Kristina DAUNORAVIČIENĖ

RESEARCH OF MECHANICAL CHARACTERISTICS OF LOADED MUSCLE

Summary of Doctoral Dissertation
Technological Sciences, Mechanical Engineering (09T)

1458–M

Vilnius VGTU LEIDYKLA TECHNIKA **2008**

VILNIUS GEDIMINAS TECHNICAL UNIVERSITY

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General Characteristic of the Dissertation

Topicality of the problem. Human work and other activities are performed because of muscle contraction and relaxation. Person's potential of performing different tasks depends on the adaptation abilities of the muscles to chosen load. Furthermore, other factors as the time-span of person ability to perform tasks together with the changes of particular muscle and its biosignals become very important. Many scientific works ranging from the formations of non-linear muscular model to the determination of different muscle characteristics dependencies on loading size and duration can be found over the field. Unfortunately, there is a luck of the researches that cover the relation of muscle‘s particular work and its biosignal energy, adaptation abilities of the muscle on the loading and also the frequency and other characteristics of the nonlinear muscle model. Main research have been made on the thumb‘s short abductor muscle (*m. abductor policis brevis*). For this point the work become more relevant. Finger muscles due to their size are least researched, though they are important not only in daily human life, but also for achievements in some of sports and same for musicians. Elementary but very essential functions as grasp, touch and other are performed by fingers. However, the other bigger hand muscle have been researched namely the brachioradialis muscle. The function of the brachioradialis is flexing the forearm at the elbow and when the forearm is pronated, the brachioradialis tends to supinate as it flexes. Characteristics of these both muscles have been compared for ensuring results reliability. Research problem of loaded muscle mechanical characteristics becomes useful, actual and timely for establishing muscle abilities to adapt to applied load and for setting its reserve of efficiency.

Aim and tasks of the work. The aim of the scientific research work is to estimate the relation between muscle's biosignal and its mechanic characteristics taking into account the loading magnitude and duration, to analyze possibilities of adaptation to the applied load and also to create methodology for calculation of muscle working characteristics and for the research of mechanical characteristics variations. There are few tasks under consideration:

1) To define the relation between the biosignal energy and accomplished work accounting the people's age and gender and to develop nonlinear dynamic model of a muscle.

2) To research the nonlinear dynamic muscle model‘s stiffness, frequency characteristics and their dependencies on loading size and duration.

3) To estimate the biosignal spectral composition and its shifts increasing the muscle's loading magnitude and duration.

4) To explain ways and to establish a methodology for calculation of the muscle adaptation to applied load and its efficiency reserve. To develop muscle work criterions and to define their ranges at different muscle work circumstances.

Scientific novelty

Present doctoral dissertation gives for the field of Mechanical Engineering science these results:

1) The muscle energy model enables to define the relation between the muscle work and its biosignal energy.

2) Nonlinear muscle dynamic model and relations of frequency and other muscle mechanical characteristics to loading size, duration, persons age, gender and other parameters are mathematically described.

3) Appointed regularities and made the methodology for evaluation of muscle biosignal spectral composition and variations of its intensity.

4) Dependencies of muscle‘s ability to adapt to applied load and its efficiency reserve are derived. Muscle‘s work criterions are developed and their calculation methodology is presented.

Methodology of research includes experimental, analytical, statistical and numerical methods.

For experimental research electromyography devices “Neuropack 2” and “Viking Quest” have been used. For invasive the EMG measurements needle electrodes, made by medical steel and 15 mm in length, have been applied. These measurements have been performed in “Santariškės” clinics of Vilnius University, room for elecromiographical procedures. Surface disposal adhesive electrodes, oval form 43x45 mm, Ag/AgCl “PE Foam”, for adults have been applied for surface EMG. Recoded EMG were transferred through “*E-biol*” interface and processed on PC. Random components of EMG signal were filtered applying special filtering technique. *MATLAB 7.1* software was used for numerical and statistical analyses.

Main research have been made on the thumb‘s short abductor muscle (*m. abductor policis brevis*). For comparing EMG measurements results, brachioradialis muscle (*m. brachioradialis*), which lies in the lateral said of forearm, has been studied. For experimental investigations and for ensuring of their accuracy, twenty health people have been invited: ten females (from 24 to 30 years) and ten males (from 28 till 60 years). The investigation has been focused on five load groups: from 8 N to 24 N. The muscle has been subjected to loading with different duration times from 5 up to 6 min and sometimes even up to 10 min. EMG measurement has been followed by a break lasting till complete relaxation of the muscle and becoming ready for the next measurement stage.

Practical value. Formed dependencies of muscle mechanical characteristics and their calculation methodology could be useful for the research of human muscles adaptation abilities to applied loads and its efficiency reserve at different loading circumstances and for analysis of muscle working stages and resources. Presented methodology could be applied for evaluation of sportsman endurance in selection to sport contest and for testing before setting working tasks for them. Therefore, muscle work criterions could be evaluated during rating of youth physical abilities, also in rehabilitation after injuries, watching for regeneration of muscle mechanical characteristics and restoration of its working abilities. Presented dependencies and calculation methodology are useful for muscle's state diagnostic and could be applied as alternative way of it. While, described muscle working criterions could be adjusted for studying efficiency state of other muscles and their groups.

Defended propositions

1) Muscle work energetic model and regularities of the ratio between muscle characteristics and biosignal energy.
2) Nonlinear dynamic muscle model, which allows estimating muscles mechanical, frequency characteristics and their variations in time.
3) Muscle‘s working criterions: time of effective muscle work and reserve of muscle capacity.
4) Double meaning of muscle‘s stiffness features at different loading circumstances.

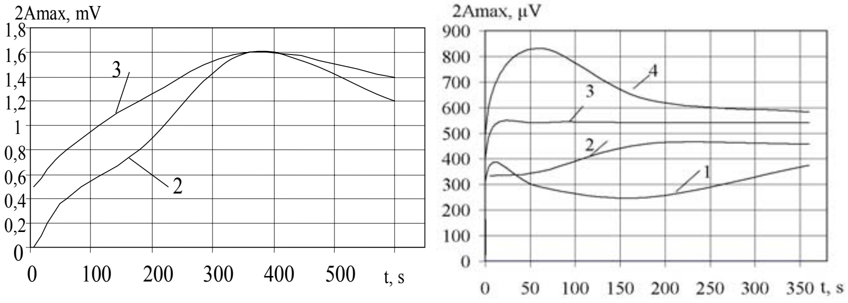
The scope of the scientific work. The scientific work consists of 6 chapters, list of literature, list of publications and addenda. The total scope of the dissertation – 152 pages, 84 pictures, 2 tables and 2 addenda.

Structure of the Work

The first chapter presents general characteristic of the dissertation: topicality of the problem, aims and tasks of the research, scientific novelty, and methodology of the research, practical value, defended prepositions and the scope of the scientific work.

The second chapter gives an analysis of existing publications related with problems of the thesis. Measurement methods of muscle biosignals are described. Research methodologies of muscle characteristics are explained. The attention is paid to problems rising during investigations. Results of accomplished research works are presented also. Finally the muscles dynamic models presented in the literature sources and characteristics of them are analyzed.

The third chapter presents the methodology, instrumentation and ways of experimental research. The statistical and spectral analyses of measured muscle‘s biosignals are made. The influence of loading size and duration to biosignal characteristic was analyzed in two biosignal measurement ways: surface and invasive, and for thumbs and brachioradialis muscles also (Fig 1).



a) b)

Fig 1. Relationships between muscle loading duration and muscle‘s biosignal characteristics as measured by surface way in male group: a) thumb‘s short abductor muscle, b) brachioradialis muscle, 1 – 0,8 N, 2 – 12 N, 3 – 18 N, 4 – 24 N

Without in figure 1 presented relations, more of them were formed and was noticed that biosignals characteristics nonlinearly vary due to loading duration. Either changes of biosignals characteristics after unload muscle were explained.

The fourth chapter presents analysis of muscle model expressed by energies. The analytical expressions of muscle stiffness and elongation (1, 2) were formulated and their variation under different loading conditions were analyzed also (Fig 2 and Fig 3). The double meaning characteristics of muscle stiffness are researched – the stiffness has linear variations as muscles is loaded for short time, and conversely as muscle is loaded longer – stiffness is nonlinear despite the magnitude of the load.

$$x(t)=\frac{1}{F}\int_0^t \frac{U^2(t)}{R}dt \text{ and when } R = const.,\ x(t)=\frac{1}{FR}\int_0^t U^2(t)dt\,, \tag{1}$$

where *x(t)* is muscle elongation, when *F(x) = const.*; *U* stands for intensity of muscle biosignal, *t* is time, *F* represents the load.

$$k(t)=\frac{F}{x}=\frac{F^2R}{\int_0^t U^2(t)dt} \text{ or when } R \neq const.\ k(t)=\frac{F^2}{\int_0^t RU^2(t)dt}\,, \tag{2}$$

where *k(t)* stands for muscle stiffness, *R* represents muscle‘s impedance.

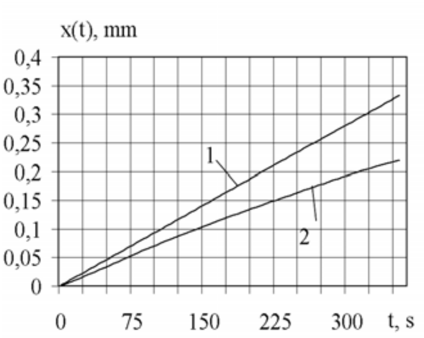


Fig 2. Dependence of muscle elongation on loading duration in male group, when muscle is loaded: 1 – 12 N, 2 – 24 N.

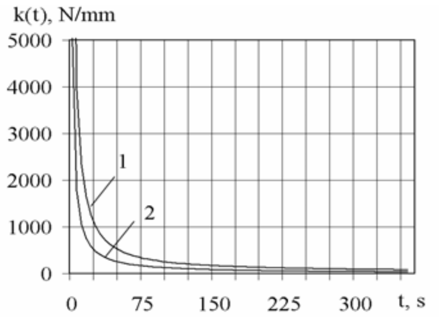
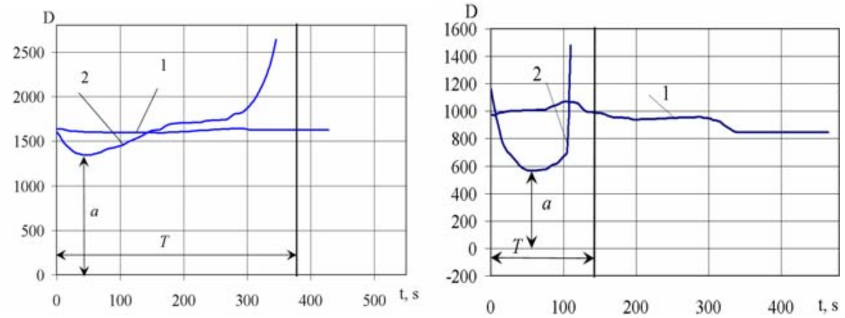


Fig 3. Dependence of muscle stiffness on loading duration in male group, when muscle is loaded: 1 – 12 N, 2 – 18 N

Muscle efficiency relations were formulated by evaluating energy of biosignal and elongation of the muscle (Fig 4) in female and male groups. Working criterions were defined.

Supposedly, both evaluating the criterion of muscle endurance by biosignal energy and by muscle elongation, it displays two main rates of muscle endurance such as time of effective muscle work and reserve of muscle capacity under appropriate loads. It is seen from figure 4, that variations of criterions of muscle endurance in loading time disclose stages of muscle state and behavior: the stage as it works effectively and when it gets into fatigue. It is clearly seen that as the major value of reserve of muscle capacity *a*, the time of muscle effective work *T* is longer. Noticed that given lesser values of loads the meanings of rates *a* and *T* are enlarged in comparison with ones got under expanded loads.



a) b)

Fig 4. Dependence of relative values of muscle endurance on the loading duration in group a) males b) females and when muscle is loaded by 1 – 12 N, 2 – 18 N, *a* represents the reserve of muscle capacity, *T* is time of time of effective muscle

Muscular frequency characteristics were researched by analytical way. The expression was got using muscle work and biosignals energy conditions while evaluating inertial and damping forces of the muscle:

$$\int m\ddot{x}dx + \int c\dot{x}dx + \int F dx = \int \frac{U^2(t)}{R}dt \text{ or } \frac{1}{2}m\dot{x}^2 + \frac{1}{2}c\dot{x}^2 + F(x) = \int \frac{U^2(t)}{R}dt\,, \quad (3)$$

where $m\ddot{x}$ represents inertial forces, $c\dot{x}$ are damping forces, F is muscular force and $\int \frac{U^2(t)}{R}dt$ stands for biosignals performing work.

After differentiation of expression (3) have been got

$$m\ddot{x}\dot{x} + c\dot{x}\dot{x} + F\dot{x} = \frac{U^2(t)}{R} \text{ or } m\ddot{x} + c\dot{x} + F = \frac{U^2(t)}{R\dot{x}}\,. \quad (4)$$

The scheme presented in figure 5 shows the existing relation between inertial, damping, muscle loading and muscle biosignals:

$$\left(F - m\omega^2 x\right)^2 + \left(c\omega x\right)^2 = \left(\frac{U^2(t)}{R\dot{x}}\right)^2. \tag{5}$$

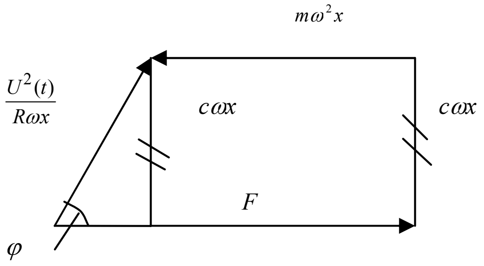


Fig 5. Graphical interpretation of expression (4)

After reformations such the expression has been got:

$$\left(m^2\omega^6 + c^2\omega^4\right)x^4 - 2Fm\omega^4 x^4 + F^2\omega^2 x^2 = \frac{U^4(t)}{R^2}. \tag{6}$$

The expression (6) shows that there are for solutions according amplitude X_1, X_2, X_3, and X_4, and six ones by frequency $\omega_1, \omega_2, \omega_3, \omega_4, \omega_5, \omega_6$, which means that the system will oscillate by four different amplitudes but also will have six different frequencies. After further research, was displayed, that values of frequencies in the spectrum decreased with loading duration get longer.

The fifth chapter covers nonlinear muscular dynamic model and its characteristics, analysis versions. Research was made by using the Runge-Kutta method. Dynamic characteristics of the muscle were analyzed and frequency and amplitude–frequency characteristics were presented graphically.

Nonlinear dynamical model of the muscle with the stiffness expressed as nonlinear function of the time:

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

The force impulse was put in to two modes for analysis of transition processes of the system:

$$F(t)=\begin{cases}0, & when\ t=0;\\ F_0, & when\ 0<t\le T_0,\\ 0, & when\ t>T_0.\end{cases} \quad \text{or} \quad F(t)=\begin{cases}0, & when\ \ t=0;\\ F_0 \sin\omega t, & when\ 0<t\le \dfrac{T_{01}}{4},\\ 0, & when\ t>T_0.\end{cases} \qquad (8)$$

where $\omega = \dfrac{2\pi}{T}$, t is the variable value of the time, T_0 stands for impulse duration T_{01} is period of oscillations. The magnitude of the load was operated from 12 to 18 N the same as have been used in the experimental research.

The stiffness graph got by experiments was approximated by Gauss (Fig 6) and polynomial functions. It was noticed, that if stiffness was approximated by different functions or was set different impulses, the form of oscillations has changed.

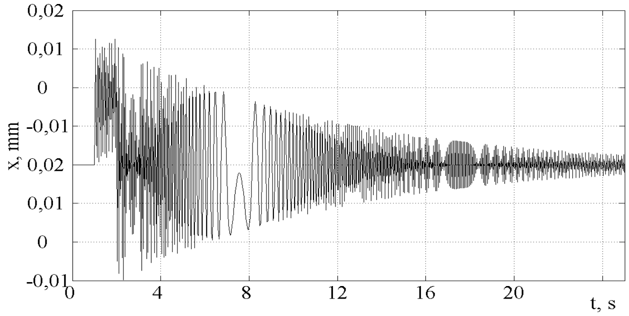


Fig 6. Muscular oscillations as the function of time (T_0 = 2 s, $F(t)$ = 12 N), when stiffness was approximated by Gaussian function

In order to explain variations of oscillations spectrum in muscle loading duration the spectral density was analyzed in time intervals. The realization of muscular oscillations (T_0 = 2 s, $F(t)$ = 12 N) was resolved in these time intervals: from 2 to 4 s, form 4 to 6 s, from 6 to 8 s, from 8 to 10 s, from 10 to 12 s and from12 to 14 s. Average values of spectral density were calculated in every range of time. The analysis of the results of spectral density presented in Figure 7 has shown that in the muscle loading beginning less 4 frequencies dominate. However when loading duration is increasing, values of frequencies in spectral realization become large and their number increase. As muscle gets fatigued frequency values gradually approach to zero and amount of them is diminishing (number of harmonics is decreasing).

Figure 8 presents alterations of dominating frequencies in muscle loading duration. Clearly seen, that values of all dominating frequencies decrease due to nonlinear dependence on longer muscle loading.

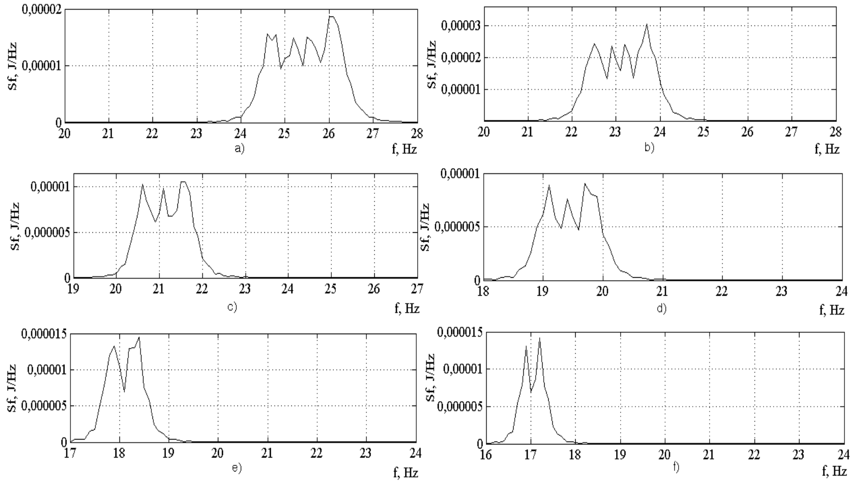


Fig 7. The dependence of muscle frequency spectrum on loading duration when T_0 = 2 s, *F(t)* = 12 N, where a) 2–4 s, b) 4–6 s, c) 6–8 s, d) 8–10 s, e) 10–12 s, f) 12–14 s

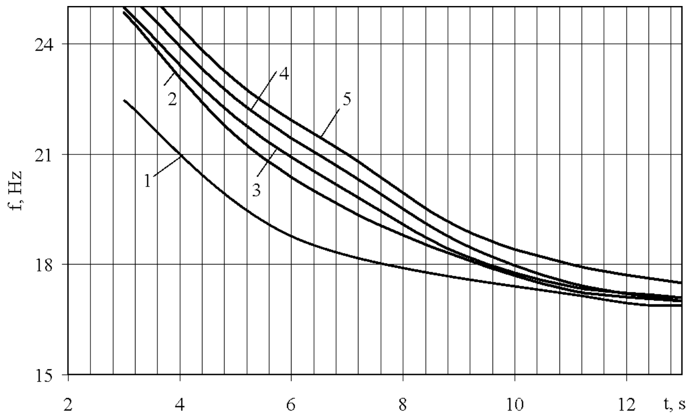


Fig 8. The relationship of oscillation frequencies *f* and loading duration *t*, where 1–5 mark the running number of frequency in the spectrum

Research results were compared with ones presented in literature.

The sixth chapter presents general conclusions.

General Conclusions

After experimental research and developing energy and nonlinear dynamic models of the muscle, as well as after analytical research of muscle mechanical characteristics the following scientific and practical conclusions were formulated:

1. Estimated, that there is existing nonlinear relation between muscle biosignal characteristics and loading size and duration, despite their measurement method – surface or invasive, and following exceptional features are observed in the biosignal characteristics:
   1.1. Biosignal spectral components nonlinearly increase due to rising load.
   1.2. The characteristic spectral band is widening in both sides due to increase of loading duration at steady size of a load. Displayed, that in the beginning of muscle loading, the width of spectral band is from 600 to 900 Hz, and in the loading end – approximately from 10 to 1200 Hz. This means, that lowest frequencies of spectral band are approaching to zero.
2. The model developed by using principle of biosignal energy equality with muscle performing work, allows:
   2.2. Estimating dependencies of muscles elongation and its stiffness on loading duration and size.
   2.3. Displayed, that loaded by steady load muscle stiffness is nonlinear and vary due to hyperbole law. There are explained dual meaning stiffness characteristics by different loading sizes and durations.
3. Muscle endurance criterions were formed by two different ways – using biosignal energy and derivative of muscle elongation. These criterions display two rates of muscle endurance:
   3.1. The time of effective work, which allows to evaluate muscle‘s work duration as it loaded.
   3.2. The reserve of muscle endurance or muscles ability to do committed work in appropriate time.
4. Made nonlinear dynamic muscle model allows to estimate:
   4.1. Dependence of muscle frequency characteristics variations on loading duration. Presented, that values of all dominating frequencies decrease due to nonlinear dependence on the longer muscle loading.

4.2. In the beginning of muscle loading there are less then 6 components of its oscillation spectrum and as muscle loading increase – their number approach to 3.

4.3. As stimulating nonlinear dynamic system of the muscle by steady frequency and load, its oscillation amplitudes increase in time.

5. Set regularities and dependencies for different gender groups are analogical and only their quantitative rates are varying. It was noticed, that males are more stayer and have a bigger reserve of muscle capacity:

5.1. Endurance criterions of man and women are differing about 15 % by lower loading sizes and as loading size increase – about 2 times. Value of males endurance criterion is about 6 times up, it means that time of effective work of man at the same load is also 6 times more than women.

5.2. Muscle stiffness characteristics at small loads are differing about 10 %, and if loads are 2 times bigger – values of muscle stiffness are about 30 %, larger,

5.3. Muscle stiffness in males and females groups has irregular variations. If the load increase in 1,5 times, muscle stiffness in males group rise approximately about 1,33 time, in females group – 1,67 times, it means that stiffness in females group increased approximately 25,6 % more than in males group.

6. Estimated regularities and formed research – calculation methodology could be used for tests of sportsmen and youth endurance and relevance to appropriate loads.

List of Published Works on the Topic of the Dissertation
In the reviewed scientific periodical publications

1. MARIŪNAS, M.; KOJELYTĖ, K. Investigation of the Relationship of Muscle Mechanical Characteristics with Biosignal Energy. *Journal: Solid State Phenomena.* 2006, Vol. 113, p. 151–156. ISBN 3-908451-21-1 (ISI Web of Science).
2. MARIŪNAS, M.; DAUNORAVIČIENĖ, K. Research of frequency characteristics of nonlinear biotronic subsystem of muscle. *Journal of Vibroengineering*. 2007, Vol. 9, No. 1, p. 31–35. ISSN 1392-8716 (ISI Master Journal List).
3. MARIŪNAS, M.; DAUNORAVIČIENĖ, K. Research of variations of frequency of non-linear dynamic model of the muscle. *Journal of Vibroengineering*, 2007, Vol. 9, Issue 2.1, p. 92–97. ISSN 1392-8716 (ISI Master Journal List).

4. MARIŪNAS, M.; KOJELYTĖ, K. Research of finger muscle's stiffness dependence on loading conditions. J*ournal of Vibroengineering,* 2004, Vol. 6, No 1, p. 33–37. ISSN 1392-8716.
5. MARIŪNAS, M.; KOJELYTĖ, K. Determination of Muscle Stiffness Performance with Allowance for Dissipation in Biotronic System. *Journal of Vibroengineering,* 2005, Vol. 7, No. 3, p. 5–10. ISSN 1392-8716.
6. MARIŪNAS, M.; DAUNORAVIČIENĖ, K. Determination and analysis of muscular endurance parameters. *Journal of Vibroengineering*, 2006, Vol. 8, No. 2, p. 1–6. ISSN 1392-8716.

In the other editions

7. MARIŪNAS, M.; KOJELYTĖ, K. Influence of muscle‘s fatigue to its biosignals‘ characteristics. In *Proceedings of the IASTED International Conference on BIOMECHANICS*, *August 23–25, 2004, Honolulu, Hawaii, USA.* A Publication of the international association of Science and technology for development – IASTED, p. 80–85. ISBN 0-88986-440-3 (ISI Proceedings).
8. MARIŪNAS, M.; KOJELYTĖ, K. Investigation of muscle stiffness dependence on muscle impedance and magnitude of load. In *Proceedings of the Third IASTED International Conference on BIOMECHANICS, September 7–9, 2005, Benidorm, Spain.* A Publication of the international association of Science and technology for development – IASTED, p. 172–177. ISBN 0-88986-532-9 (ISI Proceedings).
9. MARIŪNAS, M.; DAUNORAVIČIENĖ, K. Research of muscle endurance characteristics. *Mechanika w Medycinie, No 8, Rzeszow, 2006*, p. 135–1 42. ISSN 1472-0374.
10. MARIŪNAS, M.; DAUNORAVIČIENĖ, K. Research of muscle stiffness characteristics duality. In *Proceedings of the IASTED International Conference on BIOMECHANICS, August 28–29, 2006, Palma de Maljorka, Spain.* A Publication of the international association of Science and technology for development – IASTED, p. 7–10. ISBN 0-88986-604-X.
11. MARIŪNAS, M.; KOJELYTĖ, K. Research of muscle’s biosignals characteristics dependence on the magnitude and the duration of the load measuring in the way of invasive and surface EMG. In *Proceedings of IMEKO, IEEE, SICE 2nd International Symposium on Measurement, Analysis and Modeling of Human Functions 1st Mediterranean Conference on Measurement, June 14–16, 2004, Genova, Italy,* p. 347–351. ISBN 88-901344-0-2.
12. MARIŪNAS, M.; KOJELYTĖ, K. Raumens apkrovos dydžio ir biosignalų charakteristikų ryšio tyrimas. In *Proceedings of the International Scientific*

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APKRAUTO RAUMENS MECHANINIŲ CHARAKTERISTIKŲ TYRIMAS

Mokslo problemos aktualumas. Žmogaus darbas ir kitos aktyvios veiklos formos atliekamos dėl raumens susitraukimo ir atsipalaidavimo. Nuo raumenų gebėjimo prisitaikyti prie parinktos apkrovos dydžio priklauso žmogaus galimybė vykdyti arba ne jam pavestą darbą. Be to, tampa labai svarbu, kaip ilgai žmogus gali dirbti ir kaip kinta žmogaus tam tikro raumens bei jo biosignalo charakteristikos. Šioje srityje atlikta ne mažai tyrimų, sudarytas raumens tiesinis modelis ir nustatytos kitos raumens charakteristikų priklausomybės nuo apkrovos dydžio ir laiko. Tačiau nepakankamai ištirtas raumens atitinkamo darbo ir jo biosignalo energijos ryšys, raumens prisitaikymo prie parinktos apkrovos gebėjimas, raumens netiesinio dinaminio modulio dažninės ir kitos charakteristikos. Tyrimams pagrindiniu buvo pasirinktas nykščio raumuo. Tuo darbas tampa dar aktualesnis. Pirštų raumenys dėl savo dydžio mažiausiai tyrinėjami, nors yra labai svarbūs ne tik žmogaus buityje, bet ir pasiekimams kai kuriose sporto šakose, o taip pat muzikantams. Pirštais atliekamos pačios elementariausios, bet labai svarbios griebimo, lietimo ir kitos funkcijos. Tirtas ir kitas didesnis rankos raumuo – žastinis stipinkaulio, kurio pagrindinė funkcija – dilbio lenkimas. Minėtų raumenų charakteristikos palygintos rezultatų patikimumui užtikrinti. Apkrauto raumens mechaninių charakteristikų tyrimo problema tampa svarbi, aktuali ir savalaikė nustatant raumens adaptacijos galimybes prie parinktos apkrovos ir jo darbingumo atsargą.

Darbo tikslas ir uždaviniai. Pagrindinis disertacijos tikslas – nustatyti ryšį tarp raumens biosignalo ir jo mechaninių charakteristikų, įvertinant apkrovos dydį laike, ištirti prisitaikymo prie parinktos apkrovos galimybes bei sudaryti metodikas raumens darbingumo charakteristikoms ir mechaninių charakteristikų pokyčiams tirti. Keliami šie uždaviniai:

1) Nustatyti ryšį tarp raumens atliekamo darbo ir jo biosignalo energijos, įvertinant žmogaus lytį ir amžių bei sudaryti raumens netiesinį dinaminį modelį.

2) Ištirti netiesinio dinaminio modelio standžio, dažnio charakteristikas ir nustatyti jų kitimo nuo apkrovos dydžio ir laiko priklausomybes.

3) Nustatyti biosignalų spektrinio tankio sudėtį bei ištirti spektro pokyčius didėjant apkrovimo laikui ir dydžiui.

4) Išaiškinti būdus bei sudaryti metodiką raumens prisitaikymui prie parinktos apkrovos ir darbingumo atsargai skaičiuoti. Suformuluoti raumens darbingumo kriterijus bei apibrėžti jų ribas skirtingai apraunant raumenį.

Mokslinis naujumas

Rengiant disertaciją buvo gauti šie mechanikos inžinerijos mokslui nauji rezultatai:

1) Sudarytas raumens energetinis modelis, kuris leidžia nustatyti ryšį tarp raumens atliekamo darbo ir biosignalo energijos.

2) Matematiškai aprašytas raumens netiesinis dinaminis modelis, dažninių ir kitų raumens mechaninių charakteristikų nuo apkrovos dydžio ir laiko, žmogaus amžiaus, lyties ir kitų parametrų ryšys.

3) Nustatyti spektro sudėties ir intensyvumo kitimo dėsningumai bei sudaryta jų įvertinimo metodika.

4) Išvestos raumens gebėjimo prisitaikyti prie parinktos apkrovos ir jo darbingumo atsargos priklausomybės, sudaryti raumens darbingumo kriterijai bei pateikta jų skaičiavimo metodika.

Tyrimų metodika. Disertacijoje panaudoti eksperimentiniai, analitiniai, statistiniai ir skaitmeniniai metodai.

Eksperimentams panaudotas elektormiografai „Neuropack 2“, „VikingQuest“. EMG invaziniams matavimams buvo naudojami adatiniai elektrodai, t. y. medicininio plieno adatos 15 mm, o paviršiniams matavimams – vienkartiniai, priklijuojami, ovalo formos 43x45 mm, Ag/AgCl „PE Foam“ suaugusiems elektrodai. Invaziniai matavimai buvo atlikti Santariškių klinikose, elektromiografijų kabinete. Biosignalų registravimui ir apdorojimui buvo panaudotas specialus e-Biol duomenų įvesties ir valdymo įrenginys. Skaitinei ir statistinei analizei panaudota *MATLAB 7.1* programa.

Tyrimams pagrindiniu pasirinktas nykščio trumpasis atitraukiamasis raumuo – *m. abducor policis brevis.* Palyginamiesiems tyrimams buvo tirtas ir kitas, žastinis stipinkaulio raumuo – *m. brachioradialis*, kuris išsidėstęs šoniniame dilbio paviršiuje. Eksperimentiniams tyrimams atlikti ir jų tikslumui užtikrinti buvo pakviesta dvidešimt sveikų žmonių, dešimt moterų (nuo 24 iki 30 metų) ir dešimt vyrų (nuo 28 iki 60 metų). Tyrimui buvo parinkti šie svoriai: nuo 8 iki 24 N. Raumuo buvo apkraunamas iš pradžių 5 sekundėms, vėliau apkrovimo laikas ilginamas iki 1, 3, 6 minučių ir jeigu tiriamasis jausdavosi gerai, net iki 10 min. Po kiekvieno EMG matavimo buvo daromos pertraukos, kol raumuo visiškai atsipalaiduoja ir būna pasiruošęs kitam matavimui.

Praktinė vertė. Sudarytos raumens mechaninių charakteristikų priklausomybės bei jų skaičiavimo metodika gali būti naudojami žmogaus raumens gebėjimo prisitaikyti prie jam užduotos apkrovos ir jo darbingumo atsargos, esant skirtingoms apkrovimo sąlygoms, taip pat raumens darbingumo stadijų ir resursų tyrimams. Pateikta metodika gali būti taikoma sportininkų pajėgumo vertinimui atrankoje į atskiras sporto šakas bei jų rungtis, testavimui prieš parenkant krūvį. Be to raumens darbingumo rodikliai galėtų būti vertinami tiriant jaunimo fizinius gebėjimus, taip pat potrauminėje reabilitacijoje, stebint raumens mechaninių charakteristikų atkūrimą, jo darbingumo atstatymą. Pateiktos priklausomybės ir skaičiavimo metodika vertingos raumens būvio diagnostikai ir gali būti taikomas kaip alternatyvus jos būdas, o aprašyti raumens darbingumo įvertinimo kriterijai gali būti pritaikyti ir visų kitų raumenų bei jų grupių darbingumo būklės tyrimui.

Ginamieji teiginiai

1) Raumens darbo energetinis modelis leidžia nustatyti raumens charakteristikų ir biosignalo ryšio kitimo dėsningumus.

2) Netiesinis raumens dinaminis modelis leidžia nustatyti raumens mechanines ir amplitudines-dažnines charakteristikas bei jų pokytį laike.

3) Raumens darbingumo kriterijai atskleidžia du pagrindinius raumens darbingumo rodiklius: efektyvaus darbo trukmę ir raumens galios atsargą.

4) Raumens standis pasižymi dvejopomis savybėmis esant skirtingoms apkrovimo sąlygoms.

Darbo apimtis. Darbą sudaro 6 skyriai, literatūros sąrašas, publikacijų sąrašas ir priedai. Bendra disertacijos apimtis – 152 puslapiai, 84 iliustracijos, 2 lentelės ir 2 priedai.

Pirmame disertacijos skyriuje pateikta bendra darbo charakteristika: darbo aktualumas, tikslai ir uždaviniai, mokslinis naujumas, tyrimų metodika, praktinė vertė.

Antrame disertacijos skyriuje atlikta mokslinių darbų nagrinėjama tema apžvalga bei analizė.

Trečiame skyriuje pateikta eksperimentinių tyrimų metodika, priemonės ir būdai. Atlikta išmatuotų raumens biosignalų statistinė analizė. Išanalizuota raumens apkrovos dydžio bei apkrovimo laiko įtaka raumens biosignalo charakteristikoms, kuomet biosignalai matuojami dviem būdais: paviršiniu ir invaziniu. Išaiškinti raumens biosignalo charakteristikų pokyčiai nukrovus raumenį.

Ketvirtame skyriuje sudarytas energetinis raumens modelis, atlikta išsami jo analizė. Pateiktos analitinės raumens standžio bei pailgėjimo charakteristikos, o taip pat išanalizuotas jų pokytis esant skirtingoms raumens darbo sąlygoms. Ištirtos raumens standžio dvejopos savybės. Nustatytos raumens darbingumo charakteristikos, apibrėžti darbingumo kriterijai.

Penktame skyriuje sudarytas netiesinis raumens dinaminis modelis. Pateiktos modelio charakteristikos bei skirtingi jo tyrimo variantai. Tyrimui panaudotas Rungės–Kuto metodas. Ištirtos raumens dinaminės charakteristikos, pateiktos dažninės bei amplitudinės-dažninės raumens charakteristikos ir jų grafinės priklausomybės. Tyrimo rezultatai palyginti su eksperimentiniais tyrimais bei pateiktais literatūros šaltiniuose.

Šeštame skyriuje pateiktos bendrosios išvados.

Bendrosios išvados

1. Nustatyta, kad tarp raumenų biosignalų charakteristikų ir apkrovos dydžio bei apkrovimo trukmės yra netiesinis ryšys, kuris nepriklauso nuo matavimo būdo, t. y. nuo to, ar matavimams naudojami invaziniai ar paviršiniai jutikliai, o biosignalų charakteristikose pastebimi šie išskirtiniai požymiai:
    1.1. Biosignalo spektro sandų dydis netiesiškai didėja didėjant apkrovai.
    1.2. Apkraunant raumenį ilgesniam laikui pastovaus dydžio apkrova, charakteringa biosignalo spektro juosta platėja į abi puses. Parodyta, kad apkrovimo pradžioje spektro juostos plotis yra apytiksliai nuo 600 iki 900 Hz, o apkrovimo pabaigoje – apytiksliai nuo 10 iki 1200 Hz, t. y. žemiausi spektro juostos dažniai artėja į nulį.
2. Taikant raumens biosignalo energijos ir raumens atliekamo darbo lygybės principą sudarytas modelis suteikė galimybę:
    2.1. Nustatyti raumens pailgėjimo bei jo standžio charakteristikų priklausomybes nuo apkrovos dydžio ir apkrovimo trukmės.
    2.2. Parodyti, kad raumens, apkrauto pastovaus dydžio apkrova, standis yra netiesinis ir kinta pagal hiperbolės dėsnį. Išaiškinti dvejopas standžio savybes, esant skirtingiems apkrovos dydžiams ir skirtingoms apkrovimo trukmėms.

3. Sudaryti raumens darbingumo kriterijai dviem skirtingais būdais, t. y. pagal biosignalo energiją ir raumens pailgėjimo išvestinę. Jie atskleidžia du raumens darbingumo rodiklius:
   - 3.1. Efektyvaus darbo laiko, kuris įvertina raumens darbo trukmę, esant parinktai apkrovai.
   - 3.2. Raumens galios atsargos, arba gebėjimo atlikti paskirtą darbą nustatytu laiku.

4. Sudarytas netiesinis raumens dinaminis modelis leido nustatyti:
   - 4.1. Raumens dažnių charakteristikų kitimo priklausomybę nuo apkrovimo laiko. Parodyta, kad didėjant apkrovimo laikui jo spektro dažnių reikšmės mažėja netiesine priklausomybe.
   - 4.2. Raumens virpesių spektro sandų skaičius apkrovimo pradžioje yra ne mažesnis kaip 4, didėjant apkrovimo laikui jų skaičius mažėja. Analitiniuose tyrimuose gauta, kad egzistuoja ne mažiau kaip 6 dažniai, vėliau ilgėjant apkrovimo trukmei jų skaičius mažėja iki 3.
   - 4.3. Kai raumens netiesinė dinaminė sistema žadinama pastovaus dažnio ir dydžio apkrova, jos virpesių amplitudės netiesiškai didėja laike.

5. Nustatyti dėsningumai ir priklausomybės skirtingoms lyčių grupėms yra analogiškos, tik kinta jų kiekybiniai rodikliai. Pastebėta, kad vyrai yra ištvermingesni ir turi didesnį raumenų darbo resursą:
   - 5.1. Esant mažoms apkrovoms vyrų ir moterų darbingumo rodiklių reikšmės skiriasi apie 15 %, o apkrovoms didėjant 2 kartus, vyrų darbingumo rodiklio reikšmė yra apie 6 kartus didesnė, t. y. vyrų efektyvaus darbo trukmė tuo pačiu krūviu pailgėja 6 kartus daugiau negu moterų.
   - 5.2. Raumens standžio charakteristikos esant nedidelėms apkrovoms apkrovimo metu skiriasi apie 10 %, o esant 2 kartus didesnėms apkrovoms – raumens standžio reikšmės vidutiniškai 30 % didesnės.
   - 5.3. Raumens standis vyrų ir moterų grupėse kinta nevienodai. Padidėjus apkrovai 1,5 karto, raumens standis vyrų grupėje vidutiniškai padidėjo 1,33 karto, o moterų grupėje – 1,67 karto, t. y. moterų grupėje standis vidutiniškai padidėjo 25,6 % daugiau negu vyrų grupėje.

6. Nustatyti dėsningumai ir sudaryta tyrimo – skaičiavimo metodika gali būti panaudota sportininkų ir jaunuolių tinkamumo parinktoms apkrovoms ir ištvermingumui nustatyti.

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RECEARCH OF MECHANICAL CHARACTERISTICS OF LOADED MUSCLE

Summary of Doctoral Dissertation
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Kristina Daunoravičienė

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