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DESIGN OF THE ENDOSKELETON OF A BIOCONTROLLED HAND PROSTHESIS

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Abstract. *The article analyzes the constructions of biocontrolled prostheses that are common today on the market of prosthetic equipment, in particular the i-Limb, «Michelangelo hand» and Bebionic prostheses. It is shown that these constructions use hollow shell models of the phalanges of the fingers and the palm, which together form the exoskeleton of the prosthesis construction. This type of design is characterized by the complexity of manufacturing, and accordingly, the cost, and the irrational use of volume, since traction elements, gear elements or other elements are placed inside these hollow elements, which ensure the transmission of forces when performing bending movements of such fingers. The article proposes the use of the endoskeleton as a support base for fixing electric drives and control elements. At the same time, the structure is a group of hingedly connected elements and rods for the transmission of forces, in which simultaneous bending is ensured in all hinged joints, and the form of the performed movements is close to natural. At the same time, the volume of the finger elements is more rationally used in the proposed design, as it becomes possible to fix out external nozzles of elastomeric materials on the structure rod, which will repeat the shape of real fingers, will be soft for reliable holding of objects when performing grip movements. At the same time, it becomes possible to install sensors in such elastomeric elements to provide tactile sensations. As a result of the research, 3-D models of all prosthesis endoskeleton elements were developed and they were manufactured by 3-D printing. At the prototyping stage, bipolar stepper motors controlled by the Arduino Uno module were used as electric drives to evaluate the trajectories of the performed movements. It is shown that it becomes possible to increase the functionality due to the installation of sensors to provide tactile sensations It was established that the number of performed movements is practically the same as that of analogues, and the cost of the proposed design is much lower. At the same time, reliability is higher due to the use of a much smaller number of structural elements and their connections.*

Key words: *prosthesis, endoskeleton, bioprosthetics, hinged connection.*

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1. INTRODUCTION

An urgent task today in the field of medical device construction is the development of highly functional prostheses and orthoses for people, in particular those who have received injuries or disabilities as a result of the military aggression of the Russian Federation against Ukraine, etc., which is additionally declared in the resolution of the Cabinet of Ministers of Ukraine dated October 1, 2014 No. 518 (additionly No. 454 of April 12, 2022) [1]. However, despite the rapid development of the prosthetics industry in Ukraine, the problem of creating one's own highly functional biocontrolled hand prostheses remains.

This is often the result of the need to simultaneously and comprehensively solve a number of tasks that relate to various fields of science and technology and require the involvement of relevant highly qualified specialists. Thus, the main tasks, the complex solution of which will make it possible to develop a highly functional bio-controlled hand prosthesis, are the choice of the prosthesis moving elements design, the optimal drive of the rosthesis moving elements, provision of tactile sensations of the prosthesis elements, the method of biosignals selection and processing of the hand part that remained after amputation and ensuring

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the possibility changeability of the prosthesis individual elements when they are damaged, in particular individual fingers.

In the paper, the design of the hand prosthesis moving elements is developed by using the principles of the functioning of the endoskeleton of a real hand.

2. ANALYSIS OF THE RESULTS OF EXISTING RESEARCH

Prosthetics refers to the replacement of lost or irreversibly damaged body parts with artificial substitutes – prostheses [2]. Prosthetics is an important stage of the process of social and labor rehabilitation of a person who has lost limbs or suffers from diseases of the musculoskeletal system.

The task of bioprosthetics of the lower and upper limbs, which have been lost or damaged due to injuries or diseases, is solved by using simpler solutions. Some solutions consist in the aesthetic restoration of the limb appearance, others consist in the restoration of certain lost or impaired functions.

Active bioprostheses, which function on the basis of the use of additional external types of energy to repeat lost functions, include myotonic, traction, and biocontrolled prostheses [3–6].

The most functional in terms of the number of elementary movements provided and the restoration of the functions of the lost limb are the so-called bionic or biocontrolled prostheses, the functioning of which is ensured by the formation of control signals for the prosthesis executive elements based on the results of the selection and processing of residual signals of muscle activity of the truncated hand part.

In recent years, there has been a significant development of active prostheses biocontrol methods, which is a consequence of achievements in the field of electrophysiology, biomechanics, microelectronics, and adaptive control systems with feedback [4–6].

In a living organism, control signals are transmitted to muscles with the help of bioelectric impulses that reflect the commands of the central nervous system. Similarly, in a hand prosthesis with bioelectric control, the role of command signals is performed by biocurrents diverted from the truncated muscles of the stump. The mechanism that executes the commands is an artificial mechanical hand, which is equipped with one or more small electric actuators with autonomous power supply.

However, there are practically no domestically produced highly functional bio-controlled hand prostheses on the market of prosthetic equipment (as of 2020, only 58 enterprises produced prostheses in Ukraine, and only 6 of them produced highly functional prostheses). This is due to the difficulty of providing the necessary number of prosthesis individual movements, which is determined by selection means and processing methods of amputated limb residual muscle activity biosignals. As for foreign analogues, they are high of cost and involve the prostheses installation, adjustment and further maintenance exclusively abroad.

The most functional today is the group of biocontrolled prostheses of «Touch Bionics» (Great Britain) [6]. I-Limb model prostheses (Fig. 1) make it possible to perform a huge number of everyday tasks due to a significant number of performed elementary movements of the prosthesis components. Using a special mobile application, the prosthesis can be customized specifically for your body and type of activity, that is, you can train yourself to control the prosthesis.

Next in terms of functionality are Bebionic prostheses (Fig. 2), which are a group of biocontrolled prostheses with an electromechanical drive and microprocessor control and control of the performed movements. The last of this series is the Bebionic 3 prosthesis [6, 7]. It provides 14 different grip types and hand positions.

Biocontrolled prosthesis «Michelangelo hand» (Fig. 3) of the new generation, created in Germany, is unique in its nature and functional capabilities [7]. Prosthesis «Michelangelo hand» perceives the signals of neurons in the brain. The prosthesis is made of various metals, alloys and plastic, and the fingers repeat the structure of a human hand and move like real ones [7].

The disadvantage of the considered bioprosteses structures is the use of shell models of the fingers phalanges and the palm. Such models are hollow, inside which additional drive elements are placed, which greatly complicates the design of the prosthesis and makes it less reliable. In addition, in such structures it is practically impossible to make the fingers removable, so that in case of damage they can be replaced, instead of sending the entire hand prosthesis for service or repair. Another disadvantage is the inefficient use of the fingers phalanges volume, inside which sensors could be placed to realize the possibility of providing tactile sensations in the prosthesis.

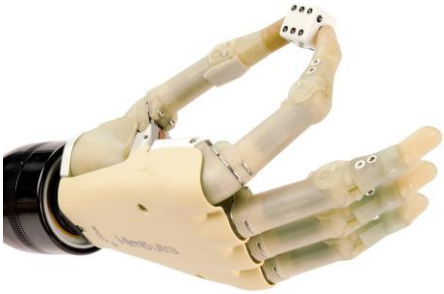


Figure 1. Appearance of the i-Limb prosthesis [6, 7]

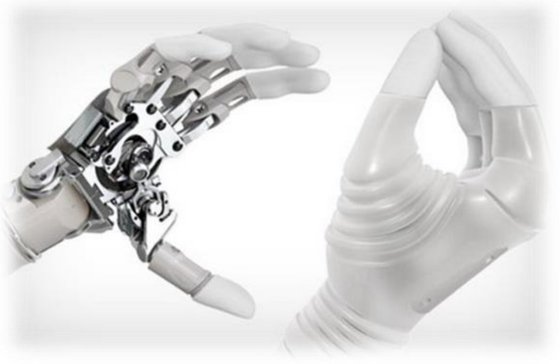


Figure 2. Appearance of the «Michelangelo hand» prosthesis [6, 7].

Figure 3. Appearance of the Bebionic prosthesis [6, 7].

In contrast to known designs, it is proposed to use a design that would be close to the natural structure of the real hand. It is proposed to use an endoskeleton as the basis of the prosthesis, to which elements of the implementation of tactile sensations could be attached. In general, the endoskeleton is a mechanism that provides support, movement, and form due to the internal framework. An example of an endoskeleton is the bone system of animals and humans. In this case, it is possible to place silicone inserts on the «bones» of the phalanges of the fingers, which would be soft and give the prosthesis an aesthetic and natural appearance, and also inside of these inserts it would be possible to place pressure transducers and realize tactile sensations. In addition, such a prosthesis would be much lighter, would have a smaller number of elements and connections, and it would be possible to implement the possibility of quick and simple replacement of individual fingers in case of damage.

The Objective of the paper is the development of the prosthesis design that would be close to the natural structure of the real hand. It is proposed to use an endoskeleton as the basis of the prosthesis, to which elements of the implementation of tactile sensations could be attached.

3. RESEARCH RESULTS

The work proposes to develop an endoskeleton of a biocontrolled prosthesis that would function according to the principle of the human hand skeleton. In Fig. 4 and Fig. 5 shows the image of the bones and the actual hand. These two images were used to determine the basic geometric dimensions for designing the prosthesis exoskeleton. So, the size of the palm bones, thumb and index finger were used as a basis. To do this, these images were loaded into a software environment for the execution of technical drawings. In Fig. 5 shows the loaded image of the hand with the parameters of the palm (positions 4 and 5) and fingers (positions 1–3) circled to the specified dimensions. The element of the palm itself is circled without taking into account soft tissues, so the dimensions are smaller than the dimensions of a real palm.

Figure 4. Image of the hand bones

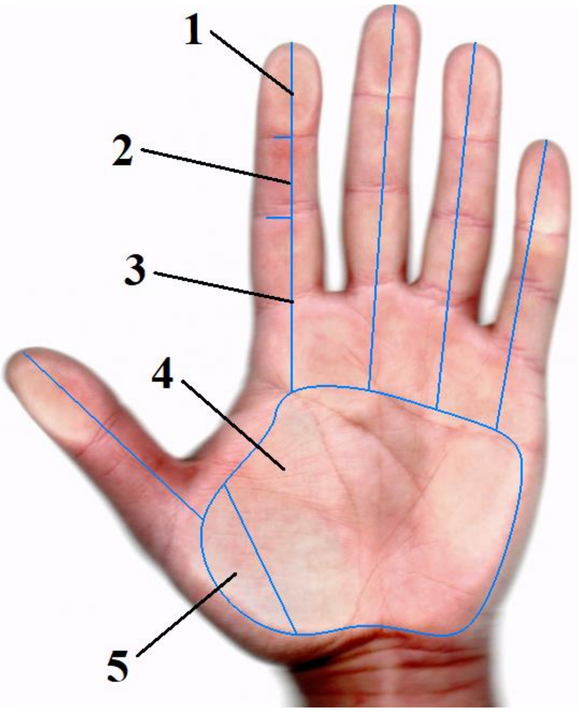


Figure 5. View of the loaded hand image with the parameters of the palm and fingers

Position 5 indicates a separate element of the palm, which ensures the removal of the thumb.

First, the structure of the index finger was designed, which would include a series of hinged elements that would correspond to the individual phalanges of the real finger, and elements that would transmit forces to these phalanges during flexion and extension of the finger. As a result of the analysis of the design of known hand prostheses, it was proposed to develop a design that would ensure simultaneous bending in all hinge joints of all finger phalanges, but when bending in individual hinge joints, individual phalanges would repeat the movement trajectory of the corresponding phalanges of a real index finger.

So, in Fig. 6 shows a simplified schematic representation of the index finger.

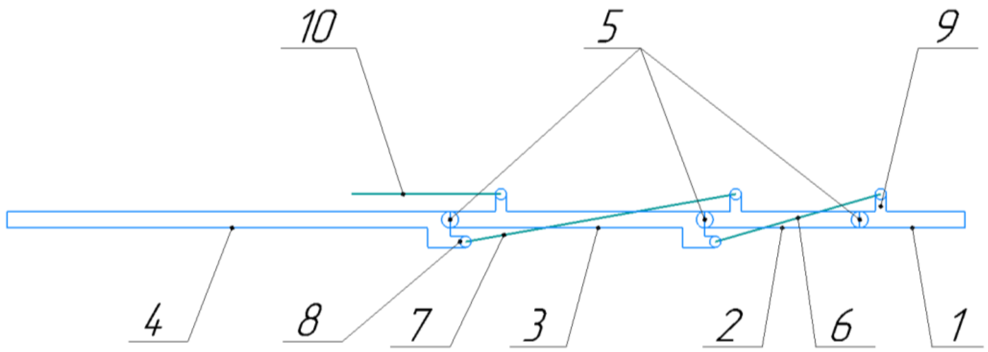


Figure 6. Simplified schematic representation of the index finger

According to Fig. 6, positions 1–3 indicate the phalanges of the finger, and position 4-the element of the palm – the base. All phalanges (1–3) are connected to each other and to the element of the palm with the help of hinge joints 5. Efforts are transmitted to each subsequent element of the phalanx from the previous one with the help of rods 6 and 7. They are also connected to the elements of the phalanx using hinged joints. Each element has protrusions 8 and 9 to which rods 6 and 7 are attached. Rod 10 is connected on one side to the protrusion of element 3, and on the other side to the element of the electric drive (not shown in the figure). Thus, when moving the rod 10 to the left in the horizontal plane, as shown in Fig. 6, the design of such a finger will begin to bend in the first hinge joint. At the same time, the rod will turn on one side in the hinged joint on the palm element, and on the other side will create a pulling force on the protrusion of element 2, causing it to turn in the corresponding hinged joint. This will occur due to the presence of corresponding protrusions 8 and 9 on the phalanx elements and the misalignment of the hinge joints of the rods with the actual hinge joints of the elements 3 and 4. Similarly, through the rod 6, a pulling force will be created on the element 1. Accordingly, when the rod 10 is moved to the left and to the right, flexion and extension of the finger will occur simultaneously in all hinge joints.

It is important to provide the designed finger structure with such geometric parameters that, in the final case, the finger bends and unfolds identically or as close as possible to the bending and unfolding of a real finger. The dimensions of the individual phalanges elements are taken from the image of a real human hand.

At the next stage, the dimensions of the structural elements were reduced to the selected and measured dimensions. The view of the resulting structure in the extended state is shown in Fig. 7.

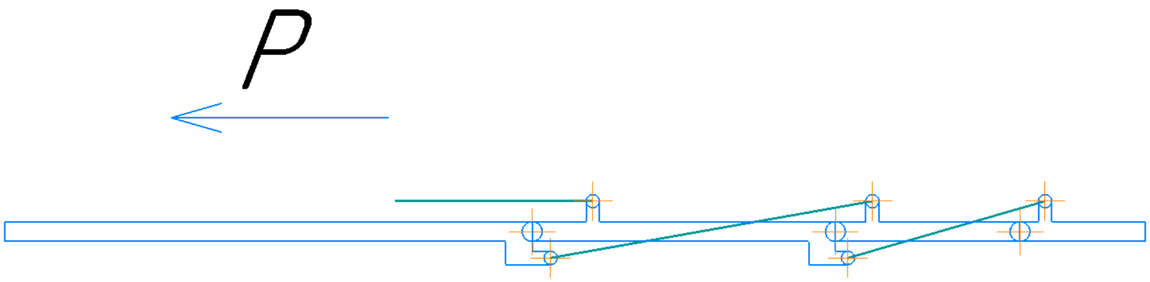


Figure 7. Projected design of the finger in the extended state

Further, the movement of individual elements of the proposed design was evaluated when the element of the finger first phalanx in the hinge joint was moved relative to the palm element by 45^0 (Fig. 8).

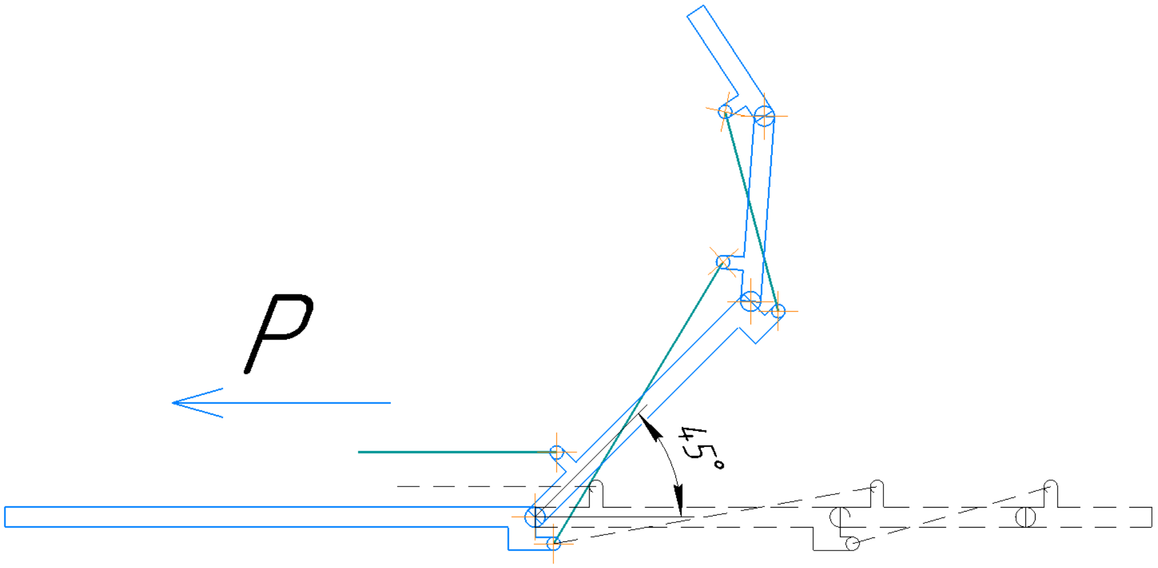


Figure 8. Movement of the finger elements when bending the first phalanx at 45^0

As can be seen from fig. 8, there is a simultaneous movement of all design elements in the corresponding hinge joints. In fig. 9 shows the movement of individual design elements when the element of the finger first phalanx in the hinged joint is moved relative to the palm element by 90^0.

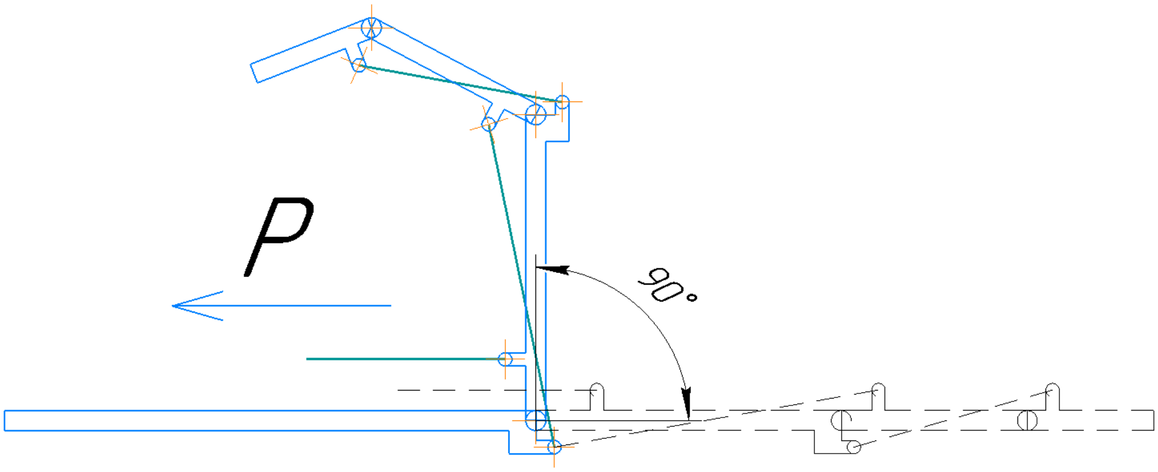


Figure 9. Movement of the finger elements when bending the first phalanx to 90^0

After observing the movements of the real finger phalanges and the one shown in Fig. 9 may be made the next conclusions. When bending the first phalanx relative to the palm of the real finger by 90^0, the α angle (Fig. 10) should be sharp ($75–85^0$), and the β angle should be obtuse ($115–125^0$).

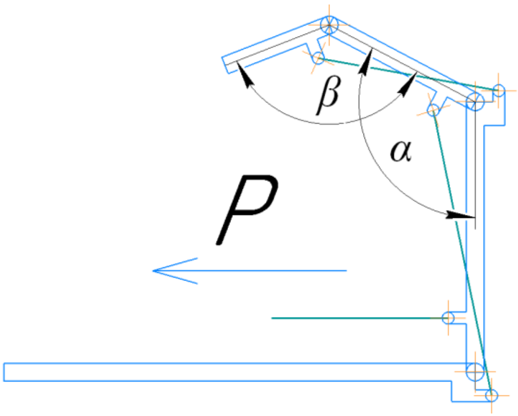
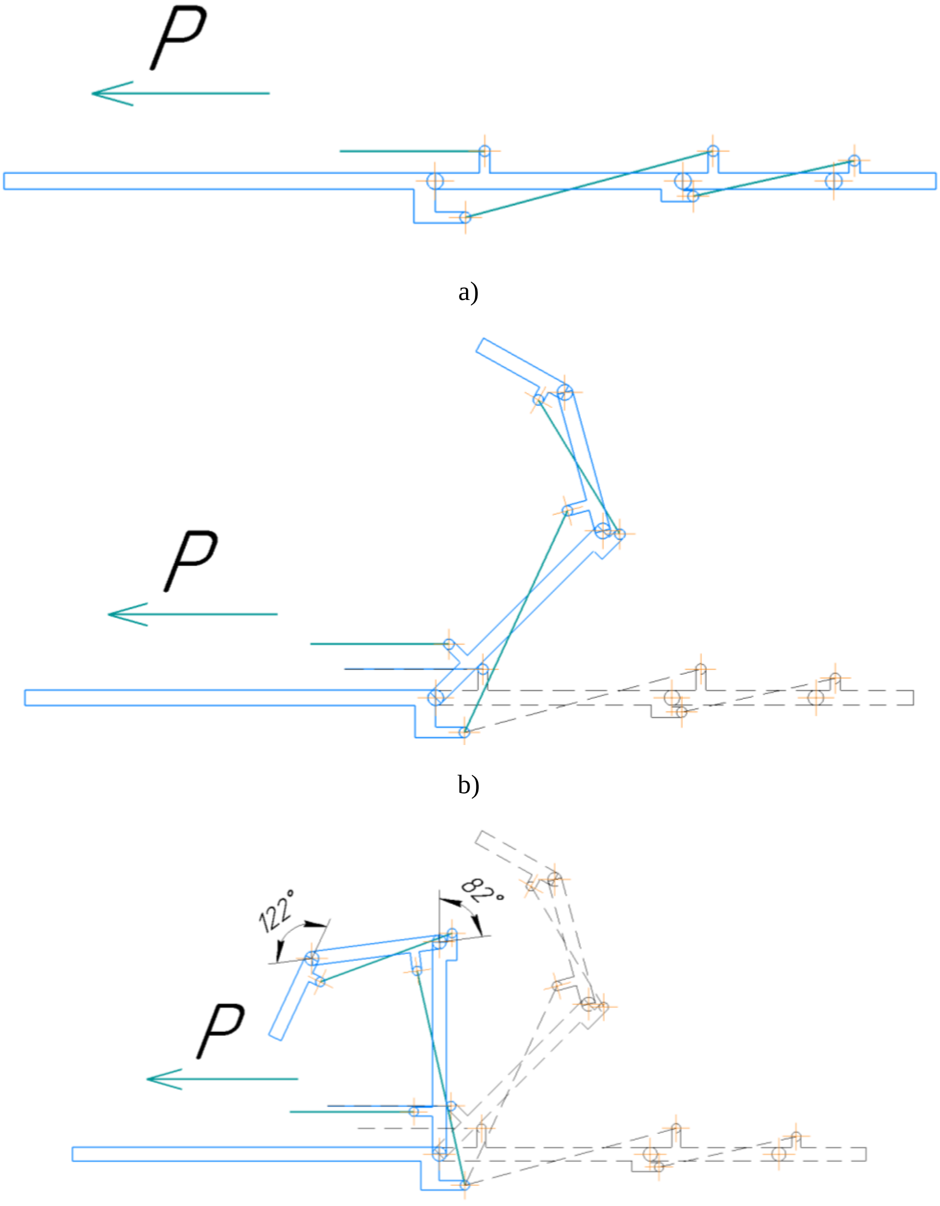


Figure 10. Features of the finger phalanges bending



a)

b)

c)

Figure 11. The resulting design.

However, in the design shown in Fig. 9, both angles are obtuse. That's why it is necessary to change the sizes of the protrusions on the finger phalanx elements and the length of the rods, respectively. For this purpose, the required rotation trajectories of each finger phalanges element were set, their placement at the angle of the first phalanx rotation relative to the palm of 45^0 and 90^0, and the optimal values were selected from a set of possible values. The resulting design is shown in Fig. 11.

For the resulting version of the design, all elements were additionally rounded to provide a more practical and aesthetic shape. Also, the rods themselves were curved so that when moving they protrude less beyond the finger phalanges elements. The resulting design is shown in Fig. 12.

The main elements of the hand prosthesis endoskeleton were designed. Based on this, a 3D design of individual elements of the endoskeleton design was performed and a drawing of the three-dimensional assembly unit was made (Fig. 13).

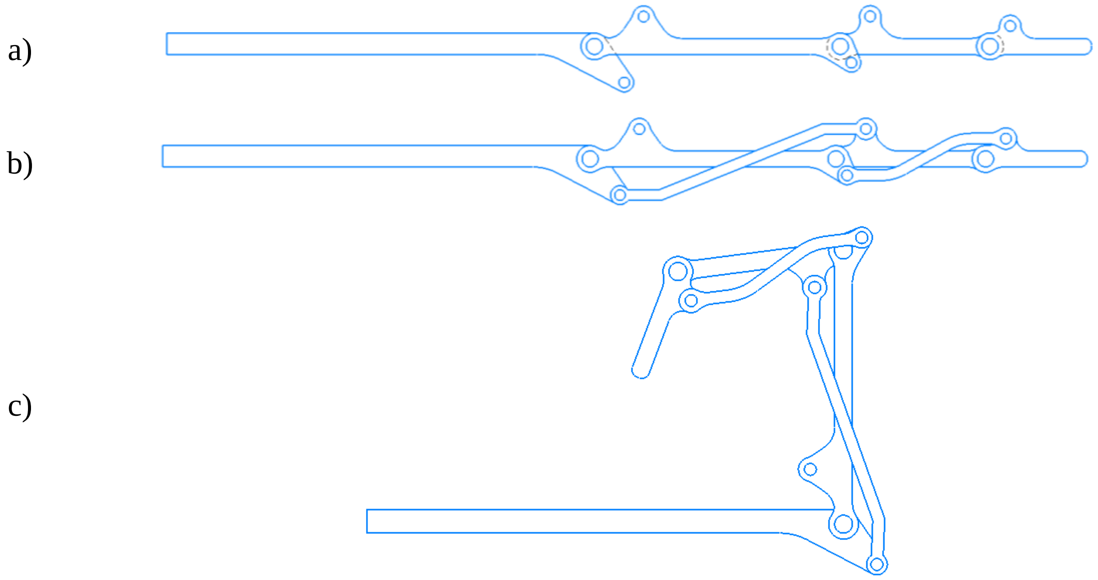


Figure 12. The obtained design of finger elements (a), together with rods (b) and when benting (c)

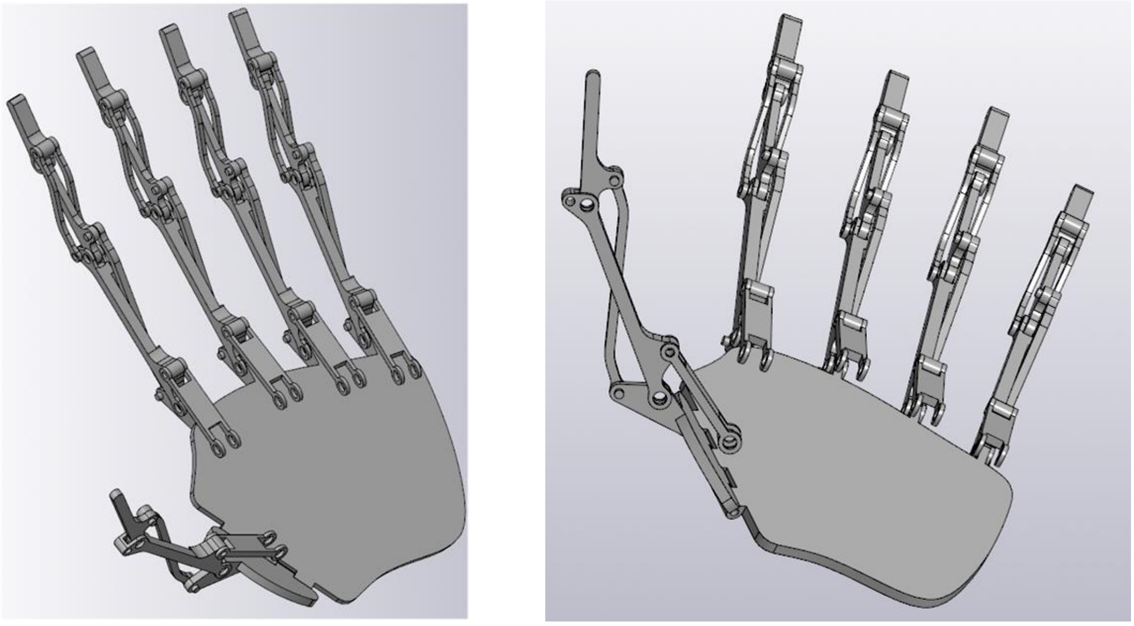


Figure 13. 3D image of the endoskeleton design as a volumetric assembly unit

Also, all design elements were made by 3D printing using the ANYCUBIC i3 MEGA 3D printer. At the same time, ABS filament of black and blue color was used. The main supporting elements were made from black filament, and the rods – from blue filament. The image of the assembled structure of the hand prosthesis endoskeleton is shown in Fig. 14.

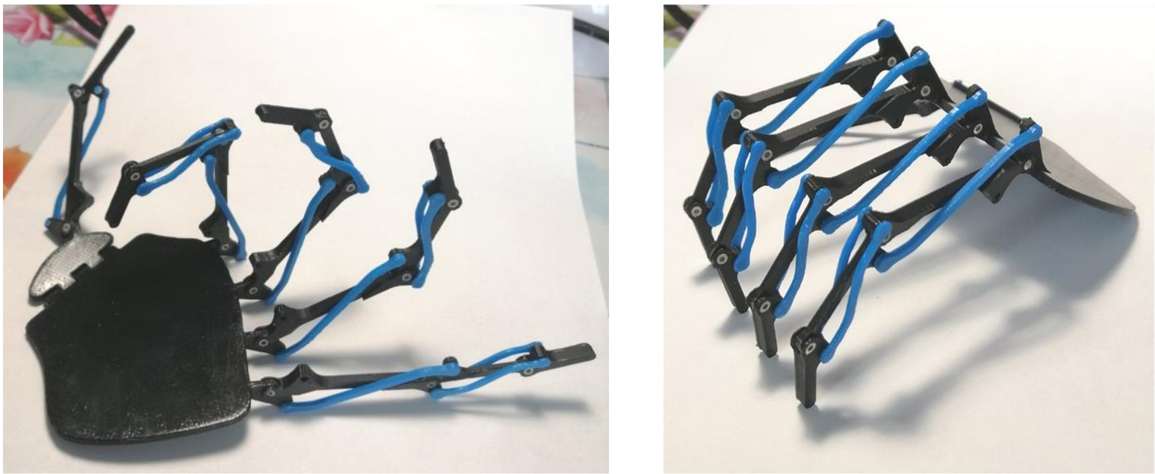


Figure 14. Image of the assembled design of the hand prosthesis endoskeleton

At the next stage, the design was improved and electric drives were added, which are bipolar stepper motors and their control drivers. Red and white PLA filament was used for printing. The actual control signals were generated by the Arduino Uno platform. The view of the prototype design of the prosthesis is shown in Fig. 15.

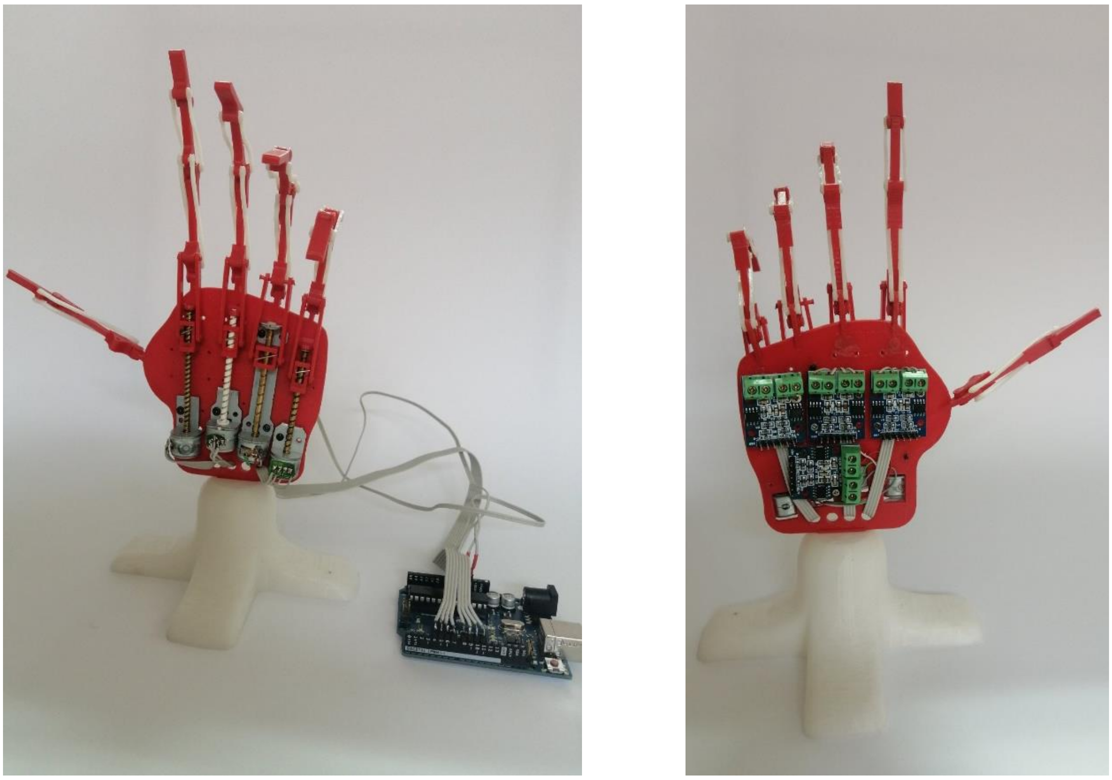


Figure 15. Prosthesis design with electric drives

SPS-15RF type bipolar stepper motors with winding resistances of 10 Ohms, operating voltage of 4.8 V, and special shafts with different thread angles were used to study the operation of the proposed design (to evaluate the speed of bending/unfolding of the phalanges. Taking into account the specifics of controlling such motors, specialized drivers L9110S were used, which are power H-bridges with a maximum load current of 1200 mA and a range of operating voltages of 2.5–12 V. During the operation of the proposed design was noted the smoothness of movements, the possibility of controlling the speed of the performed movements and the possibility of providing greater number of grips due to the bending of each finger in all hinged joints.

4. PROSPECTS FOR FURTHER RESEARCH

The proposed design is the basis for the development of a biocontrolled hand prosthesis. At the same time, for the selection and processing of biosignals for controlling such a prosthesis, it is planned to use the methods given in papers [18, 19] with appropriate modifications

Analyzing the completed assembled design of the developed endoskeleton, it revealed a number of shortcomings, which are planned to be eliminated in subsequent research. At the first, this is the effect of additional forces perpendicular to the sides of the each finger phalanges elements. So, holding a bottle of water (vertically) in such a hand, for example, the actual bottle will additionally create a load on the phalanx elements and hinge joints perpendicular to the axis of rotation. Thus, in the future design, it is proposed to make the elements of hinged joints more massive.

The printed elements can be used as bases for making molds for subsequent casting of these elements from metal alloys. In this case, the final design will be characterized by high strength and wear resistance.

It also found that the way the thumb is rotated and placed on its base needs improvement, as it is difficult to bring the index finger and thumb together when bent, for example to take a piece of paper or credit card, etc.

It is also planned to develop a design of the palm with the possibility of replacing individual fingers. This will be especially useful and effective in the practical use of the finished hand prosthesis based on the developed endoskeleton design.

5. CONCLUSIONS

The design of the endoskeleton of a biocontrolled prosthesis, which would function according to the principle of the skeleton of a human hand, was developed.

First of all, the design of the index finger was designed, which includes a number of elements with hinged joints that correspond to individual phalanges of the real finger, and elements that will transmit forces to these phalanges when bending and unfolding the finger – rods. As a result of the known hand prostheses design analysis, it was proposed to develop a design that would ensure simultaneous bending in all hinge joints of all finger phalanges, but when bending in individual hinge joints, individual phalanges would repeat the movement trajectory of the corresponding phalanges of a real finger.

The main elements of the hand prosthesis endoskeleton were designed. Based on this, 3D design of individual elements of the endoskeleton was performed and drawings of the three-dimensional assembly unit were performed.

Also, all design elements were made using a 3D printer. At the same time, ABS and PLA filament were used. Thus, in the process of 3D printing, it was determined that the weight of the structure will not exceed 30 g, which is significantly less than the weight of the analyzed analogues. Besides, the cost of such a design will be much lower and the functionality will be higher.

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КОНСТРУКЦІЯ ЕНДОСКЕЛЕТА БІОКЕРОВАНОГО ПРОТЕЗА КИСТІ РУКИ

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Резюме. *Проаналізовано конструкції біокерованих протезів, які сьогодні поширені на ринку протезної техніки, зокрема протези i-Limb, «рука Мікеланджело» та Bebionic. Показано, що в цих конструкціях використовуються порожнисті оболонкові моделі фалангів пальців і долоні, які разом утворюють зовнішній скелет конструкції протеза. Цей вид конструкції характеризується складністю виготовлення, а відповідно і вартістю, і нераціональним використанням об'єму, оскільки всередині цих* *порожнистих елементів розміщуються тягові елементи, зубчасті або інші елементи, які забезпечують передавання зусиль при виконанні згинальних рухів таких пальців. Запропоновано використання ендоскелета як несучої основи для кріплення електроприводів та елементів керування. При цьому конструкція являє собою групу шарнірно з'єднаних елементів і штанг для передавання зусиль, в яких забезпечується одночасний згин у всіх шарнірних з'єднаннях, а форма виконуваних рухів наближена до природної. При цьому в запропонованій конструкції раціональніше використовується об'єм елементів пальців, оскільки стає можливою фіксація на стержнях конструкції зовнішніх насадок з еластомерних матеріалів, які повторюють форму справжніх пальців, будуть м'якими для надійного утримання предметів при виконанні захватів. При цьому, можливим стає встановлення в такі елементи датчиків для забезпечення тактильних відчуттів. У результаті дослідження розроблено 3-D моделі всіх елементів ендоскелета протеза, які виготовлені методом 3-D друку. На етапі прототипування в якості електроприводів для оцінювання траєкторій виконуваних рухів використовувалися біполярні крокові двигуни, керовані модулем Arduino Uno. Показано, що підвищення функціональності стає можливим за рахунок встановлення датчиків для забезпечення тактильних відчуттів. Встановлено, що кількість виконуваних рухів практично така ж, як і в аналогів, а вартість запропонованої конструкції значно нижча. При цьому надійність вища за рахунок використання значно меншої кількості елементів конструкції та їх з'єднань.*

Ключові слова: *протез, ендоскелет, біопротезування, шарнірне з'єднання.*

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