Simulating cable tension in robotic systems for various conditions of upper and lower extremity rehabilitation

V S Pervuznik1, I I Cherednikov1, D I Malyshev1

1 Belgorod State Technological University n.a. V.G. Shukhov, 46, Kostyukova, Belgorod, 308012, Russia

E-mail: viktorija.kuzina@yandex.ru

Abstract. The paper discusses an optimized model of rehabilitation systems based on a cable-actuated robot designed for rehabilitation of patients with impaired motor function of upper and lower limbs. Tensile strength and cable lengths depending on joint angles are calculated to determine optimal positions of coils, with due account of the effects elasticity and gravity forces produce during rehabilitation. Based on the calculations, the positions of cable-driven actuators are determined such that the cables do not touch the patient’s body and the optimal forces of the actuators are ensured.

1. Introduction

One of the most pressing and difficult problems in medicine and neurology is rehabilitation of patients. The number of people who need rehabilitation is growing every day.

Currently, practical health care is facing a number of challenges that can be most optimally addressed with robotic systems. These challenges involve not only the treatment and rehabilitation of patients with locomotor disorders, but also their self-care functions, social adaptation, and replenishment of lost motor and communication abilities. A need to create robotic aids for people with disabilities is steadily growing. This is due to a high rate of disability among people, suffering from spinal trauma, stroke and other neurological diseases.

According to the World Report on Disability published by the World Health Organization, more than 1 billion people, about 15% of the world’s population, have some form of disability. Between 110 million (2.2%) to 190 million (3.8%) of people aged 15 and over experience significant difficulties in functioning. Moreover, disability rates are rising with an aging population and an increased burden of chronic health problems. The number of patients with severe disabling consequences of past neurological diseases, requiring special conditions for survival and special methods of rehabilitation, is about 4%. In Russia, 70% of patients who need rehabilitation are neurological patients.

Besides these problems, Russia is facing another type of disease – acute flaccid paralysis. Clinically, this type of paralysis is indistinguishable from polio paralysis, but acute flaccid paralysis causes twice as much mortality as polio paralysis and has a longer duration for recovery after the disease [1]. Subsequent upon various factors that cause extremity dysfunction, rehabilitation process should be provided in order to restore the normal functioning of the limbs.

To ensure rehabilitation of patients with locomotor disorders, robotic rehabilitation technologies have advanced significantly and have been gradually investigated in recent years. A promising trend in the rehabilitation of the upper and lower extremities is the use of cable-driven parallel robots [2-4]. A joint publication of foreign and Russian scientists presents a conceptual design of a new seated robot for
the rehabilitation of the lower extremities, as well as simplified motion control for a passive range of movement therapy \([5,6]\). The proposed design was demonstrated and verified using computer numerical simulation.

Robotic rehabilitation systems \([7-14]\), including rope-driven robots \([7,11,12,14]\), are now widely used in rehabilitation medicine to restore the motor functions of the extremities of patients with various musculoskeletal disorders.

Several cable-driven parallel robot architectures are known for rehabilitation. However, the robots presented in \([15, 16]\) are designed only for the rehabilitation of the upper limbs, which significantly limits the functionality of these systems, has a small working area \([17]\). Therapeutic procedures are enabled solely with the effort made by the patient, and the length of ropes (cables) is adjusted by the therapist \([18,19]\), while motion control of the robotic system should vary for each specific case, i.e., its control structure must be flexible.

Rehabilitation therapeutic methods vary with the upper and lower extremity treatment. Upper limb treatment focuses on restoring hand nerve, muscle action and strength development, while lower limb treatment focuses on different movements of leg joints and their synchronized movements. A number of social aspects should be respected in rehabilitation: patients' personal characteristics, their living conditions, psychological problems in the family caused by the disease, necessity to equip rooms with self-orientation means for patients, financial costs, the man-machine interaction \([20]\).

A healthy elbow joint allows flexion up to an angle of about \(40^\circ\), extension up to \(180^\circ\) \([21]\). The shoulder joint is abducted partially together with the scapula. In a healthy shoulder joint, abduction is possible up to \(90^\circ\) without the scapula, and up to an angle of \(180^\circ\) with the scapula (Fig. 2).

![Image](image_url)

**Figure 1.** Rehabilitation of the upper limbs: a – elbow flexion/extension  
b – shoulder adduction/abduction in the joint

It is known that human locomotion depends both on the basic patterns generated at the level of the spine and on the prediction and reflex-dependent precise control of these patterns at different levels \([21, 22]\). Similar physiological movements seen in healthy people should be generated in patients with lower extremity dysfunction.

Besides gait formation, the lower limbs should provide such movements as flexion and extension of the hip, flexion and extension of the knee, flexion of the ankle joint. Long-term gait training restores the synchronization of muscular action in the lower limb and, to strengthen each joint of the leg, must be practiced separately to restore motor function.

The flexion angle \([21]\) in a healthy hip joint ranges from \(-15^\circ\) to \(130^\circ-140^\circ\), and in the knee: \(0^\circ-140^\circ\) (Fig. 3).
2. Material and methods

The paper proposes a reconfigurable cable-driven parallel robotic system for both upper and lower extremity rehabilitation by rearranging the cables.

2.1. Description of configuration and movements enabled

From the analysis, it is evident that for the rehabilitation of patients and disabled people with impaired motor functions of the lower and upper extremities, the most optimal structure of a cable-actuated robot is a reconfigurable modular robotic system based on parallel cable mechanisms. Such a robotic system for the rehabilitation of the upper and lower extremities is shown in Fig. 4.

The structure is an aluminum exoskeleton, the main components of which are bolted, which greatly facilitates the assembly and disassembly, transportation, thereby ensuring the availability of the system at home. To relieve the body weight, supporting belts are attached to the supporting vest and have a height adjustment feature enabling to increase or decrease the load on the patient’s lower extremities, and use the system for patients of different sizes. Supporting belts are attached at the top of the structure to a cylindrical hinge.

A passive orthosis with hinges to replicate the human joints is used to provide correct physiotherapeutic movements in lower extremity rehabilitation. The movements are simulated by servomotors attached to the platform, connected by cam couplings to coils that actuate cables connected to the passive orthosis. In the last phase of rehabilitation, when the patient can move without any assistive devices, a treadmill is provided for gait training.

There are six exoskeletal actuators in the rehabilitation system: four – for upper limb rehabilitation, two – for lower limb rehabilitation. $A_1$ and $A_2$ actuators designed for lower extremity rehabilitation are
located on the platform fixed on struts in the front of the structure and are responsible for knee joint flexions by changing the lengths of the cables. The correct physiotherapeutic movements are provided by the passive orthosis that allows a rotational movement in the knee joint and fixes the person’s leg in the ankle joint. $A_3$ and $A_4$ actuators that abduct the human arm in the shoulder joint are fixed on the lateral crossbar in the upper part of the structure, while $A_5$ and $A_6$ actuators that provide elbow joint flexions are fixed on the front and rear crossbars in the upper part of the structure. The straps that are fixed in the upper part of the structure limit vertical and horizontal movements of the body. During rehabilitation the upper or lower extremities move by varying the length of the cables connecting the actuators and the corresponding attachment points to the patient’s body.

2.2. Mathematical model
During rehabilitation the upper or lower extremities move by varying the length of the cables connecting the actuators $A_i$ and the corresponding attachment points to the patient’s body $P_i$. To determine the coordinates of the points $P_i$, consider the kinematic diagram of the patient’s body (Fig. 5).

![Figure 4. Kinematic diagram of patient’s body](image)

Write down the coordinates of the cable fixing points $P_i$:

\[
P_1 = \begin{bmatrix} X_{P1} \\ Y_{P1} \\ Z_{P1} \end{bmatrix} = \begin{bmatrix} l_5' + X_0 \\ l_2' \cdot \sin \alpha + l_2'' \cdot \cos \alpha + Y_0 \\ -l_1 + l_2' \cdot \cos \alpha + l_2'' \cdot \sin \alpha + Z_0 \end{bmatrix}
\]

\[
P_2 = \begin{bmatrix} X_{P2} \\ Y_{P2} \\ Z_{P2} \end{bmatrix} = \begin{bmatrix} l_5' + X_0 \\ l_2' \cdot \sin \alpha + l_2'' \cdot \sin(\alpha + \pi - \beta) + l_4 \cdot \cos(\alpha - \beta) - l_6 \cdot \sin(\alpha + \pi - \beta) + Y_0 \\ -l_1 + l_2' \cdot \cos \alpha - l_3 \cdot \cos(\alpha - \beta) + l_4 \cdot \sin(\alpha + \pi - \beta) + l_6 \cdot \cos(\alpha - \beta) + Z_0 \end{bmatrix}
\]

\[
P_3 = \begin{bmatrix} X_{P3} \\ Y_{P3} \\ Z_{P3} \end{bmatrix} = \begin{bmatrix} l_5' + l_2' \cdot \cos \gamma + l_2'' \cdot \sin \gamma + X_0 \\ Y_0 \\ -l_1' \cdot \sin \gamma - l_2'' \cdot \cos \gamma + Z_0 \end{bmatrix}
\]
\[ \mathbf{P}_4 = \begin{bmatrix} X_{p4} \\ Y_{p4} \\ Z_{p4} \end{bmatrix} = \begin{bmatrix} l_5 - l_7 \cdot \cos \gamma + l_8'' \cdot \sin \gamma + X_0 \\ l_6' + Y_0 \\ -l_7 \cdot \sin \gamma + l_6' \cdot \cos \varphi - l_8'' \cdot \cos \gamma + Z_0 \end{bmatrix} \]  

(4)

\[ \mathbf{P}_5 = \begin{bmatrix} X_{p5} \\ Y_{p5} \\ Z_{p5} \end{bmatrix} = \begin{bmatrix} l_5 - l_7 \cdot \cos \gamma + l_8''' \cdot \cos \gamma \cdot \cos \varphi + X_0 \\ l_6' \cdot \sin \varphi + l_8''' \cdot \cos \varphi + Y_0 \\ -l_7 \cdot \sin \gamma + l_6' \cdot \cos \varphi + l_8''' \cdot \cos \gamma \cdot \sin \varphi + Z_0 \end{bmatrix} \]  

(5)

Cable lengths are defined as:

\[ L_i = \sqrt{(X_{Ai} - X_{Pi})^2 + (Y_{Ai} - Y_{Pi})^2 + (Z_{Ai} - Z_{Pi})^2} \]  

(6)

The coordinates \( Ai \) are chosen based on the following conditions:

1. Ensuring that all required positions of the human limb are easily attainable.
   This condition ensures the angle between the motion vector of point \( Ai \) and the \( i \)-th cable angle \( \theta_i \) when lifting the human limb in the range from -90° to 90° (Fig. 6).

   The condition for ensuring that all required positions of the human limb are attainable can be written as:

   \[ \cos \theta_i > 0 \]  

   (7)

   where \( \cos \theta_i = \frac{(X_{Ai} - X_{Pi})^2 + (Y_{Ai} - Y_{Pi})^2 + (Z_{Ai} - Z_{Pi})^2)}{L_i \Delta_i} \) > 0,

   \( X_{Pi}, Y_{Pi}, Z_{Pi} \) are the coordinates of the previous limb position, \( \Delta_i \) is the distance between the previous and current position of the limb, which is defined as:

   \[ \Delta_i = \sqrt{(X_{Pi} - X_{Pi})^2 + (Y_{Pi} - Y_{Pi})^2 + (Z_{Pi} - Z_{Pi})^2} \]  

   (8)

2. Minimization of cable tensile strength.
   The tensile strength of the cables (Fig. 7), given that the cable is anchored at the level of the center of limb mass, is defined as:

   \[ F_i = \frac{m_i g \cos \lambda_i}{\cos \theta_i} \]  

   (9)

   where \( \cos \lambda_i = \frac{Z_{Pi} - Z_{Pi}'}{\Delta_i} \).

3. In the lower extremity rehabilitation cables do not bend while in contact with the human body.
   The cables can bend if the actuator is not properly positioned, which can cause the cable to come into contact with a person’s knee (Fig. 8).
To do this, add the following condition for the second cable:

\[ \sin \psi_1 \geq \sin \psi_2, \] 

(10)

where the sines of the angles \( \psi_i \) are defined as:

\[ \sin \psi_1 = \frac{Y_{A2} - Y_{P2}}{L_2} \]

(11)

\[ \sin \psi_2 = \frac{Y_B - Y_{P2}}{\sqrt{(X_B - X_{P1})^2 + (Y_B - Y_{P1})^2 + (Z_B - Z_{P1})^2}} \]

(12)

Using the formulas (1-12), choose the location of the actuators \( A_i \), based on the three above conditions.

3. Simulation results

For simulation, the dimensions are selected, corresponding to an adult body: \( l_1 = 488; l_2 = 460; l_2' = 250; l_2'' = 100; l_3 = 409; l_4 = 250; l_5 = 200; l_6 = 70; l_6 = 50; l_7 = 302; l_8 = 180; l_9 = 50; l_8' = 269; l_8'' = 190; l_8''' = 80; l_8'''' = 80. \) The radius of the person’s knee is \( R_k = 50. \) During the simulation, their coordinates were iteratively changed for each of the actuators \( A_i. \) At each iteration, the patient’s joint angles were enumerated in the following ranges: \( \alpha = 90 - 180; \beta = 90 - 180; \gamma = 90 - 180; \varphi = 90 - 180. \)

Figure 9 shows the maximum tensile strength during rehabilitation, depending on the location of the actuators for each of the cables. Given that the positions of the coils do not satisfy conditions (1) and (2), the tensile strength is taken equal to 1000 N.
Figure 8. Cable tensile strength vs positions of actuators

The minimum tensile forces are achieved with the following actuator coordinates: \(X_{a3}=900, X_{a4}=1021, Y_{a1}=647, Y_{a2}=1487, Y_{a5}=588, Z_{a1}=-8, Z_{a2}=728, Z_{a3}=0, Z_{a4}=-8, Z_{a5}=-8\).

Figure 10 shows the relationship between cable lengths and tensile strength during rehabilitation for selected actuator positions.

Figure 9. Dependency plots: a – cable length on variations in joint angle; b – cable tensile strength on variations in the joint angle

The graphs show that the maximum tensile strength during the rehabilitation process is produced in the cable \(l_3\) and amounts to 133 N, which is an acceptable value for both synthetic and steel cables to be manufactured.

4. Discussion
In any of the rehabilitation therapies, the disabled patients with lower and upper limb impairments are treated in a critical sitting or lying position, since at this stage they cannot control their limbs. In this regard, it is challenging to treat them using a body weight support (BWS) system alone, as this requires
a certain level of fitness. Many mechanisms based on continuous passive motion (CMP) and designed for continuous or repeated therapeutic treatment cannot provide the required quality in continuous passive motion due to their complicated design, high dynamic loads and structural unwieldiness.

Thus, the developed robotic system for rehabilitation by reconfiguring is accommodated to treat a specific patient, providing rehabilitation of the upper or lower limbs. The advantages of the proposed robotic system are also a large working area, ease of assembly and disassembly, high mobility, and high carrying capacity. The use of cables instead of rigid links further reduces mass, since the actuators do not change position and are attached to a fixed base so that the only moving parts are the cables and the output link. Thus, the risk of injury due to trajectory errors and collision of RS elements with a person is significantly reduced.

5. Conclusion

The optimal positions of actuators were determined to provide the required working area and exclude the intersection of cables with the patient’s body. The tensile strength of the cables are minimal: $X_{a3} = 900, X_{a4} = 1021, Y_{a1} = 647, Y_{a2} = 1487, Y_{a5} = 588, Z_{a1} = -8, Z_{a2} = -728, Z_{a3} = 0, Z_{a4} = -8, Z_{a5} = -8$.

The authors calculated tensile strength and cable lengths depending on the joint angles and with due account of the effects elasticity and gravity forces produce during rehabilitation. They analyzed the relationship between the maximum tensile strength produced during rehabilitation and the position of the actuators for each of the cables. For the selected geometric dimensions of the robot, the maximum tensile strength during rehabilitation is 133 N, which is an acceptable value for synthetic and steel cables.

In the future, it is planned to align the results based on the mathematical model of the rehabilitation system to involve the physiological features of both male and female patients, to expand the range of physiotherapeutic exercises for patients of various builds and to work out the ergonomics of the rehabilitation system.

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