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Effects of the High-Induction Magnetic Stimulation on Viscoelastic Properties of the Biceps Brachii

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ABSTRACT Therapeutic methods taking advantage of low-frequency electromagnetic fields, or in other words, electrical currents contactless-induced by time-variable magnetic fields, enjoy an ever-growing interest in rehabilitation medicine. A great interest is paid to the question of using non-conventional techniques, such as the High Induction Magnetic Stimulation (HIMS). Based on therapeutic principles, it is possible to expect positive effects of this therapy, but this problem has not yet been considered, and thus, there are no research results supporting the HIMS application. Due to this, the target of the article presented here is to study effects of the HIMS on viscoelastic properties of skeletal muscles, since this research has till been missing. Within the framework of the present study, the HIMS was applied to 15 subjects and viscoelastic properties of the muscle were measured before and after the application. The evaluation of hysteresis curves acquired show obvious effects of the HIMS on viscoelastic muscle characteristics. After the HIMS application, the muscle tone was decreased and the elasticity of the tissue exposed was increased in the sample studied.

INDEX TERMS Biceps, high induction magnetic stimulation, muscle, myotonometry, viscoelasticity.

I. INTRODUCTION

In rehabilitation medicine, ever-growing attention is being paid to problems of the therapy of soft tissues with the use of electromagnetic fields. Therapeutic effects are dependent inter alia on the intensity of the field applied and possibly also on the frequency [1]. The High-Induction Magnetic Stimulation (HIMS) is a therapeutic method using high-intensity fields (up to 2.5 T), which produce high current density in the tissue exposed [2]. However, insufficient attention has been paid to the therapy of the locomotor apparatus with the use of the HIMS and thus, results of appropriate studies dealing with this problem are not available.

In contemporary rehabilitation medicine, magnetotherapy is a frequently used approach and thus, many commercial devices have been designed for this treatment modality. However, these devices standardly produce low-intensity induced electrical currents and thus, different effects can be expected compared to the HIMS. In general, there is a certain scepticism as to the therapy with the use of the low-frequency electromagnetic field. This is particularly due to the fact that although physiological effects of this stimulation are quite obvious, their accurate mechanism has not yet been satisfactorily explained [3] and relevant studies are still few in number. The research results available are even more restricted when considering the therapy with the use of the HIMS. However, the use of pulsed electromagnetic fields (PEMF) at different intensities and frequencies brought positive therapeutic results [3]–[6] and presented no hazard in terms of affecting the electric conduction system in the myocardium [2]. In general, the research available is particularly aimed at low-intensity fields in the therapy of joints, e.g. [7], [8] or possibly at applications of the HIMS for the Transcranial Magnetic Stimulation (TMS) [9], [10].

However, from the viewpoint of the HIMS action it seems that the therapy could be suitably employed for the treatment

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of soft tissues [6]. The assumption of positive HIMS effects is also supported by research implemented at the cellular level [11], [12]. With taking into account soft tissues, disorders of skeletal muscle manifested by changes in viscoelastic properties of the muscle concerned can be frequently encountered.

The soft tissue of muscles consists of two basic components – contractile cells and extracellular matrix (ECM) [13], [14]. The ECM fulfills many functions and particularly provides the tissues with the strength and elasticity, thus maintaining their shape, and it also serves as a biologically active scaffold. The mechanical behaviour of soft tissues is strongly affected by the concentration and structural arrangement of particular components as well as by the function of these tissues in the organism [15]. In terms of mechanics, the principal components of the ECM are collagen, elastin and proteoglycans [16]. The extracellular matrix of muscles forms fasciae, the mesodermal tissue particularly comprising collagen, known as membranous muscle capsules. Superficial fasciae continuously merge into the fibrous tissue inside of the muscle, where they form a harder envelope of muscle fibres and furthermore grow into internal structures of the muscle and thus physiologically restrict their excess tension or overloading (endomysium, perimysium, epimysium) [14]. Thus, fasciae occur on the muscle surface as well as in deep layers. They separate particular muscles one from another making possible slipping between them, and simultaneously interconnect muscles to produce locomotor chains. The fasciae can be different in the shape, compactness and volume as a tissue penetrating through the body.

Similarly, as other soft tissues, the fasciae are also subjected to stepwise reduction in length, and as far as they are not exposed to rhythmical tension changes, they become tough, and in addition, they become sites of the subcutaneous fat accumulation furthermore limiting the motion [17]. The process of fascia toughening is different in different individuals. It can also be affected by inflammatory processes, inappropriate nutrition, etc. There is, however, a principal catabolic effect of the hypokinesis on the contractile apparatus as well as on the skeletal muscle ECM, which results in the development of the muscle atrophy, reduction in the synthesis of contractile proteins and disorder of the collagen metabolism. In this situation, the metabolism of fibrillar as well as non-fibrillar collagen plays a crucial role in physical exercise and sports, and affects contractile forces applied to the skeletal apparatus [18]. Insufficient locomotor activity, characteristic for a prevalent proportion of the population, currently including even young individuals, is accompanied by certain manifestations of the muscle atrophy associated with changes in the plasticity, i.e. also in viscoelastic properties of muscles [19]. In spite of the fact that the reaction of muscle cells to a lack of activity is considered more distinct than the reaction of the ECM, the insufficient activity also involves important changes in structures of the connecting tissue, which lead to a deterioration of functional as well as structural characteristics of the skeletal muscle including its viscoelastic properties, and which are manifested by enhanced pains in the locomotor apparatus and development of degenerative changes [20]–[22].

Given the fact that the muscle is a considerably plastic tissue [14], [23], [24], it is to assume that the HIMS application is accompanied by specific mechanical strain of the muscle resulting from partial rapid contractions of the harmonic time course (muscle oscillations) or induced by waved tetanus. As already mentioned, the research results available are considerably limited and studies dealing with the HIMS application on soft tissues are mostly missing.

In our previous study, we have focused on the HIMS effect on connective tissue - patellar tendon. The results showed significant decrease in the tendon tension after HIMS exposure. Although there were some limitations, the study served us as a knowledge basis for follow-up studies. Therefore, the next logical step was to focus on different type of tissue. The muscle tissue was selected for multiple reasons. Firstly, the effect of the HIMS on skeletal muscle viscoelasticity has not yet been studied, but based on the physical intervention of this method, its application for these purposes seems to be suitable. On the other hand, the muscle tissue is structurally different from connective tissue. Therefore, it is also considerably different in terms of rheological properties. This means that it is not possible to primarily assume feasible results for different tissue types, i.e. therapy that has a positive effect on the tendon may not have the same effect in the case of exposure of muscle tissue. For these reasons, the study target is a verification of the hypothesis concerning the positive HIMS effect on the skeletal muscle viscoelasticity, which could perspectively contribute to the therapy of the locomotor apparatus disorders, such as for example the muscle spasticity.

II. MATERIALS AND METHODS

A. SUBJECTS

The basic criterion for including a participant in the present study was a negative personal anamnesis as to any locomotor apparatus disease, systemic disease and any other diseases, which could affect the elasticity of the structures examined. The anamnesis concerning the history of injuries and surgical interventions should also have been negative. Fifteen subjects aged 21.9 ± 1.8 years participated in the study. The subjects were informed about the course of the experiment and acknowledged with the target of the project and schedule of the experiment and signed their informed consents with their participation in the research and processing of personal data. The whole study was implemented under medical supervision and in agreement with the Helsinki Declaration [25].

B. EXPERIMENTAL SETUP

The elasticity of the exposed tissue was monitored for the research of dispersion effects of the high-induction magnetic stimulation. For these purposes, a myotonometer (see Fig. 1) was used, designed at the Technical University in

FIGURE 1. Equipment for measuring tissue elasticity: Myotonometer (left) and real setup in measurement implementation (right).

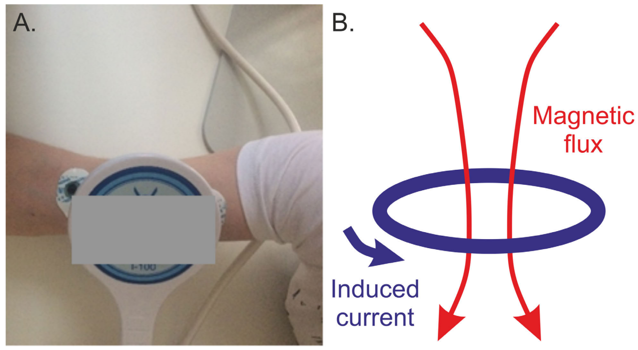

FIGURE 2. Applicator for High-Induction Magnetic Stimulation (A.), a loop of induced electric currents generated in a conductive environment (tissue) due to a time-varying magnetic field (B).

Liberec [26]–[28], which simulates the diagnostic palpation. The palpation is carried out with the help of a chosen indenter situated on a movable arm driven by a stepping motor [26], [27].

Based on the chosen indenter profile movement, it is possible to define the movement velocity, depth of the indenter impression into the tissue and number of steps (fineness) of measurements. It is possible to provide a continuous movement at a constant velocity or to achieve other complicated movement with an acceleration, breaks and waiting in a certain position, together with all the combinations of the above-mentioned situations. The movement can be defined by a fixed site, at which the appropriate force is read off. It is thus possible to obtain a dependence of the force on the impression (penetration) of the indenter, and vice versa, a dependence of the impression depth on the force applied.

The maximum possible measurable force acting on the strain gauge via the indenter is 110 N, with a resolution of 0.43 N and an accuracy of $\pm$ 1 %. The speed of movement of the indenter is linear with a deviation of 3 %, at a speed of 3.5–4 $\text{mm} \cdot \text{s}^{-1}$.

The force measured (expressed in N) can be converted and transferred to the pressure depending on the indenter chosen and the knowledge of its contact surface [28]. To ensure as uniform conditions as possible, one type of indenter, penetration velocity, maximum acting force and penetration depth were used for all measurements (detailed description follows).

This equipment also makes possible plotting the hysteresis curve of the loading and relieving force with the help of a firmware. The elastic and viscose components of the tissue studied can be expressed based on setups defined.

Possibilities of this diagnostic method were used to answer research questions concerning attempts to objectivize the efficacy of the High-Induction Magnetic Stimulation (HIMS).

The experimental measurements consist of the HIMS application with the use of the SETA-D (NPF Dipol, Vitebsk, Belarus) commercial device - see Fig. 2. The high-induction magnetic stimulation was applied to the dominant upper limb in the areas of the *m. biceps brachii* and radial or possibly ulnar ligamentum. The magnetic induction was set at a level of 1.2 T with an inductor - applicator having 100 mm in diameter. The procedure took 10 min and consisted of 10 series/min, 6 pulses in each series.

The data collection was provided immediately before and after the HIMS application. The principal hypothesis was that the biomechanical viscoelastic properties of tissues at the site of the application are significantly varied by the action of the HIMS application.

Every subject was measured with the same myotonometer setting to provide the uniformity of measurements and the possibility of subsequent data evaluation. This setting was used experimentally in a way providing the correct measurement of the whole hysteresis curve. This was particularly setting of a maximum limit of the force acting $F_{lim} = 30$ N, penetration depth $d_{max} = 20$ mm and indentation velocity $v = 3\ \text{mm} \cdot \text{s}^{-1}$. A cylindrical indenter 18 mm in diameter was used. Based on known geometry of the indenter, the contact area was calculated. The time period of one measurement with the use of the myotonometer was of 13.3 s. The muscle was measured at the centre, on the biceps tummy. The location of the measurement was determined particularly by taking into account requirements for simple identification and elimination of effects of different tissues structures.

The hysteresis curve shows the force acting in a specific penetration depth. Since the indenter motion is linear, the penetration depth is directly proportional to time. From this curve, the following statistical values (parameters) are calculated. A parameter was employed for the analysis, characterizing the maximum indentation force achieved F_{max} at a maximum penetration defined – 20 mm. This parameter characterizes the resistance of the tissue examined in the defined maximum penetration depth. A further parameter monitored was the force F_{md} characterizing the force situated on the elasticity curve (hysteresis curve midline) in the region with the highest energy, provided that this region is characterized by the penetration depth d_{md} [29]. In addition to the above-mentioned quantities, the ratio F_{md}/d_{md} and furthermore, based on a conversion to the known indenter area, also the maximum pressures achieved P_{max} or P_{md} were included into the analysis. These parameters are associated with the tissue viscosity. The last parameter monitored is the dissipation energy, i.e. the area between curves representing loading and relieving. This parameter corresponds to the tissue elasticity

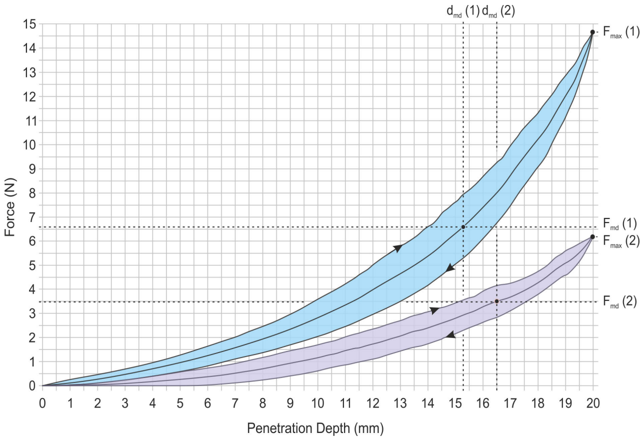

FIGURE 3. Examples of hysteresis curves characterizing viscoelastic properties of the *m. biceps brachii* before application of High-Induction Magnetic Stimulation–blue curve (1) and after the application–lilac curve (2).

and thus, a higher dissipation energy means a lower muscle plasticity [30], [31]. The parameters mentioned are shown in Fig. 3 together with an example of hysteresis curves.

In addition, parameters characterizing the deflection and inclination of each curve were also used for the curve description. These parameters were acquired by using the methodology according to [27], [31], where the Inclination Parameter is represented by a line segment between two points of the line, and the perpendicular distance from this line segment to the most distant point of the curve represents the Deflection Parameter. In the interpretation of these parameters, a fact is considered that the curve with a steeper slope, i.e. lower inclination value is closer to the Euclidian solid matter, which could be related for example to a spastic muscle whereas the healthy muscle should exert a higher Inclination Parameter, i.e. lower curve slope [31], [32]. In the case of the Deflection Parameter, the healthy muscle should exert a higher viscoelasticity and thus also a higher Deflection Parameter [31]–[33]. Thus, the Inclination Parameter indicates the muscle tone or stiffness [31], [34] and the Deflection Parameter indicates the muscle elasticity [31]. For a possible comparison of values measured in particular subjects, a normalization is then carried out according to:

$$x_{norm_i} = \frac{x_i}{\max(x)}, \quad (1)$$

where x_{norm_i} is the normalized value of the parameters for the i-th measurement, x_i is the original value of the parameter for the i-th measurement, and $\max(x)$ is the maximum value of the parameter in the dataset, where $i = 1 \ldots N$ and N is the size of the data sample i.e. the number of measurements. Thus, after this normalization, the values of Deflection and Inclination Parameters vary within the interval $\langle 0; 1 \rangle$.

Presented parameters were selected with respect to the study design. Such parameters derived from the hysteresis curve were proven to be suitable for evaluation of viscoelastic properties of muscle tissue in previous studies [26], [27], [31]. Therefore, we can consider them sufficient regarding the study design and aim of the study.

C. STATISTICAL ANALYSIS

The parameters directly obtained in the measurements on the *m. biceps brachii* were completely processed at the end of experiments, i.e. post-hoc, to avoid effects of the examination process on the evaluation at the site and in the course of the research activity.

Particular parameters acquired before and after the HIMS application were statistically compared. With respect to the sample size and refused hypothesis of the normal distribution based on Jarque-Bera [35] and Kolmogorov- Smirnof [36] tests, the statistical similarity was tested with the use of the Wilcoxon signed-rank test [37] at a significance level of $\alpha = 5$ %. The distribution of particular parameters was represented by using boxplots. The parameters represented do not include the parameter d_{max}, which was set to a fixed value, i.e. it was constant for all the measurements.

The statistical processing was carried out in the Matlab 2017a programme environment (MathWorks, Natick, United States).

III. RESULTS

The distribution of particular parameters is represented in Fig. 4 together with the indication of statistically significant differences prior to and after the HIMS application, which means that for the parameter concerned the *p*-value was obtained by means of the Wilcoxon signed-rank test is lower than 0.05.

The distributions obviously show that in all the parameters monitored, the expected behaviour was observed - reduction in the median parameters related to the force, penetration depth, energy or pressure, and vice versa increase in parameters in the cases of Inclination and Deflection parameters. In most parameters, changes were statistically significantly changed. Only two parameters, d_{md} and Inclination, were exceptional, but even in these parameters, there was an assumed course, i.e. decrease or increase in the median after the HIMS application.

IV. DISCUSSION

The distribution of particular parameters shows an obvious interindividual variability in the group of the subjects examined. However, this is not surprising. Viscoelastic properties of the muscle are affected by many factors, where for example the sex [38] or daily activity [39] play important roles. Kubo *et al.* demonstrated that there are significant differences between viscoelastic characteristics of men and women muscles. In women muscles, the stiffness and hysteresis were lower in general [38]. Kawczyński *et al.* reported changes in viscoelastic properties of muscles 24 hours after a specific training [39]. The interindividual variability is thus a quite natural phenomenon. To eliminate these influencing factors, the most homogeneous group of subjects was selected. Also, due to the study pretest-posttest design where paired testing

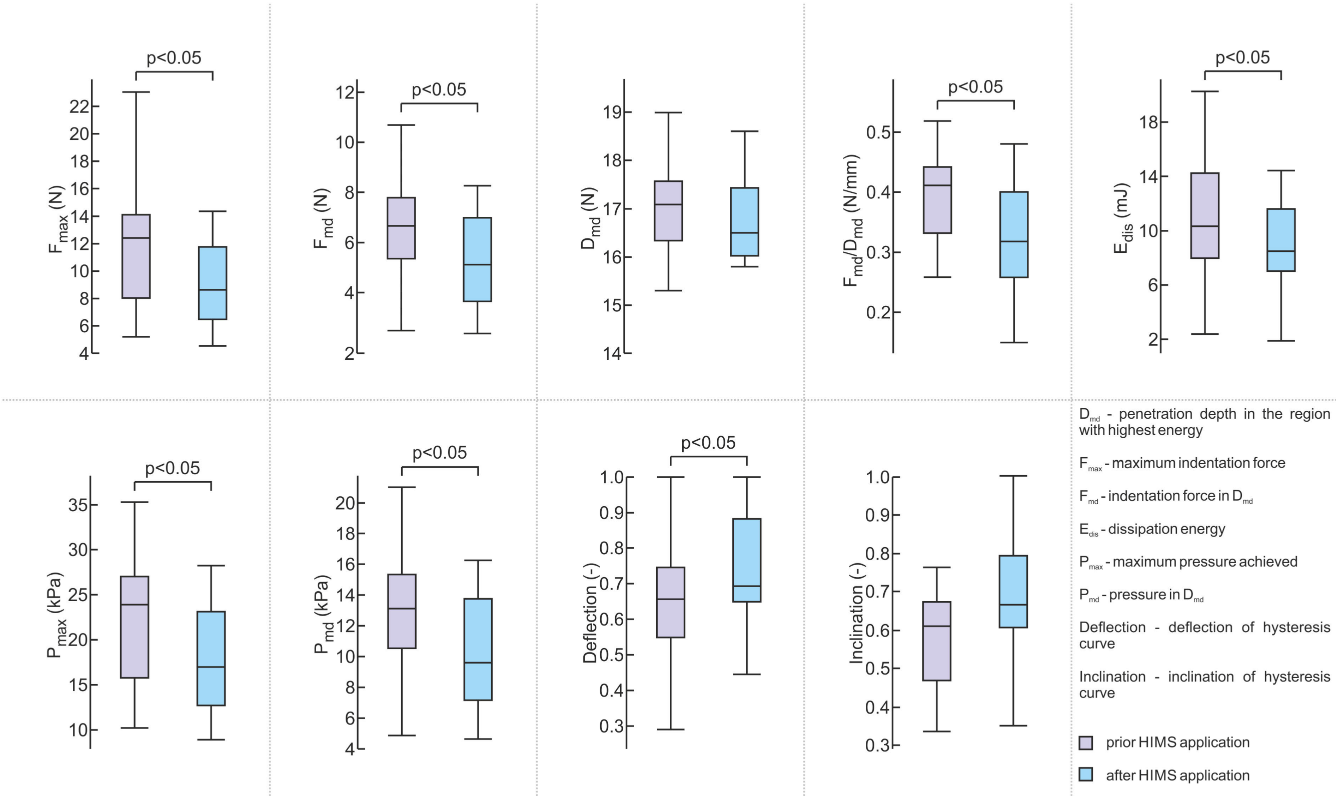

FIGURE 4. Graphical representation of distributions of particular parameters prior to and after application of High-Induction Magnetic Stimulation (HIMS) with indication of statistically significant differences in particular parameters prior to and after HIMS application.

was applied, the effect of interindividual variability is minimalized.

Given the nature of the viscoelastic properties, the therapy with the use of the PEMF at high intensities obviously positively affects the muscle elasticity. In all the parameters studied, there was an expected decrease or increase, which is illustrated by boxplots in Fig. 4. With respect to the p-values mentioned, in most parameters, there were statistically significant changes between conditions before and after the HIMS application. However, it is necessary to take into account two facts as follows. Subjects participating in the study were healthy young people and thus, the muscles exposed to the therapy were also healthy. The second fact was a single exposure of the muscle to the therapy for a period of time of 10 min. There is a possibility that after repeated exposures of spastic muscles to the HIMS, the positive effect of the therapy can be even deeper.

The values of particular parameters obtained suggest that the force necessary for achieving the defined depth was reduced. In this way it was also sufficient to induce lower pressures for the indenter penetration into the depth required. After the application of the HIMS, viscoelastic properties of the muscle were modified. The muscle became ‘‘softer’’ and thus exerted a reduced resistance and also energy losses in relieving the indenter, i.e. the parameter E_{dis} was significantly lower. The increase in the Inclination Parameter similarly indicates a decrease in the hysteresis curve slope. In practice, this means that prior to the HIMS application, the muscle is close to the condition of the Euclidian solid matter [40]. After the HIMS application, the muscle is contrastingly closer to the horizontal representation, thus being closer to the Pascal liquid matter [40]. Researchers point out a fact that the lower slope of the hysteresis curve suggests that there is a lower muscle tone and vice versa [31], [34]. The muscle tone was thus reduced after the HIMS application. As far as the shape of the hysteresis curve is concerned, the HIMS application obviously significantly affected its curvature. This is supported by a change in the Deflection Parameter. Šifta *et al.*. shows that the healthy muscle manifested a more considerable bending, which suggested that its elasticity was enhanced [31]. It is thus to state that with respect to the Deflection Parameter, the elasticity of the tissue exposed was altered after the HIMS application.

The principle of the rapid action of the high-induction magnetic stimulation HIMS on the soft muscle tissue can be explained by effects of the HIMS on the extracellular matrix rather than on the contractile muscle cells, myofibrils.

The inactivity of skeletal muscles results in losing muscle contractile proteins and the force [41], [42]. The muscle weakening is accompanied by a loss of the muscle mass and diminishing of the muscle cell size [41], [43]. A reduction in the protein synthesis and enhancement of their degradation occurs in the contractile apparatus as well as in the ECM [41]. However, we do not expect that the contractile apparatus of the muscle could be significantly affected in the course of a rather short time interval of the HIMS action in one procedure carried out with the muscle investigated,. Biomechanical affecting of the ECM at the microlevel of its structure is contrastingly a likely reason for the objectively demonstrated changes in viscoelastic muscle properties after the HIMS application. The ECM of connecting tissues actually facilitates not only their attachment to other tissues, but also plays a crucial role in the maintenance of the muscle tissue structure [44]. Rapid changes in ECM characteristics can be induced by the physical activity [45], [46], which subsequently means changes in mechanical properties of the skeletal muscle. In addition to slow changes in the collagen concentration by the action of the physical activity, rapid changes in its crosslinking were also recorded, which exerted considerable effects on mechanical characteristics of the skeletal muscle, particularly on the decrease in its stiffness [47], [48].

If one considers the original assumption, the physical principle of the HIMS and the fact that the muscle is highly plastic, then a mechanical strain exerting the nature of interrupted oscillations occurs in the muscle exposed; it is to believe that this mechanism starts adaptation mechanisms principally similar to physically induced processes of the recovery from the muscle atrophy.

The above-mentioned facts suggest that the focused HIMS energy (even in short procedure of the application of this physical intervention) is sufficient to overcome forces of undesirably weak chemical bonds and to cause a physiological conversion of the tertiary or quaternary collagen structure, i.e. to facilitate the conversion of a rather solid colloidal suspension (gel) to the state of matter with a considerable abundance of the phase sol. In this way, a return to the desirable structural form of the ECM accompanied by changes in physiological viscoelastic properties can be achieved.

V. CONLUSION

The article deals with the study of the High-Induction Magnetic Stimulation (HIMS) effect on viscoelastic properties of the skeleton muscle, specifically of the *m. biceps brachii*. The HIMS was applied with the use of a commercial instrument. The viscoelastic properties of the muscle were evaluated based on data acquired from myotonometric measurements, where the myotonometer indenter simulated the diagnostic palpation. These measurements were always carried out prior to and after the HIMS application in a group of 15 healthy subjects. From the hysteresis curves obtained, parameters were evaluated, which were subsequently statistically processed. The results of the study show that the HIMS actually affects the viscoelastic properties of the muscle exposed in a way, in which the elasticity of the muscle is enhanced and the muscle tone is reduced.

The study was limited by the number of subjects. For more complex results, it would be necessary to consider more numerous subjects exposed to the HIMS. There is also a limiting fact that the subjects were participants without any diseases and without formerly experienced injuries. This means that the muscles examined were healthy. On the other hand, the present research serves as a pilot study in the field of interest concerned with respect to the fact that no attention has still been paid to HIMS effects on the soft tissues.

The present research is thus the first study dealing with HIMS effects on the skeletal muscles and it can thus serve as an initial basis for subsequent research in this field. For the further research, the research sample should be thus more numerous not only with respect to the number of healthy subjects, but also with taking into account subjects with diseases of the tissue exposed. A comparison of HIMS effects on the soft tissue in the case of different setting of the treatment in context of the field intensity and pulse frequency could also be beneficial.

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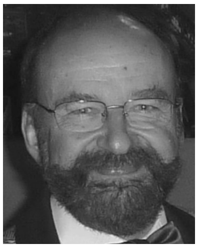

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