

An End-Effector Based Upper-Limb Rehabilitation Robot: Preliminary Mechanism Design

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Abstract—Loss of upper limb function often appears after stroke. In this paper the 3D mechanism design for an electromagnetically powered end-effector based robotic manipulator was developed for post-stroke physical therapy. The proposed system delivers a dexterous performance and has a novelty among end-effector based rehabilitation robots. Its design incorporates curved links, which expand the manipulators performance abilities, and, as a result, increase the range of types of rehabilitation therapies. The proposed robotic manipulator can provide a patient with three and two degrees of freedom in shoulder and elbow joints, respectively. It has seven degrees of freedom, and is capable of 7 kg payload. The design of manipulators linkages was optimized to decrease the weight of the system.

Index Terms—Rehabilitation, upper limb, robots, stroke

I. INTRODUCTION

Neurological impairment after stroke frequently leads to the loss of the motor skills in the limb that affects the patients ability to perform activities of daily life. Training and rehabilitation therapy offer an opportunity for motor recovery [1]–[3].

Studies show that human brain is adaptable to changing demands and capable of self-reorganization. Training with specific exercises is necessary to induce nervous systems changes, provoke motor plasticity and, as a result, improve motor recovery [4]. Thus, to restore motor capabilities, the affected limb has to be exercised [5].

A therapy regime must be intensive, repetitive and of long duration. Conventional rehabilitation therapies are effort intensive. Physiotherapists have to assist manually the patient to conduct the exercises [6]. Training is exhausting for the therapist and, as a result, time limited [7]. This fact stimulates new approaches in rehabilitation in a way it becomes more effective and prolonged.

Robot-aided therapy is an emerging part of post-stroke rehabilitation care [8], [9]. Robotic exercisers provide intensive motor therapy, which can be performed in a repetitive, accurate and controllable manner [10], [11]. Moreover, the therapeutic action of the robot can be adjusted to the patients motor abilities [12], [13]. Training with mechatronic systems has mostly shown encouraging outcomes of rehabilitation [5], [14], [15]. Robotic devices may offer the required amount of motor practice and reduce the effort of therapists conducting the rehabilitation procedure [16], [17]. This paper focuses on the upper limb rehabilitation.

Several rehabilitation robots for the upper limb have been proposed. In general, there are two types of designs: exoskeleton [18]–[20] and robotic end-effector based [21] systems. In end-effector based robotic exercisers a patients hand is attached to a hand-holder having trajectories that simulate natural movements of the arm [16]. Examples of the end-effector based robots include MIT Manus [22], [23], ARM Guide [24], MIME [21].

The aim of this project was to design an end-effector based robot for upper extremity rehabilitation. The paper is organized as follows: Section II presents the design requirements, the concept and the mechanical model of the rehabilitation system. Section III illustrates and discussed the results, while Section IV comments on conclusion.

II. METHODOLOGY

A. Proposed System Requirements

A robotic device is required to provide exercise to the patients arm in the required ranges of motion. The patient receives constant assistance, with the hand and wrist being attached to the end of the robotic arm and guided on a specific trajectory. The system is designed to support the weight of the patients upper limb, while performing exercises.

The proposed robotic device should provide a patient with five independent DOFs in the upper limb including, shoulder flexion and extension movement, shoulder abduction and adduction movement, shoulder rotation movement around its axis, elbow flexion and extension movement and shoulder rotation movement around its axis. The device needs to be designed to cover the workspace of a half-sphere with the radius of a patients arm length, centered at the shoulder of a patient. Unilateral training is required at a time.

The robotic device needs to be bidirectional, with enough number of DOFs and appropriate link structure in order to meet the requirements mentioned above. The requirements for a robotic rehabilitation device also include comfort, safety and low complexity.

B. Mechanical Design

The proposed system (Fig. 1) was designed as a stationary, end-effector based robotic device comprising of a basement A, six serial links E-J and a hand-holder plate N. The system design incorporates two curved links H and I. Link J and the

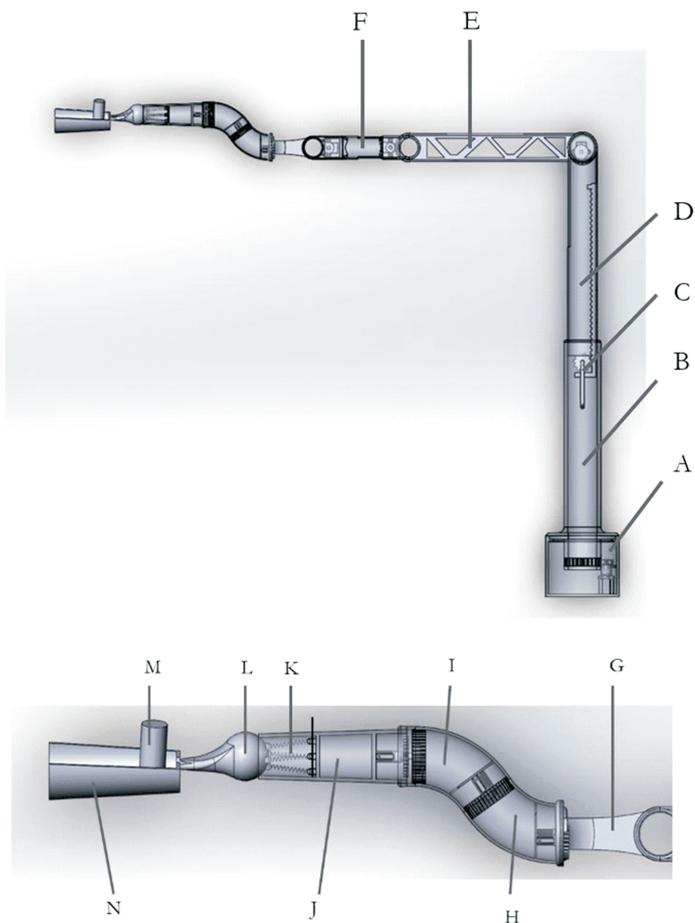


Fig. 1. Robotic exerciser design. Major components labeled: A - base for horizontal rotation, B - stationary base link(1), C - height adjusting screw, D - base link(2) for vertical passive translation, E - translational link(1), F - translational link(2), G - translational link(3), H - rotational curved link(4), I - rotational curved link(5), J - rotational link(6), K - springs to hold the ball joint, L - passive ball joint, M - handle for the patients hand, N - hand-holder plate for the patients arm.

hand-holder plate N are connected through a ball joint L. This ball joint is a passive joint, which is positioned by springs K, that are stiff and allow only little displacement of the ball joint axis in relation to the link J axis. Joints that interconnect the links are actuated by electromagnetic actuators and provide translational and rotational degrees of freedom (Fig. 2).

The patients hand and wrist part is fastened with elastic bandages to the hand-holder plate that can translate in a half-spherical workspace (Fig. 3). The shoulder and elbow joints of a patient are free and can move in compliance with his/her hand motion. The height of the robotic system is adjustable for patients of different height H (Fig. 2). In Fig. 2 baselink F can be pushed into and pulled out from the baselink G. At the desired position a height screw C in Fig. 1 fixes the structure. The whole structure, but the hand-holder plate, is to be made of aluminum; the hand-holder plate of carbon polymeric composites.

The robot was designed for use by patients with weight

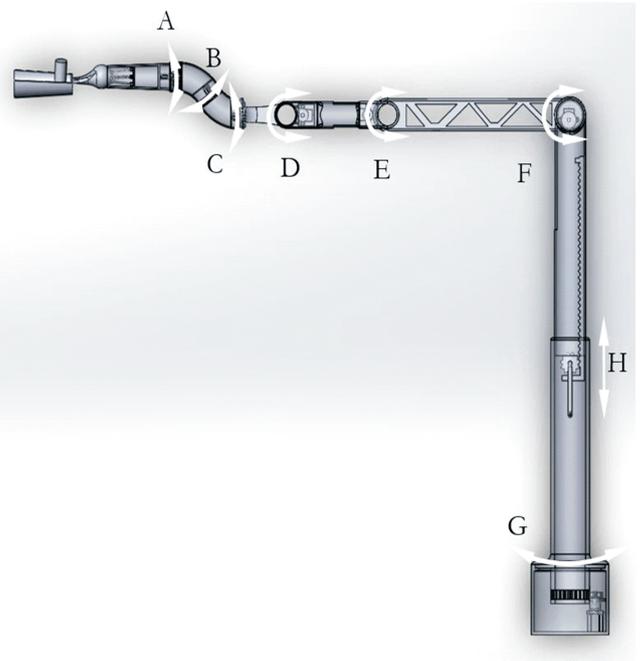


Fig. 2. Kinematic layout of the proposed robotic exerciser. (A) Actuated rotational joint(6). (B) Actuated rotational joint(5). (C) Actuated rotational joint(4). (D) Actuated translational joint(3). (E) Actuated translational joint(2). (F) Actuated translational joint(1). (G) Actuated rotational base joint. (H) Passive height-adjustable frame.

ranging from 50 to 120 kg and of the height between 160 and 190 cm. According to calculations and data on properties of body segments, a human with 120 kg weight and 190 cm height has the upper limb of 6 Kg in weight and 70 cm in length. Thus, the proposed manipulator was calculated using these assumptions. The 3D design of the robotic manipulator was made in the SolidWorks mechanical design software. The link dimensions of the robotic arm were selected as a result of optimization criteria. The optimization was based on factors like desired motion behavior and collision avoidance as well as the requirement of workspace. At first, in order to provide full extension and flexion to the patients arm, the robotic manipulator needs to be able to come into fully flexed and fully extended modes, respectively (Fig. 3a). Secondly, the length of the robotic arm should be long enough to provide full abduction-adduction to a patients arm (Fig. 3(b)). Moreover, mass compensation of the design mass was done by making holes in the link structures.

C. Actuation

The structure and operation of the manipulator depend on the type of an actuator used for its powering. Therefore, in the designing process it was important to select the most appropriate actuator type. Pneumatic, hydraulic and electromagnetic actuators have been considered as a possible powering source for the manipulator.

As the rehabilitation robot interacts with a human, the mechanism should be safe. Resiliency of the joints, or which

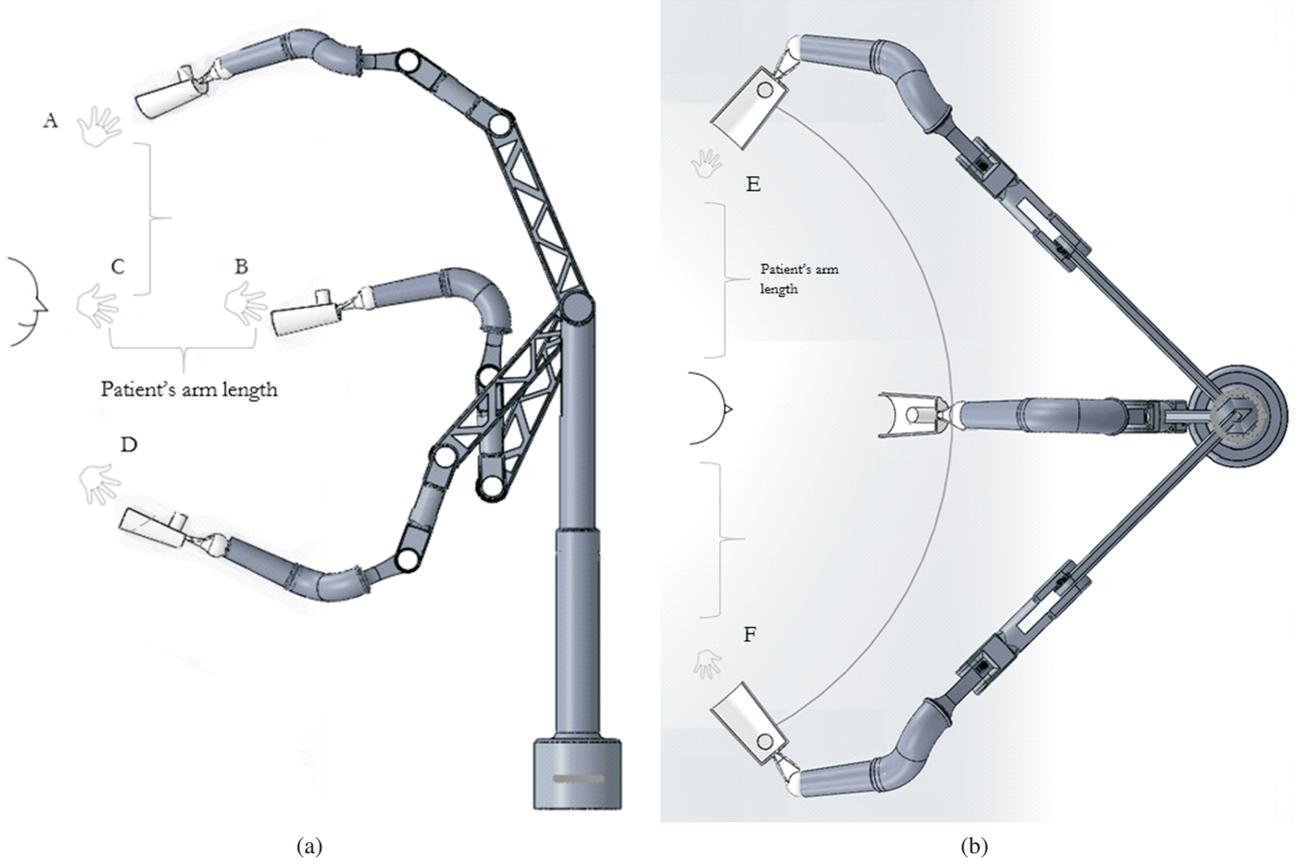


Fig. 3. Workspace of the robot. (a) Side View. (b) Top view. (A) and (D) Full shoulder extension-flexion. (B) and (C) Full elbow extension-flexion. (E) and (F) Full shoulder abduction-adduction.

is called back-drivability, is a crucial characteristic for the safe robotic-arm operation around people. Back-drivable hydraulic/pneumatic actuators are either under development, or complicated. Therefore, electromagnetic actuators for the joint powering have been selected.

Selection of the joint motors is done according to torque level that is required to drive specified links or end effector. Fig. 4 shows the simplified representation of the six link robotic manipulator for beam deflection analysis. Here M is the required torque for the translational joints D-F (Fig. 2) which needs to be calculated. The weight of the robotic arm W is assumed to be uniformly distributed; whereas the weight of the patients upper limb W_h is partly uniformly distributed, which resides on the hand-plate. The rest part of the arm which is free in space as a point mass L . Length l and mass m of the structure is considered to be from the attachment of the considered link - stationary point - to the end-effector.

The beam deflection analysis equations are derived as follows:

$$q(x) = -M(x-0)^{-2} + R(x-0)^{-1} - W(x-0)^0 - W_{hand}(x-(l-l_{hand}))^0 - L(x-1)^{-1}; \quad (1)$$

$$V(x) = -M(x-0)^{-1} + R(x-0)^0 - W(x-0)^1 - W_{hand}(x-(l-l_{hand}))^1 - L(x-1)^0; \quad (2)$$

$$M(x) = -M(x-0)^0 + R(x-0)^1 - \frac{W}{2}(x-0)^2 - \frac{W_{hand}}{2}(x-(l-l_{hand}))^2 - L(x-1)^1. \quad (3)$$

Here, equations (1) and (2) represent loading and shear functions, respectively, equation (3) expresses a moment function.

Analysis of equations (1) - (3) at the end of the manipulator yields the following equations:

$$V(l+) = R - Wl - L - W_h l_{hand} = 0; \quad (4)$$

$$M(l+) = -M + Rl - \frac{W}{2}l^2 - \frac{W_{hand}}{2}l_{hand}^2 = 0. \quad (5)$$

Here, M is the torque transmitted by the associated joint, R is the reaction force at the joint, W is the weight supported by the associated joint, W_{hand} is the weight of the part of the patients arm that resides on the hand-holder plate, l_{hand} is the length of the part of the patients arm that resides on the hand-holder plate and l is the length of the robotic arm supported by the joint.

The required torques for the rotational joints A-C and base joint G (Fig. 2) are calculated in a different manner using the following equations, that provide rotational motion not in the

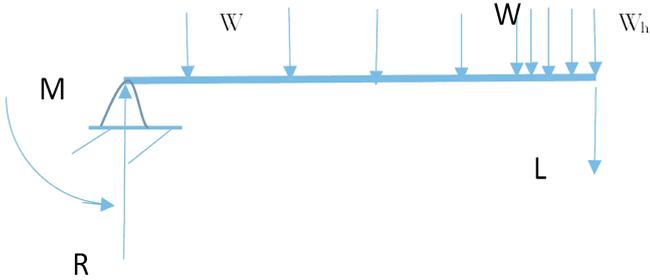
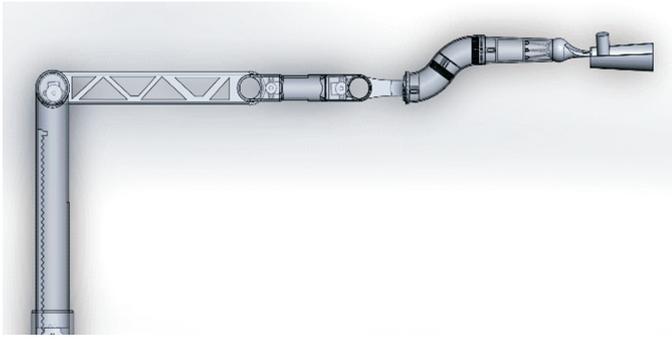


Fig. 4. Beam deflection analysis. Moment calculations.

vertical plane, but in the horizontal:

$$T = I\alpha; \quad (6)$$

$$I = mr^2, \quad (7)$$

where α is the angular acceleration (assumed to be π radians per second squared), I is the moment of inertia, m is the mass rotated by the joint, r is the radius of rotation.

III. RESULTS AND DISCUSSION

The electromagnetically actuated robotic manipulator design features a basement, two basement links, a height screw, six serial links interconnected by tree rotary joints in the vertical plane (Fig. 3) and four rotary joints in the horizontal plane, a passive ball joint (Fig. 3), springs and a hand-holder plate. The total length of the arm from the joint(1) to the end of the hand-holder is 140 mm. The structure is to be produced of aluminum and carbon polymeric composites. Specifying the material type in the SolidWorks 3D CAD software the mass of the entire robotic system is calculated to be 5.84 kg.

The robotic manipulator is fixed on the floor and a patient sits in the front of it. It is designed for the people with weight between 50 and 120 kg and height between 160 and 190 cm. The patients hand enfolds the handle M (Fig. 3) on the hand-holder plate and follows the path specified by the end-effector. The robotic arm has 7 DOF and can exert bidirectional forces, while providing a patient with 3 DOF in shoulder and 2 DOF in elbow. The workspace of the robot is a half sphere in the front of a patient, centered at his exercised shoulder. The workspace has the radius of the patients arm length and the robotic manipulator is able to cover the workspace for the patient with arm length of 70 cm (Fig. 3).

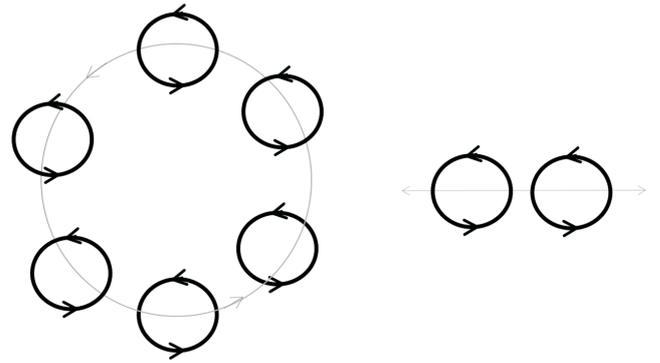


Fig. 5. Examples exercises that could be performed by the robotic exerciser, because it has curved links in its design.

The novelty of the proposed rehabilitation robot for the upper limb is its ability to revolve the patients arm, while following the desired path. This is possible due to introducing curved links into the design. When joint C (Fig. 2) rotates link H (Fig. 3) and joint B (Fig. 2) does not rotate, link I (Fig. 3) revolves around the axis of joint C (Fig. 2) and, as a result revolves the hand-holder plate with the patients arm. At the same time, to not twist the patients wrist joint A (Fig. 2) rotates in the opposite direction of rotation of joint C (Fig. 2). Examples of the paths described above are on Fig. 5.

The robotic manipulator with all included equipment such as actuators, joints, fixed on the floor and balanced. The joints are actuated separately and, therefore, are independent in motion. High dexterity of the manipulator arm (Figs. 2 and 3) allows the robot to suit patients with different motor impairments. The robotic manipulator is able to provide a patient with complex movements of full arm extension-flexion, abduction-adduction, as well as, operate in narrow, confined workspace area. Its ability to perform revolving motion of the arm, while conducting the exercises (Fig. 5), can be advantageous for the patients physical therapy. As a result, wider range of exercises makes the rehabilitation of the upper limb more effective.

The edges of the robotic structure are filleted and, therefore, will not injure the skin of the patient. The fixators are elastic and, therefore, will not interfere with the blood circulation of the patient. A flexible passive ball joint displaces when the wrist part of the patient arm to band and prevents the patients arm from feeling any discomfort.

IV. CONCLUSION

In this paper, an end-effector based robotic manipulator for upper limb rehabilitation was developed. The purpose of which is to enhance the manual therapeutic training. It is provides a patient with 3 DOF in shoulder and 2 DOF in elbow, and is capable to manipulate a payload of 7 kg. From the specifications mentioned above, the robotic manipulator meets all design requirements raised in Section II. It is powered by electromagnetic actuators, with justified pay load and dexterity. From the end-effector based rehabilitation robots available on market, proposed design for the robotic manipulator has

particular advantages for the actuation and high range of workspace.

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