ÇUKUROVA UNIVERSITY
INSTITUTE OF NATURAL AND APPLIED SCIENCES

MSc. THESIS

MUSTAFA DAĞDELEN

DEVELOPMENT OF A CONCEPTUAL MODEL FOR WRIST AND FOREARM REHABILITATION ROBOT WITH TWO DEGREES OF FREEDOM

DEPARTMENT OF MECHANICAL ENGINEERING

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DEPARTMENT OF MECHANICAL ENGINEERING

We certify that the thesis titled above was reviewed and approved for the award of degree of the Master of Science by the board of jury on 22/06/2017.

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ABSTRACT

MSc THESIS

DEVELOPMENT OF A CONCEPTUAL MODEL FOR WRIST/FOREARM REHABILITATION ROBOT WITH TWO DEGREES OF FREEDOM

Mustafa DAĞDELEN

ÇUKUROVA UNIVERSITY
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People lose their ability to use their upper limbs (shoulder, elbow and wrist) or lower limbs (hip, knee and ankle) after a stroke, spinal cord injury or aging. These people need to follow rehabilitation exercises to recover their limb's lost movements. These rehabilitation activities consist of repetitive movement of affected limb which are predetermined by a physiotherapist. Because of the problems in the physiotherapist based rehabilitation processes, robotic systems are referred nowadays since these systems are well suited for repetitive and task based operations. In this thesis, three conceptual wrist/forearm rehabilitation robots are designed in a CAD program and each conceptual model is evaluated according to their degrees of freedom, ranges of motions and compatibility for wrist/forearm rehabilitation processes. One of the concept models is selected as the most suitable for rehabilitation activities and it is prototyped. Required tests are applied to check the compatibility of the design for rehabilitation activities.

Key Words: Robot, Rehabilitation, Upper Limb, Wrist, Forearm, Stroke, Control

ÖZ

YÜKSEK LİSANS TEZİ

İKİ SERBESTLİK DERECELİ BİLEK VE ÖN KOL REHABİLİTASYON ROBOTUNUN KONSEPT TASARIMININ GELİŞTİRİLMESİ

Mustafa DAĞDELEN

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İnsanlar felç, omurilik hasarı ve yaşlanma sonucunda üst hareket (omuz, dirsek ve bilek) ya da alt hareket (kalça, diz ve ayak bileği) uzuvlarını kullanma kabiliyetini kaybederler. Bu insanlar uzuvlarının eksik olan hareketlerini geri kazanmak için rehabilitasyon aktivitelerini takip etmek durumundadırlar. Bu rehabilitasyon aktiviteleri, fizyoterapist tarafından önceden belirlenen, etkilenen uzvun tekrarlı hareketlerini içermektedir. Fizyoterapist tabanlı rehabilitasyonlardaki problemlerden dolayı, bugünlerde robotik sistemler tercih edilmektedir çünkü bu sistemler tekrarlı ve hedef odaklı operasyonlara gayet uygunlardır. Bu tezde, üç adet bilek/ön kol rehabilitasyon robotunun konsept modeli bir CAD programında tasarlanmış ve her bir konsept model serbestlik derecesi, hareket kabiliyeti ve bilek/ön kol rehabilitasyon işlemlerine uygunluğuna göre değerlendirilmişlerdir. Konsept modellerden bir tanesi bilek/ön kol rehabilitasyon aktivitelerine en uygun olarak seçilmiş ve prototip üretimi yapılmıştır. Rehabilitasyon aktivitelerine uyguluğunu kontrol etmek için gerekli testler yapılmıştır.

Anahtar Kelimeler: Robot, Rehabilitasyon, Üst Uzuv, Bilek, Ön Kol, Felç, Kontrol

EXPANDED ABSTRACT

Rehabilitation is a process applied after a stroke, spinal cord injury or lost limb functions such as aging of people. The patients suffering from these kinds of illnesses are increasing since the population of the world grows. The rehabilitation exercises include repetitive movements predefined by the well-educated physiotherapist. However, the scientists and researchers started to develop new ideas and solutions to the problems in standard physiotherapist based rehabilitation. These problems can be defined as insufficient number of physiotherapist, exhausting of physiotherapist due to the working conditions during a day and inconsistency in the exercises. Then, robots are utilized for rehabilitation exercises since the robots are not only suited for repetitive and long-term movements but also provide many kinematic (position, velocity and acceleration) and dynamic (force and torque) sensory information to the user. The scientists designed new rehabilitation robots and suitable control algorithms either for upper limb (shoulder, elbow, wrist) or lower limb (hip, knee, ankle) of human body.

In literature, many rehabilitation robots are designed with different kind of mechanism type, actuator system and control algorithm for proximal joints (shoulder, elbow, hip, knee) while the distal joints (wrist, ankle) remained passive. This study aims at developing an alternative upper limb rehabilitation robot for distal upper limb (wrist and forearm) since the distal joints should be actuated for an efficient upper limb function recovery.

Rehabilitation of wrist and forearm requires three motions to exercise as wrist flexion/extension, wrist radial/ulnar deviation and forearm pronation/ supination. Each robot joint axis should be consistent with patient’s wrist and forearm joint axis. The designed robot should also satisfy enough range for the natural human movements. Last requirement for this study is that robot should enable both passive and active exercises on the robot. In passive mode, the patient

applies a force whereas in active mode the robot applies force and torque to the joints. Therefore, these requirements are taken as reference for this study.

A 2 DOF pneumatically actuated wrist/forearm rehabilitation robot (both passive and active) and its evaluation of conceptual designs is shown in this study. Firstly, three conceptual models are designed and each of them is evaluated according to their compatibility for rehabilitation exercises by investigating their kinematic definitions, range of motions and singularity conditions. It is decided that, the third conceptual model is the most suitable one and named as *CWRR* implying that Çukurova Wrist Rehabilitation Robot. The model is prototyped in mechanical engineering laboratory.

In this study, pneumatic actuation is selected as actuator system. There are different kinds of actuation used in rehabilitation robots as electric actuation, hydraulic actuation, pneumatic artificial muscle (PAM), serial elastic actuator (SEA). However, the pneumatic actuation has high power to weight ratio and the power source, air, is atmospheric air which does not contaminate the environment. Also, the designed robot can be easily used in hospitals since there are pneumatic lines available in these environments. For the pneumatic actuation of the system, one rodless pneumatic cylinder which have 250mm stroke and 25mm piston diameter is selected. This cylinder provides wrist flexion/extension and wrist radial/ulnar deviation movements. On the other hand, one semi-rotary pneumatic actuator which has 270^{o} rotation capacity provides forearm pronation/supination movement.

Gear drive and direct drive method are applied as a transmission method. A rack and pinion gear set is used for wrist movements and direct drive method is applied at the forearm joints. The gear drive in the wrist movements reduced the speed and required enough torque for wrist movements.

The control algorithm is the most important part of a rehabilitation robot. There are different types of control algorithms existing in the literature such as admittance control, impedance control, assistive control, challenge-based control

etc. and these control algorithms are complex. In this study, a simple and low level on-off position control approach is applied to cover predefined angles (wrist angle θ_1 and forearm angle θ_2). Arduino microcontroller board which provides analogue and digital inputs/outputs is used. Also, a 4-way $5V$ DC relay card is used to switch the solenoid valves by the signals coming from Arduino. The $24V$ DC exhaust centre solenoid valves are used for the directional control of pneumatic actuators.

The prototype of concept design III, *CWRR*, is manufactured by using different kind of materials and production methods. The tests are applied and human movements are compared with robot's movement in each movement. The advantage and disadvantage of the design are determined after the tests. As a disadvantage, the pneumatic systems are well suited for high speed operations. When the working speed is reduced dramatically, the actuators cannot provide motions. Therefore, a gearbox is supplemented to operate the robot at high speeds. Also, more sensors can be mounted on the robot to sense force and speed during motions and new and efficient control algorithms can be developed by this way.

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LIST OF ABBREVIATIONS

ADL	: Activities of daily living
ROM	: Range of motion
PBR	: Physiotherapist based rehabilitation
RBR	: Robot based rehabilitation
DH	: Denavit-Hartenberg
DOF	: Degree of freedom
W. E.	: Wrist extension
W. F.	: Wrist flexion
W.R. D.	: Wrist radial deviation
W.U. D.	: Wrist ulnar deviation
F. S.	: Forearm supination
F. P.	: Forearm pronation
V	: Voltage (V)
DC	: Direct Current
A	: Ampere (A)
F	: Force (N)
T	: Torque (Nm)
D	: Piston diameter of linear cylinder (mm)
r	: Pitch radius of spur gear (mm)
A	: Effective area of the linear cylinder (mm^2)
s	: Linear actuator displacement (mm)
y	: Range of motion of linear actuator(mm)

1. INTRODUCTION

People lose their ability to use their limb's after a stroke, heart attack or injuries. These injuries can be classified as complete injury which means a complete loss in muscle power and sensation, or incomplete injury meaning some signals still have chance to pass through the injured region of the spinal cord. The majority of the causes can be traumatic events such as falls, sport injuries, accidents or other events such as infection, tumours which are defined as no traumatic. One of the most common disability, paralysis or hemi paralysis, is seen in stroke patients as well as spinal cord injury (SCI) patients. In paralysis, some parts of the body cannot be controlled or become weak. As a result of the paralysis, the face, arm, leg or entire body can be affected. Normally stroke patients are over 65 years old, but young people and even children can be affected from stroke. In Turkey, approximately 200,000 people become a stroke patient every year[1]. According to the worldwide statistics, every year approximately 15 million people suffer from stroke. Nearly 6 million of this amount die and another 5 million are permanently disabled[2].

As a result, both stroke survivors and SCI patients will need an ongoing rehabilitation process to gain some sort of the movement functions or to prevent another stroke or injury possibilities in their life. These can take weeks, months and even years after disability. Therefore, the physical rehabilitation for stroke or SCI patients is the most important process to regain their limb functions.

There are also adverse side effects of paralysis patients to the society because they are not capable of achieving activities of daily living (ADL) such as going to restroom, eating, walking, sitting, standing etc. Hence, at least one person

[1] https://www.memorial.com.tr/saglik-rehberleri/inme-hakkinda-bilinmesi-gerekenler/ (accessed by March,2017)
[2] http://www.world-heart-federation.org/cardiovascular-health/stroke/ (accessed by March,2017)

is occupied by taking care of a single patient. The need and importance of the rehabilitation processes might be clearly visualised considering the amount of time, effort, moral issues as well as any useful work that can be done by either patient or care givers. Also, it should be noted that, physical rehabilitation exercises for motor recovery in the patient's neural system are very tedious, repetitive, laborious and applied an extended period of time. Therefore, the nature of physical rehabilitation is very costly.

One of the most effective physical rehabilitation exercises is task oriented training[3] which can be categorized into two different types: physiotherapist based rehabilitation (PBR) and robot based rehabilitation (RBR). The PBR exercises are performed in the control of responsible physiotherapist. However, as the population grows all around the world, the physiotherapists cannot offer sufficient service for all stroke patients and, a physiotherapist cannot offer the same level of performance to each patient because of the nature of human performance and exercise conditions during a day. The problem can be solved by introducing robots into the rehabilitation therapies by applying RBR because robots are well suited for repetitive, long term tasks which require accuracy at the same time. The robotic systems do also offer advantages of keeping records of sensory information such as position, velocity, force and torque values obtained during the physiotherapy exercises. The obtained information can be used to develop new therapy methods and new control algorithms.

In the literature, studies on rehabilitation robots for shoulder and elbow are generally found. In these robot designs, other distal joints such as forearm and wrist remained passive joints which are not actuated actively. On the other hand, the effect of the rehabilitation of distal limbs such as wrist and forearm on the rehabilitation of other proximal limbs has a direct relationship as noted by Krebs

[3] http://www.strokengine.ca/intervention/task-oriented-training-upper-extremity/ (accessed by March, 2017)

et.al (2007). The vital role undertaken by the wrist and forearm rehabilitation requires robot design for that purpose urgently which is the objective of this study.

The general robot design criterion starts with satisfying sufficient mobility and range of motions practiced in rehabilitation exercises as well as normal human activities of daily living. Wrist normally has 2 DOF as wrist flexion (W.F.), wrist extension (W.E.) and wrist radial (W.R.D.), wrist ulnar deviation (W.U.D.). Forearm, which is not a part of wrist, has 1 DOF that is named as forearm pronation (F.P.), forearm supination (F.S.). All of them add up to 3 DOF and they have their own limited range of motions.

In this study, we aim to design a stationary, exoskeleton based, wrist and forearm rehabilitation robot to meet all 3degrees of freedom that works in the human wrist/forearm ranges of motions (ROM). Therefore, we developed three conceptual designs and evaluated all of them for compatibility with the rehabilitation exercises. One of the conceptual designs is selected to be prototyped and named as Cukurova Wrist Rehabilitation Robot (*CWRR*).

Even though, there are several alternatives for actuation methods such as hydraulic and electric actuators, the pneumatic actuation is selected. Pneumatic and hydraulic actuators have higher power to weight ratio than electric actuators. But, the hydraulic actuators have some limitations such as leakage and weight. Therefore, we decided to use pneumatic actuation in our system because air leakage is not contaminant. The gear drive is selected for wrist motions and direct drive actuation is used in forearm motions.

Therapy methods can be categorized into two methods as active and passive exercise. Therefore, the designed robot should offer both active and passive therapy modes. In the passive exercise mode (i.e., robot active mode), the robot moves the joints of patient’s limb. In the active exercise mode (i.e., robot passive mode), actuators of the robot are deactivated and patient tries to move her/his limbs by her/his own effort against robot’s resistance to the movement. Robot control is

achieved by position control. The obtained position information is recorded in computer. Hence, the progress of the patient can be tracked by this way.

The rehabilitation robots are generally very complex and expensive devices. For a wide application and reach of low-income people, an economic and cheap robot design is considered. In general, the available rehabilitation robots use electric actuators and complex control cards that are expensive. In this design, the number and size of the actuators are intended to be reduced. In addition, transmission types are selected for the best performance and suitable cost.

Our design has adjustable links (i.e., 2 passive DOFs) since the robot size should be configurable for different patients because they have varying hand and forearm sizes.

In the final step, the Denavit-Hartenberg (DH) notation is used for defining kinematics of all three conceptual designs. The obtained definitions are verified by simple geometric approach. A prototype of the selected conceptual design, *CWRR*, is manufactured in the mechanical engineering laboratory to check its performance and efficiency in rehabilitation therapies.

2. PRELIMINARY WORK

Rehabilitation robots available both commercially and academically can be divided into upper extremity and lower extremity rehabilitation robots in a broad sense. Upper extremity robots are used in rehabilitation of shoulder, elbow, wrist and forearm whereas lower extremity robots are used in rehabilitation of hip, knee and ankle. In this study, only the upper extremity robots are reviewed.

Another classification of the robots is whether it is exoskeleton based or end-effector based. The exoskeleton based robots are the ones which mirror the skeletal structure of the human body limb. These kind of rehabilitation robots are designed to attach to body limb of the patient. Each segment of the limb can be controlled and rehabilitated independently. The actuators and sensors are placed to the joint axes and the limb posture can be easily obtained in exoskeleton-based rehabilitation robots. In end-effector based robot, patient's limb contacts with the robot at the end-effector which is also called interface, and the patient's limb is moved by the movement of end-effector. These kind of robots have simple structures, they can be easily manufactured and they can be easily adjusted to fit different sized patients. Unlike exoskeleton based robots, the body limb of patient attaches to the robot at one single point. Because of this reason, it is very difficult to define the limb posture of the patient precisely and also each joint of the limb cannot be actuated independently i.e. forces and torques are applied at end-effector only.

The first exoskeleton robots are designed for human power amplification and military usage. The earliest exoskeleton device was a set of walking, jumping and running assisted mechanism shown in Fig. 2.1, designed in 1890 by a Russian named Nicolas Yagn[4]. This device used compressed gas bags to store energy that

[4] https://en.wikipedia.org/wiki/Powered_exoskeleton (accessed by March,2017)

would be used in actuation system, although it was passive in operation and required human power.

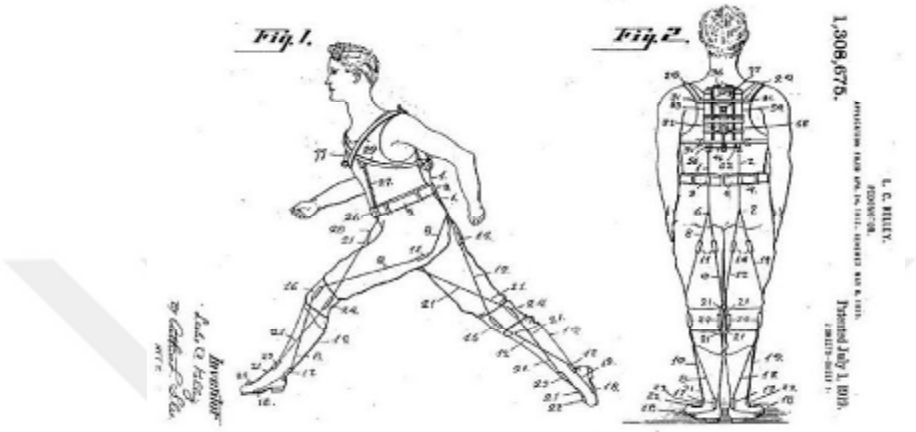


Figure 2. 1. First Exoskeleton (US Patent No:440684, the powered exoskeleton)

The first true exoskeleton was Hardiman[5] illustrated in Fig 2.2. This exoskeleton was co-developed by General Electric and United States Military in 1960s. The first experience with this exoskeleton robot pave the way for efficient interaction of humans and robots by exposing the main problems as: it was too heavy (i.e., 680 kg), it was actuated by hydraulic and electrical power system and it had a complex control algorithm. The control of the robot was based on master and slave approach which reduced the response time dramatically. Because of these reasons, the project was ceased.

[5] https://en.wikipedia.org/wiki/Hardiman (accessed by March, 2017)

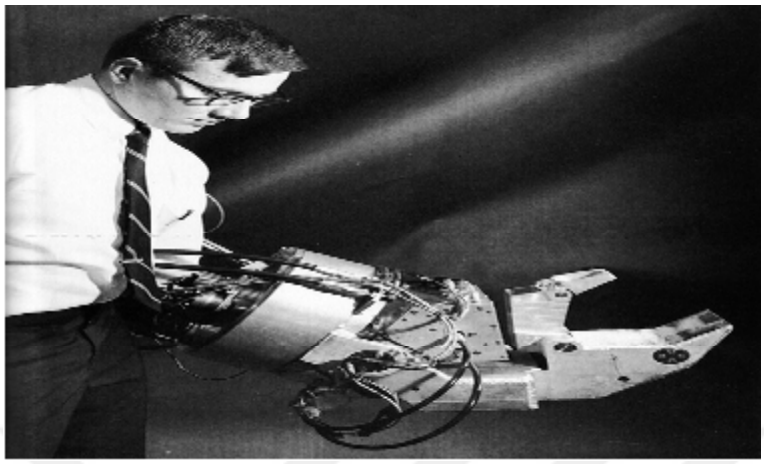


Figure 2. 2. Hardiman (General Electric Company, Hardiman Project, 1971)

In the upper extremity rehabilitation robots, studies focused on shoulder rehabilitation can be listed as MIT-MANUS (Krebs et al.,1998), MIME (Lum et al.,2005), Rupert (Balasubramanian et al., 2008), CADEN-7 (Perry et al., 2007). In these studies, MIT-MANUS requires a further discussion because it is the first developed robot for rehabilitation applied on shoulder and elbow. It is a planar robot, actuated electrically, and a parallel robot with 2 DOF. For wrist rehabilitation, a wrist module of MIT-MANUS (Fig. 2.3) is designed (Krebs et al., 2007). The wrist module is electrically actuated, serial type robot with 3 DOF. The module is capable of providing wrist radial/ulnar deviation, wrist flexion/extension, and forearm pronation/supination. The ranges of motions are $60^o/60^o$ for flexion/extension, $30^o/45^o$ for radial/ulnar deviation, and $70^o/70^o$ for pronation/supination. The robot torque outputs are sufficient to carry the patient's hand.



Figure 2. 3. The Wrist Module of MIT-MANUS (Krebs et. al., 2007)

O'Malley et. al. (2006) developed MAHI-EXO I which is a wrist and elbow rehabilitation robot. This rehabilitation robot has 5 DOF. The exoskeleton includes a revolute joint for elbow, a revolute joint for forearm, and three revolute-prismatic-spherical (RPS) joint for wrist movements. Since mechanism uses RPS joints, the wrist part is parallelogram. The elbow part and wrist part is connected in serial mode. The MAHI EXO I uses electrical actuators for their higher bandwidth property to control a large range of force magnitudes and frequencies. The exoskeleton uses cable drive transmissions at wrist and elbow movements, on the other hand forearm joint is direct drive actuated. This exoskeleton provides good range of motions as $90^o/0^o$ for elbow flexion/extension, $90^o/90^o$ for forearm pronation/supination, $45^o/45^o$ for wrist extension/flexion, $45^o/45^o$ for wrist radial/ulnar deviation and also torques transmitted to the joints are 55 *Nm*, 5.08 *Nm*, 5.26 *Nm*, 5.26 *Nm* respectively. This designed robot further improved by O'Malley et al. (Pehlivan et al., 2011) as MAHI-EXO II, illustrated in Fig. 2.4. The improved design eliminates singularity and backlash problems of MAHI-EXO I. The second design has higher torque outputs in the forearm and elbow joints as well as a passive DOF for shoulder abduction/adduction to align the mechanism with patient shoulder.

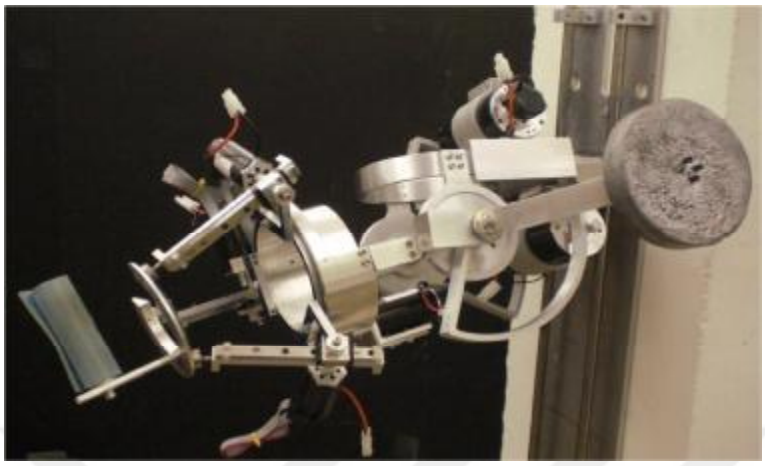


Figure 2. 4. The MAHI EXO II (O'Malley et. al., 2006)

RiceWrist developed by Gupta et. al. (2008) is also another wrist and forearm rehabilitation robot which is a modified form of MAHI exoskeleton. The robot is a force feedback wrist exoskeleton. RiceWrist is an electrically actuated device with 4 DOF. The robot uses parallelogram principle because of higher torques and higher stiffness as well as lower inertia compared to similar serial mechanisms. One of the freedoms corresponds to forearm motions as revolute joint and three of them are used for RPS (revolute-prismatic-spherical) joint for wrist motions. The robot uses direct drive actuation in forearm part and cable drive transmission in wrist motions. The workspace capability of the device is achieved fully in supination/pronation and radial/ulnar deviation as $90^o/90^o$ supination/pronation capability and $33^o/19^o$ for radial/ulnar deviation, but flexion/extension is achieved partially as $42^o/42^o$. The torque levels transmitted to the joints are same as MAHI EXO.

Parallel type mechanism in RiceWrist is converted to a serial type wrist/forearm rehabilitation robot by Pehlivan et al. (2012) as RiceWrist-S shown in Fig 2.5. Researchers aimed at improving workspace of the robot in the design of the robot. RiceWrist-S is a grounded, exoskeletal device which uses electrical actuators as well as cable drives for transmission to ensure back drivability and

zero backlash. The robot has 3 DOF and can execute three motions required for wrist and forearm rehabilitation. RiceWrist-S has good ranges of motions such as 180^o for forearm pronation/supination, 120^o for wrist flexion/extension and 70^o for wrist radial/ulnar deviation. These values are maximum span of angles carried out in the motion.

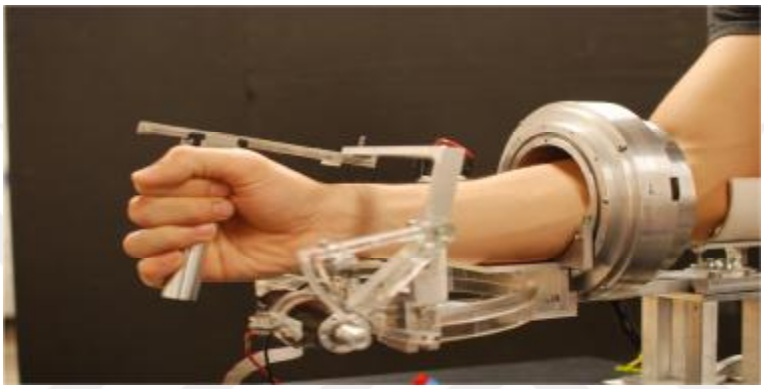


Figure 2. 5. The RiceWrist-S (Pehlivan et. al., 2012)

Another wrist rehabilitation robot, Wrist Gimbal (Fig. 2.6), available in literature is developed by Martinez et. al. (2013). It is cable driven and has 3 DOF for forearm supination/pronation, wrist flexion/extension, and wrist radial/ulnar deviation. In this robot, safety and robustness are considered firstly. The robustness and rigidity are provided by using two bearings at the end of each axis. The safety, on the other side, is achieved by hard stops for each axis, emergency button and software. In this rehabilitation robot, serial kinematic configuration is used because of its simplicity in the mechanical structure and facility in manufacturing. Wrist Gimbal uses a handle whose height can be adjusted passively since the wrist centre of motions should be aligned with the centres of the robot axes.

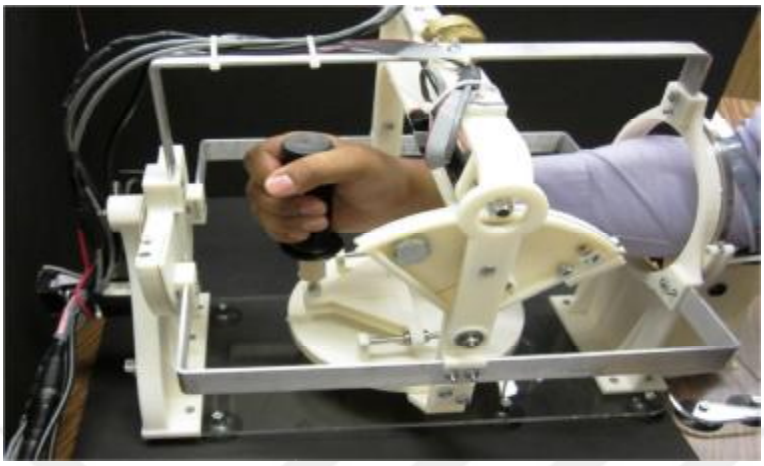


Figure 2. 6. Wrist Gimbal (Martinez et. al., 2013)

A pneumatically actuated forearm/wrist rehabilitation robot developed by Allington et. al. (2011) is Supinator Extender (SUE) shown in Fig. 2.7. SUE is designed to work with BONES exoskeleton robot (Klein et. al., 2008) and ArmeoSpring rehabilitation device[6]. SUE provides forearm pronation/supination motion and wrist flexion/extension movements. The pneumatic actuators are used in this robot for actuator's high power-to-weight ratio. The range of motion (ROM) of each movement is 90^{o} in SUE. The pneumatic cylinders are mounted away from the human body to prevent any injury and provide larger workspace for the wrist and forearm.



Figure 2. 7. Supinator Extender- SUE (Allington et. al., 2011)

[6] https://www.hocoma.com/us/solutions/armeo-spring/ (accessed by March, 2017)

Another interesting wrist and forearm rehabilitation robot published is W-EXOS (Fig. 2.8) developed by Gopura et. al. (2008). The main difference of W-EXOS from the others is that it has gear drive transmission. Electromyography (EMG) signals are used for the control of the robot. In general, it is electrically actuated, 3 DOF robot for forearm pronation/supination, wrist flexion/extension and wrist radial/ulnar deviation. The robot is exoskeleton based with serial type mechanism. The ranges of motions of the robot are $30^o/20^o$ for radial/ulnar deviation, $60^o/50^o$ for flexion/extension, $80^o/75^o$ for forearm pronation/supination, which are not fully achieving the normal ranges of motion of human. The maximum torques transmitted to the joints are 1.38 *Nm*, 1.38 *Nm* and 8.1 *Nm* for flexion/extension, radial/ulnar deviation and supination/pronation, respectively.

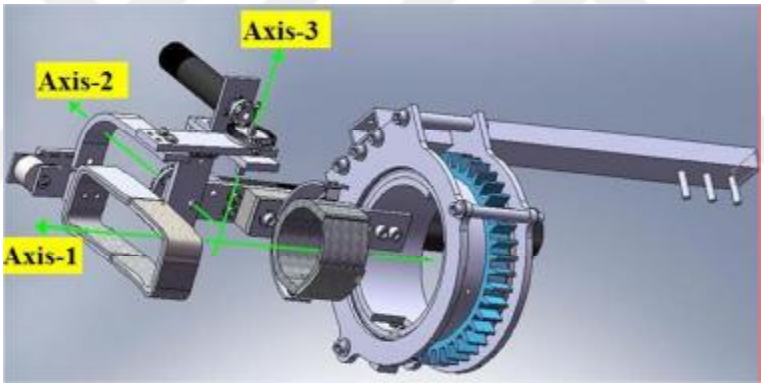


Figure 2. 8. W-EXOS (Gopura et. al., 2008)

ITT-Wrist (Masia et. al., 2009) shown in Fig. 2.9 is a wrist and forearm rehabilitation robot developed for extended range of motions, back drivability of the system in order to have natural haptic interaction, very low friction and inertia, mechanical robustness and lastly an open programing environment. ITT-Wrist is electrically actuated, serial type robot with 3 DOF for forearm pronation/supination, wrist flexion/extension and wrist radial/ulnar deviation. These motions have $80^o/80^o$, $70^o/70^o$ and $35^o/35^o$ range of motions respectively.

The torques applied to joints in this robot is 5.18 *Nm* for forearm movements, 1.85 *Nm* for flexion/extension and 2.24 *Nm* for radial/ulnar deviation.

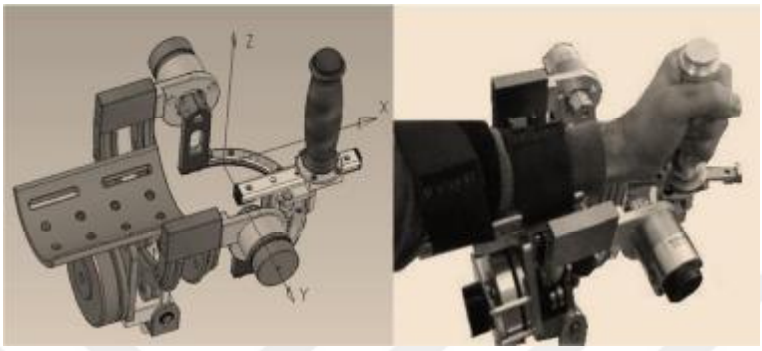


Figure 2. 9. ITT-Wrist (Masia et. al., 2009)

Oblak et. al. (2009) introduces a different type of design in the name of Universal Haptic Device (UHD) illustrated in Fig. 2.10. One of the differences is that the robot provides haptic environment and has 2 DOF, but can make three motions for forearm supination/pronation, wrist flexion/extension and wrist radial/ulnar deviation. The robot has a mechanical structure such that the user can select either the “ARM” or “WRIST” mode to which limb to rehabilitate. The other difference is that the series elastic actuators (SEA) are used.



Figure 2. 10. UHD (Oblak et. al., 2009)

DULEX (Kim et al., 2010) and DULEX-II (Bae et al., 2012) are wrist and finger rehabilitation robots actuated by both pneumatically and electrically. The first one uses pneumatic muscles whereas the second one (Fig. 2.11) uses double acting pneumatic cylinder. In both designs, finger motions are achieved by two linear electric motors. The mechanism structure of the robots is formed of two sections as wrist section and finger section. The wrist section is composed of 3-bar links and the wrist angle is manipulated with the length of the pneumatic cylinder whereas the finger section is consisting of parallel mechanism and has 90^{o} range of motion.

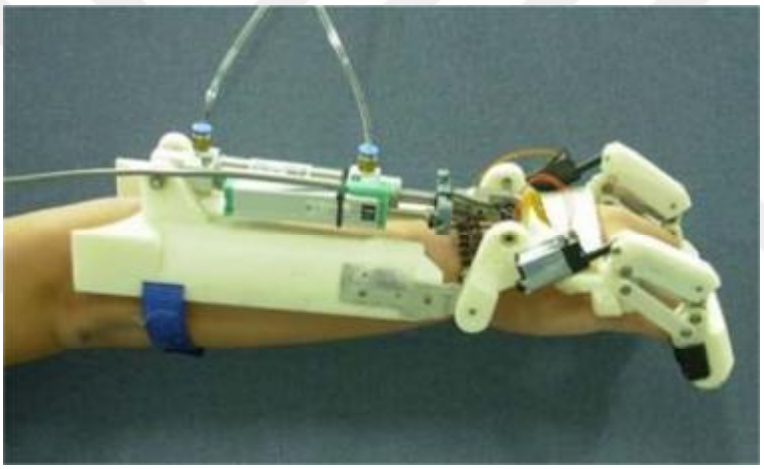


Figure 2. 11. DULEX-II (Bae et. al., 2012)

CRAMER which is Closed-chain Robot for Assisting in Manual Exercise and Rehabilitation and shown in Fig. 2.12 is introduced by Spencer et al. (2008). CRAMER was designed to rehabilitate the impaired patients with forearm and wrist motions. The robot has 3 DOF as wrist flexion/extension, wrist radial/ulnar deviation and forearm pronation/supination. The main advantage of this robot is its cost. The robot is very cheap because of parallel mechanism and off-the-shelf hobby servo motors usage. The robot is associated with a video game and the patient exercise with the robot with a game interface. The links are direct drive

actuated in this robot. Wrist actuation is done by controlling the position of handle of CRAMER with two guide rods. These guide rods are actuated by the hobby servomotors. The system contains a drawback that if the frictional forces created by the end of the handle that is sliding around the guide rods are large, the robot can be locked. The range of motions of the robot are $90^o/85^o$ for forearm pronation/supination, $10^o/15^o$ for wrist radial/ulnar deviation, and lastly $90^o/70^o$ for wrist flexion/extension. These values depend on the distance between the centre of a subjects' grip and the placement of the cuff on their wrist. On the other way, these values are below normal human forearm and wrist range of motions.

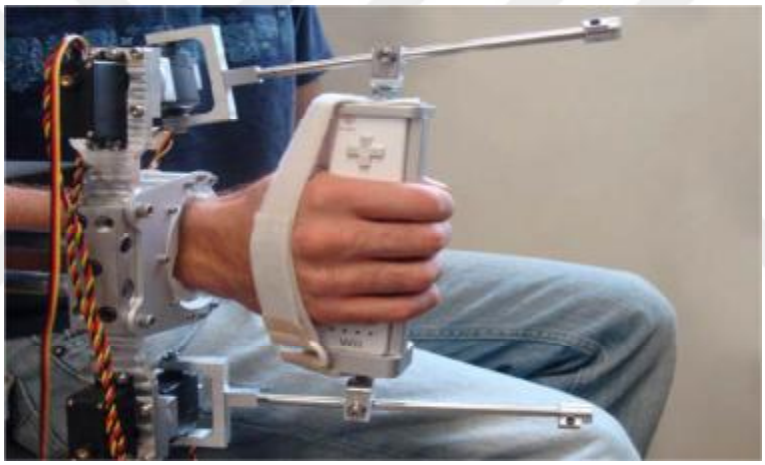


Figure 2. 12. CRAMER (Spencer et. al., 2008)

Hesse et. al. (2003) designed a grounded forearm and wrist rehabilitation device. The arm trainer illustrated in Fig 2.13, was designed to allow the bimanual practice of forearm and wrist. The device has 2 DOF as forearm pronation/supination and wrist flexion/extension. Electric motors are used as powering system in the device. The handles are used for connecting the patient's hand and the motor drive. The drives provide torques up to 5 *Nm*. Two handle sets are available one with a horizontal axis of rotation for forearm and one with a

vertical axis for the wrist movements. To switch movement direction, the device was tilted 90^{o} downward and the handles exchanged.

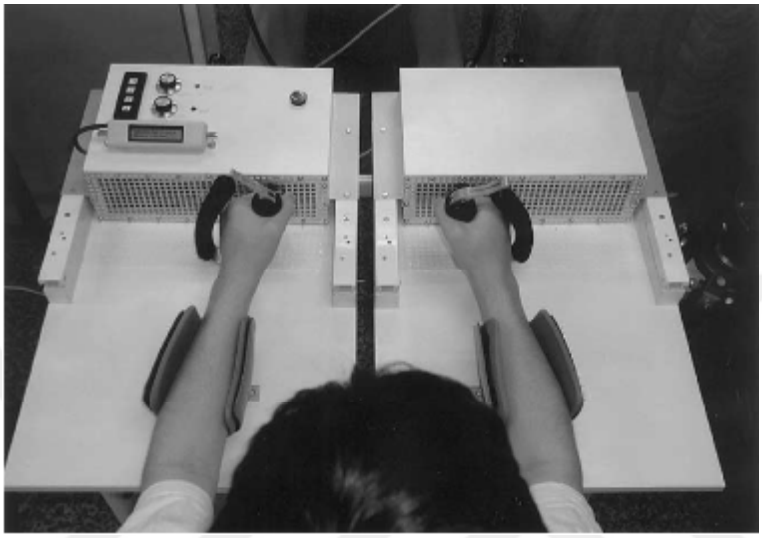


Figure 2. 13. Arm Trainer (Hesse et. al., 2003)

3.MATERIAL AND METHOD

Design of a wrist and forearm rehabilitation robot starts with identifying the design requirements at first (section 3.1.). A suitable mechanism selection of it follows in terms of robot types with developing kinematic parameters for further calculations in the developed robot designs (section 3.2.). Three conceptual designs are developed in section 3.3. The advantages and disadvantages of each design are evaluated to select optimum design. For the selected conceptual design, actuator alternatives are evaluated for efficient and economical solution in section 3.4. The control of the robot is discussed in section 3.5.

3.1. Design Requirements for Wrist Rehabilitation Robot

3.1.1. Wrist and Forearm Kinematics

Wrist and forearm which are the part of human upper limb have 2 DOF and 1 DOF, respectively. The wrist degrees of freedom correspond to wrist flexion /extension and wrist radial/ulnar deviation whereas forearm degree of freedom correspond to forearm pronation/supination.

Wrist flexion is defined as the motion of hand towards body when hand is kept at handshake position whereas the opposite of the motion is called as wrist extension. Wrist radial deviation is the motion of hand towards the body when the palm of the hand is looking downward whereas the opposite motion of the hand is called as wrist ulnar deviation. Forearm pronation is the rotation of the forearm towards the body side when the hand is in handshake position whereas the opposite motion of the hand is called as forearm supination. The range of motion for all these motions for a regular human is tabulated in Table 3.1.

Table 3.1. Range of Motion of Wrist and Forearm Motions[7]

Range of motion(ROM) of Forearm and Wrist	
Movement	**Range of**
Wrist Extension	70^o
Wrist Flexion	75^o
Wrist Radial Deviation	20^o
Wrist Ulnar Deviation	35^o
Forearm Supination	85^o
Forearm Pronation	70^o

The wrist's rotary motions have axes of rotation that pass through the capitate carpal bone shown in Fig. 3.1. The motions of wrist occur physically at four different axes. In other words, wrist flexion has axis of rotation different than wrist extension as well as wrist radial deviation's axis of rotation is different than wrist ulnar deviation's. However, wrist flexion/extension and forearm pronation/supination can be considered to have a common axis of rotation (Lo et al., 2012).

The human wrist and forearm sizes are the main input parameters in the mechanism design. Since different aged patients will work on this device, it should be adjustable to patients with varying hand sizes. In Table 3.2, hand dimensions, labelled as A, B, C, D, are collected from 13 different adults of different age/sex/weight etc. Of these adults, 2 are women and 11 are men. These parameters are shown in Fig. 3.2 and defined as:

- A is the distance from elbow to wrist rotation center
- B is the distance from wrist rotation center to palm center
- C is the palm width
- D is the human wrist diameter

[7] http://www.eatonhand.com/nor/nor002.htm (accessed by March, 2017)

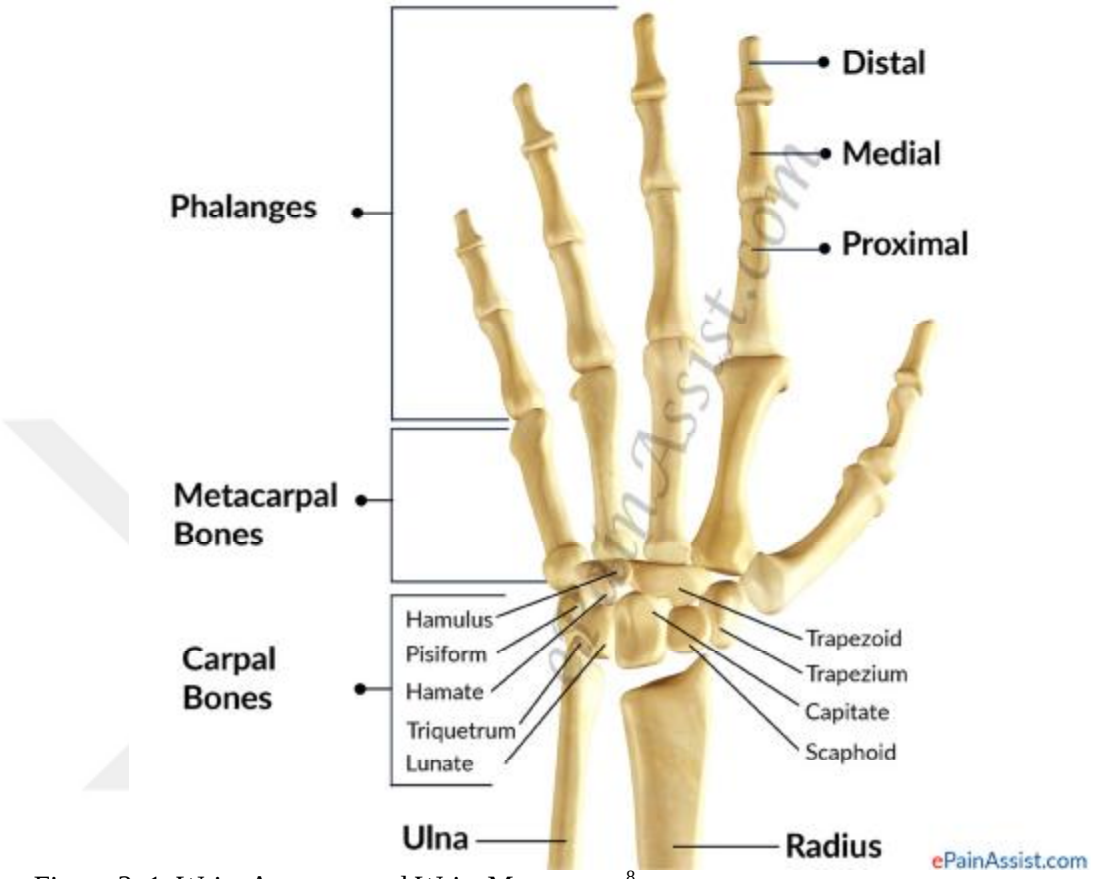


Figure 3. 1. Wrist Anatomy and Wrist Movements[8]

[8] https://www.epainassist.com/joint-pain/wrist-pain/wrist-joint-anatomy (accessed by March, 2017)

Table 3.2. Human Wrist and Forearm sizes in Turkey (M: man, W: woman)

Human Wrist and Forearm Sizes						
Participant No	***Age***	***Sex***	***A(mm)***	***B(mm)***	***C(mm)***	***D(mm)***
1	50	M	265	65	100	185
2	28	M	260	60	95	180
3	26	M	260	60	90	165
4	27	M	280	60	90	180
5	25	M	275	50	85	165
6	28	M	275	55	90	185
7	30	M	290	70	105	195
8	25	M	270	70	90	170
9	32	M	270	60	100	185
10	30	M	260	55	85	165
11	30	W	240	50	65	160
12	43	W	230	55	80	175
13	30	M	265	65	85	170

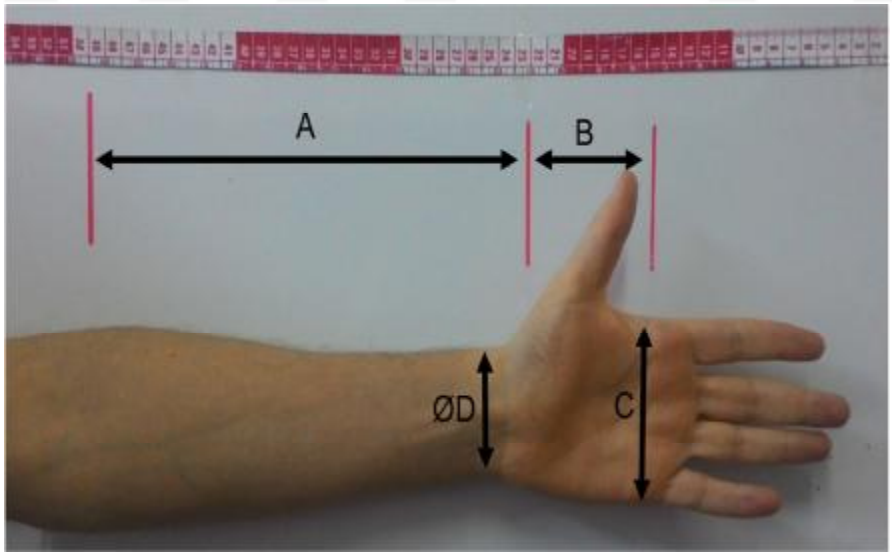


Figure 3. 2. Hand dimension parameters A, B, C, D (Hand of Mr. Dağdelen)

The minimum, maximum and average values are tabulated also in Table 3.3 in order to utilize in robot design.

Table 3. 3. Average, minimum and maximum values of dimensions

Size	*Average(mm)*	*Minimum(mm)*	*Maximum(mm)*
A	264,60	230	290
B	59,61	50	70
C	89,23	65	105
D	175,38	160	195

3.1.2. Force and Torque Requirements for Rehabilitation

The force and torque levels are another important criterion in rehabilitation robotics since the robot should satisfy enough forces to the actuated joints and overcome the resisting forces. These forces and torques depend on some parameters like moment of inertia (I) of robot links, mass properties (m) and joint friction which depends on the mechanical design of the robot as well as the parameters which depend on the resistance applied from patient to robot end-effector.

Torque output values of some wrist rehabilitation robots available in the literature are tabulated in Table 3.4. Listed robots are actuated electrically and provides constant torque output for the specified operating speed. In this table, human isometric torques at the wrist and forearm joints are also given (Tsagarakis et al., 1999).

Table 3. 4. The torque levels of the wrist robots in literature

Torque Levels	**W.F/W. E Torque(*Nm*)**	**W.R.D/W.U. D Torque(*Nm*)**	**F.P/F. S Torque(*Nm*)**
Human Isometric Torques	19.8	20.8	9.1
The Mahı Exo I	5.26	5.26	5.08
W-EXOS	1.38	1.38	8.10
ITT-Wrist	1.85	2.24	5.18

In this study, force and torque outputs in wrist motions of *CWRR* robot are calculated according to the formulations given in Eq.3.1, 3.2 and 3.3 since the pneumatic actuation will be used. The advantage of pneumatic actuation is that different torque outputs can be obtained at various speeds by changing the air pressure as well as air flow rate. In these equations, D is the piston diameter of rodless pneumatic actuator, A is the effective surface area of the piston, $P_{working}$ is the operating pressure of the air, F is the pneumatic cylinder force produced, r is the pitch radius of pinion in the gear set and finally T is the torque produced on axis of wrist movements. On the other side, torque outputs of forearm motions will be directly equal to the semi rotary actuator torque output since no transmission element exist (i.e., direct drive actuation).

$$A = \frac{\pi * D^2}{4} \qquad (m^2) \tag{3.1}$$

$$F = P_{working} * A \quad (N) \tag{3.2}$$

$$T = F * r \qquad (Nm) \tag{3.3}$$

3.1.3. Joint Stiffness and Structural Rigidity

Stiffness is the resistance to the deformation of the bodies under load basically and stiffness shows the accuracy of the robot. The robots are the mechanisms which are composed of links and connected with joints to produce a relative motion. To have a good and acceptable accuracy level in the robotics, the links and the joints should be stiff enough, because the external forces or torques applied to the end effector of the robot try to deform the links and joint elements. The accuracy issue of the robot arises when large amounts of forces are applied at the end-effector of the robot where the power is consumed actually.

Structural rigidity categorizes the state of a structure when it does not bend or flex under an applied force. A structure is rigid if it is not bended; that is if there is no continuous motion of the structure that preserves the shape of its rigid components and their pattern of their connections at the joints. In robotics, it is hard to maintain structural rigidity in serial configuration robots unlike parallel configuration (Martinez et. al., 2013). However, in order to improve the mechanical design of the robot in serial mechanism the required structural rigidity level can be obtained by using double joints or bearing instead of single bearing at single joint.

3.1.4. Backdrivability

Backdrivability is a property of mechanical design indicating that the patient is able to move the device when the device is in passive state i.e., the state by which actuators are not producing any force at mechanism joints. It increases patient safety and comfort, because it does not constrain limb movements and keeps the patient limb in a comfortable position. The need for backdrivability in rehabilitation robotics or any other robots arises from the softness and low impedance of the human joints (Maciejasz et al.,2014).

In this thesis study, the pneumatic actuator system uses 5/3 special type exhaust centre solenoid valve to enable backdrivability in the robot’s structure in

both forearm and wrist movements. *CWRR* enables the patient to move mechanism in his own effort passively and by this way he/she feels comfort. That is an advantage of our system.

3.1.5. Backlash

In robotic applications, zero backlash, i.e. the clearance between two mating parts working together as in gear pairs, are required for providing accurate position and force control (Pehlivan et al.,2012). In the design of robot, backlash problems in gear applications will be reduced by decreasing the distance between two mating gear centres such that the gears meshed tighter with low or even zero backlash[9].

3.2. Kinematic Definitions of Robots

Robots can be structurally categorized as parallel type and serial type. Parallel type mechanisms consist of links which form a closed kinematic chain. Even though parallel configuration has high load carrying capacity, high structural rigidity and good dynamic response, ROM capabilities are low and restricted (Pehlivan et al., 2012). On the other hand, serial mechanisms have open kinematic chain in contrast to parallel mechanisms. The serial configurations are easier to produce and they have larger workspaces that are more suitable for rehabilitation robotics to provide normal human ROM values. In addition to those, kinematics of serial manipulators is well suited and easier compared to parallel manipulator (Martinez et al., 2013). Because of that reason, the robot design is based on serial type manipulators.

Kinematics of robot design have to be studied for defining position, velocity and acceleration of each robot link such that the control of the robot can be based on geometric and time related parameters of motion.

[9] http://machinedesign.com/motion-control/methods-minimize-gear-backlash (accessed by March, 2017)

In serial type robots, a particular frame is attached to each joint in addition to the global (base) frame. Then, position and orientation of each link can be obtained from first by motion of frames with respect to each other and second by motion of a link within its own frame. The end-effector in serial type manipulators is the link that provides the required motion to human limb as well as force/torque transfer. Hence, the position and orientation of the end effector should be clearly defined.

Kinematic studies in robotics can be divided into two as forward kinematics and inverse kinematics. In the former one, joint variables (θ_1, θ_2, etc.) are given to obtain the final position and orientation of the end-effector (p_x, p_y, p_z). In the latter one, the objective is to obtain joint variables when the end effector position and orientation are provided. The relationship between forward and inverse kinematics is given in Fig. 3.3.

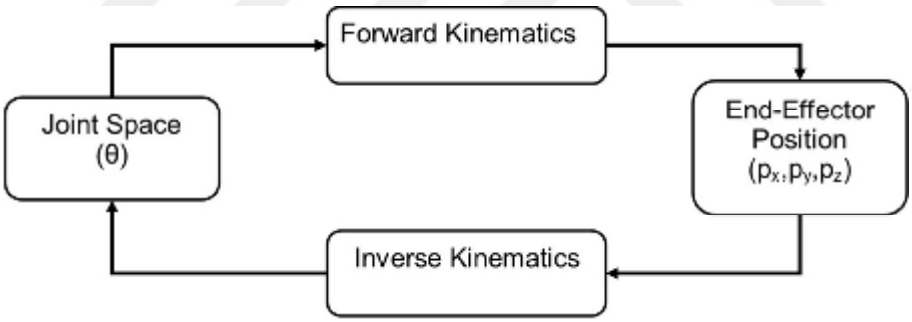


Figure 3.3. The definition of forward and inverse kinematics

In the forward kinematics studies of the designed robot, kinematic parameters are defined with respect to Denavit-Hartenberg (DH) notation. At first, a local frame is associated with each joint. Then, DH parameters for each link with respect to the corresponding local frame are developed. These DH parameters are then used to form transformation matrix for developing the relation of a particular joint with respect to the preceding one in the kinematic chain.

The DH notation have four parameters to define a robot's kinematics. Two of these parameters are rotational parameters (θ_i, α_{i-1}) whereas the others are translational parameters (a_{i-1}, d_i). The definition of each parameter is listed in Table 3.5.

Table 3.5. Four parameters of DH notation and their definition

Parameter	Definition
$\mathbf{a_{i-1}}$	The distance from z_{i-1} to z_i measured along x_{i-1}
$\boldsymbol{\alpha_{i-1}}$	The angle between z_{i-1} and z_i measured about x_i
$\mathbf{d_i}$	The distance from x_{i-1} to x_i measured along z_i
$\boldsymbol{\theta_i}$	The angle between x_{i-1} to x_i measured about z_i

By using the DH parameters listed in Table 3.5 for each link, the general homogeneous transformation matrix from frame "i" to "i-1" can be developed as given in Eq.3.4. (John J. Craig, 2005):

$$T_i^{i-1} = \begin{vmatrix} \cos\theta_i & -\sin\theta_i & 0 & a_{i-1} \\ \sin\theta_i * \cos\alpha_{i-1} & \cos\theta_i * \cos\alpha_{i-1} & -\sin\alpha_{i-1} & -\sin\alpha_{i-1} * d_i \\ \sin\theta_i * \sin\alpha_{i-1} & \cos\theta_i * \sin\alpha_{i-1} & \cos\alpha_{i-1} & \cos\alpha_{i-1} * d_i \\ 0 & 0 & 0 & 1 \end{vmatrix} \quad (3.4)$$

By using the general transformation matrix equation, the final position of the end effector can be obtained by using Eq.3.5.

$$T_{end-effector}^{base} = T_1^{base} * T_2^1 * T_3^2 * \ldots T_{end-effector}^{n} \quad (3.5)$$

In the equation of general transformation matrix, i.e., Eq.3.4, cosine and sine functions will be represented by "c" and "s", respectively for simplicity.

In addition to the forward kinematics, inverse kinematics of the designed robot is also studied. The inverse kinematics solution of the robotics can be achieved in two different ways as geometric approach or algebraic approach. The geometric approach is straightforward and useful for planar robotic structures with 2 DOF. However, the geometric solution becomes ineffective for complex robot structures. Hence, the algebraic approach becomes more suitable.

In our design, planar motions in general takes place. Hence, the geometric approach is applied for solving inverse kinematics parameters of the robot (θ_1, θ_2) such that for any given hand position, the angular positions at joints of the robot will be calculated.

The inverse kinematics problem of the serial manipulators is more difficult than forward kinematics problem. The inverse kinematic parameters of the robots are needed in the control of the robotics. Tasks to be performed by a manipulator are in the cartesian space, whereas actuators work in the joint space. Therefore, the end effector position of the robot is manipulated by adjusting the joint angles independently.

The inverse kinematics solution of the robotics mechanisms can be done in two different ways as geometric approach and algebraic approach. The geometric approach is useful for basic robot structures such as 2 DOF and planar robots. However, when the mechanism becomes complex, the geometric solution becomes ineffective and the algebraic approach provides better solution at this point.

In our study, *CWRR*, we will use geometric approach to solve inverse kinematics parameters of the robot (θ_1, θ_2). We will find the angles such that the hand position of the patient will be at desired position.

3.3. Development of Conceptual Design of *CWRR*

Three concept designs are developed based on the requirements for wrist kinematics and wrist rehabilitation exercises. The conceptual designs are evaluated according to their degrees of freedom (DOF), range of motions (ROM), their

kinematic structures, method of transmission, and their adaptability to the rehabilitation exercises.

3.3.1. Concept Design I

The first conceptual design is shown in Fig. 3.4 (front view), Fig. 3.5 (top view) and Fig. 3.6 (3D view). The design has pneumatic actuation with 2 DOF for wrist flexion/extension and wrist radial/ulnar deviation. One of the actuators is linear standard pneumatic actuator whereas the other is semi rotary pneumatic actuator. As shown in Figs. 3.4-3.6, gear transmission is used for both of the motions. The semi rotary actuator meshed with spur gear develops wrist radial/ulnar deviation whereas the linear standard actuator meshed with rack and pinion gear develops wrist flexion extension. The chosen dimensions of the mechanism are listed in Table 3.6. The ROM values for first conceptual design are also tabulated in Table 3.7.

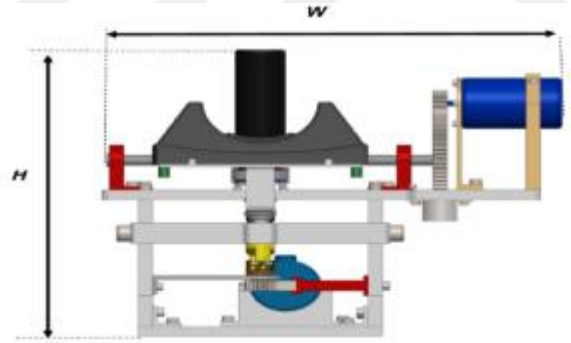


Figure 3. 4. First Concept Design I-Front view

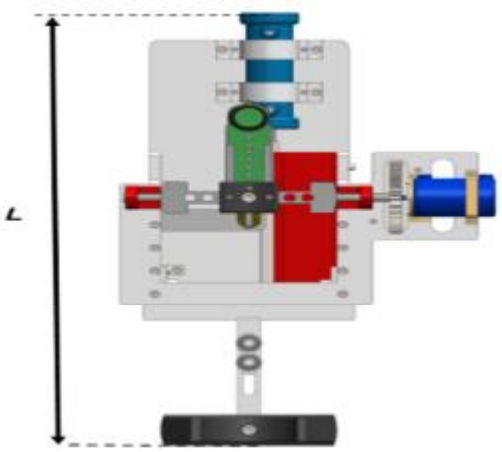


Figure 3. 5. First Concept Design I-Top view

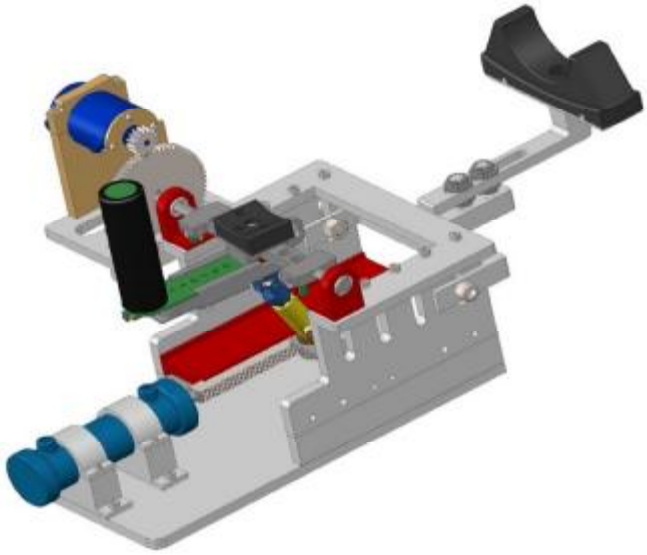


Figure 3. 6. First Concept Design I-3D View

Table 3. 6. Concept Design I-Mechanism Sizes

Mechanism Sizes	**Value(*mm*)**
Length (*L*)	575
Width (*W*)	320
Height (*H*)	284

Table 3. 7. Concept Design I movement capabilities and their ROM values

Motion	ROM(^{o})
Wrist Extension	**70^o**
Wrist Flexion	**70^o**
Wrist Radial Deviation	**20^o**
Wrist Ulnar Deviation	**35^o**
Forearm Supination	**No motion**
Forearm Pronation	**No motion**

There are four (x, y, z) frames associated to the robot's joints and base as shown in Fig. 3.7. Frame-0 is the base frame that can be considered as global reference frame which is attached to the bottom plate that is holding pinion gear. Frame-3 is associated with the midpoint of the end-effector which is the contact point of the robot and patient. Frame-1 and Frame-2 are coincident and associated with the midpoint of the rotating plate which holds the end-effector. In the kinematic structure (Fig. 3.7), there are joint variables, θ_1 and θ_2. The former one θ_1 represents the angle of wrist flexion/extension with respect to z_1 axis whereas latter one represents the angle of wrist radial/ulnar deviation with respect to the z_2 axis.

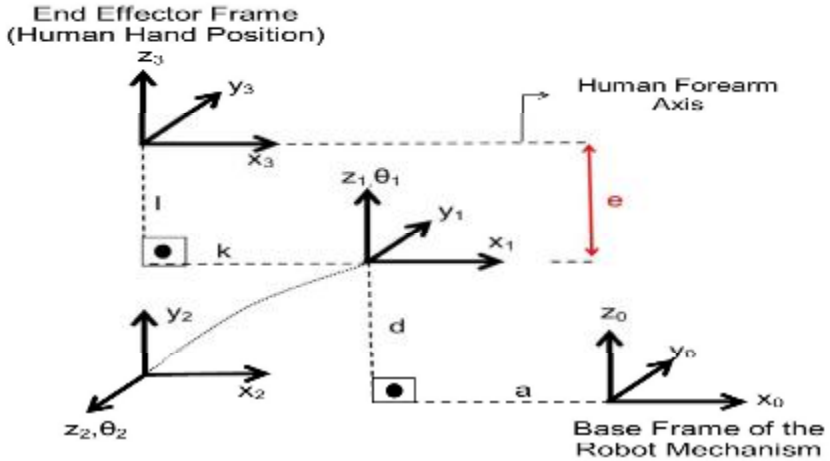


Figure 3. 7. The Kinematic Structure of the Concept Design I

The DH parameters for the design are stated in Table 3.8. From these parameters, transformation matrix can be developed as:

Table 3. 8. The DH Parameters of the Concept Design I

i	θ_i	α_{i-1}	a_{i-1}	d_i
1	θ_1	0	-a	d
2	θ_2	90	0	0
3	0	-90	-k	l

$$T_3^0 = T_1^0 * T_2^1 * T_3^2 \tag{3.6}$$

where T_1^0 , T_2^1 and T_3^2 can be defined as :

$$T_1^0 = \begin{vmatrix} cq_1 & -sq_1 & 0 & -a \\ sq_1 & cq_1 & 0 & 0 \\ 0 & 0 & 1 & d \\ 0 & 0 & 0 & 1 \end{vmatrix} \tag{3.7}$$

$$T_2^1 = \begin{vmatrix} cq_2 & -sq_2 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ sq_2 & cq_2 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{vmatrix} \tag{3.8}$$

$$T_3^2 = \begin{vmatrix} 1 & 0 & 0 & -k \\ 0 & 0 & 1 & l \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{vmatrix} \tag{3.9}$$

Carrying out calculations of equation set (3.6) -(3.9) would yield:

$$T_3^0 = \begin{vmatrix} cq_1 * cq_2 & sq_2 & -cq_1 * sq_2 & -k * cq_1 * cq_2 - l * cq_1 * sq_2 - a \\ sq_1 * cq_2 & -cq_1 & -sq_1 * sq_2 & -k * sq_1 * cq_2 - l * sq_1 * sq_2 \\ sq_2 & 0 & cq_2 & d - k * sq_2 + l * cq_2 \\ 0 & 0 & 0 & 1 \end{vmatrix} \quad (3.10)$$

As a result, the position of the end-effector for concept design-I would be obtained with respect to the global reference frame as

$$p_x = -k * cq_1 * cq_2 - l * cq_1 * sq_2 - a \quad (3.11)$$

$$p_y = -k * sq_1 * cq_2 - l * sq_1 * sq_2 \quad (3.12)$$

$$p_z = d - k * sq_2 + l * cq_2 \quad (3.13)$$

In matrix form it can be represented by P_3^0 as :

$$P_3^0 = \begin{bmatrix} -k * cq_1 * cq_2 - l * cq_1 * sq_2 - a \\ -k * sq_1 * cq_2 - l * sq_1 * sq_2 \\ d - k * sq_2 + l * cq_2 \\ 1 \end{bmatrix} \quad (3.14)$$

Verification of DH parameters are performed by setting joint position variables to initial conditions ($\theta_1=0$ and $\theta_2=0$) to check that end-effector would be in initial position.

If $\theta_1=0$ and $\theta_2=0$ the position of the end effector becomes;

$$p_x = -k - a = -(k+a) \quad (3.15)$$

$$p_y = 0 \quad (3.16)$$

$$p_z = l + d \quad (3.17)$$

In Fig. 3.7, the frames are shown in the zero position vector condition and it can be easily seen that the values found from the verification is correct. Also, the eccentricity between human forearm axis and the robot's frame is stated as eccentricity "e" in literature. The eccentricity value should be minimized and the human wrist motion axes should coincide with the robot's axes. Therefore "e" should be zero for suitable wrist rehabilitation exercises. Because of the eccentricity problem and absence of forearm motions, a new design should be searched for a better performance wrist rehabilitation robot.

3.3.2. Concept Design II

The problems faced with the first concept design leads to searching a better design. The second conceptual design has 3 DOF as wrist flexion/extension, wrist radial/ulnar deviation and forearm pronation/supination. In the first concept, there was no forearm motion. Hence, a new robot structure is designed by modifying the first concept in a way that another rotation capability is added for forearm motion.

The solid models of the new concept design are shown in Fig. 3.8 (top view), Fig. 3.9 (left side view) and Fig. 3.10 (3D view). This concept design also has pneumatic actuation. One semi rotary actuator provides wrist radial/ulnar deviation whereas two linear actuators are responsible for wrist flexion/extension and forearm pronation/supination. The dimensions of the concept design with respect to Figs. 3.8 and 3.9 are listed in Table 3.9. The ROM values of the design are tabulated in Table 3.10. Even though the second design has the same ROM values for wrist flexion/extension as well as wrist radial/ulnar deviation with the first concept design, the second design has also forearm pronation/supination.

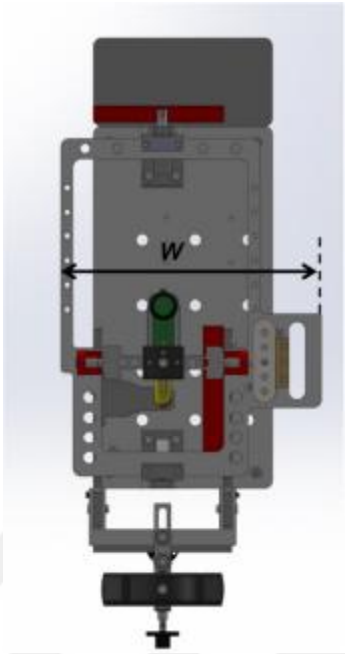


Figure 3. 8. Top view of Concept Design II

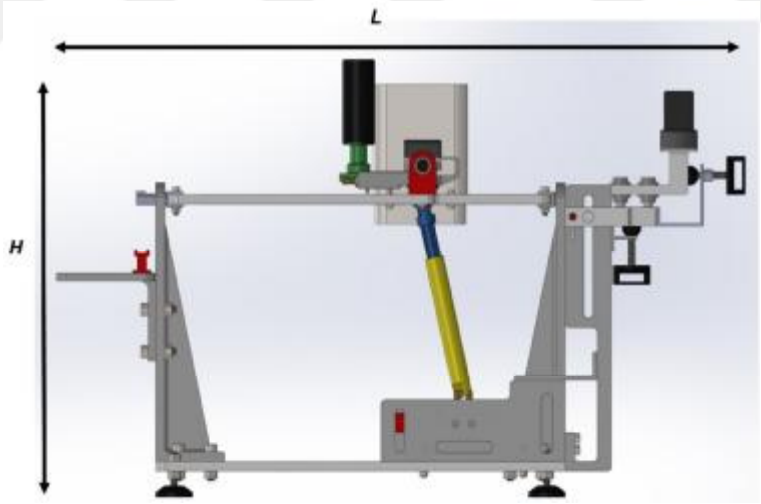


Figure 3. 9. Left side view of Concept Design II

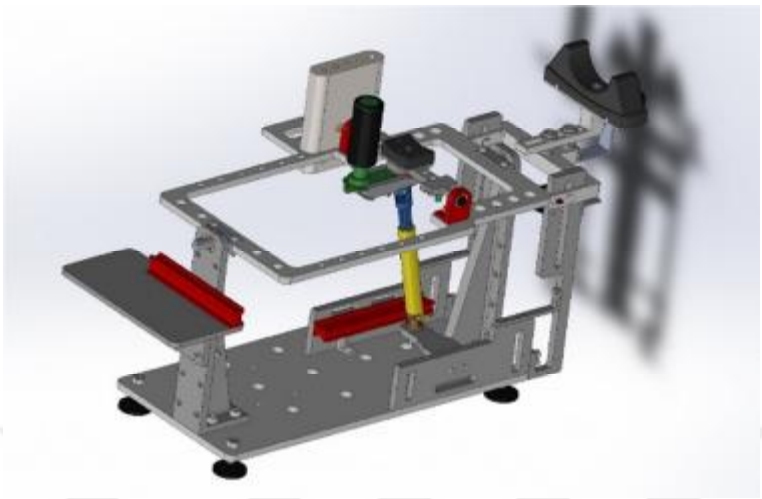


Figure 3. 10. 3D view of the Concept Design II

Table 3. 9. Concept Design II-Mechanism sizes

Mechanism Sizes	**Value(*mm*)**
Length (*L*)	748
Width (*W*)	320
Height (*H*)	432

Table 3. 10. Concept Design II-motion capabilities and their ROM values

Motion	**ROM(^{o})**
Wrist Extension	**70^o**
Wrist Flexion	**70^o**
Wrist Radial Deviation	**20^o**
Wrist Ulnar Deviation	**35^o**
Forearm Supination	**60^o**
Forearm Pronation	**60^o**

The kinematic structure of concept design-II is shown in Fig. 3.11. There are seven frames attached to each joint where the global reference frame is represented by “Frame-0” which is associated to the bottom plate that holds the

rack gear and the end-effector is associated with “Frame-6”. In the kinematic structure, the axis z_1 is the axis of rotation for wrist flexion/extension and represented by parameter θ_1. The axis z_2 corresponds to the wrist radial/ulnar deviation which is represented by parameter θ_2. Finally, axis z_4 is the axis of forearm pronation/supination that is represented by θ_4. On the other hand, “Frame-3” and “Frame-5” are intermediate frames.

The DH parameters with respect to this kinematic structure (Fig. 3.11) are given in Table 3.11. As a result, the general transformation matrix from base to end-effector can be defined as (Eq.3.18):

$$T_6^0 = T_1^0 * T_2^1 * T_3^2 * T_4^3 * T_5^4 * T_6^5 \quad (3.18)$$

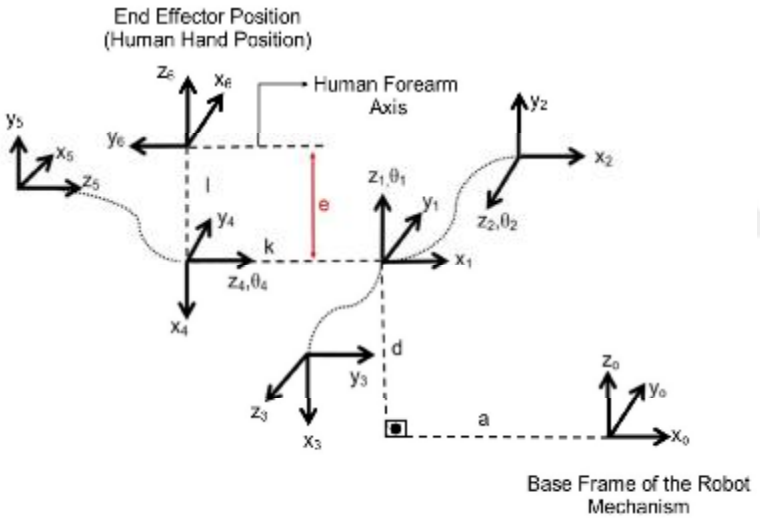


Figure 3. 11. The Kinematic Structure of the Concept Design II

Table 3. 11. The DH Parameters of the Concept Design II

i	θ_i	α_{i-1}	a_{i-1}	d_i
1	θ_1	*0*	*-a*	*d*
2	θ_2	*90*	*0*	*0*
3	*-90*	*0*	*0*	*0*
4	θ_4	*-90*	*0*	*-k*
5	*90*	*0*	*0*	*0*
6	*0*	*-90*	*0*	*l*

Each individual transformation matrix in Eq.3.18 can be listed as:

$$T_1^0 = \begin{vmatrix} c\mathrm{q}_1 & -s\mathrm{q}_1 & 0 & -a \\ s\mathrm{q}_1 & c\mathrm{q}_1 & 0 & 0 \\ 0 & 0 & 1 & d \\ 0 & 0 & 0 & 1 \end{vmatrix} \tag{3.19}$$

$$T_2^1 = \begin{vmatrix} c\mathrm{q}_2 & -s\mathrm{q}_2 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ s\mathrm{q}_2 & c\mathrm{q}_2 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{vmatrix} \tag{3.20}$$

$$T_3^2 = \begin{vmatrix} 0 & 1 & 0 & 0 \\ -1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{vmatrix} \tag{3.21}$$

$$T_4^3 = \begin{vmatrix} c\mathrm{q}_4 & -s\mathrm{q}_4 & 0 & 0 \\ 0 & 0 & 1 & -k \\ -s\mathrm{q}_4 & -c\mathrm{q}_4 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{vmatrix} \tag{3.22}$$

$$T_5^4 = \begin{vmatrix} 0 & -1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{vmatrix} \tag{3.23}$$

$$T_6^5 = \begin{vmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & l \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{vmatrix} \tag{3.24}$$

Further calculations of equations set (3.19)-(3.24) would yield:

$$T_6^0 = \begin{vmatrix} r_{11} & r_{12} & r_{13} & p_x \\ r_{21} & r_{22} & r_{23} & p_y \\ r_{31} & r_{32} & r_{33} & p_z \\ 0 & 0 & 0 & 1 \end{vmatrix} \tag{3.25}$$

Where the parameters in Eq.3.25 are:

$$r_{11} = -sq_1 * cq_4 - cq_1 * sq_4 * sq_2 \tag{3.26}$$

$$r_{12} = -cq_1 * cq_4 \tag{3.27}$$

$$r_{13} = sq_1 * sq_4 - cq_1 * sq_2 * cq_4 \tag{3.28}$$

$$r_{21} = cq_1 * cq_4 - sq_1 * sq_2 * sq_4 \tag{3.29}$$

$$r_{22} = -sq_1 * cq_2 \tag{3.30}$$

$$r_{23} = -cq_1 * sq_4 - sq_1 * sq_2 * cq_4 \tag{3.31}$$

$$r_{31} = sq_4 * cq_2 \tag{3.32}$$

$$r_{32} = -sq_2 \tag{3.33}$$

$$r_{33} = cq_2 * cq_4 \tag{3.34}$$

The end-effector position for the concept design II with respect to the base (global) frame can be obtained as:

$$p_x = l*(sq_1 * sq_4 - cq_1 * cq_4 * sq_2) - k * cq_1 * cq_2 - a \tag{3.35}$$

$$p_y = -l*(sq_1 * sq_2 * cq_4 + cq_1 * sq_4) - k * sq_1 * cq_2 \tag{3.36}$$

$$p_z = l*(cq_2 * cq_4) + d - k * sq_2 \tag{3.37}$$

In matrix form it can be represented as:

$$P_6^0 = \begin{bmatrix} l*(sq_1 * sq_4 - cq_1 * sq_2 * cq_4) - k * cq_1 * cq_2 - a \\ -l*(sq_1 * sq_2 * cq_4 + cq_1 * sq_4) - k * sq_1 * cq_2 \\ l*(cq_2 * cq_4) + d - k * sq_2 \\ 1 \end{bmatrix} \tag{3.38}$$

To verify these results we use again zero position by setting $\theta_1=0$, $\theta_2=0$ and $\theta_4=0$. Then, the positions p_x, p_y and p_z are verified as:

$$p_x = -k - a = -(k+a) \tag{3.39}$$

$$p_y = 0 \tag{3.40}$$

$$p_z = l + d \tag{3.41}$$

Even though, the concept design II is an improved version of concept design I, this new design also has eccentricity problem.

3.3.3. Concept Design III- *CWRR*

The advantages and disadvantages of the previous two concept designs pave the road for a better concept design that does not have any eccentricity problem as well as that has the capability of three motions (i.e., wrist flexion/extension, wrist radial/ulnar deviation and forearm pronation/supination) with only two pneumatic actuators. A linear pneumatic rodless actuator with rack and pinion mechanism is used for developing wrist flexion/extension as well as wrist radial/ulnar deviation. The semi rotary actuator placed on the moving platform provides forearm pronation/supination.

The dimensions of concept design III are tabulated in Table 3.12. The ROM values achievable by the design are also listed in Table 3.13.

Table 3. 12. Concept Design III-Mechanism Sizes

Mechanism Sizes	**Value(*mm*)**
Length (*L*)	700
Width (*W*)	440
Height (*H*)	470

Table 3. 13. Concept Design III-Motion capabilities and their ROM values

Motion	**ROM(^{o})**
Wrist Extension	45
Wrist Flexion	45
Wrist Radial Deviation	45
Wrist Ulnar Deviation	45
Forearm Supination	90
Forearm Pronation	90

The concept design III is represented in Fig. 3.12 (top view), Fig. 3.13 (left view) and Fig. 3.14 (3D view).

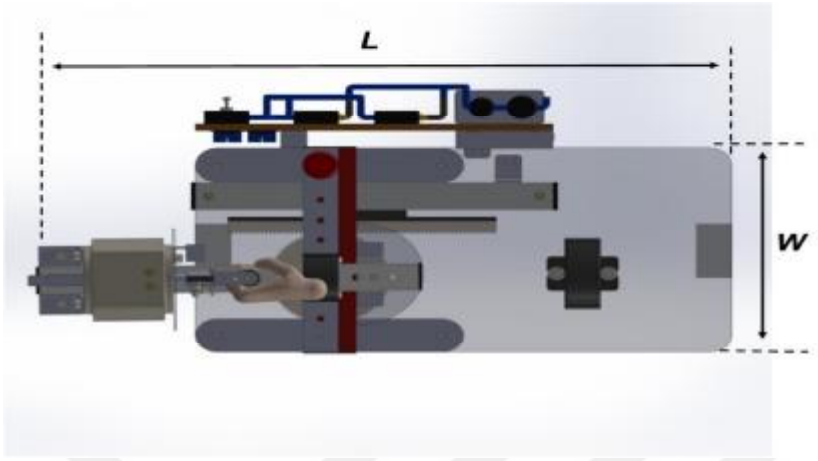


Figure 3. 12. Top view of Concept Design III-Top view

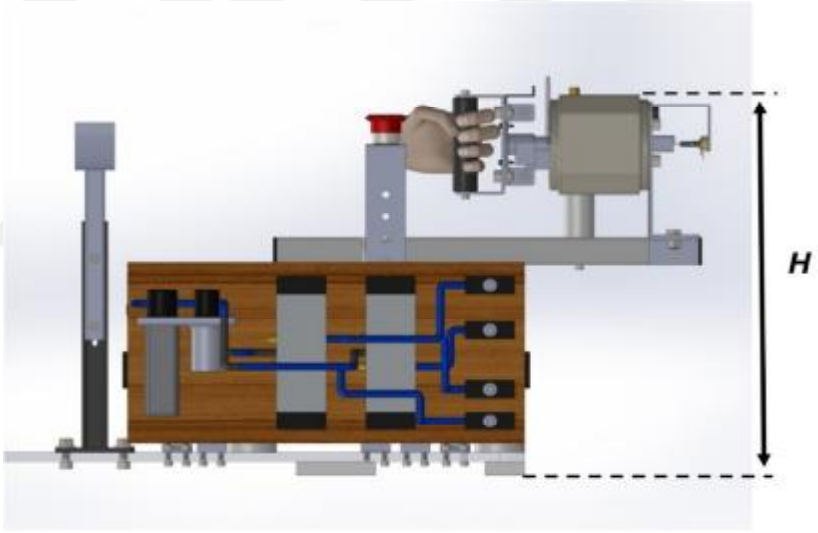


Figure 3. 13. Left view of Concept Design III-Front view

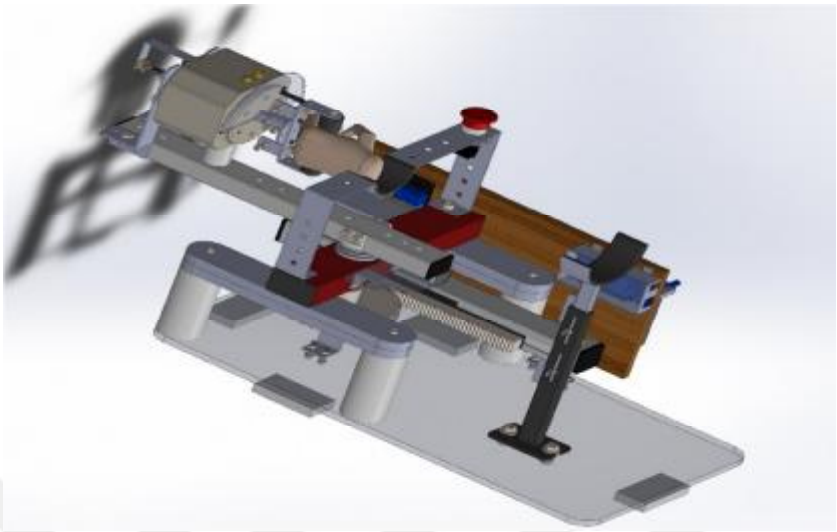


Figure 3. 14. 3D view of the Concept Design III-3D view

In Fig. 3.15, section view of the rotating platform is shown. Pinion gear is attached to main shaft which is labelled as 3. In this figure, parts 2, 3, and 4 are fixed to each other. When the pinion gear is rotated the platform is moved to get wrist motions (W.E./ W.F and W.R.D./ W.U.D). On the other side, forearm motions are produced from the semi rotary pneumatic actuator as shown in Fig. 3.15

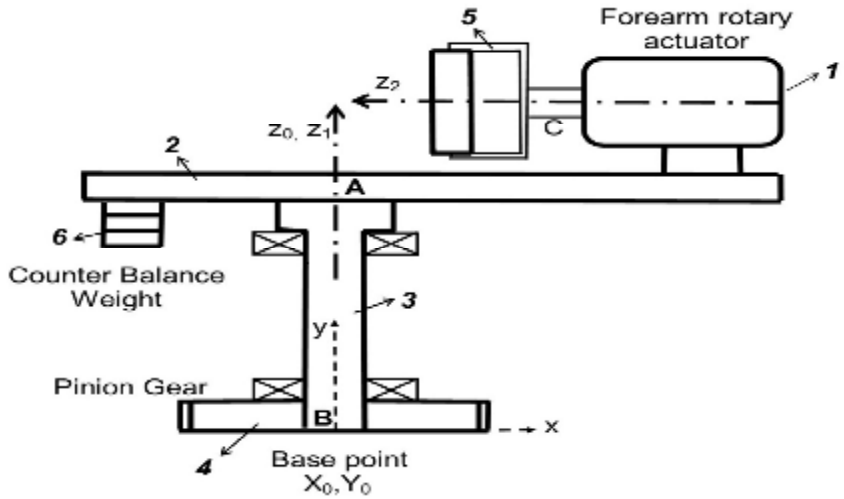


Figure 3. 15. Detailed section view of rotating platform

The motion of the pinion gear is obtained by a rack-and-pinion mechanism. The kinematic diagram of this planar mechanism at the pinion level is shown in Fig.3.16. As shown in the figure, the linear motion of the pneumatic actuator is converted into rotational motion of the pinion.

The kinematic structure of concept design III is represented as shown in Fig. 3.17. In this structure, “Frame-0” is associated with the base as global reference frame where as “Frame-2” is associated with the end-effector. Hence, rotation of the end-effector with respect to the z_1 axis represents the axis of rotation for both wrist flexion/extension as well as wrist radial/ulnar deviation based on the corresponding end-effector orientation (i.e., θ_2=0 for wrist flexion/extension and θ_2=85 for wrist radial/ulnar deviation). The parameter for rotation is represented by θ_1.

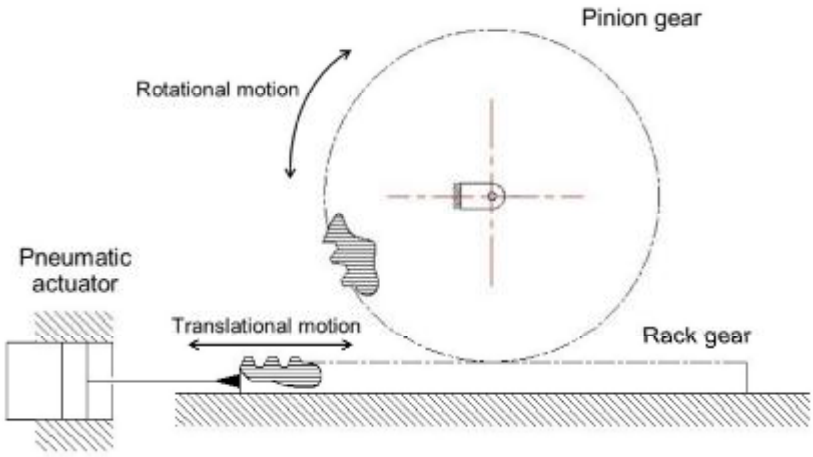


Figure 3.16. Kinematic diagram of rack-and-pinion mechanism of CWRR

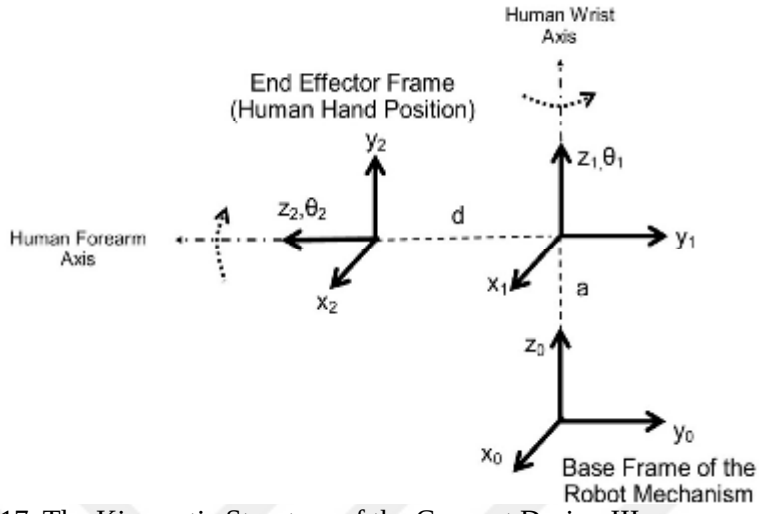


Figure 3. 17. The Kinematic Structure of the Concept Design III

The DH parameters of the concept design III based on the kinematic structure (Fig. 3.17) are given in Table 3.14.

Table 3. 14. The DH parameters of concept design III

i	θ_i	α_{i-1}	a_{i-1}	d_i
1	θ_1	*0*	*0*	*a*
2	θ_2	*90*	*0*	*d*

It should be noted that wrist flexion/extension and wrist radial/ulnar deviation motions are obtained by the same linear actuator with two different orientations provided by rotary actuator. Hence, these two motion types would have the general transformation matrix as shown by Eq.3.42:

$$T_2^0 = T_1^0 * T_2^1 \tag{3.42}$$

where θ_2=0 for wrist flexion/extension and θ_2=85 for wrist radial/ulnar deviation.

Each individual transformation matrix in Eq. (3.42) is:

$$T_1^0 = \begin{vmatrix} cq_1 & -sq_1 & 0 & 0 \\ sq_1 & cq_1 & 0 & 0 \\ 0 & 0 & 1 & a \\ 0 & 0 & 0 & 1 \end{vmatrix} \quad (3.43)$$

$$T_2^1 = \begin{vmatrix} cq_2 & -sq_2 & 0 & 0 \\ 0 & 0 & -1 & -d \\ sq_2 & cq_2 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{vmatrix} \quad (3.44)$$

Hence, the transformation matrix T_2^0 would be obtained as:

$$T_2^0 = \begin{vmatrix} cq_1 * cq_2 & -cq_1 * sq_2 & sq_1 & d * sq_1 \\ sq_1 * cq_2 & -sq_1 * sq_2 & -cq_1 & -d * cq_1 \\ sq_2 & cq_2 & 0 & a \\ 0 & 0 & 0 & 1 \end{vmatrix} \quad (3.45)$$

As a result, the position of end-effector with respect to the base frame would be defined as:

$$p_x = d * sq_1 \quad (3.46)$$

$$p_y = - d * cq_1 \quad (3.47)$$

$$p_z = a \tag{3.48}$$

Hence, P_2^0 in matrix form can be represented by :

$$P_2^0 = \begin{bmatrix} d*s\theta_1 \\ -d*c\theta_1 \\ a \\ 1 \end{bmatrix} \tag{3.49}$$

In the kinematic structure (Fig. 3.17), axis of rotation with respect to z_2 axis is also responsible for forearm pronation/supination that is represented by θ_2. It should be noted that because of the structure and design of the mechanism, angle θ_2 does not affect the position of the end-effector frame.

3.3.3.1. Inverse Kinematics of *CWRR*

In general, the developed concept design, *CWRR*, has planar motion for wrist flexion/extension when $\theta_2=0^o$ and wrist radial/ulnar deviation when $\theta_2=85^o$. Hence, for any end-effector position in global reference frame (i.e., p_x and p_y), a corresponding linear actuator position *s* can be calculated from simple trigonometry.

In Fig.3.18, the parameters for wrist radial/ulnar deviation (i.e., when $\theta_2=85^o$) are shown. On the figure, a circular trajectory for the midpoint of end-effector is drawn symbolically. Hence, for any planar coordinates of p_x and p_y, the following relationships can be written:

$$p_x = d*s\theta_1 \tag{3.50}$$

$$p_y = d*c\theta_1 \tag{3.51}$$

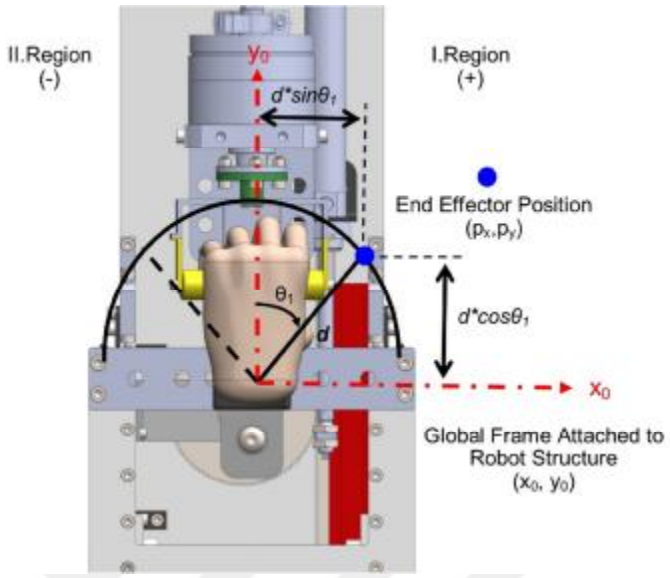


Figure 3. 18. The relation between position and joint variables

From either of these two equations (3.50-3.51), the angle θ_1 can be solved as:

$$q_1 = \sin^{-1}\left[\frac{p_x}{d}\right] \quad \text{or} \tag{3.52}$$

$$q_1 = \cos^{-1}\left[\frac{p_y}{d}\right] \tag{3.53}$$

After these calculations to determine the exact position of the point, tangent function can be used as:

$$\arctan\left|\frac{p_x}{p_y}\right| = q_1 \tag{3.54}$$

If the result comes out with positive (+) sign from the calculation of Eq. 3.54, the angle is in I. region (Fig.3.16) meaning radial deviation is in action for this configuration, otherwise if the result becomes negative (-) sign, the angle is in II. region (Fig.3.16) meaning ulnar deviation is in action.

In Fig. 3.19, parameters corresponding to linear displacement of pneumatic actuator vs angular rotation are defined as:

-*r* = the pitch radius of the pinion gear (*mm*)

-*s*= the distance translated by the actuator (*mm*)

-*y*= the range of motion of the linear actuator (*mm*)

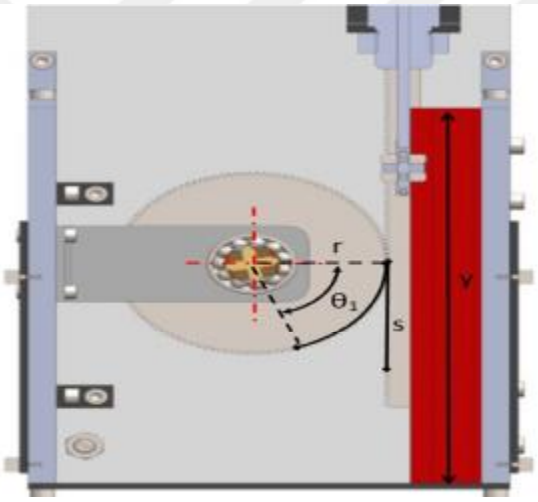


Figure 3. 19. The relation between position and joint variables

Now, considering that the circular arc translated “s” (Fig. 3.19) by the rack would be given by

$$s = r * q_1 \tag{3.55}$$

where θ_1 is in radians

Therefore, by solving for θ_1 and substituting into either Eqs.3.52 or 3.53 would yield the position of linear actuator as:

$$s = r * \sin^{-1}\left(\frac{p_x}{d}\right) \tag{3.56}$$

$$s = r * \cos^{-1}\left(\frac{p_y}{d}\right) \tag{3.57}$$

3.4. Actuator and Transmission System of *CWRR*

The actuation system of the rehabilitation robot is one of the most important part. There are several alternatives in actuation types as: electrical actuation, hydraulic actuation, pneumatic actuation, pneumatic artificial muscle (PAM), series elastic actuator (SEA) and functional elastic stimulation (FES) (Maciejasz et. al., 2014).

The electrical actuators are powered by electric current. They are chosen mostly because of their simple control and they have higher bandwidth interval to be controlled. There is a wide selection of commercially available electric actuators, however some of them are heavy and their impedance is too high for rehabilitation robots. The hydraulic actuators, on the other hand, are powered by hydraulic pressure (usually oil). They are able to generate high forces. Hydraulic actuators can operate in high precision, but they have leakage problem especially not very suitable for medical purposes. Commercial hydraulic actuators are also heavy, therefore only specially designed hydraulic actuators are used in the rehabilitation robotics.

The pneumatic actuators are powered by atmospheric air which is harmless and clean. They weigh less than electric actuators and they have lower impedance. Pneumatic actuators actually well suited for rehabilitation robotics, but their

control algorithm is complex due to the air's nonlinear behaviour. Even though their control algorithm is complex, pneumatic actuation is more similar to human's limb and muscle system. They can be either soft or hard when it is desired.

There are also other alternative actuation types different than standard actuators, such as Pneumatic Artificial Muscle (*PAM*) and Series Elastic Actuators (SEA). The PAM is a special type of pneumatic actuator with an internal bladder surrounded by braided mesh shell with flexible, but non-extensible threads. Because of their specific design, an actuator under pressure shortens, similarly to the contracting muscle. It is relatively light and exerts force in single direction. If the force is needed both in two directions, two *PAM* is needed in the system. It is difficult to control because of its slow and non-linear dynamic functions. Serial Elastic Actuators (*SEA*), on the other hand, is a generic name used for a mechanism with an elastic element placed in series with an actuator. This solution is relatively often met in the design of rehabilitation robots. It decreases the inertia and intrinsic impedance of the actuator to allow a more accurate and stable force control and increase patient safety. Lastly, Functional Elastic Stimulation (*FES*) is a technique uses both electric signals and human natural muscles. This system uses electrical current to activate nerves and contract their innervated muscles. It produces the movement of the limb using natural actuators of the body. However, it is difficult to achieve precise and repeatable movement using this technique and it may be painful for the patient.

The transmission system, on the other hand, is used for the force and torque delivery to the joint to be actuated. The transmission system in rehabilitation robotics is needed to raise torque and lower the joint speed since the movements are done in low speed ranges (Pehlivan et al., 2012). The transmission system also used to reduce robot weight by mounting the actuator away from the robot structure.

The transmission systems used for the rehabilitation robots can be gear drive, wire drive, cable drive and lastly direct drive. The gear drive uses simple

gear mesh in contact and the simplest one to be controlled. The torque increase depends on the gear ratio used in the system. Gear drives includes backlash in the system, but this clearance can be reduced by reducing the centre distance of the mating gears. The wire drive, uses wires to actuate joints. The wires and pulleys are used together. The power comes from the actuator placed away from the actuated joint and power is transmitted to these joints by wires. The cable drive, on the other hand is similar to the gear mesh but there are no teeth in mesh. The cable exists between the parts and the backlash is prevented by this way. The direct drive uses no part between the joint and actuator and the power is transmitted to the joint directly from the actuator output.

In this study, standard pneumatic actuation method is decided to be used. Our pneumatic system chart is shown in the Fig. 3.18. As the main part of the system, there is a main compressor in our mechanical engineering laboratory, 1 filter-regulation-lubrication (FRL) unit, 2 exhaust centre $24V$ DC solenoid directional control valves, 4 one-way flow control valves, 4 one-way pilot control valves, 1 double acting linear actuator, and 1 semi rotary actuator. The double acting linear cylinder is used for the wrist movements and have $25mm$ piston diameter and $250mm$ stroke. The semi rotary actuator is used for the forearm motions and have up to 270^{o} rotating capacity but later this rotation angle is limited by means of mechanical stoppers since the forearm can rotate a maximum range of 155^{o}. The patient's safety and comfort are satisfied by this way.

The solenoid valves used in our system are special type exhaust centre valves. These valves are chosen because of their advantage of position control as well as after the actuator stopped at a certain position, actuator can be moved by human intention since the air can be exhausted at centre position. In other words, the system is backdrivable. These valves have $24V$ DC power supply and can be controlled by activating the S1, S2, S3 and S4 solenoids shown in the Fig. 3.18. The pneumatic actuator system parts and their assembly on the prototype are shown in Fig. 3.21.

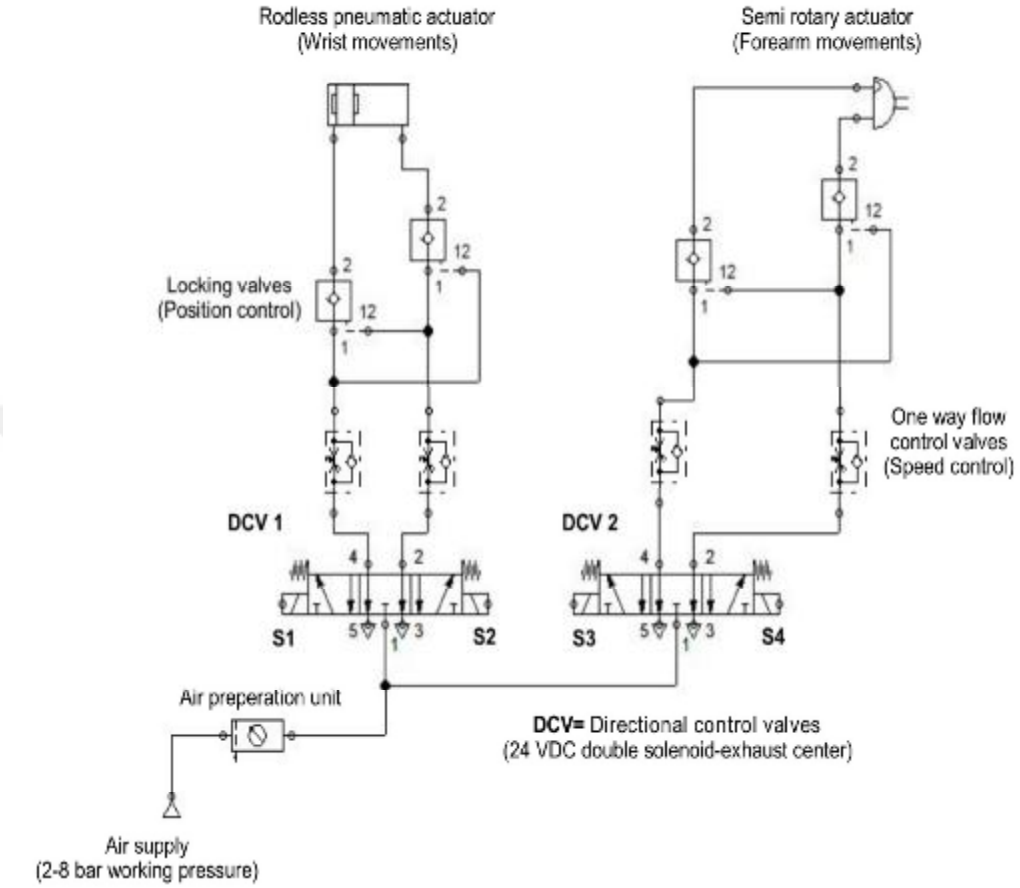


Figure 3. 20. The pneumatic scheme of *CWRR*

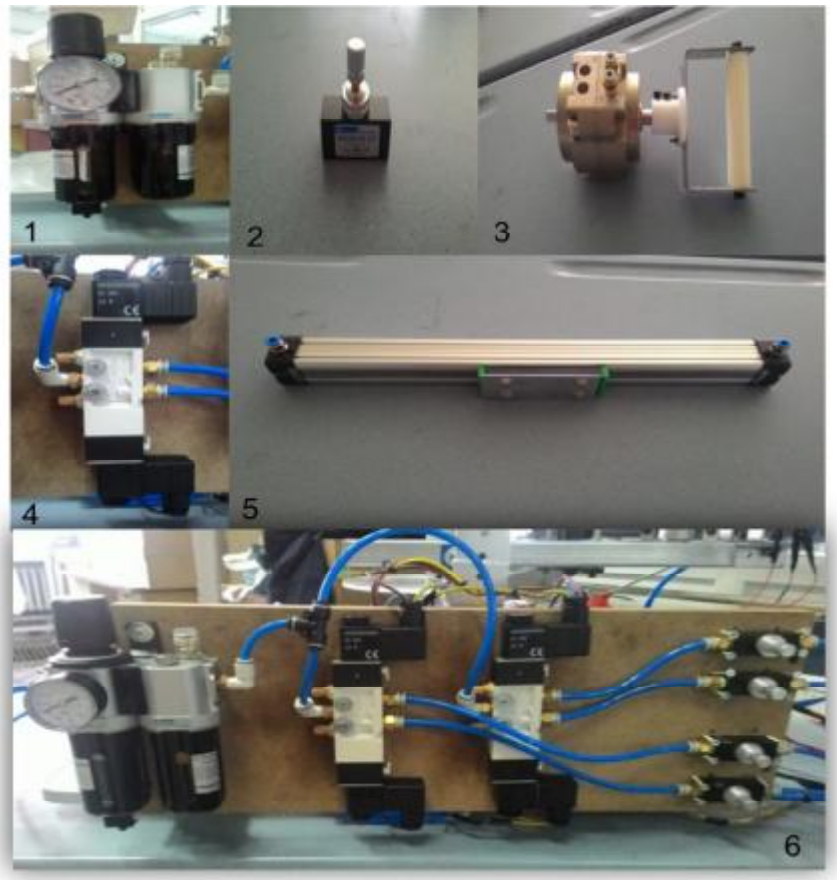


Figure 3. 21. The pneumatic system parts and assembly of pneumatic system ([1]Air preparation unit, [2] Speed control valve, [3] Semi rotary actuator, [4] Exhaust centre 5/3 solenoid directional control valve, [5] Rodless linear pneumatic actuator,[6] Pneumatic system assembly.)

As transmission system, we used rack and pinion gear sets and direct drive. The gears are designed in a CAD program and produced with a Polyoxymethylene[10] (POM) material in Adana Industry. POM, also known as acetal, is an engineering thermoplastic used in precision parts requiring high stiffness, low friction and excellent dimensional stability. They are well suited for gear parts and applications. Other parts of the transmission systems are produced in

[10] https://tr.wikipedia.org/wiki/Polyoxymethylene (accessed by March,2017)

the mechanical engineering laboratory. The gears are designed according to the speed and torque outputs as well as the mechanical structure of the robot. The gear properties used in our robot design are shown in Table 3.15 and 3.16.

Table 3. 15. Pinion gear parameters

Pinion Gear Parameters	
Module (mm)	1.5
Number of teeth	88
Pressure angle (degree)	20
Face width (mm)	20
Bore diameter (mm)	20
Hub diameter (mm)	40
Material	POM (Acetal)
Method of production	Standard cutting methods

Table 3. 16. Rack gear parameters

Rack gear parameters	
Module (mm)	1.5
Face width (mm)	20
Length (mm)	300
Pressure angle (degree)	20
Pressure height (mm)	15
Material	POM (Acetal)
Production method	Standard cutting methods

3.5. Control Algorithm and Electronic Control Equipment of *CWRR*

Control is the most important topic in rehabilitation robotics since well-designed control algorithm should be applied to the patient for quick recovery. The control equipment consists of the parts that manage the motion characteristics of the robot such as position, velocity and acceleration. Control system of a robot

receives an input signal (which is the desired output) and generates an output signal. As input signal, the sensory data are taken from the robot and/or patient. These input signals can be in three different forms as dynamic signals, kinematic signals and trigger signals (Maciejasz et al., 2014). The dynamic signals are composed of the signals related to the force or torque data measured via sensors at a specific position of the robot e.g., joints or end-effector of the robot. On the other hands, kinematic signals are the signals which convey the orientation, position, velocity or acceleration information. The trigger signals come from any triggering environment such as a button or limit switch.

The control methods in the rehabilitation robotics can be classified as high-level control method and low level control method. The high level control method is a method which control algorithms are explicitly designed to induce motor plasticity. The high level methods can be in the form of assistive control, challenge based control, haptic stimulation and couching control. On the other hands, the low-level control method can be applied by the appropriate control of the position, velocity and acceleration (Maciejasz et al., 2014).

In this study, we aim to use low-level control strategy with appropriate closed loop position control method. The kinematic and triggering signals will be used as input signals. Our wrist/forearm rehabilitation robot, *CWRR*, can be used for both active and passive rehabilitation. The triggering signals are taken from buttons (direction control buttons, emergency buttons) placed on both command table and device itself.

The control scheme of the *CWRR* is shown in Fig. 3.22. In this figure, the different connections are represented with different line types (i.e., continuous lines show electrical lines, dashed lines demonstrate pneumatic power line and centre line shows electrical power line). In the control system of *CWRR* (Fig. 3.22), there are two potentiometers attached to the wrist and forearm joints, one microcontroller card, one 4-way relay card, two solenoid valves, one command table and a computer for user interface. The position sensors send position feedback signal to

the microcontroller card determining the wrist angle θ_1 and forearm angle θ_2. The microcontroller card processes each signal and send the manipulated signal to the 4 way 5*V* relay card as digital signal i.e., 0 or 5*V*. Then, relay works according to the signal coming from the microcontroller and switches the solenoids of the directional control valves S1, S2, S3 and S4 which work with 24*V* DC power. By switching these solenoids, the mechanism position is adjusted according to the patient wrist and forearm ROM.

The Arduino microcontroller card is selected to be used in the control of *CWRR*. Arduino[11] is a microcontroller board which contains analogue and digital input/output pins up to 5*V* DC. The Arduino uses C, C++ based coding and there are many ready to use shields available. Arduino Mega 2560 K is selected to be used in this study and the related pins and their definition are illustrated in Table 3.17.

[11] https://www.arduino.cc/ (accessed by March,2017)

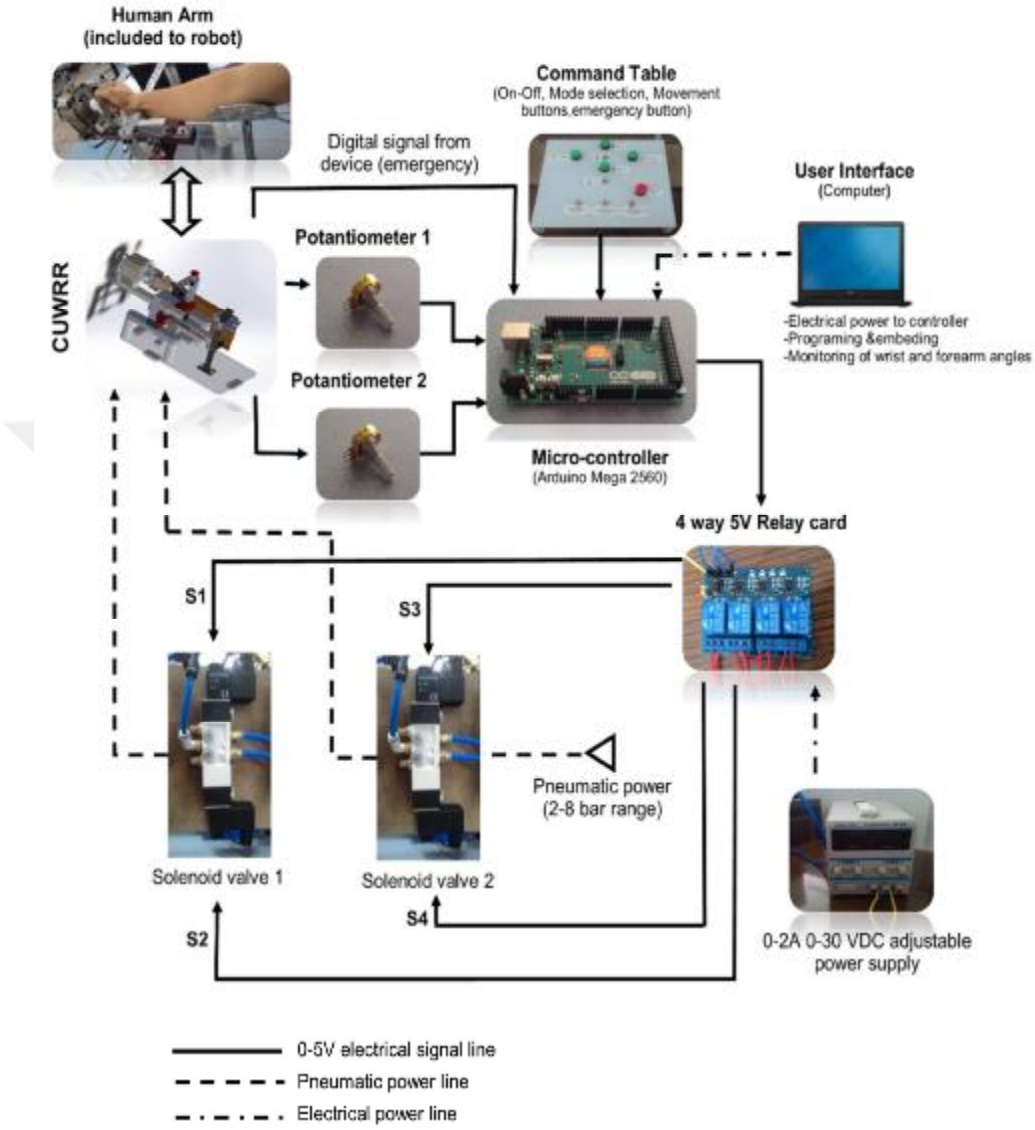


Figure 3. 22. The control scheme *CWRR*

Table 3. 17. Arduino pins and their mode in our robotic system

Arduino signals	
Input signals (Pin No)	**Definition**
13	Manual-automatic switch on command table
7	Retract linear actuator button
12	Extend linear cylinder button
6	Rotate rotary actuator in CW button
5	Rotate rotary actuator in CCW button
4	Start radial&ulnar deviation motion
3	Start Forearm pronation&supination motion
2	Start Wrist flexion&extension motion
Output signals(Pin No)	**Definition**
9	Extend linear actuator (Relay 1)
8	Retract linear actuator (Relay 2)
10	Rotate rotary actuator in CW (Relay 3)
11	Rotate rotary actuator in CCW (Relay 4)

CWRR can work in robot active or robot passive rehabilitation modes. In the case of active rehabilitation, the robot control algorithm can manipulate and send signals to the actuators by sensing the current position of the robot at each time. Therefore, required power (force/torque) is applied to the wrist and forearm joints by the robot. In the passive mode, all the power is cut off and the patient drives the robot with her/his own effort.

In active mode, there exist two types of operation as manual drive and automatic drive. The control flowcharts of active exercises are shown in Fig. 3.24and 3.25. A command table (Fig. 3.23-6) is developed for selection of exercise modes. The command table consists of the movement buttons, an emergency button, a mode switch, an on-off button.

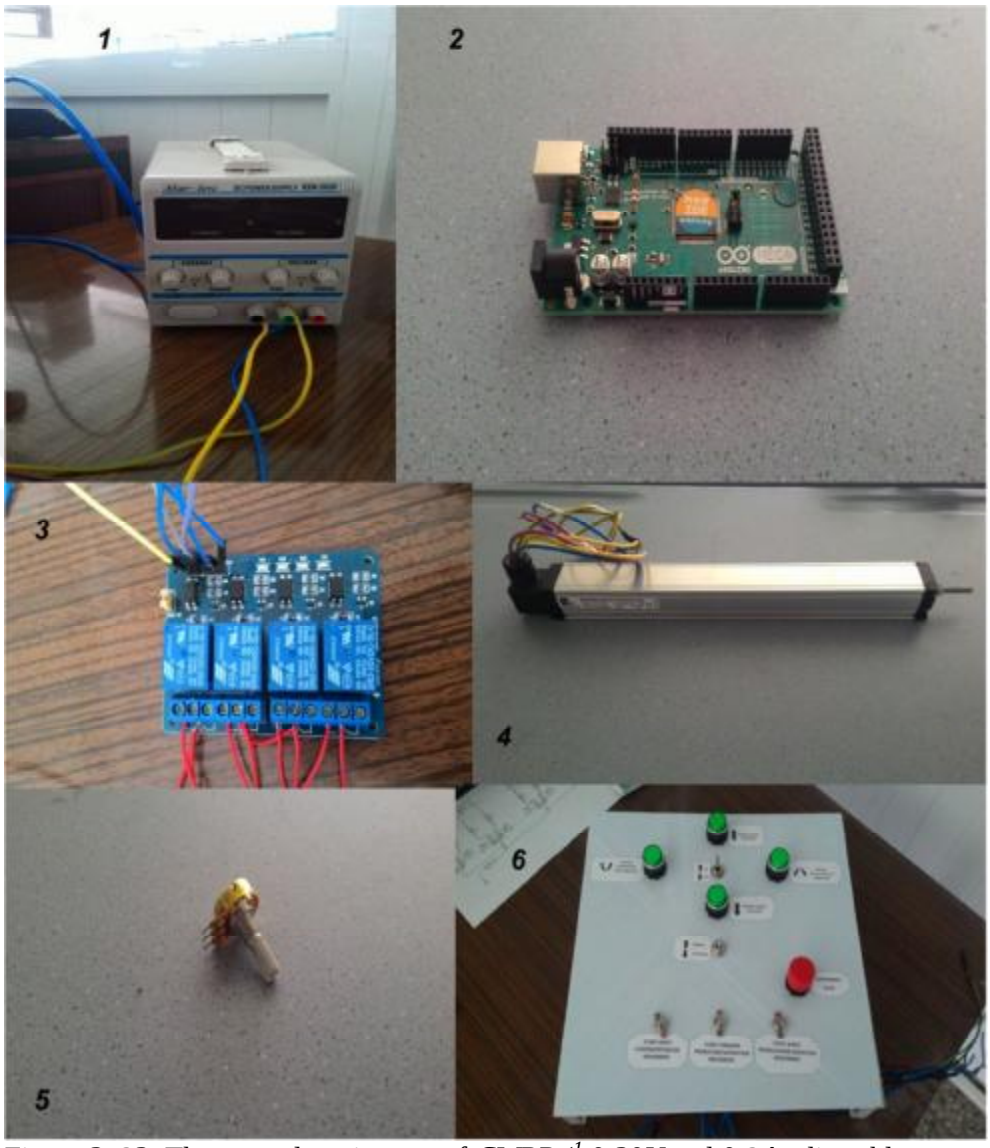


Figure 3. 23. The control equipment of *CWRR* ([1] 0-30*V* and 0-2*A* adjustable power supply, [2] Arduino mega 2560 K microcontroller card, [3] 4 way 5*V* relay card, [4] Linear potentiometers, [5] Rotary potentiometers, [6] Command table)

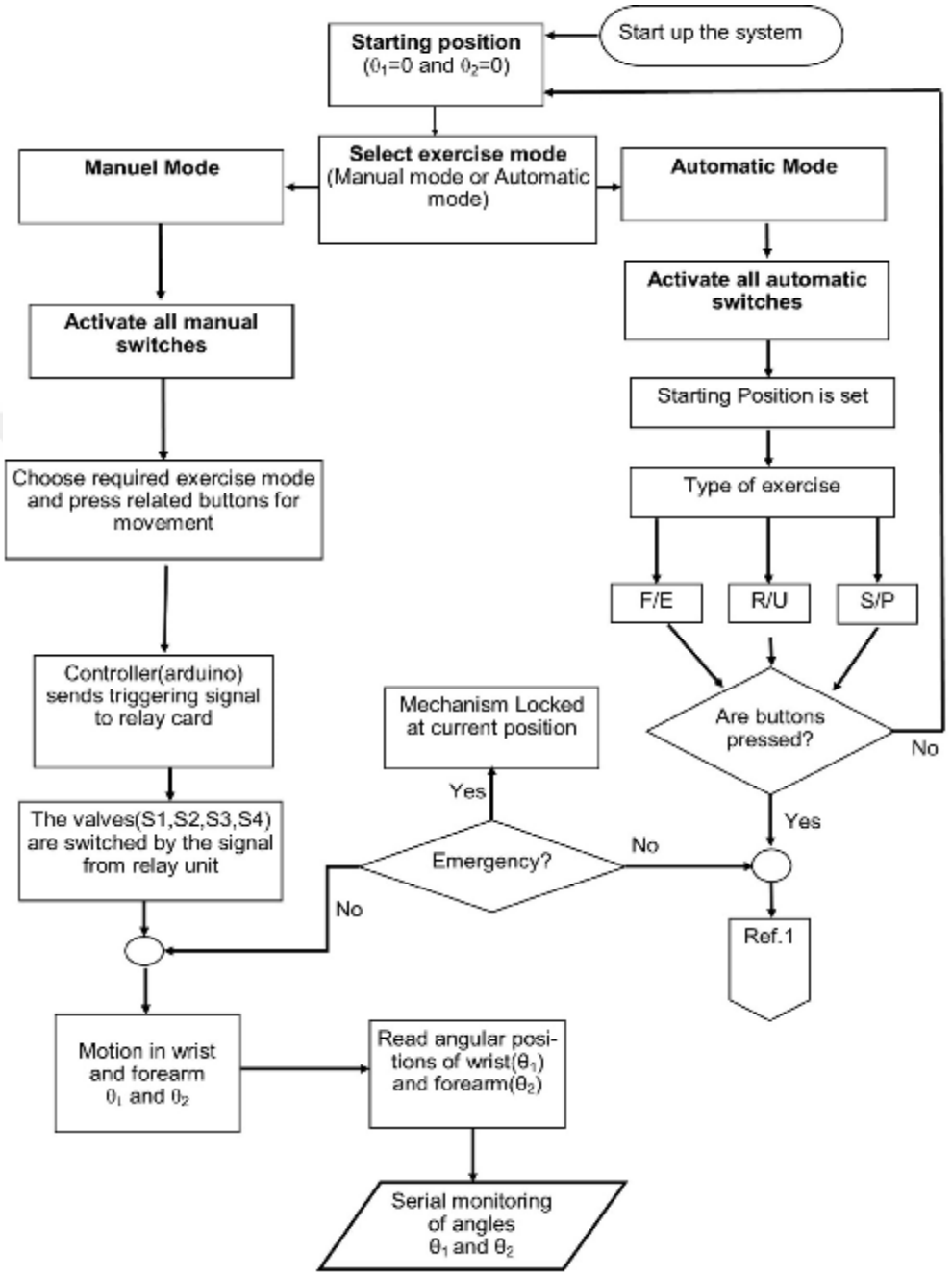


Figure 3. 24. General control flowchart of *CWRR*

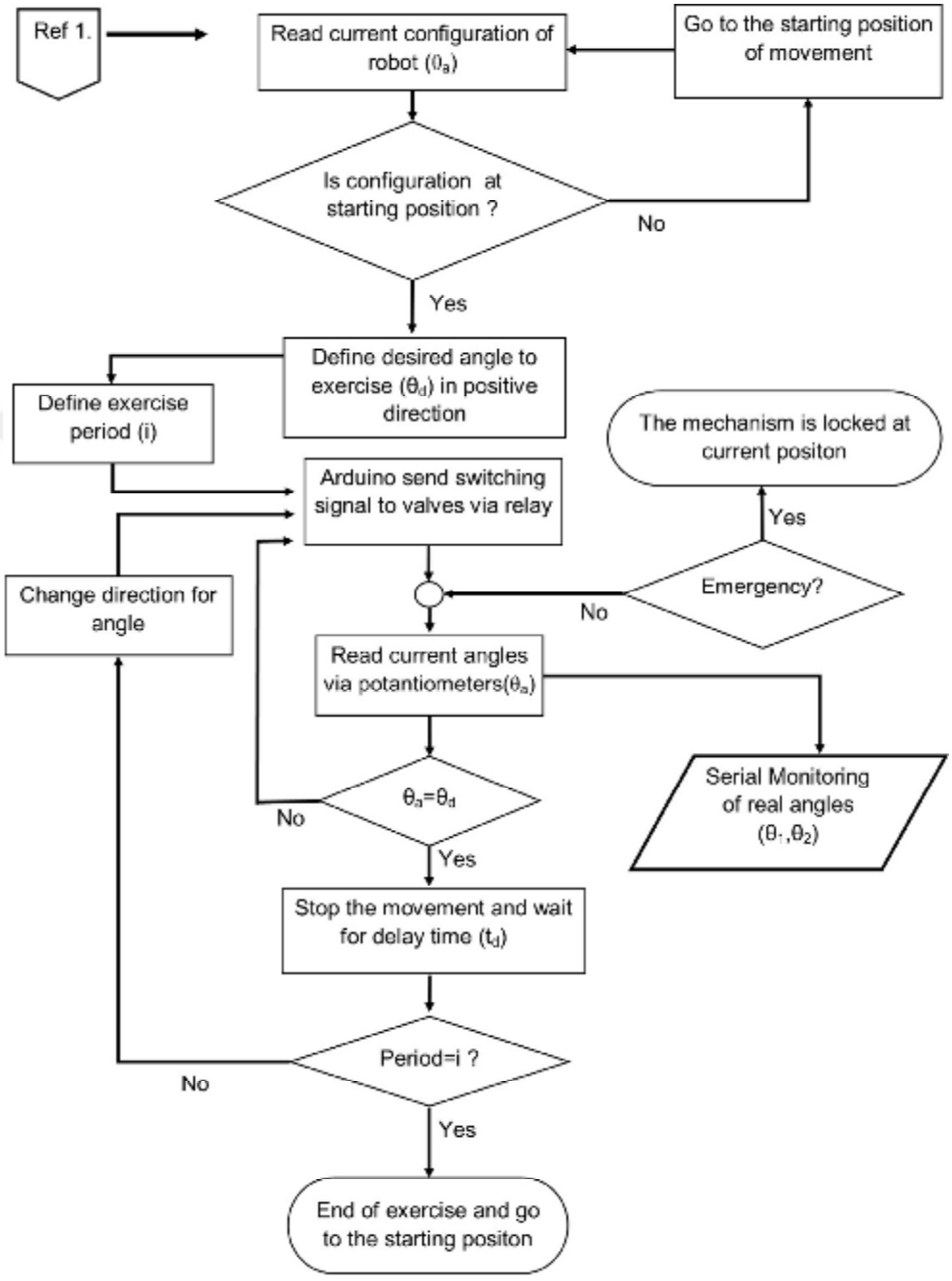


Figure 3. 25. Control flowchart of automatic modes of *CWRR*

In manual mode, button 1 and 2 are used for adjusting the displacement of the linear actuator whereas button 3 and 4 are used for adjusting the angle of the semi rotary actuator. There exists an emergency button on the command table and one on the device for patient safety. When the emergency button is pressed by the patient all the command signal, managing the solenoid valves are cut off and the position of the end-effector of the robot (human wrist) is locked at the current position. The guide for manual exercise is shown in Table 3.18.

Table 3. 18. The steps to be followed for manual control mode

Guide for manual mode control		
Wrist F/E	**Wrist R/U**	**Forearm S/P**
-Switch on the device. -Activate the manual mode. -Make sure $\theta_2=0^o$, by pressing button 3 and button 4. -Press button 1 for flexion. -Press button 2 for extension. -Press emergency button in case of any danger.	-Switch on the device. -Activate the manual mode. -Make sure $\theta_2=90^o$, by pressing the button 3 and button 4. -Press button 1 for ulnar deviation -Press button 2 for radial deviation -Press emergency button in case of any danger	-Switch on the device. -Activate the manual mode. -Make sure $\theta_1=0^o$, by pressing the button 1 and button 2. -Press button 3 for forearm supination -Press button 4 for forearm pronation

4. RESULTS AND DISCUSSIONS

In this section, the prototype of concept design III, *CWRR*, constructed in mechanical engineering laboratory, is shown. The force and torque capability of *CWRR* is determined according to the equations mentioned in section 3. Also, the range of controlled parameters (θ_1, θ_2 and s) are shown according to the equations of the kinematic definitions. Lastly, the tests and outputs of the prototype are determined via graphics.

4.1. Manufacturing the Prototype

A prototype of *CWRR* is produced according to the criteria determined in the material and method section (section 3) as well as manufacturing steps shown in Fig. 4.1, Fig. 4.2 and Fig. 4.3. The finished prototype is shown in Fig. 4.4. In the production period both metal and polymer products are used for the simplicity of manufacturing. The prototype is designed such that it can be easily assembled and disassembled as shown in Fig. 4.2.

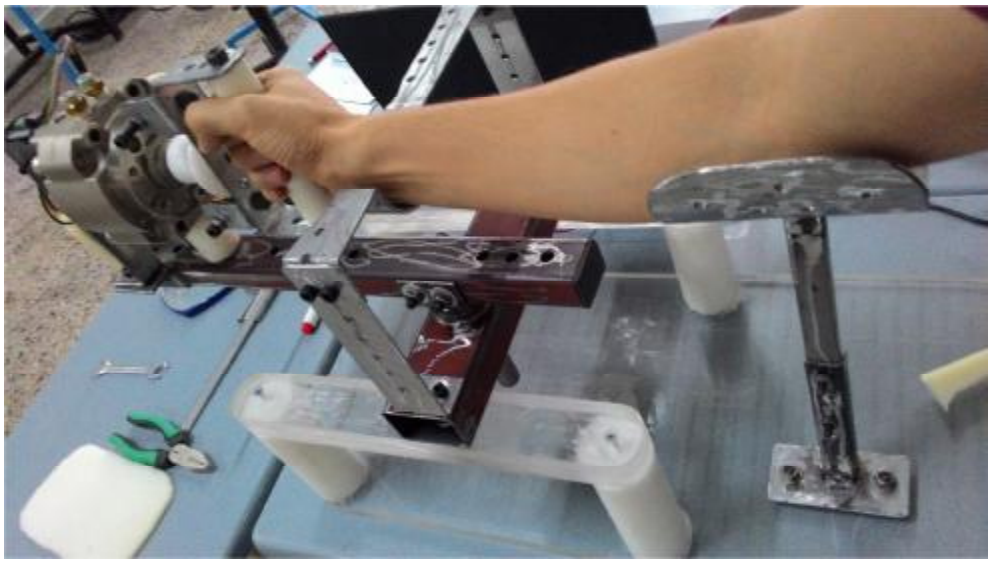


Figure 4. 1. Production process of *CWRR*

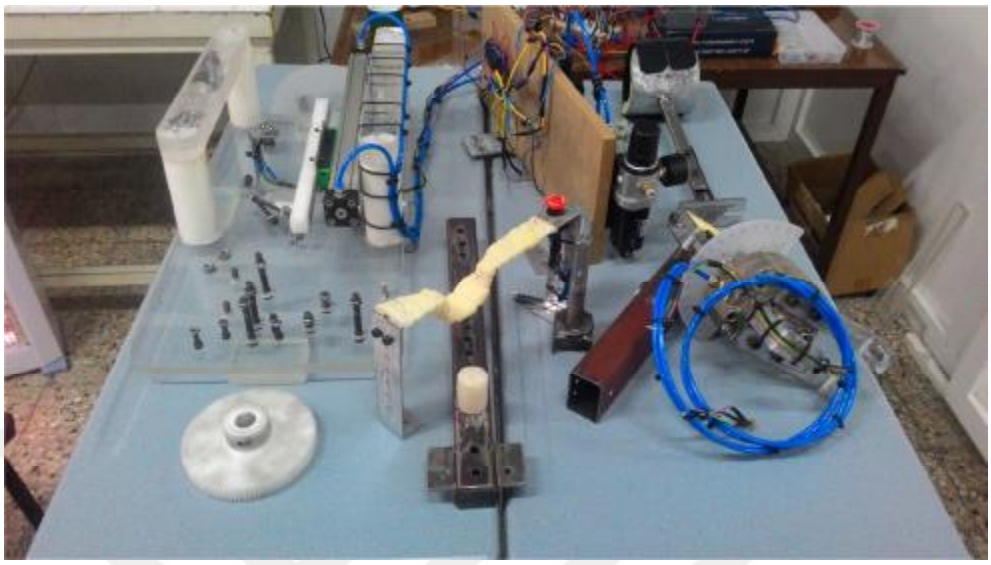


Figure 4. 2. The main components of the design

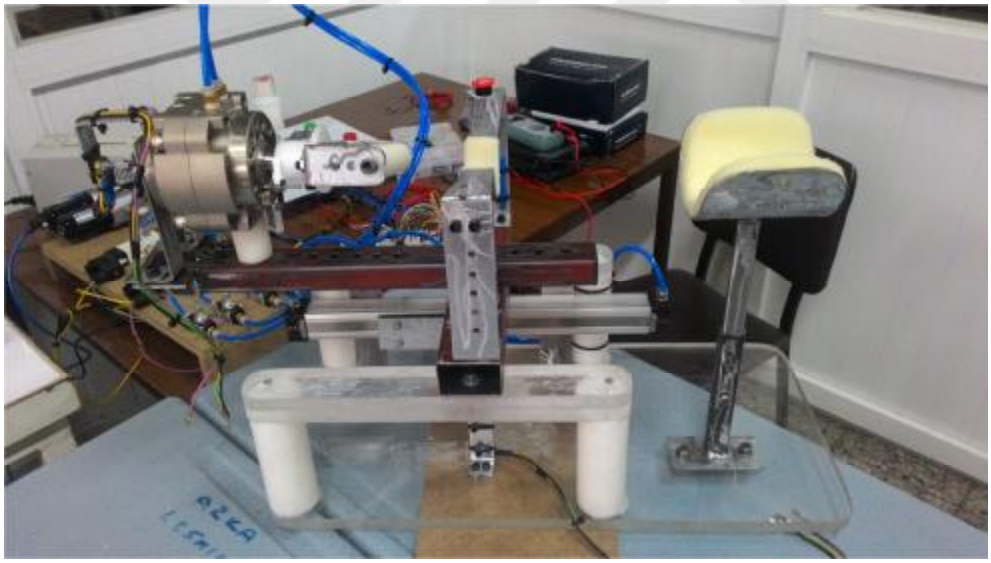


Figure 4. 3. Production process of *CWRR*



Figure 4. 4. The finished prototype of *CWRR*

4.2. Force and Torque outputs of *CWRR*

In Table 4.1 below, the torque values produced at the axis of wrist joint are evaluated for the operating pressure of 4 to 8 bar pressure. The force and torque output values are calculated by using Eqs.3.1, 3.2 and 3.3. Human isometric strength achieved at 6 bar working pressure is shown in Table 4.1. Therefore, the working pressure is set to 6 bar for this system.

Table 4. 1. The force and torque outputs for a specified operating pressure

$P_{working}$(bar)	Piston area of actuator(m^2)	Force Output (N)	Gear pitch radius(mm)	Torque Output(Nm)
4	0.0004906	196.24	66	12.95
4.5	0.0004906	220.77	66	14.57
5	0.0004906	245.30	66	16.18
5.5	0.0004906	269.83	66	17.80
6	0.0004906	294.36	66	19.42
6.5	0.0004906	318.89	66	21.04
7	0.0004906	343.42	66	22.66
7.5	0.0004906	367.95	66	24.28
8	0.0004906	392.48	66	25.90

The motions of forearm pronation and supination are actuated by direct drive. Hence, the force and torque output levels are equal to semi rotary actuator's torque output. Torque output vs operating pressure values are reported as listed in Table 4.2.

Table 4. 2. Rotary actuator effective torque output at specified pressure

Rotary Actuator Effective Torque Output	
Pressure(bar)	**Torque(Nm)**
4	14
5	18
6	22
7	26
8	30

4.3. Range of Controlled Parameters

The range for the controlled parameters (θ_1, θ_2 and s) are shown in Table. 4.3 according to the forward and inverse kinematic definitions of *CWRR* mentioned in section 3 by using Eq.3.54. (Calculations are based on r=66*mm* gear pitch radius). Since the linear potentiometer has 250*mm* working range and semi rotary actuator has 270^o rotation capability, the ROM values are satisfied for wrist flexion/extension, wrist radial/ulnar deviation and forearm pronation/supination.

Table 4. 3. The range of θ and s for each movement

Motion	$\boldsymbol{\theta_1}$ **(°)**	$\boldsymbol{\theta_2}$ **(°)**	***s=r*θ(mm)***
W.F/W.E	$-45 \le \theta_1 \le 45$	0^o(No rotation)	$-51.83 \pounds s \pounds 51.83$
W.R.D/W.U.D	$-20 \le \theta_1 \le 35$	90^o(No rotation)	$-23.03 \pounds s \pounds 40.31$
F.P/F.S	0(No rotation)	$-90 \le \theta_2 \le 90$	$s = 0$ (No translation)

4.4. Experimental Results

In this section, the robot *CWRR* is operated in order to obtain the positions achievable as well as to compare these values with a normal human hand/arm motion. The experiments are repeated for wrist flexion/extension, wrist radial/ulnar deviation and forearm pronation/supination activities. Each experiment is performed with a healthy human when the robot is in passive rehabilitation mode so that desirable position values are recorded. In the second step, the robot is operated automatically in order to obtain position values achieved by the robot with respect to time.

In Fig 4.5, forearm pronation/supination experiment results are graphed. As it is evident from the figure, the maximum and minimum range of motion values are same both in automatic mode and passive rehabilitation mode. The time difference is caused mainly by the user preferences.

Wrist flexion/extension experiment results with the robot are graphed in fig. 4.6. In this figure, there are three different trials under the robot passive mode. When the robot's automatic mode is compared with other human hand trials a significant difference is noticed. The reason behind that is the robot's rotating platform has a mass and inertia to be rotated. At the end of a range of motion where the actuator is required to switch the direction of motion a delay time (i.e.,2 sec) is required before actuator is driven. Otherwise, the angular acceleration approaches to infinity and control algorithm does not work properly. Hence, the wrist flexion/extension motions under the automatic mode has the same characteristics with the natural human hand motions.

In Fig. 4.7 wrist radial/ulnar deviation motion experiment results are shown. The robot's automatic mode results are not shown in the figure because the robot's rotation speed along the axis of radial/ulnar deviation could not be reduced with the current operating pressure and speed control valve settings. One reason for this result is that radial /ulnar deviation movement has a very small ROM value. Under the high operating pressure, the required maximum and minimum values in

wrist radial/ulnar deviation are reached in a very short time. Hence, the operating pressure should be dropped for this exercise type. However, from Fig. 4.8, it can be seen that the robot can achieve the maximum and minimum ROM values with healthy subjects.

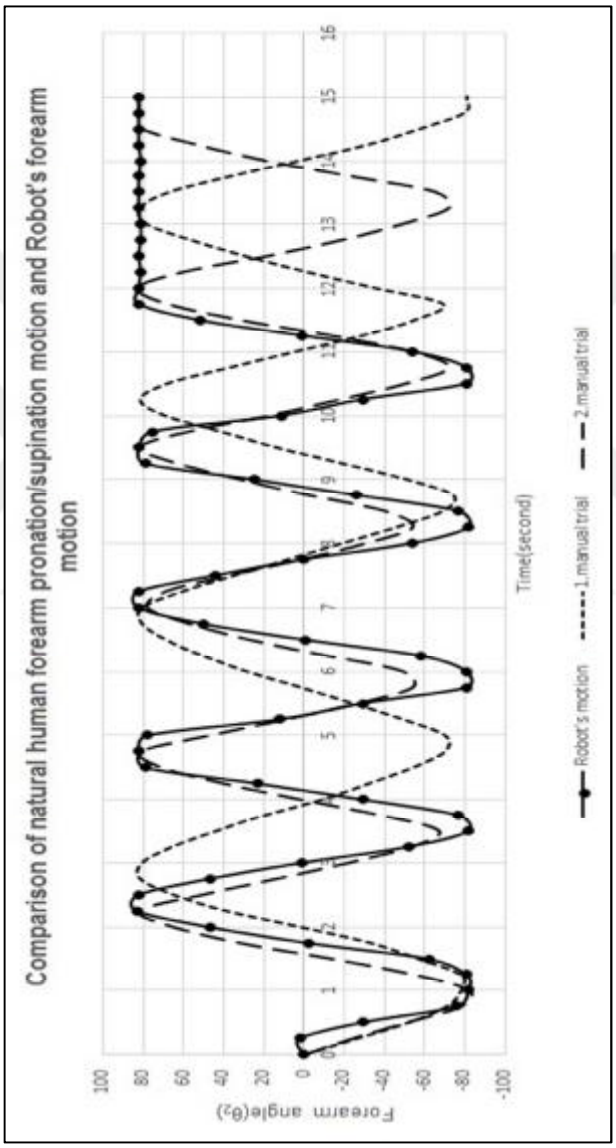


Figure 4. 5.Comparison of human natural forearm supination/pronation movement with robot's. ($\theta_1=0^o$ constant and θ_2 is oscillating between predefined forearm angles.)

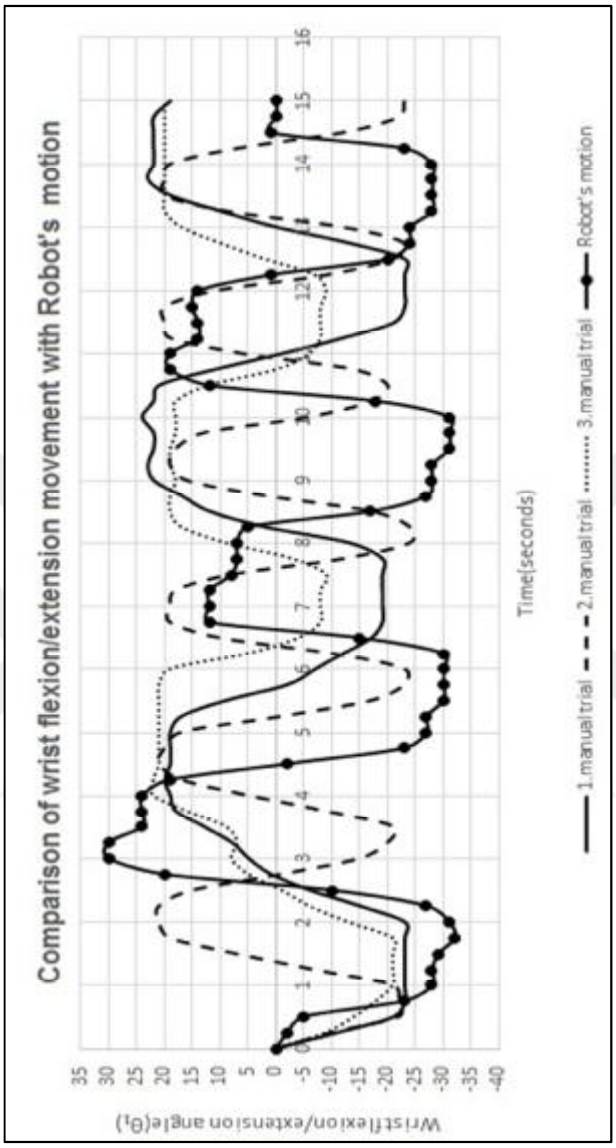


Figure 4. 6. Comparison of human natural wrist flexion/extension movement with robot's (θ_2=0^o constant and θ_1 is oscillating between predefined wrist angles.)

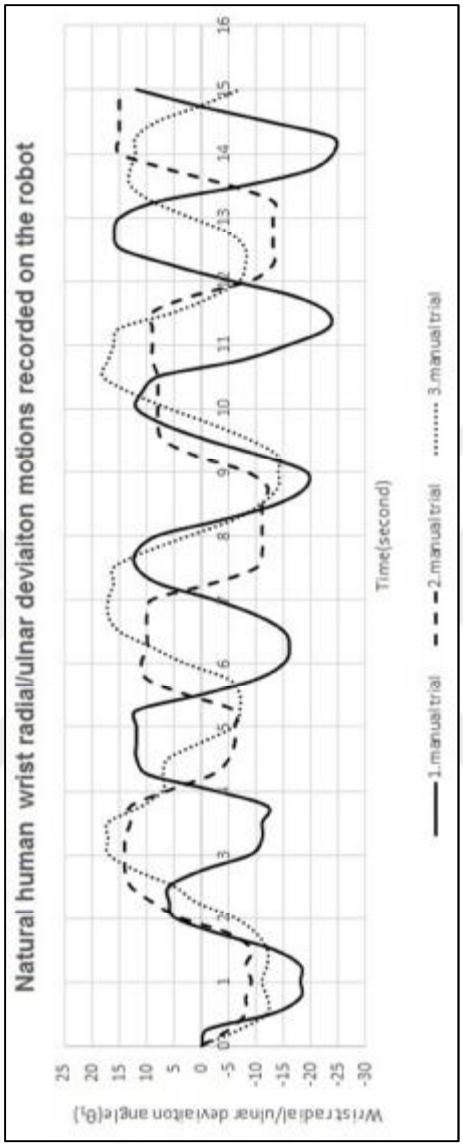


Figure 4. 7. Human natural radial/ulnar deviation movement recorded on *CWRR* (θ_2=90^o or θ_2=-90^o constant and θ_1 is oscillating between predefined wrist angles.)

5. CONCLUSIONS

Physical rehabilitation is gaining more importance as the population of the world grows. The reason behind that is people have some illnesses such as stroke, spinal cord injury etc. After these kind of illnesses, they lack of using some of their limbs (i.e., upper limb: shoulder, elbow, wrist and/or lower limb: hip, knee, ankle). They need efficient and long-term physical rehabilitation processes with well-educated physiotherapist to recover their limb's movements. However, there are some problems inherent to physiotherapist based rehabilitation. Scientist and researchers look for solutions to problems existed in rehabilitation exercises. As a solution, robots are associated with the rehabilitation exercises because they are good at repetitive and long-term exercises which requires sensory data at the same time. Different kind of rehabilitation robots (either for upper limb or lower limb) have been developed with different kind of mechanism designs, actuators and control methods. Hence, in this study, an alternative rehabilitation robot for wrist and forearm rehabilitation is aimed to be designed.

In this thesis, three concept designs are developed in a CAD program. All three concept designs are evaluated for compatibility to the wrist and forearm rehabilitation exercises. The most suitable design, concept III, called *CWRR*, is prototyped in mechanical engineering laboratory. The forward kinematics of CWRR is determined by Denavit-Hartenberg (DH) method. The inverse kinematics are found with geometrical approach.

Results of kinematic solutions showed that CWRR has the capability to cover normal human ROM values reasonably. The wrist flexion/extension has $45^o/45^o$, wrist radial/ulnar deviation has $45^o/45^o$ and forearm pronation/supination has $90^o/90^o$ ROM values where normal human ROM values are $75^o/70^o$, $20^o/35^o$ and $70^o/85^o$, respectively. From these results, it is clear that other than wrist flexion/extension activity, the other two activities can be achieved fully. The limitation in the wrist flexion/extension movement is due to the linear pneumatic

actuator stroke. If an actuator with larger stroke is used, the wrist flexion/extension ROM can be achieved fully, as well.

Arduino is used as microcontroller. Low level closed loop control algorithm is applied in this study. Position signals are used as feedback signals to control and actuate actuators. The robot can be operated in two predetermined angles with a certain period.

The developed robot can provide both robot active and robot passive modes for rehabilitation exercises. Robot works well in robot passive mode (i.e., patients applies forces and the robot is driven by the patient) whereas robot active mode (i.e., patient's limb is moved by robot) has some limitations. The robot active mode should be modified for suitable force and speed control. In both modes, the position information of wrist and forearm can be reached with respect to time such that improvements in the wrist and forearm motions can be visually shown to the doctor.

Future works will be based on the improvement of control algorithm of the robot by changing type of actuator as well as mounting speed and force sensors on the device. Computer user interface will be intended to be developed for easy operation of the robot as well as an interactive video game can be associated with exercises for better results of rehabilitation.

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CIRRICULUM VITAE

Mustafa DAĞDELEN was born in 1991. He finished high school and started to the Gaziantep University in 2009. He graduated from University of GAZİANTEP in 2014 as a mechanical engineer with first degree in engineering faculty. He started to work at ÇUKUROVA UNIVERSITY as a research assistant in 2014. He also started his MSc studies in 2014. He is studying robotics in his department.

APPENDIX

ARDUINO CODES:

(These codes includes manual control and automatic forearm pronation/supination control.)

```
void Initialize() {
  digitalWrite(10,HIGH);
  digitalWrite(11,HIGH);
}
void StopAll() {
  digitalWrite(10,HIGH);
  digitalWrite(11,HIGH);
  delay(1000);
}
void RotateCW() {
  digitalWrite(10,LOW);
  digitalWrite(11,HIGH);
}
void RotateCCW() {
  digitalWrite(10,HIGH);
  digitalWrite(11,LOW);
}
void pronation() {
  digitalWrite(11,LOW) ;
  digitalWrite(10,HIGH);
}
void supination() {
  digitalWrite(10,LOW);
  digitalWrite(11,HIGH);
}
```

```
void extension() {
  digitalWrite(9,LOW);
  digitalWrite(8,HIGH);
}
void flexion() {
  digitalWrite(8,LOW);
  digitalWrite(9,HIGH);
}

const int positiveamplitude = 40; // positive movement amplitude in automatic movements
const int negativeamplitude = -40;//negative movement amplitude in automatic movements
const int period = 5 ;   // movement period in automatic movements
int var=0;
void setup() {

  Serial.begin(9600);
    pinMode(7, INPUT); //Retract linear actuator button
    pinMode(12, INPUT); //Extend linear actuator button
    pinMode(6, INPUT); //Move rotary actuator in CW button
    pinMode(5, INPUT); //Move rotary actuator in CCW button
    pinMode(13, INPUT); //Manual-Automatic switch on command table

    pinMode(4, INPUT); //Start radial-ulnar deviaiton motion-automatic mode
    pinMode(3, INPUT); //Start forearm pronation-supination motion-automatic mode
```

```
 pinMode(2, INPUT); //Start wrist extension-flexion motion-automatic mode
 pinMode(8, OUTPUT); //Retract Linear Actuator(Relay 1)
 pinMode(9, OUTPUT); //Extend Linear Actuator(Relay 2)
 pinMode(10, OUTPUT); //Rotate  Rotary actuator in CW(Relay 3)
 pinMode(11, OUTPUT); //Rotate Rotary Actuator in CCW(Relay 4)
}
void loop() {
//Button readings
 int manual = digitalRead(13);
 int rotaryCW = digitalRead(6);
 int rotaryCCW = digitalRead(5);
 int extendLinear = digitalRead(12);
 int retractLinear = digitalRead(7);
 int autoforearm = digitalRead(3);
 int autoextension = digitalRead(2);
 int autoradial = digitalRead(4);
int wristValue = analogRead(A0);
int forearmValue = analogRead(A1);
int forceValue1=analogRead(A2);
int forceValue2=analogRead(A3);
int forearmAngle = map(forearmValue,  944,346, 70, -70);
int wristAngle = map(wristValue, 310, 487, 40, -40);
//Manual drive starts here
if (manual == 1) {
digitalWrite(8, HIGH);
digitalWrite(9, HIGH);
digitalWrite(10, HIGH);
digitalWrite(11, HIGH);
```

```
    if (rotaryCW == 1) {
      supination();
    }
    if (rotaryCCW == 1) {
      pronation();
    }
    if (extendLinear == 1) {
      extension();
    }
    if (retractLinear == 1) {
      flexion() ;
    }
  }
//Automatic movements starts
    if (manual == 0 && autoforearm == 1) {
digitalWrite(8,HIGH);
    digitalWrite(9,HIGH);
      for(int i=0;i<=period;i++) {
switch (var) {
  case 0:
  Initialize();
  var = 1;
  break;
  case 1:
  RotateCW();
  if (forearmAngle <= -40) {
    StopAll();
    var = 2;
  }
```

```
  break;
  case 2:
  RotateCCW() ;
  if (forearmAngle >= 40) {
    StopAll();
    var = 1;
  break;
    }
    }
    }
    }
}
```