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Preliminary study of the mechanical properties of striated muscle in humans

Elemente preliminare în studiul proprietăţilor mecanice ale musculaturii striate la om

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Abstract

Background. During prolonged space flights, where microgravity or the lack of gravity affects the physiology and biomechanics of the human body, one of the most important challenges in order to keep the astronauts' capacity, both in terms of health and working capacity throughout the mission, is to preserve the muscle tone and, in general, the mechanical properties of skeletal muscle as a factor in maintaining the psycho-neuro-motor control and bone consistency.

Aims. Our purpose was to investigate the mechanical response of the muscles using their response in acceleration and highlighting the spatial anisotropy response.

Methods. Accelerometers embedded in EMGS active electrodes (TRINGO system) were used, placed on the surface of the femoral biceps in an orderly arrangement around a point where a moderate short mechanical shock, similar to a Dirac delta impulse was produced. The acceleration responses in a perpendicular direction to the plane from two accelerometers were recorded: one placed along the muscle fiber and one located lateral to the first accelerometer and to the mechanical impact point.

Results. The data were used to model a transfer function with characteristics similar to a response dependent on the mutual ratio between the mechanical qualities - tone, elasticity and damping. By comparing the raw acceleration data to the associated mathematical model data, a high level of predictability of the mathematical model and also a possibility to identify the above mentioned mechanical qualities both in wave propagation along the fiber and in highlighting the propagation anisotropy on lateral directions ensued.

Conclusions. Addressing the skeletal muscle mechanical qualities in non-invasive conditions, in-vivo, ensures the possibility of monitoring their progress in special conditions for astronauts, athletes or patients with myopathic disorders.

Keywords: muscle tone, elasticity, damping, accelerometers, modeling.

Rezumat

Premize. În zborurile spaţiale de lungă durată, unde microgravitaţia sau lipsa gravitaţiei afectează fiziologia şi biomecanica fiinţei umane, unul dintre elementele de maximă importanţă pentru păstrarea capacităţilor astronauţilor, atât din perspectiva propriei sănătăţi, cât şi a posibilităţii de a-şi păstra capacitatea de muncă pe tot parcursul misiunilor, este nivelul de conservare a tonusului muscular şi, în general, a proprietăţilor mecanice ale musculaturii striate, ca factor de menţinere atât a controlului psiho-neuro-motor, cât şi a consistenţei osoase.

Obiective. Ne-am propus realizarea unor investigaţii asupra calităţilor mecanice ale musculaturii folosind răspunsul în acceleraţie a muşchiului şi evidenţierea anizotropiei spaţiale a acestui răspuns.

Metode. Au fost folosite accelerometrele înglobate în electrozii activi de EMGS ai sistemului TRINGO, plasate pe suprafaţa bicepsului femural, într-o dispunere ordonată în jurul unui punct în care a fost produs un şoc mecanic moderat, scurt, asimilabil cu un impuls delta Dirac. S-au înregistrat răspunsurile în acceleraţie pe direcţia perpendiculară pe plan, la un accelerometru plasat în lungul fibrei musculare şi la unul aflat lateral faţă de aceasta şi faţă de locul de impact mecanic.

Rezultate. Datele au fost utilizate pentru modelarea unei funcţii de transfer cu caracteristici asimilabile unui răspuns dependent de raportul reciproc între calităţile mecanice de: tonus, elasticitate şi capacitate de amortizare. Compararea datelor brute de acceleraţie cu cele din modelul matematic asociat a arătat nivelul ridicat de predictibilitate a modelului matematic, respectiv o posibilitate de identificare a calităţilor mecanice menţionate, atât în propagarea undelor în lungul fibrei, cât şi în

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evidenţierea anizotropiei de propagare pe direcţii laterale.

Concluzii. Abordarea calităţilor mecanice ale musculaturii striate în condiţii neinvazive, in vivo, asigură posibilitatea monitorizării evoluţiei acestora în condiţii speciale, atât pentru astronauţi, cât şi pentru sportivi sau pacienţi cu afecţiuni miopatice.

Cuvinte cheie: tonus muscular, elasticitate, amortizare, accelerometrie, modelare.

Introduction

During prolonged space flights, where microgravity or the lack of gravity affects the physiology and biomechanics of the human body, one of the most important challenges in order to maintain the astronauts' health and working capacity throughout the mission is to preserve the muscle tone and, in general, the mechanical properties of skeletal muscle as a factor in maintaining adequate psycho-neuro-motor control and bone consistency. This leads to the need for assessing muscular health before, during and after missions, in order to prevent and countermeasure the effects of microgravity.

Our aim is to develop a non-invasive device and method operational in microgravity, for the comprehensive analysis of muscular properties. We present here a preliminary study that was carried out with the purpose of testing the viability of our proposed method, which consists of the analysis of the acceleration response propagation pattern within a muscle bundle upon the application of a mechanical impulse.

State of the art

Muscular characteristics have been widely studied by several approaches, both invasive and non-invasive. From phenomenological approaches extracted from tests developed in sport (Bosco et al., 1983) and subjective investigations used in physical therapy and chiropractic (Conable et al., 2005; Conable et al., 2011), to biological signal energy analysis (Mariūnas & Kojelyte, 2006; Hoang et al., 2009), electromyographic analysis (Cifrek et al., 2009) and electrical impedance analysis (Rutkove, 2009), or to the biochemical perspective of the differentiated metabolism of muscle fiber types (Pesta, 2010), only to name a few references from thousands of attempts recorded in the literature since Faraday, mechanical, biochemical and electrical properties have drawn the attention of researchers in various fields of science. There was even a Nobel Prize awarded for the study of the heat generating properties of muscle contraction to researchers Hill and Meyerhof (***, 1922).

Due to the nature of our areas of interest, only non-invasive techniques have been taken into consideration for this study. Two such approaches are of special interest for us, as their findings have revealed structural and dynamic properties of muscular tissue that can be used for the assessment of muscular health in sports and space applications. The first, electric impedance myography (EIM), is based on the observation that the electrical response of a muscle that is stimulated with a high-frequency electrical current depends on the microscopic structure of the tissue ("Monitoring Muscle | MIT Technology Review," n.d.). EIM has revealed anisotropic electrical properties of muscle tissue that have proven useful in clinical applications (Chin et al., 2008).

The second approach measures elastic properties of the muscle by applying a mechanical impulse on the surface of the skin and recording the acceleration components of response. This method, termed myotonometric measurement of muscular properties, has been studied amongst others by Li-ling Chuang et al., who have developed a method for assessing different muscular properties, such as compliance (increase of tension during elongation), stiffness (magnitude of force that causes displacement), tone (resistance to passive stretching) (Chuang et al., 2011). Moreover, the Myoton myometer (Müomeetria AS, Tallinn, Estonia) was developed for the objective determination of the above properties ("Myoton muscle diagnostics - Myoton" n.d.). Myotonometric measurements have proven useful in both clinical and space applications (Schneider et al., 2015).

Hypothesis

This preliminary study is based on the premises that the mechanical properties of muscle can be identified by mapping the muscle response after applying a mechanical impulse in different longitudinal regions of the tissue. The differences between the regions indicate not only structural heterogeneities and viscoelastic constraints on the normal axis, but also irregularities and changes in the expected physiological behavior.

Materials and methods

Research protocol

The experiment was developed after obtaining the approval of the Ethics Committee and the subjects' informed consent to participate in the research.

As mentioned earlier, valuable information about the mechanical properties (tone, elasticity and dissipative capacity of mechanical energy) of a muscular system can be obtained through non-invasive monitoring by classic myotonometric measurements or by more advanced methods (as proposed by this project).

a) Place and period of the research

The experiment was performed in the Competence Center for Space Technology in support for Human Spaceflight – Starwalker laboratory of the Institute of Space Science, Magurele between 1 September 2014 and 30 September 2014.

b) Subjects

We used data obtained from the investigation of the propagation of transverse accelerations, following a moderate mechanical shock in a single volunteer human subject, on the femoral biceps muscle of his left leg.

c) Applied tests

The experiments were developed using a Trigno™ Wireless EMG electromyograph with accelerometer sensors applied on the skin surface and a short and moderate mechanical impulse (excitation). The accelerometer sensors were placed in a pattern that follows as much as possible the muscle bundle limits. The muscle used in the experiment was the femoral biceps (biceps femoris) of the left leg. A mechanical impulse was applied in the center of the explored area of the measured muscle and the values of the normal acceleration components were recorded for each of the sensors placed on the skin surface. The normal acceleration component was taken into consideration, as it is supposed to provide the most information on the amplitude of response. The same measurements were performed in order to characterize the dynamic muscular response in two circumstances:

1. the muscle was relaxed;
2. the muscle was contracted.

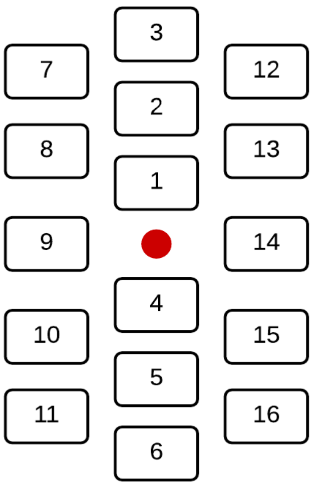

Fig. 1 – Accelerometer sensor placement in relation to the impulse application point.

d) Statistical processing

Since the experiment was purely exploratory and the aim was to see if meaningful results could be obtained in order to verify the hypothesis and to communicate the obtained data as quickly as possible, there was no mathematical processing of the experimental results, only qualitative observations were made.

Results

Our preliminary experimental results revealed that in the response to excitation through a moderate mechanical impulse, there were elements of anisotropy of the muscle mechanical response and, also, variations in the mechanical perturbation signal (wave) propagation speed along the muscle fiber in a monotonous manner with respect to the distance from the excitation impact.

Results revealed three different muscle activity dynamics, occurring successively after the application of the mechanical impulse. In what follows, we present the results obtained in the part of the experiment where impulse was applied on the relaxed muscle. Further work is necessary for the interpretation of the differences occurring in the cases of relaxed and contracted muscle.

The first type of muscular response, occurring within 15 milliseconds, is characterized by a large amplitude. Propagation along and across muscle fibers both in terms of time delay and amplitude size is observed. The shape of the response is consistent with the findings of Chuang et al. (2011).

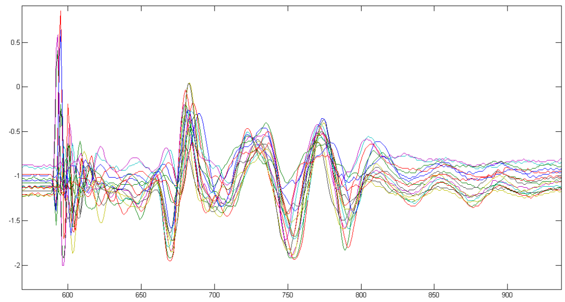

Fig. 2 – Raw signal of the 16 accelerometers, recorded upon the application of impulse on relaxed muscle.

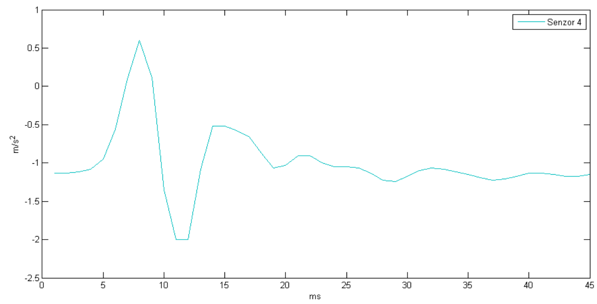

Fig 3 – Recorded acceleration signal for sensor 4 (below the impact region, along and across the muscle fiber).

The second type of response is unsynchronized in relation to the different locations where acceleration was measured. Moreover, in the range of 45 milliseconds of this phase, some muscle areas exhibit an amplification of the dumping tendency from the previous phase. Our interpretation, which needs further experimentation, is that this stage corresponds to a medullary response which superimposes on the muscular reaction to the mechanical impulse.

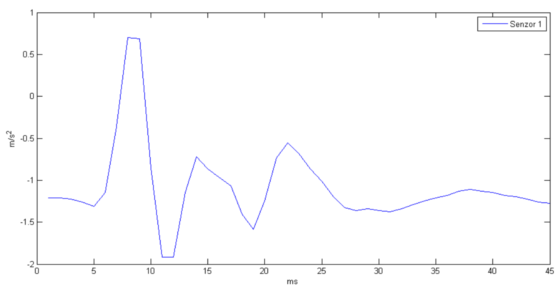

Fig. 4 – Response dumping, followed by amplification in the case of sensor 1 (above the impact region, along the muscle fiber).

The third stage is the most visible at the first application of impulse, suggesting a CNS command, which is dependent on the novelty of the stimulus. It contains highly synchronized muscular activity along and across fibers. This stage lasts for approximately 250 milliseconds and occurs 60 milliseconds after the impulse.

As stated before, the aim of the research is to offer in-depth characterization of muscular health by examining the propagation of the response to mechanical impulse through the whole muscle bundle, along and across fibers. We developed a method of analysis based on estimating the transfer function of the muscle system that produces the measured output. The method investigates the differences in the transfer function parameters obtained from the 16 accelerometers. However, further work is needed for the determination of the relationship between different propa-gation dynamics and muscle properties. Here we present only a few propagation patterns, for illustration purposes.

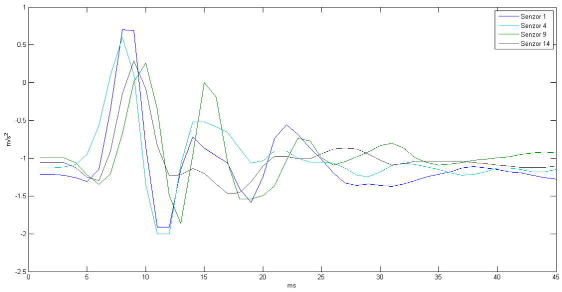

Fig. 5 – Acceleration response recorded by the closest sensors to the impact area (along fibers: sensors 1 and 4; across fibers: sensors 9 and 14).

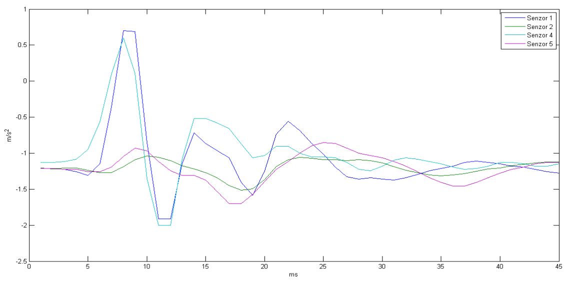

Fig. 6 – Acceleration response recorded by sensors along the impacted fiber.

The figure above shows amplitude dependence on distance from the impact region along the muscle fiber that received the impulse. For clarity reasons, we omitted signals recorded from the farthest sensors. The signals can also be compared with propagation dynamics across fibers, presented in figures 7a and 7b. Although not illustrated here, a delay is recorded in the case of these responses. Moreover, lateral asymmetry can be observed.

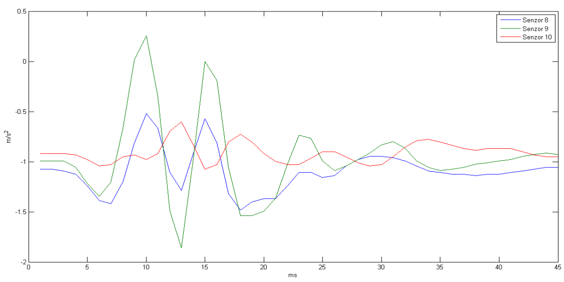

Fig. 7a – Acceleration response recorded by sensors across the impacted fiber (left side).

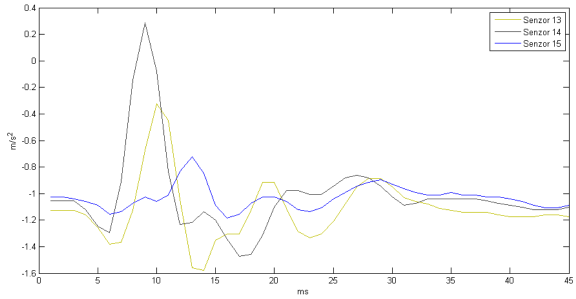

Fig. 7b – Acceleration response recorded by sensors across the impacted fiber (right side).

Discussions

Muscle response to mechanical impulse contains valuable information on the tissue's health, functional and structural characteristics. We propose a method for investigating muscle properties that takes into account the dynamic complexity of the muscle, with the aim of providing a detailed, objective description of these characteristics. So far we have tested the hypothesis that the propagation of the acceleration response to a mechanical impulse within a muscle fiber can be used for the assessment of the health of striated muscle.

Results are consistent with the state of the art and in addition, they reveal promising new information, which makes the research a useful approach to the problem of testing muscular capabilities for space applications. Further work is needed for the development of a device that applies the impulse and reads the response from several sensors arranged in a specific geometrical distribution, in order to capture information on muscular anisotropy. Moreover, future work will include establishing the analysis methodology, both in terms of transfer function parameter identification and mapping, and physiological interpretation of the results.

The present results as well as the intended in-depth investigations are encouraging for the use of the method for the astronauts' protection in space flight, because according to current knowledge the anatomical, physiological and biomechanical interaction between muscles and bones is very tight. In this respect, the studies of Sundeep Khosla (2012) evidence a link between muscle growth and bone mass increase. Cianferotti et al. (2014) stated that the endocrine properties of muscle and bone may serve to sense and transduce biomechanical signals such as loading, unloading or exercise, or systemic hormonal stimuli into biochemical signals. Under these circumstances, we consider that a mechanical characterization of the muscle would bring valuable information about the evolution of muscles and bones in microgravity.

Conclusions

1. The results are consistent with current research and reveal promising new information, which makes this study a useful approach to the problem of testing muscle capabilities for space applications.

2. Future research is necessary in order to develop a device that applies an impulse and reads the response from

several sensors placed in a controlled geometry with the main purpose of acquiring information about muscular anisotropy.

3. Future work will aim to establish the analysis methodology, in terms of identifying and mapping transfer function parameters, as well as in terms of physiological interpretation of the results.

Conflict of interest

There are no conflicts of interest regarding the experiment protocol or the result dissemination.

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