Modelling the dynamics of the force interaction between the prosthetic sleeve and the patient's hand

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Abstract. The article deals with the design processes of modern prostheses of the upper limbs, including the prosthetic sleeve. It has been established that the applied design methods and manufacturing technologies for prosthetic sleeves do not take into account the elastic-rigidity characteristics of human hand tissues interacting with the prosthesis. The review made it possible to determine the existing problems in the field of creating prosthetic sleeves. The authors considered the issues of using data from the results of the experiment to reconstruct the forces that arise between the patient's stump and the cult-receiving sleeve. A feature of the work is the study of the results of the experiment modelling the dynamics of power loads. The findings allow us to supplement the Bio Sculptor patient stump analysis system. The nature of the force interactions of the prosthesis and the human hand in the process of performing movements is considered on the basis of a virtual model.

1 Introduction

The human hand is a complex part of the body, possessing a variety of types of movement and sensitivity. Partial or complete loss of a hand leads to the loss of a person's ability to work and to perform self-care. In addition to functional loss, there is also a cosmetic defect that can be traumatic to the patient's psyche.

The frequency of hand injuries both in peacetime and in wartime is extremely high. According to recent data [1], in 2021 the number of people in Russia who suffered from hand or wrist injuries is about 40 thousand.

According to the World Health Organization (WHO) for 2019, there are 113 million people in the world with amputated limbs [2]. Considering that it is impossible to count the exact number of people with lost limbs in poor and underdeveloped countries (such as Africa), their global number could be much higher than WHO statistics. At the same time, only 5% of people with amputated limbs have access to adequate prosthetic assistance.

Currently, after amputation, a person can restore lost functions through prosthetics. A prosthesis almost always contains a sleeve that surrounds the residual limb, the prosthesis itself, and devices for connecting and adjusting the position of the sleeve relative to the prosthesis. In clinical practice, it is recognized that proper sleeve design is crucial for the

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successful rehabilitation of the patient and subsequent ease of use of the prosthesis. Designing and manufacturing the sleeve is the most time-consuming part of creating a prosthesis. Therefore, the development and implementation of modern methods for obtaining the necessary information about the patient's residual limb, computer modeling and design of the sleeve, is a relevant task. Its solution will significantly improve the quality of prostheses produced and increase their convenience of use. The issues of digitization of data collection on the condition of the residual limb and methods of sleeve construction have been previously discussed by various research groups [3-17]. The automation of the processes of obtaining primary information provides the ability to analyze the shape of the residual limb, transmit data to the 3D model design system of the patient's residual limb, and then perform the synthesis of geometric and force-moment characteristics of the sleeve.

2 Materials and methods

2.1 Designing the sleeve for a hand prosthesis

Due to the wide range of characteristics to be considered and the importance of restoring the functionality of the lost limb with maximum approximation to anthropometric appearance, only an individual approach to designing prosthetics is possible. It can provide the best results, comfort, and functionality of using the prosthesis.

The stage of designing the sleeve largely determines the quality of the prosthesis in terms of "ease of use and features". The interaction between the sleeve and the tissues of the residual limb determines the "comfort" or the presence of pain when performing movements (actions) with the prosthesis. The movements of the hand performed by a person in their daily life or in production conditions are accompanied by dynamic and other efforts. These efforts are transmitted from the prosthesis through the sleeve to the areas of the residual limb that perceive these efforts. Thus, to develop methods for high-quality sleeve design, it is necessary to answer a number of questions:

- What is the magnitude and direction of the forces that arise when performing "typical" actions and movements for the main groups of movements - "domestic", "sports", "industrial"?
- How can these efforts be "transmitted and perceived" by the skin and tissues, muscles of the residual limb of a person in the best possible way?
- In which areas of the sleeve and how should the "zones of force interaction" between the sleeve and the hand be implemented?

2.2 Automation of patient residual limb analysis

To improve the quality of the sleeve manufacturing, a device for analyzing the patient's residual limb has been developed [18], as presented in Figure 1. One of the capabilities of this device is to measure the shape of the residual limb and the elasticity of tissues at the measurement point. The obtained data form a point cloud, which is used to create a 3D model of the patient's residual limb, providing us with information for sleeve construction.

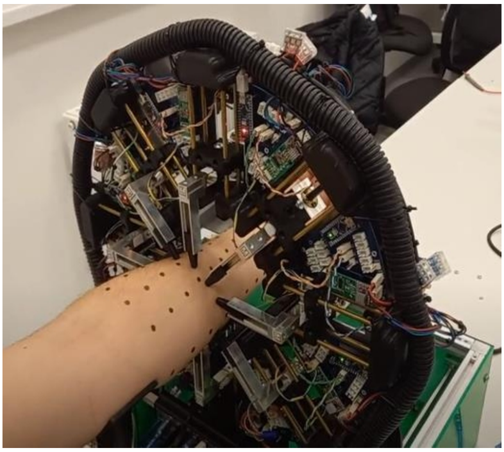

Fig. 1. Automated analyzer of the patient's residual limb.

The "BioSculptor" device for analyzing the patient's residual limb is designed by palpation. The measuring ring with 8 strain gauge sensors moves along the residual limb with an adjustable interval and palpates the tissues. The main advantage of this method is the ability to measure not only the surface, but also the physical condition of each point of the examined residual limb.

As part of the research work [19-23], the following results with practical significance were previously obtained:

1. A method for comprehensive measurement of physiological parameters of the patient's upper stump has been developed. This method allows the design of the prosthetic sleeve from different materials, taking into account the individual characteristics of the patient. Additionally, the method allows for a technological process of manufacturing the sleeve that reduces the manufacturing time to one day.

2. An algorithm for collecting and processing data to take into account the individual characteristics of the patient has been proposed. The algorithm takes into account the location of muscle, fat, and bone tissues when designing the sleeve.

3. Software has been developed that implements the construction of a prosthetic sleeve for the upper extremities of a person taking into account their individual anthropometric characteristics. (Figure 2)

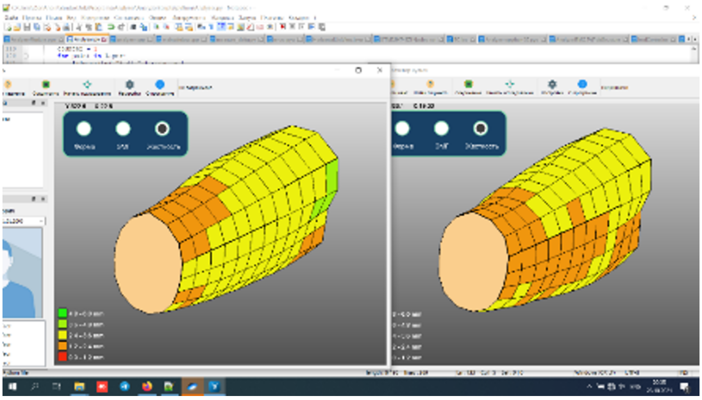

Fig. 2. Screenshot of visualization of software results.

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4. An experimental sample of a device for analyzing the upper extremities of a person has been constructed, which allows for studies of the accuracy of constructing the prosthetic sleeve. Tests of the sleeve construction system have demonstrated the effectiveness of the proposed control algorithms.

However, the work carried out on analyzing the patient's stump does not fully provide for all stages of quality sleeve manufacturing. To ensure comfort during the use of the prosthesis, it is necessary to take into account the forces acting between the stump and the sleeve.

2.3 Analysis of the force interaction between the stump and the sleeve

It is known that the use of a prosthesis can be accompanied by pain, irritation of the skin interacting with the prosthesis sleeve, and the formation of abrasions. The causes of this are loads acting on the skin and their prolonged application. Forces acting between the sleeve and the stump can be conditionally divided into forces directed perpendicular to the skin surface and forces directed tangentially to the skin surface. The former create specific normal stress, and the latter determine shear stresses. Both types of forces determine the position of the sleeve (prosthesis) relative to the stump. Naturally, exceeding the forces of a certain level will lead to destructive effects on the tissues of the arm. In particular, constant pressure reduces perfusion and can lead to ischemia and tissue necrosis. Sufficient pressure of 8 kPa is enough to cut off the skin blood flow. Often, under conditions of static load, the muscle tissue is damaged faster than the skin due to its greater vascularity and metabolic needs.

Thus, the following task can be formulated - to study the processes of force formation and reactions in the support zones of interaction between the sleeve and the stump in order to determine the force vectors, their changes when performing typical actions and movements.

3 Results

The goal of modeling is to obtain information about how the forces acting in the contact zones of the sleeve with the human hand change during various movements. The main requirements for modeling, assumptions, and limitations are:

- The movements of the human arm during its typical (characteristic) movements should be modeled.
- Inertial loads must be taken into account during modeling.
- The forces arising between the sleeve and the cartridge during arm movement must be modeled.

Assumptions and limitations:

- Force interactions between the sleeve and the cartridge occur in certain zones at the "beginning" and "end" of the cartridge receptacle.
- The "internal" distribution of forces in the skin and muscle layers of the hand is not considered.
- When building the model, it will be assumed that in the zones of force interaction, stresses caused by shear are not significant.

To conduct the research, a virtual model of the cartridge and sleeve prosthesis was developed in CoppeliaSim [25], and software for processing the results in Matlab [24].

To determine the forces acting in the contact zones of the sleeve and hand, eight virtual force sensors were installed on two zones of the cartridge receptacle. The parameters of the sleeve and hand are presented in the table.

Table 1. Initial research parameters.

Object name	Object parameters				
	Object density kg/m^3	Object mass kg	Moment of inertia X kg/m^2	Moment of inertia Y kg/m^2	Moment of inertia Z kg/m^2
Sleeve	500	0.334	0.004868	0.002871	0.004359
Forearm	1030	0.863	0.005438	0.005431	0.005055
Shoulder	1030	1.230	0.009245	0.009232	0.009206

Eight force sensors are placed at the edges of the sleeve, and each sensor allows measuring the coordinate components of the acting forces Px, Py, Pz. To check the adequacy of the model, tests were performed in which test movements were carried out with specific parameters for which the forces can be calculated analytically. During modeling, the forces acting during arm movement from a lowered to a raised position were investigated. The data obtained in CoppeliaSim were processed by the program in Matlab. The total forces acting in the sections where the sensors are located are shown in Figure 3. The blue color in the figure shows the force vector acting at the bottom of the sleeve, and the red color shows the force vector at the top of the sleeve. The length of the vector is proportional to the force magnitude.

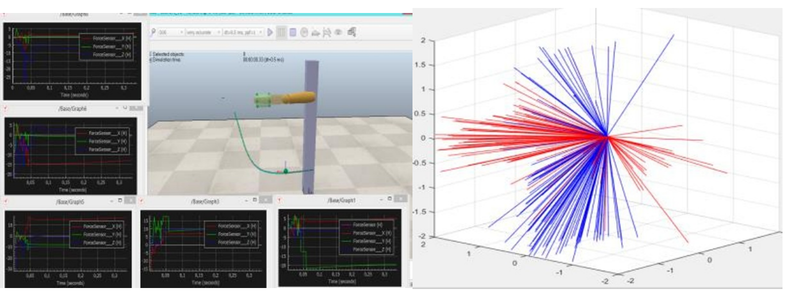


Fig. 3. Modeling the movement of the sleeve and the arrangement of force vectors when lifting the arm in front of oneself.

It can be noted that for this typical movement, there is a significant change in the direction of the forces. The magnitude of the forces also changes significantly.

We consider modeling the movement of the arm with a prosthesis along the trajectory of the movement - flexion of the arm in the forearm, while the arm is flexed at the elbow joint. The modeling results are presented in Figure 4.

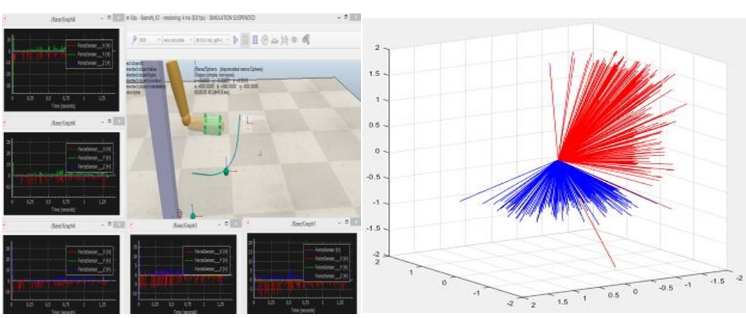


Fig. 4. Modeling the movement of the sleeve and the arrangement of force vectors when bending the elbow.

The visualization of force vectors is shown in Figure 5. This figure also shows the sleeve, the shape of which is designed based on 3D measurements of the forearm of a real person.

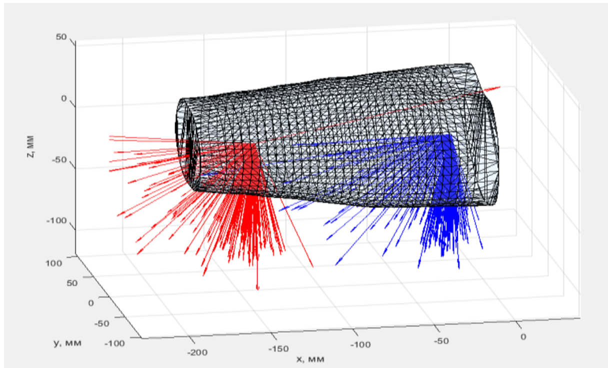
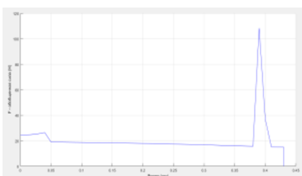
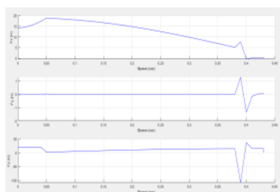
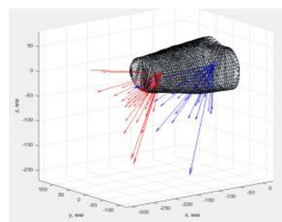
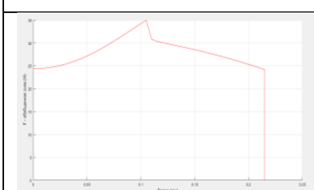
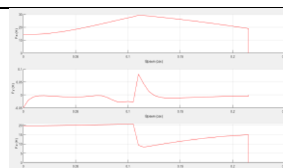
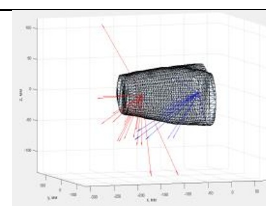
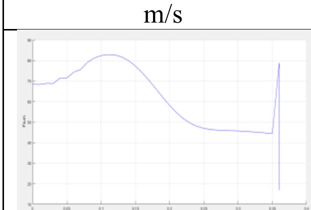
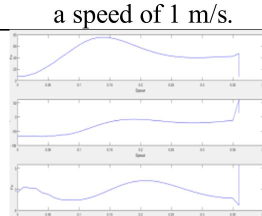
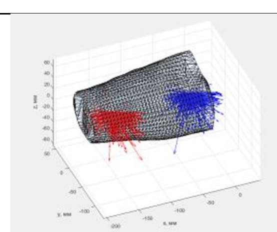


Fig. 5. Change in force vector at a speed of 0.1 m/s.

Modeling was performed at speeds of 0.5 m/s, 1 m/s, 5 m/s, and 10 m/s to analyze the influence of movement speed on the acting forces. The results are shown in Figures 6.

 General force acting on the crop at a speed of 0.5 m/s	 General force projected on the coordinate axes at a speed of 0.5 m/s.	 Change in force vector at a speed of 0.5 m/s
 General force acting on the crop at a speed of 1 m/s	 General force projected on the axes at a speed of 1 m/s.	 Change in force vector at a speed of 1 m/s
 General force acting on the crop at a speed of 5	 General force projected on the axes at	 Change in force vector at a speed of 5 m/s

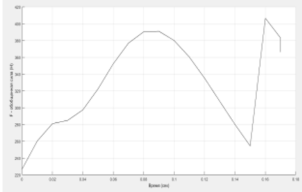
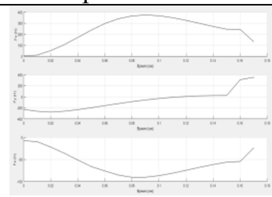
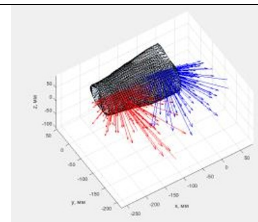
m/s	a speed of 5 m/s.	
 General force acting on the crop at a speed of 10 m/s	 General force projected on the axes at a speed of 10 m/s.	 Change in force vector at a speed of 10 m/s

Fig. 6. Influence of movement speed on the acting forces.

4 Conclusion

The developed mathematical model allows studying the elastic-dissipative processes of the force interaction between the prosthesis sleeve when performing arm movements. Changes in the direction of movement and the speed of the arm movement significantly change the vectors of acting forces. The obtained data on force interactions should be analyzed to understand how these efforts can be best perceived by the sleeves.

The conducted research and experimental work allow us to draw the following conclusions:

- A technology for forming 3D models of the surface of the sleeve based on personalized measurement data has been developed;
- A virtual model of the forearm-shoulder-prosthesis has been developed to study the force interactions in the contact areas of the sleeve-sleeves during human arm movements;
- The character of the change in force vectors in the contact areas of the sleeve during different arm movements has been determined;
- Recommendations for designing sleeve prostheses based on personalized measurement data have been developed.

The practical results of the work allow analyzing force interactions in the contact areas of the sleeves and adjusting the design and parameters of the receiving sleeve.

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