A TWO DEGREE – OF – FREEDOM ROBOTIC EXERCISER FOR REHABILITATION

Călin RUSU', Dan MÂNDRU*, Vistrian MĂTIEŞ**
') Lecturer PhD. Eng. Technical University of Cluj-Napoca, e-mail: rusucalin74@yahoo.com
') Prof. PhD. Eng. Technical University of Cluj-Napoca, e-mail: mandrud@yahoo.com
**) Prof. PhD. Eng. Technical University of Cluj-Napoca, e-mail: matiesvistrian@yahoo.com

Abstract: Current therapy exercisers having one degree-of-freedom for rehabilitating single muscle groups are limited; an efficient functional rehabilitation process requires multiple muscles group’s actions within complex movements of the limbs. In this paper an exerciser for active and passive movement of upper limb is proposed. Its structure is based on a five-bar mechanism actuated by two motors. This mechanism guides the patient’s upper limb through a series of desired exercises. The dimensional synthesis of the five-bar mechanism is based on its workspace and anthropomorphic data of the patients. Some exercises aiming the recovery of motor and cognitive skills are described and discussed. The user interfaces are given too.

1. Introduction

An important component of the actual medicine, beside the prophylactic and curative medicine, is rehabilitation, named also readaptation or reeducation, which is a complex medico-social assisting process that has as objective the reintegration of disabled in family and society, [11]. Its specific ways of action concern the achievement of optimal values for the morpho-functional capacity, psychical status, professional training, and social status. In order to obtain positive results, the rehabilitation treatment must be applied methodically and persistently, carefully controlled, aided by technical systems, which could make it more efficient, [2]. The advances that had occurred in the field of Rehabilitation Engineering are: prosthetics, orthotics, mobility aids, walk assist devices, sensorial augmentation systems, exercisers, rehabilitation robotics, assistive technology, a.s.o., [10].

Kinetotherapy is defined as an ensemble of procedures which promote motion as a basic element of rehabilitation treatment, [7]. Its task is the amelioration or liquidation of disabilities by performance’s improvement (forces, precision, and mobility of locomotion apparatus). Kinetotherapy aspects are varied, including: walking, running, gym, games, training, rehabilitation of walk and prehension, hyro-kinethoterp, and so on. The kinetic treatment is recommended in the following cases: posttraumatic affections of the locomotion apparatus, diseases of the nervous system and respiratory system, rheumatic illnesses, cardiac, metabolic and nutrition-related diseases, [1], [12].

Baker [2] presented a therapeutic wrist rotator for the passive pronation - supination of the forearm. The device, fixed to a stationary table, includes an electric actuator driving a reduction drive to provide relatively slow rotational speed and relatively high torque to the output shaft and handgrip. On / off and rotational direction switches are provided to control the device. Bernardo et al. [4] studied the possibilities to use shape memory actuators in the structure of intelligent exercisers. They developed an actuation device based on active element “U” form, made of CuZnAl alloy with two-way shape memory effect. The device is equipped with two angular voice – coil actuators coupled by levers to the upper limb. The device designed by Gregorio et al. [13] is equipped with a controller for the sensing of the position of the handle at the end of an arm in the X and Y directions and in Z direction through a hinge which permits the arm to rotate upwardly. A therapy and training device for the shoulder joint with a trunk base having two shoulders extensions on a rotational joint base was described by Hassler [14]. It has a modular structure and can produce passive motions of the shoulder and elbow. Saringer et al. [8] presented a continuous passive motion device including an upper arm support suitably fixed to a drive actuator and an adjustable forearm support. Various cuffs are provided so a patient can secure the limb to the device; so pronation – supination is passively created. More recently, Solomon et al. [17] described a therapeutic mobilisation and positioning device of joints having a control device that measures the force through the deformation of an elastic component. Elbow and wrist are the target joints and flexion-extension and pronation-supination are the assisted motions.

Current therapy machines, [18], [19] having one degree of freedom for rehabilitating single muscle groups are limited in the rehabilitation process because the functional rehabilitation requires the rehabilitation of multiple muscle groups. The increasing of the flexibility and of the functional performances is assured by using robotic systems in the kinetotherapy processes.
2. The Developed Exerciser

The proposed exerciser is designed to be used in passive and active upper limb's mobilization, aiming the reattainment of the shoulder articulations’, elbow’s and wrists’ movement capacity and patient’s motor skills. It permits a large variety of exercises, which can be accomplished automatically, and modified by programming them and allows the disabled persons’ tele-assistance. The several patients’ control by a single therapist is possible and with the aid of adequate equipment, the system can monitorize the most important of the patient’s biomechanic parameters.

According to figure 1a, user 1, in the sitting position, has its upper limb linked with mechanical structure 2 (the hand is in direct contact with a handle). The upper limb is mobilized, actively or passively, in the marked plan. Mechanical structure 2 is connected to computer 3.

The upper limb’s movement is occurring into a plane, it results that the mechanical structure must be based on two degrees of freedom mechanism. The mechanical structure presented in figure 1b is consisting in using a five-bar mechanism, the driving joints being placed at the base (elements 4 and 5 are input elements). A similar robotic exerciser is described in [3]. The dimensional synthesis of the pantalater mechanism is based on its workspace, taking into account the so-called zones of convenient reach (ZCR) of upper limbs, for the sitting position, [15], [16]. In figure 1c, 8 represent the normal ZCR, for the left upper limb, 9 – for the right upper limb, and 10 – for the both.

The exerciser responds to the requirements of passive or active motions of the arm (backward-forward projection, inner-outer rotation and abduction-adduction), of the forearm (flexion-extension and pronation – supination) and of the hand (abduction – adduction and flexion – extension), [11].

As is displayed in figure 2, the actuated joint variables are $\phi_1$ and $\phi_3$, while the cartesian variables are the (x, y) coordinates of the revolute center P. Lengths $d$, $l$ and $l_1$ define the geometry of this mechanism entirely.

The relationship between the linear velocity of the characteristic point of the mechanism P(x,y) and the angular velocities of the driving elements is:

$$J_p \begin{bmatrix} V_x \\ V_y \end{bmatrix} = J_\phi \begin{bmatrix} \omega_1 \\ \omega_3 \end{bmatrix}$$

(2.1)
where, $J_p$ and $J_\phi$ are, respectively, the direct-kinematics and the inverse-kinematics matrices of the mechanism, defined as,

$$J_p = \begin{bmatrix} l_1 \cos \varphi_2 & l_1 \sin \varphi_2 \\ l_1 \cos \varphi_4 & l_1 \sin \varphi_4 \end{bmatrix}, \quad J_\phi = \begin{bmatrix} l_1 \sin (\varphi_1 - \varphi_2) & 0 \\ 0 & l_1 \sin (\varphi_3 - \varphi_4) \end{bmatrix}$$ (2.2)

The singular configurations associated to $J_p$ respectively $J_\phi$ are called direct-kinematic singularities and inverse-kinematic singularities. The direct-kinematic singularities are located inside the Cartesian workspace and the inverse-kinematic singularities are often located on its boundaries.

When the mechanism is close to a direct-kinematic singularity, a small joint rate can generate a large velocity of the characteristic point. This means that the positioning accuracy is lower in some directions for some configurations close to direct-kinematic singularities because the encoder resolution is amplified. In addition, velocity amplification in one direction is equivalent to a loss of stiffness in this direction.

For an efficient therapy exerciser, the detection of the singular configurations is an important problem because in this case, exist some directions, for which the mechanism cannot move or can become difficult to control.

The condition number $k$ of matrix $J_p$ defined as:

$$k = \frac{1 + \cos (\varphi_4 - \varphi_2)}{1 - \cos (\varphi_4 - \varphi_2)}$$ (2.3)

quantifies the proximity to a configuration where the velocity amplification is equal in any direction.

When matrix $J_p$ attains a condition number of unity, it is termed isotropic, its inversion being performed without any round-off-error amplification. When the condition number has a value of zero, the mechanism is in a singular position. Mechanism postures for which condition $|\varphi_4 - \varphi_2| = \pi/2$ holds are thus the most accurate for purposes of the direct kinematics of the mechanism. Correspondingly, the locus of points whereby matrix $J_p$ is isotropic is called the isotropy locus in the Cartesian workspace (figure 3).

3. The Rehabilitation Exercises

For the active exercises, the therapist learns the patient about the motions to be executed, and the exerciser displaces trajectories and targets to be accomplished. In the first exercise the patient has to displace the mechanism’s characteristic point on the target circle, with displaying the precision of this task. This application is intended for active exercises. The user interface for this application is presented in figure 4. In order recover the control abilities, it is necessary that the cursor 6 to overlap on the target 4 by moving the mechanism of the exerciser. The target is placed on the circle 1 and its position can be modified. The
proximity is marked by indicators 8. The positioning error can be controlled with button 7.

The position and radius of the circles 1 and target 4 can be modified using cursors 2 respectively buttons 3 and 5. This facility allows various motions in the shoulder, elbow and wrist joints. The results are depicted in figure 4.

Fig. 3 The user interface for the first application

For passive exercises, the exerciser interacts with the upper limb, moving it through the marked points and along the desired trajectories.

The user’s interface for the second application (for passive motions) is presented in figure 5. The characteristic point of the mechanism is programmed to move along an arbitrary trajectory 5. Its form and position in the workspace could be modified, using table 1. Hereby, the range of motions performed by the patient’s limb is controlled, and the desired anatomical movements could be selected.

The speed and the direction of motion are possible to be controlled by moving the cursor along the programmed trajectory.

By interpolation of the x, y values from table 1, it’s possible to obtain wide variety of trajectories. Two examples are presented in figure 6.

In figure 7 in presented the prototype of the symmetric five-bar mechanism used for the applications. The lengths of the elements are 272 mm respectively 400 mm and the distance between the two fixed joints is 600 mm. The driving elements are actuated by two DC servomotors with reduction gears. The servomotors
are driven by linear voltage amplifiers. These amplifiers receive the command signals from the 12 bits digital to analogue converters, which are integrated in the data acquisition and control board DAQPad 1200. The transducers are, in this case, two precision rotary potentiometers.
- based on direct kinematic model, the coordinates X and Y of the characteristic point are calculated;
- these values are compared with the ones imposed by the position of the target, resulting the positioning error in Cartesian space
- if the positioning error is into the admissible range, the light indicators is settled
For the second application:
- the values for angles $\varphi_1, \varphi_3$ are calculated, taking into consideration the coordinates X and Y of the points on the trajectory,
- these values are compared with the ones received from the transducers, resulting the position and velocity errors;
- at every 5 ms an PI controller with feed-forward compensation, processes the information received from the transducers, and establishes the strategy to command the motors, aiming the error’s cancelling.

4. Conclusions

A 2 DOF exerciser was developed allowing active or passive complex motions of upper limbs taking into account individual needs. The mechanical structure is composed by a five-bar mechanism actuated by two DC servomotors. The exerciser offers the control opportunities of exercises parameters. It can adapt to anthropometric dimension and to the morpho-functional residual capability of each patient offering a more flexibility, concerning the exercise variety. Two applications were developed and described: one for active motion and the other one, for passive motion of upper limb.

References

7. Kiss, I. Fizio-kinetoterapie şi recuperarea medicală în afecţiunile aparatului locomotor, Editura Medicală, Bucureşti, 1999
18. www. alimed.com
19. www. powertrainer.com