260. Research of frequency characteristics of nonlinear biotronic subsystem of muscle

Mariūnas Mečislovas and Daunoravičienė Kristina
Vilnius Gediminas technical university
Department of Biomechanics, J. Basanavičius str. 28 a,
Vilnius, LT - 03224, Lithuania
e-mail: *Mariunas@me.vtu.lt,*
e-mail: *daunoraviciene@me.vtu.lt*
+370 6 52745015, +370 6 52744748

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Abstract: Paper presents the research of muscle nonlinear stiffness characteristics dependence on the loading duration. The nonlinear differential equation of nonlinear biotronic subsystem of muscle has been derived. Analyzing mentioned expression by numerical methods it was determined that there are three main dominant frequencies in the frequentative characteristics of the muscle and values of them and amplitudes of oscillations decline as the load time becomes longer. Comparison of analytical research results to experimental ones has shown that their regularities are nearly related.

Keywords: muscle stiffness, nonlinear system of muscle, frequentative characteristics.

Introduction

Mostly consent proposition in the literature is that muscles with their characteristics are similar to springs and this is very important for making a stable mechanical state when interacting with mechanical environment. Besides muscles mechanical impedance varies same as their activity rate.

In the nowadays scientific works research results of muscles stiffness are presented when investigating with animals muscles. And also there are presented various techniques of muscles stiffness research [1 - 4]. Muscle tissues are suppressed in special devices with forces of different magnitude and for appropriate duration [2]. In such a way researched muscle's mechanical features are presented in the form of diagrams and also is defining what amount of muscle's cells is loosing at appropriate moments of experiment [5 - 9]. Presented analytical relationships and research methodology make it possible to define the dependence of muscle's stiffness on loading magnitude and duration. Analyzing muscle's dynamic characteristics under applying not maximal, short-term loads its stiffness values could be considered constant and linear dynamic systems' methods could be used for research. In all other cases non-linearity of muscle's characteristics must be taken into account and numerical methods must be applied for the research of them [10].

In mechanical systems spring is a resilient element, while in biotronic subsystem such element is considered to be muscle. Therefore, it is very important to analyze its characteristics. Muscle is a subsystem of nonlinear biotronic system. Literature resources do not contain any works where the changes of dynamic characteristics of nonlinear biotronic subsystem of muscle would be analyzed explicitly. Therefore, it is very important to investigate the behavior of nonlinear biotronic subsystem of muscle during long-lasting load and determine the changes of an important parameter characterizing dynamic systems – frequentative characteristic.

Methods

Research has been made on the thumb's short abductor muscle (*m. abductor policis brevis*). Weight of this muscle m = 4,54 g, damping coefficient c = 0,001, excitation force $F(t)$ = 12 N, excitation time t = 10 s. Stiffness characteristic of the muscle was determined according to the methods provided in publications [11, 12]

$$k(t)=\frac{F}{x(t)}=\frac{F^2}{\int_0^t \frac{U^2(t)}{R}dt}, \tag{1}$$

where F is the muscle loading, ($F = const$), R represents the muscle impedance, $U(t)$ stands for muscle biosignal voltage values, t is the loading duration.

In the source [10] it was proposed, that through the short time loading the muscle impedance changes a little and the muscle impedance can be taken as $R(t) = const$. Therefore, the expression (1) has been transformed in such a way

$$k(t) = \frac{F}{x(t)} = \frac{F^2 R}{\int_0^t U^2(t)dt} . \tag{2}$$

However, the assumption that $R(t) = const$ is incorrect, when the muscle is loaded for the longer time and expressions (1) and (2) can not be simplified. If changes of the biosignal voltage and the muscle impedance are expressed graphically, the muscle stiffness (1) approximately can be expressed as

$$k(t) = \frac{F}{x(t)} = \frac{2F^2}{\Delta t \cdot \sum_{i=2}^{n} \left(\frac{U_{i+1}^2}{R_{i+1}} + \frac{U_i^2}{R_i} \right)} , \tag{3}$$

where Δt is a discretization pitch, U_i and U_{i-1} represent the muscle biosignal voltage values. R_i and R_{i-1} represent muscle impedance values, i = 2, 3, ..., n, n is the number of biosignal intensity points measured.

This characteristic was also compared with researches of stiffness carried out by other scientists. It was found that even the polynomial equation of 8th degree does not describe the dependence of stiffness on time explicitly enough therefore in further research it was approximated in the form of hyperbolic function

$$k(t) = \frac{1}{0{,}205447 \cdot 10^{-8} + 0{,}793353 \cdot 10^{-4} \cdot t +}$$
$$\frac{1}{+0{,}519848 \cdot 10^{-6} \cdot t^2 - 0{,}149169 \cdot 10^{-7} \cdot t^3 +} \tag{4}$$
$$\frac{1}{+0128896 \cdot 10^{-9} \cdot t^4 - 0{,}338788 \cdot 10^{-12} \cdot t^5};$$

when $0 \le t \le 100$ s.

The experimental research accomplished by foreign [14] and our native [10-13] scientists have shown approximately linear variation of muscle stiffness at short time $0 < t \le t_0$ (Fig. 1). Therefore muscle stiffness can be described by the expression (3) only if $t > t_0$.

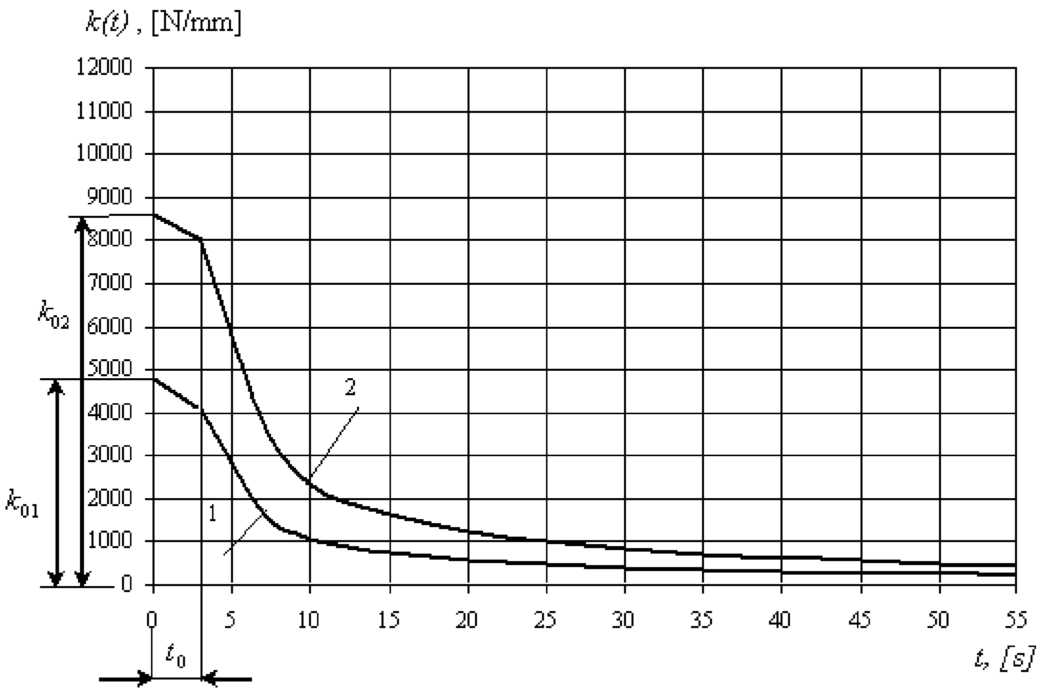

Fig. 1. The dependence of muscle stiffness on muscle loadings, when muscle was loaded 1 – 12 N, 2 – 18 N, k_0 – stiffness value at initial muscle loading moment, t_0 – initial loading moment

As muscle loading time is $t < t_0$ (Fig. 1), muscle stiffness *k(t)* can be expressed:

$$k(t) = k_0 - a_1 t\,, \tag{5}$$

where k_0 - muscle stiffness, when *t =0*, its value experimentally estimated; a_1 - value of regression coefficient.

Therefore muscle stiffness at time range $0 \le t \le \infty$ will be:

$$k(t) = \begin{cases} k_0 - a_0 t, & when \quad 0 \le t \le t_0; \\ \dfrac{2F^2}{\Delta t \sum\limits_{i=2}^{n} \left(\dfrac{U_{i+1}^2}{R_{i+1}} + \dfrac{U_i^2}{R_i} \right)}, & when \quad t_0 < t << \infty; \end{cases}$$

or (6)

$$k(t) = \begin{cases} k_0 - a_0 t, & when \quad 0 \le t \le t_0; \\ \dfrac{F^2 R}{\int_t^0 U^2(t)dt}, & when \quad t_0 < t << \infty. \end{cases}$$

The following mathematical model of nonlinear subsystem of muscle was used for the research:

$$m\ddot{x} + c\dot{x} + \int_0^t k(x,t)dt = F(t)\ . \tag{7}$$

The force impulse has been simulated in two cases:

$$F(t) = \begin{cases} 0, & when\ t = 0; \\ 12\ \ N, & when\ 0 < t \le T_0; \\ 0, & when\ t > T_0, \end{cases}$$

or (8)

$$F(t) = \begin{cases} 0, & when \quad t = 0; \\ 12\ \ \sin(\omega t), & when\ 0 < t \le T_0; \\ 0, & when\ t > T_0, \end{cases}$$

where $\omega = \dfrac{2\pi}{T_0}$, t is variable value of time, T_0 represents impulse duration. Consequently, average loading size of 12 N has been selected to be used in the research. Numerical method of Runge – Kutta was used for the research of nonlinear biotronic subsystem of muscle and for derivation of expression (5).

Muscle frequentative characteristics at variable loading time have been researched by using the expression (5). It has been noticed that if the loading time became longer, muscle frequencies would move from right to left side (Fig. 2). In the same way, not only frequencies but also amplitudes of oscillations decrease.

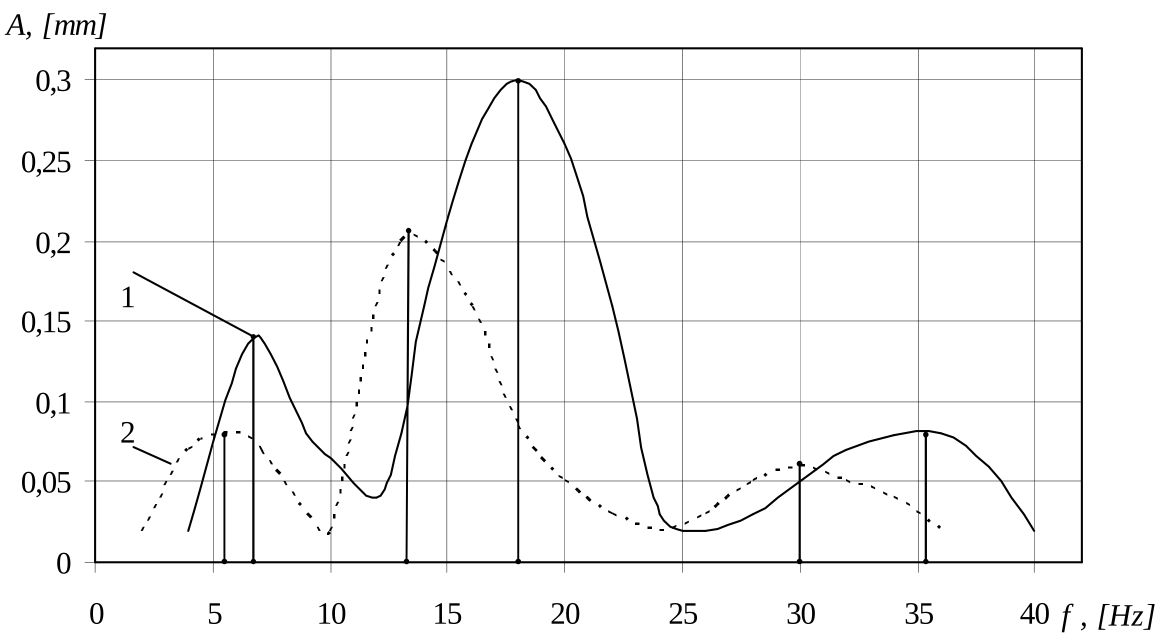

Fig. 2. Dependence of amplitude *A* on the frequency *f* when time *t* 1 – 10 s, 2 – 15 s

Analysis and results

Some of the results are presented in figures 2 and 3. They show that in biotronic subsystem of muscle are highlight defined a subharmonic of ½ of the main frequency and the higher harmonic of double frequency appears near the main frequency. As the load time becomes longer the frequency of all harmonics decreases. Therefore, the research results show that the characteristics of muscle as a biotronic subsystem are nonlinear and tend to change as the load time is becoming longer.

Stiffness characteristics were calculated according to expression (3) at different moments of loading as constant load 12 N was kept on the muscle. Furthermore, frequencies dependencies on the time have been derived by using MATLAB software (Fig. 3). It is clearly seen from these dependencies that values of three main defined frequencies are nonlinearly declining as the loading times become longer. Speaking generally this phenomenon can be explained by the fact that muscle's stiffness characteristics in the way the muscle is loaded by constant weight are nonlinearly decreasing too (Fig. 4).

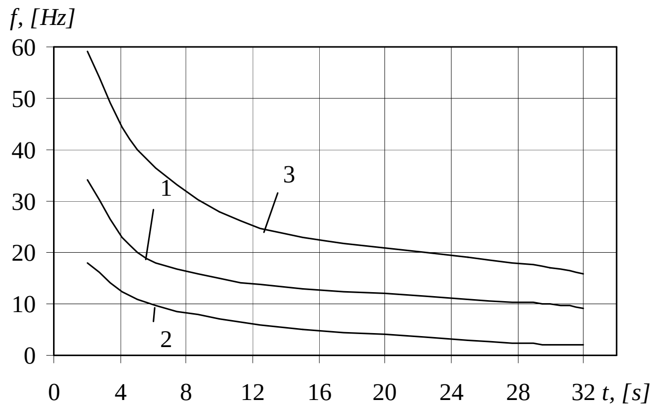

Fig. 3. The dependence of oscillation frequency *f* on the load time *t* where 1 – harmonic of the main frequency, 2 – subharmonic of ½ of the main frequency and 3 – harmonic of double frequency

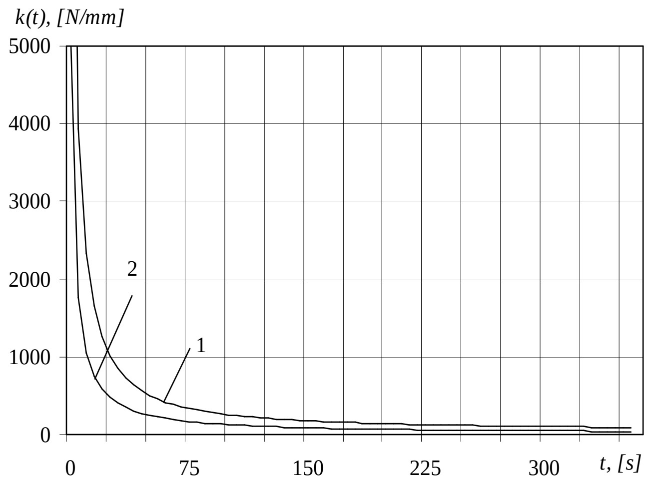

Fig. 4. Muscle's stiffness dependences on loading duration when *F* is 1) 12 N, 2) 18 N

Next, curves of variations of muscle‘s frequencies characteristics visually have been compared with ones collected by the experimental research and presented in literature [14] (Fig. 5). Although, in literature not the same muscle as in our works has been researched. It is clearly seen that regularities of calculated variations of frequencies characteristics (Fig. 4) are similar to ones presented in figure 5. In this way presented methodology could be useful for the research of muscle's frequentative characteristics and stiffness values.

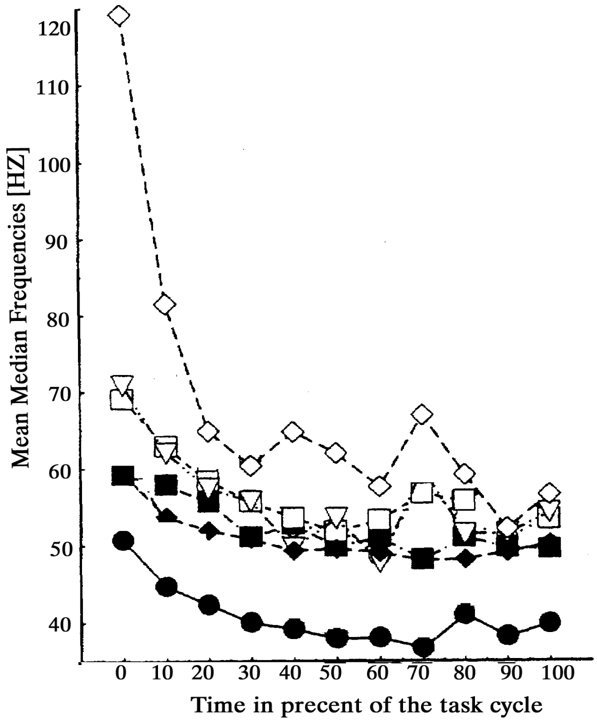

Fig. 5. The dependence of mean median frequencies on time in percent of the task cycling founded in literature [14]

Conclusions

Having summarized the research and calculation results the following conclusions can be made:

1. Harmonics of main three frequencies are notably defined in nonlinear system of muscle, i.e. harmonic of the main frequency, subharmonic of ½ of the main frequency and harmonic of double frequency;
2. As the load time becomes longer the frequency of all harmonics and the amplitude of oscillations are decreasing;
3. The characteristics of muscle as a subsystem of biotronic subsystem are nonlinear and may be linearized only under instantaneous loads;
4. Regularities of variations of muscle's frequentative characteristics got by the analytical method at different loading time are similar to consistent of ones collected by experimental way and presented in literature.

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