Simulation of Cable Driven Elbow Exosuit in Matlab

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Abstract. Exo-suit/Soft Exoskeletons are actuated using flexible actuators or cable driven systems. In a cable-driven exosuit, the routing of the cable needs to be defined mathematically to control the position of the joint. For an elbow exosuit, the actuation is applied to the elbow joint which has a single DoF. The generated movement takes place in the sagittal plane. To fabricate a cable-driven elbow exosuit, it is necessary to calculate the tension force in the string and the torque required at the elbow joint to select the cable and motor characteristics. The process of calculating these parameters are independent for any exosuit. A static model for a cable driven exo-suit has been presented. Using the model we have simulated the actuation of an elbow joint for an exosuit. The physical validation of the model will be done in future work.

Keywords: Elbow exosuit · soft exoskeleton · soft wearable device · simulation · elbow actuation

1 Introduction

Exosuits are soft wearable robotic devices that are used to assist the movement of limbs through power augmentation [1]. In the human body, several muscles work together in the actuation of joints and achieve complex motion of limbs to manipulate the environment around [2,3]. For an exosuit to achieve all the movements and to be able to assist every movement is difficult. However, few exosuit prototypes achieve assistance for multiple joints [4,5]. Considering the fact that assistance for rehabilitation and for repetitive tasks in the industries is sometimes required only at a single joint, the single joint exosuits are also significant to avoid musculoskeletal disorders. Single joint exosuit for rehabilitation [6] and assistance in industrial operations [7] have been fabricated earlier. Exosuits for the elbow joint are common among the rehabilitation devices and also among the wearable assistive devices used in industries [8]. This work presented in this paper is for a cable driven elbow exosuit that is being developed.

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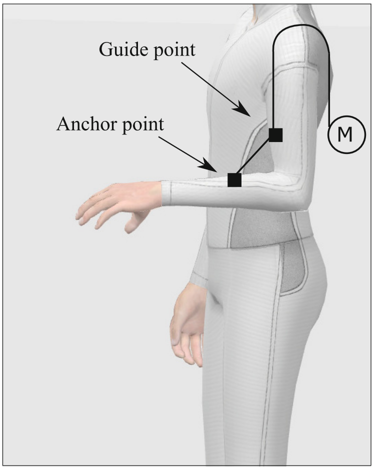

Fig. 1. Elbow exosuit

Most of the elbow exosuits are actuated by a cable-driven mechanism, apart from pneumatic [9], passive and hybrid systems [10]. Different types of cables can be used for the actuation of an exosuit [11]. The design of the elbow exosuit mostly consists of an anchor point on the forearm which is pulled towards the guide point on the upper arm, for the actuation of the elbow joint [12], Fig. 1. The motor that assists in the actuation of the elbow joint is positioned on the back of the wearer or placed as a separate stationary device which is not on the wearer's body [5,13]. To control the angular position of the elbow joint, the actuation distance of the string between the guide point on the upper arm and the anchor point on the forearm should be known. Also to fabricate the elbow exosuit, the motor capacity required to actuate the elbow joint needs to be determined. These two parameters will be useful in the selection of the cable and the motor to fabricate the exosuit. These parameters depend on the construction and design of the exosuit device. The distance of the anchor point and guide point from the elbow joint, and the weight of the loaded arm are considered. Since these parameters change from one exosuit device to another, the modelling of one elbow exosuit is different from one another.

A static model can be considered to estimate the tension in the cable and the length of the cable to be actuated for the desired angular position. In a static model the inertial forces and centrifugal forces that exist during the actuation of the elbow exosuit are neglected. Also, the friction forces at the elbow joint are neglected. Earlier models use trigonometry and properties of triangles to obtain the relation between joint angular position [14,15]. Some of the mathematical models study the dynamics of the exosuit in a deeper sense [16]. Although many mathematical models exist for the actuation of a cable-driven elbow exosuit, the calculations that are necessary like the tension in the cable based on the weight loaded onto the exosuit, need to be calculated individually for each device. Also, the selection of cable is based on the tension forces generated while actuating the exosuit, which should be calculated independently for each exosuit. Apart from that, the amount of cable to be released also differs from one device to other because of the design and placement of anchor point and guide point. Even though these calculations vary, the actuation of cable-driven elbow exosuit however remains the same among these devices and lies in the sagittal plane. A mathematical relation with the freedom to vary the distance between anchor and guide points, the mass of the hand and forearm will allow to generalize the computation of tension in cable and thereby torque at the motor. Also the amount of cable to be released by the motor for actuation can be calculated.

This paper describes the mathematical model that calculates the parameters which aid in the fabrication of a cable-driven elbow exosuit. This paper is outlined as follows. Section 1 discusses the state of the art, Sect. 2 defines the objectives of the work presented and Sect. 3 presents the static model developed for the cable driven elbow exosuit. Further, Sect. 4, Sect. 5, Sect. 6 presents the results, discussion and the conclusion.

2 Objectives

Several mathematical models exist for the kinematic and dynamic analysis of the available elbow exosuits. These models define the movement of exosuit and control. However, some of these models do not explicitly calculate the tension generated in the cable used to actuate the joint. This parameter would be necessary in the selection of the string for the actuation. Also, this tension parameter can be used in the selection of a motor when the pulley diameter is known. This paper targets to develop a simple mathematical model which allows for the variability in the position of actuation points and calculate the parameters required in the fabrication of an exosuit for the elbow joint.

The idea is to input the parameters of the weight of the forearm (loaded/unloaded) and distance of the actuation points from the elbow joint; and output the calculated parameters of tension force experienced by the string, length of string to be actuated for that configuration.
The objective is to develop a mathematical model that can calculate the

- Tension force in the actuating cable
- Length of the cable to be actuated for any joint position.

3 Methodology and Model

The elbow joint flexes and extends in the sagittal plane, and hence a 2D mathematical model will be suitable. During the actuation of the elbow joint, in a cable-driven exosuit, the objective is to control the angular position of the joint. The elbow flexion and extension can be controlled by varying the amount of cable looped or released over the pulley at the motor. Another parameter that is required is to know the value of tension in the cable at the anchor point. This tension value will allow us to select a cable that can bear the tension forces at each position.

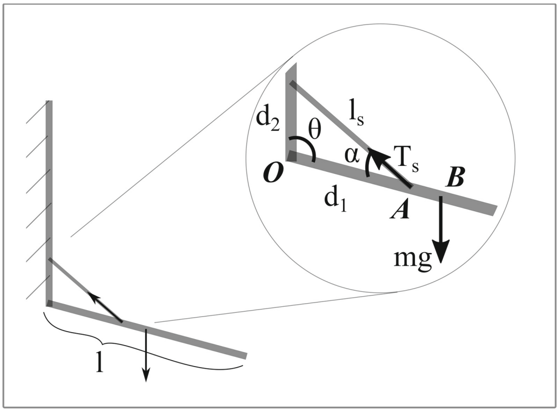

Fig. 2. Free body diagram of the Exosuit for elbow joint where m is mass of forearm and hand, T_s is tension in the cable, d_1 and d_2 are distances of guide point and anchor point from the elbow, l is the length of forearm and ls is the length of the cable between actuation points, θ is the joint angle and α is the angle made by cable with forearm

The free body diagram of the elbow joint exosuit actuation is shown in Fig. 2. Since the system forms a triangle, properties of that triangle can be used to solve for the length of the cable (l_s) for any flexion angle θ. By equating the moment generated by the force vector of mass and tension vector in the cable at the elbow joint, the tension in the cable (T_s) can be solved.

This mathematical model considers the position of the upper arm to be vertical and the elbow flexes concerning it. Also, the forearm is assumed to be homogeneous and weight is equally distributed, since it a static model. Hence, the weight of the forearm is assumed at the center of mass of the forearm. With the known value for the weight of the forearm and hand, the torque required at the elbow joint τ, to hold the forearm at an angular position 'θ' can be formulated as shown below.

$$\tau = \begin{cases} mg\frac{l}{2}\cos(-\frac{\pi}{2}+\theta), & \text{below horizontal position w.r.t ground} \\ mg\frac{l}{2}\cos(\frac{\pi}{2}-\theta), & \text{above horizontal position w.r.t ground} \end{cases} \tag{1}$$

The Eq. 1 is obtained by multiplying the perpendicular components of 'mg' and the distance from the centre of mass to the elbow joint. It can be observed that the values of τ will be the same even when the forearm is above and below the horizontal position. Hence, the torque required τ will be;

$$\tau = mg\frac{l}{2}\sin(\theta), \quad \text{for } \theta \text{ from }]0 \text{ to } \pi[\tag{2}$$

where, m - the mass of the forearm and hand
g - acceleration due to gravity
θ - flexion angle
l - length of forearm and hand

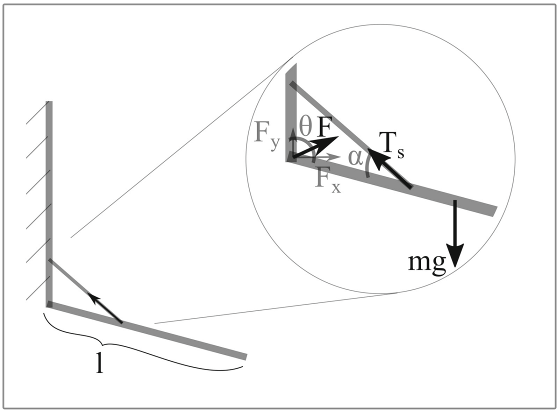

Fig. 3. Free body diagram of the forces at the elbow joint

This value of holding torque at the elbow joint τ, is the minimum amount of torque to be produced by the cable for the actuation of the forearm. The torque produced by the actuation of exosuit is because of the tension force T_s generated by the cable as shown in Fig. 2. Due to this tension force, reaction forces are also generated at the elbow joint. Since, the upper arm is assumed to be stationary, reaction forces F_x and F_y are generated at the elbow joint. From the Fig. 3, the sum of the vectors of reaction force at elbow, tension force in the cable and weight of the forearm-hand equals zero.

$$\vec{F} + \vec{T_s} + \vec{mg} = 0 \tag{3}$$

From the Eq. 3, we get the following equations of the reaction forces in x and y direction at the elbow joint.

$$\begin{aligned} F_x - |T_s| \sin(\alpha + \theta) &= 0 \\ F_y - |T_s| \cos(\alpha + \theta) &= -mg \end{aligned} \tag{4}$$

These reaction forces F_x and F_y will not produce any torque at the elbow joint. The torque is produced by the vertical component of cable tension τ_s which is $\tau_s \sin \alpha$.

The torque produced by the cable τ_s, with the known distance between the guide and anchor points from the elbow joint can be given as;

$$\tau_s = T_s \sin(\alpha) d_1 \tag{5}$$

where, T_s - Tension in the cable
d_1 - the distance between the actuation point and elbow

In static equilibrium the sum of the moment produced by the tension in the string and moment produced by the weight of forearm-hand equals zero.

$$\vec{OA} \times \vec{T_s} + \vec{OB} \times \vec{mg} = 0 \tag{6}$$

where, $\vec{OA}$ is the distance from elbow to anchor point
$\vec{OB}$ is the distance from elbow to the centre of mass of forearm-hand.

Equating the holding torque from Eq. 2 and the torque produced by the cable/string from Eq. 5, we get

$$T_s = \frac{mg\frac{l}{2}\sin(\theta)}{d_1\sin(\alpha)}, \quad \text{for } \theta \text{ from }]0 \text{ to } \pi[\text{ and } \alpha \text{ is not equal to } 0 \tag{7}$$

The value of α in the relationship can be obtained as follows,
From the law of sines,

$$\frac{l_s}{\sin(\theta)} = \frac{d_2}{\sin(\alpha)} \tag{8}$$

where, l_s - length of the string between the actuation points

Since distances to the actuation points from the elbow d_1 and d_2 are known, the length of the string l_s can be calculated,

$$l_s = \sqrt{d_1^2 + d_2^2 - 2d_1d_2\cos(\theta)} \tag{9}$$

Since the length of the string cannot be negative, all the values generated from the above equation are positive.

From Eqs. 8 and 9, the relation between θ and α becomes,

$$\alpha = \sin^{-1}\left(\frac{d_2\sin(\theta)}{\sqrt{d_1^2 + d_2^2 - 2d_1d_2\cos(\theta)}}\right), \quad \text{for } \theta \text{ from 0 to 180} \tag{10}$$

Although the equation can take values of flexion from 0 to 180°, the actual flexion of a human arm is different. From the anthropometric data the flexion of the human elbow joint for the 99 percentile man is 52° to 180° [17].

From the Eqs. 7 and 10, the tension force in the string for different weights of the forearm and hand can be calculated. Also, from the Eq. 9 the length of the string to be actuated by the motor for any given joint angle 'θ' can be calculated.

4 Results

To simulate the developed elbow exosuit actuation model, © MATLAB is used. To obtain the result from the model, the angle of the joint is considered to be flexing from 0° to 180°. An interval of 5° for the angles is taken to calculate the values of all the parameters at each position. The exosuit is considered to be unloaded and only the weight of the forearm and hand of a fully grown human is considered to be the weight that is required to be actuated. From the anthropometric data [17], the weight assumed was 2 kg at the centre of mass of the forearm for all the calculations here and results are obtained. And, the actuation points are assumed to be at a distance of 0.1 m to obtain the results when the simulations are run. The length of the forearm is assumed to be 0.3 m, which would be similar to a fully grown adult.

The joint position variable θ is related to all the other parameters involved in the actuation of the elbow joint, like the length of the cable to be actuated (l_s) and Tension in the cable (T_s) as described in the above static model. With the above-mentioned input parameters, the simulation in © MATLAB obtained the following values of Tension and length of the cable to be actuated.

The reaction forces at the elbow joint for the given configuration are predicted with the model and are shown in Figs. 4 and 5. It can be observed that reaction forces in the y direction are much higher than in the x direction at the elbow joint.

The modulus of the forces at the elbow joint for angular position from 0 to π is shown in Fig. 6. It can be pointed out that the curve is sigmoid in nature.

From the Eq. 7, the relation between the joint angle and the tension in the cable is obtained as shown in Fig. 7. The maximum tension value in the string for the assumed configuration is around 60 N. This value will be important in the selection of cable and any cable with can hold such tension force can be selected.

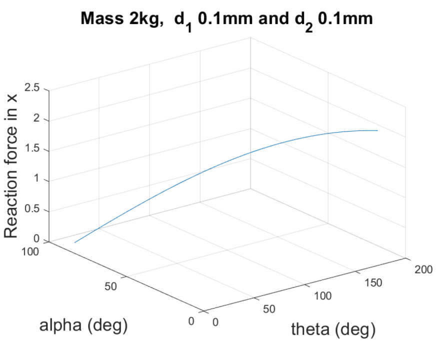

Fig. 4. Reaction force as a function if angle in x direction at elbow joint obtained from the Eq. 4

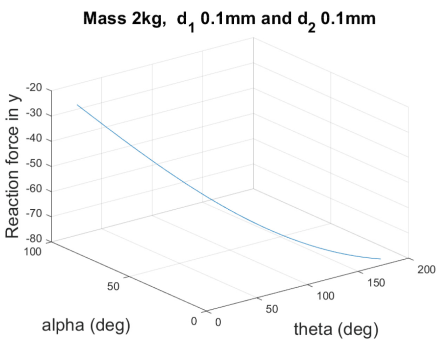

Fig. 5. Reaction force as a function of angle in y direction at elbow joint obtained from the Eq. 4

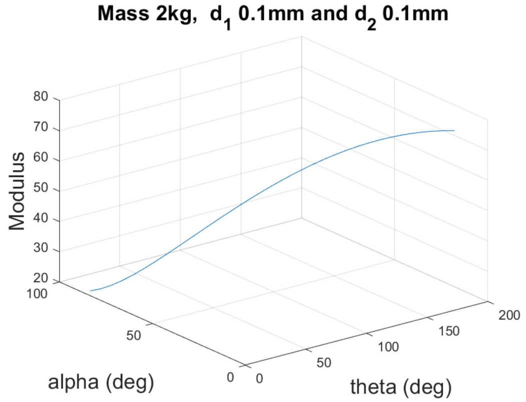

Fig. 6. Modulus of the forces F_x and F_y at the elbow joint

The relation between the variable angle θ of the elbow joint and the cable to be released/actuated by the motor is shown in Fig. 8. This graph is obtained from Eq. 9. From the figure, it can be observed that the maximum length of cable to be released by the motor in the given configuration would be 0.2 m. This parameter would be useful in designing the mechanism which should be able to release a string of 0.2 m for the complete actuation. To hold any position in between, the string to be released is also provided in the result generated by the mathematical model. It is significant to point out from the Fig. 8 that $l_s(\theta)$ is quasi-linear from 5° to 100°.

The simulation in Fig. 9 shows that the model is defined well in calculating the joint position and the length of the cable to be actuated. The stick model in the simulation represents the upper arm and forearm. The vertical line represents the upper arm and the lower line represents the forearm. The cyan line in between

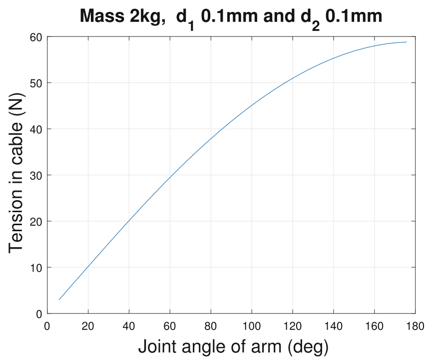

Fig. 7. Tension as a function of angle obtained from the Eq. 7

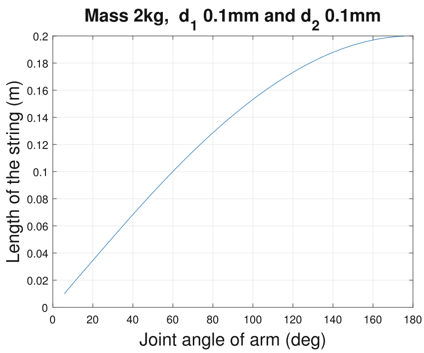

Fig. 8. Length as a function of angle obtained from the Eq. 9

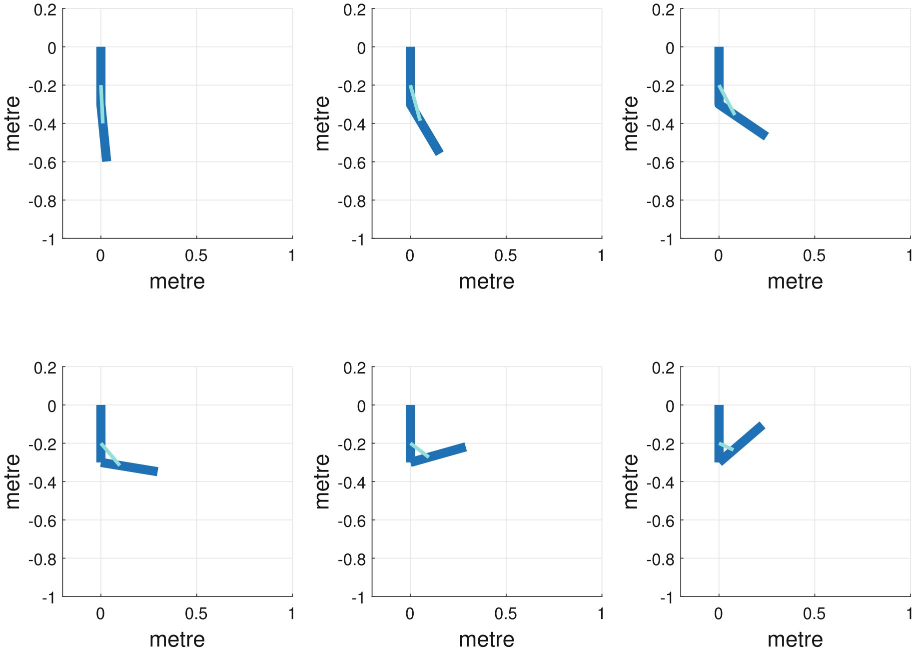

Fig. 9. Visualization of the elbow exosuit actuation shown in 2D space

represents the cable. It can be observed that when actuated the length of this cyan line is changed and it is always at tension as expected.

Although the validation of the model is not done physically, from the simulation it can be identified that the model predicts the movement of the elbow exosuit correctly.

5 Discussion

The above results provide the values of the parameters required in the fabrication of a cable-driven elbow exosuit. By changing the configuration of the exosuit, i.e., by changing the input parameters, it is possible to obtain new values for tension in the sting and actuation length of the string. By these parameters, the elbow exosuit can be designed to the newer configuration.

Future work can include the validation of this mathematical model by experimentation. Also, the approach used in developing the mathematical model to target the aid in the fabrication of an elbow suit can be adapted to a multiple DOF joint like the wrist.

6 Conclusion

In the fabrication of an elbow exosuit, it is necessary to know the tension generated in the string and the length of the string to be actuated by the motor. These parameters will help in designing the mechanism and also in the placement of the actuation points. This paper aims at developing a general elbow joint exosuit actuation model that will calculate the above parameters with any given input configuration of the exosuit.

From the values of the position of actuation points concerning to the elbow joint and the required actuation weight of the exosuit, it is possible to obtain tension in the string and length of actuation stroke between the actuation points.

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