smooth increase to 32 Nm up to a joint angle of 70° and remains unchanged, in the C model it increases sharply throughout the bending range with a maximum of 36 Nm at a joint angle of 90°. The active torque curve of the CM model is similar to the previous curve with a maximum of 18 Nm.

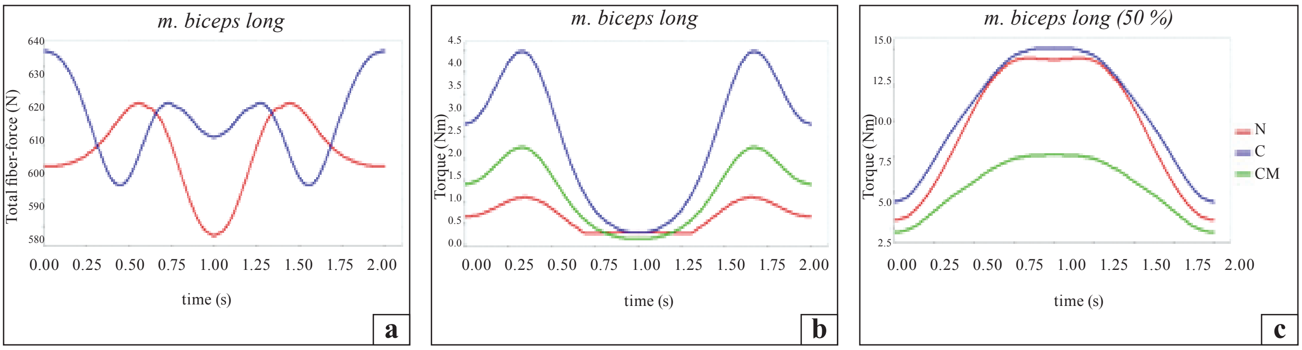

Fig. 3. Characteristics of *m. Biceps Long* for joint flexion/extension: a) *total fiber-force* (N) of models N and C; b) passive torque (without activation); c) moment during muscle activation by 50 %

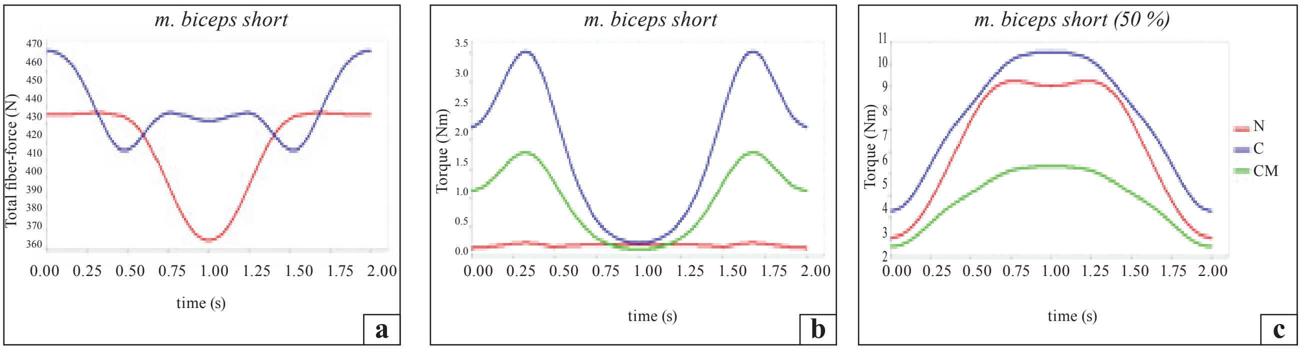

Fig. 4. Characteristics of *m. Biceps Short* for joint flexion/extension: a) *total fiber-force* of models N and C; b) passive torque (without activation); c) moment during muscle activation by 50 %

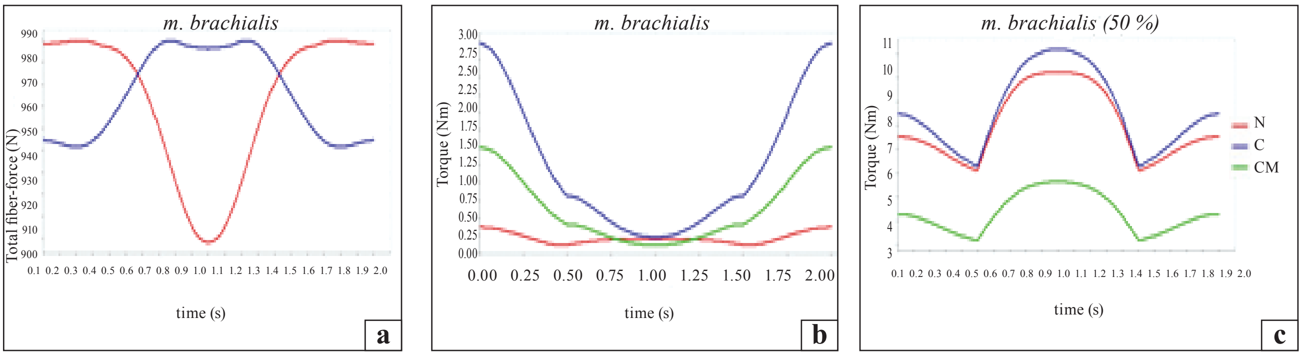

Fig. 5. Characteristics of *m. Brachialis* for joint flexion/extension: a) *total fiber-force* of models N and C; b) passive torque (without activation); c) moment during muscle activation by 50 %

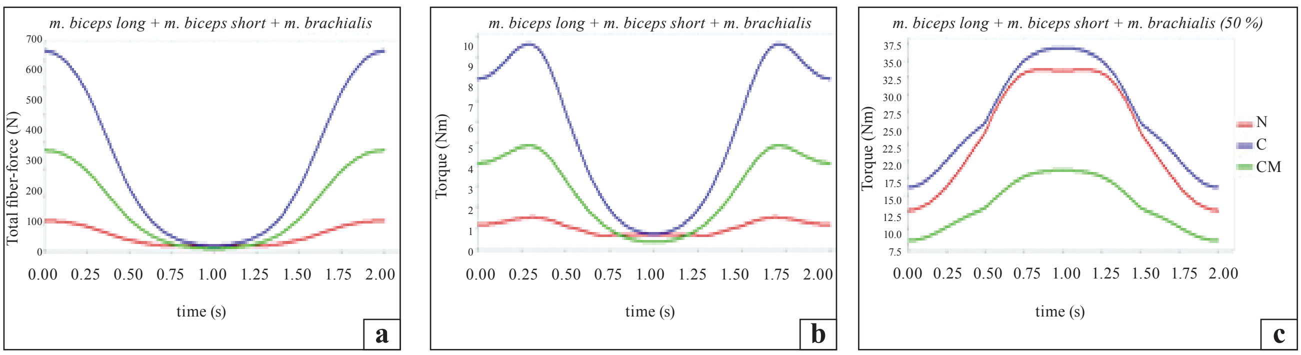

Fig. 6. Characteristics of the flexor muscles for bending/extending the joint: a) *total fiber-force* of the N and C models; b) passive torque (without activation); c) moment during muscle activation by 50 %

Discussion

Muscle strength is affected by a change in muscle length under the conditions of its contraction, so its tension occurs at different moments of its length [11]. A change in muscle length is associated with a change in the angle of the joint, that is, its change affects the force of muscle contraction and their function [12], therefore, the angle of flexion of the joint is a variable that affects the maximum force of the muscle [13–15].

According to J. E. Kasprisin and M. D. Grabiner [16], the shorter the muscle length, the greater the muscle activation. Mostly, changing the length of the muscle affects its activation.

In their study, J. Yang et al. [17] proved that the biceps muscle strength was highest at a joint angle of 56°. It is at this point that it is 20 % more than at rest. The obtained modeling results coincide with the indicators of the experimental study, although the biceps heads were considered separately in the research, the maximum muscle strength for the normal model falls on the interval from 45° to 60°.

No publications were found on the study of the change in muscle strength in the event of a change in their length for the same subject, so we can only focus on mathematical calculations — that is, a decrease in muscle length increases its activation and strength.

Regarding experimental studies of elbow joint moments for elbow joint contracture, only one publication was found on the study of elbow joint strength and torques in children with immobilization contractures after a unilateral fracture of the distal humerus [18]. The experimental conditions differed from the modeling conditions, the initial angle of the elbow joint was 45° due to the presence of a flexion contracture (10.8 ± 9.5)° and flexion was performed to the maximum possible level (more than 130°). That is, the values of full extension were omitted from the analysis. But the peak torque values produced by the flexor muscles also coincide with our results. That is, the maximum falls on the interval 50°–60° and does not exceed (2.7 ± 1.2) Nm in the interval of spread from 1 to 5 Nm; according to the results of our research, it is known that in the interval from 45° to 90° of the joint angle, the maximum torque is 1 Nm, and the maximum occurs at a bending angle of 30° — 1.8 Nm. The authors assume that various tissues are involved in limiting joint mobility, so the moment on the injured joint varies significantly — from 1 to 5.5 Nm with a median of 3 Nm. We did not study the strength of the muscles of the elbow joint, so we cannot compare, but the obtained moment indicators coincide with the curve of the CM model — that is, with the changed length of the MTE components and reduced muscle strength.

Analyzing torque indicators for changes in the length of the components of the musculotendinous element, we determined their growth in conditions of unchanged isometric muscle strength. But such an option is practically impossible after injuries and immobilization of the limb. Therefore, the CM model is closer to practical application — that is, changing the length of muscles and reducing their strength. The model shows the change in the components of MTE and muscle strength during immobilization at an angle of 90° and their state is transferred to the model, which mostly does not correspond to practical application and has a large variability. These models only show a tendency to change the components of the MTE due to immobilization, which increases the torque of the joint and when trying to apply excessive force during the development of the joint, can cause traumatic consequences.

The results of the modeling are not advisable to fully transfer to the treatment of the patient due to the great variability of the functioning of the limb after injury and immobilization. However, it is unequivocally recommended that in the case of rehabilitation measures for the development of the elbow joint in a passive mode, a torque that does not exceed 2 Nm should be applied.

Conclusions

Our research on predicting the torque of the elbow joint, which is created by the muscles, can be useful for studying specific clinical situations for elbow joint contracture, but it is not advisable to use it in full in practical activities due to the significant convention of the model parameters. Although the modeling method carried out can show tendencies to change the parameters of muscle functioning during the change of their geometry.

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

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EFFECT OF CHANGES IN THE LENGTH OF THE COMPONENTS OF THE MUSCULOTENDINOUS ELEMENT OF THE ELBOW FLEXOR MUSCLES ON THE ISOMETRIC FORCE AND JOINT TORQUE

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