The smart prosthesis as the personal agent in the amputee tactile perception process

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Abstract. This article describes the research phase aimed at the creation the sensorized smart prosthesis system to transradial amputees. The main focus of the article is on obtaining vibration frequency and amplitude that are individuality to user and which arise with the application of Force Sensing Resistors (FSRs). These sensors act as the artificial tactile mechanoreceptors. The micro vibrating motors incorporated in vibro-bracelet placed on the upper arm is used to transmit the sensation of grip force to an amputee. The signal transmission is provided by Bluetooth technology. Arduino was used as the tool for research work.

Introduction

Upper limb noninvasive myoelectrical prosthesis are demand around the world and offer the decent level of rehabilitation available today. Despite advances in microsurgery the prostheses created using the connection residual sensory nerve fibers with microelectrode arrays still remain in the stage of risky experiments and their widespread usability is a matter of the future. The success of these experiments relies on electrodes which are in contact with the neural tissue. Meanwhile state of the art myoelectric prosthesis is high effective unit that allows users a larger adaptability to different tasks.

The main disadvantage this prostheses type is the lack of tactile feedback. Thanks to the microelectronics achievements this problem is solving [1], [2], [3].

Practice shows that the best way to mimic a feeling of human touch is the sensors use. However, the sensors cannot operate independently. For their full-fledged work, is required a system, the final element of which is a device that allows the amputee to transmit sensations of interaction with the surrounding environment. Microvibration motor (or tactor) become such an element.

As a result of evolutionary transformations, the myoelectric prosthesis has acquired a chain of characteristics: sensory, mechatronic, vibrotactile. But these made it possible to implement tactile feedback is lacking in early myoelectric prostheses. Moreover, the vibrotactile feedback (VTF) stimulation take on individual parameters depend upon the user-amputee physical cognitive and affective characteristics.

The combination of technological features with user needs on microprocessors base made it possible to characterize these devices as smart prostheses.

1. The smart prosthesis role in amputee rehabilitation

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At some point in the study of sensors with the capabilities of high-quality information transfer to the amputee about the nature of his via prosthetic contact with the environment, the term “sensing” began to be used in the scientific papers. It is clear that the for object of research does not always find an adequate characteristic concerning its properties. In addition, a man-made device that imitates a product of living nature, when it reaches similarity, is often described either in terms with the addition of “artificial” or with the use of those verbal characteristics that previously belonged to live matter. The same happened with the term and ultimately with the concept of sensing.

No matter how perfect the prosthesis of the upper limb or its part is, it’s still a rehabilitation tool – kind an agent - in the process of human perception. We have a deal with the problem connecting live with not live, organic with not organic in prosthetics in our research. Something the same is in robotics, with the difference that there is the contact the artificial antropomorphic object with man, not inextricable link with him like in the area of concern to us [4], [5].

Our research is aimed at the rehabilitation of people who have lost one of their hands. Their peculiarity is that they can return to work after successful prosthesis fitting. This distinguishes mentioned category from those who suffered more serious injuries and lost, for example, both upper limbs. In this case, other agents (rehabilitation systems) are applicable, in particular the use of the Inductive Tongue Control System [6].

Therefore, it is very hard to endow with the sense the technical rehabilitation aids (TRAs). It is a conventional term for artificial organs and processes connected with the physical, mental and emotional human spheres. So, it would be better to use the term “sensing” in the system 'prosthesis – person’.

The term “sense organs” is not an exception meaning - a specialized peripheral anatomical and physiological system, which, thanks to its receptors, ensures the receipt and primary analysis of information about the condition of the body’s external and internal environment. Receptors are the primary link here. Earlier we have already dwelt on the role of various skin receptors kinds responsible for touch [7]. In turn, touch is habitually regarded as a set of sensations born in the cerebral cortex, which are a subjective reflection of objective reality. In the context of the present research we are interested in the sensations of vibration and pressure, for which the receptors named the Vater-Pacinian corpuscles are responsible.

Today in prosthetics the compensatory principle is implanting high-precision sensors into an artificial hand and efforts to replace the skin receptors with these sensors. Thus, sensors that can create a sense of pressure and / or vibration in an amputee are quasi receptors. Therefore, we can name the integration prosthesis with sensors that provide an amputee the sensations as sensorization.

2. Sensorization type as the smart prosthesis R&D base
Solving the problems related to the hand prosthesis sensorization, two interrelated directions in the world practice should be taken into account. The first trend concerns the reception and transmission of a signal of grip force (compression), as well as its differentiation. The force sensors are responsible for this process. In a number of sources these sensors are referred to as press sensors. The second one is related to touch, in transmission characteristics of which the touch sensors are involved. Some sources name it contact sensors.

According to the latest publications, for a certain number of sensorized prostheses developers, the topic of touching within the concept of an amputee quality of life has high priority. The psycho-emotional state of a person who has lost a hand is considered by them as the dominant factor of project activity [8].

In order to increase the “sensitivity” of sensors, on the one hand, and to combine touch and pressure devices, on the other, developers are searching for structures and materials that can respond to stimuli with an effect as close to the skin receptors as possible. Particularly intensive work is underway to create artificial skin and electronic skin (e-skin) [9], [10], [11], [12].

Despite the researches intensification it should be noted that most of them are far from practical application type. Meanwhile the urgent need for high-quality prosthesis presupposes the search for
structures and technologies, the innovative nature of which does not prevent their production. In this regard the smart prosthesis developed by MERI of RAS team can be described as novel, simple, cost-effective and user-friendly due to an integrated approach to the experimental part of the study.

3. Individualization through vibrotactile stimulation method

It is known that the generator potential (depolarization) can be detected in the unmyelinated ending of the Vater-Pacinian corpuscle when it is compressed. This results in short burst of impulses in the sensory fibre, which adapts in 1 - 2 seconds to zero or very low frequency. According to modern concepts, the main function of Pacinian corpuscles in the skin is vibration detection. The frequency of vibrations to which they respond are in the range of 70 - 1000 Hz. They are most sensitive in the middle of the range of 200-400 Hz, where skin deformation of only 1 μm is a sufficient stimulus.

Our skin contains two types of receptors that allow to feel the vibration. These are the tactile bodies of Meisner, "specializing" in slow vibrations, and the already mentioned Vater-Pacinian corpuscles which are responsible for determining high-frequency vibrations. Most smartphones vibrate at a frequency of 130-180 Hz, which falls on the range between the sensitivity peaks of these two types of receptors. This is probably why smartphones vibrate calls to use both types of receptors. But some think that the Pacinian corpuscles take a greater part in the formation of the sensation of vibration.

For our experiment to give a sensation of touch in the “hand prosthesis - amputee” system and to replace Pacinian corpuscles that are found in the glabrous skin of the fingertips a Force Sensing Resistors (FSRs) were chosen. The principle of the FSR is to change the resistance value depending on how much pressure is being applied to the active area. The more force applied, the less resistance from the FSR. Figure 3 shows the construction of the FSR.

![Figure 1. FSR Construction](image)

For a simple force-to-voltage conversion, the FSR device is tied to a measuring resistor in a voltage divider (Figure 2(a)). The output to this setup can be described with the following equation:

\[ V_{\text{out}} = \frac{R_m V_s}{(R_m + R_{FSR})} \]

In the equation \( R_m \), \( R_{FSR} \) values represent the resistances of the measuring resistor RM and FSR, respectively. \( V_{out} \) is the voltage outputted from the sensor, \( V_s \) is the voltage inputted to the FSR.

The measuring resistor, RM, is chosen to obtain the desired sensitivity range for the force under current limiting. Depending on the impedance requirements of the measuring circuit, the voltage divider may be supplemented with an operational amplifier. The output FSRs voltage changes proportional to the applied force magnitude: it increases with increasing force and decreases with decreasing force (Figure 2(b)).
In our experiment a 10 kΩ measuring resistor was selected for the voltage divider. At the same time FSRs reliably work in the range from 20 grams to 800 grams.

To implement a sure grip of an object with a prosthetic hand, an amputee must use at least three fingers (thumb, index and middle). Based on this, and also with the aim of minimizing the amputee efforts on the perception of information from FSRs, a sensor system of three FSRs has been adopted. Thus, to improve the functionality of a hand prosthesis in three artificial fingers we incorporated FSRs to sense the touch of the object and detect the grip force the amputee hand.

The FSRs placement on the myoelectric prosthetic hand is presented in Figure 3.

![Figure 3. FSRs location](image)

The information from each FSR is transmitted via Bluetooth to the microprocessor installed in the prosthetic socket, encoded and then transmitted via the Bluetooth microcontroller to the vibrating devices placed into the vibro-bracelet on the upper arm (Figure 4).

![Figure 4. The Vibration bracelet](image)

Vibro-bracelet includes three vibrating motors, a microprocessor, a microcontroller with Bluetooth and a power source. The coded signals from the sensor system through vibration motors are transmit-
ted to the mechanoreceptors of the patient’s upper arm skin to create amputee sense of contact with the object. Each finger corresponds to a separate vibration motor.

The used vibration motors operate at a nominal voltage of 5v and a current of 40mA in accordance with the Arduino Nano microcontroller PWM ports specification. The PWM signal is calibrated programmatically so that when a maximum force is applied to the sensor, the increasing duty cycle does not exceed the 100% threshold, where the pulse width is 2 ms.

The results of the studies are shown in Figures 7-8. Figure 7 shows the minimum average values of the $V_{out}$ voltage and the nominal current $I_{vibra}$ of the vibrating motor that the amputee confidently distinguish as the different in value vibration signals.

![Figure 5](image)

**Figure 5.** Dependence of average values FSR $V_{out}$ voltage and nominal current of the $I_{vibra}$ vibrating motor.

Figure 6 illustrates the dependence of the voltage $V_{vibra}$ on the vibration motor in the forces range from 20 to 300 grams.

![Figure 6](image)

**Figure 6.** The vibromotor voltage in force range from 20 to 300 grams.

Our experiment performed on the created test complex the elements of which (Figure 7) allows to identify all the features of the signal received from the prosthesis interaction with a stimulus. Depend on the applied force to the resistive sensors located on the finger tips, the corresponding PWM signals transmit to the individual vibration motor. Thus, every time when a force is applied the vibration motor acts on the upper arm area receptors and this signal will decoded then by amputee. The aim is to adapt optimally the signal for the amputee, who would realize the grip force degree without being overloaded physically and psychologically.
Figure 7. 1, 2 - Arduino microcontroller; 3 - Bluetooth (master); 4 - Bluetooth (slave); 5, 6 - Force Sensing Resistors (type 1, type 2); 7 - vibrating motors; 8 - power supply

Note that microcontrollers Arduino receive analogue signals from external sources and convert it to digital ones through the general-purpose input/output (GPIO) ports. The microcontroller ports are designed to work with logical zero and logical unit levels and allow digitize analog signals with level limitation and generate various shapes signals using PWM and a low-pass filter. For digitizing the vibration signal is using the ADC.

In future, it is assumed that microelectromechanical systems (MEMS), including microcontrollers and sensors will be used for the sample being introduced into production for the microminiaturization of the component base.

4. Conclusions
Our research in sensorization and vibrotactile stimulation areas will be ongoing. The individualization noninvasive myoelectric prosthetic hand is our aim. We believe that amputee comfort is the main criterion for the prosthesis. Therefore, we used the Bluetooth technology in a way that had not previously been used in feedback experiments by other teams. We also designed the spiral bracelet instead of the usual cuff which allows to embed the vibration system into it more efficiently.

Not only hardware and software but the advances in higher amount of user training allow bringing this safe and economic devices to amputee for fulfilling communications with real world. We aware that the hand smart prosthesis creation necessitates interdisciplinary cooperation, close interaction with potential users of these devices and coordinating various social institutions involved in the development of prosthetics [13].

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