A Novel Mechanical Design and Analysis of an Exoskeletal Assistive Robot for Human Upper Limb

İnsan Üst Uzvu için Bir Yardımcı Dış İskelet Robotunun Yenilikçi Mekanik Tasarımı ve Analizi

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***Abstract*— Physical medicine and rehabilitation are important for elderly and disabled people. Everywhere and every time therapy concept is a key role in the field of rehabilitation. If this concept is performed effectively, people who need rehabilitation can be treated in a shorter period, with less hassle and cost. In this study, in order to assist physically disabled, injured or elderly persons, a novel mechanical design and analysis of an exoskeletal assistive robot for human upper limb are developed. The exoskeletal assistive robot system has 3 degrees of freedom. It is actuated with servo motors. Robot design is based on assisting the most basic daily movements. The usefulness of proposed mechanical design is discussed and shown with simulation results.**

***Keywords*— Exoskeletal robot, assistive robotics, physical medicine and rehabilitation**

***Özet*— Fiziksel tıp ve rehabilitasyon yaşlı ve engelliler için önemlidir. Her yerde ve her zaman terapi konseptinin rehabilitasyon alanında önemli bir rolü vardır. Bu kavram etkili bir şekilde gerçekleştirilirse, rehabilitasyon ihtiyacı olan kişilere daha az güçlük ve maliyetin yanında daha kısa sürede tedavi sağlanabilir. Bu çalışmada, fiziksel engelli, yaralı veya yaşlı kişilere yardımcı olmak amacıyla, insan üst uzvu için bir dış iskelet yardımcı robot mekanik tasarım ve analizleri geliştirilmiştir. Yardımcı dış iskelet robotu 3 serbestlik derecesine sahiptir. Hareketler servo motorlar aracılığıyla sağlanır. Robot tasarımında, en temel günlük hareketleri destekleme özelliği esas alınmaktadır. Önerilen mekanik tasarımın yararlılığı simülasyon sonuçları ile gösterilmiştir.**

***Anahtar Kelimeler*— Dış iskelet robotu, yardımcı robot, fiziksel tıp ve rehabilitasyon**

I. INTRODUCTION

The number of people who are in need of being assisted for their the most basic daily movements is increasing day by day. It is claimed that it will be a major problem for health industry in the coming decades. In order to solve this problem, assistive robotic technologies have advanced considerably in an effort to meet expectations of people. Assistive robotics is a technology used by individuals with disabilities in order to perform daily movements. The primary goal of assistive robots is to support disabled people by increasing quality and efficiency of daily movements. In the last fifteen years, assistive robotic technologies have been progressively investigated and developed. Assistive technology includes mobile devices such as walkers and wheelchairs, addition to this, there are more advance technologies such as robotic devices consisting of hardware and software parts, the most essential point is that these parts have to meet some important specifications.

The design specifications of an exoskeletal assistive robot are given below [1];

- Safety: Unlike industrial robots, assistive robots has more interaction with humans, thus design must be trustworthy.
- Cost: Being low cost is important for manufacturing of the robot.
- Autonomy: Because of the assistive robots are used for all daily life activities, robustness has to be achieved for many conditions.

- Usability: They are used by elderly people, thus it has to be easy to understand working principle and instruction of the robot.

Moreover, axiomatic design method is used to meet person's requirements in robot-human interaction systems. The main concerns of this method are mentioned below;

- Human safety
- Lightness
- Portability
- Wearability
- Adjustability
- Cost

In this study, to obtain the specifications mentioned above, optimum design parameters and structure of an exoskeletal assistive robot for upper limbs are investigated. Design challenges such as choosing material and adjustable size for an optimum exoskeletal assistive robot for human upper limb are discussed.

II. HUMAN ARM AND ANATOMY

The shoulder and elbow consist of five bones of the upper limb: the clavicle, the scapula, the humerus, the ulna and the radius [2] [3]. They can be seen from Fig.2 and Fig.3.

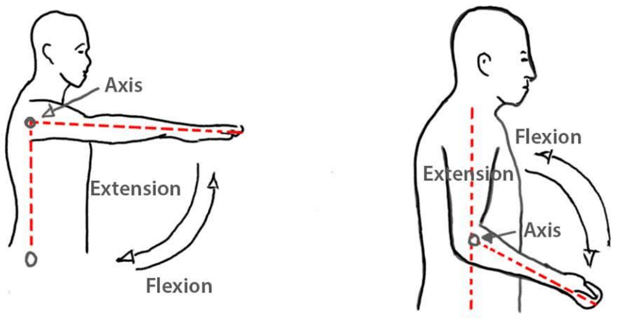

Figure 1: Movements of shoulder and elbow.

From a biomechanical point of view, the human anatomy can be represented as a set of rigid bodies connected by joints. In robotic rehabilitation, biomechanical models can be used for the design as well as the control of the prototype to simplify the interaction mechanism between the human and the robot. Mechanical analyses are carried out to validate the kinematic structure of the robot and its actuators dimensions. The human arm has three complex articulations; the shoulder, the elbow and the wrist. Our design is dedicated to support the most basic daily movements for shoulder, elbow and wrist. These movements can be seen from Fig.1. The degrees as intervals for these movements are mentioned in Table 1 [4].

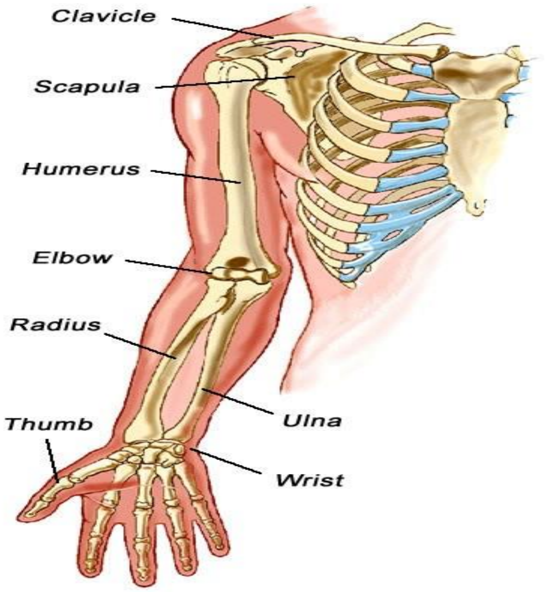

Figure 2: Human arm. [2]

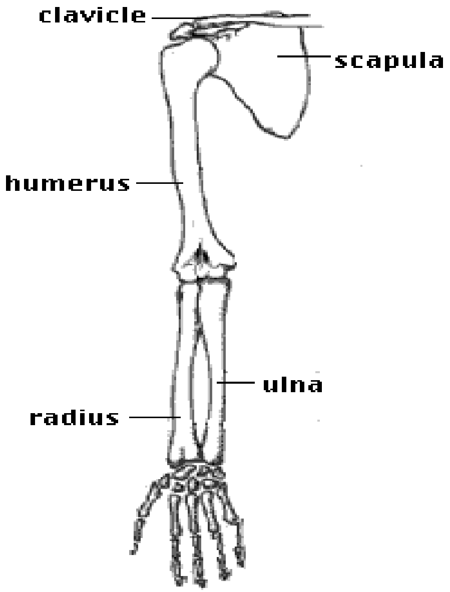

Figure 3: The clavicle, the scapula, the humerus, the ulna, the radius. [3]

Table 1: The average range of the shoulder and the elbow joints of the human arm. [4]

Movement	Elbow flexion	Shoulder flexion	Shoulder rotation	Shoulder adduction
Range of Motion	0˚ - 150˚	-50˚ - 180˚	-80˚ - 100˚	0˚ - 180˚

Robotic exoskeleton systems have been studied for the purposes of industry or medical applications since 1960. The nature of the requirements for assistive robotics, such as different control approaches containing safety, user-friendliness and being low cost was studied by Q.Meng and

M.H.Lee [1]. The research area of skill learning assistive robots was investigated by Hsien-I Lin [5]. In this study, in order to assist physically disabled, injured or elderly people, a novel mechanical design including adjustable parts for the user's limb and mechanical analysis for providing safety of the user are investigated. Optimum material selection is discussed considering the forces on the joints while the robot assists the user for daily movements.

III. MECHANICAL DESIGN

The main purpose of an exoskeleton is not only to provide efficient motion assistance to the human limbs, but also to guarantee the safety and the comfort of the user. That is why matching of the human anatomy is one of the most important criteria for an exoskeleton design. The mechanical structure of our design is shown in Fig.4 and Fig.5, mainly consists of three links and three joints covering the basic degrees of freedom of the human arm. The robot is designed to meet 3 DOF for ensuring person's daily movements. Each joints; the elbow, the shoulder and the wrist has one degree of freedom providing flexion/extension movements. The range of motion of the robot's joints is limited to provide a workspace which is compatible with anatomic constraints of the user. The robot has to have easy adaptation property to different bone sizes.

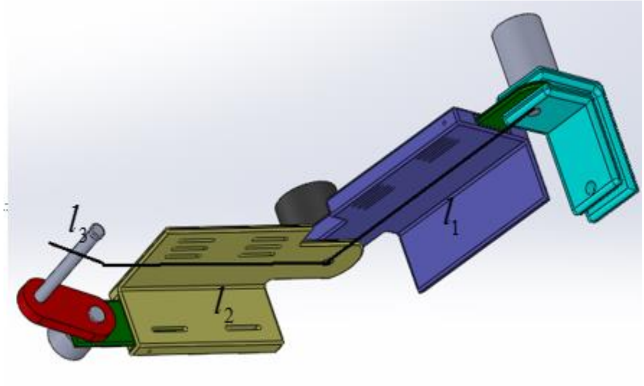

Figure 4: Exoskeletal Assistive Robot (Isometric View).

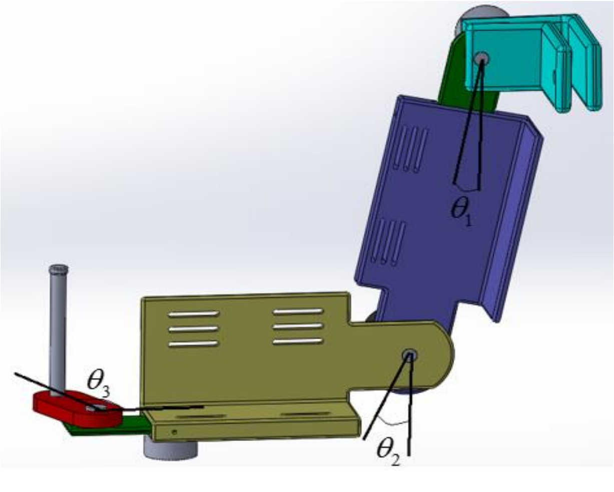

Figure 5: Exoskeletal Assistive Robot (Front View).

l_1, representing *humerus,* refers to the distance between the shoulder and the elbow. l_2, representing *ulna*, refers to the distance between the elbow and the wrist. l_3 refers to the distance between the end of the *metacarpal* bones.

In the equations shown below, F icons represent the forces on the joints, subscripts are used to describe the direction of the forces, for example F_{01} means the force applied to link 1 by the base numbered as 0, X and Y components of these forces are calculated from the inverse of the matrix A shown in Eq.7, this matrix is created using Newton-Euler Method, after calculating the inverse of the matrix A, it becomes possible to calculate the vector B multiplying each sides of Eq.7 by the inverse of A, F_H represents the external forces on the end effector of the robot, such as glass, bag, *etc*. m_1 represents the mass of the first link, m_2 represents the mass of the second link and m_3 represents the mass of the third link. I_{G1} is the inertia of the first link, I_{G2} is the inertia of the second link, I_{G3} is the inertia of the third link. T_1 represents the torque of the first motor, T_2 represents the torque of the second motor, T_3 represents the torque of the third motor.

$$\begin{aligned}F_{01X} &= \frac{(m_1 - m_2 + m_3)l_1}{2}\left(\ddot{\theta}_1 \sin\theta_1 + \dot{\theta}_1^2 \cos\theta_1\right)\\ &+ (m_3 - m_2)\frac{l_2}{2}\left(\ddot{\theta}_2 \sin\theta_2 + \dot{\theta}_2^2 \cos\theta_2\right)\\ &+ m_3\frac{l_3}{2}\left(\ddot{\theta}_3 \sin\theta_3 + \dot{\theta}_3^2 \cos\theta_3\right) - F_{HX}\end{aligned} \tag{1}$$

$$\begin{aligned}F_{01Y} &= (m_1 - m_2 + m_3)\frac{l_1}{2}\left(\ddot{\theta}_1 \cos\theta_1 - \dot{\theta}_1^2 \sin\theta_1\right)\\ &+ \frac{(m_3 - m_2)l_2}{2}\left(\left(\ddot{\theta}_2 \cos\theta_2 - \dot{\theta}_2^2 \sin\theta_2\right) + g\right)\\ &+ m_3\left(\frac{l_3}{2}\left(\ddot{\theta}_3 \sin\theta_3 - \dot{\theta}_3^2 \cos\theta_3\right) + g\right) - F_{HY}\end{aligned} \tag{2}$$

$$\begin{aligned}F_{21X} &= (m_2 - m_3)\left[\frac{l_1}{2}\left(\ddot{\theta}_1 \sin\theta_1 + \dot{\theta}_1^2 \cos\theta_1\right) + \frac{l_2}{2}\left(\ddot{\theta}_2 \sin\theta_2 + \dot{\theta}_2^2 \cos\theta_2\right)\right]\\ &- m_3\frac{l_3}{2}\left(\ddot{\theta}_3 \sin\theta_3 + \dot{\theta}_3^2 \cos\theta_3\right) + F_{HX}\end{aligned} \tag{3}$$

(4)

$$\begin{aligned}F_{21Y} &= (m_2 - m_3)\left[\frac{l_1}{2}\left(\ddot{\theta}_1 \cos\theta_1 - \dot{\theta}_1^2 \sin\theta_1\right) + \frac{l_2}{2}\left(\ddot{\theta}_2 \cos\theta_2 - \dot{\theta}_2^2 \sin\theta_2\right) + g\right]\\ &- m_3\frac{l_3}{2}\left(\ddot{\theta}_3 \sin\theta_3 - \dot{\theta}_3^2 \cos\theta_3\right) + F_{HY}\end{aligned}$$

$$\begin{aligned}F_{23Y} &= \frac{m_3}{2}l_1\left(\ddot{\theta}_1 \cos\theta_1 - \dot{\theta}_1^2 \sin\theta_1\right) + \frac{m_3}{2}l_2\left(\ddot{\theta}_2 \cos\theta_2 - \dot{\theta}_2^2 \sin\theta_2\right)\\ &+ \frac{m_3}{2}l_3\left(\ddot{\theta}_3 \sin\theta_3 - \dot{\theta}_3^2 \cos\theta_3\right) + \frac{m_3}{2}g - F_{HY}\end{aligned} \tag{5}$$

$$\begin{aligned}F_{23X} &= \frac{m_3}{2}l_1\left(\ddot{\theta}_1 \sin\theta_1 + \dot{\theta}_1^2 \cos\theta_1\right) + \frac{m_3}{2}l_2\left(\ddot{\theta}_2 \sin\theta_2 + \dot{\theta}_2^2 \cos\theta_2\right)\\ &+ \frac{m_3}{2}l_3\left(\ddot{\theta}_3 \sin\theta_3 + \dot{\theta}_3^2 \cos\theta_3\right) - F_{HX}\end{aligned} \tag{6}$$

$$\underbrace{\begin{bmatrix} 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 \\ \frac{l_1}{2}\sin\theta_1 & \frac{l_1}{2}\cos\theta_1 & -\frac{l_1}{2}\sin\theta_1 & -\frac{l_1}{2}\cos\theta_1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & -\frac{l_2}{2}\sin\theta_2 & -\frac{l_2}{2}\cos\theta_2 & -\frac{l_2}{2}\sin\theta_2 & -\frac{l_2}{2}\cos\theta_2 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & \frac{l_3}{2}\sin\theta_3 & \frac{l_3}{2}\cos\theta_3 & -\frac{l_3}{2}\sin\theta_3 & -\frac{l_3}{2}\cos\theta_3 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \end{bmatrix}}_{A} \underbrace{\begin{bmatrix} F_{01X} \\ F_{01Y} \\ F_{21X} \\ F_{21Y} \\ F_{23X} \\ F_{23Y} \\ F_{HX} \\ F_{HY} \\ T_1 \\ T_2 \\ T_3 \end{bmatrix}}_{B} = \underbrace{\begin{bmatrix} \frac{m_1 l_1}{2}\left(\ddot{\theta}_1 \sin\theta_1 + \dot{\theta}_1^2 \cos\theta_1\right) \\ \frac{m_1 l_1}{2}\left(\ddot{\theta}_1 \cos\theta_1 - \dot{\theta}_1^2 \sin\theta_1\right) \\ m_2\left[\frac{l_1}{2}\left(\ddot{\theta}_1 \sin\theta_1 + \dot{\theta}_1^2 \cos\theta_1\right) + \frac{l_2}{2}\left(\ddot{\theta}_2 \sin\theta_2 + \dot{\theta}_2^2 \cos\theta_2\right)\right] \\ m_2\left[\frac{l_1}{2}\left(\ddot{\theta}_1 \cos\theta_1 - \dot{\theta}_1^2 \sin\theta_1\right) + \frac{l_2}{2}\left(\ddot{\theta}_2 \cos\theta_2 - \dot{\theta}_2^2 \sin\theta_2\right) + g\right] \\ m_3\left[\frac{l_1}{2}\left(\ddot{\theta}_1 \sin\theta_1 + \dot{\theta}_1^2 \cos\theta_1\right) + \frac{l_2}{2}\left(\ddot{\theta}_2 \sin\theta_2 + \dot{\theta}_2^2 \cos\theta_2\right) + \frac{l_3}{2}\left(\ddot{\theta}_3 \sin\theta_3 + \dot{\theta}_3^2 \cos\theta_3\right)\right] \\ m_3\left[\frac{l_1}{2}\left(\ddot{\theta}_1 \cos\theta_1 - \dot{\theta}_1^2 \sin\theta_1\right) + \frac{l_2}{2}\left(\ddot{\theta}_2 \cos\theta_2 - \dot{\theta}_2^2 \sin\theta_2\right) + \frac{l_3}{2}\left(\ddot{\theta}_3 \sin\theta_3 - \dot{\theta}_3^2 \cos\theta_3\right) + g\right] \\ I_{G1}\ddot{\theta}_1 \\ I_{G2}\ddot{\theta}_2 \\ I_{G3}\ddot{\theta}_3 \\ F_{HX} \\ F_{HY} \end{bmatrix}}_{C} \tag{7}$$

$$A^{-1} = \begin{bmatrix} 1 & 0 & -1 & 0 & 1 & 0 & 0 & 0 & 0 & -1 & 0 \\ 0 & 1 & 0 & -1 & 0 & 1 & 0 & 0 & 0 & 0 & -1 \\ 0 & 0 & 1 & 0 & -1 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 & -1 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & -1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ -\frac{l_1}{2}\sin\theta_1 & -\frac{l_1}{2}\cos\theta_1 & l_1\sin\theta_1 & l_1\cos\theta_1 & l_1\sin\theta_1 & -l_1\cos\theta_1 & 1 & 0 & 0 & l_1\sin\theta_1 & l_1\cos\theta_1 \\ 0 & 0 & \frac{l_2}{2}\sin\theta_2 & \frac{l_2}{2}\cos\theta_2 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -\frac{l_3}{2}\sin\theta_3 & -\frac{l_3}{2}\cos\theta_3 & 0 & 0 & 1 & l_3\sin\theta_3 & l_3\cos\theta_3 \end{bmatrix} \tag{8}$$

IV. MECHANICAL ANALYSIS AND MATERIAL SELECTION

Before material selection for joints of exoskeletal assistive robot, the forces on the joints have to be found, thus the trade-off can be determined between human safety criteria and cost criteria, to do this, Eq. (1-6) are be used. A sinusoidal wave with period of 6.28 second and 1 radian is used as a trajectory for θ_1, θ_2 and θ_3 parameters, The values of $F_{HX} = F_{HY} = 1.8\,N$, $L_1 = 0.3\,m$, $L_2 = L_3 = 0.5\,m$, $m_1 = m_2 = m_3 = 1\,kg$ are determined as design parameters .

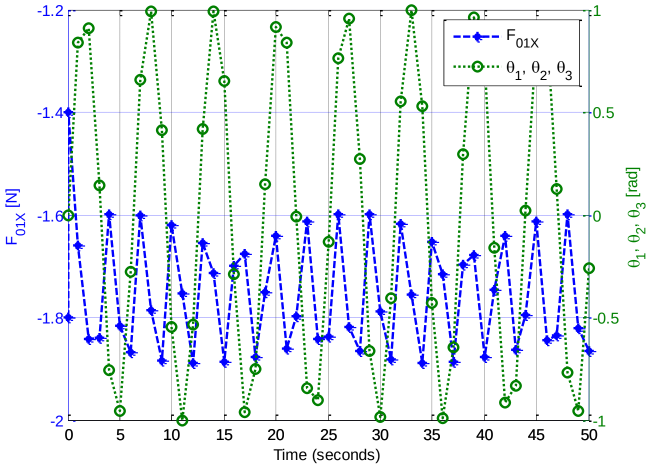

Figure 6: F_{01X}

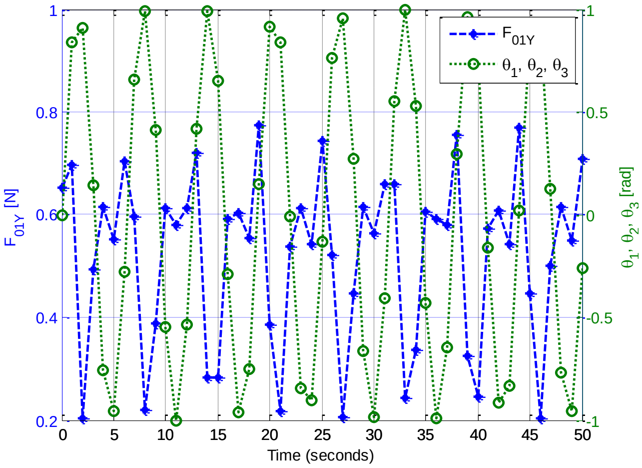

Figure 7: *F_{01Y}*.

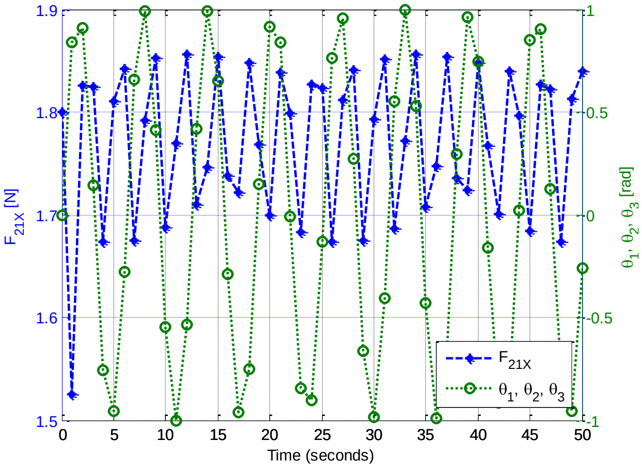

Figure 8: *F_{21X}*.

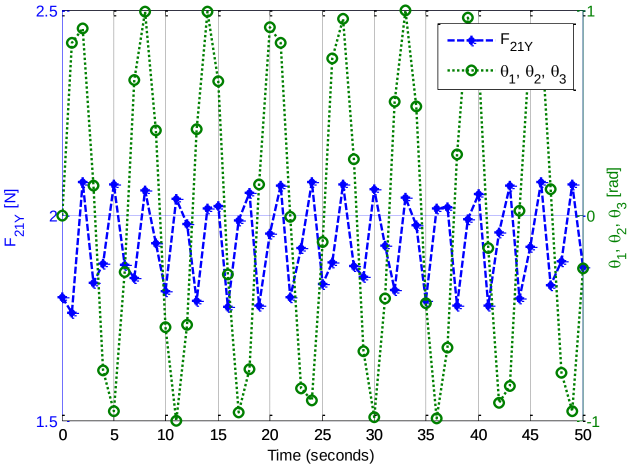

Figure 9: *F_{21Y}*.

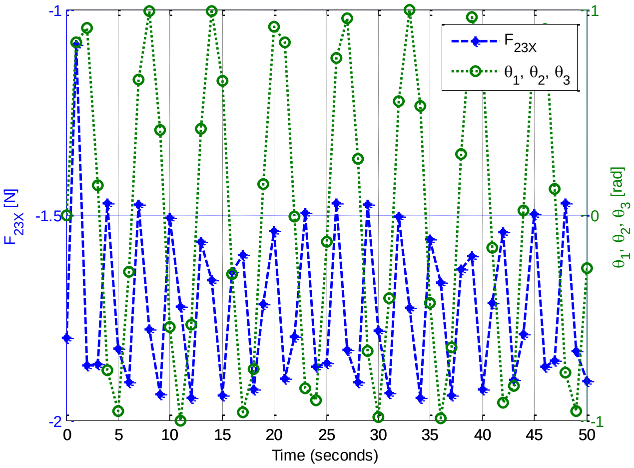

Figure 10: *F_{23X}*.

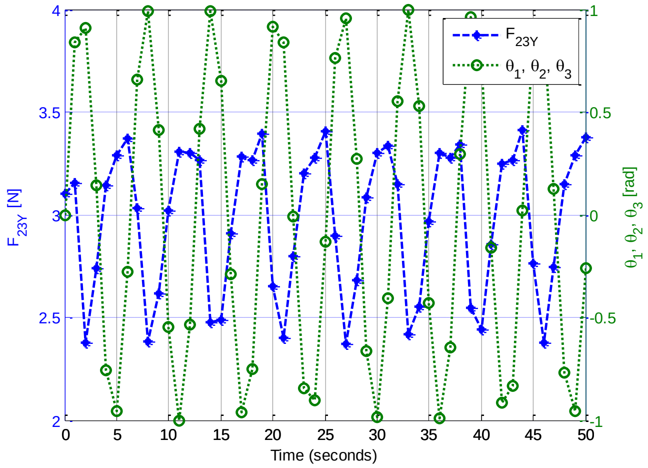

Figure 11: *F_{23Y}*.

V. CONCLUSION

Considering the results force-time graphs in Fig.6, Fig.7, Fig.8, Fig.9, Fig.10 and Fig.11, forces on the joints are in the range of 2.5-3.5 interval. When it is considered that the designed joint diameters in the range of 40-60 mm interval, carbon fiber material can provide the desired strength, lightness and economic advantage. If the economic possibilities are limited, materials like polyethylene can be used to make a trade-off between strength and being economic, however, this manufacturing option can cause some undesired incidents which harm to user when the robot has high loads, thus it cannot meet the most important axiomatic design method which is human safety criteria.

VI. FUTURE WORKS

The exoskeletal assistive robot designed in this work will be manufactured in Mechatronics Laboratory of Mechatronics Engineering Department at Yildiz Technical University and it is being planned to design appropriate algorithms for controlling servomotors, so that people in need of help can easier achieve their daily routines.

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