Section **VI** **BIOMECHANICS AND SPORTS ENGINEERING**
Секція **БІОМЕХАНІКА ТА ІНЖЕНЕРІЯ СПОРТУ**

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SYNTHESIS OF A PASSIVE UNLOADING ORTHOSIS WITH MECHANICAL FEEDBACK

Abstract. The development of new assistive devices for walking requires a high quality design implementation of the synthesized devices and taking into account additional requirements for a biomechanical system. In this paper, the existing designs of orthoses with passive unloading are analyzed and ways to expand their functionality are considered. It is shown that the presented designs of unloading knee orthoses have linear elastic characteristics, which cannot provide an extension of the functionality of these auxiliary devices. The paper proposes an improvement of the presented structures of passive unloading orthoses by adding mechanical feedback to their design. The study was carried out using the theory of modified kinematic graphs, which determines the analysis and synthesis of passive elastic devices with the possibility of self-management. Based on the kinematic schemes of the considered orthoses, models in the form of structural graphs were obtained and a further possibility of expanding the functionality of the synthesized device by adding an additional mechanical structure was determined. The analysis of synthesized passive orthoses with added controls was carried out, which showed their full performance and expansion of control capabilities. Also, according to the results of the analysis, the optimal variant of the synthesized device was chosen with its subsequent design implementation using Autodesk Inventor Series CAD. Based on the results of the study, it is shown that the use of the proposed theory of modified kinematic graphs is an effective means of synthesizing new self-controlled orthoses.
Key words: kinematic graph, knee orthosis, mechanical connection, device synthesis, elastic system.

Introduction

The high intensity of life dictates new requirements for the physical activity of a modern person. To improve the quality of performing various tasks, it is necessary to resort to the help of special auxiliary devices. To solve problems related to stabilization, unloading and correction of anatomical and biomechanical axes, protection of joints and segments of the musculoskeletal system, it is customary to use static and dynamic orthoses.

The main task of passive-unloading orthoses is to implement the target elastic characteristics of limb unloading, which are characteristic of a particular person or generalized with a certain characteristic of its movement. The existing designs of passive unloading orthoses with metal elastic elements are most often able to realize only a linear elastic characteristic. In this regard, the ability to control the rigidity of an elastic system is extremely limited. This excludes the possibility of the target elastic characteristics being realized by such orthoses. Improving the functionality of passive resilient unloading orthoses by adding an additional mechanical structure with controls can help solve this problem.

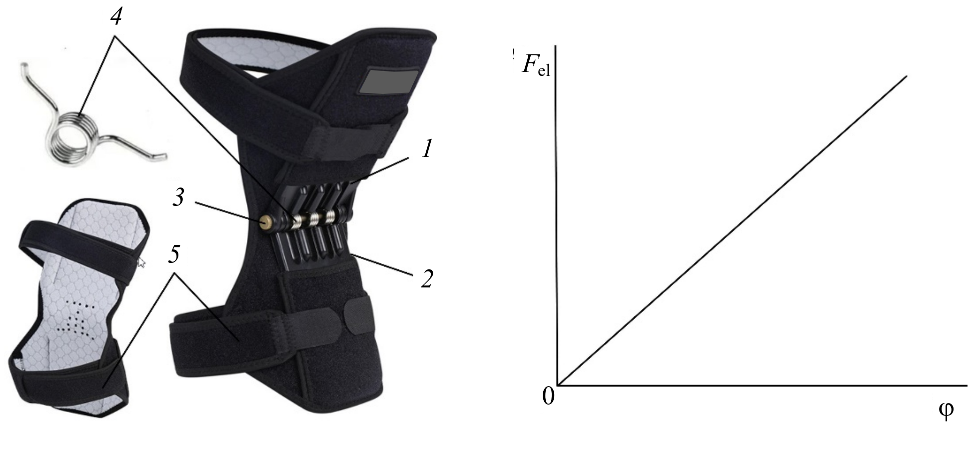
Considering all of the above, the synthesis and further analysis of fundamentally new unloading orthoses with metal elastic elements is extremely important, the functionality of which, in reproducing the target elastic characteristic, is expanded due to the introduction of additional mechanical structures into their basic structure that cause feedback.

Literature review

An orthosis is an external orthopedic device for stabilizing, unloading and correcting anatomical and biomechanical axes, protecting joints or segments of the musculoskeletal system. Orthoses are designed to increase human strength and endurance [1, 2]. Orthoses can also be described as redundant mechanical and/or electromechanical (mechatronic) devices. When applied to the human body, they form biomechanical systems. Orthoses are intended for the rehabilitation and support of the functions of the human musculoskeletal system. Also, some designs of orthoses provide for the correction of problems associated with age-related changes in the human body [3]. Sitting-standing movement is a daily activity that requires significant torque generation and coordinated movement in several joints at once [4]. Knee braces help to reduce the torque in the human knee joint, as well as change the biomechanics of the whole body, in particular, increase the linear momentum of the upper body and reduce the anterior deviation of the center of mass. The main requirements for the design of orthoses are portability, efficiency, ergonomics and low cost.

Existing unloading orthoses are usually elastic systems. Considering them as mechanical systems, such devices can be divided into passive, operating solely due to elasticity and dissipation, and active, requiring some control system, devices for changing elastic and dissipative characteristics, and sometimes an external power source [5, 6]. Despite the variety of designs of existing orthoses, their design can be improved taking into account the individual needs of a person [7].

So, for example, there is a passive knee orthosis with metal elastic elements that are installed in parallel and form an elastic system, due to which the orthosis has a relief effect on the knee joint (Fig. 1, *a*). But, the elastic characteristics of this orthosis are linear and do not quite coincide with the biomechanical parameters required in this case (Fig. 1, *b*).



a *b*

Fig. 1. Passive elastic unloading orthosis of the knee joint with metal elastic elements: appearance and components of the orthosis (*a*); elastic characteristic of the orthosis (*b*); *1*, *2* – base plates, *3* – axle, *4* – torsion springs, *5* – fabric segment with belts, reinforced with plastic mesh.

To implement the target elastic characteristics in the unloading orthosis and thereby expand its functionality, it is possible to use special fixators, rollers or cams in the orthosis design to more accurately reproduce the desired elastic characteristic [8, 9]. So, there is an unloading orthosis with an additional mechanism that provides some control over its elastic characteristics. A spring block is built into this design, which creates (in addition to the action of muscles) certain external elastic forces in the joint [10, 11]. According to the creators of this design, the rational selection of spring parameters can reduce the amount of muscle effort in a given orthopedic joint (Fig. 2). When roller 5 is rotated clockwise or counterclockwise, the elastic characteristic of the orthosis changes due to the direction regulator, and the system works as an assistant when walking (Fig. 2, *a*) or squatting a person (Fig. 2, *b*).

Considering that the presence of an additional mechanical element in this design in some way affects its elastic characteristics, it is quite obvious that the use of a specialized scientifically based approach to the synthesis of such devices will be very effective and will provide more significant results.

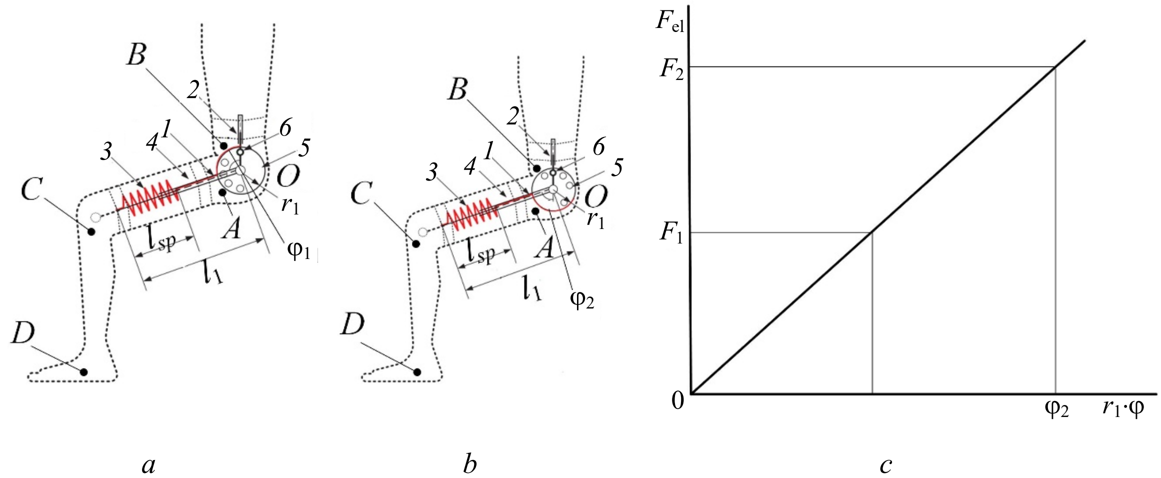


Fig. 2. Unloading orthosis with an adjusting roller: application when walking (*a*); application when squatting (*b*); elastic characteristic of the orthosis (*c*); *1*, *2* – telescopic links; *3* – elastic element; *4* – cable; *5* – roller; *6* – retainer

Research method

The synthesis of a new device and the determination of the design differences of several devices in this work is based on the theory of Professor I.I. Sidorenko, which determines the analysis and synthesis of passive elastic devices with the possibility of self-tuning (controlled change of one or more parameters) based on modified kinematic graphs [12].

The advantage of a graph as a modeling tool is that it allows you to combine physically related parameters of different nature, for example, displacement – force, for elastic systems. All functional interactions between the elements of the simulated device, which do not lead to the formation of real kinematic pairs, but cause the presence of elastic or dissipative bonds, are represented as virtual kinematic pairs of the 4th class. In this case, it is possible to model the full functional interaction of the device elements and determine the relationship between changes in its kinematic and non-kinematic characteristics. This makes it possible to carry out the synthesis of passive self-controlled devices with a mechanical control system, which have extended functionality, in contrast to existing uncontrolled devices of the same purpose.

Usually, the use of a model in the form of a kinematic graph allows one to judge the degrees of freedom of a mechanical structure, so for a flat mechanism, the degree of freedom will be:

$$W = 3(p_{\Sigma} - 1) - 2q_5 - q_4 - q_c \pm k \, , \tag{1}$$

where p_{Σ} is the number of poles of the kinematic graph, which determine the moving links of the mechanism; q_5 is the number of graph edges that determine kinematic connections in the form of kinematic pairs of the 5th class; q_4 is the number of graph edges that determine kinematic connections in the form of kinematic pairs of the 4th class; k – excess connection (mobility), if the mechanism is not rational; q_c is the number of graph edges equal to the number of non-kinematic links (elastic, dissipative, etc.) between the rigid links of the device, while this component does not affect the kinematic characteristics of the device and can be considered as an excess kinematic pair.

During modeling, the following principles should be used [12] – an idealized representation of the structure of an ordinary flat passive elastic (dissipative) device with one parameter subject to controlled change (causing a self-controlled device) is a modified kinematic graph (not bipartite), characterizing its mobility by the following condition:

$$W = 3(p_{\Sigma} - 1) - 2q_5 - q_4 - q_c = 1 - q_c, \quad (2)$$

where p_{Σ} is the total number of graph vertices corresponding to the number of rigid links of the device; q_5 is the number of graph edges, equal to the number of kinematic pairs of the 5th class; q_4 is the number of graph edges, equal to the number of kinematic pairs of the 5th class.

The next principle is that the nature of self-management by the properties of a device, when it is modeled by a modified kinematic graph, can be judged using an indicator in the form of a cyclomatic number:

$$\sigma = q - p + 1 \geq 2, \quad (3)$$

where q is the number of graph edges, regardless of the type; p is the number of graph vertices, regardless of their type.

The third principle is that more detailed information about the analyzed or synthesized mechanism is given by the addition matrix, which is a more detailed analogue of the adjacency matrix and determines not only the presence of a contact, but also gives an idea of its characteristics.

Determining constructive differences in several models at the same time, analyzing their graph models by element-by-element comparison of their cycles, is a rather difficult task. This is especially true for multi-element models, where the number of cycle elements can be very significant. In this case, it is recommended to use adjacency matrices M, in which 0 or 1 are entered – respectively, the absence or presence of contact between the elements of the device p_i:

$$M = \begin{array}{c|c|c|c|c} & p_1 & p_2 & \cdots & p_i \\ \hline p_1 & 0 & 1 & 0 & 1 \\ \hline p_2 & 1 & 0 & 0 & 0 \\ \hline \cdots & 0 & 0 & 0 & 1 \\ \hline p_i & 1 & 0 & 1 & 0 \end{array}, \quad (4)$$

where i is the number of device elements.

By using the assembly matrix M^*, which is an extended version of the adjacency matrix, more efficient analysis can be performed in terms of identifying design differences. The difference between the assembly matrix and the adjacency matrix is that the existing contacts are given weight coefficients q_n, which determine n classes and types of both kinematic contact and non-kinematic connection types:

$$M^* = \begin{array}{c|c|c|c|c} & p_0 & p_1 & \cdots & p_i \\ \hline p_0 & 0 & q_1 & q_2 & 0 \\ \hline p_1 & q_1 & 0 & \cdots & q_n \\ \hline \cdots & q_2 & \cdots & 0 & q_1 \\ \hline p & 0 & q_n & q_1 & 0 \end{array}, \quad (5)$$

It should be noted that the use of an assembly matrix similar to (5) in the analysis of the structural difference of systems that have many elements in their composition allows you to quickly and without errors find the existing design differences.

The criterion for choosing between the synthesized devices is the minimum energy of the graph [12]. This approach is widespread and is based on the principle of minimum energy of an optimal mechanical system, which is determined by the graph corresponding to it. The energy of the graph is represented as the sum of the absolute values of the adjacency matrix:

$$E(M) = \sum_{i=1}^{n} |\lambda|_i , \qquad (3)$$

where λ_i, $i = 1, \ldots, n$ are the eigenvalues of the adjacency matrix.

Results

Two of the most common designs of passive unloading orthoses of the knee joint were selected for analysis (Fig. 1, *b* and Fig. 2). In this case, the orthosis (Fig. 2) will be called the sample for analysis *AA*, and the orthosis (Fig. 1, *b*) – the sample for analysis *AB*.

For an idealized representation of the presented samples, their computer 3D models were created. Checking their kinematics using Autodesk Inventor Series confirmed their performance and allowed to obtain the corresponding kinematic diagrams. On the basis of kinematic schemes, models of the devices under consideration were obtained in the form of kinematic and modified kinematic graphs, followed by determination of the differences between the obtained models (Fig. 3).

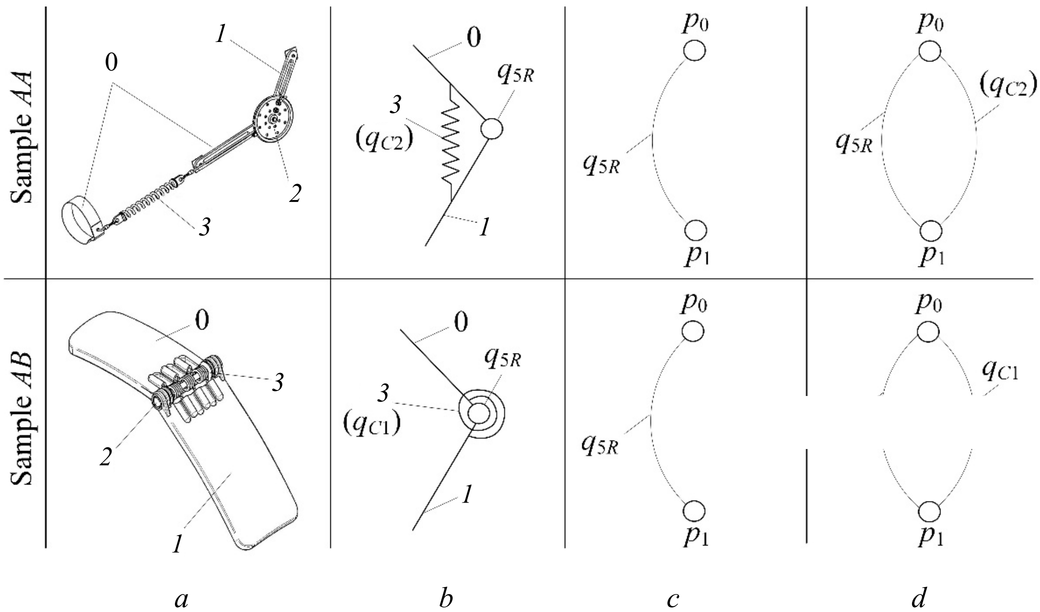


Fig. 3. Idealized representation of the basic device: 3D computer model (*a*); kinematic diagram (*b*); kinematic graph (*c*); modified bipartite kinematic graph (*d*)

The simulation was carried out with the calculation that: the expected orthoses are flat elastic mechanisms; p_i is a vertex of the graph from the total number p_Σ, which perceives the *i*-th element of the orthosis with a high numerical rating; the numbering of the vertex in each of the graph models starts with the vertex p_0, which determines the fixed link 0, for example, on the lower leg; for the edge of the graph q_5, compliance with the functional contact interaction between the sense organs (0 – on the lower leg and *1* on the thigh) and corresponds to the kinematic pair of the 5th class. For a more detailed structuring of the model, possible types of such a rib are accepted, which correspond to a rotational and translational kinematic pair (q_{5R} and q_{5T}, respectively). For simplification, it is assumed that the orthosis has one elastic element, the presence of which determines the elastic characteristic, which must be changed in a controlled manner, which causes the presence in the model of a connection (graph edge) $q_{C1} = 1$ or $q_{C2} = 1$, depending on the type of elastic element used.

For the obtained models of samples, the calculation of the degree of freedom and the definition of self-control was carried out, both on the basis of the model in the form of a kinematic and modified kinematic graphs (Table 1). Based on the results of the kinematic graph calculation, the considered orthoses are non-self-controlled flat passive elastic devices with one parameter, which can be subject to controlled change.

Table 1

Calculation of the degree of freedom by graph models, determination of signs of self-governance

Sample	Degree of freedom when modeling with a kinematic graph by expression (1)	Degree of freedom in the case of modeling by a modified kinematic graph by expression (2)
AA	$W = 3(2 - 1) - 2 \cdot 1 = 1$	$W = 3(2 - 1) - 2 \cdot 1 - 1 = 0$ Bipartite graph - the condition is not met, the device is not self-managed
AB	$W = 3(2 - 1) - 2 \cdot 1 = 1$	$W = 3(2 - 1) - 2 \cdot 1 - 1 = 0$ Bipartite graph – the condition is not met, the device is not self-managed

Having calculated the cyclomatic number by expression (3) for the obtained models (Table 2.), it can be argued that the considered models of orthoses in the form of MKG (modified kinematic graphs) have one cycle. One cycle always determines the main functional interaction of the orthosis elements, which determines their performance (hereinafter referred to as the main cycle), and the other (if any) determines self-control – determines the functional interaction of the orthosis elements, providing a controlled change in its specific parameter (in the subsequent control cycle).

Table 2

Calculation of the cyclomatic number for models in the form of modified kinematic graphs (expression (3))

Sample *AA*	Sample *AB*
$\sigma = 2 - 2 + 1 = 1$; condition is not met	$\sigma = 2 - 2 + 1 = 1$; condition is not met

Based on this, the determination of the corresponding cycles for the studied samples was carried out (Table 3).

Table 3

Definition of the main cycle and the control cycle based on the calculation of the cyclomatic number of models in the form of MKG

№	Cycles	Sample *AA*	Sample *AB*
1.	Main cycle	$p_0 - q_{5O} - p_1 - q_{C1} - p_0$	$p_0 - q_{5O} - p_1 - q_{C2} - p_0$
2.	Control cycle	is absent	is absent

The use of adjacency matrices (4) for the models under consideration and their subsequent comparison by the subtraction operation determines the zero matrix, which indicates the identity of the adjacency matrices for models *AA* and *AB*. Based on this, the orthoses in question are also identical in their structure, but are not identical at all. For the samples under consideration, the following weighting coefficients were introduced: q_{5R} weighting coefficient – 1; elastic contact q_{C1}, due to the tension spring, has a weighting factor of 2; elastic contact q_{C2}, due to the helical rotation spring, has a weighting factor of 3. Then, after applying the addition matrix (5) and comparing them with the subtraction operation, a non-zero matrix was obtained, which determines the difference between the considered samples in terms of design and causes the revealed difference between the elements of the main cycles p_{C1} and p_{C2} (Table 3), which determine the difference in elastic contact between the links 0 and 1.

When synthesizing the structure of new devices based on the model of the basic device (Fig. 4, *a*), in order to minimize the number of possible solutions, the following restrictions were applied: the possible number of kinematic pairs of the 4th class $q_4 = 1$; the possible number of kinematic pairs of the 5th class $q_5 = 2$ and one additional link pd (which determines the replacement of the kinematic pair of the 4th class with two pairs of the 5th and one additional link according to Assur); the number of elastic elements is unchanged $q_C = 1$. The new structure of the orthosis must necessarily have one additional link p_2 (departure from the bipartite graph), which determines the presence of the edge of the graph q_C (contact with the elastic element to control the elastic characteristic of the device) and determines the creation of a translational (according to the accepted method of changing the elastic characteristic of the device) kinematic pair 5-th class with one of the links of the basic device, for example, from p_2 (Fig. 4, *b*).

Variations with the elements defined in the constraints, with the verification of the above synthesis conditions (Table 4, Table 5 and Table 6) made it possible to obtain two variants of the graph model of the device (Fig. 4, *c*). According to the obtained graph models, the kinematic schemes of the synthesized devices are reproduced (Fig. 4, *d*).

Table 4

Calculation of the degree of mobility, determination of signs of self-control

Sample	Degree of freedom in modeling by a modified kinematic graph (2)
1	$W = 3(4 - 1) - 2\cdot 4 - 1 = 0$; The graph is not bipartite - the condition is met, the device is self- control
2	$W = 3(3 - 1) - 2\cdot 2 - 1 - 1 = 0$; The graph is not bipartite - the condition is met, the device is self- control

Table 5

Calculation of the cyclomatic number according to the condition (3)

Sample 1	Sample 2
$\sigma = 5 - 4 + 1 = 2 \geq 2$ – the condition is met	$\sigma = 4 - 3 + 1 = 2 \geq 2$ – the condition is met

Table 6

Definition of the main cycle and the control cycle (cycles with a common edge)

№	Cycles	Sample 1	Sample 2
1.	Main cycle	$p_0 - q_{5O} - p_1 - q_C - p_0$	$p_0 - q_{5O} - p_1 - q_C - p_0$
2.	Control cycle	$p_0 - q_5 - p_2 - q_5 - p_3 - q_5 - p_1 - q_C - p_0$	$p_0 - q_4 - p_2 - q_5 - p_1 - q_C - p_0$

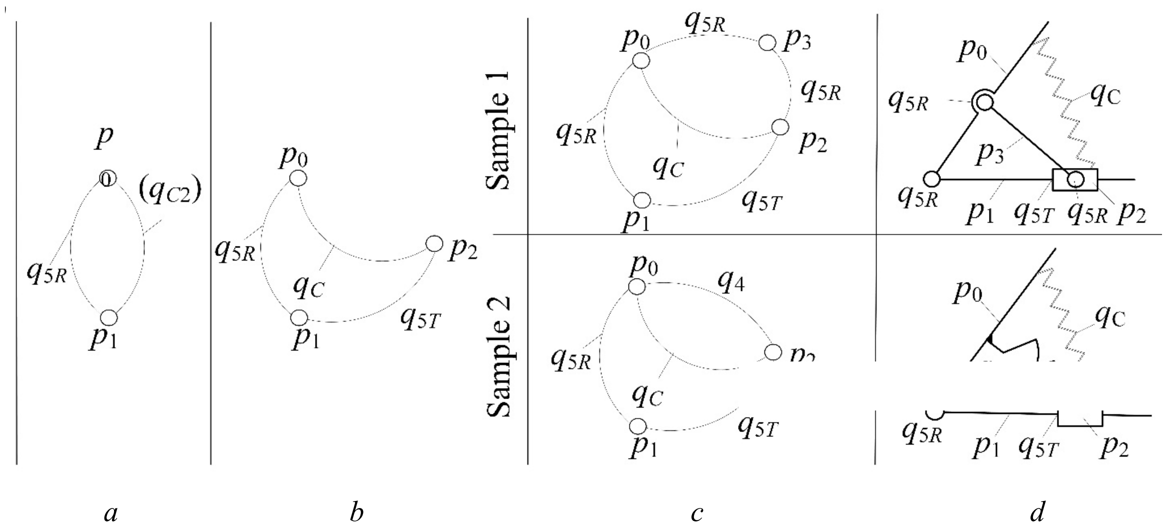


Fig. 4. Synthesis of a passive-unloading orthosis with an additional mechanical structure: modified kinematic diagram of the basic device (*a*); modified kinematic diagram of the device with controls (*b*); models of synthesized devices under synthesis conditions (*c*); kinematic schemes of synthesized devices (*d*)

To calculate the energy of the graph, instead of the adjacency matrices, its analogue was used – the addition matrix, which determines not only the presence of a contact and its necessity for constructive reasons, but also its type, technological complexity, etc. Depending on the type of contact, the edges of the models in the form of modified kinematic graphs (Fig. 4, *b*) were given the appropriate weighting coefficients (Table 7).

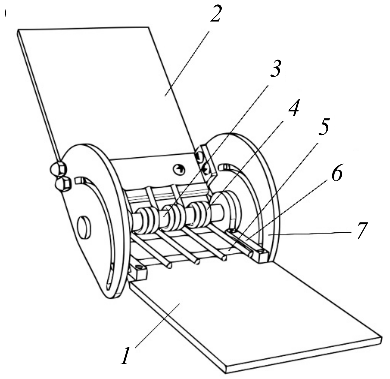
Table 7

Weight coefficients k_B of model edges in the form of modified kinematic graphs

№	Designation (Parameter name)	k_B	Note
1	q_C (Elastic connection)	1	Availability required
2	q_{5T} (translational kinematic pair of the 5th class)	2	Availability required
3	q_{5R} (rotational kinematic pair of the 5th class)	3	–
4	q_4 (kinematic pair of the 4th class)	4	–

Taking into account the weight coefficients in the addition matrix, characteristic matrices were compiled for the models of synthesized devices. After obtaining the characteristic polynomials and the roots of the characteristic polynomials for each matrix, the corresponding energies of the graphs were calculated using expression (6): $E(M_{C1}) = 12.58$, and $E(M_{C2}) = 11.46$. A discrepancy of 9 % in calculating the energy of graph models of synthesized devices allows us to determine that option 2 can be considered the best option, which has a kinematic pair of the 4th class in its structure, since the energy of its graph is the smallest [12].

The design implementation of the prototype of the synthesized device was carried out using the Autodesk Inventor Series CAD package based on the synthesized kinematic scheme determined as a rational one (Fig. 4, *c*, option 2). The device consists of links (langets) *1* and *2*, for fixing on the limbs, pivotally connected with the help of axis *3* (Fig. 5). The elastic system of the orthosis consists of twisted cylindrical helical (torsion) springs 4, the axes of which coincide with the axis of the hinge, one end of which is in contact with splint *2*, and the other with a cylindrical rod 5 moving in guides 6 fixed on splint *1*, while the axis is parallel hinge axis between splints. The ends of the cylindrical rod enter the curvilinear grooves of two adjusting sectors *7* fixed on the splint *2*.



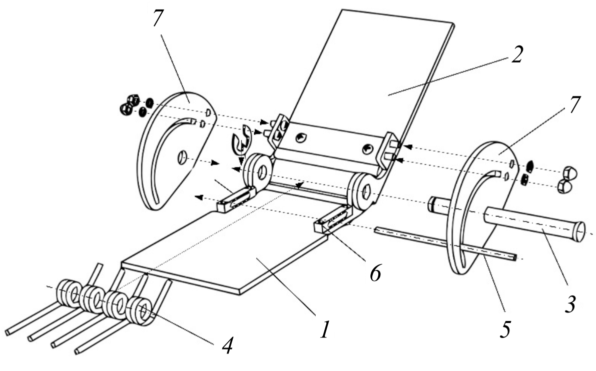


Fig. 5. Prototype of a passive unloading orthosis with mechanical feedback: design (*a*); assembly diagram (*b*)

The device works as follows, when the limb is bent, the angle between splints *1* and *2* changes, which causes deformation of the twisted cylindrical helical (torsion) springs *4*. Contact of one ends of the spring with a movable cylindrical rod causes a change in the load shoulder on them depending on the angle between the splints, since the rod is in contact with the curved grooves of the adjusting sectors *7* and, when they are rotated, has a linear movement along the guides *6*. The amount of linear movement of the cylindrical rod *5* along the guides *6*, depending on the angle between the splints, can be with a change in the direction of movement and is due to the shape of the curved groove in the adjusting sectors *7*, which causes the reproduction of the necessary (target) elastic characteristics of the orthosis.

It should be noted that in terms of its functional features, namely, the transformation of a controlled signal in the form of an angular displacement (in our case, the angle between the langets φ) into a corrective signal in the form of a displacement of a cylindrical rod *5*, which determines the change in the "point of application" of the load to the elastic element *4* according to the law , due to the shape of the curved groove on the adjusting sectors *7*, an additional mechanical structure, consisting of a cylindrical rod *5* and adjusting sectors *7*, is a feedback of the synthesized system implemented mechanically. From a mechanical point of view, the mechanical feedback of the synthesized device is a cam mechanism with kinematic closure. Since the shape of the curved groove can have different curvature and cause a non-linear corrective movement relative to a linear controlled one, the resulting mechanical feedback is characterized by a non-linear one. Thus, the synthesized orthosis can be attributed to a knee prophylactic passive unloading orthosis with metal elastic elements and non-linear mechanical feedback.

Conclusion

As a result of the synthesis, two fundamentally new structures of passive unloading orthoses with mechanical feedback were obtained. Their further analysis determined their full performance and the expected expansion of functionality. This indicates that the application of the accepted theory of modified kinematic graphs is an effective tool for the synthesis of new structures of self-controlled orthoses and allows you to get their workable prototypes with the least amount of time.

It has also been confirmed that the presence of an additional mechanical structure significantly expands the functionality of passive orthoses and brings their ability to reproduce elastic target characteristics closer to active ones.

It has been established that the elastic characteristics that can be reproduced using one of the synthesized devices, considered as the optimal solution, cannot be reproduced by any of the currently existing designs of passive orthoses.

The results of the synthesis and the given constructive implementation of a passive unloading orthosis with mechanical feedback can be used to create orthoses for other limbs, the biomechanics of which determines the rotation of one part of the body relative to another.

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