Design and Development of Cable Driven Upper Limb Exoskeleton for Arm Rehabilitation

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Abstract—this paper describes the design and kinematic analysis of a 5 DOF upper limb powered robotic exoskeleton for rehabilitation of the patients who survived stroke and the elderly who do not have enough strength to move their limbs freely. It was observed that the existing upper extremity exoskeletons were bulky and heavy which made them limited to applications and the complexity of the system increases with the number of DOF's considered. Therapies in rehabilitation process doesn't require much complex designs. This create a need to develop an exoskeleton which is economical, light weight device to provide more dexterity than the existing one. The proposed wearable exoskeleton builds upon our research experience in wire driven manipulators and design of rehabilitative systems. The cable drive system will help in reducing the overall weight of the Exoskeleton. This non-localized actuation system allows the use of more powerful motor enabling greater lifting strength for the user. The system was designed to create an intention-driven robotic control approach, by which the exoskeleton can assist the user to move the arm during the rehabilitation process. The cad model of exoskeleton and its fabrication using light weight material and its kinematic analysis, Simulink simulation are explained in this paper.

Index Terms— Assistive robotics; daily activities; exoskeleton; human arm; upper limb; kinematics; equations of torque; rehabilitation robotics; CAD model of exoskeleton; design of exoskeleton.

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1 INTRODUCTION

A person with an impaired limb requires constant therapy to regain strength to perform daily activities such as holding or shaking hand, griping, pinching, etc. Such treatment is called rehabilitation [1]. Research states that about 40-50% returns to work after thorough rehabilitation [2] but this rehabilitation therapy involves a dedicated therapist, enormous amount of time, money and resources [3]. In this case Robot-aided physical rehabilitation has been proposed to support the rehabilitation team in providing high-intensity therapy, consisting of repetitive movements of the impaired limb [4]-[6]. Robots can allow patients to receive a more effective and stable rehabilitation process, and therapists to reduce physical workload. Robots can also offer reliable tools for functional assessment of patient progress and recovery by measuring physical parameters, such as speed, direction, and strength of patient residual voluntary activity [7]. Common architectures of rehabilitation robots include: end-point manipulators [8], [9]-[12] cable suspensions [13]-[15] and exoskeletons [16]-[29]. An exoskeleton for physical rehabilitation is a non-portable mechanical device that is anthropomorphic in nature, is “worn” by the user and fits closely to his or her body [29].

A robotic rehabilitation device is attractive since it can potentially offer uniform performance over longer durations and provide quantitative outcome measures. Current robotic rehabilitation devices for the upper extremity can be broadly classified based on how human subjects interact with the machine: 1) handle on the end-effector, 2) wearing as an exoskeleton [30].

In order to assist physically disabled or elderly people, to increase the strength of the upper limb and for self-rehabilitation purposes, various upper-limb power-assist exoskeletons and robots have been developed such as MIT-Manus [31], MIME [32], ARM-Guide [33], NeRebot [34] and ARMin [35], Bi-Manu-Track [36],IntelliArm [37], SUEFUL-7[38], MGA [39, 40], L-Exos [41], RUPERT IV[42], BONES[43], WOTAS [44], UTS Exoskeleton[45, 46], UL-EXO7 [47], and Pneu-Wrex [48]. So many exoskeletons existed today can be viewed from two aspects, mechanical and control system aspect. All of them can work in passive mode, in which the robotic device moves the patient's arm, and active mode, in which movement is either partially assisted (voluntary but inadequate function) or resisted (voluntary and selective function) by the robotic device [49]. Another possible modality is bimanual exercise, in which active movement of the unaffected arm is mirrored by simultaneous passive movement of the affected arm by the robotic device. Most of the robotic devices were designed for training the proximal upper limb (shoulder and elbow) of the hemiparetic arm, while few also included functions dedicated to wrist [50] and hand [51] rehabilitation, mainly because of their greater complexity.

New research are also ongoing in this field, Yagi [52] discussed an upper-limb power-assist system to assist workers with lifting a 30-kg rice bag without inducing lower back pain. The system used a pneumatic actuator to support shoulder and elbow movement.. Kai et al [53] has proposed a shoulder exoskeleton incorporating a compliant continuum mechanism. This continuum mechanism could passively deform itself to accommodate different patient anatomies while providing pure assistances. Hua et al [54] discussed about an experimental based design method for a compatible 3-DOF shoulder exoskeleton with an adaptive center of rotation (CoR) by matching the mechanical CoR with the anatomical CoR to

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reduce human machine interaction forces. Experiment is done on 6 persons to validate the CoR motion adaptation ability by measuring the human–machine interaction force during passive shoulder joint motion. Sunil et al [55] proposed a natural arm with a goal to make a lightweight and wearable exoskeleton having 4DOF with shoulder and elbow motions. Abhishek et al [56] presented the mechanical design of a haptic arm exoskeleton that balances design tradeoffs inherent in haptic exoskeleton device design. It can be seen that this exoskeleton design meets the desired workspace specifications for all joints except the elbow joint. The device is capable of 90◦ of elbow extension, which is approximately 30◦ less than the design specification.

Nicola et al [57] discussed about NEUROExos, a novel powered exoskeleton for elbow rehabilitation. This exoskeleton possesses three main innovative features: the double-shelled links, the four DOF passive mechanism and a compliant antagonistic actuation system.Antonio et al [58] exposed the mechanical design of the L-Exos, an upper-limb exoskeleton for force feedback in virtual environments. This system was integrated in an experimental set-up for robotic-assisted neuro-rehabilitation in virtual reality and evaluated on a group of eight chronic stroke patients in the execution of robotic-assisted reaching .Hugo et al [59] described about a control method for a lower limb powered exoskeleton that enables a paraplegic user to perform sitting, standing, and walking movements. The different maneuvers are commanded by the user based on postural information measured by the device. Slavka et al [60] reviewed about commercially available devices, and their actuation, hardware, and movements they make possible are described. Ying et al [61] proposed a new approach to estimate GH-c using measurements of shoulder joint angles and cable lengths. This helps in locating the GH-c center appropriately within the kinematic model. As a result, more accurate kinematic model can be used to improve the training of human users. Haoyong et al [62] presented a compact compliant force control actuator design for portable rehabilitation robots to overcome the performance limitations of current Series Elastic Actuators (SEA). Zhijun et al [63] studied two surface electromyogram (sEMG) based control strategies for a power-assist exoskeleton arm .For this a force control method is used to make the exoskeleton robot behave like humans in order to provide better assistance. Kazuo et al [64] analyzed about an electromyogram (EMG)-based impedance control method for an upper-limb power-assist exoskeleton robot is proposed to control the robot in accordance with the user's motion intention. Muceli[65] proposed a proportional control strategy that could be practically applied in amputees for the real-time control of multiple degrees-of-freedom. Artificial neural networks were used as the control strategy to estimate the position of the complex wrist and hand movement. Su [66] presented electromyogram (EMG)-based neural network control of an upper-limb power-assist exoskeleton robot, which could predict the user's motion intention precisely. A four degrees-of-freedom system actuated by pneumatic muscles on the shoulder, elbow and wrist was built to assist the patients with achieving therapy at home or in the clinic [67] which was safe and easy to use. Rosen [68] constructed an exoskeleton structure, including two links and two joints, to demonstrate the feasibility of using an EMG-based control.

Robot-aided rehabilitation is slowly convincing the community of therapists to be as good as or even better than manual therapy. Powered exoskeletons, despite their higher system complexity, can provide assistance independently to each user's joint. This allows to better retrain the correct physiological muscle-skeletal synergies, minimizing and controlling any compensatory movement. Most upper-limb powered exoskeletons are made of bar-shaped links, coupled with the user's limb segments through multiple orthotic shells or cuffs. This solution, while simple, introduces problems in terms of encumbrance, inertia, and kinematic compatibility with the limb, resulting in a poor wearability of the robot.

These exoskeleton device has a rigid mechanical structure, which can only lend itself for training purposes. Wearability and continuous use as a support device is not possible; most existing/recent exoskeletons fall under this category and the final systems still appear to be bulky with actuators and controllers, other designs have been limited to modeling and simulation. To make exoskeletons economical, lighter, wearable, and can provide more dexterity than the existing one new designs has to be adopted that are cable based. And this system has to be designed to create an intention-driven robotic control approach, by which the exoskeleton can assist the user to move the arm during the rehabilitation process.

2 KINEMATIC ANALYSIS OF UPPER ARM

The kinematic model gives relations between the position and orientation of the end effector and spatial positions of the joint – links. Forward kinematics of the exoskeleton is analyzed using D-H Convection. The exoskeleton is modelled as a chain of rigid links interconnected by revolute and / or prismatic joints. To describe the position and orientation of a link in space, a co-ordinate frame is attached to each link. The position and orientation of frames relative to the previous frame can be described by a homogeneous Transformation matrix. Figure 1.1 shows various range of motion of the arm when performing various tasks.

3 D-H PARAMETER OF THE MODEL

Recently human exoskeleton developers proposed 9 DOF of human arm model to cope with scapular motion. But here we are assuming for the 5 DOF human arm

1. 3 DOF for shoulder
2. 2 DOF for the elbow

The first step was to determine the co-ordinates forms according to D-H convection for the upper limb. In order to allow for the common base form for both arm, the base coordinate system (X0, Y0, Z0) was located in the body, midway between the shoulders.

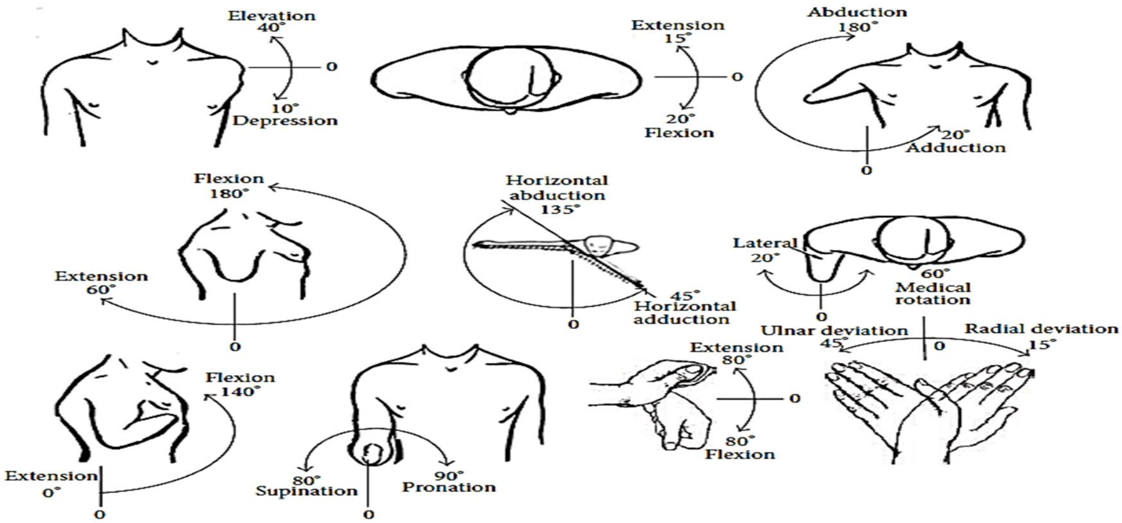

Figure 1.1 Different types of Arm Motion [69]

Then in one of the arm, three frames corresponding to 3DOF were located at the center of the joint.

- Circumduction (X1, Y1, Z1)
- Adduction – Abduction (X2, Y2, Z2)
- Flexion – Extension (X3, Y3, Z3)

In the elbow there are two frames corresponding to the following rotation

- Flexion – Extension (X4, Y4, Z4)
- Supination – Pronation (X5, Y5, Z5)

Table 1.1 shows the range of motion of the human arm, for this project it is assumed that the exoskeleton will also be able to have the same range of motion.

Table 1.1 Arm Range

Joint	βi (Range of motion in degree)
Base	0o
Shoulder	(-90o) medial rotation/ later rotation (+90o)
Shoulder	(-180o) abduction/ adduction (+50o)
Shoulder	(-180o) flexion/ extension (+80o)
Elbow	(-10o) flexion/ extension (+145o)
Elbow	(-90o) pronation/ supination (+90o)

Homogeneous Transformation matrix for n links is given by the Eq. 1.2.

$$^{n-1}T_n = \begin{bmatrix} \cos(\theta i) & -\cos(\alpha i)\sin(\theta i) & \sin(\alpha i)\sin(\theta i) & ai\cos(\theta i) \\ \sin(\theta i) & \cos(\alpha i)\cos(\theta i) & -\sin(\alpha i)\cos(\theta i) & ai\sin(\theta i) \\ 0 & \sin(\alpha i) & \cos(\alpha i) & di \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

(1.1)

So considering the D-H parameter values of the links in the Table 1.2.

Table 1.2 D-H Parameter of Exoskeleton

	Link Length	Link Angle (°)	Joint Distance	Joint angle(°)
Links	ai	αi	di	θi
1	0	-90	0	θ1
2	0	+90	0	θ2
3	l1	0	0	θ3
4	0	+90	0	θ4
5	l2	+90	0	θ5

Let c1, c2, c3, c4, c5, s1, s2, s3, s4, s5 are given for the following values

c1 = cos (θ1); s1 = sin (θ1)

c2 = cos (θ2); s2 = sin (θ2)

c3 = cos (θ3); s3 = sin (θ3)

c4 = cos (θ4); s4 = sin (θ4)

c5 = cos (θ5); s5 = sin (θ5)

Putting first link parameters in homogeneous matrix:

$$0T1 = \begin{bmatrix} c1 & 0 & -s1 & 0 \\ s1 & 0 & c1 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (1.2)$$

Putting Second link parameters in homogeneous matrix:

$$1T2 = \begin{bmatrix} c2 & 0 & s2 & 0 \\ s2 & 0 & -c2 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (1.3)$$

Putting third link parameters in homogeneous matrix:

$$2T3 = \begin{bmatrix} c3 & -s3 & 0 & c3 * l1 \\ s3 & c3 & 0 & c3 * l1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (1.4)$$

Putting fourth link parameters in homogeneous matrix:

$$3T4 = \begin{bmatrix} c4 & 0 & s4 & 0 \\ s4 & 0 & -c4 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (1.5)$$

Putting fifth link parameters in homogeneous matrix:

$$4T5 = \begin{bmatrix} c5 & 0 & s5 & 0 \\ s5 & 0 & -c5 & 0 \\ 0 & 1 & 0 & l2 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (1.6)$$

Final transformation matrix (A) is the product of all the five transformation matrix from Eqs. 1.2 – 1.6.

$$A = 0T1.\ 1T2.\ 2T3.\ 3T4.\ 4T5. \qquad (1.7)$$

$$A = \begin{bmatrix} n_x & O_x & a_x & x \\ n_y & O_y & a_y & y \\ n_z & O_z & a_z & z \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (1.8)$$

Where

$$n_x = \cos\ \sin^2 t1t2t5 + \cos(\cos(-\sin^2 t1t3 + \cos^3 t1t2t3)\,t4 + \sin(-\cos\sin t1t3 - \cos^2 \sin t1t2t3)\,t4)\,t5 \qquad (1.9)$$

$$O_x = \sin(-\sin^2 t1t3 + \cos^3 t1t2t3)\,t4 - \cos(-\cos\sin t1t3 - \cos^2 \sin t1t2t3)\,t4 \qquad (1.10)$$

$$a_x = -\cos^2 \sin t1t2t5 + \sin(\cos(-\sin^2 t1t3 + \cos^3 t1t2t3)\,t4 + \sin(-\cos\sin t1t3 - \cos^2 \sin t1t2t3)\,t4)\,t5 \qquad (1.11)$$

$$x = l2(\sin(-\sin^2 t1t3 + \cos^3 t1t2t3)\,t4 - \cos(-\cos\sin t1t3 - \cos^2 \sin t1t2t3)\,t4) - \sin t1l1.\,(\cos t3) + \cos^2 t1t2l1.\,(\cos t3) \qquad (1.12)$$

$$n_y = \sin^3 t1t2t5 + \cos(\cos(\cos\sin t1t3 + \cos^2 \sin t1t2t3)\,t4 + \sin(\cos^2 t1t3 - \cos\sin^2 t1t2t3)\,t4)\,t5 \qquad (1.13)$$

$$O_y = \sin(\cos\sin t1t3 + \cos^2 \sin t1t2t3)\,t4 - \cos(\cos^2 t1t3 - \cos\sin^2 t1t2t3)\,t4 \qquad (1.14)$$

$$a_y = -\cos\sin^2 t1t2t5 + \sin(\cos(\cos\sin t1t3 + \cos^2 \sin t1t2t3)\,t4 + \sin(\cos^2 t1t3 - \cos\sin^2 t1t2t3)\,t4)\,t5 \qquad (1.15)$$

$$y = l2(\sin(\cos\sin t1t3 + \cos^2 \sin t1t2t3)\,t4 - \cos(\cos^2 t1t3 - \cos\sin^2 t1t2t3)\,t4) + \cos t1l1.\,(\cos t3) + \cos\sin t1t2l1.\,(\cos t3) \qquad (1.16)$$

$$n_z = \cos\sin t2t5 + \cos(-\cos^2 \sin t2t3t4 + \sin^3 t2t3t4)\,t5 \qquad (1.17)$$

$$O_z = -2\cos\sin^2 t2t3t4 \qquad (1.18)$$

$$a_z = -\cos^2 t2t5 + \sin(-\cos^2 \sin t2t3t4 + \sin^3 t2t3t4)\,t5 \qquad (1.19)$$

$$z = -2\cos l2 \sin^2 t2t3t4 - \sin t2l1.\,(\cos t3) \qquad (1.20)$$

Final X, Y and Z coordinates of the end with respect to base frame can be obtained from x, y, z values and orientation of the end link is obtained form n, o, a values. Values of each element in the transformation matrix (A) is given from Eqs. 1.9 - 1.20.

4 TORQUE CALCULATION

Torque calculation for the exoskeleton is done by considering an average person of weight 80kg and height 175cm.From the mean segmented weight of the body based on the study done by Plagenhoef.et al for males, we can calculate the weight of the arm segments [24]. Based on this study Upper arm is 3.25 % of total body weight and Forearm is 1.87 % of total body weight

H and W are the average height and weight respectively

H = 175 cm

W = 80 kg

Upper arm length (u) of a human of height H and mass W can be calculated from the Eq. 1.21.

u = 0.186 H (1.21)

= 0.186 x 175

= 3255 mm

Forearm length (l) can be calculated from the Eq. 1.22.

$$l = 0.146\,H \qquad (1.22)$$

$$= 0.146 \times 175 \quad = 2555\text{ mm}$$

Total length of the arm (a) can be calculated by the Eq. 1.23.

$$a = u + l \qquad (1.23)$$

$$= 3255 + 2555$$

$$= 5810\text{ mm}$$

Based on Plagenhoef.al study, mass of the upper arm (W_{ua}) and forearm (W_{fa}) can be calculated from the Eqs. 1.24 and 1.25.

$$W_{ua} = 3.25\%W \qquad (1.24)$$

$$= 3.25\% \times 80 = 2.6\text{ kg}$$

$$W_{fa} = 1.87\%W \qquad (1.25)$$

$$= 1.87\% \times 80 = 1.496\text{ kg}$$

W_{tp} is the total mass of the arm, using the Eq. 1.26. the total mass of the arm can be calculated.

$$W_{tp} = W_{ua} + W_{fa} \qquad (1.26)$$

$$= 2.6 + 1.496 = 4.096\text{ kg}$$

W_{eq} is the mass of the exoskeleton in the forearm and is assumed to be 2 kg,

$$W_{eq} = 2\text{kg}$$

W_{te} is the total mass of the forearm and exoskeleton, it is calculated using the Eq. 1.27.

$$W_{te} = W_{eq} + W_{fa} = 3.496 \qquad (1.27)$$

From the Eq. 1.28. Te is the torque required for elbow movement with the exoskeleton part.

$$T_e = W_{te} \times l \qquad (1.28)$$

$$= 3.496 \times 0.25555 = 0.893\text{ kgm} = 89.323\text{ kg cm}$$

W_{ex} is the total mass of the exoskeleton,

$$W_{ex} = 3\text{kg}$$

W_t is the total mass, when exoskeleton is attached to full arm can be obtained using the Eq. 1.29

$$W_t = W_{ex} + W_{tp} \qquad (1.29)$$

$$= 3 + 4.096$$

$$= 7.096\text{ kg}$$

Using the Eq. 1.30, T_s is the torque require for the mass W_t

$$T_s = W_t \times a \qquad (1.30)$$

$$= 7.096 \times 0.581$$

$$= 4.122\text{ kg m}$$

$$= 412.2\text{ kg cm}$$

Motor selection for the actuation of the exoskeleton is done based on the torque calculated.

5 SIMULINK SIMMECHANICS

The model of the exoskeleton is implemented in Matlab with the use of SimMechanics, a toolbox within the Simulink package. The SimMechanics program scheme having the form of interconnected blocks shows how the physical components with geometric and kinematic relationships of the robot are mutually interconnected. The SimMechanics program enables one to model mechanical systems by bodies and joints, to simulate their motion, to change easily the structure, to optimize system parameters, and to analyze results all within the Simulink environment. This approach does not require cumbersome deriving differential equations of the system and presents an easy and fast way to obtain the dynamic model of the system and saves time and effort. The blocks have an input and output and parameters can be given to each block. For each joints there is axis of rotation and for the bodies it is the mass, the inertial tensor, the center of mass, body dimensions, and coordinate system on each end of the body. The Matlab Simulink model for the exoskeleton is shown in Fig 1.2.This will help to simulate the motion of the exoskeleton in the virtual environment and by changing the input parameters of each block the motion of links can be constrained within the range and analysis of the exoskeleton can be done.

6 MODELLING AND FABRICATION

Modelling software Solidworks 2014 is used to model the parts and each parts were created separately with respect to the different parameters of a human body. The shoulder joint was given the concept of free movement which can be adjusted by the user. The whole structure is made of which is lighter in weight and much hardy than any other similar material.

High torque DC geared motor is used for controlling the joint movements of shoulder griddle, glenohumeral joint, and elbow joint for gross positioning. For the motion of wrist joint small DC servo motor is being used for fine positioning. The exoskeleton,parts as shown in Figs. 1.3. was fabricated from using Acrylic material and nylon connected using steel links.

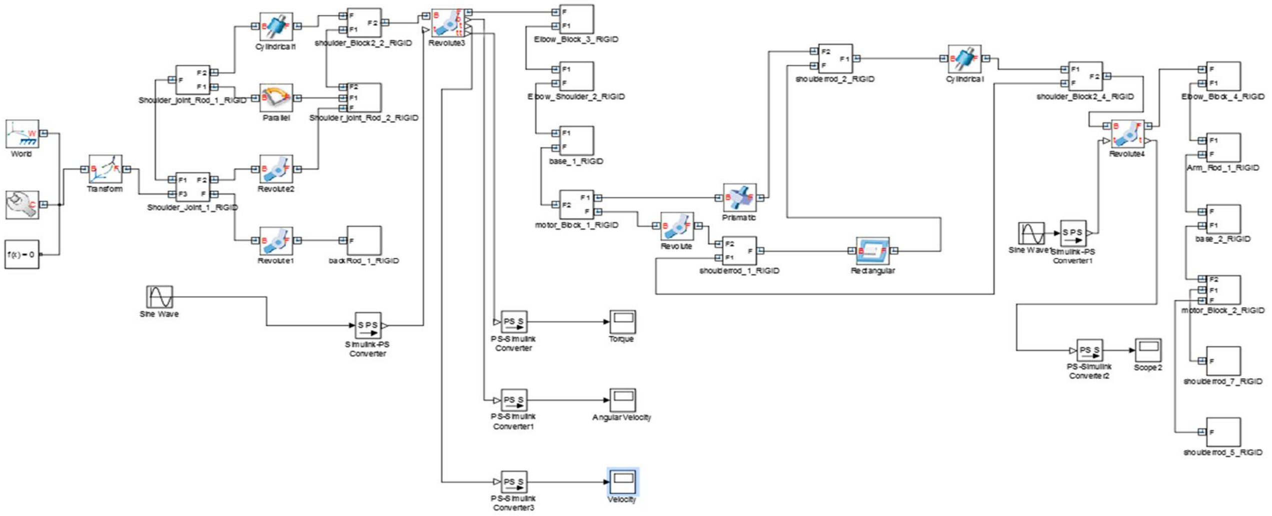

Figure .1.2 Simulink model of the Exoskeleton.

For the actuation of the part, a cable drive system is provided and the return action is done using tension spring.

The cable system will allow the device motor to be mounted on the user's back or can be placed separately, instead of attaching motor directly to the actuated joint. Thus the cable drive system will help in reducing the overall weight of the skeleton. This non-localized actuation system allows the use of more powerful motor enabling greater lifting strength for the user. The elbow motor is mounted on the steel link as shown in Fig 1.3 and 1.4. This will help in adjusting the position of the motor and to optimize the future designs.

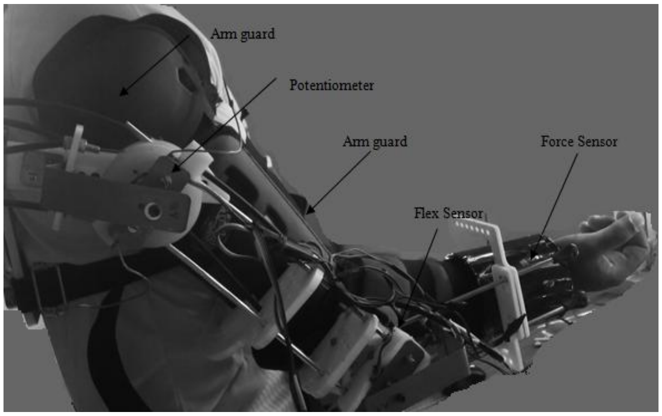

Figure 1.3 Fabricated Exoskeleton

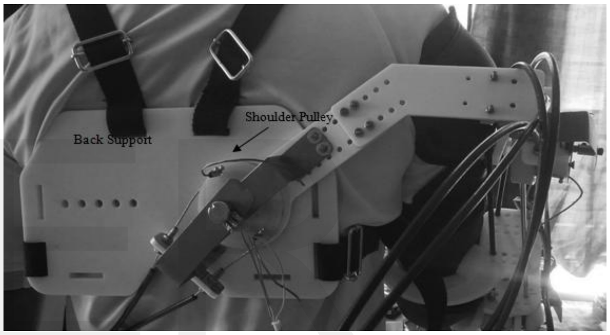

Figure 1.4 Cable system for the Exoskeleton

7 CONCLUSION

The design and development of the upper limb exoskeleton with 5 DOF is accomplished with SolidWorks 2014 software and the direct kinematic models of the prototype has been created based on Denavit-Hatenberg convention. Matlab Simulink model of the exoskeleton was created for real time simulation. A flexible cable driven actuation system is used for the actuation of the elbow part. This cable-driven approach used in the design and can assist in achieving a relatively lightweight, high-performance device.

REFERENCES

[1] Marcello Mulas, Michele Folgheraiter , Giuseppina Gini ; "An EMG- controlled Exoskeleton for Hand Rehabilitation", 9th International Conference on Rehabilitation Robotics, Chicago, USA,28 june to 1 july,2005

[2] L.Dovat, O. Lambercy, E. Burdet at al., "A haptic knob for rehabilitation of stroke patients", , International conference on intelligent robots and systems, China,October 2006.

[3] Donna scott,"Return to work following stroke: a literature review, interim coordinator for community & ltc, swo stroke network".

[4] S. Barreca, S.L. Wolf, S. Fasoli, and R. Bohannon, "Treatment interventions for the paretic upper limb of stroke survivors:a critical review", Neurorehabilitation and Neural Repair, vol. 17(4), pp. 220-226, 2003.

[5] H.M. Feys, W.J. De Weerdt, B.E. Selz, G.A. Cox Steck, R. Spichiger, C.E. Vereeck, K.D. Putman, G.A. Van Hoydonock, "Effect of a therapeutic intervention for the hemiplegic upper limb in the acute phase after stroke. A single-blind, randomized, controlled multicenter trial", Stroke, vol. 29(4), pp. 785-792, 1999.

[6] G. Kwakkel, R.C. Wagenaar, J.W. Twisk , G.J. Lankhorst, J.C. Koetsier, "Intensity of leg and arm training after primary middle-cerebral-artery stroke: a randomized trial", Lancet, vol. 354(9174), pp.191-196, 1999.

[7] G. Kwakkel, B. Kollen, and H. Krebs, "Effects of robot-assisted therapy on upper limb recovery after stroke: A systematic review", Neurorehabilitation and Neural Repair, vol. 22, pp.111-121, 2007.

[8] H.I. Krebs, N. Hogan, M.L. Aisen, and B.T. Volpe, "Robot-Aided Neurorehabilitation", IEEE Transactions on Rehabilitation Engineering vol. 6(1), pp. 75-87, 1998.

[9] S.E. Fasoli, H.I. Krebs, J.Stein, W.R. Frontera, and N. Hogan, "Effects of Robotic Therapy on Motor Impairement and Recovery in Chronic Stroke", Archives of Physical Medicine and Rehabilitation, vol. 84(4), pp. 477-482, 2003.

[10] P.S. Lum, C.G. Burgar, D.E. Kenney, and H.F. Machiel Van der Loos, "Quantification of Force Abnormalities During Passive and Active-Assisted Upper-Limb Reaching Movements in Post-Stroke Hemiparesis", IEEE Transactions on Biomedical Engineering, vol. 46(6), pp. 652-662, 1999.

[11] S. Micera, M.C. Carrozza, E. Guglielmelli, G. Cappiello, F. Zaccone, C. Freschi, R. Colombo, A. Mazzone, C. Del conte, F. Pisano, G. Minuto, and P. Dario, "A Simple Robotic System for Neurorehabilitation", Autonomous Robots, vol. 19(3), pp. 271-284, 2006.

[12] D.J. Reinkensmeyer, C.D. Takahashi, W.K. Timoszyk, A.N. Reinkensmeyer, and L.E. Kahn, "Design of robot assistance for arm movement therapy following stroke", Advanced Robotics, vol. 14(7), pp. 625-637, 2001.

[13] R. Loureiro, F. Amirabdollahian, M. Topping, B. Dressen, and W. Harwin, "Upper Limb Robot Mediated Stroke Therapy – GENTLE/s Approach", Autonomous Robot, vol.15 (1), pp. 35-51, 2003.

[14] D. Mayhew, B. Bachrach, W. Rymer, and R. Beer, "Development of the MACARM-a Novel Cable Robot for upper Limb Neurorehabilitation", in Proc. of the IEEE International Conference on Rehabilitation Robotics, Chicago, US, pp. 299-302, 2005.

[15] A. Stienen, E. Hekman, F. Van der Helm, G. Prange, M. Jannink, A. Aalsm, and H. Van der Kooij, "Freebal: Dedicated gravity compensation for the upper extremities", in Proc. of the International Conference on Rehabilitation Robotics, Noordwijk, The Netherlands, pp. 804-808, 2007.

[16] Z. Jia-Fan, Y. Can.Jun, C. Ying, Z. Yu, and D. Yi-Ming, "Modeling and control of a curved pneumatic muscle actuator for wearable elbow exoskeleton", Mechatronics, vol. 18, pp. 448-457, 2008.

[17] K. Kiguchi, T. Tanaka, and T. Fukuda, "Neuro-fuzzy control of a robotic exoskeleton with EMG signals", IEEE Transactions on Fuzzy Systems, vol. 12(4), pp. 481-490, 2004.

[18] J.C. Perry, J. Rosen, and S. Burns, "Upper-Limb Powered Exoskeleton Design", IEEE/ASME Transactions on Mechatronics, vol. 12(4), pp. 408-417, 2007.

[19] A. Frisoli, L. Borelli, A. Montagner, S. Marcheschi, C. Procopio, F. Salsedo, M. Bergamasco, M.C. Carboncini, M. Tolaini, and B. Rossi, "Arm rehabilitation with a robotic exoskeleton in Virtual Reality", in Proc. of IEEE International Conference on Rehabilitation Robotics, Noordwijk, The Netherlands, pp. 631-642, 2007.

[20] A. Frisoli, F. Salsedo, M. Bergamasco, B. Rossi, and M.C. Carboncini, "A force-feedback exoskeleton for upper-limb rehabilitation in virtual reality", Applied Bionics and Biomechanics, 1754-2103, vol. 6(2), pp. 115-126

[21] N.G. Tsagarakis and D.G. Caldwell, "Development and Control of a 'Soft-Actuated' Exoskeleton for Use in Physiotherapy and Training", Autonomous Robots, vol. 15, pp. 21-23, 2003.

[22] C. Carignan, J. Tang, S. Roderick, and M. Naylor, "A Configuration-Space Approach to Controlling a Rehabilitation Arm Exoskeleton", in Proc. IEEE International Conference on Rehabilitation Robotics, (ICORR), Noordwijk, The Netherlands, pp. 524-531, 2007.

[23] E. Rocon, J.M. Belda-Lois, A.F. Ruiz, M. Manto, J.C. Moreno, and J.L. Pons, "Design and Validation of a Rehabilitation Robotic Exoskeleton for Tremor Assessment and Suppression", IEEE Transactions on Neural Systems and Rehabilitation Engineering, vol. 15(3), pp. 367-378, 2007.

[24] T. Nef, M. Mihelj, and R. Riener, "ARMin: A robot for patient-cooperative arm therapy", Medical and Biological Engineering and Computing, vol. 45(9), pp. 887-900, 2007.

[25] M. Mihelj, T. Nef, and R. Riener, "ARMin II – 7 DoF rehabilitation: mechanics and kinematics", in Proc. of IEEE International Conference on Robotics and Automation (ICRA), pp. 4120-4125, 2007.

[26] R.J. Sanchez, E. Wolbrecht, R. Smith, J. Liu, S. Rao, S. Cramer, T. Rahman, J.E. Bobrow, and D.J. Reinkensmeyer, "A Pneumatic Robot for Re-Training Arm Movement after Stroke: Rationale and Mechanical Design", in Proc. of the IEEE International Conference on Rehabilitation Robotics (ICORR), pp. 500-504, 2005.

[27] R.J. Sanchez, J. Liu, S. Rao, P. Shah, R. Smith, T. Rahman, S.C. Cramer, J.E. Bobrow, and D.J. Reinkensmeyer, "Automating Arm Movement Training Following Severe Stroke: Functional Exercises With Quantitative Feedback in a Gravity-Reduced Environment", IEEE Transactions on Neural Systems and Rehabilitation Engineering, vol. 14(3), pp. 378-389, 2006.

[28] A. Schiele and F.C. van der Helm, "Kinematic Design to Improve Ergonomics in Human Machine Interaction", IEEE Transaction on Neural Systems and Rehabilitation Engineering, vol. 14(4), pp. 456–469, 2006.

[29] A.M. Dollar and H. Herr, "Lower Extremity Exoskeletons and Active Orthoses: Challenges and State-of-the-Art", IEEE Transactions on Robotics, vol. 24, pp. 144-158, 2008.

[30] Ying Mao and Sunil Kumar Agrawal, Member,"Design of a Cable-Driven Arm Exoskeleton (CAREX) for Neural Rehabilitation",IEEE Transactions on Robotics, Vol. 28, No. 4, August 2012

[31] Krebs, H.I., Hogan, N., Volpe, B.T., Aisen, M.L., Edelstein, L., Diels, C., "Overview of clinical trials with MIT-MANUS: a robot-aided neuro-rehabilitation facility," Technol. Health Care.; 7(6):419-23,1999

[32] Burgar, C.G., Lum, P.S., Shor, P.C., Machiel Van der Loos, H.F., "Development of robots for rehabilitation therapy: the Palo Alto VA/Stanford experience," J. Rehabil. Res. Dev.; 37(6):663-73, 2000.

[33] Reinkensmeyer, D.J., Kahn, L.E., Averbuch, M., McKenna-Cole, A., Schmit, B.D., Rymer, W.Z., "Understanding and treating arm movement impairment after chronic brain

injury: progress with the ARM guide," J. Rehabil. Res. Dev.; 37(6):653-62.

[34] Fanin, C., Gallina, P., Rossi, A., Zanatta, U., Masiero, S., "NeReBot: a wire-based robot for neurorehabilitation," Proc.of the 8th International Conference on Rehabilitation Robotics; Daejeon (Korea): Human-Friendly Welfare Robot System Engineering Research Center; pp.23-26, 2003.

[35] Nef, T., Riener, R., "ARMin-Design of a novel arm rehabilitation robot," Proc. of the 9th International Conference on Rehabilitation Robotics; Chicago, Illinois. Madison (WI): Omnipress; pp. 57-60, 2005.

[36] Hesse, S., Schulte-Tigges, G., Konrad, M., Bardeleben, A., Werner, C., 2003, "Robot-assisted arm trainer for the passive and active practice of bilateral forearm and wrist movements in hemiparetic subjects," Arch.Phys. Med. Rehabil.; 84(6): 915-20.

[37] Yupeng, R., P. Hyung-Soon, and Z. Li-Qun,." Developing a whole-arm exoskeleton robot with hand opening and closing mechanism for upper limb stroke rehabilitation," IEEE International Conference on Rehabilitation Robotics, 2009.

[38] Gopura, R.A.R.C., K. Kiguchi, and L. Yang.,2009," SUEFUL-7: A 7DOF upper-limb exoskeleton robot with muscle-model-oriented EMG-based control," IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS).

[39] Nef, T., M. Guidali, and R. Riener.,2009,"ARMin III–arm therapy exoskeleton with an ergonomic shoulder actuation", Applied Bionics and Biomechanics, vol. 6, no. 2, pp. 127-142.

[40] Carignan, C., J. Tang, and S. Roderick, 2009." Development of an exoskeleton haptic interface for virtual task training," IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS).

[41] Liszka, M.S., 2006."Mechanical design of a robot arm exoskeleton for shoulder rehabilitation"., ProQuest.

[42] Frisoli, A., M. Bergamasco, M.C. Carboncini, and B. Rossi, 2009.,"Robotic assisted rehabilitation in virtual reality with the L-EXOS", Advanced Technologies in Rehabilitation, vol. 145, pp. 40-54.

[43] Balasubramanian, S., W. Ruihua, M. Perez, B. Shepard, E. Koeneman, J. Koeneman, and H. Jiping, 2008." RUPERT: An exoskeleton robot for assisting rehabilitation of arm functions," Virtual Rehabilitation.

[44] [44]. Klein, J., S.J. Spencer, J. Allington, K. Minakata, E.T. Wolbrecht, R. Smith, D.J. Reinkensmeyer, 2008." Biomimetic orthosis for the neuro rehabilitation of the elbow and shoulder (BONES)," 2nd IEEE RAS & EMBS International Conference on Biomedical Robotics and Biomechatronics (BioRob).

[45] Rocon, E., J.M. Belda-Lois, A.F. Ruiz, M. Manto, J.C. Moreno, and J.L. Pons, 2007. Design and Validation of a Rehabilitation Robotic Exoskeleton for Tremor Assessment and Suppression, IEEE Transactions on Neural Systems and Rehabilitation Engineering, vol. 15, no. 3, pp. 367-378.

[46] Chetcuti, G., 2011, "Control Of a Robotic Upper Limb Exoskeleton for Use In Muscular Strength Augmentation and Rehabilitation", 2011, University of Technology Sydney: Sydney. p. 92.

[47] UTS: NEWSROOM. Robotics lab promises a new world for people with disabilities. 2011 [cited 2012 23 March]; Available from: http://newsroom.uts.edu.au/news/2011/11/robotics-lab-promises-a-new-world-for-people-with-disabilities.

[48] Sanchez, R.J., Jr., E. Wolbrecht, R. Smith, J. Liu, S. Rao, S. Cramer, D.J. Reinkensmeyer, 2005,"A pneumatic robot for re-training arm movement after stroke: rationale and mechanical design".,9th International Conference on Rehabilitation Robotics (ICORR).

[49] Prange, Gerdienke B., Jannink, Michiel J.A., Groothuis-Oudshoorn, Catharina G.M., Hermens, Hermie J., IJzerman, Maarten J., 2006, "Systematic review of the effect of robot-aided therapy on recovery of the hemiparetic arm after stroke," J. of Rehab. Res. & Dev., 43 (2). Pp.171-184. ISSN 0748-7711

[50] Charles, S.K., Krebs, H.I., Volpe, B.T., Lynch D., Hogan N., 2005, "Wrist rehabilitation following stroke: initial clinical results," Proc. Of the 9th International Conference on Rehabilitation Robotics; Chicago, Illinois. Madison (WI): Omnipress; p. 13-16.

[51] Merians, A.S., Jack, D., Boian, R., Tremaine, M., Burdea, G.C., Adamovich, S.V., Recce, M., Poizner, H., 2002 "Virtual reality-augmented rehabilitation for patients following stroke," Phys Ther.; 82(9):898-915.

[52] Yagi, E.; Harada, D.; Kobayashi, M, 2009"Upper-limb power-assist control for agriculture load lifting"; Int. J. Autom. Technol. 2009, 3, 716–722.

[53] Kai Xu, Jiangran Zhao, Dong Qiu,You Wang, 2014 "A Pilot Study of a Continuum Shoulder Exoskeleton for Anatomy Adaptive Assistances", ASME Journal of Mechanisms and Robotics, Vol. 6 / 041011, pp.1-9.

[54] Hua Yan, Canjun Yang, Yansong Zhang, Yiqi Wang, 2014 "Design and Validation of a Compatible 3-Degrees of Freedom Shoulder Exoskeleton with an Adaptive Center of Rotation", ASME Journal of Mechanical Design, Vol. 136 / 071006-1.

[55] Sunil K. Agrawal, Venketesh N. Dubey,John J. Gangloff, Jr.Elizabeth Brackbill,Ying Mao,Vivek Sangwan,2009 "Design and Optimization of a Cable Driven Upper Arm Exoskeleton", ASME Journal of Medical Devices, Vol. 3 / 031004, pp. 1-7.

[56] Abhishek Gupta, Marcia K. O"Malley, 2006 "Design of a Haptic Arm Exoskeleton for Training and Rehabilitation", IEEE/ASME Transactions on Mechatronics, Vol. 11, No. 3, pp.280–289.

[57] Nicola Vitiello, Tommaso Lenzi, Stefano Roccella, Stefano Marco Maria De Rossi, Emanuele Cattin, Francesco Giovacchini, Fabrizio Vecchi, Maria Chiara Carrozza,2012 "Neuroexos: A Powered Elbow Exoskeleton for Physical Rehabilitation", IEEE Transactions on Robotics, Vol 12, pp. 220-230.

[58] Antonio Frisoli, Fabio Salsedoa, Massimo Bergamascoa, Bruno Rossib, Maria C. Carboncinib, 2009"A force-feedback exoskeleton for upper-limb rehabilitation in virtual reality",Journal in Applied Bionics and Biomechanics. Vol. 6, No. 2, pp. 115–126.

[59] Hugo A. Quintero,Ryan J. Farris,Michael Goldfarb,2012, "A Method for the Autonomous Control of Lower Limb Exoskeletons for Persons with Paraplegia", ASME Journal of Medical Devices, Vol. 6 / 041003, pp. 1-5.

[60] Slavka Viteckova, Patrik Kutilek, Marcel Jirina, 2013, "Wearable lower limb robotics: A review ", Journal of Bio-cybernetics and Biomedical Engineering, Vol.33, pp. 96–105.

[61] Ying Mao2, Xin Jin,Sunil K. Agrawal, 2014"Real Time Estimation of Glenohumeral Joint Rotation Center With Cable-Driven Arm Exoskeleton (CAREX)—A Cable-Based Arm Exoskeleton", ASME Journal of Mechanisms and Robotics, Vol. 6 / 014502, pp. 1-4.

[62] Haoyong Yu, Sunan Huang, Gong Chen, Nitish Thako,2013"Control design of a novel compliant actuator for rehabilitation robots", 7th Journal of Mechatronics Vol 23, pp 1072–1083.

[63] Zhijun Li, Baocheng Wang, Fuchun Sun, Chenguang Yang, Qing Xie, Weidong Zhang, 2013“sEMG-Based Joint Force Control for an Upper- Limb Power-Assist Exoskeleton Robot”, IEEE Journal on Biomdical and Health Informatics, Vol. 18 , No. 3, pp. 1043-1050.

[64] Kazuo Kiguchi, Yoshiaki Hayashi, 2012“An EMG-Based Control for an Upper-Limb Power-Assist Exoskeleton Robot”, IEEE Transactions on Systems, Man, and Cybernetics - Part B: Cybernetics, Vol. 42, No. 4, pp. 1064-1071.

[65] Muceli, S.; Farina, D., 2012, “Simultaneous and proportional estimation of hand kinematics from EMG during mirrored movements at multiple degrees-of-freedom”, IEEE Trans. Neural Syst. Rehabil. Eng. 2012, Vol 20, pp.371–378.

[66] Su, H.; Li, Z.; Li, G.; Yang, C., 2013, “EMG-based Neural Network Control of an Upper-limb Power-assist Exoskeleton Robot. In Advances in Neural Networks; Springer: Berlin,Germany; pp. 204–211.

[67] Sugar, T.G.; He, J.; Koeneman, E.J.; Koeneman, J.B.; Herman, R.; Huang, H.; Schultz, R.S.; Herring, D.; Wanberg, J.; Balasubramanian, S.; et al., 2007,“Design and control of RUPERT: A device for robotic upper extremity repetitive therapy”, IEEE Trans. Neural Syst. Rehabil. Eng., Vol 15;pp. 336–346.

[68] Soumya KantiManna.;Subhasis Bhaumik., 2013 ,“A Bioinspired 10 DOF Wearable Powered ArmExoskeleton for Rehabilitation”, Journal of Robotics., Vol 1, pp.1-15.