A Study of Feasibility for a Limb Exercising Device

G. Carbone, C. Aróstegui Cavero, M. Ceccarelli and O. Altuzarra

Abstract This paper deals with the design of a robotic device for limb exercising. The attached problem is outlined to identify the main limb exercising features as referring to upper limbs and cable driven robotic solutions. A novel design solution is proposed as consisting in a portable low-cost user-friendly cable driven manipulator. Numerical models and simulations are carried out to verify the feasibility of the proposed solution in terms of operation and motion ranges.

Keywords Robot design · Biomechanics · Limb exercising · Cable-driven robots

1 Introduction

Limb exercising has attracted significant research interest due to its practical usefulness for sport training and rehabilitation and there are even several patents proposing machines for limb exercising, or exoskeletons for human walking assistance or for rehabilitation purposes [1–4]. Some authors have also proposed the use of cable driven robots for limb exercising and physiotherapy applications. In fact, cable driven robots are a special class of parallel mechanisms, whose trusts consist of cables, [5]. This feature allows a significant reduction of inertia and a reduced risk in human robot interactions as well as reduced manufacturing costs, [5]. Significant examples of cable driven robot for rehabilitation can be NeReBot (NEuroREhabilitation robot), a three DOFs cable driven parallel robot for post stroke upper-limb rehabilitation, [6]; CALOWI (Cassino Low-Cost Wire Driven), a four cable robot for limb exercising and rehabilitation, [7]; MACARM (Multi-Axis

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Cartesian-based Arm Rehabilitation Machine), an eight cable robot for upper limb rehabilitation, [8].

Besides a wide literature on the topic there are still several issues to be addressed. For example, the structural frame of a cable driven robot can be significantly larger than the usable workspace. Instead, as users are often injured or disabled people, it is important that the size and shape of the structural frame facilitates the access to workspace area. Additionally, easy portability could allow the use of a robot in a home environments to increase users' motivation towards the training/rehabilitation process. For this purpose, the attached problem has been addressed aiming to identify a novel design solution being easily portable while having low-cost user-friendly features.

2 The Attached Problem

Limb exercising consists in motions that activate limb muscles in various ways to keep them fit. Physical rehabilitation is the process of helping patients in regaining control over parts of their body after an illness or a traumatic event. In particular, upper limbs rehabilitation after stroke consists mainly on physical repetitive exercises of the injured limb. These exercises include movements such as flexion and extension, pronation and supination, adduction and abduction and circular movements of shoulder and elbow, [9].

There are several reasons for this transition from conventional methods to a robot-oriented approach. For example, in the current ageing society, the demand for rehabilitation exercises is expected to grow considerably while available therapists are expected to slightly decline. Accordingly, the use of robots, several patients can be treated at the same time under the supervision of a single therapist, increasing productivity and efficiency. Moreover, robots can support long duration exercises keeping the required precision while tiredness can affect therapist treatment, [10]. Additionally, robotic systems can record information such as position, trajectory, force and velocity and then archive this data and compare it to check the progress of patients. They can also provide acoustic and visual feedback, helping the patient maintain a high level of attention during the session, allowing patients achieve autonomy in the exercises may increase motivation towards following the rehabilitative therapy. In short, rehabilitation robotics can provide high-intensity, repetitive, task-specific treatment of the injured limb and can help monitor patient progress, [11].

Among the different robotic structures existing, the cable driven parallel robots have characteristics that make them suitable for rehabilitation purposes. As already mentioned, they have large workspace and can be reconfigured by simply changing the attachment points or the actuators positions. These features allow the adaptation to different patients and different rehabilitation exercises. In fact, unlike other robots such as industrial ones, rehabilitation robots need to be adapted to the particular characteristics of each patient, taking into account not only the type of exercise required, but also the physical characteristics, perception and pain threshold of each patient. Besides, their transportability makes them easy to be placed aside a wheelchair or a bed and easy to be stored after treatment. In terms of commercialization, they have a low cost mechanical structure and simple maintenance, which may also contribute to be used by patients at home. Furthermore, they are intrinsically safe for patients and therapists thanks to the use of cables instead of rigid links. Finally, the way in which the patient perceives the treatment is of great importance. In this regard, the use of wires increases the acceptability by the patient, who feels guided and not constrained by the machine, [10–12].

3 Cable Driven Robots Features

Cable driven parallel manipulators are a special class of parallel mechanisms, whose trusts consist of cables whose lengths are adjustable to control the end-effector's position and orientation [12]. That is, the pose of the end-effector, determined by its degrees of freedom (DOFs), is manipulated by actuating motors that extend or retract the cables. As [12] points out, the condition for a mobile platform with n DOFs to have a fully controlled motion is having, at least $m = n + 1$ cables. This derives from the fact that, due to their nature, cables require positive tension. They can only exert pulling action, being able to carry loads in tension but not in compression, so redundant cables are needed to avoid uncontrollable situations. Figure 1 shows the general structure of a spatial cable driven parallel robot and its main components.

4 Proposed Design Solution

A specific design procedure has been outlined as proposed in the flow-chart in Fig. 2 aiming to carry out the design of a proper mechanical structure as based on key aspects such as limb exercising/rehabilitation requirements, training motions as defined in medical protocols as well as constraints given by size limitation of home

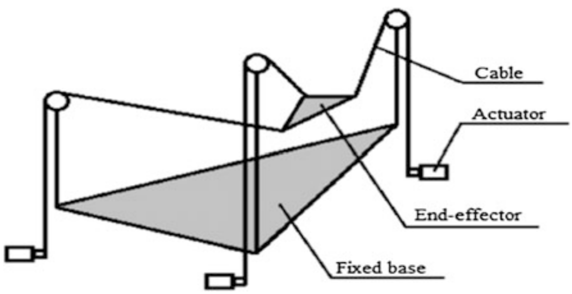


Fig. 1 A scheme of a cable driven parallel robot with its main components

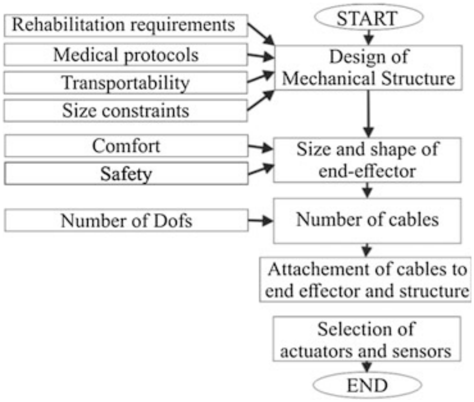


Fig. 2 A flow-chart of the design procedure

environments, easy operation, comfort, safety, transportability. Accordingly, the shape of the mechanical structure has been defined as shown in Fig. 3 also to achieve an easy placement of the device in a room edge and a wider easily accessible workspace as compared with cubic shapes of many existing cable driven parallel robots such as [7, 8]. The proposed structure can accommodate 6 or more cables. However, the more cables, the less low-cost easy-operation the robot becomes. Thus, a balance should be found between the number of DOFs under control and the complexity of the mechanism.

The proposed design has been thought to have a maximum of six cables. The way in which these cables are attached to the end-effector will determine which DOFs are under control. Depending on the kind of exercise, some cables could be disconnected. For instance, to provide flexion-extension movements four cables are enough. Gravity is another issue to be taken into account. A distinction should be made between acute stroke patients, whose limbs need to be totally guided as they do not have autonomy to move them, and patients who are able to move their limbs following the rehabilitative exercise. In the first case, gravity has to be considered as

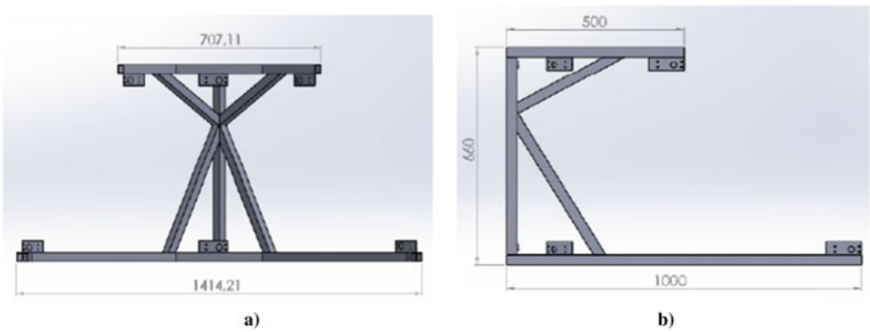


Fig. 3 A 3D model of the proposed mechanical structure with main sizes in mm: **a** *front view*; **b** *side view*

the limb is acting as deadweight. Focusing on the forearm, a first study will focus at elbow flexion-extension and horizontal adduction-abduction movements. Both of them are angular displacements of the forearm, being the elbow joint the centre of rotation of this motion. The trajectory followed by the wrist is a circumference arc along the plane defined by the median longitudinal plane of the arm. The difference between both movements is the orientation of that plane. While in the flexion-extension it is vertical, in the adduction-abduction it remains horizontal. Being the trajectory a circumference arc along the same plane, the degrees of freedom that need to be under control are two for the position of the center of gravity in that plane and one for the orientation of the reference system attached to the end-effector. Being the pose of the end-effector in the arm's plane defined by three degrees of freedom, the number of cables required by the kinematics is four: three on the top of the frame and one extra cable on the bottom to fulfil the positive tension requirement. The adjustment of the lengths of these cables makes the end-effector/upper limb, follow the desired trajectory.

A kinematic model can be established for the proposed design solution by expressing the position of the end-effector as function of the coordinates of the cable attachments to the mechanical structure and as function of the cable lengths. In particular, Fig. 4a, b, c show kinematic schemes as referring to a 3D view, plane X-Y, and plane X-Z, respectively. The Inverse Kinematics Problem (IKP) consists on finding the cable lengths as function of the end-effector degrees of freedom. As shown below, in both cases the length of each cable can be written in terms of difference of coordinates of its endpoints.

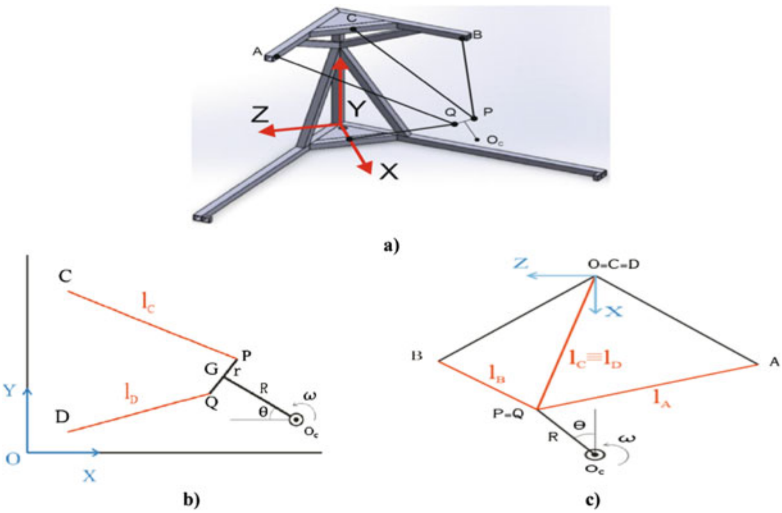


Fig. 4 Kinematic schemes: **a** a 3D view with reference frame and location of cable attachments; **b** X-Y (flexion-extension) plane; **c** X-Z (adduction-abduction) plane

Firstly, for the flexion-extension movement, the kinematic scheme of cables C and D is shown in Fig. 4b. Because of the symmetry of the structure and arm position it moves along plane π, so the IKP for this cables is simplified. The length of the cable, l_C, is defined by points C and P, which represent the attachment points of the cable to the motor and to the upper face of the end-effector, respectively. Two reference frames have been considered: OXY is the fixed frame and GX_GY_G is the moving frame associated to the end-effector center of gravity. Parameter R indicates the length of the forearm, while parameter r indicates the distance from the center of gravity of the end-effector to the attachment point P, this is, half the height of the frame arms. θ represents the angular displacement of the arm axis and also the orientation of the moving reference frame with respect to the fixed one. It is indeed one of the three DOFs to define the pose of the end-effector. The other two DOFs are related to the position of the frame arms in the plane, and could be defined by the coordinates of the center of gravity or by the coordinates of point P. Finally, since the trajectory followed by point G is a circumference arc, it is interesting to write the equations in terms of the coordinates of its rotation center, OC.

Thus, the following equations can be written for the kinematics of cable C by referring to a planar motion of the end effector within the plane shown in Fig. 4b,

$$l_C = \sqrt{\overline{CX}_P^2 + \overline{CY}_P^2} \tag{1}$$

$$\overline{CX}_P = X_P - X_C = X_{Oc} - R\cos\theta + r\sin\theta - X_C$$

$$\overline{CY}_P = Y_P - Y_C = Y_{Oc} + R\sin\theta + r\cos\theta - Y_C$$

where X_i and Y_i are the X and Y Cartesian coordinates of the i-th point; r and R are geometrical sizes of the end-effector and θ is the angular displacement of a limb in the X-Y plane, as shown in Fig. 4. Similar equations can be written for cable D. Cables A and B do not just move along plane π, but along the space in the three dimensions. However, the equations for their lengths l_A and l_B can be defined similarly to the ones of cables C and D, as difference of coordinates of their endpoints. Accordingly, for cable A one can write

$$l_A = \sqrt{\overline{AP}_X^2 + \overline{AP}_Y^2 + \overline{AP}_Z^2} \tag{2}$$

$$\overline{AX}_P = X_P - X_A = X_{Oc} - R\cos\theta + r\sin\theta - X_A$$

$$\overline{AY}_P = Y_P - Y_A = Y_{Oc} + R\sin\theta + r\cos\theta - Y_A$$

$$\overline{AZ}_P = Z_P - Z_A = -Z_A$$

A similar equation can be obtained for cable B. Accordingly, Eqs. (1) and (2) can be combined with the similar equations for cables B and C to provide a set of four equations in four unknown that are the kinematic relationship between cable lengths and end-effector position and orientation for a planar motion of the end effector. The above-mentioned equations allow to calculate the cable lengths for any desired end effector pose for a planar motion of the end effector. Similar equations have been defined and solved for other planned motions of the end effector. The above-mentioned equations have been used for validating the operation of the proposed design solution within Solidworks Motion environment.

5 Numerical Simulations

Numerical simulations have been carried out both by using the models given by Eqs. (1) and (2) and a 3D CAD model within Solidworks Motion simulation toolbox. In particular, Fig. 5a, b, c show snapshots taken from the Solidworks Motion simulation of the adduction training movement: when the forearm is at 0°, 45°, and 90°, respectively. It is to note that the simulations have been carried out by using the values reported in Tables 1 and 2. In particular, Fig. 6a shows an angular motion of the forearm by 45° corresponding to a displacement of the wrist (point $\mathbf{O_C}$) from 685 to 731 mm from the attachment of cables at point P. This motion range is within the feasible motion range of the chosen servomotors and pulleys. Several other training trajectories have been tested within Solidworks Motion

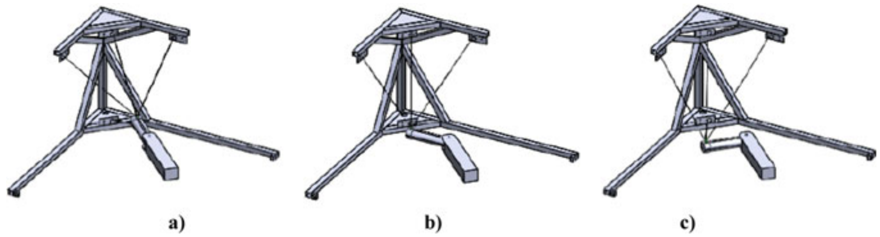


Fig. 5 Snapshots taken from a Solidworks Motion simulation of the adduction training movement: **a** forearm at 0°; **b** forearm at 45°; **c** forearm at 90°

Table 1 Values of main kinematic parameters used for the simulation of the extension mode

OCX [mm]	OCY [mm]	R [mm]	r [mm]
879.88	30	215	27

Table 2 Coordinates of attachment points of cables with pulleys

X_A [mm]	Y_A [mm]	Z_A [mm]	X_B [mm]	Y_B [mm]	Z_B [mm]	X_C [mm]	Y_C [mm]	X_D [mm]	Y_D [mm]
327.7	618.5	−279.7	356.7	618.5	308.6	196.4	618.5	196.4	58.5

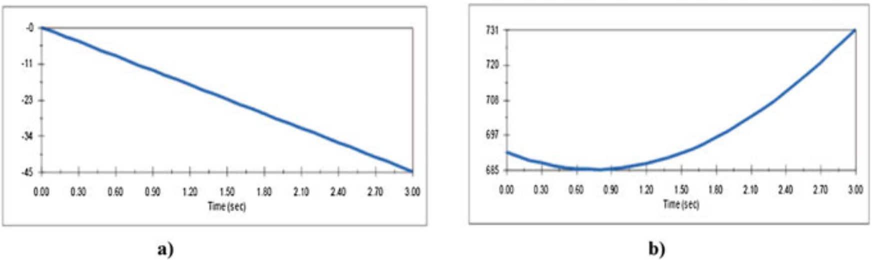


Fig. 6 Plot outputs from the simulation in Fig. 5: **a** angular displacement (°) of the forearm over time (s); **b** distance (mm) of point O_C (attachment of the wrist) relative to point P (attachment of the first two cables) over time (s)

environment Data from the Solidworks Motion simulations have been also compared with results obtained by using Eqs. (1) and (2) with very good matching of results.

6 Preliminary Tests on a Built Prototype

Preliminary experimental tests have been carried out as shown in Fig. 7. In particular, Fig. 7a, b, c show snapshots taken from an experimental test of the adduction training movement: when the forearm is at −45°, 0°, and 45°, respectively. The achieved motion properly matches with the simulated operation in Fig. 5. Further work should be carried out for improving the control and of the used servomotors as well as for taking into account the flexibility of cables into the control loop as well as the effect of human limb weight and inertia.

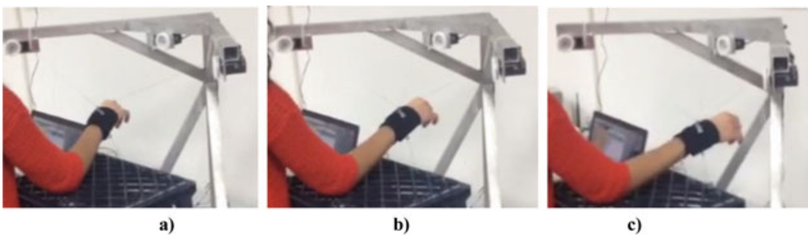


Fig. 7 Preliminary experimental tests of the adduction training movement at LARM in Cassino: **a** forearm at −45°; **b** forearm at 0°; **c** forearm at 45°

7 Conclusions

This paper deals with the development of a device for limb exercising. In particular, the main limb exercising features have been identified, mainly as referring to upper limbs. A novel cable driven parallel manipulator has been proposed as a solution for achieving a portable low-cost user-friendly upper limb exercising device. Numerical models and simulations as well as preliminary experimental tests have been carried out to verify the feasibility and practical usefulness of the proposed solution.

Per la presentazione (Figs. 8, 9, 10 and 11).

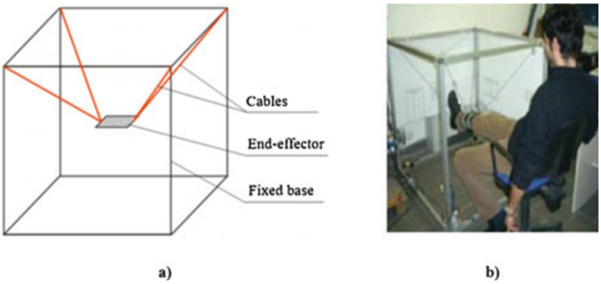


Fig. 8 A four cable driven parallel manipulator CALOWL: **a** structural diagram; **b** application as support for limb rehabilitation

Fig. 9 NeRebot: **a** structure diagram; **b** overall view [6]

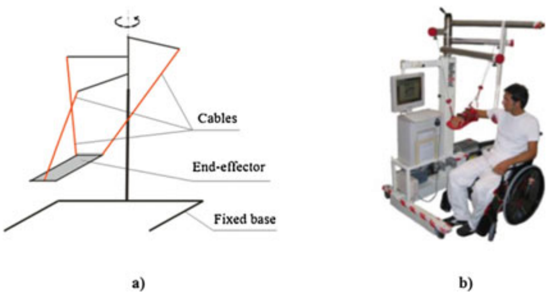
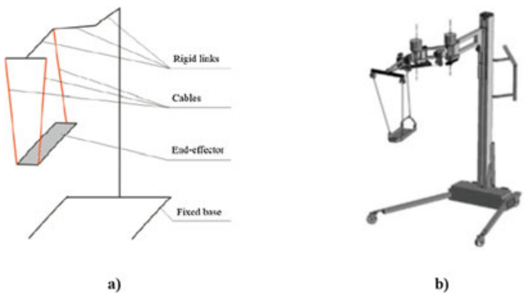
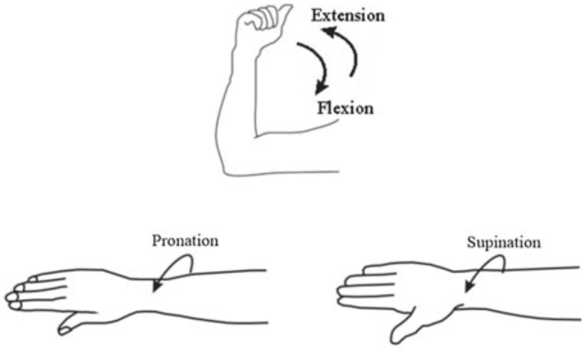


Fig. 10 MariBot rehabilitation robot: **a** Structural diagram; **b** design of the prototype





Elbow joint movements: Flexion-Extension; Pronation-Supination.

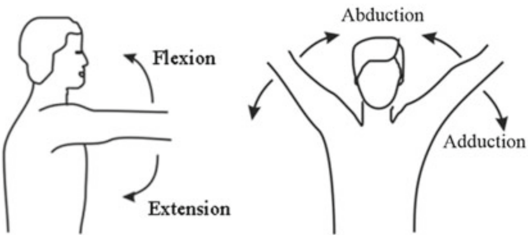


Fig. 11 Shoulder joint movement: Flexion-Extension; Abduction-Adduction

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