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Development of a Universal Finger Module for Various Degrees of Amputation

Ivan V. Krechetov[1*], Arkady A. Skvortsov[2], Ivan A. Poselsky[3]

[1] *Researcher, Office of scientific research and development, Moscow Polytechnic University, Moscow, Russia.*

[2] *Head of OSRD, Ph.D., Professor, Office of scientific research and development, Moscow Polytechnic University, Moscow, Russia*

[3] *Head of NTC "Automated technical systems" Moscow Polytechnic University, Moscow, Russia*

[1*]ivan.krechetov.63@mail.ru

Abstract — *This paper describes the results of research on the development of a bionic finger module intended for human upper limb prostheses. A feature of the implementation is the design with the placement of the servo, which includes a motor, a gearbox, and a feedback sensor inside the finger. Thus, each finger is a complete autonomous module, which allows it to be used both for the implementation of a complete hand prosthesis and for finger prosthetics in patients with partial hand amputation. The key advantage of the design is the use of a built-in gearbox based on a cycloidal transmission, which can significantly increase the resistance of the finger to the loads arising from the gripping and power holding of various objects. Within the framework of the article, the design of the pin is presented, including the internal elements and the results of the analysis of the mechanical strength of the most loaded elements are presented. Load simulation made it possible to modernize the structure in order to eliminate critical points and possible breakdowns during operation, as well as outline the directions for further work. The developed finger module will make it possible to implement a complete hand prosthesis with characteristics that are not inferior to those of the world's leading manufacturers. At the same time, the cost of a full hand will be significantly lower than analogs.*

Keywords — *bionic finger, upper limb prosthesis, partial palm prosthesis.*

INTRODUCTION

According to statistics [1-3], there are about 1.5 cases of amputation per 1,000 people in the world. Of these, 30% are due to amputations of the upper limbs. Thus, in the world about 3 million people have various degrees of upper limb amputation. The most complete statistics for the United States provided by the National Center for Health Statistics:

- Every year in USA 50000 new amputations,
- 30% persons with amputations in USA have upper limb loss
- 61000 persons have most common partial hand amputation with loss of 1 or more fingers,
- 25000 persons have next common loss of one arm,
- 70% of all persons with upper limb amputations have amputations distal to the elbow,
- In US 41,000 persons are registered who had an amputation of hand or complete arm

Loss of limbs is accompanied by disability, stress, depression and a significant decrease in the quality of life. The solution to this problem is the installation of a prosthesis. Cosmetic prostheses, which have a decorative function, as well as traction prostheses, providing the simplest functionality are not very convenient for users, therefore, among people with upper limb amputations, the number of refusals from prostheses is quite high. A more effective solution is to install a bionic prosthesis, which is highly mobile and provides wide functionality.

In recent years, many different bionic prostheses have appeared on the market. Along with large manufacturers such as Ottobock, OSSUR and Vincent Systems, small companies also present their solutions. A large number of open prosthesis designs are also presented.

A significant drawback limiting the massive use of bionic prostheses is their extremely high cost. Cheap prostheses made using 3D printing technologies have an extremely low resource and require frequent repair or complete replacement.

According to statistics, the most common case is partial amputation of the hand and loss of fingers. In many cases, a person who has lost fingers can learn to use the remaining ones and adapt to daily life. However, very often such cases become a very serious problem, since the functioning of the hand without fingers is impaired, and a full-fledged prosthesis cannot be installed. In a similar situation, partial prosthetics helps, i.e. installation of a finger prosthesis without a palm. The situation is complicated by the fact that there are very few finger prostheses on the market and those that do have a cost similar to a full hand.

In the previous article [4] devoted to this project, the authors showed that bionic hand prostheses can be conditionally divided into two types: with drives located inside the fingers [5-8] and inside the palm [9-14]. The advantages and disadvantages of both types of construction are shown. Based on the concept of the project for the development of the bionic prosthesis and because of the analysis of existing structures, it was decided to place the actuators inside the fingers.

The developed structural and layout solutions in terms of integrating the finger servo inside the proximal phalanx structure will make it possible to perform complex types of prosthetics for patients with amputations of individual fingers, partial loss of the hand, and separation of the hand. Such injuries account for a significant share of the total demand for upper limb prostheses, therefore developments in this area have a potentially good commercialization potential. Now, there are only two such prostheses on the market:

- Vincent Evolution by Vincen Systems [5]
- i-digits by OSSUR (former Touch Bionics) [6]

Thus, each finger of the bionic hand consists of 2 phalanges, driven by one servo, which is located inside the body of the finger. The deflection of the thumb to the side is carried out using an additional finger.

METHODOLOGY

When developing the layout of the finger module, the following conditions were formulated that the design must satisfy:

1. Finger sizes should be 9-12 cm in length, with the ability to easily change the length for assembling hands of different sizes. The section of the finger should be no more than 15x20mm, and the height of the finger should be greater than the width. This requirement is due to the need to provide additional clearance between the fingers for the installation of a protective cosmetic glove.
2. The finger should have two active, movable joints. With two joints, one installation, or "zero" phalanx and two main, working phalanges: proximal and distal, are obtained. A real human finger has three phalanges, but implementing a similar arrangement would unnecessarily complicate the design without gaining any significant advantages.
3. The zero phalanx should have a minimum length, but provide a secure attachment of the finger in the palm of the hand, and also be able to be installed in a frame base for partial hand prosthetics.
4. The distal phalanx of the toe should be kinematically connected to the proximal phalanx. That is, when bending the proximal joint, the distal one should bend proportionally. When extending the proximal joint, the distal must be extended.
5. The motor, together with the gearbox and the distal phalanx drive, must completely fit into the proximal phalanx.
6. When choosing the type of gearbox, preference should be given to a self-locking one. Locking the finger joints will significantly reduce the energy consumption of the motor while maintaining a given position.
7. The gear ratio of the reducer should be selected based on the finger compression time in the range of 0.5-1 s.
8. A feedback sensor for the motor control loop should be located inside the finger.
9. The mechanical details of the pin must be simple and meet the requirements of mass production technologies such as injection molding and milling. In this case, the milled parts must be processed on 3-axis machines. Injection molds for parts should be without additional mechanization.

A miniature collector motor with a coreless rotor was chosen as the main drive for the pin. The motor has the following characteristics:

TABLE I. COMPARISON OF PROSTHESES BY CAPACITY

Size	12x15 mm
Rated rpm	30,000 rpm
Rated torque	1 mRt
Starting torque	5 mRt
Rated voltage	7.4 V
Rated current	0.15 A
Starting current	2.5 A

With full flexion of the finger, the proximal phalanx, rigidly connected to the output shaft of the gearbox, rotates 90°. With the given requirements, this turn should be carried out in 0.5-1 s, that is, at a speed of 0.5-0.25 r/s, or 30-15 rpm. To achieve these speeds, a gearbox with a gear ratio in the range of 1000:1 - 2000:1 can be used with the selected motor. At the same time, the developed starting torque, taking into account losses, will be 3-7 Nm, which, in terms of the compression force of the entire arm, will be 100-200 N.

A very high gear ratio of the gearbox will require a large number of stages, or the use of special types of gearboxes that allow a high gear ratio in one stage.

High loads during the forceful compression of the fingers require increased strength from the output stage of the gearbox. Wave, cycloidal and worm gearboxes have the highest load capacity. A feature of the wave and cycloidal gearboxes is that a large number of teeth are engaged in them at any given time. For comparison, if conventional cylindrical gears have 1-2 teeth in engagement, then wave gear has about 40% of all teeth. In this way, the load is distributed over the teeth and the gearbox is able to work in very difficult conditions.

Each of the selected gearbox types has both advantages and disadvantages. The wave reducer incorporates a flexible gear, which is rather difficult to manufacture in miniature sizes. The worm gear is the easiest to manufacture, but has a very low efficiency, especially under high load. The most interesting is the cycloidal reducer. It provides a high gear ratio with compact dimensions, is capable of withstanding high loads and can be used as an output stage for a pin drive.

With a given pin size, a gearbox with an outer rim diameter of about 15 mm can be placed inside it. This diameter makes it possible to obtain a gear ratio of 30: 1 with a cycloid tooth diameter of 1 mm. A larger gear ratio will require a reduction in the diameter of the teeth and a decrease in the eccentricity of the drive shaft, which will significantly increase the likelihood of teeth overshooting under a high load, or with an external impact.

Thus, the common pin servo gearbox consists of a primary gearbox on conventional spur gears and an output stage in the form of a cycloidal gearbox. With an output stage ratio of 30:1, the primary gear ratio should be between 33:1 and 66:1. By changing this ratio, one can create several different variants of fingers with different values of speed and effort.

In accordance with the stated requirements, the layout and design of the pin was developed. A three-dimensional model of the finger is shown in Figure 1.

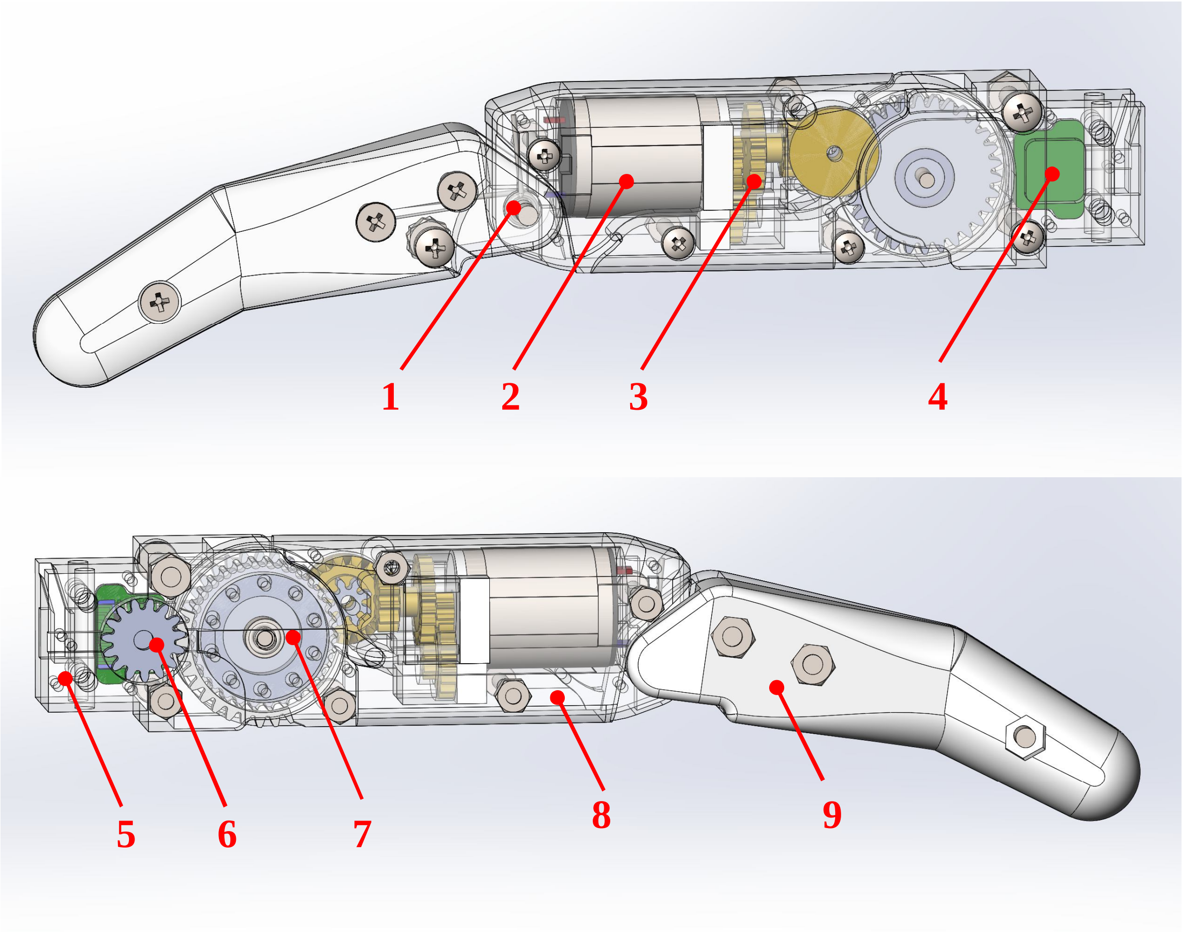

Fig. 1. Three-dimensional model of a finger.

In figure XX, the following details are indicated by numbers: 1 - return spring, which provides extension of the distal joint; 2 - finger servo motor; 3 - primary gearbox; 4 - contactless feedback sensor; 5 - zero phalanx for securing the finger in the palm; 6 - permanent magnet with a drive gear for the feedback sensor; 7 - secondary cycloidal reducer; 8 - the body of the proximal phalanx; 9 - the body of the distal phalanx.

With active daily use of a bionic prosthesis, its design is exposed to high loads. No matter how thrifty the user is, eventually the user can hit the prosthesis on the table, pinch it by the door, and drop it onto the concrete floor. In this case, the loads are alternating signs, since their direction can be arbitrary. Such loads place increased demands on the structural strength of the bionic prosthesis. At the same time, because the device is wearable and must have a minimum weight, it is impossible to manufacture parts with a large margin of safety. Thus, it is necessary to simulate the strength of the most critical nodes subjected to maximum loads in order to determine the balance between mass and sufficient safety factor. Calculation of strength characteristics by means of virtual modeling will allow to identify the most loaded places of the mechanical structure, in which destruction is likely and to carry out revisions to eliminate them.

Analytically, it is obvious that the maximum loads fall on the fingers, when squeezed or the impact on the finger from the side. The body of the hand is made of elastic material and allows the finger to move freely under load within a few degrees.

The direct compression load on the pin is transferred to the pin reducer output stage. The cycloidal gearbox of the output stage of the common pin gearbox allows the external load to be distributed between the gears. In this case, the most loaded part is the carrier of the gearbox output shaft.

The carrier is a plastic boss integrated into the zero phalanx of the pin, with eight holes and steel pins pressed into them. When an external load is applied to the manipulator, or the electric motor is turned on, a pair of driven gears of the drive transfer the load to the pins, forming a bending moment. Figure **Error! Reference source not found.**2 shows the appearance of a separate carrier with pins and schematically shown loads.

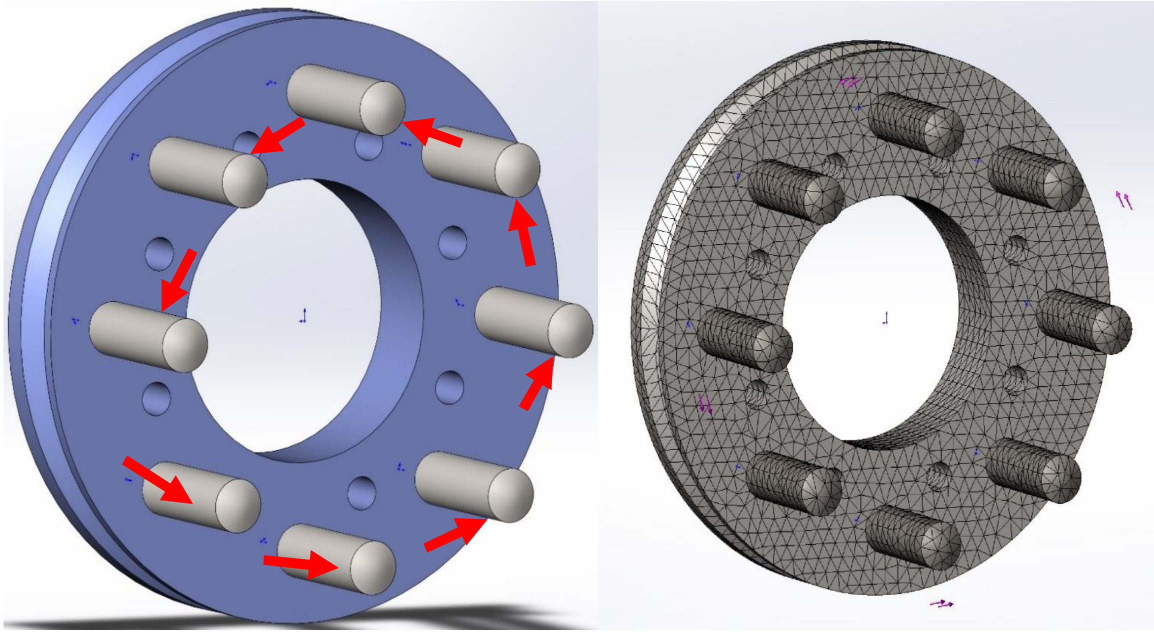

Fig. 2. Carrier with pins and a grid of elements.

Solid modeling creates a mesh of elements, i.e. the object is broken into small cubes and then their interaction is calculated. The element size was 0.1 mm, the number of elements was about 20 thousand.

Figure 3 shows the result of the strength simulation of the load applied to the pins of the pin flexion drive. The torque is 5 Nm.

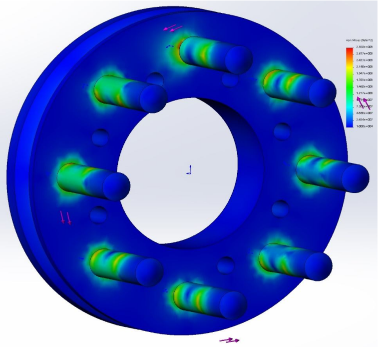

Fig. 3. Simulation of the load on the carrier of the pin drive

As can be seen from Figure 3, the maximum stress arising in the part does not exceed the yield strength of the plastic from which the parts are made. The nominal drive torque of the pin is 1.5 Nm. Thus, the part has a threefold safety factor.

The next highly loaded element is the zero phalanx of the finger, which is inserted into the body of the prosthesis hand and perceives lateral loads on the fingers. When the finger tip of the prosthesis strikes a solid object, a high destructive stress arises at the base of the null phalanx. To increase its strength, it is impossible to change the internal structure and the only option for increasing the strength is to increase the thickness of the material. However, an excessive increase in thickness is unacceptable, because this leads to a decrease in the interdigital distance and possible contact of the bases of the fingers, which entails the inability to use a protective cosmetic glove.

As mentioned above, during modeling, the model is broken into elements. To perform modeling, the models of the zero phalanxes of the finger were slightly simplified. Eliminated thin elements that do not affect strength, but require a decrease in the mesh spacing, i.e. breakdown into even smaller elements. At the same time, their number increases sharply, which increases the complexity of the model and the load on the computing power. Figures 4-5 show the original and simplified left and right zero phalanges.

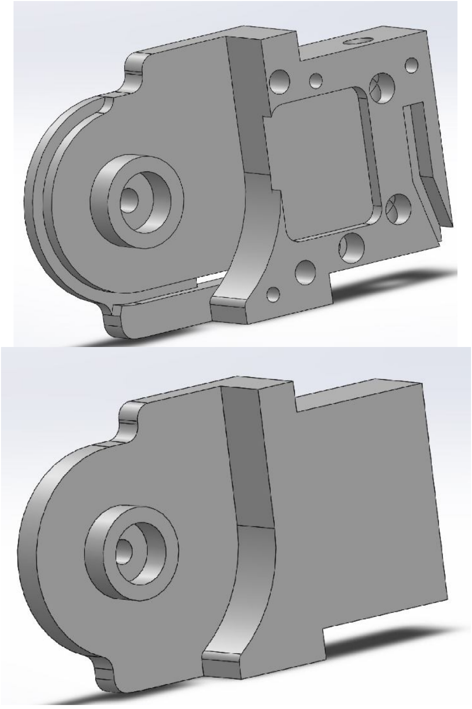

Fig. 4. Left zero phalanx

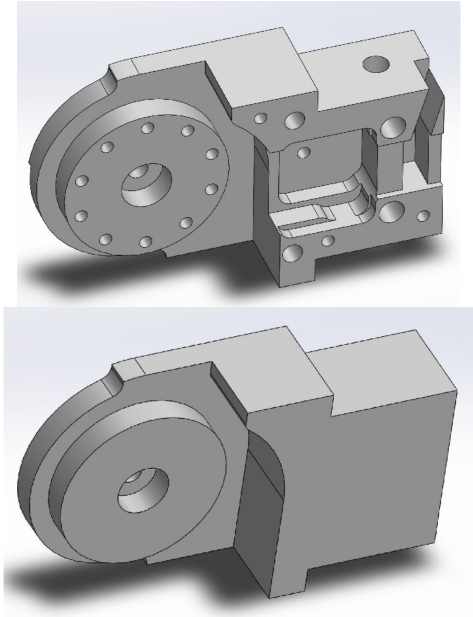

Fig. 5. Right zero phalanx

The internal elements of the halves of the proximal phalanx were similarly simplified. They do not carry any mechanical load and can be neglected. Figure 6 shows the assembly of the null and proximal phalanx with the calculated mesh of elements. The cell size was 1 mm. The number of elements is about 60 thousand.

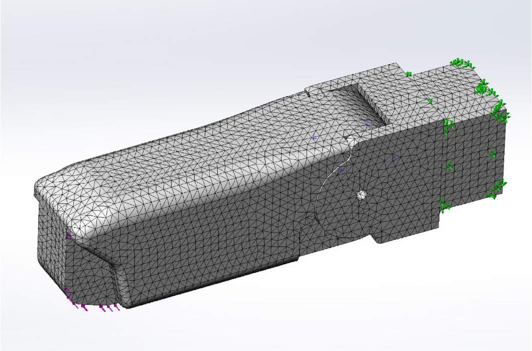

Fig. 6. Grid of elements

A force of 200 N was applied to the tip of the proximal phalanx as a mechanical load during the simulation. Figure 7 shows the simulation result, where stress areas are highlighted in different colors. The areas of maximum stress in which structural failure are possible are shown in red.

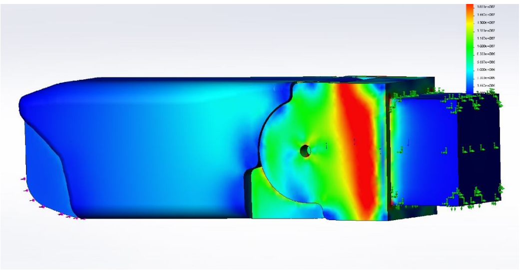

Fig. 7. Simulation of stress under load

To increase the strength, the walls of both zero phalanges were increased by 0.25 mm. The simulation result for the same load is shown in Figure 8.

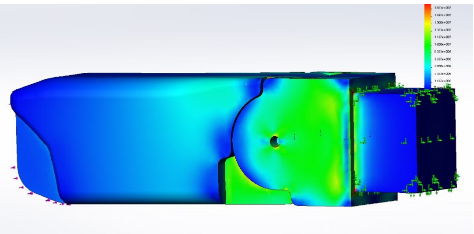

Fig. 8. Simulation of stress under load

As it can be seen from the figure, the maximum stress in the walls has decreased and the part is able to withstand the applied load. However, the mechanical design allows for making the walls even thicker and providing a margin of safety. Further, the walls were increased by another 0.25mm. Figure 9 shows the result of modeling the modified zero phalanges.

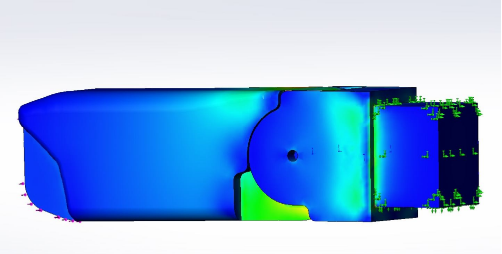

Fig. 9. Simulation of stress under load

Because of the revision, the walls of each half of the zero phalanx were increased by 0.5 mm. The increase in weight was only 1 g per finger, or 5 g for the entire hand. Figure 10 shows the original and modified phalanxes.

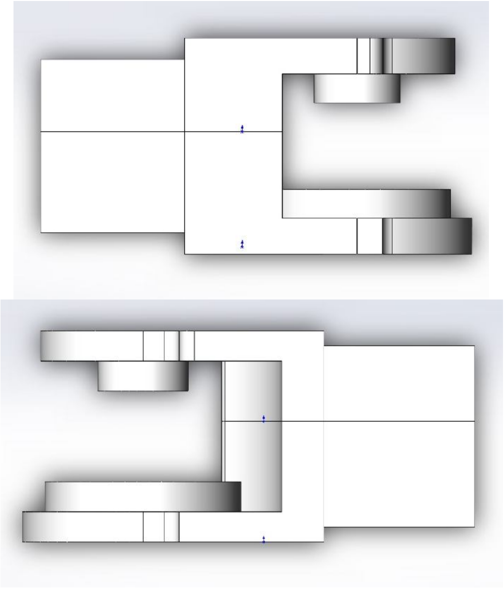

Fig. 10. Original and modified zero phalanges

In accordance with the developed model, a mock-up of the finger module was made on CNC equipment. The material used is polyacetal, which has a low coefficient of friction and is highly durable. According to the initial requirements formulated during the development of the model, the structural parts have a simple shape, without closed internal cavities, which allows the use of polymer injection molding technology for mass production.

The total weight of the finger, including all housing elements, gear, motor, feedback sensor and fasteners, was 32 grams.

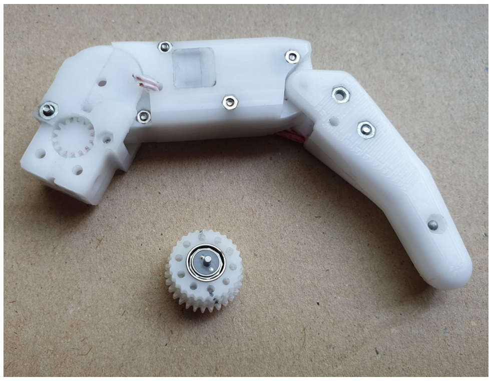

Fig. 11. Manufactured pin and internal gears of the cycloidal reducer assembly.

TABLE II. COMPARISON OF PROSTHESES BY CAPACITY

Parameter	beBionic 3 (OttoBock)	iLimb Revolution (OSSUR)	Vincent Evolution (Vincent Systems)	Authors' solution
Palm opening time, sec	1.0	1.2	1.5	0.5
Maximum compression force, N	128	120	120	130

As follows from Table 2, the developed prosthesis design provides a similar compression force, while the compression speed is 2 times higher.

RESULTS

Because of work on the project, the following results were obtained:

- A general arrangement of the bionic prosthesis finger has been developed, including a kinematic diagram, a servo drive with a gearbox and a feedback sensor.
- The mechanical design of the pin module has been developed, having a simple configuration and suitable for mass production by injection molding.
- An analysis of the strength of highly loaded structural elements was carried out and a material for the manufacture of parts was selected.
- A test model of a finger module was made on CNC equipment.
- Natural tests of the finger model were carried out and the achieved parameters were measured.

DISCUSSION

After the manufacture and experimental studies of the finger module, a comprehensive analysis of the results was carried out, which made it possible to evaluate the results achieved, identify design features and outline the directions for further work.

The achieved dynamic characteristics of the finger, such as the speed and the developed force, are comparable to the real hand of a living person and are not inferior to the prostheses of the hands of the world's leading manufacturers. At the same time, the use of the primary and secondary stages of the gearbox allows you to change the gear ratio of the primary stage and select the required speed and pin force. This feature will enable the development of a product line and will allow the user to choose a hand prosthesis with the characteristics the user needs.

A finger weight of 32 grams, or 160 grams for all five fingers, suggests the possibility of realizing the entire hand with a weight of no more than 300 grams for a passive wrist and 400 grams for a wrist with a rotation servo. Placing the finger actuators within the fingers themselves frees up a large amount of space within the palm, making it possible to place the wrist rotation servo within the palm. Unlike prostheses from other manufacturers, in which the wrist drive is a separate module, the built-in drive will significantly shorten the total length of the prosthesis and install it in patients with a long residual part of the living arm.

The user without damage, which provides additional resistance to shock loads, can bend the distal phalanx of the finger, driven by a flexible cable and returned to its original position by a return spring. Changing the length of the distal phalanx allows you to change the length of the fingers and select the size of the entire hand in accordance with the user's requirements. The implementation of a one-piece distal phalanx made of hard plastic showed insufficient flexibility of the fingertip. This problem can be eliminated by adding an additional soft insert, similar to the finger pads of a living person. Manufacturing the entire distal phalanx entirely from a softer plastic is not possible due to the excessive flexibility and mobility in the distal joint. The soft phalanx will deform under load, it will be possible for the shaft of the joint rotation axis to exit from its guide grooves and further separate the distal phalanx from the proximal one.

Thanks to the use of a cycloid gear at the output stage of the gearbox, the pin drive is able to withstand significant physical loads that occur when gripping and holding objects. The polyacetal used for the gearbox parts has high strength and shock resistance. As planned, the details of the structure were designed with a simple form, without internal cavities, which would require creating a mold for casting with additional moving elements. Thus, it is possible to provide a very low production cost of the finger modules. However, it is possible to significantly increase the strength of the finger by replacing plastic in some places with metal. According to the results of strength modeling, the most loaded part is the zero phalanx of the finger. If it is made not by casting from polymers, but by milling on a CNC machine from aluminum alloy 2024, or 6061, then the strength of this part will increase by 2-3 times. Similarly, one can replace the built-in plastic gearbox with a metal gearbox made of brass or steel. At the same time, the strength of the proximal joint, which depends on the proximal phalanx, will increase 2-3 times. Replacing plastic parts with metal ones will significantly increase the relative cost, compared to the cost of a completely plastic finger, but in absolute terms, a partially metal finger and a full hand prosthesis built on its basis will have a cost significantly lower than any analogues of the world's leading manufacturers.

The developed finger module has a built-in feedback sensor based on a non-contact Hall sensor. It provides precise positioning and adaptive control capability. In addition to the feedback sensor, the main control module, located in the palm of your hand, has a current sensor that measures the consumption of the electric motor during operation. This sensor allows you to calculate the torque developed by the motor and recalculate it into the effort developed by the entire finger. This provides precise, precise dosing of force and the ability to hold fragile or flexible objects without deforming them. This indirect method of calculating the force through the current consumption is highly dependent on the quality of the gearbox, the outer glove and temperature, which can significantly reduce the accuracy of the calculations. Force transducers that measure the load by a direct method have much higher accuracy. Modern force sensors are compact and can be integrated into the fingertip. The distal phalanx of the finger has a large margin of free space and allows you to place 1-2 force sensors that can measure the load applied from different directions.

CONCLUSION

Analysis of the results and parameters obtained during the work on the project shows that the developed finger module has excellent characteristics and the complete prosthesis developed on its basis will have functionality that is not inferior to the best samples of the world's leading manufacturers. At the same time, it is possible to realize the full cost of a hand prosthesis much lower than any analogs.

The outlined further directions of research, with their successful implementation, will significantly increase the strength of the finger module and, as a consequence, the entire prosthesis as a whole. The implementation of additional feedback sensors will increase the control precision and ease of use of the prosthesis.

Implementation of the finger in the form of a complete autonomous module will allow it to be used as a component of a complete hand prosthesis and for prosthetics of individual fingers in patients with partial hand amputation.

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