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Development of an Assistive Robot for the Torque Analysis of Upper Extremity Joints

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Abstract—Main objective of this research is to find out the torque characteristics and its relation to critical parameters that are essential to run an exoskeleton. The torque required for the arm movements, joint torques because of gravity and residual forces are the key parameters that one need to consider while designing an exoskeleton for the upper extremity joints. For finding out these parameters, experiments were conducted to measure the forces in the forearm while moving the arm to the various position. These force values were converted to torques at the elbow and shoulder, and these values are presented in the paper. The existing exoskeletons were bulky and cumbersome which made them limited for this application. The complexity of the existing exoskeletons created the need for an economical, lightweight system which can provide more dexterity. Rehabilitation therapies do not require extremely complex exoskeleton designs. The proposed exoskeleton was built upon our research experience in wire driven manipulators in the rehabilitation robotics. This cable drive approach will reduce the overall weight of the exoskeleton and helps in a robust control of the arm movements. This paper describes the analysis the experimental data obtained from five subjects.

Index Terms—Assistive robotics, CAD model of exoskeleton, daily activities, design of exoskeleton, exoskeleton, human arm, kinematics, medical robots, rehabilitation robotics, upper limb.

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1 INTRODUCTION

When designing an exoskeleton device to physically interact with humans , it is important to have a human model in order to properly regulate the desired interaction. Developing an exoskeleton device for the upper extremity requires knowledge of joint stiffness, joint torque, position of center of gravity of each segment and the residual force capability of the users. It is beneficial if the device can be scale between the users based on simple measurements such as heights and weights. It is both a very difficult and time intensive process to develop an individual device for different people making such option unfeasible.

In this study, 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 [1]- [3].

This paper investigates the dynamic analysis of an exoskeleton for arm rehabilitation while performing daily activities. Our approach is based on first defining a precise set of actively executed movements that are common in daily activities and then measuring the force, torque and angle of maximum torque required to perform these motions. Robots enable patients to receive a more effective and stable rehabilitation process, and assist therapists by reducing their 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 [4]. This analysis is important for the optimization of design, force feedback and smooth movements of the developed device.

Recent developments in the field of robot assisted rehabilitation and power augmentation are of great interest to researchers. Yagi [5] discussed an upper-limb power-assisted system to assist workers with lifting a 30-kg rice bag, without inducing lower back pain. Kai et al [6] 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. Sunil et al., [7] proposed a natural arm with the goal of making a lightweight and wearable exoskeleton having 4DOF with shoulder and elbow motions. Nicola et al., [8] discussed NEUROExos, a novel powered exoskeleton for elbow rehabilitation. This exoskeleton possesses three main innovative features: the double-shelled links, the four DOF passive mechanisms and a compliant antagonistic actuation system.

There are several other research studies in measuring the joint properties and activity relating to upper limb movement. Sunnegardh`et al. studied the strength of normal children aged between 8 and 13 [9]. Mathur et al., conducted a study on time-dependent linear decrease in the muscular strength of subjects [10]. However, the results of these studies are not sufficient to model a subject for control of an upper limb exoskeleton.

A systematic review confirms the potential for robotic assisted devices; they elicit improvement in the upper limb functions. A new cable driven exoskeleton which is economical, light and wearable, that can provide more dexterity than the existing one is presented in this paper. Recent research confirms that robot assisted rehabilitation therapies are equivalent to high intensive manual therapy and comparable results can be obtained.

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2 MODELLING OF EXOSKELETON AND FABRICATION

To analyze the exoskeleton system, CAD model of the parts were created separately with respect to the different parameters of a human body and converted into ANSYS model that could be used for the dynamics analysis and structural analysis, the CAD model is as shown in Fig 1.

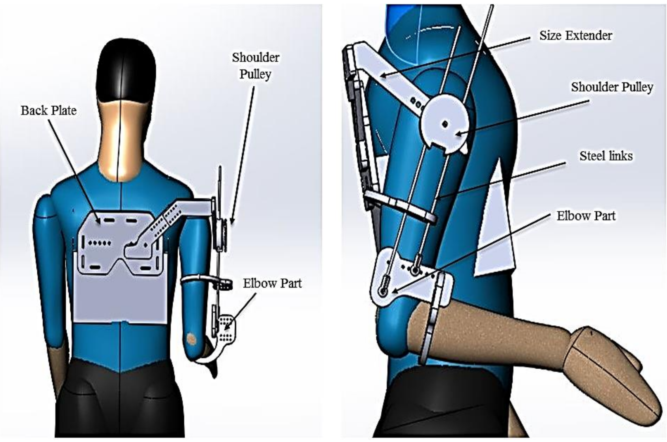

Fig 1. Model of the Exoskeleton

ANSYS model used for the dynamic analysis of the exoskeleton device is shown in Fig.2.The shoulder joint is given the concept of free movement which can be adjusted by the user. The whole structure is made of light material so that the subject does not feel the weight of the exoskeleton. Arm guards are provided for protecting the arm from direct contact with the human body. The developed device has 3 DoF with a passive actuation system by using a cable driven system. This non-localized actuation system allows the use of a more powerful motor, enabling greater lifting strength for the user. This will help in adjusting the position of the motor and to optimize the future designs.

3 DYNAMIC ANALYSIS OF THE EXOSKELETON

The analysis is carried out by applying different loads to each part of the arm segments and the torque required to move these parts is predicted. This study helps in assessing the range of torque required for moving the exoskeleton, selection of driving mechanism and optimizing the controller design. Initially, the elbow flexion torque is calculated, from which the maximum and minimum torque is calculated and these are given in Fig.1. For this study the load of the lower arm is varied from 1 kg to 10 kg and the torque required is calculated.

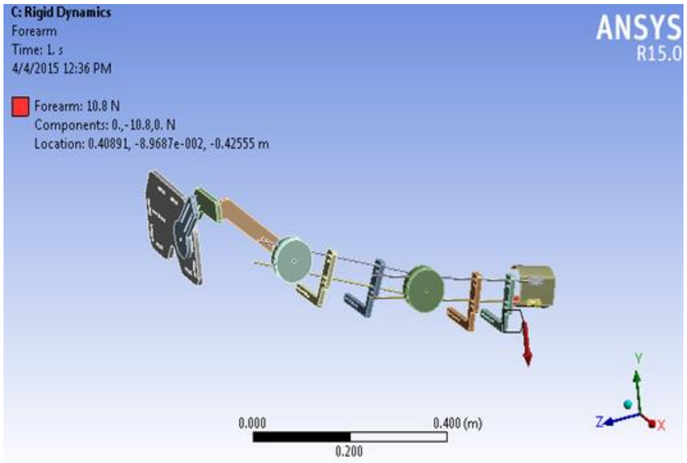

Fig 2. Dynamic Analysis Model

For the shoulder movement, a weight of 3kg is applied to the wrist and the maximum torque required for the shoulder flexion is obtained, as shown in Fig.2. From the two graphs, it is clear that a motor that can provide a torque of 20 to 25 Nm is required for the motion of the exoskeleton, for carrying an arm weight of 10 to 14 kg.

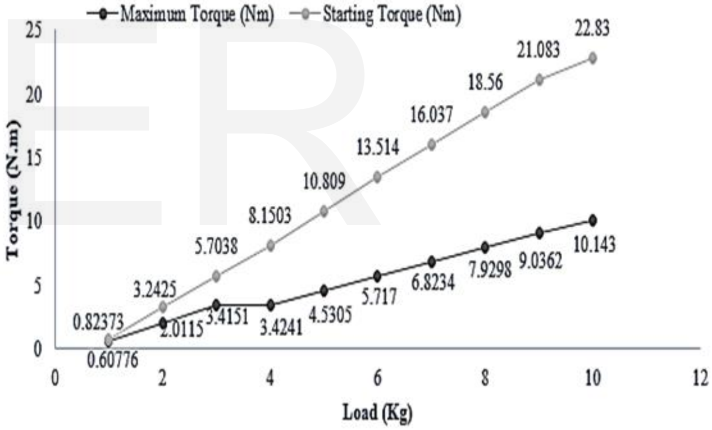

Fig 3. Elbow load vs Torque chart

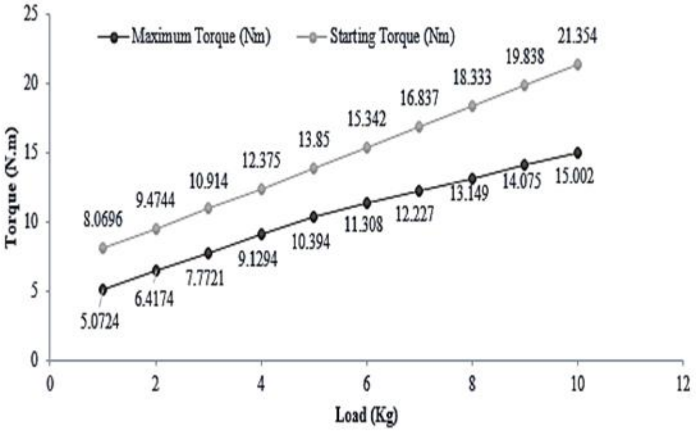

Fig. 4. Shoulder load vs Torque chart

4 CONTROLLER AND DRIVE MECHANISM

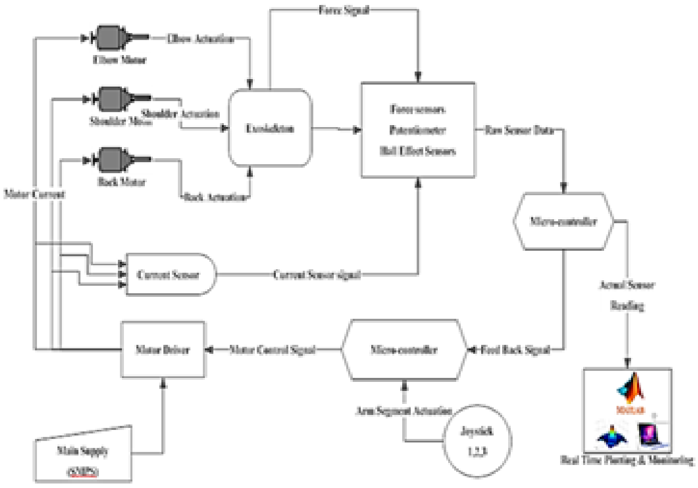

Fig 5. Schematic of the exoskeleton system

The exoskeleton needs to be controlled properly to make it fit for the required purpose, for this a controller must be designed and an effective drive mechanism must be selected. The controller requires a microcontroller which is fast enough to control the motion of the system and to monitor the sensors. This system consists of three force sensors, three potentiometers for angle measurement and three current sensors for measuring the current drawn from the motors. Two microcontrollers are used to control and monitor the working process of the arm exoskeleton. An Atmega1280 microcontroller is used to control the exoskeleton and an Atmega 168 microcontroller is used for monitoring the sensor data. This is connected to the MATLAB interface where real-time plotting and monitoring of system is carried out, schematic of the entire system is shown in the Fig below.

High torque DC geared motors are 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 used for fine positioning. The exoskeleton is fabricated from Acrylic and nylon; connections are made using steel links. This will help in adjusting the position of the two parts for accommodating various arm dimensions. For the actuation of the exoskeleton, a cable drive system is provided, shown in Fig.7 and this will allow the device motor to be mounted on the user's waist or be placed separately, instead of attaching the motor directly to the actuated joint. Thus, the cable drive system will help in reducing the overall weight of the skeleton.

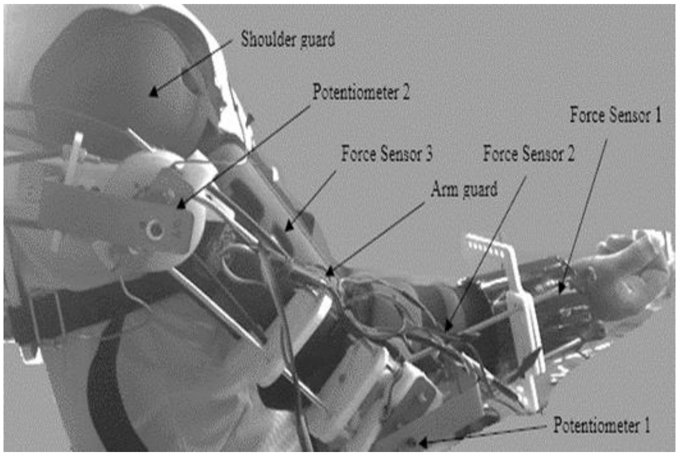

Fig 6. Fabricated Exoskeleton

5 SENSORS

For the experiment three force sensors are used for measuring the gravitational force acting on the exoskeleton for moving the arm. The ratio of voluntary to gravitational force is very small for weak individuals; therefore, it becomes important to accurately characterize the passive force (gravitational and passive joint resistance) to better measure the voluntary component. Initially, the residual force due to the weight of the arm is measured, when actuating the exoskeleton this residual torque is reduced and the torque required for actuating the device is measured. The angle at which maximum torque is measured. One force sensor is placed at the wrist, the other is placed at the center of mass of the forearm and the upper arm. The potentiometer sensors are placed at the arm joints to measure the angle of rotation Fig.5-6. Hall Effect sensors are used for monitoring the current to the motor. It is clear that at the position at which the maximum torque is required, the motor will draw more current to do the required operation.

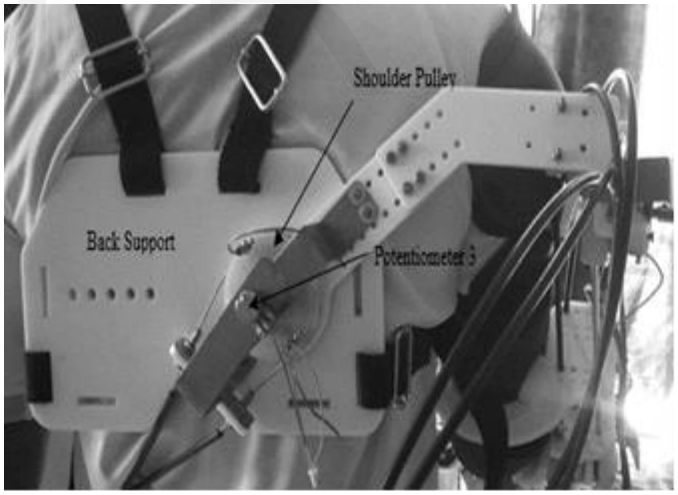

Fig 7. Cable system for the Exoskeleton

6 EXPERIMENT ON THE EXOSKELETON

Values for segmented mass and center of mass are obtained from anthropomorphic tables based on the subject's height, weight, and limb segment lengths [11]. For each subject, several body measurements are taken, including height, weight, upper arm length, and lower arm length.

The experiment is conducted on five subjects and for each subject a specified number of motions are carried out to determine the torque required from these motions. From this, the angle at which maximum torque is required for the movement is found out. This will help in predicting the motor torque required for each movement and smoothly controlling the motor for these motions.

Table I. Human weight and arm dimensions

Subjects	Weight (kg)	Height (cm)	Arm Dimensions				Location of COM from Distal End	
			Forearm		Upper Arm			
			Length (cm)	Weight (N)	Length (cm)	Weight(N)	Lower Arm	Upper Arm
1	68	165	24.0	10.8	30.6	18.0	13.5	17.4
2	75	175	25.5	11.9	32.5	19.9	14.4	18.5
3	70	173	25.2	11.1	32.1	18.6	14.2	18.3
4	63	166	24.2	10.0	30.8	16.7	13.6	17.5
5	67	170	24.8	10.6	31.6	17.8	13.9	18.0

7 COMPARING THE ANALYTICAL AND EXPERIMENTAL WORK

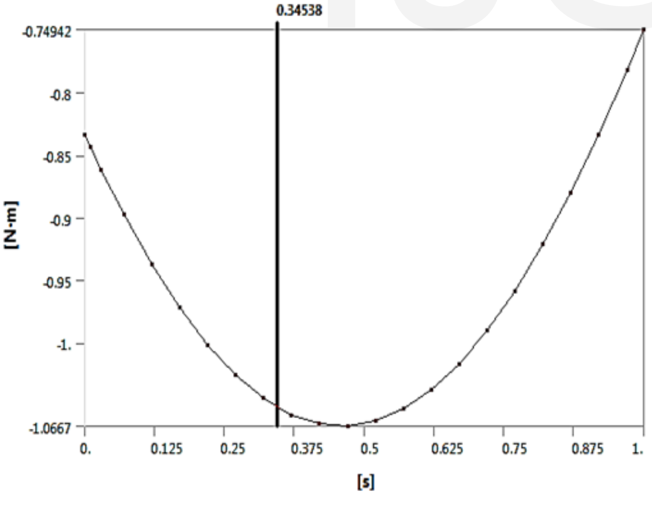

Fig 8. Dynamic analysis of the exoskeleton for subject 1 having a Forearm weight of 10.8N. From the experimental work and analytical work carried out for the exoskeleton it is found that the torque required for moving the arm falls within the analytical range. The dynamic study is carried out up to 100 N and the torque required for moving

To produce the power required to move a load of 100 N, heavy torque motors are needed, these motors are of large size when compared to the 750gm motor used for the experiments. But this dynamic analysis approach gives an idea about the maximum torque required when the exoskeleton device is used for power augmentation instead of rehabilitation. In that case, hydraulic or pneumatic drives are applicable.

Since the exoskeleton is developed for rehabilitation purpose, testing a load is limited up to 30N.Figure.8 shows the Dynamic analysis of the exoskeleton for subject 1 having a Forearm weight of 10.8N. This experimental study gives the maximum torque angles for the exoskeleton where the smooth controlling of the motor is needed to achieve the required movement shown in Fig.9. Even though the testing is not carried out up to 100N load the dynamic analysis also shows that the maximum torque angles remains the same and the experimental results are shown in the Fig 10 polar chart. The result obtained is similar to the result study conducted by Ragonesi et al [11], and it shows that gravity is a dominant component of passive torque.

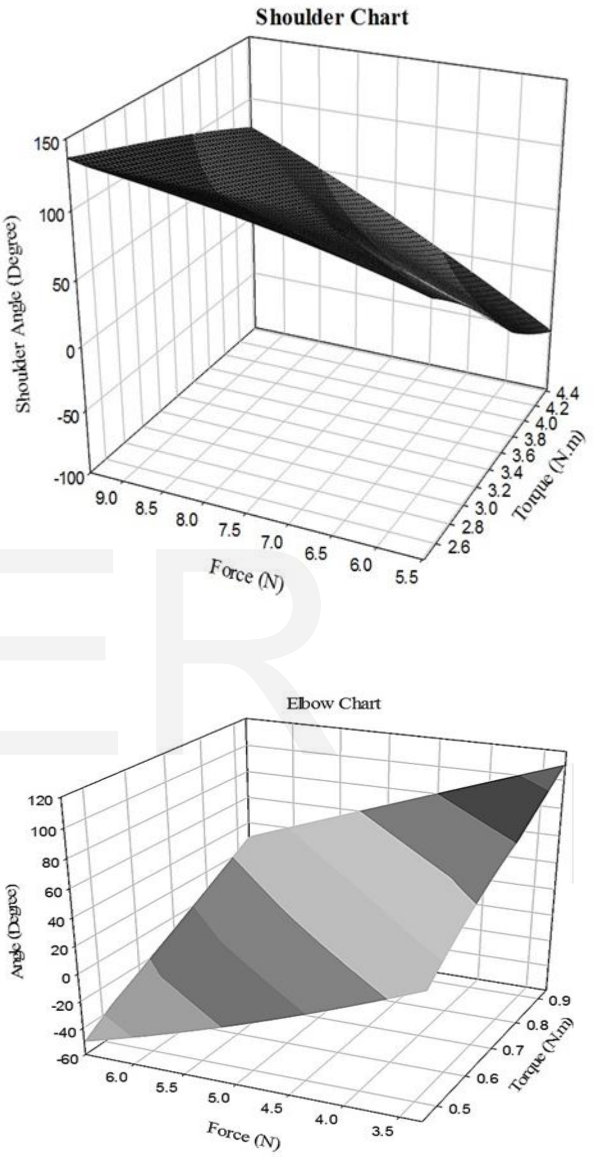

Fig 9. Force, torque and maximum angle chart for Shoulder and Elbow

From the polar charts, we are able to determine the angles at which the muscles have to generate maximum strength for the arm movements. This will help in predicting the recovery of the patients on a fast scale.

If the rehabilitating patients can generate a residual torque similar to the torque generated for the segmental movement then the patients can be considered as able patients, in that case the force acting on the exoskeleton is in only the arm weight due to gravitation. Figure11-12, gives the idea about the current drawn by the shoulder and elbow motor in performing the activities, this is in turn proportional to the energy spend by the human muscles for the arm movements.

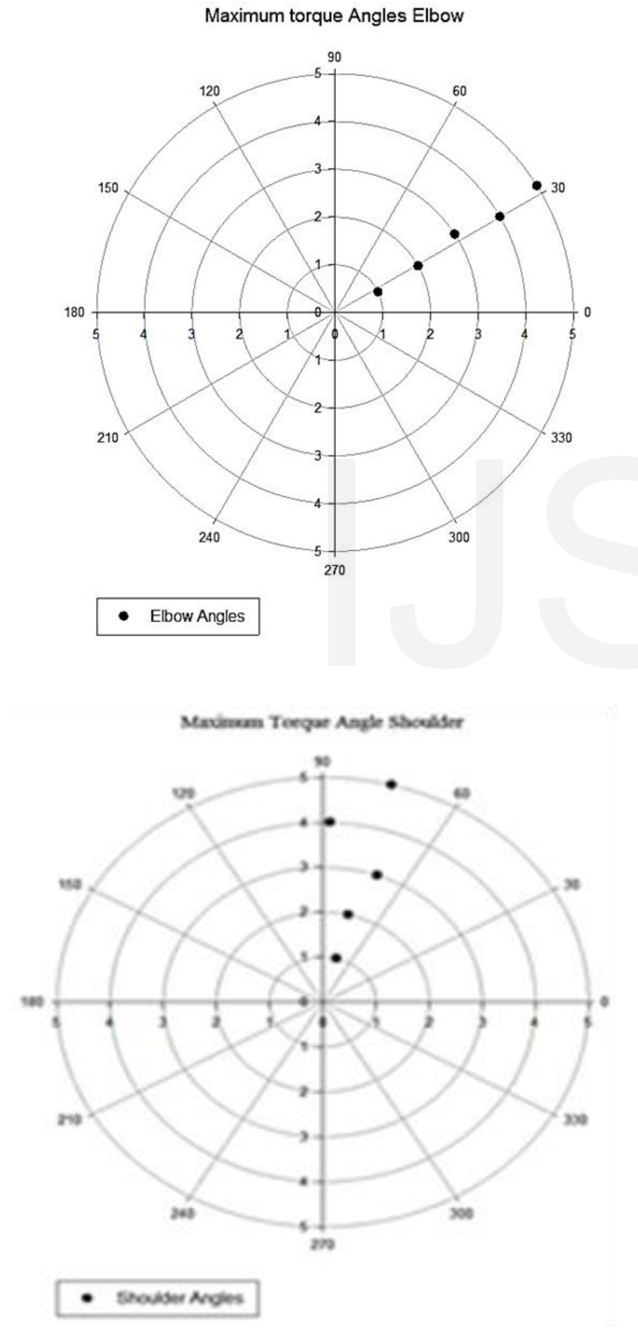

Fig .10. Polar chart for Angle at which maximum torque for elbow and shoulder

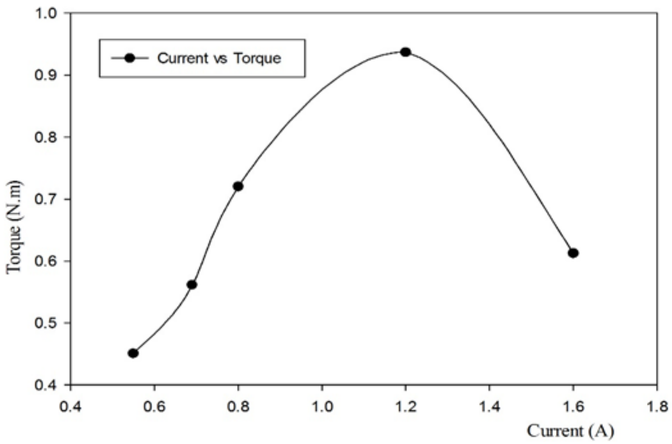

Fig.11. Elbow Torque vs Elbow motor current

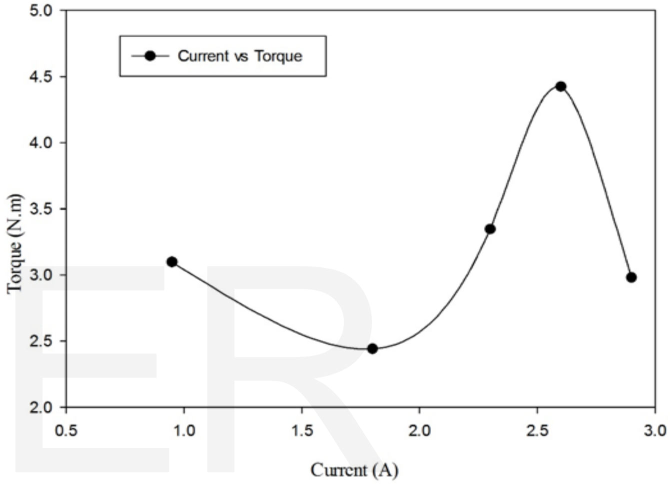

Fig.12. Shoulder Torque vs Shoulder motor current.

8 CONCLUSION

Rehabilitation exoskeleton robot, a new type of medical equipment and typical man- machine integration equipment, is a hot research field in robots. This paper discusses the modelling of a light weight rehabilitation robot for arm rehabilitation, its dynamic analysis, controller design and experimental results. The frame work can be generalized to a wide range of exoskeleton systems designed for both augmentation and rehabilitation. In future, we plan to apply this frame work to optimize the controller and develop a modular exoskeleton from the results obtained.

The development of training methods allows us to tailor the exoskeleton system to match patient needs. The above results show the performance indices associated with training strategies and clinical evaluations. It is expected that these kinds of tools and methods will soon become necessary for the rehabilitation process. The movements and the data extracted from a healthy arm can be used as a reference for validating the change in the impaired limb. Similar to the study explained here many more new approaches in rehabilitation study of the human arm using exoskeleton devices can be guaranteed.

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