Design of mechanisms of a robotic system for rehabilitation of the lower limbs

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Abstract. The article describes the main stages of developing a robotic system for the rehabilitation of the lower limbs based on the "tripteron" robot. The structure of a robotic system has been designed, consisting of a 3-PRRR parallel mechanism, which provides the angles of rotation of all joints of the patient's leg required for rehabilitation and a passive orthosis for supporting the limb. At the first stage, the positions of the active mechanism links are determined. The output link of only one kinematic chain, making a translational movement in the vertical direction, will experience a maximum load. A design diagram of this kinematic chain was built, and the reactions of the supports were determined at the second stage. At the third stage, kinematic dependences were obtained, and an engine was selected that would provide the required torque at the required speeds.

1. Introduction

There are currently many problems in practical health care, the optimal solution to which is the use of robotic tools. These tasks concern the treatment and rehabilitation of patients with disorders of the musculoskeletal system and the implementation of the functions of their self-service, social adaptation, and replenishment of the lost motor and communication functions. It should be noted that the need to create robotic aids for people with disabilities is steadily growing.

In any of the rehabilitation procedures, the treatment of patients with disabilities with impaired motor functions of the lower and upper limbs occurs in a critical sitting or lying position, since patients at this stage cannot control the movements of their limbs. Treating them using only the BWS (body weight support) system is difficult, as it requires a certain level of physical fitness. Continuous passive motion (CPM) is one of the most common therapies in the early stages of treatment when patients have low or uncontrollable limbs. Many CPM-based mechanisms intended for continuous or repeated therapeutic treatment cannot provide the required quality when performing continuous passive movement due to their complex design, high dynamic loads, and structural cumbersoness. These mechanisms include the commercially available devices for rehabilitation Motion maker [1] (Switzerland), and the Lambda mechanisms [2], the professional trainer Supine [3], NEUROBike [4], Physiotherabot [5], and AIST-Tsukuba [6]. The relevance of stationary rehabilitation robotization is due to the low cost relative to solutions such as exoskeleton [7]. The low-price segment of rehabilitation equipment consists of systems that provide circumferential movement of the legs, due to the pedal drive, this method covers only a small part of the required operations in gait rehabilitation. On the other hand, the exoskeleton is the ultimate tool for rehabilitation, but the cost of such...
equipment is estimated at millions of rubles. The article proposes a system for rehabilitating the lower limbs based on a parallel manipulator [8-12]. The proposed solution will occupy a separate niche as a multifunctional, affordable device for rehabilitation.

2. Design model

In Figure 1 shows a block diagram of the proposed rehabilitation system. In the rehabilitation system structure, an active 3-PRRR parallel robot of the tripteron type proposed by Kong and Gosselin [13] and a passive orthosis were used. The active 3-PRRR parallel mechanism provides the required rehabilitation angles of all the patient's joints, the passive orthosis is used to support the patient's lower limb. The active mechanism consists of three kinematic chains $A_iB_iC_iD_i, i = 3$ and has three degrees of freedom - translational movements along each of the axes. The rehabilitation platform's position, which is an equilateral triangle $D_1D_2D_3$ with a center at point $P$ and a radius of the circumscribed circle $R$, is determined by linear displacements $q=(q_1,q_2,q_3)$. We introduce the following notation: $a_i$ - the distance between points $A_i$ and $B_i$, $b_i$ - between $B_i$ and $C_i$, $c_i$ - between $C_i$ and $D_i$, $d_i$ - between $B_i$ and $D_i$. A serial RRRR mechanism is used to secure the human leg. Its hinges match the patient's joints. The $E$ hinge provides two movements of the hip joint: rotation in the sagittal plane with angle $\alpha$ and abduction of the leg with angle $\gamma$ - between the projection of the $EF$ link on the $XOY$ plane and the $OY$ axis. In the hinge $F$ of the knee joint, the rotation of the $FP$ link relative to $EF$ by an angle $\theta$ is provided. In the process of rehabilitation, it is required to provide angles in the hip, knee and ankle joint when walking: $\alpha \in [-20^\circ,10^\circ], \theta \in [120^\circ,180^\circ], \gamma \in [0^\circ,25^\circ]$ [14].

![Figure 1. Lower limb rehabilitation system: (a) - block diagram of the system, (b) - 3D model of the system.](image)

At the first stage of designing a rehabilitation system, it is important to determine the maximum useful work that the robot should provide. Based on the structural diagram (figure 1), we can conclude that with the links' unification, the maximum load falls on the link that moves along the $Z$ axis. This is because, in one of the directions, this link will perform work aimed at overcoming gravity, as opposed to the remaining links, the direction of movement of which is perpendicular to the gravity vector. Thus, if we carry out the strength calculation of the kinematic chain 3, and the solution satisfies the conditions, it can be argued that the remaining links with a margin will be provided with the necessary engine operation. The robot's kinematic scheme is built so that the working area is 10-15% larger than the trajectory described by the human foot while walking, with a person's height up to 190 cm [14].
Consider the system in a static state. The link's peak load will be provided at the maximum extension of the kinematic chain 3 (figure 2).

Figure 2. Position of the kinematic chain: (a) - arbitrary; (b) - at maximum load.

Let's build a design scheme to determine the reaction of the support of the input link. This scheme can be represented as a static beam with a rigid fixing. Thus we determine the static load on the structure, taking into account the metal consumption and the patient's weight (figure 3).

Figure 3. Design diagram of the kinematic chain 3 connected to a passive orthosis.

To calculate the structure, it is necessary to set some parameters of the proposed robot. The load is generated as follows:

- $q_1$ – distributed load throughout the entire structure link, reflecting the own weight of the elements to which the hinge $B$ belongs, the profile pipe 2 mm thick and about 323.5 mm long - the $BC$ link, the $C$ hinge, the profile pipe 2 mm thick, and about 323.5 mm long - $CP$ link, orthosis $PE$ - consists of a hinge and two profiled pipes with a thickness of 2 mm and a total length of about 900 mm. The calculation uses a 40x40 mm pipe profile. Thus, we obtain a structure mass of about 8.5 kg, which is approximately equal to 0.07 kN·m⁻¹ distributed load on a section of 1.2 m;

- $F_1$ – the force acting on the pivot $P$. This force replaces the weight of the brace attachment elements as well as the movement mechanism of the ankle, which will include the servo, pivot, support and restraint. The total weight of the elements should not exceed 5 kg;

- $F_2$ – the force acting on the hinge $P$. It takes into account unexpected loads such as plaster and all kinds of tires;
AR – support reaction at point A;

$M_A$ – bending moment about point A;

$q_2$ – distributed load throughout the orthotic, including the mass of the rehabilitated limb. We find the mass of the patient’s lower limb by the formula [15]:

$$m_x = B_1 + B_2 m + B_3 H,$$

(1)

Where $m$ is the mass of the whole body, kg; $H$ – body length, cm; $B_1, B_2, B_3$ – coefficients of the regression equation. Substituting the tabular values, the average leg mass for a person with a height of 190 cm is 15 kg, taking into account a margin of 20%. We take the effort required to bend the knee, 0.5 kN·m, on a plot of 0.45 m. As a result, we get the input data for the calculation: $L = 1.2$ m; $q_1 = 0.07$ kN·m$^{-1}$; $q_2 = 0.5$ kN·m$^{-1}$; $F_1 = 0.05$ kN; $F_2 = 0.02$ kN.

The design of the orthosis is unknown at this stage of design. Suppose the maximum flexion angle is no more than 60°. Consequently, the structural elements form an equilateral triangle with the center of mass located in the center. It follows from this that it is possible to simplify the design scheme for preliminary calculation. The links $PF$ and $FE$ are represented as a straight section of $PE$ with a length $z_2$ compensating for the load $q_2$ (figure 4). A more detailed calculation can be made after an accurate determination of metal consumption and design optimization.

**Figure 4.** Design model for determining shear force and bending moment.

We compose the equations of static equilibrium [16]:

$$\sum F_y = -q_1 \cdot 1.2 -q_2 \cdot 0.45 - F_1 - F_2 + R_A = 0$$

(2)

Plot №1 $(0 \leq z_1 \leq 0.747$ m)\n
$$Q_y = R_A - q_1 \cdot z_1,$$

$$M_y = R_A \cdot z_1 - M_A - q_1 \cdot \frac{z_1^2}{2}.$$

Plot №2 $(0 \leq z_2 \leq 0.45$ m)\n
$$Q_y = q_1 \cdot z_2 + q_2 \cdot z_2,$$

$$M_y = -q_1 \cdot \frac{z_2^2}{2} - q_2 \cdot \frac{z_2^2}{2},$$

where $Q_y$ - shear force, kN; $M_y$ - bending moment, kN·m.

As a result of solving the equations, we construct diagrams of transverse and bending stresses.
The main elements of this robot are the ball screw, as well as the guide and carriage. Since the calculation performed shows a static load, it is worth considering a margin of 20-30% when choosing components. Thus, based on the list of products, the most suitable is LLTHC 30 U Bottom Bracket.

After determining the link’s load, it is necessary to determine the engine power to provide the required torque. In this robot, the translational movement of the link is provided by rotating the screw. Therefore, the required torque will depend on the gear ratio of the ball-screw transmission, and thus the pitch and diameter of the screw become the key variable. Since the screw’s pitch will affect the linear speed of the slide, it is necessary to carry out an analytical calculation that will allow us to understand the required engine power at a given speed. The model SFU01605-4 was chosen as the ball screw (ball screw). Let's set the initial parameters: screw diameter $d_s = 0.016\, \text{m}$; screw thread pitch $P_B = 0.01\, \text{m}$; coefficient of friction $\mu = 0.2$; screw length $l_i = 0.7\, \text{m}$; efficiency applied force $\eta = 0.88$, taking into account a margin of 30% $N = 517\, \text{N}$; travel time $t = 3\, \text{s}$.

The ball screw pitch $P_B$ is the distance the nut moves when the shaft is turned one revolution, i.e. gear ratio of ball screws. Using the gear ratio, we calculate the engine torque $M$ required to apply a given force $N$ to the node:

$$M = \frac{N \cdot P_B}{2\pi \cdot \eta}, \text{N} \cdot \text{m}$$

(3)

To determine the number of engine revolutions, it is necessary to determine the slider’s speed of linear movement. The angular velocity of link 2 will be equal $\omega = 0.7\, \text{rad} \cdot \text{s}^{-1}$.[15].

We compose a design scheme for calculating the speed of the links (figure 5). Since points $P$ and $D$ have the same speed of movement, it is enough to find the speed of one point, therefore, we represent point $P$ as a hinge fixed on the translational pair 3, which will allow us to determine the dependence of linear and translational speeds. The lengths of links 1 and 2 are 0.38 m.

**Figure 5.** Design scheme of a passive orthosis.

Thus, the speed of linear movement of the slider 3 can be determined using the method of the instantaneous center of speeds. Point $P_{ICS}$ - instantaneous center of speeds (ICS) for the $FP$ link, we find the distance to the ICS:
Then the required number of engine revolutions $n$ at a given speed of movement $v_p$ is calculated by the formula:

$$n = \frac{v_p}{P_B}, \text{rpm}$$

(6)

The gearbox is not used in the design, therefore,

$$n_s = n_m$$

(7)

where $n_s$ is the rotational speed of the screw, $n_m$ is the speed of the motor shaft.

Calculate the load power:

$$P_0 = \frac{2\pi \cdot n_m \cdot M_1}{60}, W$$

(8)

3. Results and discussion

On the constructed diagrams (figures 6, 7), the distribution of the load on the robot kinematic chain is clearly shown, it can be concluded that the required metal consumption of the chain in each of its sections.

The maximum shear force is 0.38 kN. Given the input characteristics, we will select the engine to provide the required performance. Thus, 2250 rpm characterizes the speed of rotation of the engine while providing a force of 0.93 kN·m. These characteristics can be achieved with both a stepper and a servo motor. However, in the case of a stepper motor, maximum torque is obtained at low rpm, and the servo motor provides maximum torque at high rpm. Rehabilitation of patients is often carried out at a relatively low speed, but significant efforts are made to flex the patient's joints with cerebral palsy. Consequently, the priority in the selection of equipment is motors with a predominance of parameters, similar to stepper types.

We will choose the SME60S-0040-30AB model as the engine, the technical characteristics of which are shown in figure 8.
4. Conclusion
As a result of the design of the robot, it was determined that the kinematic chain 3 was maximally loaded, while a peak stress is arisen when the kinematic chains 1 and 2 reach their extreme positions other than zero. The maximum transverse stress falls on the input link of the kinematic chain 3 and is 0.38 kN, and the bending moment in this link was 0.32 kN·m. It was calculated that with a screw pitch of 10 mm, the engine must reach 2250 rpm so that the tripteron can provide the orthotic flexion rate equal to $\omega = 0.7 \text{ rad} \cdot \text{s}^{-1}$. Since the task of rehabilitation of the lower limbs requires the preservation of torque at low engine speeds and at an estimated 2250 rpm, the SME60S-0040-30AB engine was chosen, which would also provide a power reserve for short-term dynamic loads.

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