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Textronic System to Muscle Electrostimulation

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Abstract**—**In the paper the research of flat textile products for use as electrodes was presented. Material's resistance measurements were carried out to determine the suitability of the textiles. Based on the received results of studies different types of textile electrodes were designed. Textile electrodes tests were carried out on human phantoms. The electro-conductive properties of human forearm phantom were also described. Based on this results special electro-conductive hydrogels with electro-conductive particles were feasible. The hydrogel is an important element of the forearm's phantom model of a survey of electrodes for muscle electrostimulation. The hydrogel is an equivalent human skin and tissue. The hydrogel should have a permanence and recurrence of the electro-conductive properties.

Keywords**—**Electro-conductive textiles, electrostimulation, forearm phantom, resistance measurement, textile electrodes.

I. INTRODUCTION

THE electro-conductive flat textile products are may be applied to especially in medical applications such as: systems monitoring physiological parameters [1], or for bioimpedance spectroscopy [2], textile sensors for cardiac monitoring [3, 4], textile electrodes [5] etc. Electrotherapy is an important part of physical therapy, which is used for medicinal purposes in various types of electrical stimuli. Accordingly, applied electric current can cause a therapeutic effect of a stimulus and analgesic (neuromuscular stimulation, pain-killing, improvement of tissue perfusion, decreased muscle tone, easing inflammation, accelerate the absorption of edema, improve metabolism, tissue regeneration etc.) [6, 7, 8]. In the framework of the project titled "Textronic system to electrical stimulation of muscles" implemented under the Operational Programme Innovative Economy, the optimal design of the textile electrodes intended for electro-stimulation of muscles is carried out. The textile electrodes are the new product which can replace the traditional metal or graphite electrodes. They are elastic and good fitted to body shape (legs or arms). At the same time they do not give feelings of discomfort or pressure, and they are more friendly to the patient. Especially they can be used to muscles electrostimulation during the therapy. The electrodes require studies proving its usefulness. In order to test the textile electrodes model mapping impedance properties of forearm's phantom was constructed. Estimation of electroconductive properties the human forearm is needed to phantom construction.

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The properties can be evaluated on the basis on measurements of surface resistance of the skin and its capacity. These quantities depend on skin moisture, electrolyte, thickness of the epidermis and individual human characteristics etc. Current studies are an important contribution to the development of a new area of engineering knowledge called textronics, which combines three areas: textiles, electronics and computer science [9].

II. MATERIALS AND METHODS

Flat textile products for the textile electrodes should not cause patient's allergic reaction. The textile materials should have a good electrical conductivity. Moreover an important is the stability of the textile electrodes for long-term measurements. Selected properties of electro-coductive textile samples are presented in Table I.

TABLE I
ELECTROCONDUCTIVE TEXTILE SAMPLES

Kind of textile material	Material	Surface mass	Thickness
-	-	g/m2	mm
Woven fabric	Metallized nylon (Sn, Cu, Ag)	82	0.07
	Silver fibres	76	0.19
		149	0.41
	PES/ Nickel metallized	155	0.30
		65	0.17
		83	0.09
		152	0.32
Knitted fabric	Silver fibres	135	0.55
		109	0.39
		134	0.37
	Silver monofilaments	47	0.29
	Silver fibres	128	0.47
Non-woven fabric	Graphite fibres	64	0.40
	PES/ Nickel metallized	251	1.75

The measure of electro-conductive properties of textiles is the resistance. To determine the resistance four-point probe technique was used [10]. For this purpose textile samples of seventy millimeters square were prepared. Electric scheme for resistance measurement is shown in Figs. 1 and 2. Four brass electrodes were located at sample surface so close to edges as possible. Two adjacent electrodes were powered by a precision current source DC Power Supply Agilent E3644A (range: 0-8 V and 8 A). Between the other two electrodes voltage drop was measured using multimeter Agilent 34410A (6½ Digit, range: 0-1000 V). The pressure of a single electrode on the sample was 23 kPa.

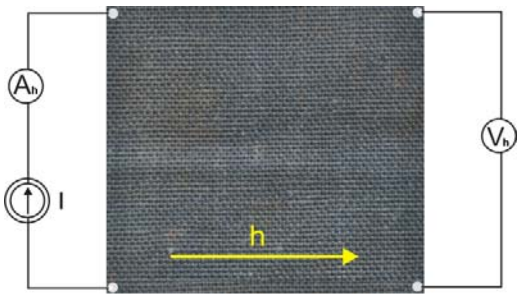

Fig. 1 Electric scheme for horizontal resistance measurement [11]

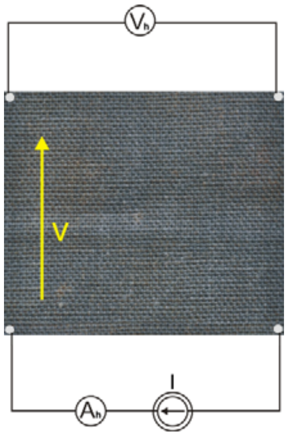

Fig. 2 Electric scheme for vertical resistance measurement [11]

Thus the horizontal resistance (1) and vertical resistance (2) was obtained:

$$R_h = \frac{U_h}{I_h} \tag{1}$$

and

$$R_v = \frac{U_v}{I_v} \tag{2}$$

III. Results of Resistance Measurements of Textile Samples

The choice of textiles for the electrodes requires analysis of the electro-conductive properties of the material. The criteria for selecting the optimum textile material for the construction of the electrode were proposed [11]. It is assumed that the order of the criteria is important. The first criterion assumes that the measured resistances not exceed 100 Ω. This condition results from the need to reduce power losses at the electrode. It can make the heat generated in the textile electrodes. The second criterion assumes that the relative expanded uncertainty of measured resistances not exceed 12 %. The preliminary studies have shown that the relative expanded uncertainty of resistance can be increased to several percent.The assumed value is based on conducted experiments.

The third criterion assumes that the difference between the horizontal and vertical resistances is relatively small. It was assumed that:

$$\Delta = \frac{|R_h - R_v|}{\min\{R_h, R_v\}} \leq 0.3 \tag{3}$$

Considering the extreme case let $R_h \leq R_v$ and R_v = 100 Ω. Then the ratio Δ is 0.3 for R_h = 77 Ω. It means that the biggest difference between horizontal and vertical resistances, which can occur, is 23 Ω. This value is satisfactory.

The resistance measurements were carried out at ambient conditions: temperature of 24.5 ^{o}C, relative humidity of 36 %. The samples were acclimated under the same conditions. Drop voltage between other electrodes was read with 30 seconds time interval. Measurements were repeated three times. The values of average horizontal and vertical resistances of textile samples and relative expanded uncertainty of the resistances are presented in Table II. The significance level of 0.05 was assuming. Moreover calculation of uncertainties type B was performed by uniform distribution assumption.

TABLE II
Results of Resistance Measurements of Textile Samples

Horizontal resistance (Ω)	**Relative expanded uncertainty of horizontal resistance (%)**	**Vertical resistance (Ω)**	**Relative expanded uncertainty of vertical resistance (%)**
4.33	12	1.13	12
41.94	12	23.06	12
20.22	12	15.26	12
113.17	11	34.57	10
46.48	12	37.91	12
85.19	12	20.98	12
77.18	12	46.78	12
358.61	13	4.83	10
45.16	12	52.13	12
57.94	20	230.79	20
67.19	12	103.50	12
86.43	12	35.68	12
2445.83	41	10.00	58
12.36	16	59.34	16

The horizontal resistance changed from 4.33 Ω to 2445.83 Ω. The vertical resistance changed from 1.13 Ω to 230.79 Ω. The relative expanded uncertainty varied widely from 10% to 58%, which results from the textile structure [11].

The research showed that all the subsequent criteria satisfy three textile materials:

- knitted fabric containing silver fibres of resistances R_v=45.16 Ω and R_v=52.13 Ω;
- woven fabric containing silver fibres of resistances R_v=20.22 Ω and R_v=15.26 Ω;
- woven fabric made of PES and nickel metalized of resistances R_v=46.48 Ω and R_v=37.91 Ω.

IV. Design of the New Textile Electrodes

Metal or rubber electrodes are commonly used in electrotherapy treatment (Fig. 3).

The main properties of typical electrodes:
-Raw material – electroconductive rubber
-Square resistance – 10 Ω -50 Ω
-Quite stiff
-Not easy fit to the body
-Require very strong elastic band
-Typical shape

Fig. 3 View of typical rubber electrodes

The alternative is textronic electrical systems with the textile electrodes. These electrodes are made of electro-conductive textile material and they are an integral part of the clothing structures such as shirts or socks.

The three criteria satisfied electro-conductive textiles such as knitted fabric made of silver fibres, woven fabric made of silver fibres and nickel metalized woven fabric made of PES. The chosen electro-conductive textile materials were used to the manufacture of prototype textile electrodes. The microscopic photos of selected fabrics are presented in Table III.

TABLE III
THE MICROSCOPIC PHOTO OF SELECTED ELECTROCONDUCTIVE TEXTILE MATERIALS [11]

Knitted fabric (silver fibres)	Woven fabric (silver fibres)	Woven fabric (PES/Nickel metallized)
		

The elastic bandage was used as the base of construction and as the element of clothing structures. The polyurethane foam of the 3 mm thickness was used as the filling. The size of electrode was 35 x 35 mm, where the active electrostimulation surface was 30 x 30 mm. The peripheries of electrode were made from electro-conductive yarns. This kind of construction obtains uniformly supply of stimulation current. The scheme of single electrode is presented in Fig. 4.

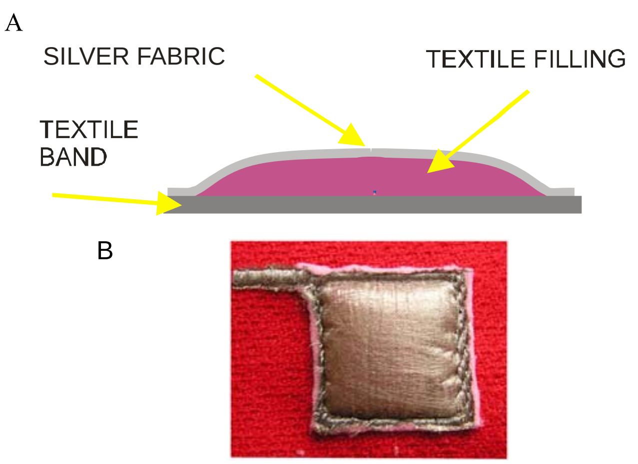

Fig. 4 The scheme of elementary electrode [4]

The new idea is to create the few textile electrodes in one clothing structures – matrix electrode. The electrodes can be connected in many ways, which increases the sites undergoing stimulation therapy. The particular elementary electrodes in the matrix electrode have got laminar structures. There were used different methods like sawing and embroidery method to electrode construction. The simplified scheme of matrix electrode is presented in Fig. 5. The matrix electrode consists of six elementary electrodes. The elementary electrode was distributed on surface of the size 100 x 120 mm.

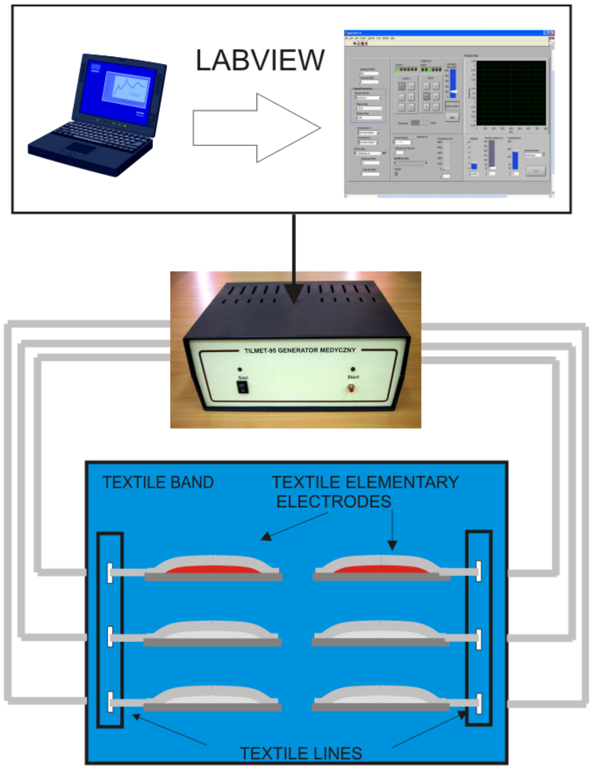

Fig. 5 The simplified scheme of prototype textile matrix electrode connected with special medical generator (A); the photo of realization prototype textile matrix electrodes (B) [11]

V. ELECTROCONDUCTIVE PROPERTIES OF HUMAN SKIN

In the first stage the skin impedance measurements which components resistance and capacitance were carried out. The direct measurement method and RLC meter was used (Fig. 6a). The research was conducted for DC current and three kind of frequency 100 Hz, 1 kHz and 10 kHz. Another measurement based on indirect method (Fig. 6b) where two outer electrodes (E1, E4) were connected to the generator and another two (inner) electrodes were connected to oscilloscope (measurement devices). All measurements were carried out on creators. The electrodes were displacement in constant distance on right human's forearms.

In measurements the electrodes made of medical polyethylene foam were used. They are well arranged along the natural curves of the body. The chosen electrodes are repeatedly used. They can be unstick and dislocated on different measurement placed on human skin. In presented measurement each electrodes were used once. The resistance measurements obtained using the direct method is presented in Table IV.

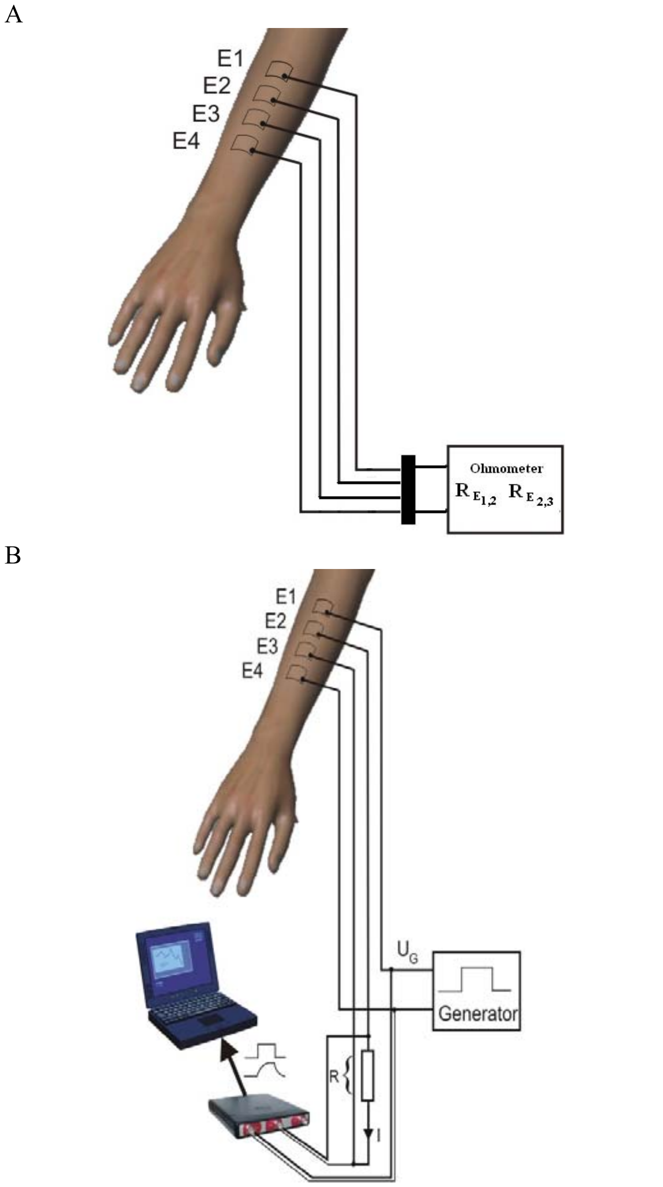

Fig. 6 The simplification of measurement stand scheme: a - direct method, b – indirect method [12]

TABLE IV
THE AVERAGE VALUE OF HUMAN LIMB RESISTANCE – DIRECT METHOD

Parameter	Electrodes		
	E1,2	E2,3	E3,4
Distance between electrodes, cm	5	5	5
Resistance, Ω	131	212	107

The next stage of research was measurement impedance according to indirect method (oscilloscope). This method is come from simplification model of human skin, presented in Fig. 7. [7, 8]. The resistance R_s is a result of existence extracellular fluid and R_1 is a result of intracellular fluid and C is skin capacity.

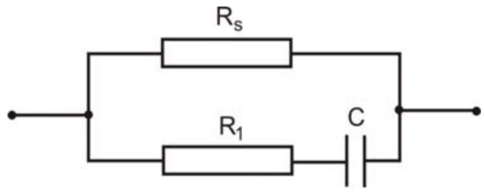

Fig. 7 Substitute scheme of human skin

The step function had got 5,2 V. The voltage level was selected in accordance with doctors instructions. In the same time it was recorded the voltage from two inner electrodes. The example of voltage step function and the current response presents Fig. 8 and real course presents Fig. 9.

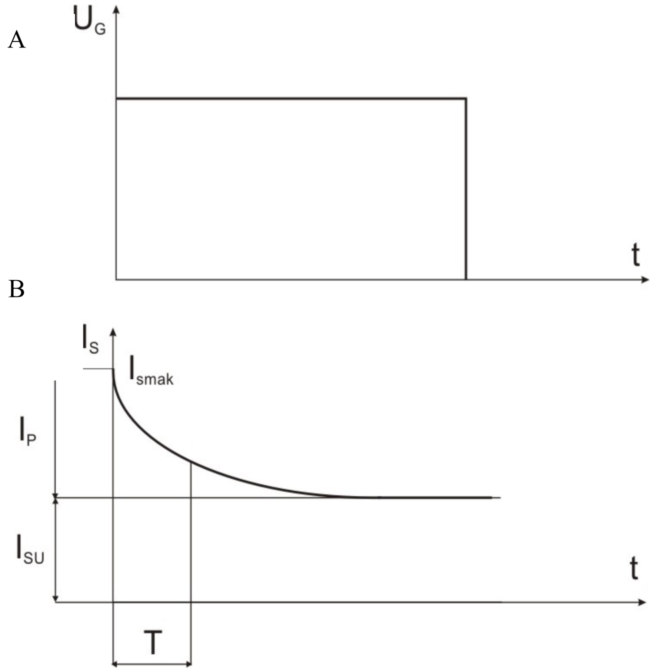

Fig. 8 The example of measurement results received using indirect method A - stimuli impulse, B - the voltage answer [12]

In the Fig. 8 I_{smak} is the maximal value of human skin, I_P – the transition current, I_{SU} – the steady current value, $T = R_1C$ – the time constant, and U_G – the generator voltage.

Based on equation:

$$R_s = \frac{U_G R_1}{U_R} \quad (4)$$

where: U_R – the voltage drop on resistance R,
R – the resistance to measurement current, and

$$I_P(t) = I_P\ e^{-\frac{t}{T}} \quad (5)$$

Human skin resistance R_S and R_1 according to the model from Fig. 7 was calculated. The example of average value of resistance obtained from second method for one man is $R_S = 346\ \Omega$ and $R_1 = 88\ \Omega$, C= 1,27 μF.

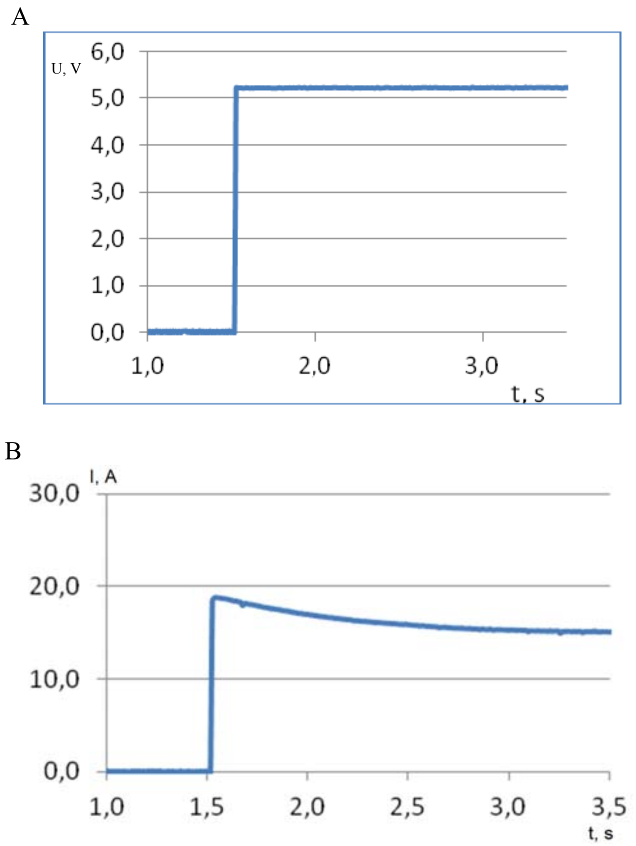

Fig. 9 The step function of voltage (A), the current response (B) register on forearm

Based on received result authors took the trial to created special hydrogels with different electroconductive particles. They took the assumptions that the average value of resistance should be the similar in 30 % of variation and the resistance distribution on the hydrogels surface should be uniform. Fig. 10 shows a map of resistance R distribution on the surface of the chosen hydrogel containing carbon particles.

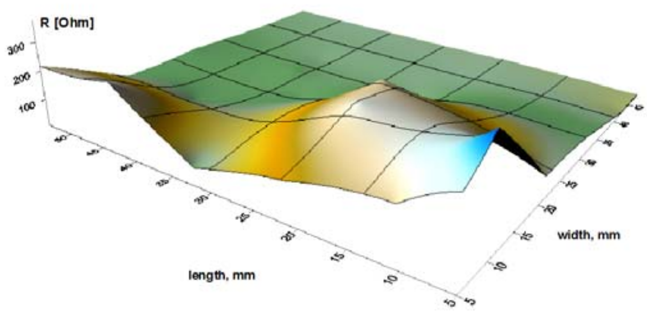

Fig. 10 The chosen map of resistance distribution on the surface of the hydrogel containing carbon particles [12]

It was also conducted long time research during the 140 hours. The measurement received results for three samples of hydrogels presents in Fig. 11. The measurement was done also for three different frequency of measurement. Escort ELC – 3133A meter was also used to the research.

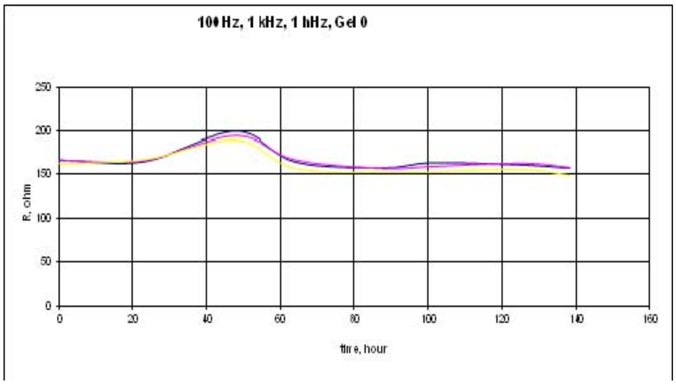

Fig. 11 The long time measurements of hydrogels resistance [12]

VI. Concept of the Electroconductive Properties of Forearm's Phantom

Phantom is designed to study manufactured, new textile electrodes. In the design of the project is expected to make the phantom in the form of a cylinder. The inner part of the cylinder will be filled with hydrogel of impedance close to the average impedance of soft tissue and bones of the human forearm (Fig. 12). The forearm's phantom is to ensure the stationarity of parameters. Textile electrodes can be placed on the phantom in different ways, depending on the type of therapy. They can be placed on the surface of the forearm and then the stimulation signal is the surface current. If electrostimulation is a cross-current that penetrated skin, soft tissue and bone, that the electrodes are placed on the opposite side of the forearm. The phantom model assumes that the average surface resistance of hydrogel will be similar to the average surface resistance of the human forearm. Moreover, it is important that the distributions of surface resistance and capacitance in the case of the hydrogel and forearm were comparable. The distributions should not diverge from one another significantly, meet the selected criteria. Generally the phantom imitates impedance properties of human limbs.

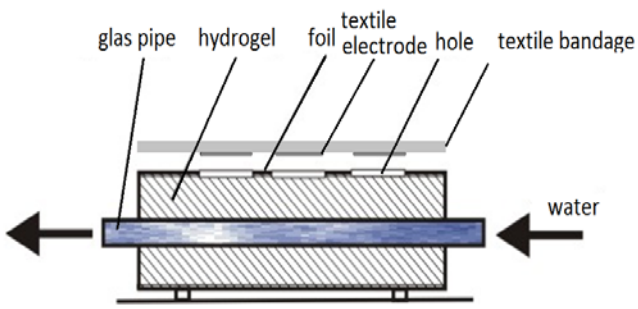

Fig. 12 The simplified diagram of the forearm's phantom, the measurement part for textile electrodes – hydrogel with gap for textile electrodes [12]

The measurement stand was presented in Fig. 13.

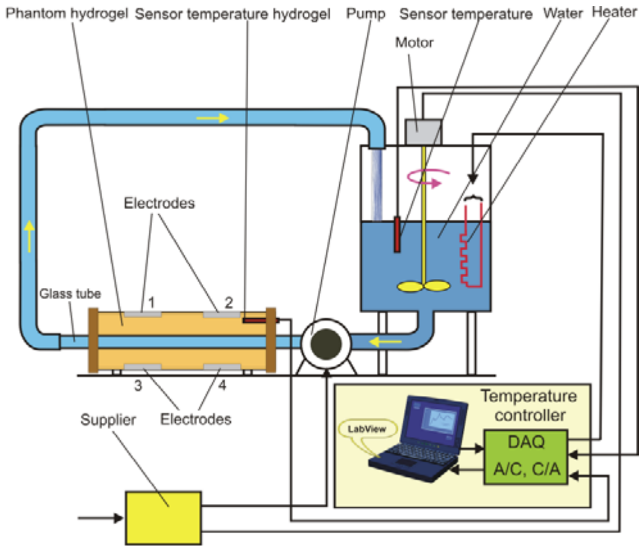

Fig. 13 The simplification of forearm's phantom scheme [12]

The forearm phantom consists of a cylinder with glass pipe inside. The pipe is full of water which flows and heats phantom to temperature of human body. The glass pipe imitates properties of human's bone. It is covered with piece of hydrogel that imitates electroconductive properties of soft tissue of limb. Temperature of phantom is stabilized around the value of human body temperature by control system. The system consists of virtual controller which was built in Lab View. The humidity of outside cover of cylinder is kept by the hydrogel which has special property of moisture maintaining**.**

VII. Electrostymulation Current Measurement

Stimulation AC current flowing from the medical generator induced electromotive force, e in miniature measurement coil.

$$e = -z\frac{d\Phi}{dt}. \tag{6}$$

Taking into account the:

$\Phi = B \cdot S$, and $B = \mu_0 \cdot H$, and $z \cdot I = H \cdot l$, and $l = 2\pi \cdot r$,

where: Φ - magnetic flux, B –flux density, S –coil area, μ_0 – permeability of vacuum, z – number of coils, H – magnetic field strength, l –circumference coil and r –radius coil. Therefore, the electromotive force will be determined by the relationship (7):

$$e = -\frac{z \cdot S \cdot \mu_0}{2 \cdot \pi \cdot r}\frac{di_g}{dt}. \tag{7}$$

The phenomenon of induced electromotive force can be written in another form:

$$e = -M\frac{di_g}{dt}. \tag{8}$$

Electromotive force created in the coil by the mutual inductance M. Voltage is converted amount of current flowing by the electrode. Measured current is determined by the current flowing through the measuring coil (9).

$$i_g = -\frac{1}{M}\int_0^T e\,dt. \tag{9}$$

Magnetic flux changes in the current cycle of stimulation. The placement an inductive sensor is shown in Fig. 14.

Because e = -u, therefore, by measuring the voltage at the terminals of the coil, and integrating them, will be processed intensity of the current (10).

$$i_g = \frac{1}{M}\int_0^T u\,dt. \tag{10}$$

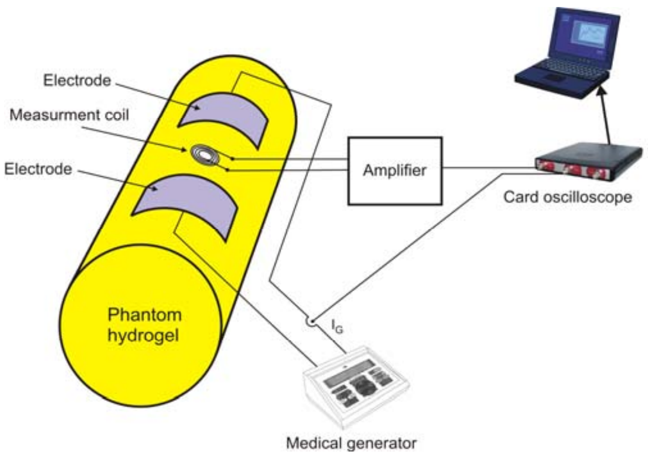

Fig. 14 The scheme of current measurement system dunder electrodes

The measuring coil is placed on the phantom surface between two electrodes. It measures the surface's current or its part depending on the current depth penetration into the hydrogel phantom. The coil sensor is connected with amplifier, and the output amplifier attached to the oscilloscope card.

Similarly, but with different sensors placement, you can measure the crossover (crossing) stimulation current, which is flowing between the electrodes placed on the opposite side of the phantom limb or hydrogel. To check the proper work of the measuring system, electrodes fed with sinusoidal voltage. The surface current flows between the electrodes. Therefore, the voltage generated by the measuring coil is determined by the relation (11).

$$u = R_s \cdot i_1 + L\frac{di_1}{dt} \tag{11}$$

where: u – coil voltage, i_1 – coil's current, R_s – substitute resistance consisting of coil resistance and the input resistance of the amplifier, L – coil inductance.

Preliminary investigations on the stand from Fig. 14, shows the need to change parameters of the coil in relation above.

Air core inductor, coils had 300 turns, and the resistance of the coil was R = 37.92 Ω, and inductance L = 2.71 mH and magnification factor of coil goodness Q = 0.449. Recorded waveform of the current flowing from the generator and the current surface is shown in Fig. 15.

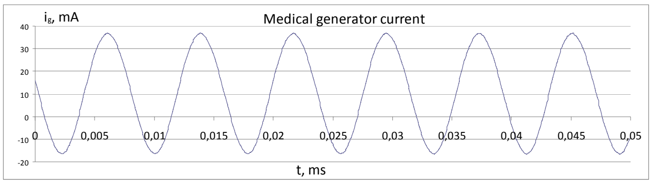

Fig. 15 Medical generator current

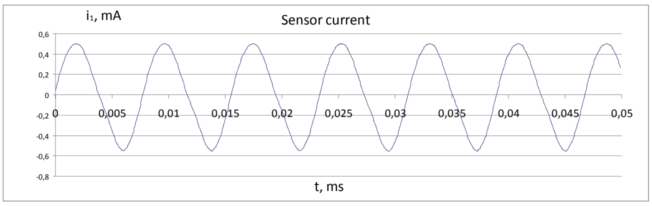

Fig. 16 Surface current on hydrożel

The waveform obtained from coil sensor measure the part of electrostimulation current, because their geometrical dimension is too small for contain all magnetic flux. Magnetic flux is generating by electrical current path between electrodes.

VIII. Application

This kind of textronic system can be used in personal rehabilitation clothing (Fig. 17), which can improve and hasten the effectiveness of patient service in the clinics.

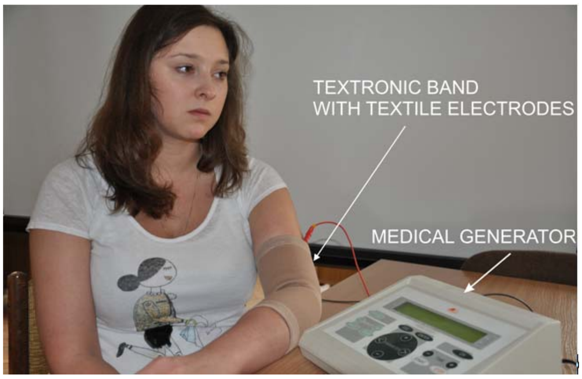

Fig. 17 The example of application of textronic system to muscles electrostimulation

IX. Conclusion

Prototype of textile electrode used in muscles electrostimulation has to be tested on a special model. This model should imitate electroconductive properties of muscles. The textile electrode requires a lot of research that enables to identify its properties. Based on research of electroconductive properties of human forearm special electroconductive hydrogels were chosen. Selected hydrogels are an important part of the forearm's phantom. The most important properties of selected hydrogels are resistance.

The average value of this quantity is 175 Ω which corresponding with resistance value on human skin. The long time test show satisfies stationary resistance parameters.

Textile materials for electrostimulation should have a good electrical conductivity.

The most important parameter, from textronic's point of view, is resistance of textile surface. There are many methods of determining the surface resistance. The useful method is four-point probe technique. However, it requires modification and needs to be adapted to the textile objects.

The identification of textile material resistance should be aware of the impact of various quantities on the measurement results. The chosen electro-conductive textile materials were used to design the prototypes of electrodes for muscles electrostimulation. Textile electrodes fit well to the shape of the treated limb. This results influence on reduction of the transition resistance between the electrode and the skin. This may affect the improvement of therapy.

Acknowledgment

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