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RESEARCH ARTICLE

Mechatronic Rehabilitation System for Upper Limbs

Sistema mecatrónico de rehabilitación para extremidades superiores

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ABSTRACT

Currently there is great interest in the development of machines that meet the demand to rehabilitate the upper and lower extremities, due to injuries caused by strokes, traumatic incidents or accidents, neuromuscular diseases, which are increasing day by day. The objective of this work is to present the kinematic analysis of an upper limb rehabilitation machine for patients who suffered a stroke. The rehabilitation machine has 3 degrees of freedom (DOF), uses a flexible cable, and can provide shoulder movements: flexion-extension, external rotation, abduction; and elbow flexion movements, among others. The kinematic analysis of some basic movements is presented by means of vector loop analysis. In addition, the simulation results in the MSC Adams environment show that the rehabilitation machine can provide smooth passive rehabilitation movements.

KEYWORDS: continuous passive motion; rehabilitation robot; rehabilitation robotics; upper limb rehabilitation machine.

RESUMEN

Actualmente existe un gran interés en el desarrollo de máquinas que atiendan la demanda para rehabilitar las extremidades superiores e inferiores, debido a lesiones provocadas por enfermedad vascular cerebral, accidentes traumáticos, enfermedades neuromusculares, que día a día van en aumento. El objetivo de este trabajo es presentar el análisis cinemático de una máquina de rehabilitación de miembros superiores para pacientes que han sufrido una enfermedad vascular cerebral. La máquina de rehabilitación es de tres grados de libertad (GDL), utiliza un cable flexible y puede proporcionar movimientos del hombro de: flexión-extensión, rotación externa y abducción; y movimiento de flexión del codo, entre otros. Se presenta el análisis cinemático de algunos movimientos básicos que puede proporcionar esta máquina mediante el análisis de un lazo vectorial. Además, los resultados de la simulación en el entorno de MSC Adams muestran que la máquina de rehabilitación puede proporcionar movimientos de rehabilitación pasivos suaves.

PALABRAS CLAVE: movimiento pasivo continuo; rehabilitador de extremidades superiores; robot rehabilitador; robótica de rehabilitación.

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I. INTRODUCTION

A cerebrovascular accident (CVA) is typically caused by a hemorrhage or blockage in the blood vessels of the brain, which damages the brain cells, even causing death. The number of disabled people due to a stroke is increasing day by day, it is expected that it will continue to increase at an alarming rate in the United States and several countries around the world [1], [2]. A patient who suffered a stroke generally has loss of movement in the middle of the body, paralysis, or hemiplegia, requiring immediate rehabilitation to recover part of the mobility in the extremities. In addition, human beings are prone to traumatic incidents which cause injuries to the lower and upper extremities, which also require rehabilitation therapy during their recovery process.

Rehabilitation in patients in upper or lower extremities needs repetitive and progressive training exercises. To improve the effectiveness of rehabilitation, the use of robotic devices or machines is recommended. Since the early 1990s and up to the present, researchers and some companies have proposed and developed various assistance and rehabilitation devices to address this problem. Mechatronics in upper and lower extremities rehabilitation is a relatively new research field. Rehabilitation machines are tools for rehabilitation purposes that allow patients to perform basic and combined movements as part of their rehabilitation program.

The objective of rehabilitation is to recover the motion abilities, missed in a traumatic incident, through physical therapy as quick as possible. The constant increase in patients with injuries and the lack of physical therapists to provide proper care have led to the rise of robotic systems and rehabilitation machines. These mechanical devices do not replace the physical therapist but serve as support during the therapy process. In the last two decades, a large number of robots for upper extremity rehabilitation have been proposed. However, most of these robots are made up of rigid links and, mostly, of complex mechanisms such as those shown in [1]-[4].

On the other hand, rehabilitation machines using flexible cables have also been proposed [5]-[9]. The use of cable-actuated machines presents certain advantages such as: 1) it provides a greater number of movements, 2) it requires low power actuators in comparison with machines that use rigid links, 3) they are lighter, so they have low inertia and 4) they turn out to be cheaper machines.

Huang *et al.* [5] developed a gravity-compensated control strategy for an upper extremity cable-driven rehabilitation robot, which is capable of estimating gravity torque in real time with position feedback. They carried out tests with seven healthy subjects, assigning them movement tasks in four different directions (up, down, left, and right), in a 3D vector space, tracking human-machine interaction movements, see Figure 1. In [6] it was implemented a sliding mode control with a nonlinear disturbance observer, designed for the robot to solve the problem of unpredictable disturbances during robot-assisted training.

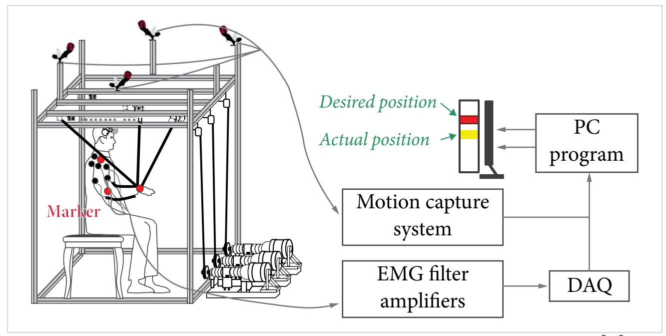

Figure 1. Upper extremity cable-driven rehabilitation robot [5].

Beer *et al.* [7] propose an arm rehabilitation machine with a multi-axis Cartesian system (MACARM), see Figure 2. This machine has a large workspace and was evaluated with a load of 4.5 kg, which represents the weight of the patient's arm. It has 6 DOF and has 8 engines.

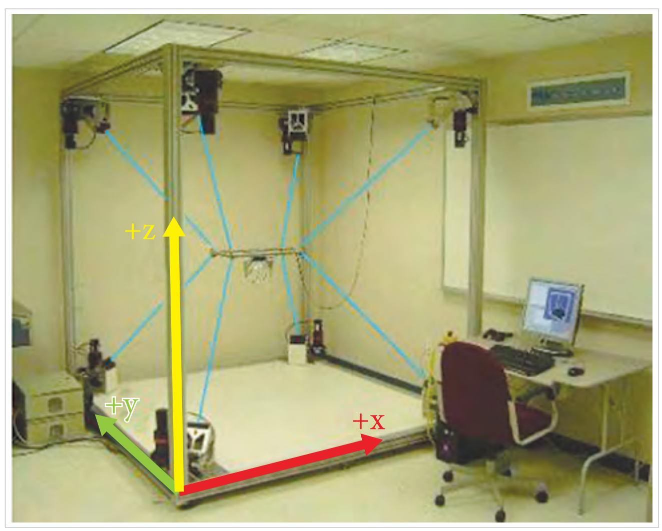

Figure 2. MACARM cable robot for upper limb neurorehabilitation [7].

VA 3-DOF cable-driven upper limb rehabilitation robot (CDULRR) is reported in [8]. The controller includes three modes of operation: resistive, assistive, and restraint. The robot features a fuzzy logic tuner in assistive mode to adaptively and dynamically modify the level of robotic assistance; to avoid patient dependency on robotic support. Another parallel cable-driven upper limb rehabilitation robot (PCUR) was reported in [9]. The static stiffness of the PCUR is related to cable tension, cable arrangement, and cable stiffness. The PCUR consists of seven cable-driven units to move a movable platform to propel the affected limb to perform rehabilitation actions.

In [10] a portable 3 DOF cable-driven upper extremity rehabilitation robot based on a 3D printing framework is proposed. The robot provides an active/passive training model in certain shoulder movements, namely, abduction/adduction, and flexion/extension, see Figure 3. Another cable-actuated exoskeleton with variable stiffness for upper limb rehabilitation is presented in [11]. The adjustable stiffness of the cable-actuated exoskeleton is achieved by cable tension.

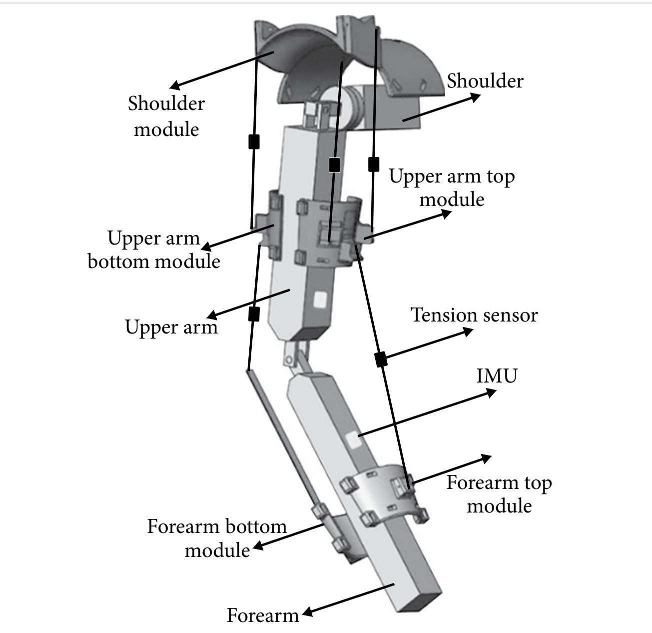

Figure 3. Portable 3-DOF cable-driven upper extremity rehabilitation robot [10].

In this paper, the design of a robot for the rehabilitation of upper limbs with a flexible cable of 3 DOF is presented. The machine provides the necessary movements to carry out the rehabilitation of an upper extremity. For the shoulder, these motions are: flexion, extension, abduction, adduction, internal rotation, external rotation and circumduction; for the elbow, the machine provides flexion. Table 1 shows the maximum values for the movements of the shoulder [12] and elbow [13], as per Figures 4 and 5, respectively.

TABLE 1
Maximum Values for Shoulder and Elbow Movements

Movement Type	Maximum Value
Shoulder	
Flexion	180°
Extension	50°
Adduction	48°
Abduction	134°
Internal rotation	34°
External rotation Circumduction	142° 360°
Elbow	
Flexion	140-150°
Extension	2-10°
Supination Pronation	90° 80-85°

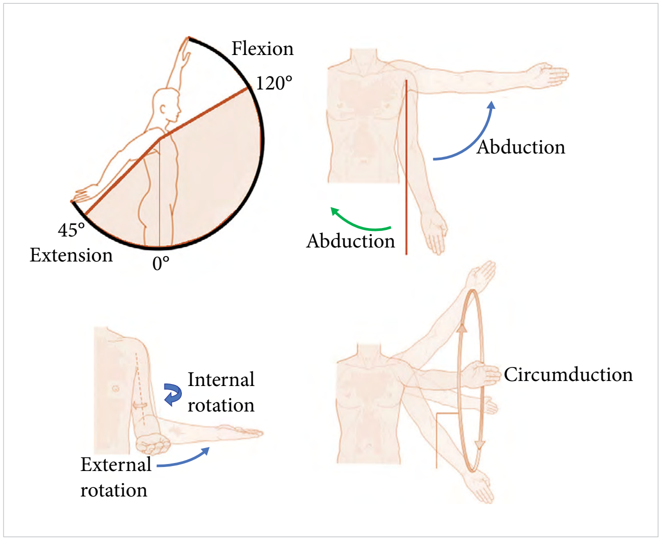

Figure 4. Basic shoulder movements.

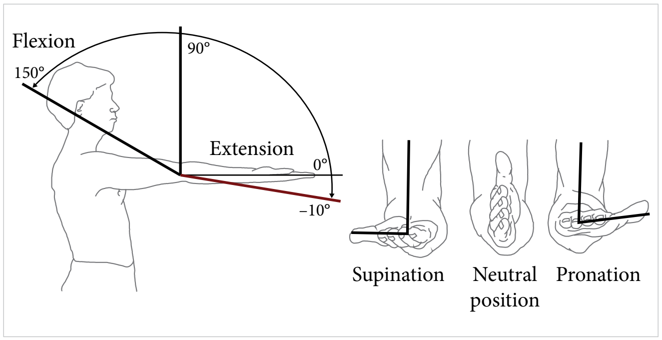

Figure 5. Basic elbow movements.

II. METHODOLOGY

A. DESCRIPTION SYSTEM

Figure 6 shows the proposed upper limb rehabilitation machine that uses linear systems and a cable-pulley system. The system has 3 DOF, with two linear guides for movements located in the X and Y axes. The movement in the Z axis is obtained through the cable-pulley system. This end-effector machine has the advantage of easy operation, wide range of motion, and can be used to rehabilitate both upper limbs, adjustable for different patients (adolescents and adults). For user safety, the physical prototype will have limit switches, as well as an automatic stop control that will be directly operated by the user.

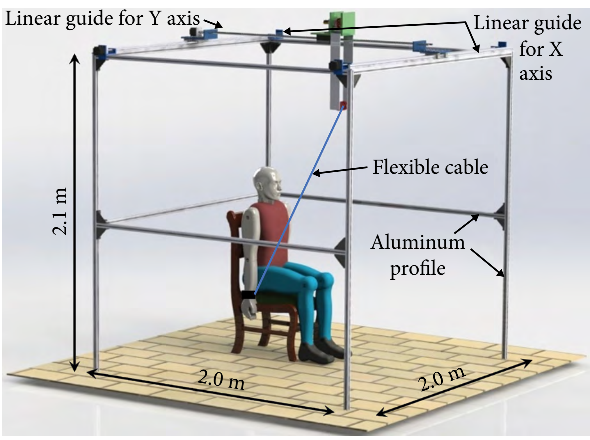

Figure 6. Upper limb rehabilitation machine.

B. ANALYSIS OF REHABILITATION MOVEMENTS

These movements are simple or basic, in other words, it is a pure movement of a joint. However, the rehabilitation system can provide combined movements. Next, the kinematic analysis is presented for some rehabilitation movements that can be performed on this machine. In all analyses, the vector $\boldsymbol{R}_1$ represents the variable cable length that changes as the movement is performed, $\boldsymbol{R}_3$ represents a constant vector, from a user's joint (e.g., elbow, wrist, or shoulder) to the fixed point of the machine's pulley, and $\boldsymbol{R}_2$ represents the user's limb (forearm - 23 cm, or entire limb - 48 cm), see Figures 6 and 7.

Elbow flexion movement

Elbow flexion is considered a pure movement. For the loop closure equation, the vector loop shown in Figure 7 is considered.

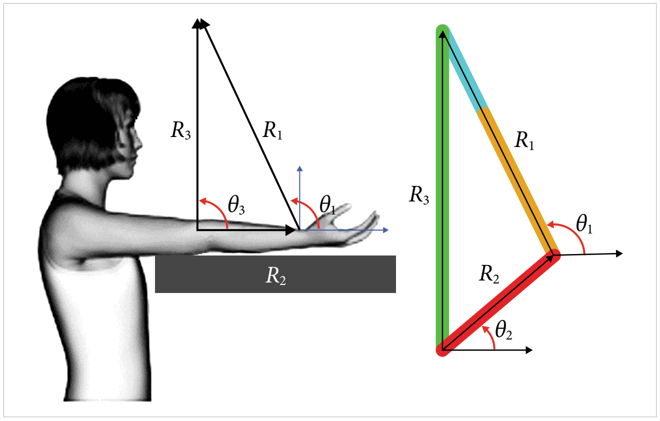

Figure 7. Loop closure equation for elbow flexion movement.

Considering Figure 7, the following vector loop equation of the three-bar mechanism is used, given by

$$\boldsymbol{R}_1 + \boldsymbol{R}_2 = \boldsymbol{R}_3 \tag{1}$$

In complex form:

$$\boldsymbol{r}_1\boldsymbol{e}^{i\theta_1} + \boldsymbol{r}_2\boldsymbol{e}^{i\theta_2} = \boldsymbol{r}_3\boldsymbol{e}^{i\theta_3} \tag{2}$$

From Figure 7, the known data are the magnitude of all the links: r_3 is the length from the elbow joint to the rehabilitator pulley, it will always remain constant, r_2 is the length of the forearm and r_1 is the known length of the cable where its magnitude varies depending on the position on the limb in the rehabilitation exercise. The angle $\theta_3 = 90°$ (constant), leaving θ_1 and θ_2, corresponding to the angles of the cable and the elbow, to be determined. Figure 8 shows elbow flexion angle φ, considering the reference shown in Figure 5.

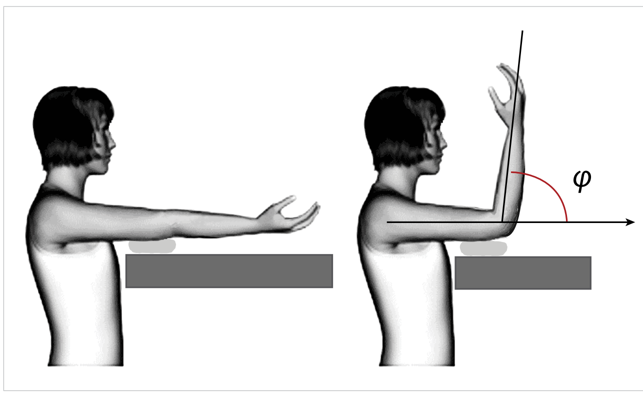

Figure 8. Arm position in elbow flexion movement.

Using Euler's formula, $re^{j\theta} = r\cos\theta + jr\sin\theta$, and considering the known data and after algebraic manipulation, we have to:

$$\theta_1 = \cos^{-1}\left(-\frac{r_2}{r_1}\cos\theta_2\right)$$
$$\theta_2 = \sin^{-1}\left(\frac{r_3^2 + r_2^2 - r_1^2}{2r_2r_3}\right) \tag{3}$$

To obtain the velocities, we derive (2) and by changing the variables $\dot{\theta}_1 = \omega_1$ and $\dot{\theta}_2 = \omega_2$ we have:

$$r_1e^{j\theta_1}(j\omega_1) + \dot{r}_1e^{j\theta_1} + r_2e^{j\theta_2}(j\omega_2) = 0 \tag{4}$$

Using Euler's formula, considering the known data and after algebraic manipulation, we obtain:

$$\omega_1 = \frac{-(\dot{r}_1\sin\theta_1 + r_2\omega_2\cos\theta_2)}{r_1\cos\theta_1}$$
$$\omega_2 = \frac{-\dot{r}_1(\sin\theta_1\tan\theta_1 + \cos\theta_1)}{r_2(\cos\theta_2\tan\theta_1 - \sin\theta_2)} \tag{5}$$

Similarly, (4) is derived to obtain the acceleration analysis ($\dot{\gamma}_1 = \ddot{\theta}_1$ y $\dot{\gamma}_2 = \ddot{\theta}_2$). Therefore, we obtain:

$$\gamma_1 = \frac{-2\dot{r}_1\omega_1\cos\theta_1 + r_1\omega_1^2\sin\theta_1 + x_2 - x_1\cot\theta_2}{r_1(\cos\theta_1 - \sin\theta_1\cot\theta_2)}$$
$$\gamma_2 = \frac{-2\dot{r}_1\omega_1\sin\theta_1 - r_1\gamma_1\sin\theta_1 + x_3}{r_2\sin\theta_2} \tag{6}$$

where
$x_1 = -2\dot{r}_1\omega_1\sin\theta_1 - r_1\omega_1^2\cos\theta_1 + \ddot{r}_1\cos\theta_1 - r_2\omega_2^2\cos\theta_2$
$x_2 = -\ddot{r}_1\sin\theta_1 + r_2\omega_2^2\sin\theta_2$
$x_3 = -r_1\omega_1^2\cos\theta_1 + \ddot{r}_1\cos\theta_1 - r_2\omega_2^2\cos\theta_2$

Elbow external rotation movement

The elbow external rotation vector loop equation is obtained from Figure 9. Where $\boldsymbol{R}_2$ is the vector that represents the forearm, $\boldsymbol{R}_3$ is the reference vector and $\boldsymbol{R}_1$ is the vector that represents the cable.

$$\boldsymbol{R}_1 + \boldsymbol{R}_2 = \boldsymbol{R}_3 \tag{7}$$

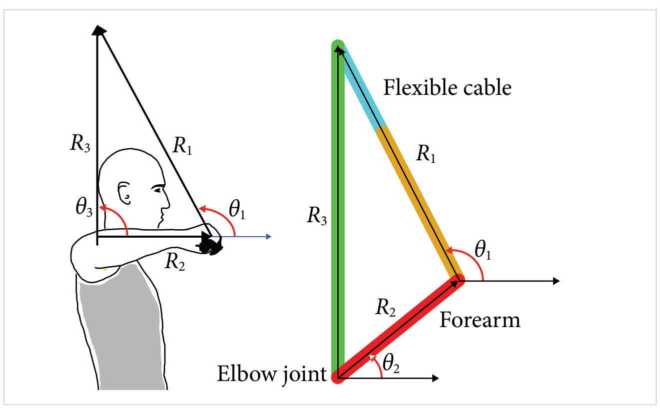

Figure 9. Loop closure equation for Elbow external rotation movement.

From Figure 9, the known data are the magnitude of all the links (r_1 is the known length of the cable where its magnitude varies depending on the position on the limb in the rehabilitation exercise) and θ_3 is constant, leaving θ_1 and θ_2, corresponding to the angles of the cable and the elbow, to be determined. Therefore, the answer is the same as for the elbow flexion movement (3), (5) and (6).

Shoulder extension movement

The shoulder extension vector loop equation is obtained from Figure 10.

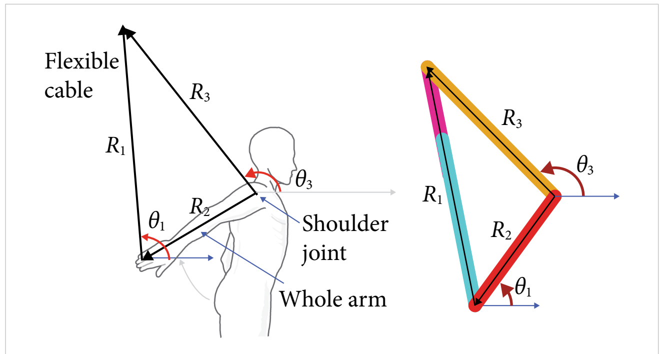

Figure 10. Loop closure equation for shoulder extension movement.

In a similar way, the relations of position, velocity and acceleration are obtained.

$$\theta_2 = \cos^{-1}\left(\frac{r_3\cos\theta_3 - r_1\cos\theta_1}{r_2}\right)$$
$$\theta_1 = \cos^{-1}\left(\frac{r_2^2 - r_1^2 - r_3^2}{2r_1r_3}\right) + \theta_3 \tag{8}$$

$$\omega_1 = \frac{-(\dot{r}_1\sin\theta_1 + r_2\omega_2\cos\theta_2)}{r_1\cos\theta_1}$$
$$\omega_2 = \frac{-\dot{r}_1(\cos\theta_1 + \sin\theta_1\tan\theta_1)}{r_2(\cos\theta_2\tan\theta_1 - \sin\theta_2)} \tag{9}$$

$$\gamma_1 = \frac{-2\dot{r}_1\omega_1\cos\theta_1 + r_1\omega_1^2\sin\theta_1 + x_5 - x_4\cot\theta_2}{r_1(\cos\theta_1 - \sin\theta_1\cot\theta_2)}$$
$$\gamma_2 = \frac{-2\dot{r}_1\omega_1\sin\theta_1 - r_1\gamma_1\sin\theta_1 + x_6}{r_2\sin\theta_2} \tag{10}$$

where
$x_4 = -2\dot{r}_1\omega_1\sin\theta_1 - r_1\omega_1^2\cos\theta_1 + \ddot{r}_1\cos\theta_1 - r_2\omega_2^2\cos\theta_2$
$x_5 = -\ddot{r}_1\sin\theta_1 + r_2\omega_2^2\sin\theta_2$
$x_6 = -r_1\omega_1^2\cos\theta_1 + \ddot{r}_1\cos\theta_1 - r_2\omega_2^2\cos\theta_2$

Shoulder abduction movement

Next, the equations of the kinematics of the vector loop for a shoulder abduction movement (see Figure 11) are presented.

$$\theta_1 = \cos^{-1}\left(\frac{r_3\cos\theta_3 + r_2\cos\theta_2}{r_1}\right)$$
$$\theta_2 = \theta_3 + \cos^{-1}\left(\frac{r_2^2 + r_3^2 - r_1^2}{2r_2r_3}\right) \quad (11)$$

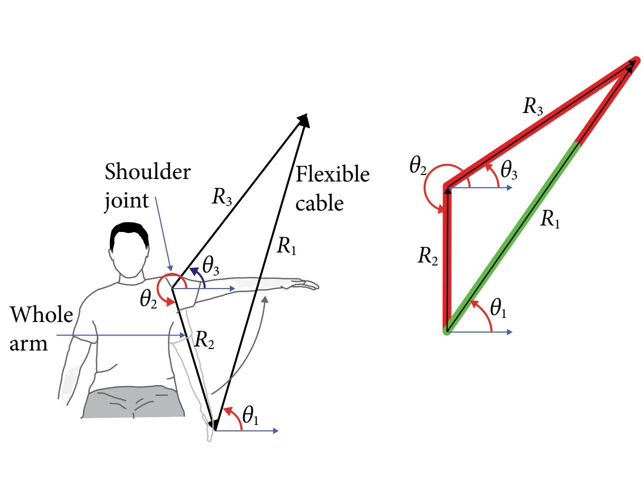

Figure 11. Loop closure equation for Elbow external rotation movement.

$$\omega_1 = \frac{-\dot{r}_1(\cos\theta_1 + \sin\theta_1\tan\theta_2)}{r_2(\cos\theta_1\tan\theta_2 - \sin\theta_1)}$$
$$\omega_2 = \frac{-(\dot{r}_1\sin\theta_1 + r_1\omega_1\cos\theta_1)}{r_2\cos\theta_2} \quad (12)$$

$$\gamma_1 = \frac{-2\dot{r}_1\omega_1\sin\theta_1 + r_1\omega_1^2\cos\theta_1 + x_7 + x_8\tan\theta_2}{r_1(\cos\theta_1\tan\theta_2 - \sin\theta_1)}$$
$$\gamma_2 = \frac{-2\dot{r}_1\omega_1\cos\theta_1 - r_1\gamma_1\cos\theta_1 + x_9}{r_2\cos\theta_2} \quad (13)$$

where
$x_7 = -\ddot{r}_1\cos\theta_1 + r_2\omega_2^2\cos\theta_2$
$x_8 = -2\omega_1\dot{r}_1\cos\theta_1 + r_2\omega_1^2\sin\theta_1 - \ddot{r}_1\sin\theta_1 + r_2\omega_2^2\sin\theta_2$
$x_9 = r_1\omega_1^2\sin\theta_1 - \ddot{r}_1\sin\theta_1 + r_2\omega_2^2\sin\theta_2$

III. RESULTS AND DISCUSSION

Some simulations were performed in MSC ADAMS (Automatic Dynamic Analysis of Mechanical Systems) software to verify the kinematics equations. In these simulations, Figure 12 to Figure 14, the rigid links, including the cable, were considered so that, in future work, they could be compared with the tests on the physical prototype and determine the error in the movement trajectories due to the use of the flexible cable.

For the elbow flexion movement, see Figure 12, a function was used to move the cable, defined by (14), and for the shoulder extension movement, the function (15).

$$u_1(t) = 27\sin\left(\frac{t}{5}\right)\ [\text{cm}] \quad (14)$$

$$u_2(t) = 24\sin\left(\frac{57t}{200}\right)\ [\text{cm}] \quad (15)$$

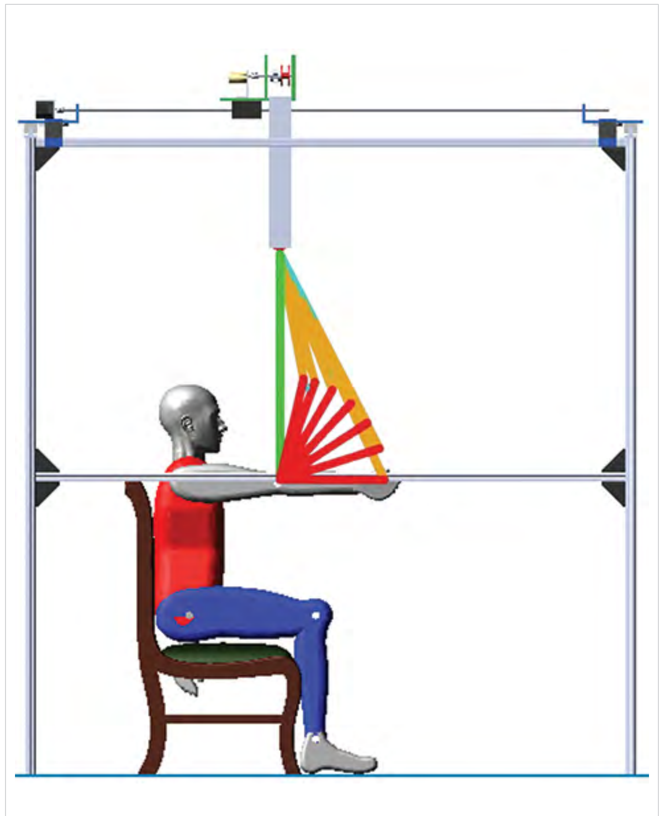

Figure 12. Elbow flexion simulation response in MSC Adams.

Figure 13 shows the response for the elbow flexion movement (θ_2). It starts at the angular position of 0° and goes to a value of 80°, in a time of 7.8 s. The responses of displacement, velocity and angular acceleration are smooth trajectories, without abrupt changes.'

Similarly, for the shoulder extension movement, Figure 14, it starts at an angle of 270° and goes to a value of 230°, in a time of approximately 5.2 s. The displacement, velocity and angular acceleration curves also present smooth behavior.

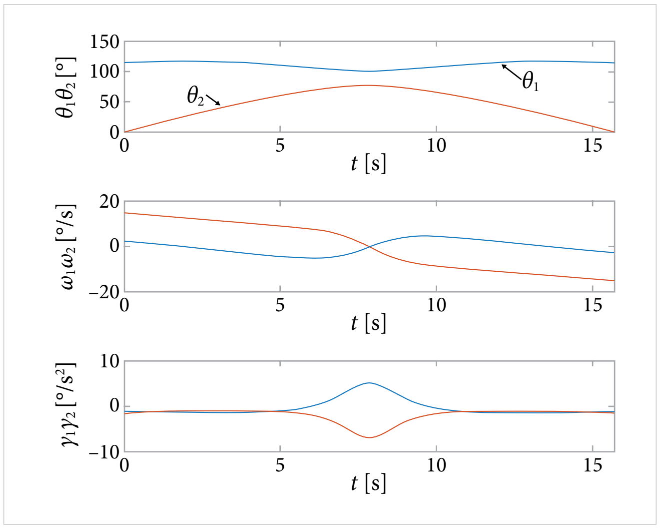

Figure 13. Elbow flexion movement response.

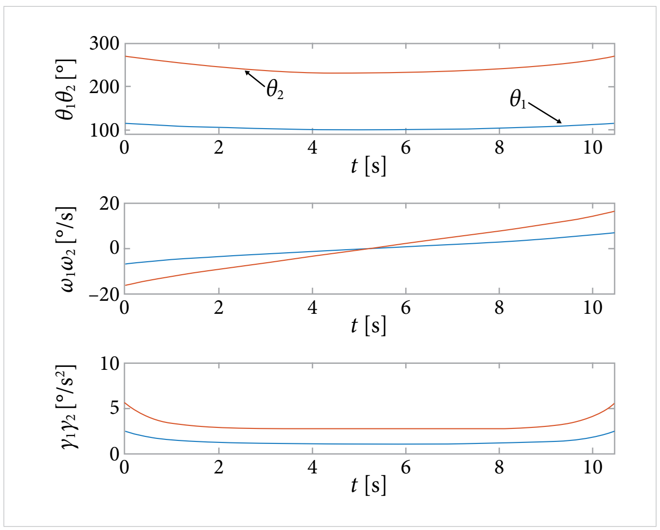

Figure 14. Shoulder extension movement response.

This machine is designed to provide rehabilitation to patients who have suffered a stroke in its early stages, when they have lost mobility in an upper limb but do not have much stiffness in the joints.

The difference between this machine and those reported in the literature is that it contains only 3 actuators, when the others contain more than 7 actuators [7], [9]. This is also reflected in the fact that the kinematic analysis is less complex, since other machines when they use more than 3 cables [5]-[9] become a parallel system, which increases the complexity of the kinematic analysis. Also, another advantage is that being a crane-type system, a greater range of movement is achieved, allowing users with different limb lengths to perform rehabilitation exercises.

IV. CONCLUSIONS

This article proposes a 3 DOF upper extremity rehabilitation machine using a flexible cable. The machine configuration allows providing basic and combined movements, such as shoulder movements of flexion-extension, abduction-adduction, and internal-external rotation, as well as elbow flexion movements.

This article reports the kinematics for some movements and some simulation results for elbow flexion and shoulder extension movements. The results show that with this machine various rehabilitation exercises for upper extremities can be provided with smooth movements.

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