Design of a Cable-Driven Four-Bar Mechanism for Arm Rehabilitation

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Abstract. This paper presents the design of an assistive mechanism to be used for the rehabilitation of human arm. First the motions of two types of rehabilitation exercises are described. The motions are planar motions, so a planar four bar mechanism is designed. The synthesis problem is formulated as a three-position synthesis problem. Next, the actuation issue is addressed. Actuation via cables is preferred for better force transmission. The connection point of the cable to the mechanism is optimized considering the curvature of the coupler point curve. Finally, multiple pulleys are designed for enhancing force transmission.

Key words: Rehabilitation mechanism, kinematic synthesis, cable driven mechanism, actuation design

1 Introduction

Physical treatment and rehabilitation are among the most energy and time consuming treatment topics in medical science. The repeatability of the motions is an issue when the exercise is manually performed by a therapist. Another problem in the therapist supervised process is that keeping track of the improvements in the patient's health is insufficient and subjective. In addition, number of therapists and their daily working hours are limited, so the patients need to repeat the exercises with the help of other people which makes them more dependent on others. A solution to these problems is to devise autonomous exercise systems.

Robotic scientists introduced many solutions to support physical treatment exercises in the past decades. A few examples are the 2 degrees-of-freedom (dof) MIT-Manus [2], 6-dof MEDARM [1], 6-dof ARMin [3] and 7-dof CADEN-7 [4]. There are several spatial manipulators of exoskeleton type and planar/spatial manipulators of end-effector type for rehabilitation. A common property of all such systems is that they are optimized for supporting many possible motions and they have multi-dof. Some of the systems are actuated through cables which allows to mount the motors on the base, hence decreases the amount of moving mass. Cable transmission is used for joint actuation in serial kinematic chains in literature.

This study is about the design of an assistive mechanical device to be used for two different arm rehabilitation exercises. The information about these exercises are obtained from the medical doctors in Dokuz Eylül University in Izmir. These exercises include more than one joint and muscle group to be active. Such type of motion is called synergic. First exercise is performed in a vertical plane as shown in Fig. 1. The patient moves the hand from a further point to the back of the head. The other exercise is performed in an oblique plane that makes a 30° angle with the floor. For this motion, patient move the hand back and forward on a straight line parallel to the floor. Both exercises are path independent, i.e. how the patient moves the hand from the initial position to the final position is not of importance. These two motions can be accomplished with (a) different mechanisms, (b) a multi-dof mechanism or (c) a re-configurable single dof mechanism. Obviously, the simplest solution would be using a single dof mechanism, if possible. In this study, we investigate such a solution.

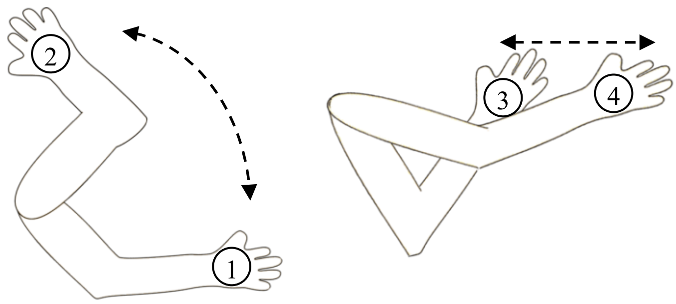

Fig. 1 Exercise 1 (side view) and exercise 2 (top view)

2 Mechanism Design and Description of the Model

The proposed system is designed for two planar synergic motions of arm rehabilitation presented in Section 1. The planes of motion are different, but since one of the revolute joints is selected to be concurrent with the shoulder center, the whole mechanism can be rotated about a fixed axis to switch from the vertical plane (90°) to the oblique (30°) plane, or vice versa. So, the rotation can be accomplished by a revolute joint between the ground and the plane of the mechanism. For both motions, the problem can be formulated as a motion synthesis problem for which the two poses will be enough since the motions are path-independent. Also, the predefined poses (poses 1, 2, 3, 4 in Fig. 1) are described such that the elbow angle can be taken to be the same for pose 2 in exercise 1 and pose 3 in exercise 2. Therefore the mechanism design problem is formulated as a 3-position problem (poses 1, 2=3, 4). Mechanism design is explained in this section. The actuation design is given in Section 3.

2.1 Kinematic Synthesis

It is required that the system supports both upper and forearms. Shoulder center is assumed to be fixed during the motion and motions are planar. There is no wrist motion, so the human arm can be modelled as a 2R (R: revolute joint) planar serial kinematic chain. By completing this chain to a 4R closed loop kinematic chain, a four-bar mechanism is obtained to support upper and forearms. The four-bar mechanism is preferred over other alternatives due to its constructional simplicity.

In graphical motion synthesis for 3 positions, the circle points can be arbitrarily chosen (2 arbitrary parameters) for each of the dyads [7]. However, one of the dyads is predefined in this problem, because the coupler link is attached to the forearm and the rocker is attached to the upper arm. Therefore, length and position of rocker link is fully defined. Also, the circle point of the remaining dyad is constrained to be on the central line (the line connecting wrist center end elbow center) of forearm in order to achieve a more compact design. Hence, there remains only one arbitrary parameter, which is used to maximize the crank angle rotation.

The three poses of the upper (full lines) and front (dashed lines) arms are presented in Fig. 2. These poses are determined via discussions with the medical doctors. The upper arm length is selected as 330.1 mm, which is the estimated upper arm length for a male with 170 cm height according to Sağır [6]. The forearm length is irrelevant for kinematic synthesis. So, the three poses of one of the dyads of the four-bar mechanism is already predefined. The other dyad is obtained via graphical synthesis for 3 positions. The synthesis steps are not presented here for conciseness. The mechanism dimensions obtained are presented in Section 2.2.

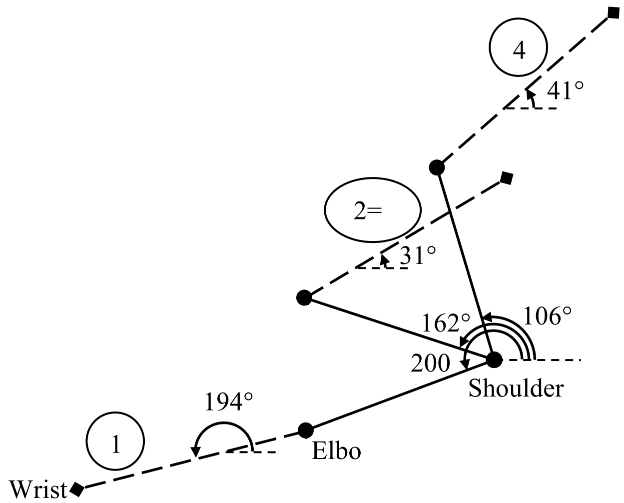

Fig. 2 The three poses of the front and upper arms

2.2 Kinematics & Parameters

In Fig. 3, B_0 and B joints represent shoulder and elbow centers, respectively. Rocker length is a_4 = 330.1 mm. After three position synthesis, the other four-bar link lengths are determined as a_1 = 295.2 mm, a_2 = 191.9 mm and a_3 = 202.1 mm. The link lengths result in a double-rocker type four-bar mechanism. Forearm is attached to extension of coupler link BH, where H represents the center of mass of the hand and |BH| = h_3 = 375.9 mm following Plagenhoef [5].

Motion starts at a very close pose to singularity, where the upper and forearms are almost inline (Pose 1 in Fig. 2). If we would actuate the mechanism through link A_0A, the initial torque requirement would be high. Therefore, the mechanism is actuated by a cable attached to the coupler link at point C, the location of which is given by parameters |BD| = b_3 and |DC| = c_3.

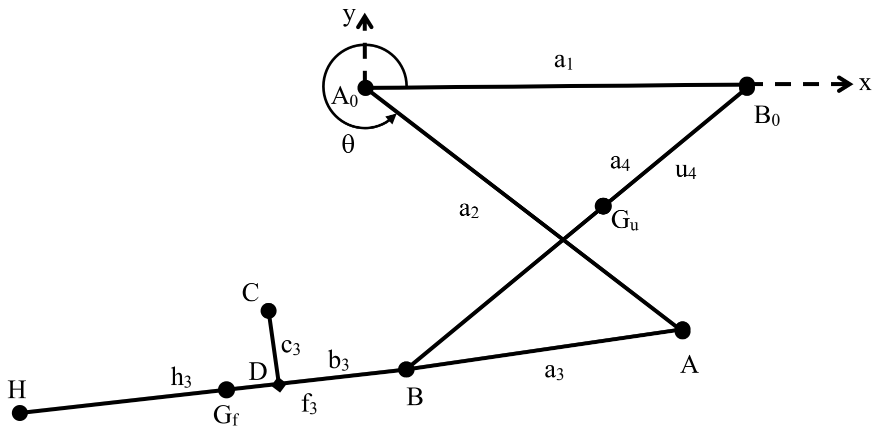

Fig. 3 Kinematic Parameters

3 Actuation Optimization

The force analysis is performed for a male with 170 cm height and 100 kg mass. Then, the estimated mass and center of mass values for the arms can be calculated as $m_{upperarm}$ = 3.25 kg, $m_{frontarm}$ = 1.87 kg, m_{hand} = 0.65 kg, $|B_0G_u|$ = u_4 = 143.9 mm and $|BG_f|$ = f_3 = 142 mm following Plagenhoef [5]. A simple construction of the mechanism is done with aluminum links and the link masses are taken as m_2 = 0.2 kg, m_3 = 0.59 kg and m_4 = 0.35 kg. Motion from pose 1 to pose 2 takes place in a vertical plane, while the second motion takes place in an oblique plane making 30° with horizontal, so the weights in the second motion are multiplied with sin30° = 0.5. With these forcing conditions, the work done during the motion from pose 1-to-4 is determined. If the mechanism is actuated from A_0A link, the initial torque requirement is 60 N·m (Fig. 4). The angle of A_0A link is θ = 340° for pose 1, θ = 180° for pose 2 (≡ pose 3) and θ = 75° for pose 4. The sudden change at θ = 180° in Fig. 4 is because loading condition changes, that is, weights are halved. In practice, the portions before and after θ = 180° correspond to separate motions of the mechanism in vertical and oblique planes. The total work done is computed as 13.3 N·m. The ratio of peak torque to average torque value is 12.74. Due to this non-uniform torque requirement, we devised an alternative way of actuation, where the coupler link is driven with a cable attached to the coupler point C. A uniform torque distribution is desirable for better dynamics and also for better force compliance of the machine and hence safer interaction with the patient.

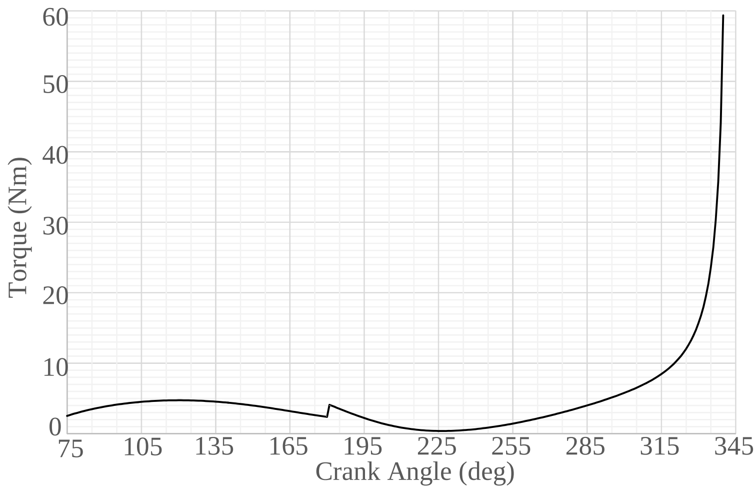

Fig. 4 Torque requirement before cable actuation

The system requires to be actuated only in one direction against gravity, so cable actuations is suitable. The location of the connection point C should be optimized for better transmission characteristics. In order to formulate the transmission characteristics, we define the pressure angle, α, as the angle between the velocity vector of C and the cable direction. The ideal case for better transmission is obtained for α = 0, in which case all cable force is used along the displacement of C. It is possible to design a cam as the pulley of the cable. However, for constructional simplicity we preferred a circular pulley. In that case, α cannot be zero for all times and when α ≠ 0 there will be a component of the cable force which is perpendicular to the velocity of point C. Such a component does not do any useful work and it is balanced by joint reaction forces. α depends on the trajectory of point C, which is determined by parameters b_3, c_3, and location of the pulley, which can be represented by two more parameters. Instead of optimizing α based on these four parameters, we make a further simplification and assume that the cable direction will not change much during the motion. This simplification results in an optimization problem with b_3 and c_3 parameters only. Keeping cable direction approximately constant and pressure angle α remains close to zero means that the trajectory of point C is a straight curve. Any point on links A_0A and B_0B trace circular arcs, so the cable is attached to the coupler link.

We devised an iterative procedure to locate a point with a straight path. In order to check the curvature of the path of point C, the path is discretized into short line segments for 1° increments of θ (angle of link A_0A) and angles between consecutive segments is recorded. An objective function, Φ, is defined as the sum of the squares of the angles. A matrix of objective function outputs are evaluated for $-a_3 \leq b_3 \leq h_3$ and -200 mm $\leq c_3 \leq 200$ mm. The minimum value of the objective function is obtained for b_3 = 2.5 mm and c_3 = -6 mm. However, when the coupler curve is inspected, it is seen that the curve is not as straight as desired. So, instead of having only one pulley in the system, we added intermediate pulleys in order to fit several line segments on the coupler point curve instead of a single line.

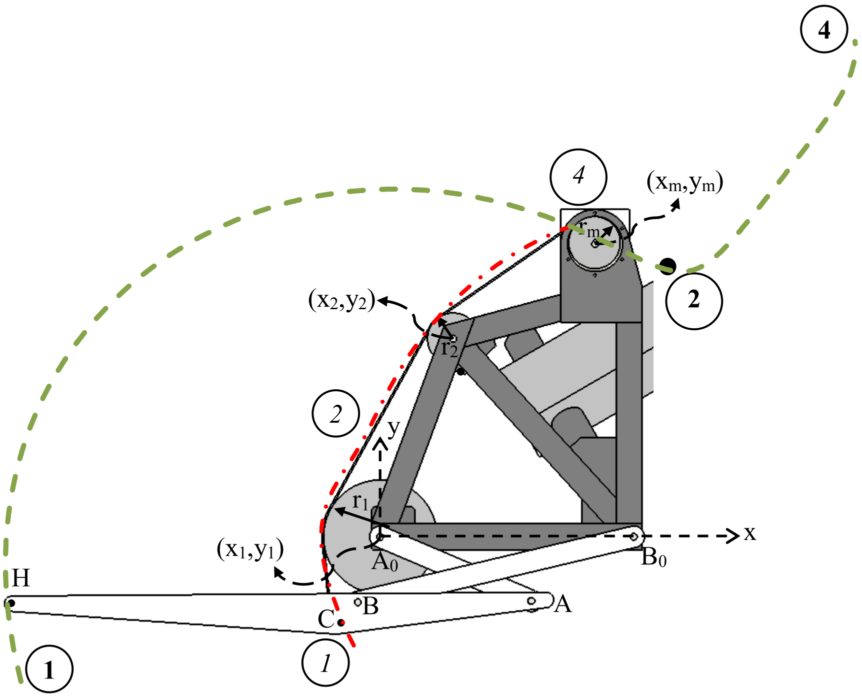

Fig. 5 Cable actuation solution with three pulleys

In Fig. 5, there are two intermediate pulleys with radii r_1 and r_2 besides the pulley connected to the motor. The motion of coupler point C starts from the lowermost section of the path (pose 1) and initially the actuation cable is in contact with all three pulleys. As the motion continues, the cable is disengaged from the first pulley and Exercise 1 is concluded at pose 2. For Exercise 2, the cable is never engaged to pulley 1. During the motion in Exercise 2, at some point the cable is disengaged from pulley 2.

It is necessary to decide on how many pulleys are needed and determine the location and radii of the pulleys. First, the coupler curve is dissected into two (for 1 intermediate pulley case) and the objective function Φ is evaluated for both sections for $-a_3 \leq b_3 \leq h_3$ and -200 mm $\leq c_3 \leq 200$ mm. Of course this procedure depends on the location of the point of dissection on the coupler curve. The location of dissection point is parameterized by the corresponding θ angle. By changing the dissection point, the optimum value for Φ is monitored. The resulting curve is not straight enough again, so the coupler curve is dissected into three sections. The same procedure for seeking optimal dissection points is followed and a satisfactory result is obtained for dissecting the curve for at θ = 275° and θ = 120°. The optimal location of point C is determined as b_3 = 25.5 mm and c_3 = -27 mm. Next, three lines are fit to the three sections of the coupler curve. Pulley 1 should be tangent to lines 1 and 2, Pulley 2 should be tangent to lines 2 and 3 and finally the pulley attached to the motor should be tangent to just line 3. The radii of the intermediate pulleys are selected intuitively considering the coupler curve. The radius of the pulley connected to the motor is selected such that the pulley makes no more than 3 full rotations. The pulleys are located at (x_1, y_1) = (0, 0) mm, (x_2, y_2) = (85, 230) mm and (x_m, y_m) = (250, 340) mm (short after pose 4) and the radii are selected as r_1 = 70 mm, r_2 = 32 mm and r_m = 30 mm (Fig 5).

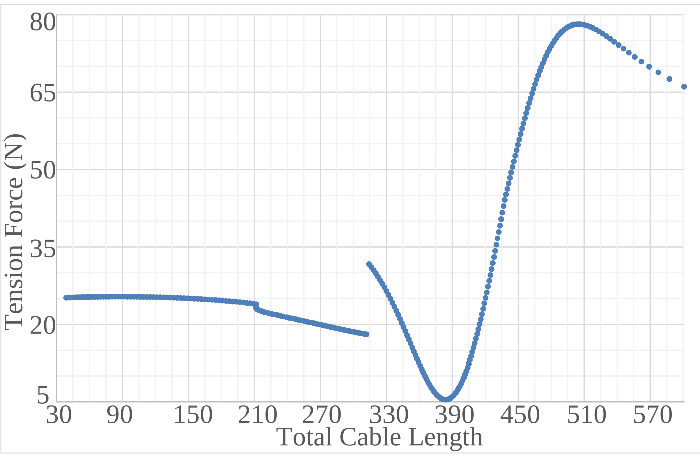

Fig. 6 Force requirement versus cable length

The force requirement versus cable length is depicted in Fig. 6. Of course, once again the total work done is 13.3 N·m. The ratio of peak force to average force value is 2.4, so the actuation force variation is considerably improved. However, introducing multiple pulleys introduces functional and constructional problems. These problems are to be solved in future studies.

6 Conclusions

This study presents the design of a rehabilitation assistance mechanism in order to perform two exercises of the human arm. The exercise motions are planar predetermined motions, so a planar single-dof mechanism is designed. The main challenge in the design was how to actuate the mechanism. It turned out that, when the mechanism is actuated from one of its joints, the variation of the torque requirement is not desirable. So a cable-actuation design is performed.

The solid models for the designed four-bar mechanism and the pulleys are constructed, however they are not presented in this study due to space limitations. A prototype will be manufactured and tests will be performed in the future.

Acknowledgments We would like to thank Prof. Özlem Şenocak, Prof. Özlen Peker ve Prof. Özlem El from Dokuz Eylül University for their support during problem definition of this study. Some parts of the project that are not mentioned in this paper are carried out in RWTH Aachen University as a M.Sc. Thesis work under supervision of Jascha Norman Paris.

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