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Design and prototype of an active assistive exoskeletal robot for rehabilitation of elbow and wrist

E. Mohammadi[a], H. Zohoor[b,*] and S.M. Khadem[a]

a. *School of Mechanical Engineering, Sharif University of Technology (SUT), Tehran, Iran.*
b. *Center of Excellence in Design, Robotics and Automation, SUT; Academician, The Academy of Sciences of IR Iran.*

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Abstract. Due to the increasing number of people suffering from physical disabilities in the elbow and wrist, developing an assistive wearable robot seems crucial. These disabilities are mostly common in elderly people and people who are suffering from spinal injury or stroke. In this paper, a wearable assistive robot for rehabilitation of the wrist and elbow is developed. The mechanism has 3 Degree of Freedom (DoF); two active DoF for assisting the flexion/extension of the elbow and wrist, and a passive one in order to have unconstrained supination/pronation of the forearm. The motors and sensors were chosen based on kinematic constraints governing the motion of arms and wrists. Finally, with the intention of evaluating the performance of the robot, some preliminary experiments were conducted using a prototype of the designed wearable robot. Experimental results showed that the proposed assistive robot meets its design goals and can assist patient motion in the desired DoF.

1. Introduction

In recent years, the number of people suffering from physical disabilities such as full or partial loss of function in the shoulder, elbow or wrist has been increasing rapidly. Sport injuries, occupational injuries, spinal cord injuries and strokes are some of the main reasons for such disabilities. Rehabilitation programs are the main treatment for these kinds of patients. In order to assist the physically disabled, injured, and/or elderly persons, or to ease their rehabilitation treatment, researchers have been developing exoskeleton robots.

In the 1960s and 1970s, wearable robots were studied for medical and industrial applications [1,2]. The main function of developed wearable robots is to assist the wearer by enhancing their strength and endurance. In civilian areas, exoskeletons could be used to help workers survive dangerous environments. The medical field is another prominent application of exoskeleton robots. For instance, these robots can be used for improved precision during surgery [3,4].

Over the last decade, due to the increasing number of impairments limiting the physical function of limbs (in the elderly, or the disabled, or as a result of surgery mishap) much attention has been devoted to developing rehabilitation wearable robots and exoskeletal robots for assisting patients in their daily lives. Kiguchi developed an active robot with 4 Degrees of Freedom (DoFs) and a remote center of motion on the shoulder joint. This robot was designed for supporting horizontal and vertical flexion/extension of the shoulder, flexion/extension of the elbow and supination/pronation of the forearm [5]. In another similar study, ARMin, a 4 DoF wearable robot was developed by Nef et al. [6]. This rehabilitation robot was used in medical clinics for remediation of impairments and disabilities of the shoulder and promotion of its mobility through simple physical tasks. Another 4 DoF upper limb exoskeleton was designed by Moreau,

*. *Corresponding author.*
E-mail address: zohoor@sharif.edu (H. Zohoor)

which has a gravity compensation exoskeleton for rehabilitation. This robot has employed brushless motors to actuate shoulder abduction-adduction, shoulder flexion-extension, shoulder internal-external rotation and elbow flexion-extension [7].

Ryu at el. designed and manufactured another wearable exoskeleton that can be used to lift heavy things. This robot is a whole body exoskeleton that is provided with a proper load distribution [8]. Another whole body exoskeleton was designed by Ugurlu et al. that can be used for rehabilitation and power augmentation purposes. This robot was controlled using electromyography signals acquired from users [9].

Due to their heavy weight and high volume, most of these robots are difficult to wear. Consequently, this drawback has impeded their widespread application. CADEN-7, the 7 DoF robot designed by Perry et al. has eliminated this difficulty by using the open human-robot attachment for both upper and lower arm segments [10]. An ABLE lightweight robot was developed by Garrec [11]. This robot was an anthropomorphic upper limb exoskeleton integrally actuated by a highly reversible ball-screw and cable. The robot was designed for shoulder articulation and the forearm-wrist, and was used in medical rehabilitation, teleoperation or haptics. Another robot, named W-EOXS, was developed to assist the motion of forearm supination/pronation, wrist flexion/extension and radial/ulnar deviation by Gopura and Kiguchi [12]. The novelty of this study was in consideration of the offset of the wrist axis, which was not seen in previous designs. Therefore, the robot could not cause any undesirable pain in the subjects' wrist. Pehlivan et al. proposed another forearm exoskeleton with 3 DoF, including the forearm, wrist flexion-extension and wrist radial-ulnar [13].

Cable transmission is used in some exoskeleton systems in order to reduce the mass of the system carried by the user. In these complex systems, motors are located at the base frame and forces are transmitted to the joints and end-effector through cable tension [14,15].

As mentioned, most rehabilitation robots are heavy, so, they are assembled on a table or a stand. Their application is limited inside medical clinics and they can rarely be used as assistive robots for performing daily routine tasks. On the other hand, there are some patients who have disabilities in the 7 DoF of their arm. Therefore, by developing an assistive robot for specific DoF of the arm, the robot weight can be significantly reduced and its application can be broadened. This wearable robot can be used without direct supervision of a doctor, inside the home and/or work setting to help patients in their everyday tasks, such as eating or drinking.

The design requirements are now described. It includes the design methodology, as well as the thorough physical structure of different parts of the robot and their functions. Moreover, a thorough kinematic and dynamic analysis of the mechanism is presented and used to acquire the required actuation torques and define the workspace of the robot. The mechanism is modeled using MATLAB Simulink software. This model is used to study the workspace of the robot and ensure that the mechanism meets its design goals.

2. Mechanical design

The purpose of this study is to design and develop a wearable robot to assist people with wrist and elbow disabilities. To have a better range of motion [13], 2 active DoF were considered for flexion/extension of the elbow and wrist. The range of motion of the elbow and wrist joints is $0°$ to $-140°$ and $-80°$ to $80°$, respectively [16]. Wrist radial/ulnar deviation is very small, and incorporating this motion into our design would make the mechanism complex and heavy. By fixing this joint in its neutral position, we would avoid this issue. Due to the existence of a carrying angle, the supination/pronation of the forearm cannot be neglected. Therefore a passive DoF is considered for this rotational movement of the forearm. The range of motion of this movement is between $0°$ and $160°$ [16].

Figure 1 shows the designed robot, modeled in SolidWorks software (version 2012). The robot consists of 4 links and two drive units. The first link or the arm link is the ground link of this mechanism. It is firmly attached to the arm using an arm cuff and Velcro strips. The second link or the forearm link is connected to the forearm in the same way as the first link. The third link is the wrist holder, which supports the supination/pronation of the forearm. The wrist holder can freely rotate in the wrist frame which is attached to the second link. The wrist frame consists

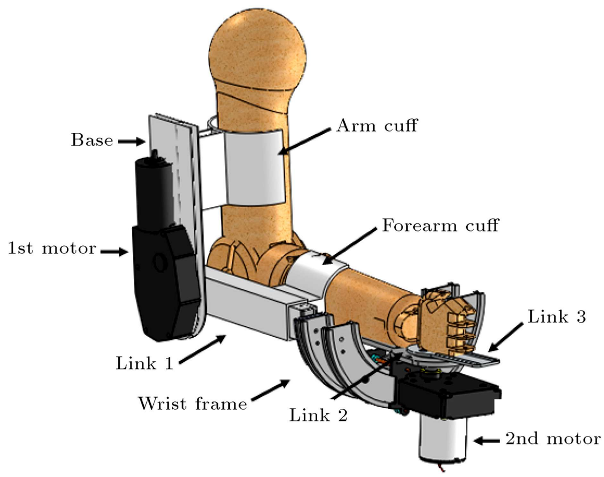

Figure 1. 3D model of the designed mechanism.

of an outer semicircular frame which serves as a guide for the rotation of the wrist holder. The subject's hand is placed on the wrist holder and it aligns subject's forearm and the forearm link. The fourth link is connected to the wrist holder using a revolute joint. It is attached to a handle which is held by the subject. The subject's fingers are attached to the handle using Velcro strips.

Two DC motors are used for actuating the flexion/extension of the elbow and wrist. The first is attached to the base link and rotates the forearm link. The axis rotation of the 1st motor is adjustable and should be in line with the axis rotation of the elbow. The second DC motor is attached to the 2nd link and rotates the 3rd link. The axis of rotation of the 2nd motor is also adjustable and matches the axis of rotation of the wrist. People of different size should be able to use this robot. In order to make this mechanism adjustable to different sizes, both the DC motors and the active revolute joints can be easily attuned using two adjustment screws. Also, by using mechanical stops, the range of motion of the DoF are limited within a permissible range so that the robot cannot hurt the patient. Table 1 shows the workspace of the proposed robot compared to a human's arm and wrist range of motion.

As mentioned, a passive DoF was integrated into the mechanism to have unconstrained supination/pronation of the forearm. Neglecting this motion during the flexion/extension of the elbow would result in enormous pain in the forearm of the patient. The semicircular guide used to simulate supination/pronation of forearm is shown in Figure 2.

In this mechanism, the roller, which is mounted on two couples of ball bearings, moves along the circular guide. The circular frame itself is attached to the forearm link via a linear guide. This linear guide uses a slider and allows the mechanism to adapt itself to different forearms with different lengths.

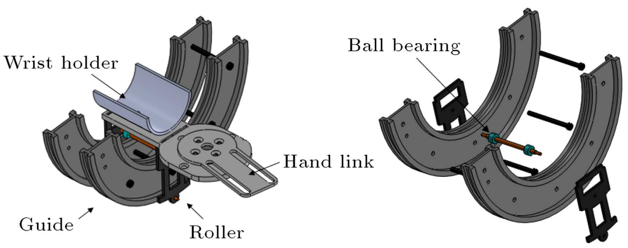

Figure 2. Exploded view of the semicircular guide and its components.

Table 1. Comparison between robot's workspace and human's arm and wrist range of motion.

	Work space(degree)	
Joint	**Human [10]**	**Exoskeleton**
Elbow	[0 140]	[0130]
Forearm	[0160]	[0150]
Wrist	[-80 80]	[-7575]

3. Kinematic and dynamic analysis

In order to find the driving torques for actuation of the wrist and elbow, and to make sure the actuation forces do not harm the patient, we need to solve the kinematic and dynamic equations governing the motion of the mechanism. The proposed robot has a serial mechanism. Therefore, by assigning coordinate frames to the mechanism joints, based on the Denavit-Hartenberg (D-H) frames convention, and achieving D-H parameters, kinematic equations can be obtained. Furthermore, using the Newton-Euler method, dynamic equations of the robot are acquired. The velocity and acceleration of each link and the weight of a simple object held in the patient's hand (such as a glass of water) are inputs of these equations. By solving these equations, driving torques for actuation of elbow and wrist joints are achieved. Figure 3 shows the assignment of frames and joints of the serial mechanism.

The D-H parameter of the exoskeleton is shown in Table 2, where i is the axis (joint) number, which is aligned with the $\hat{Z}_i$ coordinate system located at each joint, a_i is the distance from $\hat{Z}_i$ to $\hat{Z}_{i+1}$ measured along $\hat{X}_i$, α_i is the angle between $\hat{Z}_i$ and $\hat{Z}_{i+1}$ measured about $\hat{X}_i$, d_i is the distance from $\hat{X}_{i-1}$ to $\hat{X}_i$ measured

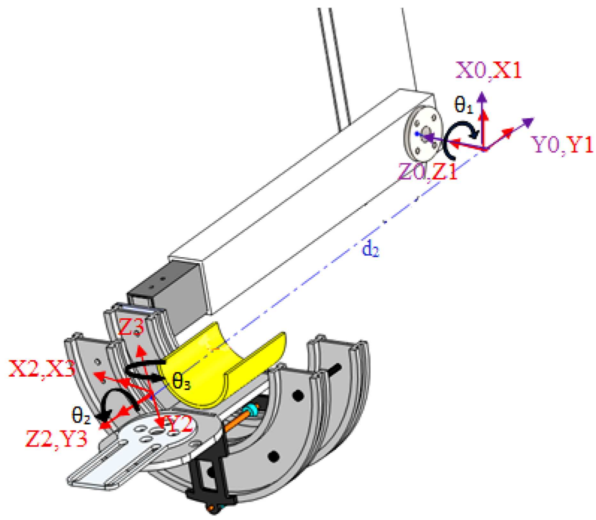

Figure 3. Joint coordinate frame assignment.

Table 2. Robot's D-H parameters.

i	α_{i-1}	a_{i-1}	d_i	θ_i
1	0	0	0	θ_1
2	$\pi/2$	0	d_2	θ_2
3	$\pi/2$	0	0	θ_3

along $\hat{Z}_i$, and θ_i is the angle between $\hat{X}_{i-1}$ and $\hat{X}_i$ measured about $\hat{Z}_i$.

First, two frames are placed on the elbow joint in such a way that the z-axis of the frames points outward along the joint's axis of rotation. The other two frames representing the forearm and wrist joints are placed on the wrist joint, as shown in Figure 3. Table 2 shows the serial robot's D-H parameters. Frames are assigned to the mechanism joints based on these parameters.

Based on these frames, the total transformation matrix was calculated in Eq. (1) [17], which is shown in Box I.

3.1. Singularity points

A robot singularity occurs when robot axes are redundant (more axes than necessary to cause the same motion) or when the robot is in certain configurations that require extremely high joint rates to move at some nominal speed in Cartesian space. The presence of singularities in a manipulator's effective joint space or work space can profoundly affect the performance and control of the manipulator, variously resulting in intolerable torques or forces on the links, loss of stiffness or compliance, and breakdown of control algorithms. The analysis of kinematic singularities is, therefore, an essential step in manipulator design.

The main method for identifying singular configurations of the robot is to study its Jacobian. The time derivative of the kinematics equations yields the Jacobian of the robot, which relates the joint rates to the linear and angular velocity of the end-effector. By knowing the transformation matrix from Eq. (1), shown in Box I, we can easily find the position of the robot's end-effector in the global frame:

$$^{0}P_{\text{tip}} = {}^{0}_{3}T\,{}^{3}_{4}P, \tag{2}$$

$$^{3}_{4}P = \begin{bmatrix} 0 \\ H_3 \\ 0 \end{bmatrix}, \tag{3}$$

where $^{j}_{i}P$ shows the position of the ith link in the jth frame. Taking the derivative of the tip position would give us the Jacobian matrix as shown in Box II.

Singular configurations happen when the Jacobian does not have an inverse. Thus, by finding values that make the determinant of the Jacobian equal to zero, we can find singular positions.

By solving the singular value problem, it was found that singular configurations are when θ_1 or θ_2 are equal to 0 or 180 degrees. $\theta_{1\&2} = 180$ is out of the workspace of the robot. Also, singularity points become important for unactuated DoF. Here, θ_2, which represents supination/pronation of the forearm, is the only unactuated DoF. But, this robot is a wearable orthosis, which is used to modify the structural and functional characteristics of the skeletal system. In this case, the robot is attached to the arm. Therefore, around singular points ($\theta_2 = 0$), the musculoskeletal structure of the arm works as a spring and damper

$$^{0}_{3}T = \begin{bmatrix} \sin(\theta_1)\sin(\theta_3) - \cos(\theta_1)\cos(\theta_3)\sin(\theta_1) & \cos(\theta_3)\sin(\theta_1) + \cos(\theta_1)\sin(\theta_2)\sin(\theta_3) & \cos(\theta_1)\cos(\theta_2) & d_2\sin(\theta_1) \\ -\cos(\theta_1)\sin(\theta_3) - \cos(\theta_3)\sin(\theta_1)\sin(\theta_2) & \sin(\theta_1)\sin(\theta_2)\sin(\theta_3) - \cos(\theta_1)\cos(\theta_3) & \cos(\theta_2)\sin(\theta_1) & -d_2\cos(\theta_1) \\ \cos(\theta_2)\cos(\theta_3) & -\cos(\theta_2)\sin(\theta_3) & \sin(\theta_2) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}. \tag{1}$$

Box I

$$^{0}J = \begin{bmatrix} H_3(\cos(\theta_1)\cos(\theta_3) - \sin(\theta_1)\sin(\theta_2)\sin(\theta_3)) + d_2\cos(\theta_1) & H_3\cos(\theta_1)\cos(\theta_2)\sin(\theta_3) & -H_3(\sin(\theta_1)\sin(\theta_3) - \cos(\theta_1)\cos(\theta_3)\sin(\theta_2)) \\ H_3(\cos(\theta_3)\sin(\theta_1) + \cos(\theta_1)\sin(\theta_2)\sin(\theta_3)) + d_2\sin(\theta_1) & H_3\cos(\theta_2)\sin(\theta_1)\sin(\theta_3) & H_3(\cos(\theta_1)\sin(\theta_3) + \cos(\theta_3)\sin(\theta_1)\sin(\theta_2)) \\ 0 & H_3\sin(\theta_2)\sin(\theta_3) & -H_3\cos(\theta_2)\cos(\theta_3) \end{bmatrix}. \tag{4}$$

Box II

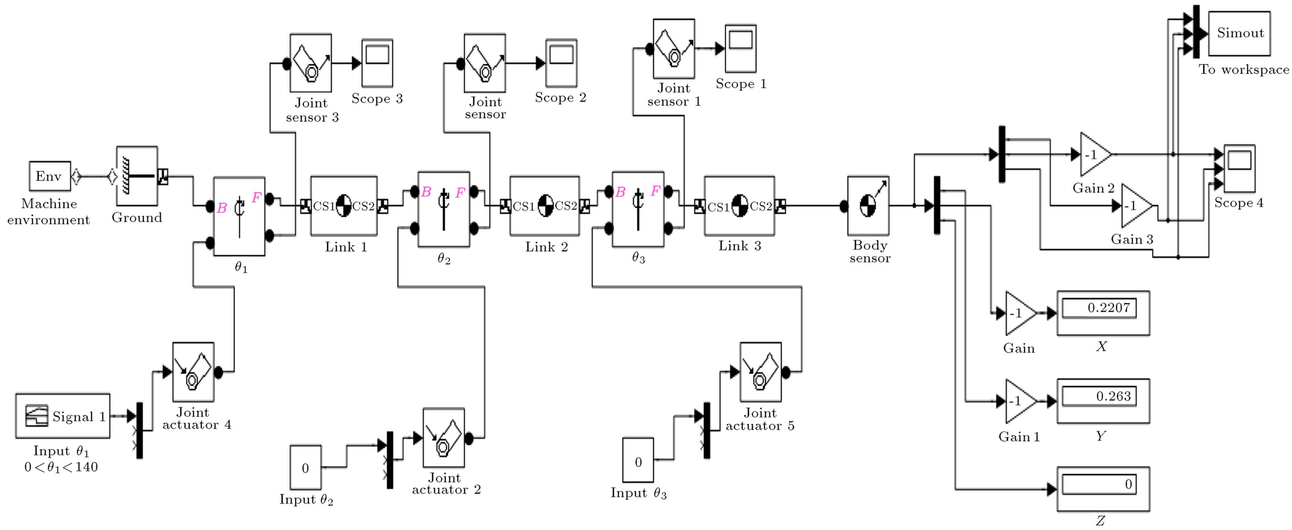

Figure 4. Robot's model in Simulink environment.

system and confines the velocities of the joints. So, for this mechanism, singular configurations do not cause any problems.

3.2. Dynamic analysis

Using forward kinematics, exact displacement in each joint, and the velocity and orientation of the links, are achieved. Furthermore, by means of the Newton-Euler method, dynamic equations governing the motion of the robot were obtained [17]. The inward iterations are as follows:

$$^{i}f_i = {}^{i}_{i+1}R^{i+1}f_{i+1} + {}^{i}F_i, \tag{5}$$

$$^{i}n_i = {}^{i}N_i + {}^{i}_{i+1}R^{i+1}n_{i+1} + {}^{i}P_{C_i} \times {}^{i}F_i + {}^{i}P_{i+1} \times {}^{i}_{i+1}R^{i+1}f_{i+1}, \tag{6}$$

$$\tau_i = {}^{i}n_i^{T\,i}\hat{Z}_i, \tag{7}$$

where:

τ	Joint torque in $\hat{Z}$ axis
f_i	Force in ith joint
n_i	Torque in ith joint
F_i	Applied force on the center of mass of the ith link
N_i	Applied torque on the center of mass of the ith link

In order to implement the effects of gravity, we can simply put ${}^{0}\dot{v}_0 = g$, where g is the gravity vector.

4. Modelling

In this section a simulated model of the proposed robot is presented. This model was developed to verify the dynamic and kinematic equations governing the motion of the mechanism. Also, it is used to study the performance of the robot. The modeling of the robot was done using the Robotics Toolbox in the MATLAB Simulink program. The developed mechanical model in SolidWorks, along all its constraints, was imported in the Simulink environment. The acquired Simulink model is shown in Figure 4.

To verify the kinematic equations, we gave the developed model a set of inputs and compared the results with the results obtained by solving the equations analytically. The system inputs are:

$$\theta_2 = \theta_3 = 0, \qquad \theta_1 = 10.t, \qquad 0 < t < 14\,\text{sec}. \tag{8}$$

In order to solve dynamic and kinematic equations analytically, the exact magnitude of the mechanical properties of the robot links, and the physical properties of the subject's arm, such as its length and weight, are needed. The mechanical properties of each link are calculated using the 3D model of the robot, which was previously developed using Solidworks software. Also, anthropometric data from literature was used to find the mechanical characteristics of a human arm [18]. Figure 5 shows the analytical results compared with the results of the model.

To verify the dynamic equations, a constant torque equal to 1 N/m (a real value that can be produced by carrying a spoon or cellphone) was given to model as the input of the first joint. Then, forces at the end effector of the robot were measured. To measure these forces, a spring with known stiffness was attached to the robot tip. By computing the deflection of the needle in response to the input torque, forces applied by the robot were measured. In the next step, these forces were given to the analytical model as a set of inputs. The resulting torque in the first joint was found by solving the equations. It should be the same

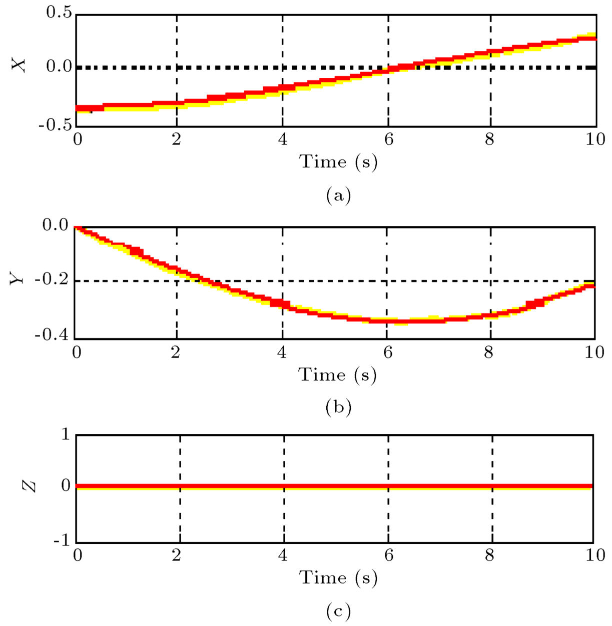

Figure 5. Position of robot end effector in response to a certain input. Yellow line: results of Simulink model; and red line: analytical results.

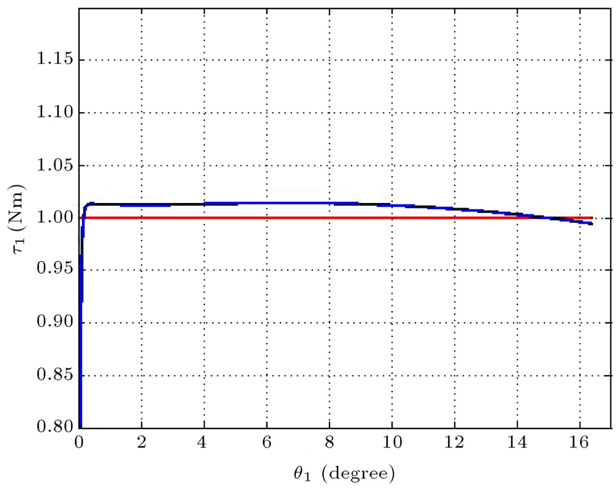

Figure 6. Comparison of applied torque to the Simulink model with the torque acquired by solving dynamic equations.

as the model input (equal to 1 N/m). Figure 6 shows the applied torque to the model compared to the torque acquired by solving dynamic equations. As seen, the forces are almost the same. The small observed error might be due to numerical computation and round-off errors.

5. Prototyping

In this section, the developed model is used to study the interaction of the robot and the human hand. Based on this study, the proper actuation mechanism is chosen. Finally, a prototype mechanism is manufactured.

Table 3. Mechanical properties of subject's arm.

Arm length	Forearm length	Arm weight	Forearm weight
21.6 cm	29 cm	1.92 Kg	0.72 Kg

Table 4. Mechanical properties of the robot's links.

Link	Mass (kg)	Link length (cm)
1	0.241	15 to 22
2	0.260	14
3	0.023	4 to 8

To develop a model for a human hand, anthropometric data from literature was used. The subject's arm length and weight are implemented in the model, based on the worst case scenario. The anthropometric properties of a man with maximum length and weight are calculated and are shown in Table 3.

This data was further incorporated in the model to find the mechanical properties of the robot attached to the subject's arm. The final values for the links mass and length are given in Table 4, where Link 1 is considered an assembly of link 1, the wrist frame, the forearm cuff and elbow coupling; Link 2 is an assembly of link 2 and the 2nd motor; and Link 3 is an assembly of link 3 and wrist coupling.

Using the identified model, the torques applied on the elbow and wrist joints relative to the joints angular position are acquired and presented in Figures 7(a) and 5(b), respectively.

Maximum required actuation torque for the elbow joint is at 95° and it is equal to 6.7 N.m. Also, maximum required torque in the wrist joint is equal to 0.87 N.m and is at 0°. Other than the robot and arm weight, joint friction can also affect the required driving torque. Therefore, the joint and actuator friction is required to be identified. The resisting friction can be estimated by the following equation:

$$\tau_{\text{friction}} = c\ \text{sgn}(\dot{\theta}) + \nu\dot{\theta}\ \tau_{\text{friction}} = c\text{sgn}(\dot{\theta}) + \nu\dot{\theta}, \quad (9)$$

where c is the coefficient of friction and ν is the coefficient of viscous friction. By adding Eq. (9) to Eq. (7), the maximum required actuation torque can be found.

Since the robot moves slowly to prevent any harm, and well lubricated bearings have also been incorporated in fabrication of the robot, the coefficient of viscous friction is assumed to be negligible. Still, the coefficient of friction (static coulomb friction) needs to be identified. Friction is the static friction that needs to be overcome to enable the relative motion of the links. In this work, the value of the required current to initiate robot motion in each of the 2 DoF is calculated, and the relative torques are used as friction torques. By

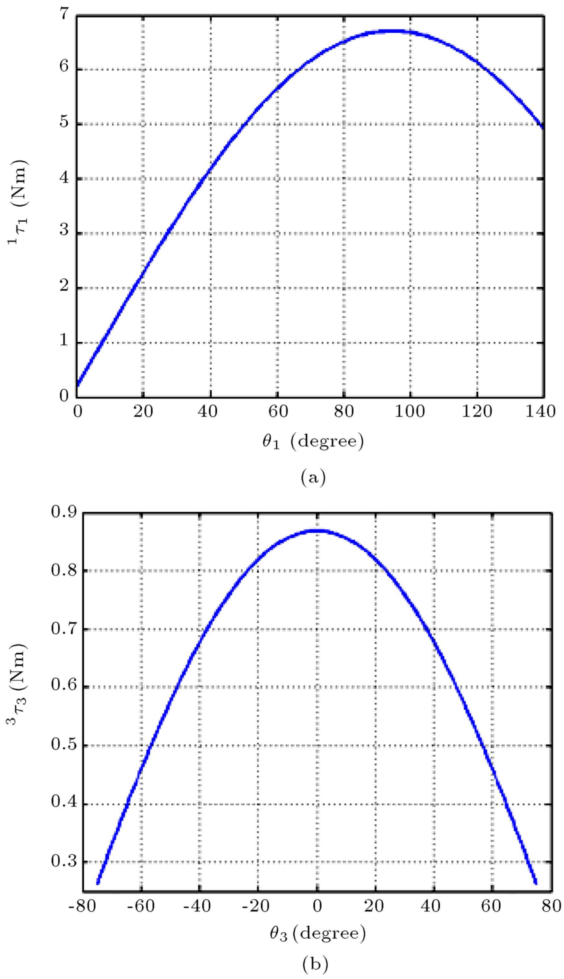

Figure 7. Torque vs. angular position for flexion/extension of (a) elbow and (b) wrist.

incorporating the effects of friction, the required torque for actuation of the elbow and wrist are 6.701 N.m and 0.871 N.m, respectively.

The whole weight of the robot should be carried in the elbow joint. Therefore, a 13 watt DC gear motor (1.13.055.220, Buhler Co, Germany) and worm gearbox with ratio of 1:200 are responsible for flexion/extension of the elbow. By using auto-lock gearboxes, the robot can hold the subject's arm at the specified angle after reaching the desired position without applying any torques. Therefore, the exoskeletal robot is stable. Another 3.9 watt DC motor (82860001, Crouzet Co., France), with a gearbox with ratio of 1:130, actuates flexion/extension of the wrist.

The fabricated prototype of the designed robot attached to the subject's arm is shown in Figure 8.

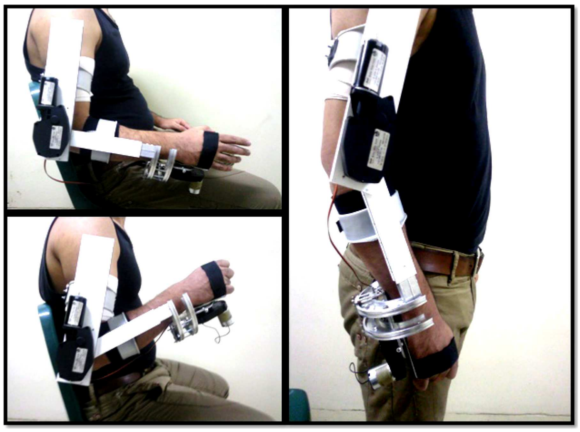

Figure 8. Prototype of the proposed wearable assistive robot.

6. Conclusion

In this study, a wearable robot for assisting people with physical disabilities in their wrist and elbow is presented. In this research, we have tried to develop a simple and light wearable robot that can be easily used outside medical clinics by the patient. This robot helps people with impairments in their wrist and elbow to accomplish daily tasks, such as drinking and eating.

In order to wear this robot, the elbow joint should be positioned at 90 degrees. Then, the subject can easily put it on. The robot is fixed on the subjects arm using Velcro straps. Also, the robot's arm link was designed in such a way that it can be used by patients with different arm lengths.

The robot weighs less than 1.1 kg, which is lighter than similar wearable robots. Also, it can be easily attached to the patient's wheelchair, if he or she is using one. This robot can be used for daily tasks at home or at work with the permission of the relevant physicians. However, this conclusion is limited by the fact that the experiments were performed only on one subject. Experiments in more realistic conditions are needed to approve this conclusion. The next steps in this study would be optimization of the designed mechanism to further reduce its weight, and development of the third active DoF for the radial/ulnar deviation of the wrist.

Acknowledgment

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Biographies

Esmaeil Mohammadi received his MS degree in Mechanical Engineering from Sharif University of Technology, Iran, in 2013. His current research interests are biorobotics, intelligent robots, and application of robotics in rehabilitation. He has also taken out two patents from his MS degree thesis.

Hassan Zohoor was born in Esfahan, Iran, in 1945. He received his PhD degree from Purdue University, USA, and spent his postdoctoral time at the same university. Currently, he is Distinguished Professor of Mechanical Engineering at Sharif University of Technology, Tehran, Iran, Academician and Rector of the Center for Science and Technology Studies of the Academy of Sciences of IR Iran, and also Member of the Executive Board of the Association of Acadamies and Societies of Sciences in Asia. He is author or co-author of over 460 scientific papers, and has supervised over 200 graduate theses. He was President of Shiraz University, Iran, and the founder, President and developer of principal codes and regulations of Payame Noor University, Iran. He has also been the recipient of several honors and awards, such as the Allameh Tabatabaei, a special award of the National Elite Foundation, the award of distinguished professor of Iran, and the Ross Ade Award at Purdue University, USA.

Mohsen Khadem received his BS and MS degrees in Mechanical Engineering from Shiraz University, and Sharif University of Technology, Iran, in 2010 and 2013, respectively. He is currently working towards his PhD degree in Electrical and Computer Engineering at the University of Alberta and is working on robotics-assisted minimally invasive surgery. His current research interests are medical robotics and image-guided surgery.