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MODELLING THE DYNAMIC PROCESS OF MUSCLE CONTRACTION

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Abstract.
Mathematical models of muscle contraction based on the hypotheses of Hill and Huxley were investigated. Models of muscle tissue force under isometric and dynamic conditions were developed, incorporating phenomenological relationships and cross-bridge kinetics. Comparison with experimental data confirmed the adequacy of these models for describing biological processes in muscle tissues..
Keywords: muscle contraction, load, mathematical model, force, tension.

Introduction

It is important to determine the structural adaptability and plasticity of skeletal muscle during limb lengthening. It has been shown [1] that muscle and fascia overload leads to microcirculatory disturbances and tissue hypoxia. Therefore, determining more precise parameters of skeletal muscle function during the distraction osteogenesis procedure in a non-invasive and minimally traumatic manner will create conditions for adaptive growth of preserved muscle fibres during the distraction and fixation phase. The modelling of the contractile activity of muscle tissue is also particularly relevant at the present time due to attempts to create artificial muscles based on active and adaptive materials [2] using different physical principles of force generation.

Research results

An adequate mathematical model of real muscle tissue should be able to describe the anisotropy of its properties, the non-linearity of its deformation, the changes in its mechanical properties during activation of the contractile function and the influence of these factors on the activation process. One of the basic approaches to the mathematical modelling of the physiological process of muscle contraction is the steady-state relationship between the constant contraction rate υ and the load p (isotonic muscle contraction) [2]:

$$(p+a)\upsilon = b(p_0 - p), \tag{1}$$

where a and b – parameters of Hill's equation [1], which depend on the type of muscle and on the conditions of the experiment, in particular on temperature.

The Hill model is a purely phenomenological model, reproducing phenomenology rather than a mechanism of behaviour. It does not incorporate the internal laws of muscle contraction. A common drawback of the Hill model is the assumption that the force-velocity relationship must be satisfied immediately after a change in load. This is not consistent with experimental data on the recovery of force tension after a step change in muscle length. This led to the creation of a more advanced model of muscle contraction based on the kinetics of transverse bridges, which is based on the ratchet principle (sliding thread theory) of A. Huxley's muscle contraction [2]. This is the mechanism of force generation in muscle fibres based on the interaction between the proteins actin and myosin [1].

In general, the dependence of the damping force is as follows:

$$p = \rho \int_{-\infty}^{+\infty} r(x) n(x,t) dx, \tag{2}$$

where $n(x)$ – is the proportion of bridges (myosin heads that can attach to actin to generate force) with displacement x that are in a bound state; $r(x)$ is the elastic force developed by each bridge, which is an elastic element with displacement x.

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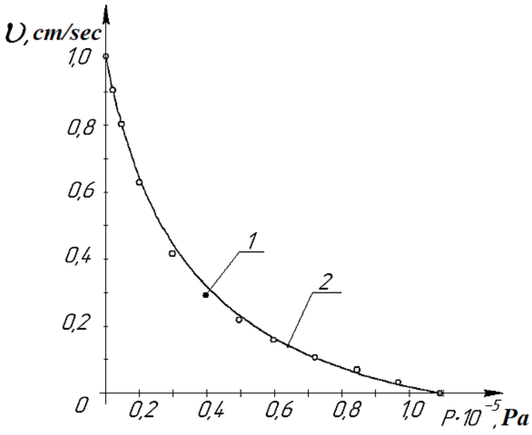

1 – Hill model; 2 – Huxley model

Fig. 1 – Comparative diagram of the dependence of the force applied to the muscle on the speed of contraction

If we assume that the bridge is a linear elastic element, i.e. the elastic force developed by it is $r(x) = kx$, then the force developed by the muscle is determined by the formula $p = \rho k \int_{-\infty}^{+\infty} x \cdot n(x) dx$ and can be calculated as a function of contraction velocity, the result can be compared to the change in force applied to muscle tissue as a function of time according to the Hill hypothesis [2].

Comparison of the results of the theoretical study of the force applied to the muscle according to the Huxley hypothesis (Fig. 1) shows agreement with the theoretical data according to the Hill model within an accuracy of 4.2%.

Conclusions

In order to identify the physiological processes of the musculoskeletal system, the hypotheses of A. Hill and A. Huxley were chosen as a basis, which describe the physiological process of muscle tissue contraction in the modes of isometric tetanus and muscle contraction (lengthening) at a constant speed with a high degree of adequacy.

The results of the theoretical and experimental study [2] of the physiological process of muscle contraction prove the rationality of using the theory of sliding filaments and transverse bridge cycling as the basis for force generation and muscle contraction.

Improving the accuracy of identifying the physiological process of muscle contraction by developing effective methods of mathematical modelling will increase the reliability of predicting the kinematic and force parameters of the musculoskeletal system in the development of artificial implants in mechanical bioengineering.

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МОДЕЛЮВАННЯ ДИНАМІЧНОГО ПРОЦЕСУ М'ЯЗОВОГО СКОРОЧЕННЯ

Анотація.

Досліджено математичні моделі м’язового скорочення на основі гіпотез Хілла та Хакслі. Розроблено моделі силового навантаження м’язової тканини для ізометричного та динамічного режимів, що враховують феноменологічні залежності та кінетику поперечних місточків. Порівняння з експериментальними даними підтвердило адекватність моделей для опису біологічних процесів у м’язах.

Ключові слова: м’язове скорочення, навантаження, математична модель, сила, розтяг.

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