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Robotization of industrial production using exoskeletons with textile elements

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Abstract. In this paper, the design of the upper limps exoskeleton on a textile basis is considered as a means of increasing the efficiency of manual labor at industrial facilities and enterprises of the fuel and energy complex. The material presents an analysis of existing exoskeleton solutions, features of the implementation of assistance in the considered exoskeleton, presents a mathematical apparatus that describes the movements of the exoskeleton and the results of numerical simulation. Conclusions are drawn about the applicability of the proposed solutions to facilitate the manual labor of workers in industrial enterprises.

1 Introduction

Despite recent advances in the field of automation, most tasks at industrial facilities and enterprises of the fuel and energy complex still require human intervention [1-4]. Currently, the problem of industrial injuries is the most acute. Every year, an increasing number of employees of heavy industries take sick leave due to disorders or injuries of the musculoskeletal system. Most industrial injuries of the musculoskeletal system, having occurred once, will be with their carrier for a very long time. For example, various kinds of intervertebral hernia, as well as various injuries of the shoulder joint, moreover, these diseases are difficult to remission and prone to relapse.

To solve this problem, it is necessary to carry out the development of various exoskeleton complexes that will redistribute and compensate for the load, partially unloading the musculoskeletal system, thereby minimizing the risks of industrial injuries, as well as returning to production employees who, due to the recurrence of various injuries, were limited in the implementation of various kinds of technological processes [5-8]. Early research and development on exoskeletons was primarily for rehabilitation or orthopedic purposes, while industrial applications were limited by the low power of available actuators and batteries.

Recently, so-called “soft” exoskeletons have been actively spreading in the field of exoskeletons. These products have a better fit, are lighter and more portable than their metal counterparts. Research by the Harvard Biodesign Lab has shown that a soft exoskeleton can reduce the metabolic cost of human walking.

This paper discusses the applicability of soft upper limps exoskeleton, designed to support the operator's hands when working with heavy objects at a height above the shoulder.

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2 Analysis of existing exoskeleton technologies

More and more new exoskeletons are appearing in the world, designed to increase operator productivity and reduce the risk of injury, some of them are already at the stage of active sale and delivery to production [7-12]. Industrial exoskeleton complexes can be classified by the presence of an electric drive (active, passive), by compensated limbs (upper limb exoskeleton, lower limb exoskeleton, full exoskeleton), by weight (1-10kg – light, 10-30kg – medium, 30kg or more – heavy) [13].

To assess the scope of application, a classification of upper limps exoskeleton is proposed. It is based on the height at which the exoskeleton system will be most effective and where it will provide the maximum supporting force. Height from 0 to 100 cm can be covered by exoskeleton complexes, whose direct task is to help a person with extension in the hip joint and unload the lumbar spine. Various developments can serve as examples of these devices, such as: Exoheaver Lowebacker (Exomed, Russia) and Paexo back (Ottobock, Germany). These exoskeletons are designed to work with loads at heights from 0 (i.e. directly from the floor/ground) to 100 cm and more. This happens due to the fact that the preload of elastomers in the position when a person is trying to take the load from a given height is minimal, therefore, the useful effect of exoskeletons is reduced to a minimum.

Most of the following exoskeleton complexes are capable of providing maximum force at a height of 100 to 150 cm. Devices with an elastic compensator perform well with this part of the work, since the peak of its tension falls just at the separation of the load from the surface, which is the most difficult point in terms of load in the entire amplitude of human movement in the exoskeleton. Height from 100 to 150 cm is the main one in this type of work, the loads carried in such conditions can reach a significant mass, and employees of various enterprises need the help that an exoskeleton can provide.

The upper limps exoskeleton helps a person to keep the weight of the hands with the load / tool, taking part of the load from the deltoid muscle of the shoulder, increasing the performance and endurance of the operator while working in the exoskeleton complex. The maximum load at which the exoskeleton will give tangible compensation is 20 kg in each hand. By increasing the load, the efficiency of the exoskeleton will decrease. The exoskeleton is designed for work above shoulder level. The optimal angles for work are 40 - 115 degrees relative to the vertical axis of the body.

Fig. 1 shows the scheme of fixing the considered exoskeleton on the user.

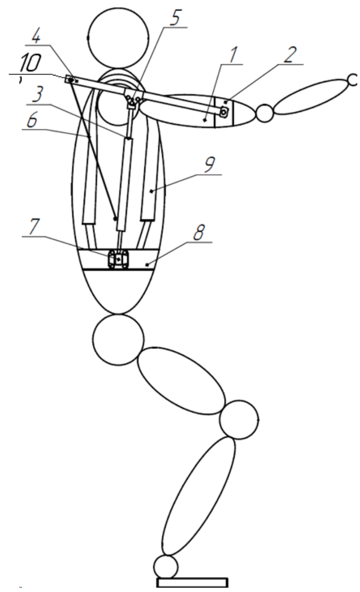


Fig. 1. Scheme of the upper limbs exoskeleton.

The shoulder cuff (2) of the exoskeleton is connected to the shoulder (1) of the operator. The operator's hand is supported by a gravitational compensator (3) connected to the shoulder link of the exoskeleton (4) through the shoulder joint (5) and a rigidly stretched inelastic cable (6). In the design, for maximum mobility and repetition of human anthropometric data, there is a ball joint (7), which is rigidly fixed on the unloading belt (8). To prevent the belt from shifting relative to the human body, special fixing straps (9) were made, which the operator puts on his shoulders by analogy with a backpack. At the end of the shoulder link of the exoskeleton (4), an electromechanical drive (10) is fixed, which is a screw-nut transmission connected through a cylindrical gearbox to an electric motor. It serves to increase the shoulder, in order to directly increase the compensating moment of the exoskeleton. This will be done by adjusting the link offset through the data processing of the sensor system.

The device is an anthropometric textile base, which is tightly fastened to the operator. A hinge is attached to the belt of this element, on which two links are attached, in one of which a hydraulic compensator is installed, and the other, on a one-coordinate hinge, is attached to the compensator rod. Further, the second link is attached through the cuff to the operator's shoulder on one side, and on the other hand, it is connected through an inextensible cable with the first link. An electromechanical drive is attached to link number two, which, by increasing the length of the link, also increases the load compensation.

At a working height of 150 to 200 cm, passive devices with an elastic compensation module have a weak degree of compensation, since the elastic elastomer has almost no tension. To improve efficiency, a controlled electric drive based on a DC motor and a ball screw is installed in the design.

On fig. 2 shows a general view of the exoskeleton design, developed to operate at a height of 150 to 200 cm.

Fig. 2. Appearance of the upper limbs exoskeleton.

3 Design features of the upper limbs exoskeleton

The device is an anthropometric textile base, which is tightly fastened to the operator. A hinge is attached to the belt of this element, on which two links are attached, in one of which a hydraulic compensator is installed, and the other, on a one-coordinate hinge, is attached to the compensator rod. The second link is attached through the cuff to the shoulder of the operator on one side, and on the other hand it is connected through an inextensible cable with the first link. An electromechanical drive is attached to link number two, which, by increasing the length of the link, also increases the load compensation.

In addition to the main modules that produce the main compensatory effect, a certain base plays an important role in industrial exoskeleton complexes, on which the main mechanisms will be located, and which, directly, will become an intermediate link between a person and an exoskeleton. In most industrial exoskeleton complexes for supporting the upper limbs, a kind of textile vest or backpack acts as a support base, which is securely fixed on the operator’s body and evenly distributes the load from the exoskeleton throughout the human body in such a way that the weight of the product and load is not felt by the worker. Docking with a person occurs by analogy with a backpack - through slings and fastexes, as shown in fig. 3.

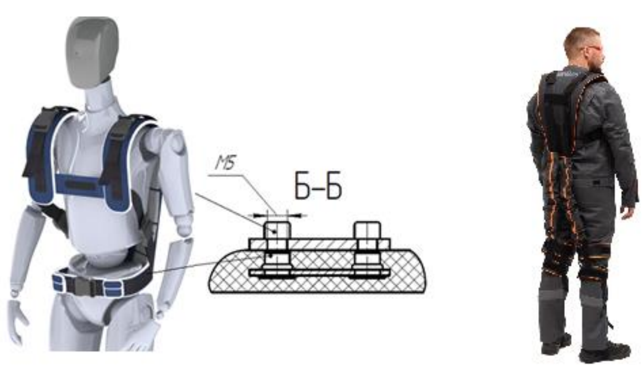


Fig. 3. Pairing the soft exoskeleton with the operator's torso.

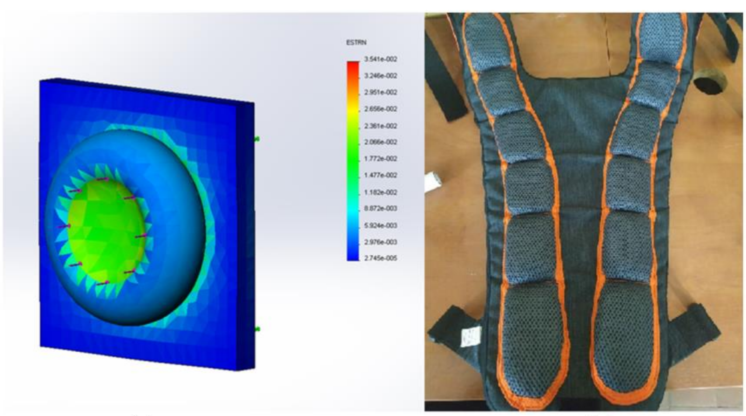
As you can see, this product is no exception. A special textile vest-backpack was developed for him. This module combines strength and reliability, and at the same time has all the parameters to ensure that the comfort of using the exoskeleton remains at a high level. These characteristics have been achieved through an iterative design approach and close contact with manufacturing.

This rucksack vest uses a three-material multi-layer inner lining. Since the textile structure in this exoskeleton serves as a link between the person and the compensating element, it must be rigidly fixed in order to avoid various backlashes and shortcomings in the operation of the entire structure. To do this, metal is riveted inside the vest through the EVA (Ethylene-vinyl acetate), and then it is screwed to the brackets of the compensating elements through threaded rivets. The rigidity of the EVA in this product also plays an important role. To avoid unscrewing the structure under load, at the junction of metal and textile, it is necessary to put a sufficiently strong EVA – at least 50 Shore hardness units, depending on the load. In this product, materials with hardness up to 70 Shore are used in some places.

In this product, the choice of fabric is very important. In many workplaces where the use of an exoskeleton complex is necessary, unfavorable working conditions are very common [15-18]. Various splashes of technical fluids, high temperatures and ordinary mechanical damage should not disable the product or slow down the workflow of an employee of the enterprise. Therefore, when choosing a fabric, you need to consider all of the above factors. The textile basis of the exoskeleton uses Oxford fabric with a density of 120g/m2 (300D) with water-repellent impregnation. Also, various refractory materials were considered for the enterprises of the coal and metallurgical industries. On fig. 3 shows a textile base in combination with passive elastic expansion joints.

An important role in the operation of the exoskeleton complex is played by how convenient it is for the operator to work in it, because being in the product requires a work shift of 8-12 hours, so that the unloading of certain joints occurs evenly and there are no relapses of chronic diseases, as a result of a sharp application of the load. We call this parameter operating comfort, and in order to achieve performance that satisfies the operator, a number of additions were introduced into the vest. For example, such as ventilation pads in the front of the product – similar ones can be found on tourist and hiking backpacks. The bottom line is to distance the human body and reduce its contact area with the product and thereby avoid excessive sweating and discomfort caused by it.

In Solidworks, using the Simmulation tool, a study of the static loading of a fragment of the fastening system was carried out. The research results are shown in fig. 4.



(a) (b)

Fig. 4. Results of the static analysis of the suspension attachment (a) and the appearance of the exoskeleton vest.

A simplified model of the design of the textile base of the exoskeleton was taken to correctly assess the force acting on the spacer elements of the product. A force was applied to this structure, which is equal to the maximum load experienced by this part of the product during the active execution of technological operations, namely 50N. The materials were specified in accordance with real analogues, subsequently installed in the exoskeleton vest, which is shown in Fig. 4. Based on the simulation results, it can be seen that the deformation in the foam element is 35mm, which is an acceptable parameter, with a total height of 40mm. Thus, a layer of air remains between the spacer elements, which provides the necessary ventilation and helps to avoid excessive sweating and discomfort.

For additional comfort during operation, it was decided to add a special layer of polyurethane foam to soften the contact points of the operator with the product.

Despite the importance of operating comfort when wearing the exoskeleton complex, the main role in the quality criteria of the product is played by its compensatory effect.

4 Math modeling of the upper limbs exoskeleton

Consider the kinematic scheme of the mechanism shown in Fig. 5.

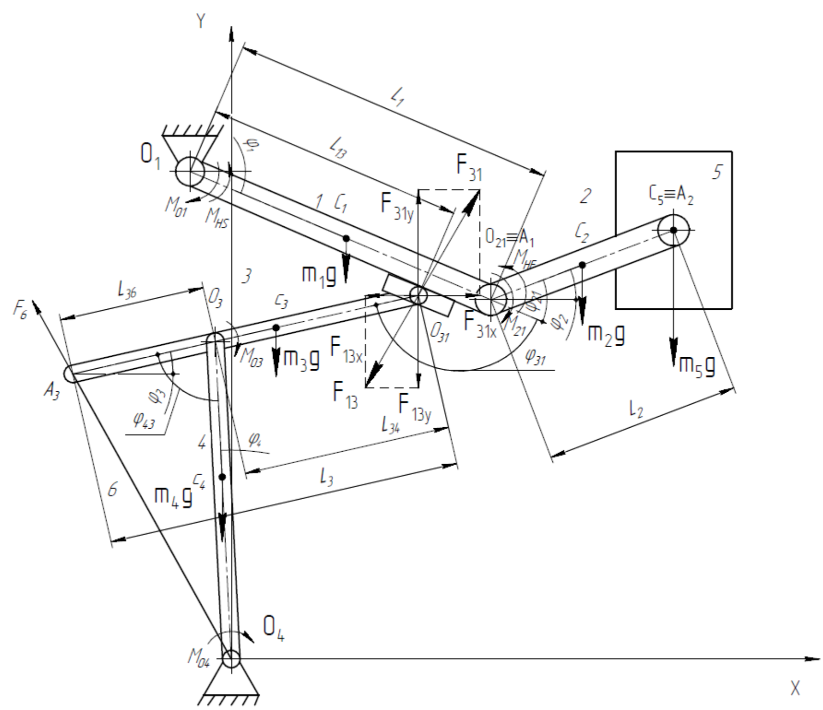


Fig. 5. Kinematic calculation scheme of the exoskeleton.

To analyze the kinematic structure, it is necessary to know the number of degrees of freedom of the mechanism, therefore, it is necessary to use the Chebyshev formula for flat mechanisms, according to which the total number of degrees of freedom of the kinematic structure relative to the fixed link (base) is determined by the relation:

$$W=3(n-1)-2P5-P4 \tag{1}$$

where n – is the total number of links in the kinematic chain; p is the number of kinematic pairs with degrees of freedom. Thus, from the above calculations it follows that the designed structure has one degree of freedom.

For an adequate analysis of the compensating effect of the exoskeleton, it was decided to first simulate a human hand under a load of 15 kg without auxiliary actions from the product. On the model, a person performs flexion in the shoulder joint, as this is one of the basic exercises that are found everywhere in production.

When creating the model, the following assumptions were made:

• joint are considered ideal;
• the object is considered as fixed;
• we neglect the size and shape of the human hand, assuming that the contact of the links with the surface occurs through points.

Based on the modeling tasks in this work, the first step is to find the forces that act on the upper limb of a person when lifting a load.

Let's make the equations of the moments for a hand:

$$T_1 = [(m_1 + m)a_1^2 + m_2a_2^2 + 2m_2a_1a_2cos\varphi_2]\ddot{\varphi}_1 + [m_2a_2^2 + m_2a_1a_2cos\varphi_2]\ddot{\varphi}_2 - m_2a_1a_2(2\dot{\varphi}_1\dot{\varphi}_2 + \dot{\varphi}_2^2)sin\varphi_2 + (m_1 + m_2)ga_1cos\varphi_1 + m_2ga_2\,cos(\varphi_1 + \varphi_2) \quad (2)$$

$$T_2 = [m_2a_2^2 + m_2a_1a_2cos\varphi_2]\ddot{\varphi}_1 + m_2a_2^2\ddot{\varphi}_3 + m_2a_1a_2\dot{\varphi}_1^2\,sin\,\varphi_2 + m_2ga_2cos(\varphi_1 + \varphi_2) \quad (3)$$

Thus, the value of φ is obtained:

$$\varphi = \begin{bmatrix} \sum_{i=0}^{5} a_i t^i \\ 0 \end{bmatrix}, \dot{\varphi} = \begin{bmatrix} \frac{\Delta\varphi_1}{dt} \\ 0 \end{bmatrix}, \ddot{\varphi} = \begin{bmatrix} \frac{\Delta\dot{\varphi}_1}{dt} \\ 0 \end{bmatrix} \quad (4)$$

Mathematical models and graphs obtained in the Matlab/Simmulink environment will be considered as methods for studying cargo compensation by an exoskeleton complex. For the objectivity of calculations, it is necessary to first simulate a person's hand with a load, and then with active compensation (with the maximum extended arm of the electric drive).

Let's place a load equal to 15kg on the end of a person's arm and simulate raising the arm 45 degrees from the vertical.

As a result, we get graphs of the moment and the reaction force, which is directed to the shoulder, which can be seen in Fig. 6 on top.

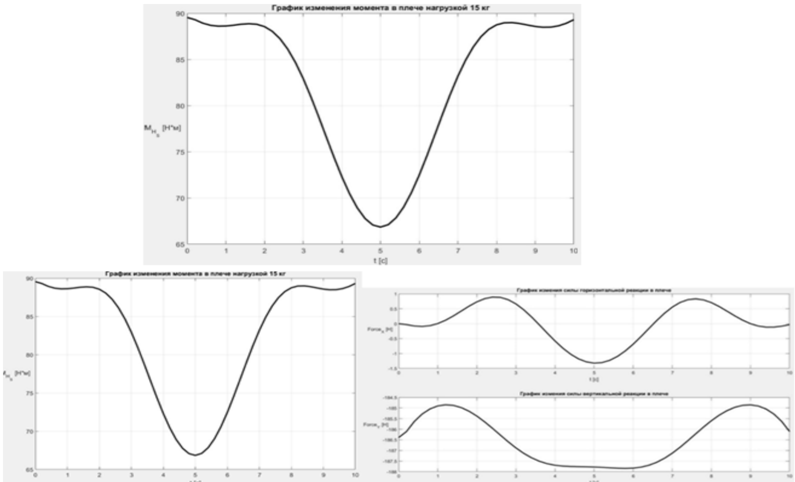


Fig.6. Results of numerical simulation of the exoskeleton system.

Based on this graph, it can be seen that the peak moment is reached by the operator in the first second of simulation and is approximately 90 N. Fig. 6 shows a graph of the change in the reaction force. Analyzing this graph, you can see that the force varies within 188N throughout all ten seconds. If we fit the simulation of raising a hand in two seconds instead of ten, then we can get the graph shown in Fig. 6 from below.

Get the equations necessary for modeling the exoskeleton complex of the upper limbs, based on the diagram shown in Fig. 5.

$$M_{O2} = -0.5m_2g\ L_2cos(\varphi) - \ m_5gL_i\ cos(\varphi_2) \tag{5}$$

$$\ddot{\varphi}_{21} = \frac{(M_{HF}-M_{21})}{J_2} \tag{6}$$

Substituting the values of M_{21}, we get the following:

$$\ddot{\varphi}_{21} = \frac{(M_{HF}-0.5m_2g\ L_2\cos(\varphi)- m_5gL_i\cos(\varphi_2))}{J_2} \tag{7}$$

Let's write down the equations describing the movement of the moving part of the exoskeleton:

$$\ddot{x}_{031} = \frac{-F_{13}+F_{6x}-F_{6x}+F_{31x}}{\sum m_i}(i = 1 \ldots 5) \tag{8}$$

$$\ddot{y}_{031} = \frac{-\sum_{i=1}^{n=5} m_ig+F_{31y}-F_{13y}+F_{6y}+F_{6y}}{\sum_{i=1}^{n=5} m_i} \tag{9}$$

Below are moment equalities for other parts of the exoskeleton complex:

$$M_{O3} = -mg(L_{34} - 0.5L_3)\cos(\varphi_3) - F_{13y}L_{34}\ \cos(\varphi_3) + F_{31y}L_{34}\cos(\varphi_3) - \\ -F_6L_{36}\cos(\varphi_3), \tag{10}$$

where $L_{36} = f(F_{13} - F_{31})$

$$\ddot{\varphi}_3 = \frac{M_{O3}}{J_3} \tag{11}$$

Substituting the values of M_{O3}, we get the following:

$$\ddot{\varphi}_3 = \frac{M_{03} = -mg(L_{34} - 0.5L_3)\cos(\varphi_3) - F_{13y}L_{34}\cos(\varphi_3) + F_{31y}L_{34}\cos(\varphi_3) - F_6L_{36}\cos(\varphi_3)}{J_3} \quad (12)$$

$$M_{O1} = M_{HS} - 0.5m_1gL_1\cos(\varphi_1) - c_{2x}A_{2x}m_5g + F_{31y}L_{13} - F_{13}L_{13} \quad (13)$$

$$\ddot{\varphi}_1 = \frac{M_H + M_{HF} - M_{O1}}{J_1} \quad (14)$$

Substituting the values of M_{O1}, we get the following:

$$\ddot{\varphi}_1 = \frac{M_H + M_{HF} - M_{HS} - m_1g*L_1*0.5\cos(\varphi_1) - c_{2x}*A_{2x}*m_5g + F_{31y}*L_{13} - F_{13}*L_{13}}{J_1} \quad (15)$$

Next, we will create a block diagram of the exoskeleton, which is shown in Fig. 7 in the MATLAB program in the Simulink environment. In addition, there is a frame from the animation of the exoskeleton.

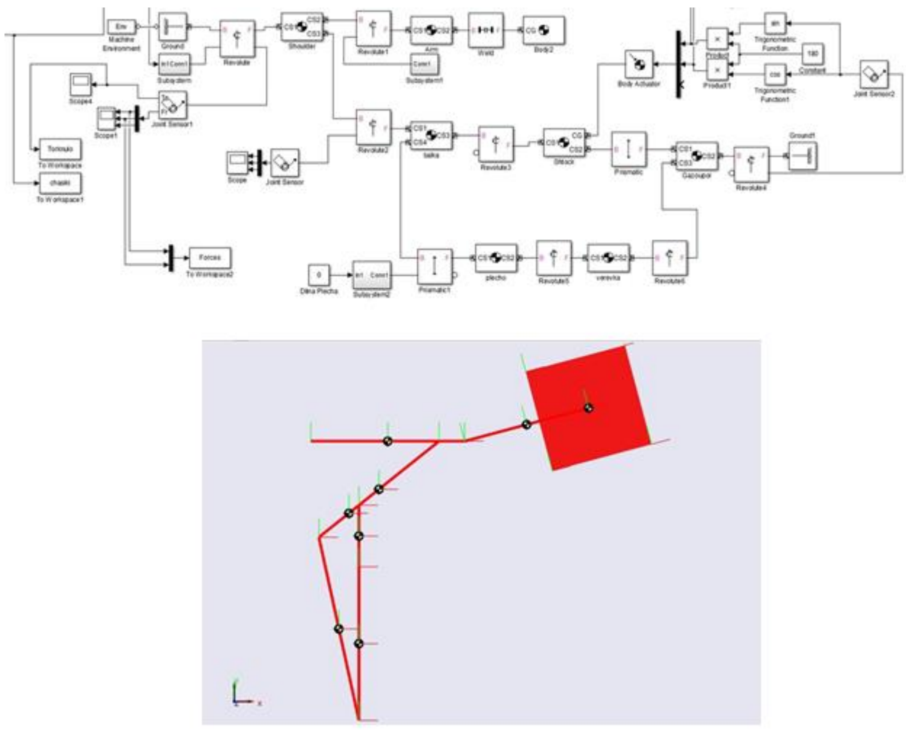


Fig.7. Exoskeleton model in MATLAB/Simulink.

From this block diagram, graphs of the moment and reaction force in the operator's shoulder can be extracted. These graphs are presented in fig. 8.

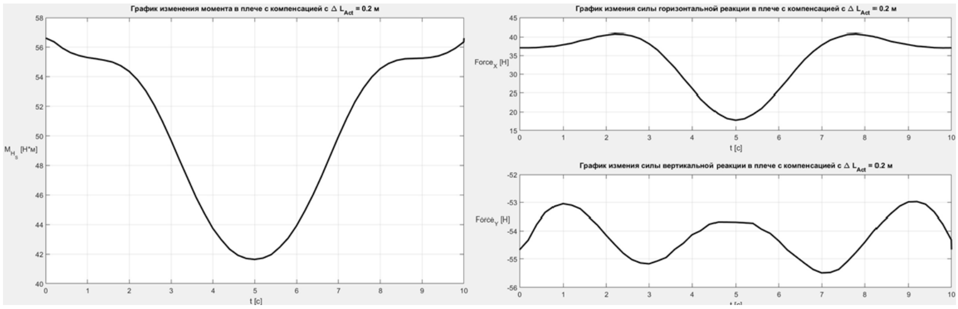


Fig.8. Simulation graphs with an increase in the shoulder by 0.2m, which was provided to us by a linear drive.

5 Conclusions

Comparing this graph with the first one, in which there is no exoskeleton impact on a person, we can conclude that we managed to achieve moment compensation within 35N, which is 40% of the total moment on a person with a load of 15kg.

Analyzing these graphs and comparing them with the original ones, where there was no compensation from the exoskeleton, we can conclude that the vertical reaction in the shoulder decreased by 133N, which is 70% of the entire reaction that appears in the human shoulder as a result of lifting a load of 15 kg. Thus, the compensating effect of the exoskeleton complex removes about 70% of the load on the shoulder joint from the operator when working with a load of 15 kg.

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