Laws of Motion of the Lower Extremities and Structural-parametric Synthesis of Electro-hydraulic Executive Modules of the Active Exoskeleton According to the Criterion of Energy Sufficiency

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Abstract. The object of the research is the electro-hydraulic executive modules (drives) of the exoskeleton of the lower extremities with a rigid structure of the power frame. The problem of schematic and parametric execution of modules located in the linkage joints of the exoskeleton which is used for verticalization of patients is considered. The aim of the study is to estimates energy consumption, sensitivity, establish a rational structure and parameters of modules that provide programmed movement according to the criterion of energy sufficiency. The laws of motion and diagrams of loads required for lifting a patient from a sitting position are presented.

1. Introduction
Currently, exoskeletons are increasingly being used in various fields of activity. One of the most important fields is medicine, where they are successfully used for the rehabilitation of patients with dysfunctions of the musculoskeletal system, in particular, verticalization of patients [1, 2]. For solving this problem, the most common are active exoskeletons of the human lower extremities, which have a rigid power frame. The most important and one of the primary groups of tasks in the development of such exoskeletons is the choice of looks and the optimal structural-parametric synthesis of the system of executive power modules (EM), which provide controlled movement of the movable links of the exoskeleton – the hip, lower leg and foot [3, 4].

A set of difficult and contradictory requirements is imposed on such EM: compactness, power capacity, responsiveness with increased power indicators, wide control ranges for speed and traction properties, stability of characteristic, elimination of conditions that are uncomfortable for the patient in
normal and emergency modes of operation, minimal noise and energy, reliability, safety of use, lack of service, autonomy (in the cases of some conditions of use), reasonable cost, etc. [5–7]

Traditional schematic design of EM (geared electric drives on the exoskeleton frame, pneumatic motors based on deformable shells – hoses, etc) either:
• repeat familiar and well-developed technical solutions from various fields of technology without taking into account the specifics of this system [3, 4]; (as an exception, we can note the works [8, 9] devoted to the development of a circular electro-hydraulic actuator used in the exoskeletons)
• limited by the available possibilities for completing in the absence of a commercially available machine and hardware base for a specific purpose [10,11];
• strive to correspond to the unsubstantiated opinion that devices that perform only certain functions inherent in humans should also copy the “natural” schematic design of the corresponding parts of the body (simplified principle of biomimicry in technology).

In terms of the set of requirements for EM, the most promising are adaptive electro-hydraulic modules with rotary movements of the output elements, built into the articulated joints of the moving links of the exoskeleton. These EM should have a united schematic and design performance, combined control, allow the use of both analog and discrete information signals, receive power from low-noise regulated power unit capable of operating in both volatile and autonomous modes (under specified operating conditions).

Optimizing the implementation of the system requires the solution of the following priority tasks presented in this work:
• determination of the laws of motion of the movable links of the exoskeleton during the verticalization of the patient, calculation of the parameters of the laws;
• establishing the type and parameters of load diagrams in the hip, knee and ankle joints of the movable links of the exoskeleton during vertical movement of the patient of various masses;
• estimating of energy consumption and determination of the principle of energy flow control in the EM, formation of a rational structure of modules;
• calculation of EM in the joints (hinges) of the links according to the criterion of energy sufficiency for the found laws of the patient’s verticalization.

2. Description of the system
We consider the structure of the exoskeleton of the lower extremities presented in Fig. 1. This design models each leg as three links connected by cylindrical joints.

![Figure 1. Kinematic scheme of the exoskeleton.](image-url)
The following designations are introduced on the scheme:

• $C_2$, $C_3$ и $C_4$ – are centers of mass of the lower legs, hips and body, respectively;
• $A_1$, $A_2$ и $A_3$ – are joints, connecting the links of the exoskeleton;
• $\phi_2$, $\phi_3$ и $\phi_4$ – are angles of rotation of the links of the exoskeleton, which are counted from the axis $x$ in the counterclockwise direction;
• $M_2$, $M_3$ и $M_4$ – are control moments created by drives located in the joints $A_1$, $A_2$ and $A_3$ respectively;

3. **Algorithm for calculating the parameters of an electrohydraulic actuator**

To calculate the main parameters of the power section of the electro-hydraulic EM, it is necessary to estimates the traction and speed characteristics required for the system to work. For this one can use a model of exoskeleton dynamics described by one of the methods [12–14], in particular, using the Lagrange formalism [15, 16]. In this case, the equations of motion have the form:

$$\mathbf{A}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{D}(\mathbf{q})\dot{\mathbf{q}}^2 + \mathbf{F}(\mathbf{q}) = \mathbf{P}(\mathbf{q}) = \mathbf{M},$$

where:

• $\mathbf{q} = (\phi_2, \phi_3, \phi_4)^T$ – is Lagrange coordinates vector, and $\dot{\mathbf{q}}^2 = (\dot{\phi}_2^2, \dot{\phi}_3^2, \dot{\phi}_4^2)^T$ – is the vector of squares of generalized velocities;
• $\mathbf{A}(\mathbf{q}) = \begin{pmatrix} J_2 & J_{23}c_{23} & J_{24}c_{24} \\ J_{23}c_{23} & J_3 & J_{34}c_{34} \\ J_{24}c_{24} & J_{34}c_{34} & J_4 \end{pmatrix}$ – inertial force matrix, and $J_2, J_3, J_4, J_{23}, J_{24}, J_{34}$ – reduced moments of inertia;
• $\mathbf{F}(\mathbf{q}) = \begin{pmatrix} 0 & J_{23}s_{23} & J_{24}s_{24} \\ -J_{23}s_{23} & 0 & J_{34}s_{34} \\ -J_{24}s_{24} & -J_{34}s_{34} & 0 \end{pmatrix}$ – velocity force matrix;
• $\mathbf{D} = \text{diag}(\mu_2, \mu_3, \mu_4)$ – matrix of dissipative forces having a diagonal form, and $\mu_2, \mu_3, \mu_4$ – viscous friction coefficients;
• $\mathbf{P}(\mathbf{q}) = (M_{G2} \cos \phi_2, M_{G3} \cos \phi_3, M_{G4} \cos \phi_4)^T$ – gravitational force vector, and $M_{G2}, M_{G3}, M_{G4}$ – constant values characterizing the maximum moments of gravity;
• $\mathbf{M} = (M_2 - M_3, M_3 - M_4, M_4)^T$ – is generalized forces vector corresponding to control moments.

Here are introduced abbreviations for writing trigonometric functions $c_{jk} = \cos(\phi_j - \phi_k), s_{jk} = \sin(\phi_j - \phi_k)$.

3.1. **Programm Motion and Loads Diagram**

Assuming the use of an exoskeleton in the task of verticalization patients, we will consider lifting a person from a sitting position as a programmed movement. Note that the problem of modeling the process of getting up using optimization methods was considered in [17]. The values of the angles in the joints at different times for the considered movement are given in Table I. Here, for the transition from the previous state $\phi_i(t_{k-1})$ to the next $\phi_i(t_k)$ the law of change of the angle $\phi_i$ is used in the form [18] (at $t \in [t_{k-1}, t_k]$):
Table 1. Joint Angles on Programm Motion.

| Time (t) | Joint angles |  |
|---------|--------------|---|
| 0       | \( \varphi_2 \), ° | \( \varphi_3 \), ° | \( \varphi_4 \), ° |
| 85      | 180          | 90            |
| 75      | 180          | 90            |
| 70      | 180          | 70            |
| 70      | 180          | 60            |
| 70      | 140          | 50            |
| 90      | 90           | 90            |

The graphs of angular velocities obtained with the above method of specifying the dependences of the angles of rotation are shown in Fig. 2.

![Angular velocities of joints](image1)

**Figure 2.** Angular velocities of joints.
Solving the equations of dynamics (1) with respect to the control torques, we obtain:

\[ M_4 = M_{c4} \cos \phi_4 + \mu_4 \phi_4 + J_{24} \left( \dot{\phi}_4 c_2 - \phi_2^2 s_2 \right) + J_{34} \left( \dot{\phi}_3 c_3 - \phi_3^2 s_3 \right) + J_4 \phi_4, \]
\[ M_3 = M_{c3} \cos \phi_3 + \mu_3 \phi_3 + J_{23} \left( \dot{\phi}_2 c_3 - \phi_2^2 s_3 \right) + J_{33} \left( \dot{\phi}_3 c_3 - \phi_3^2 s_3 \right) + J_3 \phi_3 + M_4, \]
\[ M_2 = M_{c2} \cos \phi_2 + \mu_2 \phi_2 + J_{22} \left( \dot{\phi}_2 c_2 + \phi_2^2 s_2 \right) + J_{32} \left( \dot{\phi}_1 c_2 + \phi_1^2 s_2 \right) + J_2 \phi_2 + M_3. \]  

Calculation of speeds and control torques according to the above formulas makes it possible to obtain load diagrams (LD) for considered program movement when lifting the patient. Fig. 3 shows LD for hip (a), knee (b) and ankle (c) EM at different weight and size parameters. The gray curves correspond to the mass of the “human – exoskeleton” system equal to 100 kg and the patient’s height of 200 cm, and the black curves correspond to the mass of 60 kg and the height of 160 cm.

3.2. Calculating Parameters of the Electrohydraulic Actuator

The analysis of the LD shows that the limiting values of the required power of the EM do not exceed 150 W, which allows the use of the throttle principle of power flow control, which is the simplest, lowest-cost (in terms of implementation) and gives compact technical and structural solutions [19].

The condition of energy sufficiency is formulated as a complete coverage of the entire set of LD by the mechanical characteristic (MC) of the executive module, which has the form of a parabola with apex on the axis of loads (torques) [20]:

\[ MX \geq \sum \Delta H. \]  

**Figure 3.** Load diagrams (black and gray solid lines) and mechanical characteristic (black dashed and dotted lines).
The conventionally “convex” form of the LD dominating in terms of energy consumption for the hip and knee joints makes it possible to calculate the drive part of such EM from the condition of combining the most energy-consuming (calculated) point with the mode of the highest available power of the MC. In this case, the optimization of the EM is achieved according to the criterion of energy sufficiency. For the ankle joint, the alignment of points is unattainable, and the minimum possible parabola of the MC only touches the particular LD at the points of the greatest required power. These calculated points are marked in Fig. 3, and parabolas of the MC are shown by dotted lines for an exoskeleton with a patient weighing 100 kg, and dashed lines – for a patient weighing 60 kg.

![Figure 4. Physical form of the executive module.](image)

Table II shows the rounded values of the coordinates of the calculated points, the highest available powers, the braking torques, the angular velocities of idling for the EM of the three hinges of the exoskeleton for a patient weighing 100 kg.

**Table 2.** The values of the parameters characterizing the load at the points of the greatest required power.

| System mass, kg | Parameter name | hip joint | knee joint | ankle legs |
|-----------------|----------------|-----------|------------|------------|
| 100             | Torque output, Nm | 80        | 300        | 250        |
|                 | Speed of the angular velocity, 1/s | 0,40      | 0,44       | 0,17       |
|                 | Power consumption, W | 32        | 132        | 42         |
| 60              | Torque output, Nm | 33        | 120        | 119        |
|                 | Speed of the angular velocity, 1/s | 0,43      | 0,44       | 0,13       |
|                 | Power consumption, W | 14        | 53         | 16         |

3.3. *Model of the Electrohydraulic Actuator*

From Table II it follows that to unify system of the exoskeleton’s executive module, all hinges can be equipped with the same EM. Although in order to reduce the mass, size and power indicators for each weigh group of patients, it is preferable to use EM of different standard sizes.

The appearance of the EM is shown in Fig. 4. The module includes:
• an electro-hydraulic amplifier that receives an electrical information signal from the control unit and is connected to the power supply unit by pressure and drain lines;
• rotary hydraulic motor of special design;
• sensor of the shaft rotation angle.

Table III presents the rounded calculated values of the volume constant (per radian of shaft rotation) of the rotary hydraulic motor EM, the characteristic size \( H \) of the module, the required fluid flow for the design mode, the nominal diameter of the hydraulic lines \( D_{np} \), depending on the pressure in the pressure hydraulic line, which is equal 6,3/12,5 MPa.

### Table 3. Calculated values of the Parameters of the Executive Module.

| System mass, kg | Parameter name | Parameter name | Parameter name |
|-----------------|----------------|----------------|----------------|
| 100             | Volumetric displacement, cm\(^3\)/rad | hip joint | 19/9, 6 | 71/3, 6 | 60/3, 0 |
|                 | Characteristic size, mm | knee joint | 65/5, 0 | 130/90 | 115/85 |
|                 | Flow demand, l/min | ankle legs | 0,5/0,2 | 1,9/0,9 | 0,6/0,3 |
|                 | Diameter of the conditional passage, mm |       | 2,0/1,2 | 4,2/3,0 | 2,4/1,7 |
| 60              | Volumetric displacement, cm\(^3\)/rad | hip joint | 8/4,0 | 29/4,4 | 28/1,3 |
|                 | Characteristic size, mm | knee joint | 50/3,5 | 85/5,8 | 85/5,8 |
|                 | Flow demand, l/min | ankle legs | 0,2/0,1 | 0,8/0,4 | 0,2/0,1 |
|                 | Diameter of the conditional passage, mm |       | 1,4/1,0 | 2,7/1,9 | 1,4/1,0 |

### 4. Results

As a result of this work:
• performed mathematical modeling of the states of the exoskeleton links during verticalization of patients;
• the characteristic laws of motion of the movable links of the exoskeleton have been established;
• load diagrams were obtained in the link joints for patients with different weights and heights;
• found a schematic and structural solution of the executive module for embedding in the hinges of the movable links;
• the module was calculated according to the criterion of energy sufficiency;
• the obtained schematic and design solutions make it possible to consider that the electro-hydraulic actuators installed in the hinges of the moving links of the exoskeleton increase the compactness and efficiency of the drive system of these devices.
5. Conclusion
Solving questions of the dynamics of the system EM, schematic design, optimization of the parameters and operating modes of the supply unit together with the EM system represent a separate group of tasks, the consideration of which is supposed to be performed in the following works on this topic.

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