ISSN 1812-5123. Russian Journal of Biomechanics, 2009, Vol. 13, No. 1 (43): 7–17

Russian
Journal
of Biomechanics
www.biomech.ru

BIOMECHANICAL INTERPRETATION OF SKELETAL MUSCLES MIOMETRY FOR SPORTSMEN

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Abstract. The technique of the muscular tissue viscoelastic characteristics determination using dynamic indentation is offered. New structural model of muscular tissue as three-component system is developed. The first component characterizes the biotissue in a passive state; the second component corresponds to muscle actuation; the third component corresponds to formation and accumulation of the substances blocking actomyozine interaction. The model is used for description of myometric muscle indices kinetics (during the transition from passive state to stressed one) and fatigue process during repeated performing of oarsmen exercises by oarsmen.

Key words: skeletal muscles, activation of contractile function, fatigue, viscoelastic characteristics, miometry.

INTRODUCTION

Classical problem of biomechanics is the description of functioning of the locomotive systems as a combination of rigid bodies and deformable connections [4]. Results of the solution of this problem are used at optimization of rehabilitation procedures and sports trainings, improvement of surgical operations and a safety of labor activity.

Prediction of kinematical and dynamical parameters of the locomotive system means presence maximum full and trustworthy information about mechanical properties of contractile elements – skeletal muscles. Now, two various approach for identification of mechanical properties of muscular tissues may be used.

1. Measurements *in vitro* assume allocation and special processing of a biotissue sample. It allows us to make standard tests (tension, compression, relaxation, etc.) of samples and to study contractile activity of a muscle by electrostimulation in isometric or isotonic conditions [3]. The basic disadvantage of measurements *in vitro* is a discrepancy of received experimental data and properties of a vital muscular tissue. Besides *in vitro*, it is not possible to investigate all variety of conditions of a skeletal muscle (various modes of loading, stages of fatigue and relaxation, etc.).

2. Measurements *in vivo* allow us to determine mechanical parameters of a skeletal muscle in an organism without surgical intervention. The widespread method of similar measurements is indentation of a skin in the location of a studied skeletal muscle [6]. For determination of mechanical characteristics of biotissue by means of indentation, it is necessary to solve corresponding contact problem on indentation of a rigid stamp into material sample. The solution of a similar problem for a muscular tissue is complicated by

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nonlinearity of deformation and viscosity of a muscle, and also the complex form and heterogeneity of investigated object. Therefore, in known attempts of dynamic diagnostics of skeletal muscles state, as a rule, the penetration depth of indenter at given force, frequency of vibrations and speed of indenter rebound after loading have been determined.

Comparison of values of these parameters for people with different physical state, modes of functioning of the locomotive system, and at various stages of fatigue allows one to estimate the current condition of a specified skeletal muscle. However, these values are taking into account not only mechanical properties of a muscular tissue but also a configuration of a muscle and parameters of the measurement. In this connection, the parameters registered by miometry, cannot be considered as mechanical characteristics of a muscular tissue that essentially reduces self-descriptiveness of measurements.

Earlier, authors [9] had been offered a technique to determine the following mechanical characteristics of a muscular tissue: initial instant Young's modulus (E) and parameters of simple exponential kernel of relaxation by results of dynamic indentation of muscles by means «Miometer *UT* 98-01» device [8]. The given technique is based on the solution of a problem on indentation of viscoelastic half-space by absolutely rigid indenter. The basic lack of a technique given in [9] consists in the necessity of essentially nonlinear equations solution. The given circumstance considerably complicates automation of experimental data processing. So, in [9] the mechanical characteristics have been determined only for one muscle (a two-headed muscle of a shoulder) in the given condition without study of dynamics of parameters at various loadings of a muscle. The conclusions made and the suggested interpretation requires an additional justification and approbation.

The aim of the present study is an improvement of muscular tissue's viscoelastic characteristics identification for simplification of the mathematical description.

SIMPLIFICATION OF IDENTIFICATION TECHNIQUE

As well as in [9], for reception of the initial information on mechanical properties of a skeletal muscle, the device «Miometer *UT* 98-01» has been used. Steel indenter with weight m = 20 g, having the flat circular foundation with radius R = 1.5 mm interacts with a surface of a muscle (is more exact, an integument in the location of a muscle). The indenter having initial speed v_0 after impact interaction makes damping vibrations together with the attached mass of the muscle. Accelerometer registers acceleration of the indenter with the given step in time. On the received experimental dependence of acceleration on time, three "conditional" miometrical parameters of the muscle are calculated: 1) frequency of vibrations of indenter F (Hz); 2) decrement of vibration D, and 3) stiffness H (N/m) which is equal to the ratio of the maximal value of force reaction of a biotissue to the maximal depth of indentation.

To pass from "conditional" parameters of the muscle to mechanical characteristics of the muscular tissue as biomaterial, in paper [9] the contact problem of interaction of rigid indenter with viscoelastic half-space was solved. The muscular tissue was considered as isotropic incompressible linear viscoelastic material having the following dependence of axial stress σ on longitudinal strain ε at uniaxial stress state

$$\sigma(t) = E\left(\varepsilon(t) - A\int_0^t \exp\left[-\beta(t-x)\right]\varepsilon(x)dx\right). \qquad (1)$$

Here, E is instant Young's modulus; A, β are the parameters of simple exponential kernel of relaxation. It is shown in [9] that according to the physical equation (1), the time dependence of indentation depth is determined by function

$$u(t)=\frac{v_0}{\rho^2+n^2+w^2-2\rho n}\left[2ne^{-\rho t}+e^{-nt}\left(\frac{\rho^2+w^2-n^2}{w}\sin(wt)-2n\cos(wt)\right)\right]. \quad (2)$$

Values w and n in function (2) are connected with conditional miometrical parameters

$$w=2\pi F, \quad n=DF. \quad (3)$$

For determination of value ρ, the solution of system of three nonlinear equations is required

$$\begin{cases} -2n\rho^3e^{-\rho t_1}+\dfrac{n}{w}\left(\rho^2(3w^2-n^2)+(n^2+w^2)^2\right)e^{-nt_1}\sin(wt_1)+ \\ +\left(\rho^2(3n^2-w^2)-(n^2+w^2)^2\right)e^{-nt_1}\cos(wt_1)=0, \\ -2n\rho e^{-\rho t_2}+e^{-nt_2}\left[\dfrac{n}{w}\left(w^2+n^2-\rho^2\right)\sin(wt_2)+\left(w^2+n^2+\rho^2\right)\cos(wt_2)\right]=0, \\ \rho^2e^{-\rho t_1}+e^{-nt_1}\left[\dfrac{\rho^2(n^2-w^2)-(n^2+w^2)^2}{2nw}\sin(wt_1)-\rho^2\cos(wt_1)\right]= \\ =-\dfrac{H}{m}\left[e^{-\rho t_2}+e^{-nt_2}\left(\dfrac{\rho^2-n^2+w^2}{2nw}\sin(wt_2)-\cos(wt_2)\right)\right]. \end{cases} \quad (4)$$

From system of equations (4) at given w and n, the values t_1, t_2, ρ are determined. The moment of time t_1 corresponds to the first minimum of acceleration of the indenter. The moment of time t_2 corresponds to the first maximum of indentation. At known values of w, n, and ρ, it is possible to determine the viscoelastic characteristics of material according to [5]

$$\beta=\frac{\rho\left(\rho^2-3n^2+w^2\right)+2n\left(n^2+w^2\right)}{\rho^2+n^2+\omega^2-2n\rho}, \quad A=\frac{(\beta-\rho)\left(w^2+\rho^2+2n\beta-3n^2\right)}{2n\beta+w^2-3n^2},$$
$$E=\frac{m}{0.851\pi R}\left(2n\beta+w^2-3n^2\right). \quad (5)$$

It is known [1] that for soft biotissues there are typically negligibly small values of long-term Young's modulus. In phenomenological models for the description of viscoelastic deformation of such materials, Maxwell's element [7] is often used including consecutively connected elastic (spring) and viscous (damper) elements. Long-term Young's modulus is expressed through instant modulus E and parameters of a kernel of relaxation A, β as follows:

$$E_1=E\left(1-\frac{A}{\beta}\right)=E(1-A\tau)\cdot$$

Here, $\tau=\dfrac{1}{\beta}$ is the time of relaxation. If value E_1 is neglected for an investigated material, an equality should be satisfied

$$A=\beta. \quad (6)$$

Having added condition (6) to expressions (5), we obtain system of the equations for determination of values E, A, β, and ρ. Having solved this system, for viscoelastic characteristics of a material, we may write down

$$\tau = \frac{1}{A} = \frac{1}{2n} = \frac{1}{2FD}; \quad E = \frac{m}{0.851\pi R}(w^2 + n^2) = \frac{mF^2}{0.851\pi R}\left(4\pi^2 + D^2\right). \tag{7}$$

It was required to use equations (3)–(5) according to earlier proposed technique of identification [4] for determination of viscoelastic characteristics. The simplified technique means usage of equations (3) and (7). Within the framework of the simplified technique for characterization of viscoelastic deformation of a skeletal muscle, two parameters are used: instant Young's modulus E and time of relaxation τ. For determination of these parameters, it is enough to know frequency and decrement of vibration of indenter by the device «Miometer *UT* 98-01».

To estimate the error of identification caused by an additional assumption (6), we shall determine instant Young's modulus and time of relaxation of various skeletal muscles of members of the combined team of Belarus on rowing on kayak and canoe. Miometrical measurements by means of the device «Miometer *UT* 98-01» were carried out in laboratory of physical training and sports of Gomel State F. Skorina University. Results of measurements and values of mechanical characteristics of muscular tissues are given in table. The values calculated by the simplified technique (3) and (7) are presented in brackets. It is possible to note that a divergence of values of the mechanical characteristics calculated by detailed and simplified techniques of identification, does not exceed 4% for instant Young's modulus and 11% for time of relaxation. The error was determined in percentage of the corresponding values calculated by the technique using expressions (3)–(5).

CHANGE OF MIOMETRICAL PARAMETERS AT ACTUATION OF A MUSCLE

As follows from table, at transition of a muscle from a passive condition in a stressed one there is a change of registered value of Young's modulus of the muscular tissue. In work [9], the interpretation of the given phenomenon based on model of a tense string was offered. Cross loading (indentation) of the tense muscle is accompanied by occurrence of an additional force of resistance which is proportional to the force generated in the muscle at actuation of contractile function. According to the given model, parameter β of a kernel of relaxation at activation does not change, and parameter A decreases proportionally to increase in Young's modulus. However, the data of table testifies that the hypothesis (6) is applied both for passive and for a stressed condition of the muscle. Hence, specification of the interpretation resulted in [5] is necessary.

For development of new interpretation of change of viscoelastic properties of a muscular tissue at actuation, we shall consider a muscular monofibre as the cylindrical shell formed by a viscoelastic material [7]. The given shell contains actinic and myosinic strings of sarcomere. Strings of sarcomere do not render essential effect on mechanical behaviour of a string in a passive condition. Therefore, characteristics E_p, A_p, τ_p determined for a passive muscle should be used as the parameters describing mechanical behaviour of a material of an shell. At activation of contractile function, the internal volume of the shell modeling a muscular monofibre, gets significant cross rigidity. The given phenomenon is caused by occurrence of cross actomyosin bridges which not only cause relative sliding strings of sarcomere, but also interfere with cross compression of a monofibre. Toughening of internal volume can be interpreted as formation inside an shell the "reinforced" linear elastic phase which modulus of elasticity (E_f) is much higher than the modulus of elasticity of a material of shell, $E_f >> E_p$. Thus, the muscular tissue in an active condition represents the biphase reinforced composite.

Table

Miometric parameters and viscoelastic characteristics of skeletal muscles of sportsmen–oarsmen

Muscle	Parameters and characteristics									
	Passive state of muscles					Stressed state of muscles				
	F, Hz	*D*	*H*, N/m	*E*, кPa	τ, ms	*F*, Hz	*D*	*H*, N/m	*E*, кPa	τ, ms
Musculus obliquus externus abdominis	8.7±0.34	0.81±0.12	184±6.8	15.5 (15.2)	68.6 (71)	9.4±0.49	0.59±0.02	239±11	17.7 (17.6)	84.5 (90.2)
Muscles of prelum abdominate	8.3±0.41	1.16±0.07	139±7.5	14.5 (14)	50.2 (51.9)	10.7±0.6	1.04±0.12	169±13	23.8 (23.2)	40.7 (44.9)
Biceps muscle of the shoulder	11.3±0.39	1.1±0.11	198±6.4	26.7 (25.9)	37.1 (40.2)	18.4±0.5	0.82±0.08	433±12	68.7 (67.8)	31.6 (33.1)
Tricipital muscle of the shoulder	14±0.47	1.79±0.09	248±8.1	42.8 (41.7)	18.7 (20)	25.2±0.7	1±0.14	487±11	125 (128)	20.2 (19.8)
Broadest muscle of back (pterygoid points)	12±0.24	0.66±0.04	204±7.6	28.5 (28.7)	65.3 (63.1)	12.3±0.8	0.84±0.11	345±9	30.5 (30.3)	45.1 (48.4)
Thorcal muscle	11±0.27	1.06±0.16	173±6.4	24.9 (24.5)	39.6 (42.9)	12.1±0.5	0.79±0.08	257±8	29.5 (29.3)	51.3 (52.3)
Musculus deltoideus	12.5±0.21	1.25±0.13	251±5.9	32.6 (32)	29.3 (32)	13.5±0.7	0.89±0.19	342±14	36.8 (36.6)	39.2 (41.6)
Musculus trapezius	13.1±0.33	1.47±0.13	271±9.2	37 (35.6)	25.2 (26)	19.6±0.9	0.88±0.14	496±7	78.2 (77.1)	26.8 (29)
Long radial wrist extensor	14.3±0.32	1.19±0.19	258±7.3	42.2 (41.7)	27.1 (29.4)	21.3±0.9	1.16±0.21	486±16	92.5 (92.4)	21.3 (20.2)

At definition of effective mechanical properties of this composite in a direction transverse to reinforced elements, it is used the simplified averaging corresponding to "consecutive" connection of elastic elements

$$\varepsilon = (1 - c_f)\varepsilon_m + c\varepsilon_f . \qquad (8)$$

Here, ε, ε_m, ε_f are the deformations of a muscular tissue, the shell and "reinforcing" phase, respectively; c_f is the volume fraction of "reinforcing" phase.

Behaviour of a composite material in a direction of indentation (transverse to a reinforcing element) and behaviour of an isotropic material of the shell are described by the physical equation (1). Solving the given equation concerning deformation, we receive

$$\varepsilon(t) = \frac{1}{E}\left(\sigma(t) + A\int_0^t \exp\left[-(t-x)\left(\frac{1}{\tau} + A\right)\right]\sigma(x)dx\right).$$

The material of reinforced elements is considered as linear elastic, hence: $\varepsilon_f = \dfrac{\sigma}{E_f}$.

Having substituted expressions for deformations in the equation (8) and having executed mathematical transformations, it is possible to determine effective characteristics E_a, A_a, and τ_a of composite modeling a muscular tissue in an active condition

$$E_a = \frac{E_p E_f}{(1-c_f)E_f + c_f E_p}, \quad A_a = A_p \frac{(1-c_f)E_f}{(1-c_f)E_f + c_f E_p},$$
$$\tau_a = \tau_p \left[1 - A_p \tau_p \left(1 - \frac{(1-c_f)E_f}{(1-c_f)E_f + c_f E_p}\right)\right]^{-1}. \qquad (9)$$

Taking into account that the modulus of elasticity of a muscle in a passive condition E_p is small in comparison with the similar modulus of a reinforced element, system (9) can be rewritten as

$$c_f \approx 1 - \frac{E_p}{E_a}, \quad A_a \approx A_p, \quad \tau_a \approx \tau_p . \qquad (10)$$

If the hypothesis (6) is true for a passive condition of a muscle according to expressions (10), it will be true and for its stressed condition. The suggested interpretation of process of a muscle actuation allows us to characterize the given process by the volume fraction c_f which is determined by the first equation of system (10).

The value c_f characterizes the volume accessible for cross actomyosin bridges. Hence, c_f is connected with internal structure of sarcomere which is practically identical for all skeletal muscles. It is possible to assume that values of a volume fraction c_f for various muscles are close. Really, average value of c_f calculated by formula (10) for all considered muscles (table) varies in the limited interval 0.362 ± 0.215. The analysis of table shows that the ratio of Young's modulus in passive and stressed conditions correlates with the ratio of rigidities H. If a volume fraction c_f is calculated by the formula

$$c_f = 1 - \frac{H_p}{H_a}, \qquad (11)$$

that as a result of averaging for all considered muscles, we receive $c_f = 0.374 \pm 0.11$. Thus, c_f describing efficiency of reduction of a muscle can be determined both under formula (10) and by means of ratio (11), and from the point of view of stability of results, use of the ratio of rigidities $\dfrac{H_p}{H_a}$ is preferable.

CHANGE OF PARAMETERS OF A MUSCLE DURING FATIGUE ACCUMULATION

The suggested model of a muscular tissue as biphase composite allows us to interpret change of miometrical parameters not only at actuation, but also at fatigue of a muscle. Intensive actomyosin interaction is accompanied by accumulation in a muscular tissue of the substances interfering the realization of contractile function. Within the framework of the offered structural model of a muscular tissue, the given phenomenon can be considered as occurrence in a composite of a new phase which volume fraction $\overline{c}$ grows on a measure of fatigue.

Let us neglect viscosity of a material of the given phase and we accept that Young's modulus of this material $\overline{E}$ considerably surpasses Young's modulus of a muscular tissue in passive condition $\overline{E}$ >> E_p. Using the same mathematical transformations, as at conclusion of ratio (10), we find instant Young's modulus $\overline{E}_p$ and time of relaxation $\overline{\tau}_p$ of a muscular tissue in a passive condition in view of fatigue

$$\overline{E}_p = \frac{E_p}{1-\overline{c}}, \quad \overline{\tau}_p = \tau_p . \tag{12}$$

Hence:

$$\overline{c} = 1 - \frac{E_p}{\overline{E}_p}. \tag{13}$$

Occurrence in space between strings of sarcomere of rigid inclusions reduces the space accessible for actomyosin cross bridges. Initial, prior to the beginning of process of fatigue, the volume of such bridges is determined by volume fraction c_f (10). Therefore, the volume fraction $\overline{c}_f$ of cross bridges at the given stage of fatigue can be determined as a difference

$$\overline{c}_f = c_f - \overline{c} = E_p \frac{E_a - \overline{E}_p}{E_a \overline{E}_p} \approx H_p \frac{H_a - \overline{H}_p}{H_a \overline{H}_p} . \tag{14}$$

On the other hand, the volume fraction $\overline{c}_f$, by analogy to value c_f is determined by the ratio of Young's modulus in a passive condition to corresponding value in a stressed condition

$$\overline{c}_f = 1 - \frac{\overline{E}_p}{\overline{E}_a} \approx 1 - \frac{\overline{H}_p}{\overline{H}_a} . \tag{15}$$

Thus, process of fatigue of skeletal muscles is characterized by value of a volume fraction $\overline{c}_f$ which is determined by ratio (14) or (15).

As an example of use of the developed technique of the description of fatigue change process of miometrical parameters of human gastrocnemius muscles has been investigated at performance of physical exercises. Experimental research was carried out on the basis of research laboratory of physical training and sports of Gomel State F. Skorina University. The properties of gastrocnemius muscles were invastigated at the athletes having a level of sport qualification not lower than 1 category. Measurements by the device « Miometer UT 98-01» were made in a zone of the lateral head of the muscle (m. gastrocnemius caput laterale). Each value of miometrical parameter has been received by averaging of the values measured for 8 sportsmen. The maximal statistical error at averaging corresponds to decrement D in an stressed condition of the muscle and forms 32% from average value of miometrical parameter.

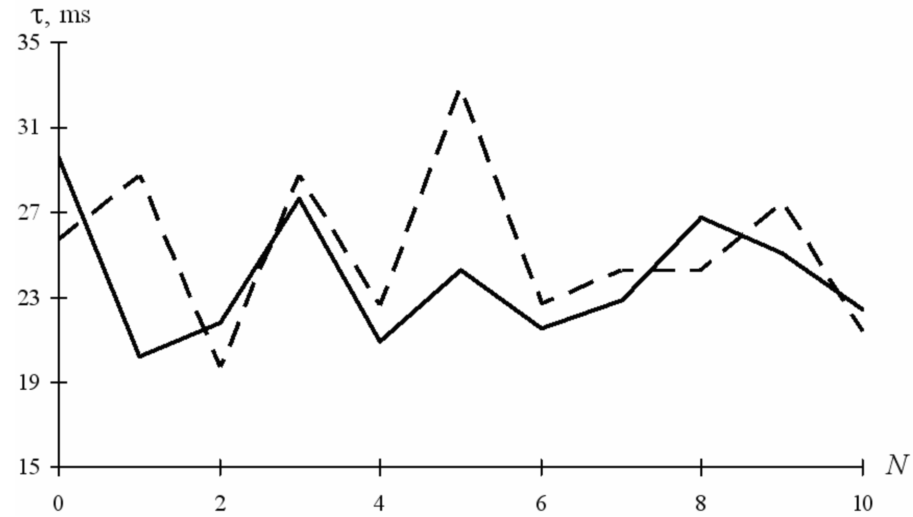

Fig. 1. Change of relaxation time during exercise performing. Solid curve – time of relaxations in passive condition; dotted line– in stressed condition

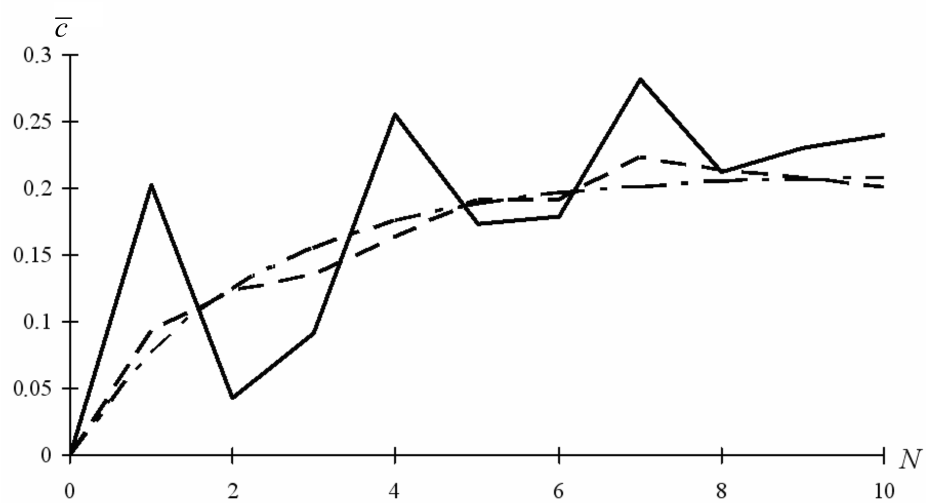

Fig. 2. Change of volume part $\overline{c}$ characterizing accumulation of fatigue during exercise performing. Solid curve corresponds to usage of Young's moduli; dotted line denotes rigidities *H*; dash-dotted line denotes aproximation (16)

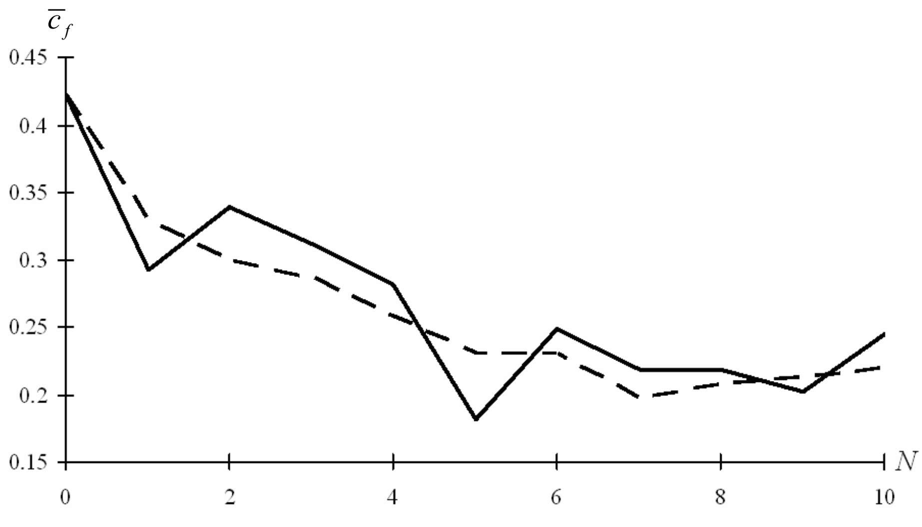

Fig. 3. Change of volume fraction $\overline{c}_f$ during exercise performing. Solid curve corresponds to usage of formula (15); dash line obtained by formula (14)

To establish effect of fatigue on miometrical parameters, the operating mode admitting the periodic control of a condition has been given to the muscle. As that exercise, the rise on the foot on height of 5 cm during 30 s without a contact between the heel and a floor was carried out at the subsequent rest by duration of 1 min. After each exercise *F, D*, and *H* parameters of muscles were measured in passive and stressed conditions. By formulas (7), corresponding values of characteristics *E* and τ were calculated. Then, by formula (13), the volume fraction $\overline{c}$ which characterizes process of accumulation of fatigue was calculated. By formula (15), the volume fraction $\overline{c}_f$ describing realization of contractile function at various stages of fatigue process was determined. As a result, dependences of characteristics $\overline{E}_p, \overline{\tau}_p, \overline{E}_a, \overline{\tau}_a, \overline{c}, \overline{c}_f$ on exercises number *N* previous to the moment of measurement have been found.

Within the framework of the present work, we consider only an initial stage of process of fatigue ($N < 11$). Change of miometrical parameters at continuation of performance of exercise, and also during 3 day after refusal of performance of exercise [2] can be a subject of the further researches.

Dependence of relaxation time of a muscle in passive and stressed conditions on quantity *N* of exercises is submitted in Fig. 1. It is possible to note that the value of registered time of relaxation practically does not change at transition of a muscle in an stressed condition. The given supervision confirms legitimacy of the third equality of system (10). The dependences in Fig. 1 allow one to assert that process of fatigue accumulation does not render essential effect on time of relaxation.

Influence *N* on a volume fraction $\overline{c}$ is calculated by formula (13), from what the opportunity of replacement of the ratio of Young's moduli by the ratio of rigidities *H* follows. In Fig. 2, the opportunity of approximation of dependence $\overline{c}$ (*N*) by exponential function of a kind

$$\overline{c}\ (N) = 0.21\left(1 - e^{-0.45N}\right) \tag{16}$$

is shown as well.

The root-mean-square deviation of results of use of function (16) from values of a volume fraction $\overline{c}$, calculated by formula (13) proceeding from rigidity *H*, makes 0.029, that allows us to use the suggested approximation. Differentiating function (16) on *N*, we receive

$$\frac{d\overline{c}}{dN} = 0.45\left(\frac{c_f}{2} - \overline{c}\right).$$

In other words, growth rate of a volume fraction $\overline{c}$ is directly proportional to free volume in which the inclusions interfering with muscular reduction can be formed.

At calculation of a volume fraction $\overline{c}_f$ (Fig. 3), we use only rigidity *H*. As one would expect, accumulation of fatigue results in decrease of intensity of realization of contractile function of a muscle. Results of use of ratios (14) and (15) for determination of the volume fraction $\overline{c}_f$ differ rather insignificantly (the root-mean-square deviation makes 0.082). The given circumstance confirms legitimacy of use of the suggested model of a muscle, as a three-component system, for the description of process of muscular fatigue.

Conclusions

As a result of the analysis of the miometrical data, it was established that at biomechanical modelling of skeletal muscles, it is possible to neglect value of long-term

Young's modulus of a muscular tissue. It was shown that change of characteristics of a muscle at transition in a stressed condition maybe is caused by occurrence in sarcomere of the rigid phase corresponding to actomyosin cross bridges. The assumption was made that change of miometrical parameters at an initial stage of fatigue process also is connected with accumulation in the muscle a some phase which rigidity essentially surpasses rigidity of the muscular tissue in a passive condition. Thus, intensity of processes of activation and fatigue of a muscle is characterized by the volumetric fraction of corresponding rigid phases which volume fractions are determined by the ratio of Young's moduli before and after described process. Legitimacy of use of the suggested model of the muscle, as three-component system, for the description of muscular fatigue, and an opportunity of replacement of the ratio of Young's moduli by the ratio of rigidities determined by the device «Miometer UT 98-01» was shown.

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БИОМЕХАНИЧЕСКАЯ ИНТЕРПРЕТАЦИЯ ДАННЫХ МИОМЕТРИИ СКЕЛЕТНЫХ МЫШЦ СПОРТСМЕНОВ

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В работе усовершенствована ранее предложенная авторами методика определения вязкоупругих характеристик мышечной ткани по результатам динамического индентирования на основе идентификации модели мышцы как трехкомпонентной системы. Основная компонента характеризует материал мышечной ткани в пассивном состоянии; вторая компонента относится к функционированию актомиозиновых мостиков в стадии сокращения мышцы; третья компонента учитывает образование и накопление веществ, препятствующих актомиозиновому

взаимодействию в процессе утомления мышцы. Модель использована для описания кинетики миометрических показателей мышцы (при переходе из пассивного состояния в напряженное), а также процесса усталости при многократном выполнении однотипных упражнений спортсменов–гребцов.

Ключевые слова: скелетные мышцы, активизация сократительной функции, утомление, вязкоупругие характеристики, миометрия.

Received 20 January 2008