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Upper Limb Robot Arm System Design and Kinematic Analysis

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Abstract: In this study, a wearable upper limb robot arm design has been designed for individuals who experience discomfort in the arm muscle and experience power loss. The user with arm discomfort can attach the designed system to her arm and perform daily life activities like healthy individuals. The upper limb robot arm system is designed in Solidworks program. The system is attached to the waist of the user and wraps the entire arm. The designed robot arm system is designed to be produced of 5 cm thick aluminum material. Angular servo motors are mounted from the joints to the wrists and elbows. The linear motor is mounted to the shoulder part of the upper limb system to provide both vertical and horizontal movement. Necessary analyses were done for the mechanism designed with the help of Solidworks software. The safety coefficients of the arm, hand, and shoulder apparatuses were calculated for a maximum load of 250 N. Later, restrictions were made for the necessary movements and the powers and torque values of the motors to be used were calculated. Also, maximum displacements were determined by making force distributions for the arm, hand, and shoulder parts of the system.

Keywords: Robot arm design, motion analysis, force analysis, finite element method, angular and linear motors

Üst Uzuv Robot Kol Sistemi Tasarımı ve Kinematik Analizi

Öz: Bu çalışmada, kol kasında rahatsızlık hisseden ve güç kaybı yaşayan kişiler için giyilebilir bir üst ekstremite robot kol tasarlanmıştır. Kol rahatsızlığı olan kullanıcı, tasarlanan sistemi koluna bağlayabilir ve sağlıklı bireyler gibi günlük yaşam aktiviteleri gerçekleştirebilir. Üst ekstremite robot kol sistemi Solidworks programında tasarlanmıştır. Sistem kullanıcının beline bağlanıp tüm kolu saracak şekilde dizayn edilmiştir. Tasarlanan robot kol sistemi 5 cm kalınlığında alüminyum malzemeden üretilecek şekilde tasarlanmıştır. Köşeli servo motorlar eklemlerden bileklere ve dirseklere monte edilir. Doğrusal motor, hem dikey hem de yatay hareket sağlamak için üst ekstremite sisteminin omuz kısmına monte edilmiştir. Solidworks yazılımı yardımıyla tasarlanan mekanizma için gerekli analizler yapılmıştır. Kol, el ve omuz aparatlarının güvenlik katsayıları maksimum 250 N yük için hesaplanmıştır. Daha sonra gerekli hareketler için kısıtlamalar yapılmış ve kullanılacak motorların güç ve tork değerleri hesaplanmıştır. Ayrıca, sistemin kol, el ve omuz kısımları için kuvvet dağılımları yapılarak maksimum yer değiştirmeler belirlenmiştir.

Anahtar Kelimeler: Robot kol tasarımı, hareket analizi, kuvvet analizi, sonlu elemanlar yöntemi, açısal ve lineer motorlar

1. Introduction

With the widespread use of robotic studies today, many studies have been done on exoskeleton robots and their limb designs, production, and controls. To provide safe movement in dangerous and difficult situations for humans, studies on exoskeleton arms and legs, which have a structure like the human arm and leg structure, have begun to become widespread [1]. Also, interest in an exoskeleton has increased in recent years. [2]. In previous studies from exoskeleton robots, sub-

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platform fixed manipulators were used for industry. However, when human anatomy is examined, it is understood that human movements are much more comfortable than these manipulators. To overcome these constraints in fixed platform manipulators, exoskeleton robot designs have been started [3]. Recently, promising progress has been made in the field of human-exoskeleton robot interaction [4]. These robots are still an open area of research due to their complex mechanical design, various aid strategies (for different types of patients), and the precision of the mechanism [5]. As a typical physical user-robot interaction, exoskeleton robots have been developed to improve the performance of a healthy user or to provide walking support and walking rehabilitation to users with reduced functionality [4]. Also, exoskeletons, defined as wearable, mechanical structures that increase a person's strength, are designed to physically assist employees in performing their duties, thereby reducing their exposure to the relevant physical condition [6]. These devices should act in harmony with the human anatomy and create a minimum interaction force between the users without any obstacle or limiting their movements in performance enhancement studies [4]. Exoskeleton robot structures are devices that must be performed as closely as possible with human movements by communicating between human and mechatronic systems. The exoskeleton robot system is a human-machine interactive system. Exoskeletons are an example of human-robot collaboration. The exoskeleton robot is worn by man and the mechanical structure is activated by the effect of information signals [7]. Exoskeleton robots are designed to be able to move by the movements of human limbs [8]. Exoskeleton robot is expressed as a structure that supports the user and protects it from the external environment. The application of the exoskeleton can be divided into three main groups: manpower enhancements, haptic interactions, and rehabilitation [9]. In recent years, exoskeleton robots have been extensively developed to support and strengthen human muscle strength [10]. User-worn exoskeleton robots help increase the ability to support and load the user. These robots can increase the ability of the human limb and/or treat weak muscles, joints, or skeletal parts [4, 9]. Also, these robots are used for auxiliary limbs in people with walking disabilities or the elderly and increasing power in healthy individuals [4]. An efficient exoskeleton robot with a proper structure should show the same dynamic behavior as a human limb. The ideal situation cannot be provided for many reasons such as the quality of the motor and sensors used, and structures formed during the design phase. The degree of freedom of an exoskeleton robot must be equal to the degree of freedom of the limb to be used so that it must compensate for movements in the respective axes. The normal joint opening of the human limb for movements should be provided by the robot, and if the robot has more than the required joint opening, this dangerous situation must be prevented with necessary restrictions [8]. The mass of a robot arm will change the arm's controllability inertia and dynamic behaviors such as efficiency. It provides the necessity of optimization of the robot arm [22]. Exoskeleton robots also have less effective but easier to use structures. These technologies, called passive exoskeleton robots, are lighter than robots with sensors and actuators, and there are no control mechanisms. It has been developed to support workshop employees [7]. Active exoskeleton robots are developing day by day with the development of used motion algorithms, motors, drivers, and other equipment, structures that are faster, more capable, self-learning, and closest to human anatomy [11]. Exoskeleton robots are very complex because they have direct interactions with the user's limb and are very difficult to model. Even if the dynamics of the exoskeleton are known, the dynamics of the human limb are not typically known and are largely variable from one person to another [11]. The human body consists of 2 main limbs. These are the lower limb, which deals with the legs and feet, and the upper limb that takes the human arm and body. These robots can be grouped as therapeutic systems and motion support systems according to their usage. While therapeutic systems are generally used in physical therapy centers, motion support systems are designed for a single user so that the patient can perform the necessary activities in daily life [8].

Since the use of upper limbs is very intense in daily life, people's quality of life is negatively affected when any discomfort occurs in this area. Cerebrovascular and neuromuscular diseases are increasing in parallel with the increasing age average in the world. Rehabilitation robots are also important for physiotherapy of patients who lose their limb motor skills due to these diseases. The use of these robots shortens the treatment process and provides the opportunity for treatment to more patients. Also, rehabilitation robots can make movements accurate and repeatable. One of the important application areas of biomechanics is exoskeleton robots [8].

The most common analysis is the daily life activities used in the construction of exoskeleton robots. Thanks to this analysis, the limits of force and movement that the wearable exoskeleton robot can produce are determined. These robots can perform 10 to 15 N of power and free daily life activities [12]. The upper extremity robotic devices can generally be divided into two types: prosthesis and orthosis. The prosthesis is an artificial substitute that can be worn instead of a missing body part. The orthosis is an orthopedic device that can be used to support and correct a person's deformities or increase the functionality of the moving parts of the body [13].

In this study, a robot arm design suitable for wearing and with increased mobility was designed for individuals with discomfort in the upper limb arm muscles and/or loss of strength. The design utilizes an angular servo motor for wrist movement, an angular servo motor for elbow movement, and two linear servo motors for shoulder movements. The point that the system supports is the waist and back of the user (without forcing the user). A computer-aided design (3D software) program was used to make the design and necessary analyzes. Movement and speed restrictions suitable for the human body are considered in the design. Movement capabilities, positions, and speeds of the designed mechanism have been tried to be determined by using kinematic analysis. The force and speed data of the motors have been calculated for the determining speeds and loading conditions. The main carrier parts of the mechanism are designed to be produced from 5mm thick aluminum alloy. For the highest loading condition of the mechanism, the most critical part of the whole was determined using the finite element method. Also, the safety coefficient and maximum deformation rate of this piece were determined by the Von Mises criterion.

2. Robot Arm Design and Analysis

2.1. Robot Arm Design

Robot arm systems can be made in different types according to the complexity of the worksites and the difficulty of the work to be done. Depending on the situation of the business areas, the features can be increased by adding special joints and connections to cartesian, cylindrical, spherical, and articulated type robot systems [14].

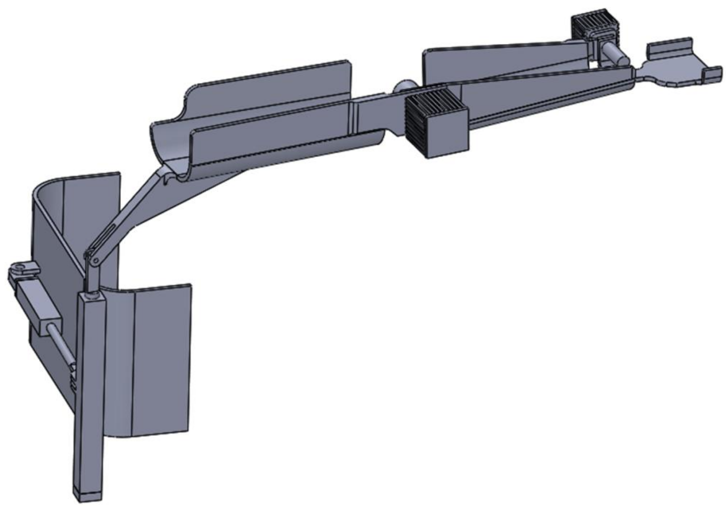

Figure 1. Upper limb robot arm mechanism

Exoskeleton robot arms are also determined according to the needs of the system to be worked on. There are robot arms that can move in only one direction, as well as robot arms that can move in many directions [3]. In this study, a robot arm was designed to assist the arm and support the treatment in individuals with muscle discomfort, weakness in the arm, or non-arm muscle function. SolidWorks 3D design software was used in designing the upper limb robot arm and making the necessary analyzes. The material of the upper limb robot arm is designated as an aluminum alloy Al 2024 (due to its specific head [15]). The designed upper limb robot arm mechanism is shown in Figure 1.

2.2. Motion Analysis

The dynamic behavior of structures under the influence of movements and loads is very important for the analysis of mechanisms [16]. Movement (position) analysis of the upper limb robot arm mechanism was made by handling the parts that make up the system separately. The robot arm is designed with upper support and an adjustable top. Movement of the robot arm is provided based on the joints of the human arm. The movement was carried out with the help of the servo motors placed in the 3 joint areas in the upper limb. Angular servo motors are added to the wrist and elbow, and two linear servo motors are added to the shoulder. The motion analyses of the mechanism have also been tested with the SolidWorks program. Movement and rotation angles of the wrist, elbow, arm, which should be compatible with the human body, were calculated, and necessary restrictions were made. The rotation angles of the upper limb robot arm system in the wrist, elbow, and shoulder joints are given in Figure 2. In the design, the angle of the wrist is given at an angle value like that of the human wrist motion. The back movement of the wrist of a healthy individual was found to be within the range of ± 70°-80° without difficulty, and the wrist movement of the mechanism was limited to ± 70° (Figure 2a). Movement is provided by an angular servo motor placed on the wrist joint.

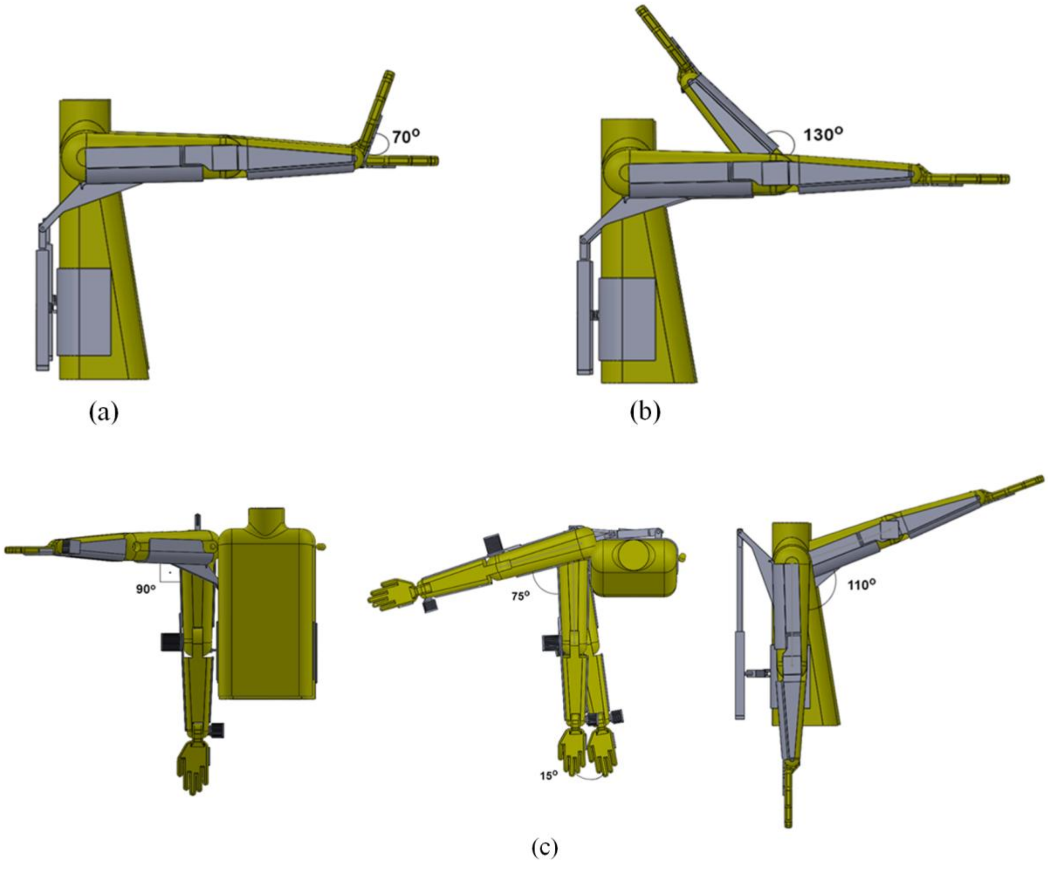

Figure 2. Robot arm mechanism positions and angle limitations a) wrist, b) elbow and c) shoulder

In the study, a servo motor was placed in the elbow joint of the system and the angular motion was provided with this motor. The ability to move the elbow motion at an angle between 0°-130° with the horizontal was limited. The movement and angle value of the mechanism is shown in Figure 2b.

The human shoulder joint has a rotating structure. Two linear motors are attached to the shoulder of the exoskeleton robot arm to provide a 2-axis movement. Thanks to this engine, the person's arm will gain 2-axis mobility both horizontally and vertically. Movement angles of the system in the shoulder joint are shown in Figure 2c. In the shoulder joint, the vertical movement angle of the arm on the side surface is limited to 90°, the horizontal angles of the shoulder movement are limited to 15° in the negative direction and 75° in the positive direction. The maximum angle of the vertical movement of the designed system on the obverse is determined to be 110°.

Servo motors are used in dynamic load and speed change, positioning, periodic operation, high stability requirements. Synchronous motors with permanent magnets in the rotor, controlled by modern electronic drives. Since there are no commentators and brush elements like in direct current (DC) servo motors, they are manufactured in reliable, stable, and small dimensions. With the sinus-shaped current applied to the three-phase windings, a rotating field is created in the air gap [11]. The angular movements that should occur on the shoulder part of the exoskeleton robot arm are provided with the help of 2 linear motors and the necessary joint. A linear motor is an electrical machine that gives the rotor the ability to move on the linear axis through the push and pull forces created by the magnetic field effect. The forces created by the correct polarization of the coils in the structure and the correct placement of permanent magnet materials, if any, are the same as in the rotating motor structure. The linear motor can be considered as a rotary motor with an infinite radius [17]. Performance and efficiency are an important concept in exoskeleton robots. To achieve optimum performance in exoskeleton robots, exoskeleton robots should be created not only in shape but also in an anthropomorphic and ergonomic structure. The state of common positions of human movements and the distribution of degrees should be examined and created according to the data obtained. The number of actuators and sensors should be high enough. Despite that, the cost of movement of more active exoskeleton robots should below. The length of the limbs in the exoskeleton should be adjustable. The sizing should be adjusted over a wide range so that it is suitable for use by individuals with different physical characteristics. The outer skeleton must be firm and light. A metal exoskeleton structure should be able to support heavy loads. The exoskeleton robot must have a fixed control mechanism. The energy of the robot should be long-lasting and self-rechargeable [18]. In the design to be made, it should be able to meet the speed and torque requirements and enable data to be retrieved when needed. It must be in a structure that will not harm the user in terms of mechanical and electrical risks and must provide the necessary safety conditions [19]. Besides, effective control strategies are required for the exoskeleton to work in harmony with the human limb. Common strategies include position control and impedance control [20]. Control methods used in exoskeleton applications; external input signals can be used by the user. Required input signals for the controller; encoders, force sensors, pressure sensors, electromyography (EMG) sensors, accelerometers, etc. In many applications where many standard measuring elements as well as standard measuring elements are not enough, specially designed sensors are used to measure the required input signals [21]. EMG signals are an indicator of muscle activation and are measured using skin-bound electrodes on the muscles. Many studies have used EMG signals to control an exoskeleton [20]. While designing the robot arm, the nervous muscular system of the human body should be examined in detail. The material structure to be used when creating the robot arm, the actuator, and the sensor structure should be analyzed. When the user wears the wearable robot arm, he/she should be able to perform daily activities easily. Sensors and actuators should be selected appropriately for the purpose to be attached to the wearable robot arm for movement [21]. Developed exoskeleton systems should allow free movement when the robot does not need it [22].

A robot consists of joints that perform translation and rotation and parts that connect these joints [23]. The human upper limb consists of a total of 6 joints (excluding fingers). Three of them are in one arm and the other three are on the other arm. These joints (wrist, elbow, and shoulder) provide the movement of the human upper limb. Servo motors are placed in the wrist and elbow part of these joint parts of the wearable robot arm mechanism designed in the Solidworks program, and linear motors are placed in the shoulder region. The reason why a linear motor is preferred to the shoulder region is the human shoulder joint, thanks to its spherical structure, it can move in 3 axes simultaneously. The first movement is the angular movement made from left to right, on the axis parallel to the ground; the arm moves forward (flexion) and back (extension). In this way, the human arm can move a total of 120° towards 70-75° forward and 40-45° rearward [24]. The second movement is the rotation movement of the arm around its axis. This movement takes place up to 90° thanks to the spherical joint head. The third movement is the movement of the arm that moves from front to back on the axis parallel to the ground (abduction) and approach to the body. The human arm can open up to 120° in the shoulder joint and bring it closer to the body up to 15°. Limb-joint models are preferred during the biomechanical examination of the human body [4]. A robot arm consists of joints that are connected in series or parallel. The problems used to determine the position of the robot's endpoint to go by giving certain angles to each joint of the robot arm are called advanced kinematic problems. Conversely, the problems used in finding the angles that the joints must take for the endpoint of the robot arm to go to the desired location are called inverse kinematic problems [25]. For the robot arm to carry out daily life activities easily, wearability and kinematic compatibility should be made to these robots [26]. The deformation and residual vibration of the robot arm cause the positioning accuracy to decrease and the robot arm mass and moment of inertia affect its dynamic behavior, such as controllability and efficiency; Also, these factors often contradict each other. Therefore, the optimization of the design of the robot arms is becoming increasingly important.

Kinematic calculations are very important for the robot's mobility and motion analysis. With the robot kinematics, the speed, force, and acceleration analyses of the robot are obtained [23]. The internal structure of the designed system is shown in Figure 3.

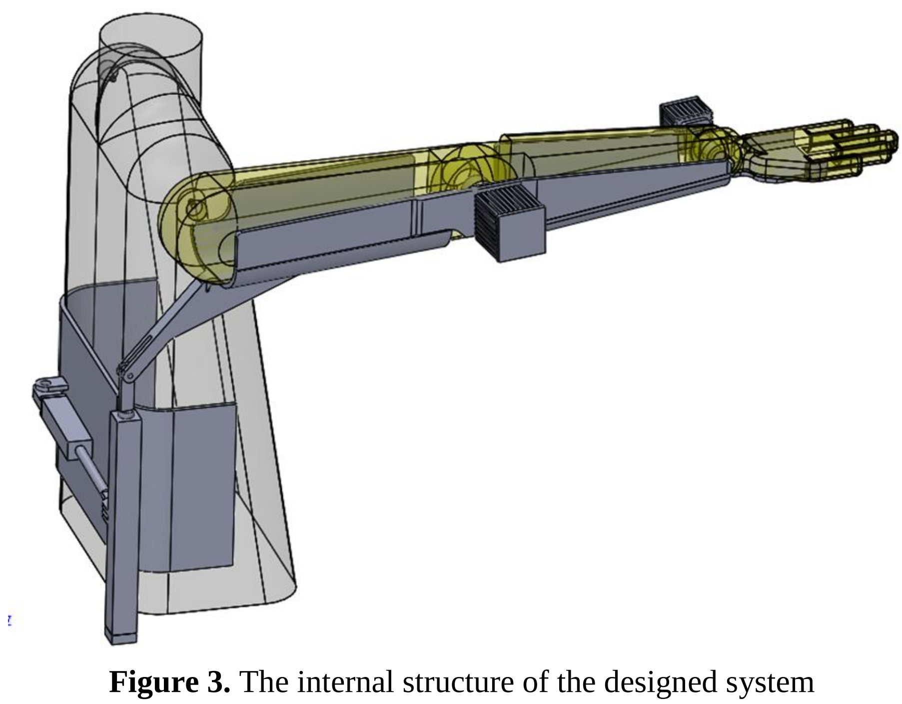

Figure 3. The internal structure of the designed system

To understand how a system behaves by considering its specific conditions, it is necessary to calculate the dynamic magnitudes of this system such as force, inertia, and energy. Forward kinematics of the robot; it deals with the relationship between the positions, speeds, and accelerations of the robotic ligaments. A robot is formed by connecting auxiliary parts to the main body with linear or rotating joints [23].

Most upper-limb exoskeletons have movements from the shoulder to the wrist joint. Multiple rotary joint robots can have configurations that cause a degree of freedom (DOF) reduction. This occurs in configurations where the axes of the two rotary joints are aligned with each other [20]. 3D motion analysis has been widely used to characterize the movement of the shoulder, elbow, and wrist in the upper extremity [13].

The force analysis of the upper limb robot arm mechanism has been done separately for the positions where we will obtain the highest loading status and highest torque values and for each joint. Torque (moment) values to joints will be obtained as a result of force analysis. According to these moment values, minimum torque values required for servo motors will be found. To operate the system safely, the motor torque value that will operate safely was calculated by multiplying the torque values obtained by the safety coefficient (1.5). In calculations, wrist joint; Point A, elbow joint; Point B, and shoulder joint are coded as point C. Also, some special abbreviations for these calculations are explained in detail below. Point A loading status is shown in Figure 4, the loading point B is shown in Figure 5, and point C loading status is shown in Figure 6.

- Wrist joint (point A) (Figure 4):

Me: hand mass (≈1 kg = 10 N), Mea: hand equipment mass (≈100 gr ≈ 1 N)

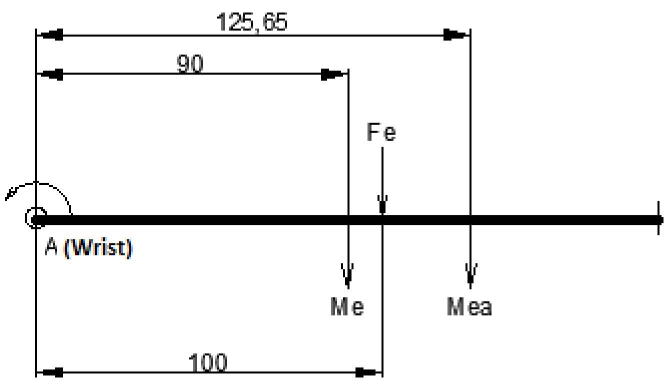

Figure 4. Point A loading status

$\sum TA = (Me \times 90\ mm) + (Fe \times 100\ mm) + (Mea \times 125.65\ mm)$

$\sum TA = (10\ N \times 0.09\ m) + (250\ N \times 0.1\ m) + (1\ N \times 0.12565\ m) = 26.02565\ Nm \approx 26\ Nm$

Safe torque value to be used in motor selection (for wrist): 39 Nm

- Elbow joint (point B) (Figure 5):

Mö: forearm mass (≈ 2 kg ≈ 20 N), Möa: forearm equipment mass (≈ 475 gr ≈ 4.75 N), Mem: wrist servo motor mass (≈ 385 g ≈ 3.85 N)

$\Sigma TB = (Mo \times 140\ mm) + (Moe \times 154.24\ mm) + (Mem \times 280\ mm) + (Ma \times (90\ mm + 280\ mm)) + (Fe \times (100\ mm + 280\ mm) + (Mea \times (125.65\ mm + 280\ mm)$

ΣTB= (20 N × 0.14 m) + (4.75 N × 0.15424 m) + (3.85 N × 0.28 m) + (10 N × 0.37 m) + (250 N × 0.38 m) + (1 N × 0.40565 m) = 103.71629 Nm ≈ 104 Nm

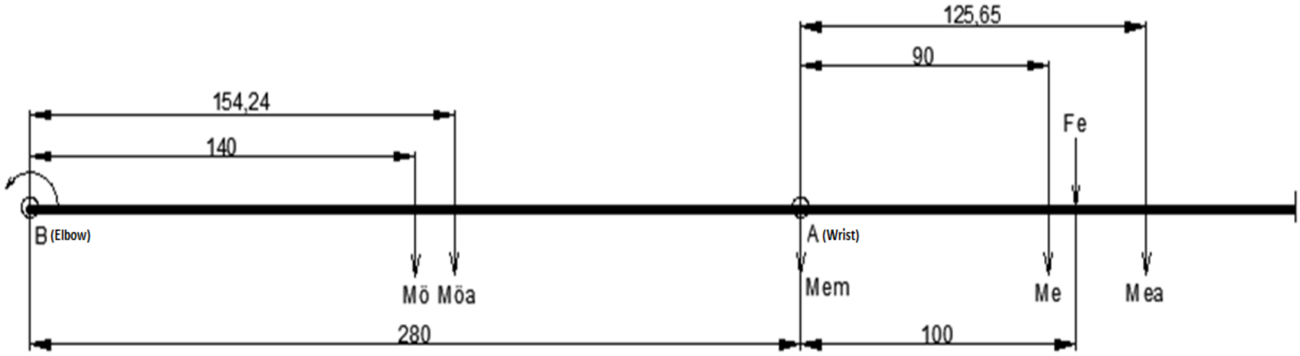

Figure 5. Point B loading status

Safety torque value to be used in motor selection (for elbow): 156 Nm

- Shoulder joint (point C) (Figure 6):

Mo: shoulder mass (≈3 kg ≈ 30 N), Moa: shoulder apparatus mass (≈830 gr ≈ 8.3 N), Mom: elbow motor mass (≈630 gr ≈ 6.3 N)

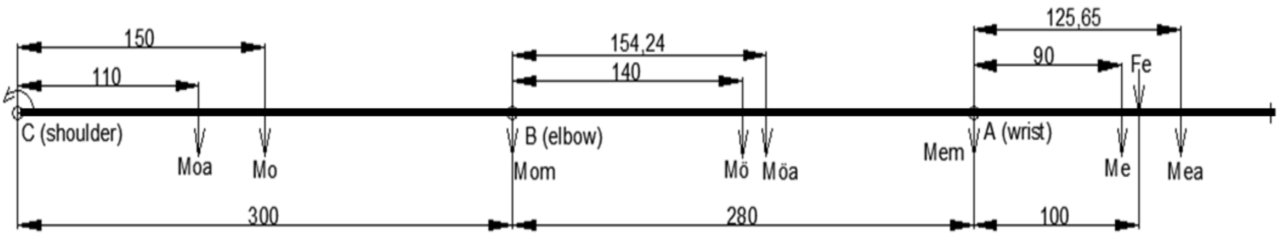

Figure 6. Point C loading status

ΣTC= (Moa × 110 mm) + (Mo × 150 mm) + (Mom × 300 mm) + (Mo × (300 mm + 140 mm) + (Moa × (300 mm + 154.24 mm) + (Mem × (300 mm + 280 mm) + (Me × (300 mm + 280 mm + 90 mm) + (Fe × (300 mm + 280 mm + 100 mm) + (Mea × (300 mm + 280 mm + 125.65 mm)

ΣTC= (8.3 N × 0.11 m) + (30 N × 0.15 m) + (6.3 N × 0.3 m) + (20 N × 0.44 m) + (4.75 N × 0.45424 m) + (3.85 N × 0.58 m) + (10 N × 0.67 m) + (250 N × 0.68 m) + (1 N × 0.70565 m)

ΣTC= 0.913 Nm + 4.5 Nm + 1.89 Nm + 8.8 Nm + 2.15764 Nm + 2.233 Nm + 6.7 Nm + 170 Nm + 0.70565 Nm = 197.89929 Nm ≈ 198 Nm

Safety torque value to be used in motors selection (for shoulder): 297 Nm

3. Finite Element Analysis

As a result of the position and torque analysis of the mechanism, finite element analysis was performed in the maximum loading state for each part that constitutes the mechanism. It is possible to predict the deformation that will occur on the part in advance for the maximum loading condition of the parts planned to be manufactured with the finite element method [27, 28]. In this context, it is necessary to design the parts to be produced first. It is necessary to determine which material the designed parts will be produced. If the material and/or design are not suitable for the maximum loading situation, necessary changes must be made. After entering the material, forced and support point data (areas and support points where the load will be applied) to the software, the network, and mesh structure required for the solution must be determined. The mesh structure is directly effective in achieving the closest correct result and solution time. The sparse mesh weave shortens the solution time and distances it from the correct result, whereas frequent mesh weave will waste a long time to find the correct result [27, 29]. In the study, the mesh size varying within the range of 0.5-2 mm was used with the Tetrahedral mesh structure (in the narrowed areas of the design, mesh structures are reduced to the extent predicted by the program). For design parts, plastic deformation is undesirables, but an elastic deformation is also expected in the loading state. The most commonly used equation for such part geometries of the designed mechanism is the general equation of Von Mises Criteria given in Equation 1.

$$\sigma_v = \sqrt{½\,[(\sigma_{11}-\sigma_{22})^2 + (\sigma_{22}-\sigma_{33})^2 + (\sigma_{33}-\sigma_{11})^2 + 6(\sigma_{23}^2 + \sigma_{31}^2 + \sigma_{12}^2)]} \quad (1)$$

The system consists of three main parts. These are the wrist section, arm section, and shoulder section. The safety coefficient was calculated for the most critical point of the part that will provide and support wrist movement for 250 N (≈25 kg) loading situations. The safety coefficient for the wrist motion was 2.39 and the maximum displacement was approximately 0.06 mm. The loading status and the maximum displacement point for this part, which provides the wrist movement, are shown in figure 7.

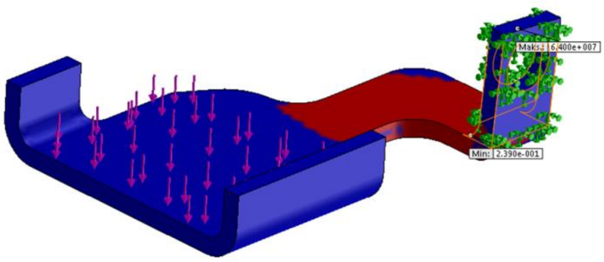

Figure 7. Loading status and maximum displacement point for the part that provides wrist movement

The second part of the designed upper limb robot arm system is the elbow (forearm) part. For the torque values (point B) obtained from the force analysis, the safety coefficient of the relevant design is calculated under 156 N load as 1.4 and the maximum displacement was ≈ 0.05 mm. The mesh structure and loading status of the part providing the forearm movement are shown in Figure 8.

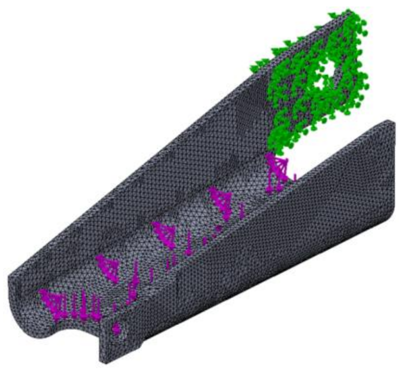

Figure 8. Mesh structure and loading status of the part that will make the elbow movement

As a result of the force analysis for the third part (for shoulder, figure 9) of the robotic arm system, the torque of 297 N was calculated. As a result of the effect of this torque value on the part performing the shoulder movement, the safety coefficient was calculated as 2.9 and the maximum displacement has been found.

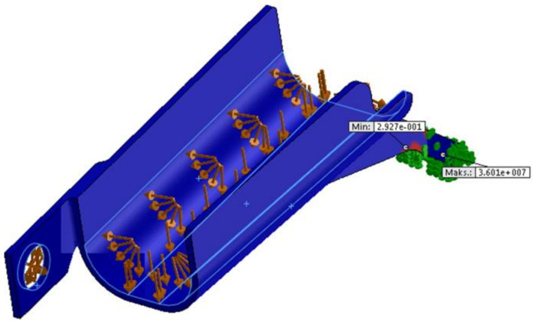

Figure 9. The mesh structure of the shoulder part

4. Conclusion and Suggestions

With the development of technology, robotic studies have gained speed day by day. Different studies have been carried out in many areas with robotic applications. There are possibilities to apply in many fields such as health, military, production, cybernetics. Automation systems, robotic arms, wearable exoskeleton robots, therapeutic robotics systems are some of the applications of robotics.

In this study, a wearable robot arm mechanism was designed for patients with discomfort in the upper limb. All the design elements that make up the mechanism were made in the 3D program. The robot arm is composed of 3 parts. Wrist part, arm part, and shoulder part have been designed and assembly separately. For the 3 joint zones in the human upper limb; two servo motors are used to give the wrist and elbow movement, and two linear servo motors are preferred to give the shoulder part mobility in three axes. Movement analysis of the design was made in computer-aided engineering software and after the necessary movement restrictions were made for the human body, the mobility of the wearable upper limb robot arm was determined. For the wrist part, this angle was calculated as 130° for the elbow part and 90° for the shoulder part (75-15°) and 110° for the vertical. Also, the linear motor stroke length is determined as 235 mm for the up and down movement of the shoulder and the stroke length of the linear motor used to rotate is 100 mm. The system was designed as a prototype. The system should be adjustable according to the patient's arm length and width.

The human body can be used as a model to increase the features of robot arm systems and gain new motion axes. Also, an electronic circuit can be added to the system for future work and the system can be operated autonomously. This upper limb robot arm system can be developed for other parts of the human body and can be used for physical therapy.

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