Development of muscular tissue electrical analog and designing the device for biopotential registration

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Abstract. The development of a compatible SPICE human muscle analog and designing a device for testing the equipment and components of the electromyography signals (EMG) recording device are presented. The tools used to simulate a real EMG signal in the NI Multisim software. A muscle model has been developed, the basis of which is a linear-frequency modulating oscillator, which generates a signal with the frequency of 50–500 Hz and with the amplitude of 100 mV, which emulates the behavior of a nonsynchronous muscle signal. Muscle and nervous tissue was studied using the biopotentials oscillograms in the LabVIEW measurement systems development environment.

1. Introduction

Electrical potentials occur in all muscles and nerves of a living organism. They can be found in any living cell or organ. An elementary biological cell that produces electrical energy is a separate cell. The potential difference between the excited and unexcited parts of the cell arises in such a way that the potential of the excited part is always less than the potential of the unexcited part. There is also a biopotential between different areas of the tissue. In some cases, this difference in electrical potentials is important, and in others it is a side value for the vital activity of the organism and is a by-effect in its activity [1].

Biopotentials are not constant values and are changing depending on the physicochemical state of the cell or tissue, concentration and composition of the salt solutions contacting with them [2].

Using oscillograms of biopotentials, we can examine muscular or nervous tissue. Obviously, in this case, the potential difference is determined by the combination of the potentials of individual cells. Living cells can be roughly considered as electrical generators. Then the total potential difference, as well as the resistance of the tissue, will obviously depend on the nature of the cells connection. In some cases, the cells form series connection. The EMF produced in this case can reach several hundred millivolts [3].

2. Problem Definition

The signal from the muscle is extremely weak and its amplitude ranges from a few microvolts to 4–5 mV [4].

Usually, during the registration of biopotentials between the electrodes that lead the potential, there is not a single fiber, but the whole system (trunk) of muscle or nerve fibers, i.e. there is a parallel connection of biological generators. Therefore, the value of EMF in this case remains approximately the same as that of a single fiber, and the resistance of the source of EMF (tissue resistance) decreases. Thus, the resistance of a single centimeter of a single nerve fiber is several tens of MOhm, and the

resistance of one cm of the nerve trunk is tens of kOhm [5]. It should be noted that the voltage generated by a muscle or nerve tissue is usually significantly less than the voltage generated by a separate fiber, due to the short-circulating effect of various extracellular fluids, connective shells, etc.
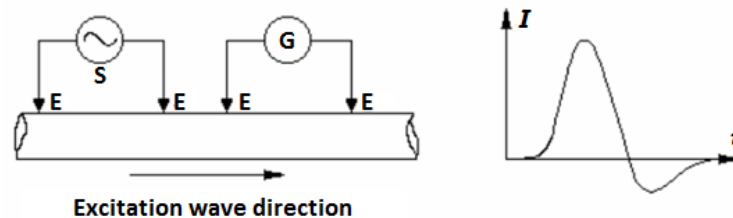

Figure 1. Scheme of muscle electrical analog and the signal $I(t)$ [3]: S — stimulant; G — galvanometer; E — electrodes

Figure 1 schematically shows the electrical excitation of the nerve fiber and the extraction of action potentials by ground electrodes. These potentials arise along the fiber during the propagation of excitation wave, accompanied by the appearance of sections with different potentials, which are recorded by a sensitive galvanometer [3]. The above method of applying electrodes to a fiber for reading biopotentials is called a bipolar or two-phase lead (this registers a two-phase action potential) [6].

In most cases, the following scheme (Figure 2) is used to register the signal with microprocessor devices: instrumental operational preamplifier with a gain of at least 100 and the main amplifier with adjustable gain, (20 times on average) [7].
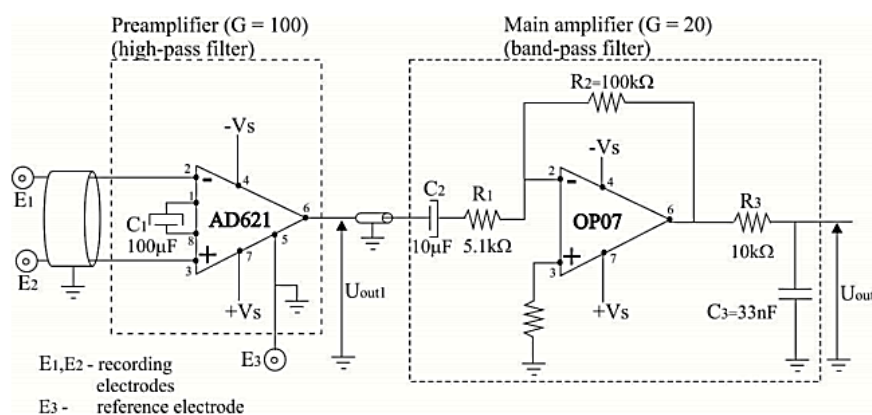

Figure 2. Instrumentation amplifier circuit

However, during reading of the EMG signal various background noise occur caused by the electronic equipment and physiological factors [8]. Therefore, the EMG signal is processed and analyzed to obtain the necessary information. In order to properly analyze the EMG signal different types of advanced technologies are used, such as wavelet transform, independent component analysis, empirical mode decomposition, and higher order statistics [9].

3. Solutions

Designing electronic equipment requires checking the existing solutions, testing the operation of circuit components, adjusting and selecting components. As it is not wise to constantly implement the circuit diagram in the form of a board, emulation software is used [10]. The most convenient and powerful tool for simulating analog circuits is NI Multisim. The latest versions of the software have improved functionality, new tools for modeling, so that the development and creation of electrical circuit designs can be performed much more accurately and quickly. NI Multisim can interact with the

LabVIEW measurement system development environment, which allows you to compare theoretical data with real data, during the creation breadboard circuits directly [11].

This reduces the number of design errors and speeds up projects implementation. The downside of this is increased system requirements for equipment. The load on the processor and memory during the work with large circuits and during tracing is very high.

Despite the fact that this and other similar software have an expanded base of elements, they lack components emulating the human body, namely, there are no tools for modeling a real EMG and ECG signals. Based on this, the purpose of this work is to develop a compatible SPICE model of a muscle for testing equipment and components of the developed EMG recording device.

4. Implementation

4.1. Creating the SPICE model

A model of an electronic device (based on the industrial standard SPICE 3F5) that emulates the work of a human muscle is created in the circuit simulation software Multisim. When creating the model, the Model Makers are used to set the parameters of the model of elementary cells of the circuit ("primitive"). Based on unit cells, a "subcircuit model" is created in the standard SPICE syntax, using the existing parts as a frame [12].

Subcircuit models are created from a set of devices that contain models of primitives, voltage and current sources, and other subcircuit models.

Every subcircuit model begins with a string, beginning with the <.SUBCKT> statement, after which goes the name of the subcircuit model <SubcircuitName> and the external nodes of the subcircuit that will be connected with other components <N1> <N2> ... <N...>. The subcircuit should end with the <.ENDS> statement [13].

A subcircuit model <TstModel> is shown in Listing 1. This subcircuit corresponds to the following diagram drawn in Multisim, shown in Figure 3. Nodes 1 and 2 are the two nodes that will be connected outside the subcircuit model. They are defined as external nodes by including them in the first line of the subcircuit model. A resistor, a capacitor, and a diode are all primitives. The only parameters defined for the resistor and capacitor are their values, but the diode has additional parameters defined by using the <.MODEL> statement.

Listing 1. Simple SPICE model of a diode limiter
```
1. .SUBCKT TstModel 1 2
2. dD1 0 2 1BH62__DIODE__1
3. cC1 0 2 1e-006
4. rR2 1 0 3000
5. rR1 1 2 1000
6. .MODEL    1BH62__DIODE__1 D
7. + IS=5.950e-006 N=4.031e+000 RS=2.677e-002
8. + BV=1.200e+002
9. + EG=1.110e+000 XTI=3.000e+000 TT=5.760e-007
10. + FC=5.000e-001 KF=0.000e+000 AF=1.000e+000
11. .ENDS TstModel
```
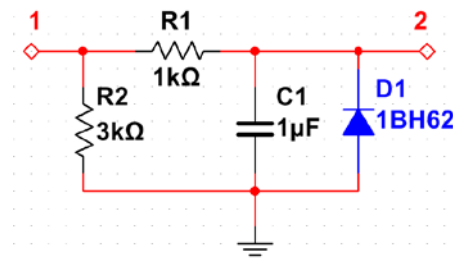
Figure 3. Electrical circuit of a diode limiter model

For research and modeling the information was obtained on the EMG signal using medical equipment designed for these purposes [14]. This device is a 2-channel electroneuromyograph (Figure 4a) with a built-in keyboard that includes:

- 2 channels are optimized for quick testing of motor and sensory conducting and needle EMG
- portable (can work with a laptop)
- "all in one": stimulants, recording channels, control, display
- high quality recording: quantization frequency of up to 100 kHz
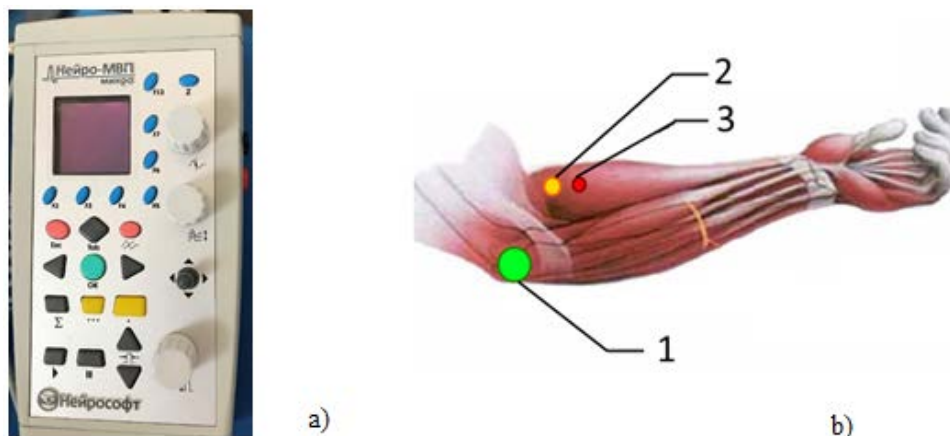- current stimulator for two outputs with ultrafast switching.

Figure 4. Biopotential reading: a) signals recorder [14]; b) leads connection

During the experiment on the reading a signal from one muscle (Figure 4b), it was found that the signal from the muscle can be obtained most stably in some positions of the arm: relaxed hand — the signal is practically not recorded; clenched fist — the signal with a variable frequency of 100 up to 500 Hz (mild clench — amplitude of 1–2 mV, while undoing the fist —increased amplitude).

4.2. Development of a muscle model
The basis of the model is a linear-frequency modulating oscillator, which generates a signal with a frequency of 50–500 Hz with an amplitude of 100 mV that emulates the behavior of a muscular asynchronous signal [15]. To obtain two potential antiphase signals, an inverting amplifier with the gain of 1 and a non-inverting repeater are installed to create the same signal delay.

Resistors R7-R8 represent the resistance of the skin of the test-subject. On the resistors R9-R14 the division factors of 1:1 are created to test the signal, 1:10 for the most tense muscle that is resisted, 1:15 for the most tense muscle that is not resisted, 1:20 for weakly tense equivalent to the contraction of antagonist muscle, 1:50 for relaxed muscle and interferences.
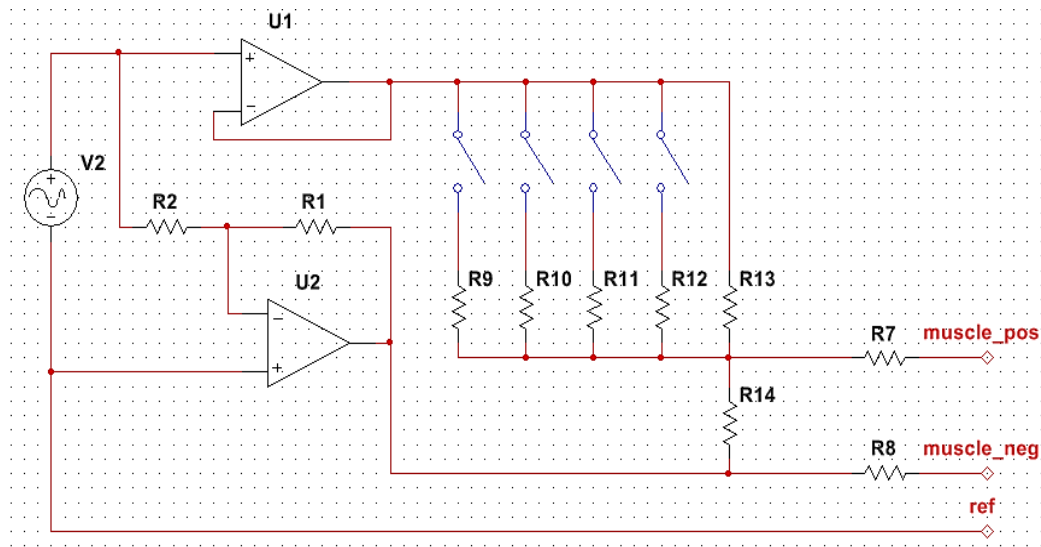
Figure 5. The developed circuit of the model

Based on this circuit, the PCSPICE muscle model was developed. A part of the model is shown in the Listing 2.

Listing 2. A fragment of the developed model

1. .SUBCKT MUSCLEMODEL ContDeb ContMax ContMid ContLow GND muscle_pos ref muscle_neg
2. …
3. S1 signal_sorce_pos divider ContDeb GND sw1
4. S2 signal_sorce_pos divider ContMax GND sw2
5. S3 signal_sorce_pos divider ContMid GND sw3
6. S4 signal_sorce_pos divider ContLow GND sw4
7. .model sw1 vswitch(Ron=1p Roff=1G Von=3.3 Voff=0.5)
8. .model sw2 vswitch(Ron=9k Roff=1G Von=3.3 Voff=0.5)
9. .model sw3 vswitch(Ron=14k Roff=1G Von=3.3 Voff=0.5)
10. .model sw4 vswitch(Ron=19k Roff=1G Von=3.3 Voff=0.5)
11. rR5 signal_sorce_pos divider 49000
12. rR10 signal_sorce_neg muscle_neg 10000
13. rR9 muscle_pos divider 10000
14. rR8 ref signal_sorce_neg 1000000
15. rR7 divider ref 1000000
16. rR6 divider signal_sorce_neg 1000
17. …
18. .ENDS

At the beginning of the model, the input and output signals of the ContDeb ContMax ContMid ContLow module are described — inputs for connecting buttons or control devices, GND — common wire for signal input, muscle_pos ref muscle_neg — output signals from the "muscle". Further, lines 3–6 describe the connection of buttons and control circuit. Lines 7–10 indicate the parameters of the buttons and the conditions for changing their state in the model properties. Lines 11–16 describe the remainder of the dividers on the resistors and the output connections.

Next, you need to embed this model into the libraries of Multisim environment. To do this, you should open the model configuration wizard in the toolbar. During the work, the environment will offer to name the model, enter the number of contacts, enter symbol and connect and configure the model itself [12].
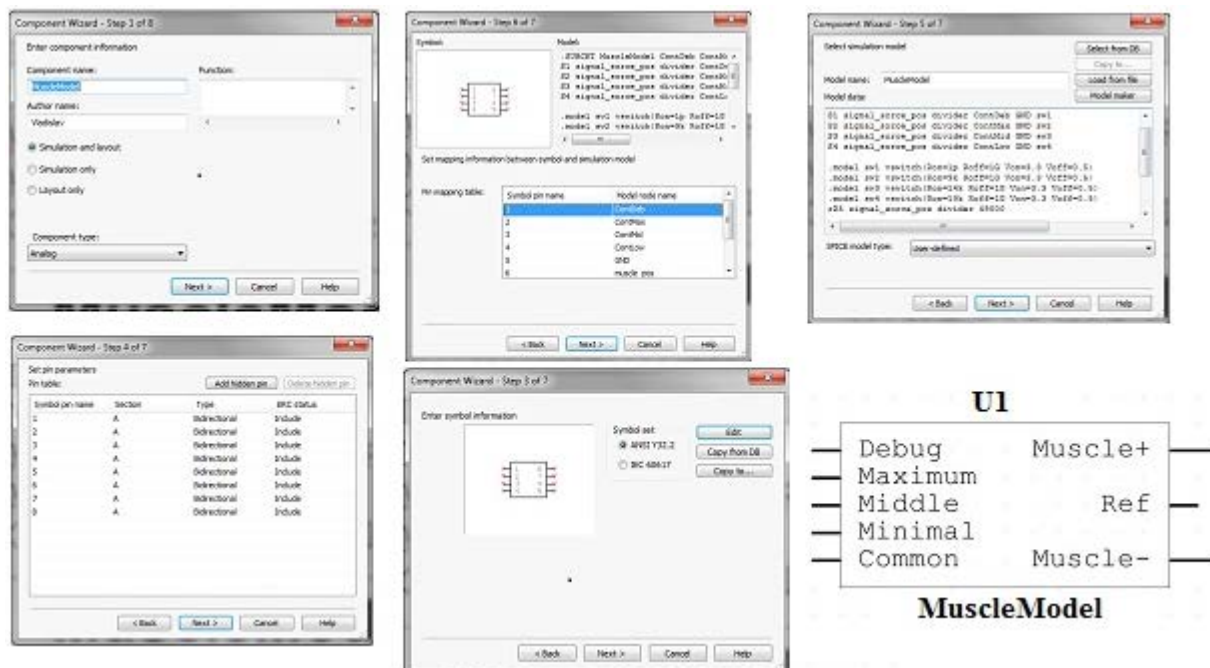
Figure 6. Model configuration wizard and the model in Multisim environment

5. Experiment

5.1. Testing the model. Configuring the circuit for the EMG device

After the model implementation, it is possible to proceed to the development of the simplest concept of an EMG, on the basis of which one could evaluate the performance of the model and the values it produces (Figure 7).
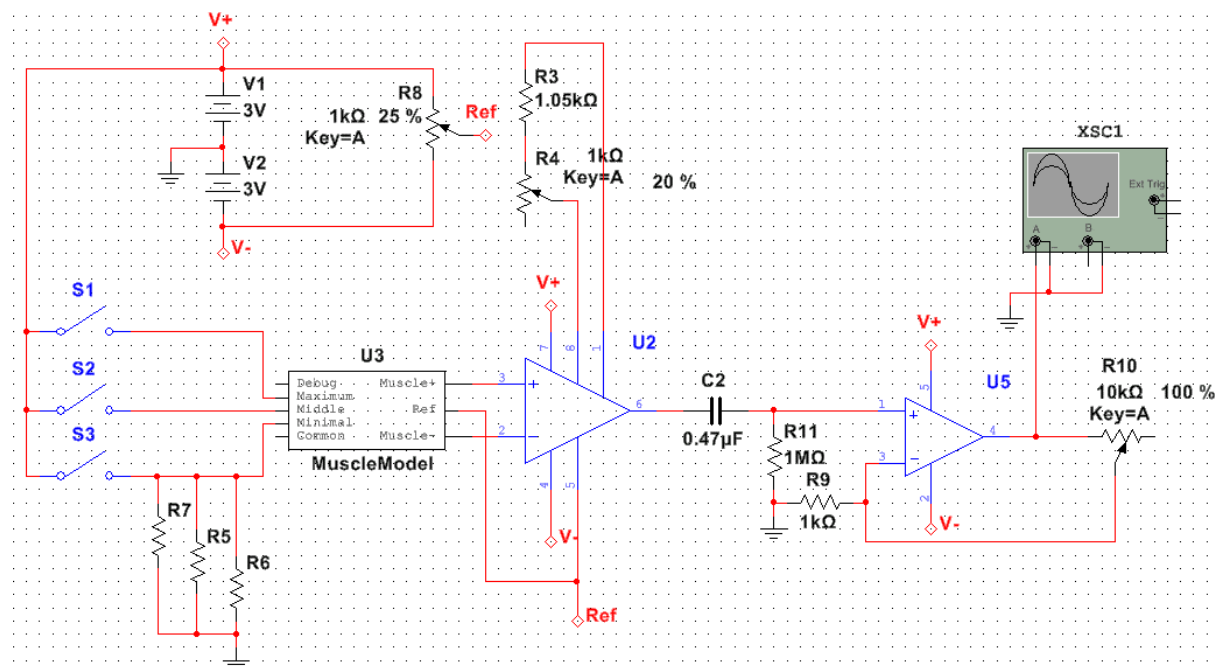
Figure 7. The circuit of EMG recorder in Multisim

In the center of the circuit there is a MuscleModel muscle model, to the inputs of which the switches are connected and connected to the common wire. When the state changes from low to high, the mode is switched and the signal is output to the **Muscle +** and **Muscle –** contacts. This signal is amplified by an instrumental operational amplifier and is transmitted to a scaling amplifier, the signal from which comes to the XSC1 oscilloscope [16]. The received signal is shown in Figure 8.
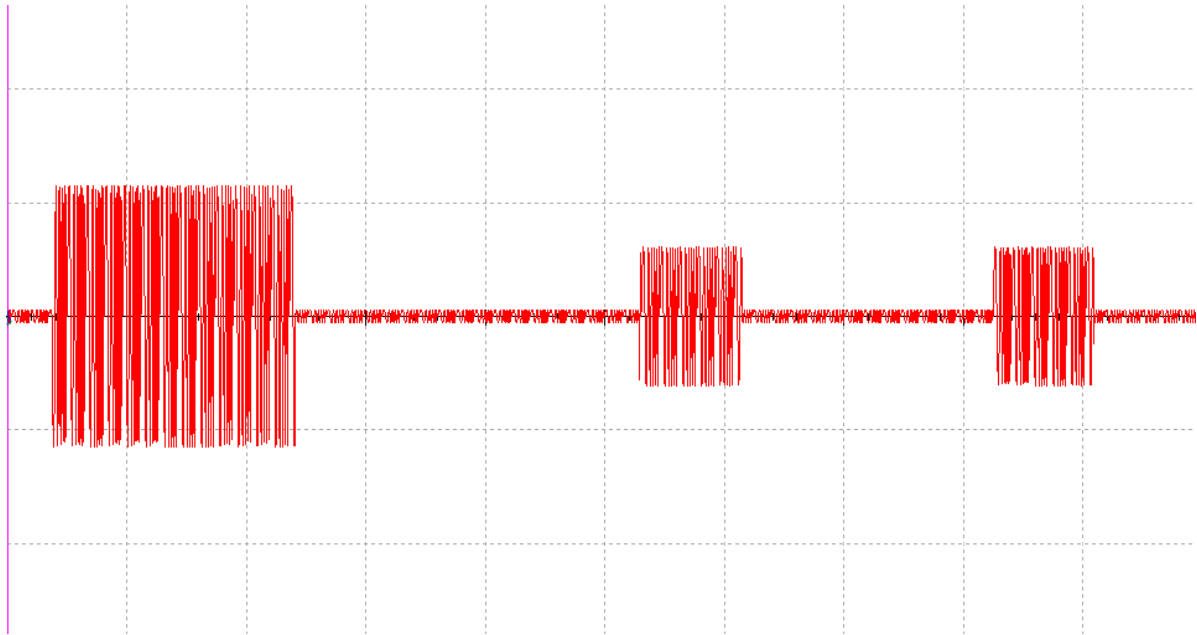

Figure 8. Data from the Multisim oscillograph. Vertical sweep of 1 V/point, horizontal sweep of 200 ms/point

The Multisim software is a link in the NI's end-to-end design system and has the interface to LabView NI. A series of measurements of EMG signals is carried out against the noise. In the LabView software environment a virtual device for visual observation of test signals is developed. Further processing of the real EMG signals was carried out using the NI hardware and software [17]. The front panel of the virtual device (Fig. 9) shows the waveforms of the signals from the registration device and the setup window of the interface part.
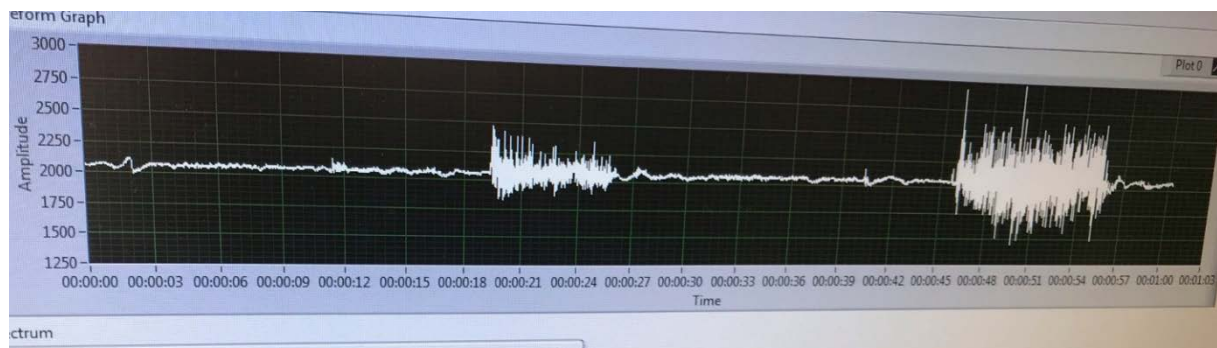

Figure 9. Data from real device

6. Conclusion

In the course of this work, an electrical model of human muscle and a device for testing equipment and components of a EMG recording device were created. During the development, the tools for simulating the real EMG, ECG signals were used in the NI Multisim software.

The SPICE model developed can be implemented in other modern electrical circuit modeling environments that support the SPICE standard. The model has controlled inputs and allows assessing the performance of designed mobile electronics, in particular the muscle signal recorders for bionic prostheses.

The device model in Multisim couples with NI LabView software and hardware. In the LabView software environment, a virtual device is built for visual observation of the EMG test signals.

The SPICE model can be used during designing the manipulator devices for industrial and bionic robots. The SPICE model has an open source code and the possibility for development with the addition of noise from external sources, random noise from the work of muscle fibers, etc.

7. References

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