Master's Thesis
석사 학위논문

# Design of A Clinically Relevant Elbow Exoskeleton Robot for Stroke Patients

Dongjin Lee (이 동 진 李 棟 珍)

Department of Robotics Engineering

로봇공학 전공

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Advisor : Professor Pyunghun Chang
Co-advisor : Professor Sungho Jang

by

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A thesis submitted to the faculty of DGIST in partial fulfillment of the requirements for the degree of Master of Science, in the Department of Robotics Engineering. The study was conducted in accordance with Code of Research Ethics[1]

07. 08. 2015

Approved by

Professor (Advisor) Pyung Hun Chang ( Signature ) Chang

Professor (Co-Advisor) Sung Ho Jang ( Signature )

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[1] Declaration of Ethical Conduct in Research: I, as a graduate student of DGIST, hereby declare that I have not committed any acts that may damage the credibility of my research. These include, but are not limited to: falsification, thesis written by someone else, distortion of research findings or plagiarism. I affirm that my thesis contains honest conclusions based on my own careful research under the guidance of my thesis advisor.

# Design of A Clinically Relevant Elbow Exoskeleton Robot for Stroke Patients

Dong Jin Lee

Accepted in partial fulfillment of the requirements for the degree of Master of Science.

05. 26. 2015

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## ABSTRACT

The number of stroke patients is increasing each year. In this situation and with growing interest in improving the quality of life for the handicapped, rehabilitation robots are growing in importance. Among them, exoskeleton robots will help many disabled and old people to be able to live normal lives. Also, it can be utilized in physiotherapy and occupational therapy.

The purpose of this thesis is the design of a clinically relevant elbow exoskeleton that meets the clinical requirements. At first, the proposed robot was designed to have sufficient torque for passive exercise therapy of post-stroke patients with spasticity (≤ MAS grade 3). Because the therapy of patients with high level spasticity can be hard work for therapists by increased muscle tone, and the patients cannot get enough rehabilitation treatment.

Secondly, the proposed robot was designed to guarantee the safety for the robot-aided passive training of patients with spasticity. Robot-aided therapy can be an advantage in the strength and repetitive motion for alleviation and prevention of spasticity, but it is not trustworthy in safety issues. Thus, a safety algorism that includes catch detection and mode change was applied to this robot system to insure the patient’s safety by providing compliant motion to spastic arm.

Thirdly, medical robot needs to meet the requirements in clinical field. Thus, the proposed robot was designed to have modular feature that is easy to assemble and disassemble with existing hand robot for practical use. It can be useful for therapist’s work and merits as it is able to undercut.

In addition, this robot is also adjustable to 90% of Korean people's arms. In the design of this exoskeleton robot, ergonomic aspects are considered so that therapists can use this robot easily and the patient will be felt comfortable. This robot also can be applied to both the right arm and the left arm through segmentation and reassembly.

Keywords: Exoskeleton robot, Elbow rehabilitation, Stroke, Spasticity, Ergonomic design

# List of Contents

Ⅰ. INTRODUCTION

Ⅱ. BACKGROUND AND CLINICAL FIELD STUDY

Ⅲ. LITERATURE STUDY

Ⅳ. Development Strategy

Ⅴ. SYSTEM DESIGN

Ⅵ. CONCLUSION

# List of Tables

# List of Figures

# Ⅰ. INTRODUCTION

## 1.1 Purpose of Research

Hemiplegia is paretic condition localized to one side of the body. That’s because any damage to the motor cortex on one side of the brain leads to paralysis of the opposite side of the body, as shown in figure 1-1.[1]

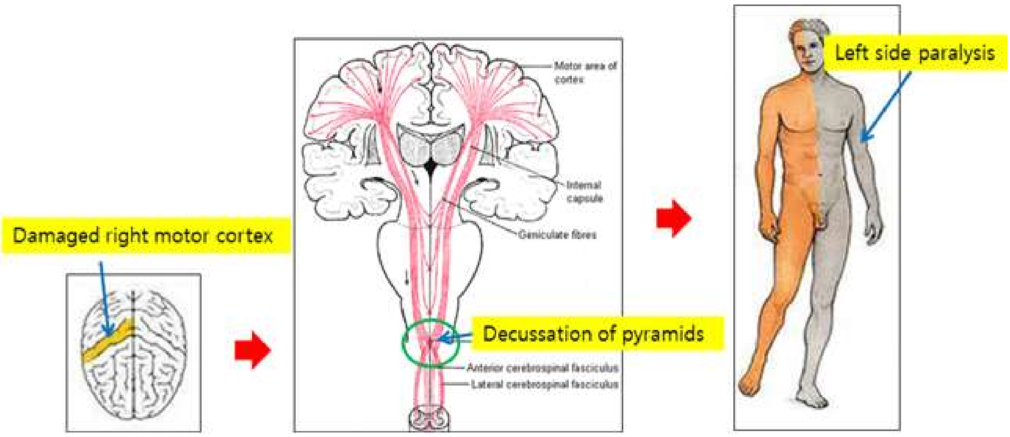


Figure 1-1. Hemiplegia

This is a symptom of stroke and spasticity can be observed in this lesion. Strokes in general are caused by disturbance of blood supply to the brain and can cause permanent neurological damage or death. The risk factors are hypertension, diabetes, hypercholesterolemia, trauma, etc. About 80% of strokes are ischemic strokes by obstruction of a blood vessel.[2] In Korea, the proportion of ischemic strokes among all strokes increased from 43% in 1995 to 65.2% in 2003, as shown in figure 1-2.[3]

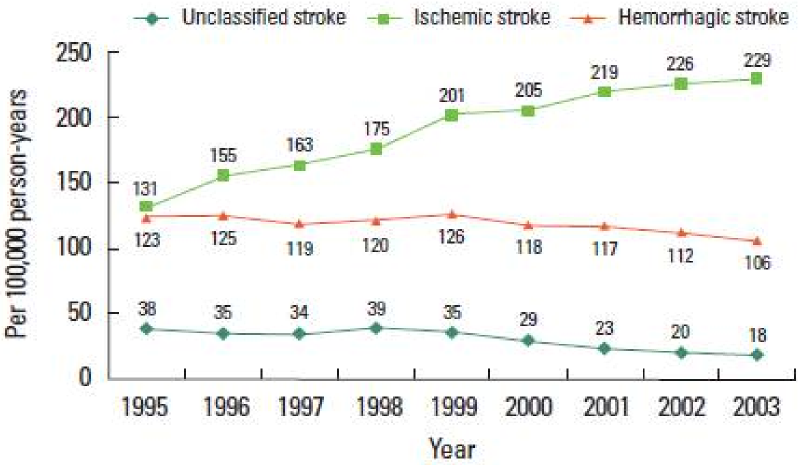


Figure 1-2. Stroke incidence in population with 35-74 years

The number of stroke patients is increasing each year. Also, a research has shown that the quality of life in stroke patient is associated with possibility of their activities of daily life, such as eating, bathing, clothing, toileting, etc.[4] In this situation and with growing interest in improving the quality of life for the handicapped, rehabilitation robots are growing in importance. Among them, exoskeleton robots will help many disabled and old people to live more normal lives as the exoskeleton robots are suitable for prevention of joint contracture, encouragement of the patient’s initiative, and improvement of the quality of life.[5] It can also be utilized in physical therapy, occupational therapy.

Post-stroke patients who have elbow spasticity were often observed in condition of flexed arm at rehabilitation medicine department of hospital. However, when it left without any care, the spasticity will lead to rigidity or contracture and even harder to do daily life because the motion will be restricted with pain. Therefore, early and continuous rehabilitation therapy for spastic elbow joint is absolutely necessary in order to prevent the rigidity and contracture as well as enabling patients to do daily life.

The patients with high level spasticity such as MAS grade 3 may have a considerable stiffness. Therefore, therapists can be a burden to provide an exercise treatment and the patients may not get enough rehabilitation therapy. Also, according to the survey of existing research and robot, it was able to recognize that consideration about patient with spasticity and practical aspects for use in hospital are inadequate yet.

This thesis proposes a design of a clinically relevant elbow exoskeleton robot that meets the clinical requirements and realizes the interactive movement with an existing novel hand exoskeleton for practical use. According to the clinical requirements, the proposed robot includes sufficient power to activate the stiff elbow for patients who have spasticity (until MAS grade 3) and modularity. Above this, it has some features that are easy to wear, adjustability and low cost. The target of this robot is stroke patients who may have spasticity, so safety for spasticity rehabilitation needs to be also considered. Thus, a safety algorithm is applied to this robot system to ensure patient's safety by suppressing excessive movement.

## 1.2 Structure of Thesis

This Thesis consists of the following:

Chapter 2 provides the background needed to understand this research. There will be a description of strokes in general and the symptoms. The therapy methods of stroke patients in hospitals are studied. On the basis of this, specific rehabilitation strategies are arranged for robot-aided therapy in chapter 4.

Chapter 3 understands existing exoskeleton robots and related research. From this work, current status of researches in upper limb exoskeleton robot, and strengths and weaknesses for each robot are examined.

Chapter 4 sets the target of a proposed robot by using the results of field and literature studies. And it will be discussed about what we need to do for our targets. After setting the specific contribution points, the required specifications will be set for each of points.

Chapter 5 explains the process of design and shows the results. Using the 3D design tool (Solidworks 2012), the simulation is conducted. The implementation process and the experiments to verify the achievement will be illustrated.

Chapter 6 concludes this research. There is a summary of this research, the constraints, and the future direction.

# Ⅱ. BACKGROUND AND CLINICAL FIELD STUDY

## 2.1 Stroke and the Symptoms

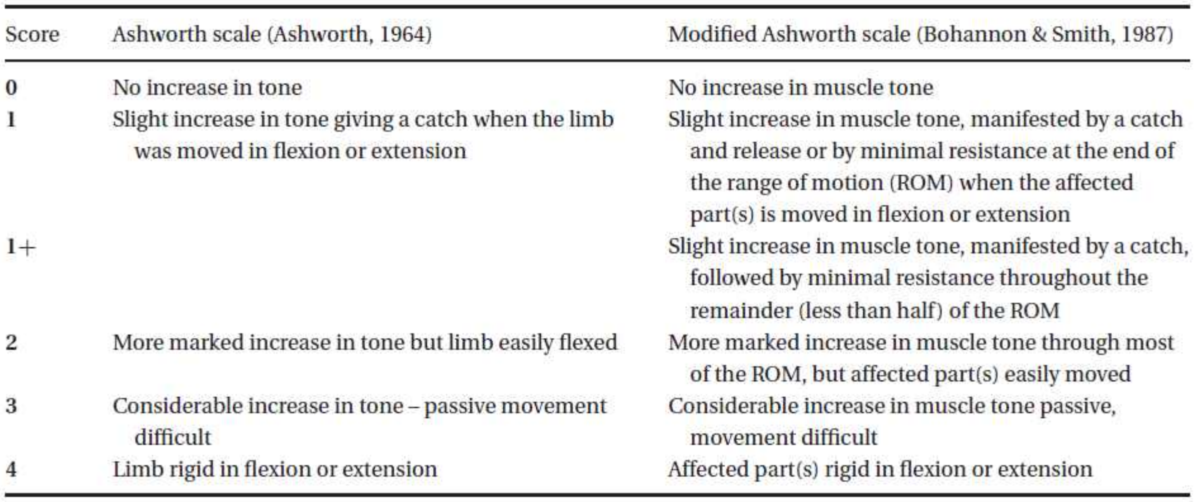
A stroke is a life-threatening cerebrovascular diseases caused by the disturbance of blood supply to the brain. According to the Korean Stroke Society, strokes are the second most common cause of death in Korea.[6]

As for the risk factors, there are hypertension, diabetes, hypercholesterolemia, trauma, etc. About 80% of strokes are ischemic strokes by obstruction of a blood vessel.[2] A leading reason of this is the eating habits consisting mainly of fatty food like meat. This phenomenon is becoming more serious in developing countries. In Korea, the ratio of ischemic strokes among all strokes is increasing more and more.[3]

There are two types of stroke: hemorrhagic stroke and ischemic stroke. Hemorrhagic stroke is due to bleeding from a blood vessel and ischemic stroke is due to closure of a blood vessel. Also, the types of stroke can vary depending on the position of disease, such as middle cerebral artery territory infarction, anterior cerebral artery territory infarction, posterior cerebral artery territory infarction, etc.[7]

### 2.1.1 Spasticity

Spasticity is a common secondary complication following brain injury or spinal cord injury. The most widely used definition of spasticity is motor disorder characterized by a velocity dependent increase of muscle tone in stretch reflexes.[8] Treatment methods are mainly exercise therapy and medicinal therapy. Due to velocity dependent characteristic, the affected part can be also moved easily when slow velocity is applied. But, if the affected part is moved quickly, it is possible to generate jerks or spastic catch. But it depends on who it is. Figure 2-1 represents MAS, most commonly used spasticity measurement index.



| Score | Ashworth scale (Ashworth, 1964) | Modified Ashworth scale (Bohannon & Smith, 1987) |
|---|---|---|
| **0** | No increase in tone | No increase in muscle tone |
| **1** | Slight increase in tone giving a catch when the limb was moved in flexion or extension | Slight increase in muscle tone, manifested by a catch and release or by minimal resistance at the end of the range of motion (ROM) when the affected part(s) is moved in flexion or extension |
| **1+** | | Slight increase in muscle tone, manifested by a catch, followed by minimal resistance throughout the remainder (less than half) of the ROM |
| **2** | More marked increase in tone but limb easily flexed | More marked increase in muscle tone through most of the ROM, but affected part(s) easily moved |
| **3** | Considerable increase in tone – passive movement difficult | Considerable increase in muscle tone passive, movement difficult |
| **4** | Limb rigid in flexion or extension | Affected part(s) rigid in flexion or extension |

Figure 2-1. Spasticity measurement index

### 2.1.2 Contracture

Contracture is a condition of an abnormal limitation of a joint. It is usually caused by prolonged hypertonic spasticity. Once they occur, it is not easy to be exercised or stretched. Thus, the best thing is to prevent contracture from the onset.

## 2.2 Therapy Method for Stroke Patients

Rehabilitation training after having a stroke is important in order to recover motor functions. This is due to the fact that a program like this can help reorganization of the cortex according to the concept of brain plasticity.[9] Also, consistency of this therapy can prevent secondary complications, such as spasticity and contracture.

The strategies for therapy that clinicians can encourage after hemiplegic stroke are as follows : acute hospitalization during the first week, inpatient rehabilitation from second weeks to 6th weeks, outpatient rehabilitation from months 1st to 6th, and individual goal setting beyond 6 months.[10]

In order to observe real stroke patients and the symptoms and the rehabilitation methods, an internship was performed in the rehabilitation medicine department of Yeungnam University Medical Center. Through this internship, overall rehabilitation process could be overviewed. At first, the doctors manage all patients and therapists and make a diagnosis and a prognosis. And, through brain image and the functional recovery, therapeutic aim is set. Thus, they have great responsibilities for patient’s recovery.

### 2.2.1 Rehabilitation in ward

Stroke patients just after surgery cannot help staying in bed, because they are unconscious or cannot move themselves yet. Even among this stage, spasticity or contracture of patient’s limb could become even worse. For this reason, physical therapy for those patients is definitely necessary.

In hospital, there are physical therapists in the waiting room to help these kinds of patients. They go around the ward in a cycle and execute treatment, such as passive articulation exercise and functional electrical stimulation (FES).

### 2.2.2 Physiotherapy

Physiotherapy is a therapy to relieve pain and promote healing. The therapy usually takes no more than 30 minutes. In hospital, there exists a therapy room for physiotherapy. In here, therapists aim to help patients to stand up and walk alone in a right posture.

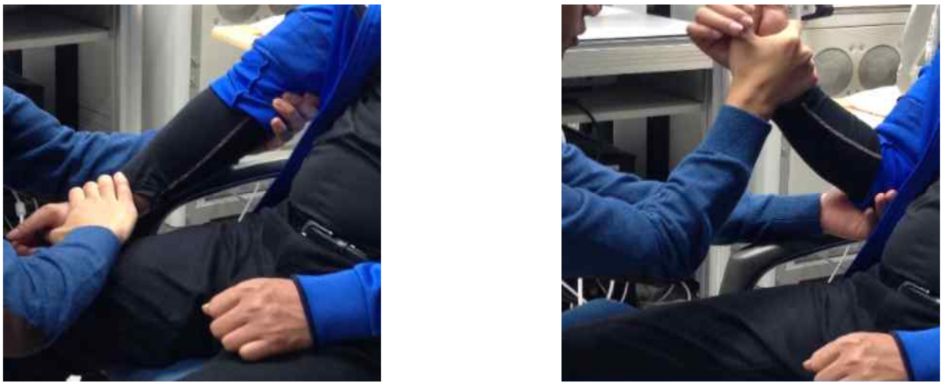
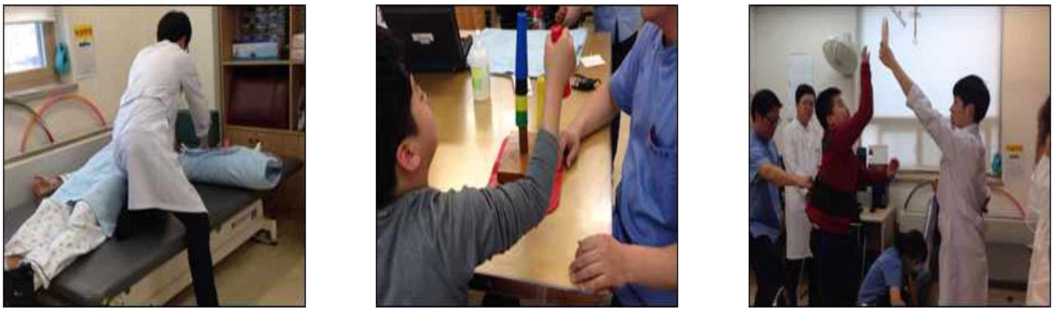


Figure 2-2. Elbow physical therapy

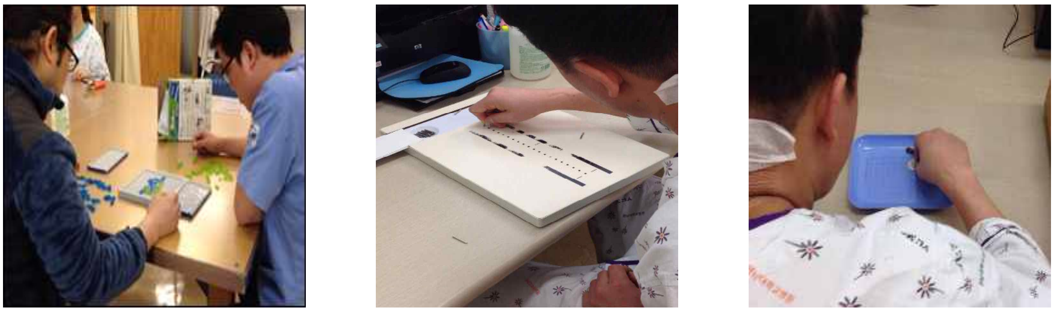
Figure 2-2 shows elbow physical therapy process. Therapist holds the upper arm in one hand and moves the forearm in the other.

### 2.2.3 Occupational therapy

Occupational therapy aims to help that patients are able to do activities of daily living (ADL) themselves. In comparison with physiotherapy, there are more interesting and amusing methods to attract voluntary participation. In this therapy room, the therapy target is mainly concentrated on upper-limb training that is related to ADL. There is variety of methods in occupational therapy to restore the upper-limb function as shown in figure 2-3.



a. passive training b. cup stacking c. reaching



d. board game e. pegboard f. pinch training

Figure 2-3. Upper-limb training

## 2.3 Elbow Joint Anatomy

The elbow joint is a complex joint with the three articulating surfaces between radius, ulnar and humerus. It consists of humero-radial joint, humero-ulnar joint, and proximal radio-ulnar joint. The humero-radial joint provides rotational motion, and the humero-ulnar joint provides hinge-type motion.[7]

The anteriorly measured angle between the upper arm and forearm at maximal extension is averagely 167˚. In lateral view, the extension is commonly 0˚. Hyper-extension (-10˚) is usually possible in children. The angle at maximal flexion is 150˚.

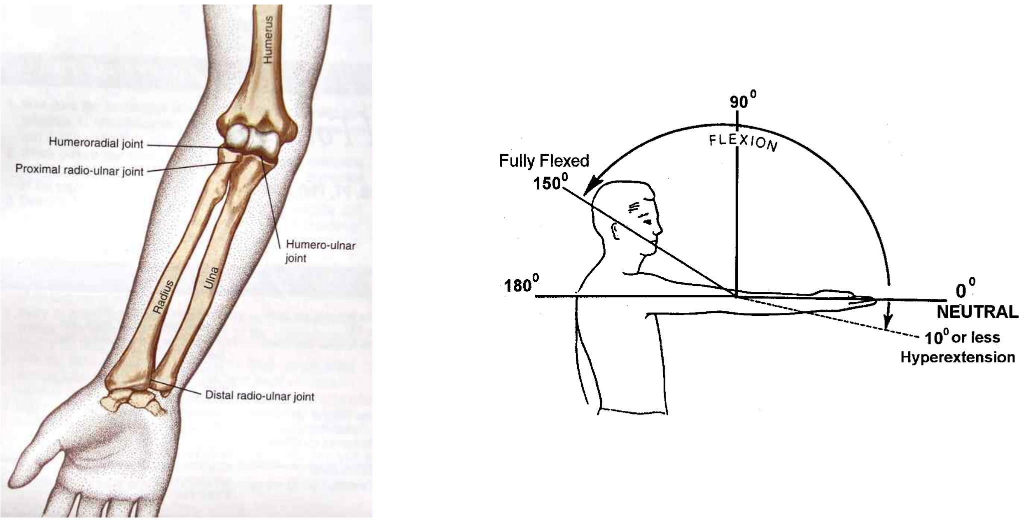


Figure 2-4. Elbow joint anatomy in anterior view[11] and Range Of Motion in lateral view[12]

## 2.4 Perception of Problem

The elbow plays an important role in function of the upper-limb. This intermediate joint between forearm and upper arm allows the hand to reach its objectives. A 50% reduction of ROM of this joint can lead to an almost 80% loss of upper limb function.[13] The figure 2-5 below represents that loss in area of forward reach is increasing according to degrees of elbow flexion contracture.[11]

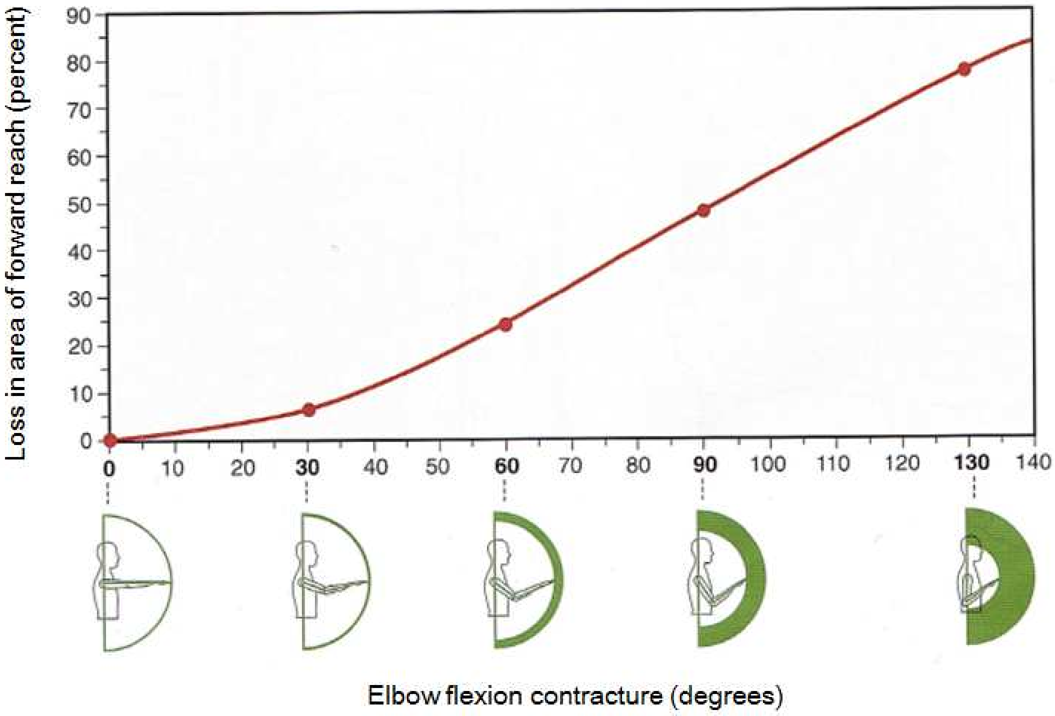


Figure 2-5. Loss in area of forward reach according to elbow flexion contracture

If the flexion contracture is under 30˚, the area of reaching is only reduced until 6%. However, if the flexion contracture exceeds 30˚, the loss in area of forward reach is considerable.

If there was no movement for a long time without any therapy, the elbow is susceptible to get stiffness more and more due to its articular and muscular complexity.[14] Therefore, elbow rehabilitation must be started as soon as possible. Elbow rehabilitation is essential because elbow plays important roles in activities of daily living as shown in figure 2-6.[11]

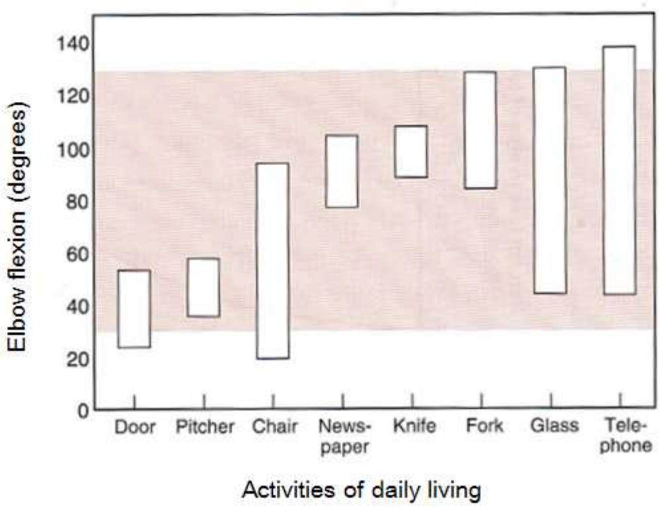


Figure 2-6. Required ROM of elbow joint for activities of daily living

# Ⅲ. LITERATURE STUDY

In this chapter, existing robots were surveyed. From this work, current status of researches in the field of upper limb rehabilitation robots and the strengths and weaknesses for each robot were examined. After that, information through the study is going to make good use. The strength will be strengthened and the weakness will be made up. Design specification will be proposed by comparing with existing robots in chapter IV.

## 3.1 Categorization of Rehabilitation Robot

This part is about categorization of rehabilitation robot. The robot can be classified according to various standards. On the basis of mechanical structure, there are two types of rehabilitation robots: end-effector type and exoskeleton type. The characteristic of end-effector type robots is one point interaction with patients. Thus, it is not able to control each joints of human. But the advantage is easiness of length adjustment by different persons. Contrary to end-effector type, the exoskeleton type robots have several point or plane in order to interact with patients. Therefore, the length adjustment to different body size is more difficult than the former. That's because each segment must be adjusted and required accurate alignment with real joint axis. Nevertheless, it has some advantageous features, such as exact arm posture and separated control of each joint. This feature is important if the subject's elbow flexors are spastic.[15] That is because exoskeleton robot can avoid inducing force to the shoulder which may have shoulder subluxation.

In addition to mechanical structure, rehabilitation robot is also classified on the basis of other standards: stationary type and portable type, assembled type and stand-alone type. Stationary type means that volume and mass of a robot are too big to move somewhere. Almost the whole robots are this stationary type because of the actuator's mass. Naturally, portable type robot doesn't have high power motors but easy to hand-carry.

The target of this rehabilitation robot design is the stroke patients who may have spastic elbow flexors. Thus, exoskeleton type is suitable for that purpose. And, it's modular that can be used as both assembled type and stand-alone type.

In this chapter, it will be reviewed about exoskeleton type robots except for end-effector type robots. Because this thesis is about the design of an elbow exoskeleton. Thus, the category is divided to two types. Firstly, the study about assembled type robot that includes from hand to shoulder as well as elbow will be processed. After that, the study about stand-alone type that focuses on the training of elbow part will be presented. Once again, the design this thesis propose is modular available with two types. Separately, investigation about spasticity purposed robots was carried out.

## 3.2 Assembled Type Robot

First of all, the study about assembled type robots will be presented. Those are MGA exoskeleton, IntelliArm, and ARMin III. These robots are also stationary as many functions and actuators are installed. Let’s start with MGA exoskeleton.

### 3.2.1 MGA exoskeleton[16]

Figure 3-1. MGA exoskeleton

MGA exoskeleton is developed to be used for power assist as well as rehabilitation purpose in Maryland University and Georgetown University in USA. The full name is Maryland and Georgetown Army exoskeleton. Specifically, the maximum torque of this robot is 69Nm based on the point of 72Nm that is comparable to the maximum torque of elbow flexion of the average adult male. It also has simple driving system organized in one axis, as shown in figure 3-1. But the volume is considerably large to the lateral side. Besides, it has disadvantages of unavailability of patients who have hand paralysis, possibility of hitting with trunk. Nowadays, this robot is focused on VR training and shoulder rehabilitation.

| Items | Contents |
|---|---|
| Manufacturer | Maryland University and Georgetown University |
| Driving system | DC motor and linkages |
| Range of motion | 0~142° |
| Maximum torque | 69Nm |
| Weight | No information |

Table 3-1. MGA exoskeleton

### 3.2.2 IntelliArm[17]

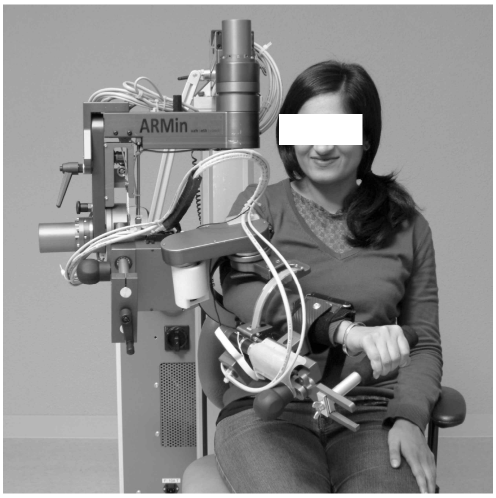
Figure 3-2. IntelliArm

IntelliArm has 7 active degrees of freedom and 2 passive degrees of freedom for effective rehabilitation. For elbow joint, it has a motor at the medial side, as shown in figure 3-2. The advantages are simple mechanism, easiness to wear, and that it is able to move the elbow part and the hand part simultaneously. It is also impossible to be applied to both arms. The maximum torque available at elbow joint is 32Nm that is barely enough torque with overcoming the gravity. Thus, this robot is unsuitable for spasticity purposed exercise therapy that needs sufficient force.

| Items | Contents |
|---|---|
| Manufacturer | Rehabilitation Institution of Chicago (RIC) |
| Driving system | DC motor and linkages |
| Range of motion | 0~130° |
| Maximum torque | 32Nm |
| Weight | No information |

Table 3-2. IntelliArm

### 3.2.3 ARMin III



[redacted]

Figure 3-3. ARMin III

ARMin is widely known as one of the most advanced exoskeleton robots. Until now, ARMin III is latest version and commercialized by the name of Armeo power through Hocoma corporation. This robot has totally 6 degree of freedom. The features are adjustable cuff, adjustable height, and adjustable length. In addition, it can be applied to both arms and it has laser pointer to align with center of glenohumeral joint. The purpose of this robot is ADL training. Like IntelliArm, the maximum torque at elbow joint is 32Nm.

| Items | Contents |
|---|---|
| Manufacturer | Swiss Federal Institute of Technology Zurich (ETH Zurich) |
| Driving system | DC motor and linkages |
| Range of motion | 0~120° |
| Maximum torque | 32Nm |
| Weight | No information |

Table 3-3. ARMin III

## 3.3 Stand-alone Type Robot

Next, the research result about stand-alone type robots are going to reviewed. These types of robots are focused on one target joint that is elbow.

### 3.3.1 WOTAS[18]

Figure 3-4. WOTAS

WOTAS robot was developed by Rocon et al at CSIC in Spain. The purpose of this robot is to assist the daily life, especially by tremor suppression. For this reason, this robot is wearable and light. But, it has low power to be used in rehabilitation of stroke patients.

| Items | Contents |
|---|---|
| Manufacturer | Spanish National Research Council (CSIC) |
| Driving system | DC motor and linkages |
| Range of motion | No information |
| Maximum torque | 8Nm |
| Weight | 850g |

Table 3-4. WOTAS

### 3.3.2 MyoPro

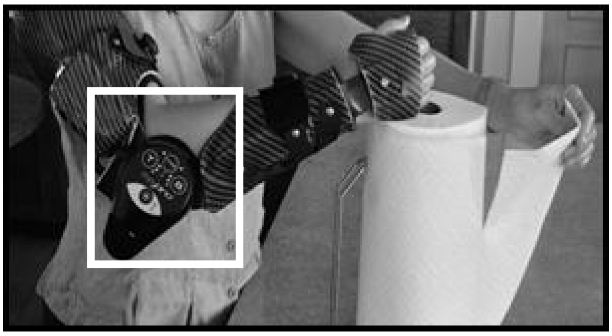


Figure 3-5. MyoPro

MyoPro is originally developed in MIT and commercialized now. This robot assists the movement of paralyzed arm based on the myoelectric signal. It is offered in customizing to fit with the size of each person. The power is low, so it cannot be used to patients who have severe spasticity.

| Items | Contents |
|---|---|
| Manufacturer | MIT and Myomo Inc. |
| Driving system | DC motor and linkages |
| Range of motion | No information |
| Maximum torque | 7Nm |
| Weight | 1.25kg |

Table 3-5. MyoPro

### 3.3.3 MAHI exo II [19]

Figure 3-6. MAHI exo II

MAHI exo II was developed in Rice University and Houston University in USA. The purpose is rehabilitation of forearm for stroke patients. The features are possibility of wearing with both arms by placing the two motors in different directions. But, by doing so, the armpit may be hit with frame or motor. In addition, it has difficulty to wear and ROM(Range Of Motion) is restricted from 0° to 90° due to forearm movement mechanism.

| Items | Contents |
|---|---|
| Manufacturer | Rice university and Houston university |
| Driving system | DC motor and linkages |
| Range of motion | 0~90° |
| Maximum torque | 11.61Nm |
| Weight | No information |

Table 3-6. MAHI exo II

## 3.4 Spasticity purposed robot

As the result of survey, there are two robots related to spasticity. One is MSE[20] and the other is HESS[21]. However, both of them were not provide any rehabilitative exercise. Let's examine them in detail.

### 3.4.1 HESS and MSE

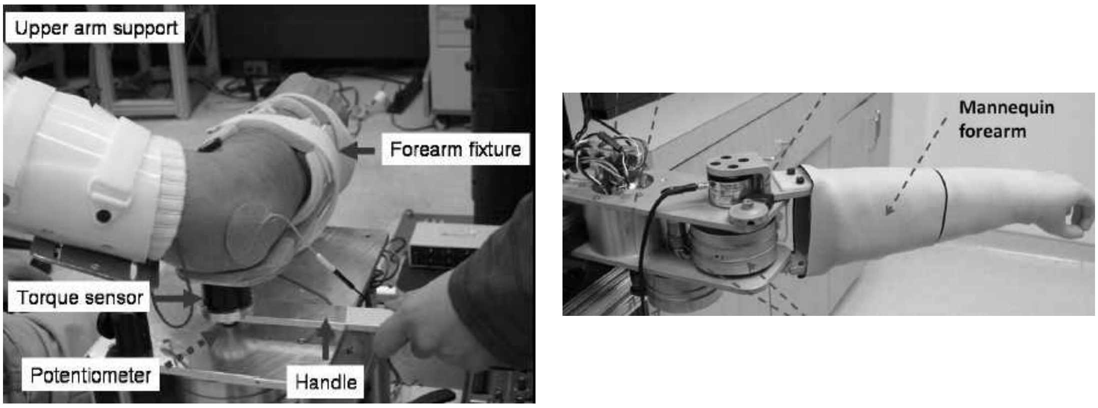


Figure 3-7. Manual Spasticity Evaluator(MSE) and Haptic Elbow Spasticity Simulator(HESS)

At first, MSE is developed to evaluate the spasticity quantitatively. This robot can be used as tool that assesses the catch angle, range of motion and joint stiffness by therapist. Furthermore, it shows that instant velocity and variation of torque are reliable measure to determine the catch angle. The other one, HESS is designed to recreate the clinical feeling of elbow spasticity based on quantitative measurements of MSE. From this system, doctors can diagnosis without meeting patients in person.

# Ⅳ. DEVELOPMENT STRATEGY

In this chapter, it clarifies the target of proposed robot on the basis of the information obtained from chapter II and III. After setting the target, it will be discussed about what we need to do in order to help the target. And then, the required specifications will be set for each of points.

## 4.1 Target Group

As noted in chapter II, rehabilitation about stroke patients is important. Among the symptoms of the stroke patient, spasticity is the most common complication. If the spasticity is neglected for a while, it can lead to rigidity or contracture. Therefore, the situation is going from bad to worse. Also, the patients with high level spasticity such as MAS grade 3 may have a considerable stiffness. Therefore, therapists may have a burden to provide an exercise treatment and the patients may not get enough rehabilitation therapy.

Thus, the main target group is set as post-stroke patients who have spasticity level less than or equal to grade 3 according to MAS (Modified Ashworth Scale). Usually, patients who have MAS grade 4 are treated with medication or surgery.

| | |
|---|---|
| Target 1 (main) | Post-stroke patients with spasticity ( ≤ MAS grade 3 ) |
| Target 2 | Emergency patients (unconscious) or Acute patients |
| Target 3 | Chronic patients |

Table 4-1. Target group

In addition, the prevention of spasticity needs to be started early. Thus, second target is emergency or acute cate patients. Lastly, the third target is set as chronic patients who have incomplete recovery of upper-limb, even though the lower-limb was pretty recovered.

## 4.2 Target Environment and tasks

Target environment is hospital, especially rehabilitation medicine department. In that place, the person who meets the patients and gives treatment is therapist. Thus, the main real user of rehabilitation robot to be designed can be regarded as physical therapist and occupational therapist. For use in hospital room, rehabilitation robot needs to take up not that much space, so it can be used in ward, as well as physical therapy room and occupational therapy room. In addition, medical devices must satisfy the requirement of hospital administrators, as well as users such as therapists and patients.

Upper limb of most stroke patients is flexed. Thus, it needs to be stretched through physiotherapy. The first strategy for movement is repetitive exercise. This exercise can also help to recovery the weakness and prevent contracture by providing passive ROM movement. The second strategy is active resistive exercise. In active mode, robot is not supporting patient’s movement. Thus, patients must move their arm spontaneously. According to the patient’s capacity, the degree of difficulty can be adjusted by controlling impedance parameters.

## 4.3 Strategy Setting

In this section, it is going to fix the points about what we need to do for target group, target environment and target task.

First of all, our main target group is post-stroke patients who have spasticity. Most of stroke patients have this spasticity although the degree is various. The rehabilitation of spastic arm is necessary because it may lead to contracture or pain if the spasticity is left untreated. According to MAS as an indicator of spasticity, grade 4 represents that the affected part is already rigid in flexion and extension. Thus, therapeutic exercise is applicable in less than grade 3. Even if it were so, MAS grade 3 indicates that the movement is not easy because of considerable increase in muscle tone. Therefore, treatment of the spasticity especially in grade 3 can be hard work for therapists and insufficient for patients. As the result, we are going to design the robot that has sufficient torque for rehabilitation of spastic arm with MAS grade 3.

Secondly, the target environment is hospital. For use in hospital, several problems must be resolved such as cost constraints, equipment size, and usability issues.[15] When the proposed rehabilitation robot proves its efficacy better than conventional methods, hospital administrators will accept the device. Thus, we need to design the robot that can meet the requirements above. Accordingly, the proposed robot will have modularity so it can be assembled and disassembled for practical use. It also makes possible the hospital to use the device in cheaper price since it is available as each module.

Lastly, it is about the target tasks. Our main target task is passive exercise that is helpful to recovery of affected part and prevention of contracture. Rehabilitation robot has good merits to provide the repetitive and accurate exercise. However, it may not respond well to any disturbance compared to human so it can lead to safety issue. Post-stroke patients with spasticity may have symptoms such as rapid muscle contractions, muscle spasm, and exaggerated tendon jerks. Thus, we need to design the robot safe for any disturbance during passive exercising therapy.

| | |
|---|---|
| Point 1 | Proposed robot is supposed to have sufficient torque for spastic arm<br>( ≤ MAS grade 3 ) |
| Point 2 | Proposed robot is supposed to guarantee safety for robot-aided therapy of patients with spasticity |
| Point 3 | Proposed robot is supposed to modular for practical use in hospital |

Table 4-2. Strategy setting

Several types of rehabilitation robots were examined before (Chapter III). Among them, the assembled type robots have no choice but to accept their stationary property. Meanwhile, the functions and the power are quite good compared to the stand-alone type. Also, this type of robot is expensive and unwelcomed to hospital. On the other hand, the stand-alone type robots are cheaper than the former. But, it tends to not satisfy clinical requirements, such as power. Under the three kinds of points, the proposed robot has the following features in comparison with existing robots.

(*: point1, **: point 2, ***: point3)

| **Criteria** | **Assembled type robots** | | | **proposed robot** | **Stand-alone type robots** | | |
|---|---|---|---|---|---|---|---|
| | **MGA** | **IntelliArm** | **ARMin III** | | **WOTAS** | **MyoPro** | **MAHI exo II** |
| Maximum torque* | 69Nm | 32Nm | 32Nm | 59.78Nm | 8Nm | 7Nm | 11.61Nm |
| Consideration about Spasticity** | X | X | X | O | X | X | X |
| Modularity*** | X | X | X | O | X | X | X |
| Availability to both arms | X | X | O | O | X | X | O |
| Production cost | High | High | High | Low | Low | Low | Medium |

Table 4-3. Comparison with existing robots and arrangement of characteristics

## 4.4 Required Specifications

In this section, the required specifications will be set to realize each strategy points. First of all, it is necessary to know how much force therapists need to move spastic arm of post-stroke patients according to point 1.

Before the specific design, the actuators for moving part should be carefully decided. Mostly, stroke patients with spasticity have spastic flexion syndrome.[22] So, it needs to know the force necessary to extend the elbow. Thus, it goes through experiment procedure as follows.

Figure 4-1. Digital dynamometer

At first, this experiment is processed for 12 therapists who experienced elbow spasticity of MAS grade 3 and 1 patient of MAS grade 2.5 in Yeungnam University Medical Center. To measure the force, a digital dynamometer, named MicroFet2 is used, as shown in figure 4-1.

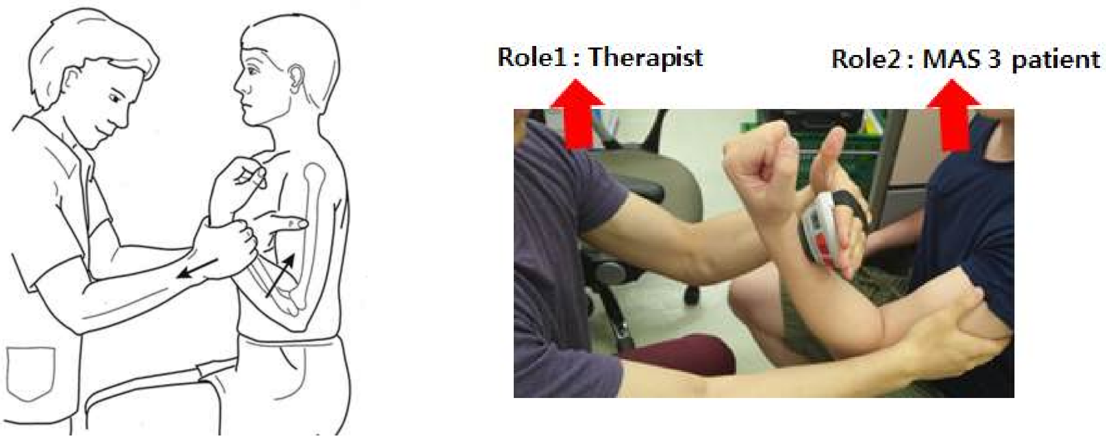


Figure 4-2. Experimental setting

In figure 4-2, Role 1 is therapist who has treatment experience about MAS grade 3 and Role 2 is also skilled therapist enough to mimic the patient with spasticity of MAS grade 3. By using dynamometer, therapist (Role 1) rehabilitates the Role 2 in order to measure the reaction force of the MAS 3 patient. The trial is performed in three times per person. As a result of experiment, the maximum force is obtained. The value is 171.8N.

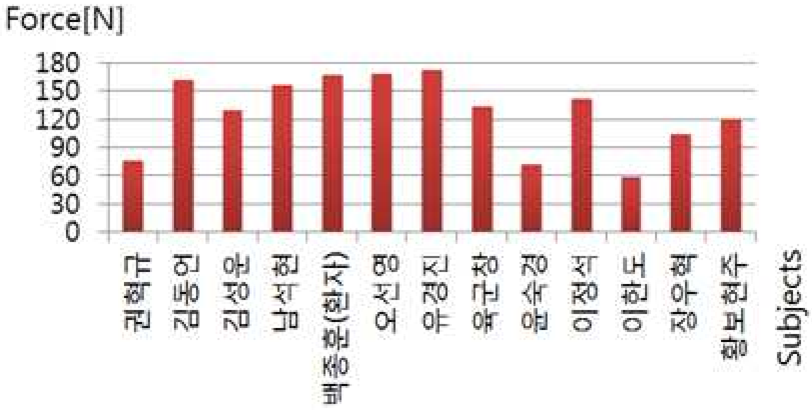


Figure 4-3. Maximum force of each subject

Based on mean value of elbow-wrist length, the torque that is required to move human elbow joint is calculated as below.

$$\begin{aligned}\tau_{hj} &= F \times d \\ &= 171.8[N] \times 0.257[m] \\ &= 44.15[N \cdot m]\end{aligned}$$

Not only that, the torque by weight of human arm and existing robot needs to be also considered. The free body diagram and the calculation are as below. The weight of hand robot and wrist robot was measured by using an electronic scale (resolution: 5g). The weight of human hand and forearm utilized maximum values of the statistical data getting from foreign researches.[23, 24] About the length, maximum values of data are used.

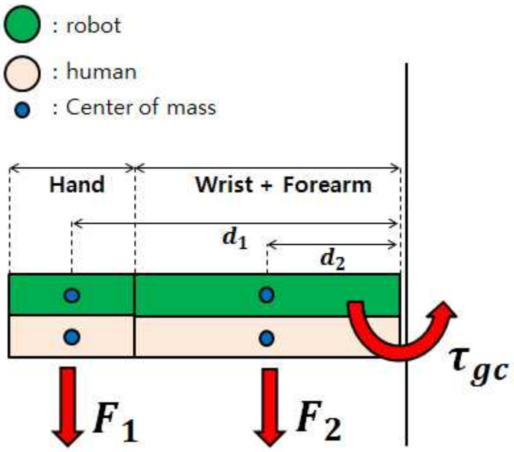


Figure 4-4. Free body diagram

$$
\begin{aligned}
\tau_{gc} &= (F_1 \times d_1) + (F_2 \times d_2) \\
&= (Hand\ robot + Hand)[kg] \times 9.8\left[\frac{m}{s^2}\right] \times (Hand\ half\ length + Arm\ length) \times 10^{-3}[m] \\
&+ (Wrist\ robot + Forearm\ link + Arm)[kg] \times 9.8\left[\frac{m}{s^2}\right] \times Arm\ half\ length \times 10^{-3}[m] \\
&= (1.71 + 0.55)[kg] \times 9.8\left[\frac{m}{s^2}\right] \times (106 + 320) \times 10^{-3}[m] \\
&+ (0.79 + 0.65 + 1.162)[kg] \times 9.8\left[\frac{m}{s^2}\right] \times 160 \times 10^{-3}[m] \\
&= 13.5[N \cdot m]
\end{aligned}
$$

Thus, the required torque is represented as follows.

$$
\begin{aligned}
\tau_{required} &= \tau_{gc} + \tau_{hj} \\
&= 13.5 + 44.15 \\
&= 57.65[\mathrm{N} \cdot \mathrm{m}]
\end{aligned}
$$

Usually, exoskeleton robots are kinematically equivalent to human-limb, so the arm posture can be fully determined depending on the movement of robot. Thus, exact alignment is necessary for proper exercise. For this reason, exoskeleton robot must be designed suitable for the structure of the human body. Before the detail design, this part figures out the design considerations biomechanically.

Firstly, we need to decide the range of motion that can be performed through our proposed robot. Understanding the ROM (Range Of Motion) is the most fundamental element in the design of rehabilitation robot not only in rehabilitation treatment.

| Joint | Range Of Motion |
|---|---|
| Hyper Extension | -10° ~ 0° |
| Extension | 0° |
| Flexion | 0° ~ 150° |

Table 4-4. Elbow joint range of motion

During robot-aided therapy, robot can provide patient with steady and accurate exercise as shown in the graph on the left of figure 4-5. On the other hand, it can neglect any abnormal signs of patients, so the therapeutic robot may have a bad influence on the condition of patient. Thus, we are going to deal with this safety issue. Patients with spasticity may have symptoms such as rapid muscle reflexes (catch), muscle spasm, and exaggerated tendon jerks. If those symptoms occur during robot-aided therapy, robot needs to cope with this problem.

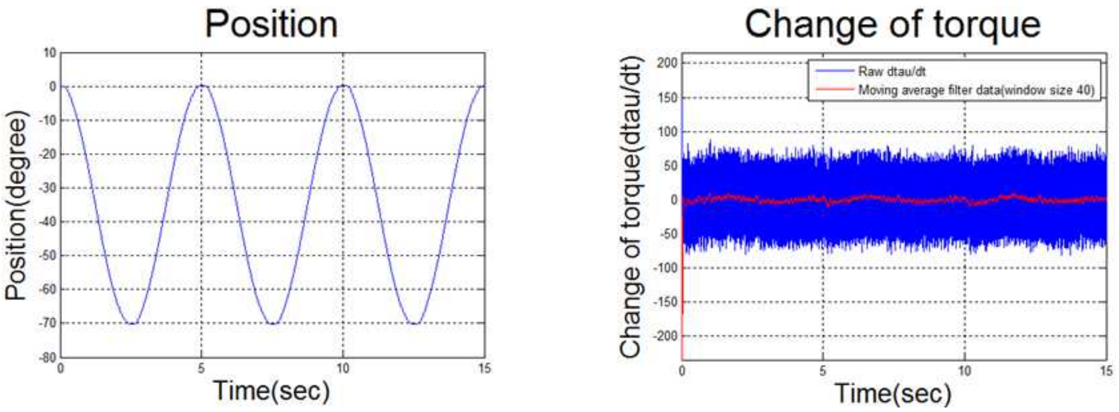
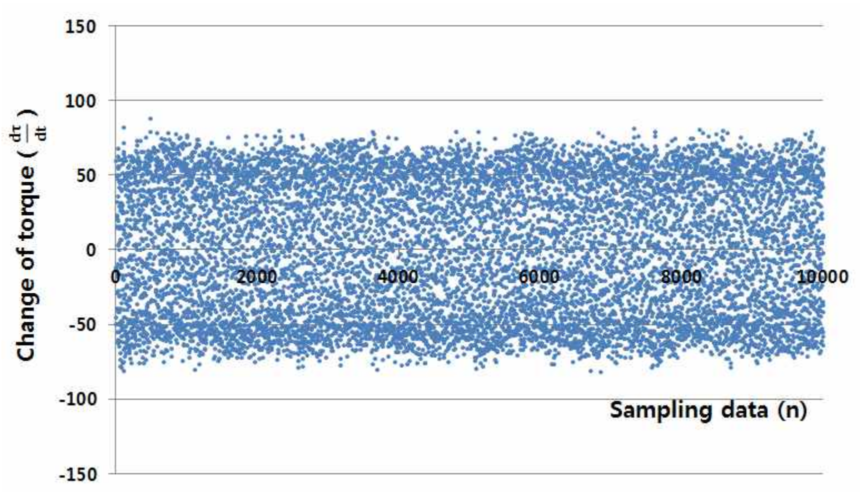


Figure 4-5. Data acquisition during passive exercise without any disturbance

Once, robot has to detect whether any disturbance occurs or not. According to the survey results, dτ(t)/dt was used as a reliable measure to determine the catch angle.[20] So, an experiment was executed to determine the detection threshold. As shown in figure 4-5, dτ(t)/dt values were collected during about 25 seconds without any disturbance.

The sampling time was 2ms and it means that data is collected at 500 times per second. For statistics process, ten thousand of data had been collected during 20 seconds as shown in figure 4-6. The maximum value was 88.15 and the minimum value was -81.59, so the range was 169.73. The average and the standard deviation(σ) were 0.07 and 44.29 respectively.



| | |
|---|---|
| **The number of samples** | 10000 |
| **Range** | 169.73 |
| **Average** | 0.07 |
| **Standard deviation** | 44.29 |

Figure 4-6. Statistics process

According to 68-95-99.7 rule of statistics, 99.7% of the values lie within three standard deviation (3σ). In our system, the standard deviation is 44.29 and 3σ is 132.87. Even so, there is still 0.3% of probability. Thus, we decide the threshold to 7σ which expected frequency outside range is 1/390,682,215,445.

For modular design, several required information is investigated. First of all, the information about forearm length is acquired from statistical data by Size Korea as shown in table 4-5.[25] This information is going to be utilized in practical design, chapter V. Because the hand robot that is combined with proposed robot will limit the users.

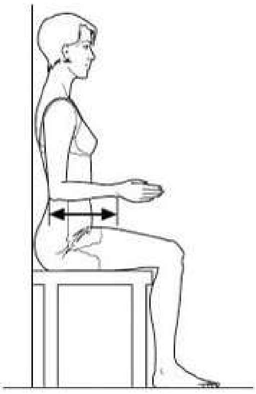


Figure 4-7. Measurement of elbow-wrist length

| **Sex** | **Age** | **Number of participants** | **Mean (mm)** | **The lower 5% (mm)** | **The upper 95% (mm)** |
|---|---|---|---|---|---|
| Male | 20 ~ 75 | 2750 | 267.33 | 237.5 | 293.5 |
| Female | 20 ~ 75 | 2445 | 245.42 | 226.5 | 265.5 |
| Total | 20 ~ 75 | 5195 | 257.02 | 229.5 | 288 |

Table 4-5. Elbow-wrist length

# Ⅴ. SYSTEM DESIGN

In this chapter, the design process of elbow exoskeleton robot will be explained step by step. The explanation includes design process, simulation, and the experiment results.

## 5.1 Design Process

Design process will be explained step by step in accordance with the contribution points. The first thing is about the design of an elbow exoskeleton robot that can provide sufficient torque for stroke patients with spasticity, specifically MAS grade 3. And then, it will be shown that how the robot is designed to modular and practical according to point 3. After overall description about mechanical design, the process of safety design that is point 2 will be explained.

### 5.1.1 Design for Sufficient Torque

First of all, there was consideration about motor, drive, and the mechanism for driving part. A combination of motor and drive must be able to produce more than required torque that was calculated in section 5.1, biomechanical design. Simultaneously, the size and weight of driving part should be also taken into consideration. Thus, various trials are attempted to find a proper combination of motor and drive.

As types of actuator, there is hydraulic actuator, pneumatic actuator, and electric actuator. Hydraulic actuator is powered by oil pressure. Their system is relatively complex and heavy. Pneumatic actuator is powered by compressed air. They are lighter than electric actuator, but it is required special compressor on the outside. Also, these two actuators have a little difficulty of control. Even though electric actuator is heavy than pneumatic actuator, it is easy to control. Thus, electric actuator powered by electric current is selected. Besides, electric actuator can provide high power and is available in wide selection.[26]

As elements that satisfy the requirements, Maxon brushless dc motor (EC-4pole 30), Maxon planetary gear head (GP-42 C), and THK harmonic drive (CSG-20-100) were selected.

EC-4pole 30 GP-42 C CSG-20-100

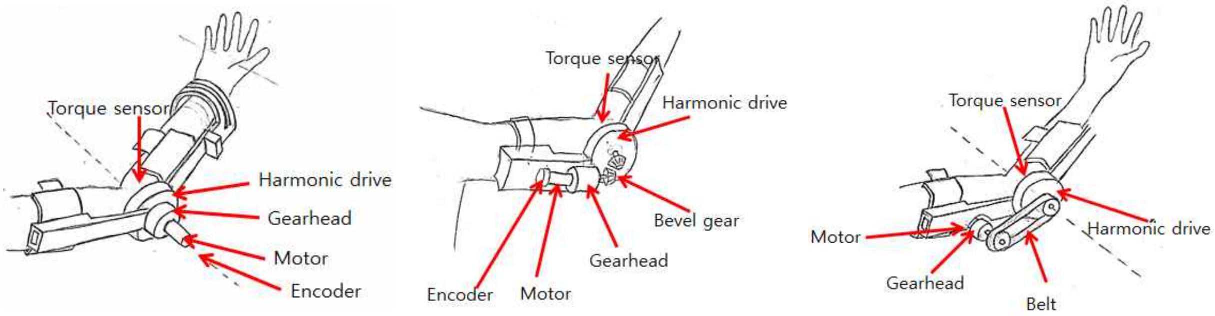
Figure 5-1. Selection of motor, gear, and harmonic drive

EC-4pole 30, a BLDC motor has high power for that volume and weight as brushless dc motor. The specification is 135mNm and 15900rpm, respectively. GP-42 C, a gear head is compatible with EC-4pole 30 and has reduction gear ratio of 6:1 (efficiency: 90%). Lastly, harmonic drive is CSG series of SAMICK HDS and the model number is CSG-20-100. The bigger middle number, it means that the permission torque is bigger. In number 20, the maximum permission torque is 64Nm. The last number, 100 means gear reduction ratio 100:1 (efficiency: 82%). As a result, the output torque is calculated as below.

$$\begin{aligned}\tau_{output} &= \text{Motor torque} \times \mathit{Gear\ ratio} \times \mathit{Harmonic\ drive\ gear\ ratio} \\ &= (135 \times 10^{-3}) \times (6 \times 0.9) \times (100 \times 0.82) \\ &= 59.78[\mathrm{N \cdot m}]\end{aligned}$$

$$\begin{aligned} \mathrm{v}_{output} &= \text{Motor speed } \times Reduction\ gear\ ratio \times Harmonic\ drive\ reduction\ gear\ ratio \\ &= (15900) \times \left(\frac{1}{6}\right) \times (\frac{1}{100}) \\ &= 26.5[\mathrm{rpm}] \\ &= 0.44[\mathrm{Hz}] \end{aligned}$$

In sequence, the location of driving parts determined from above should be chosen. To select the optimal position, it requires careful consideration such as convenient wear and freedom of movement. If the driving parts are located in upper side or medial side of upper arm, it may disturb the flexion motion or hit the trunk of body. Therefore, the location of motor and gear should be located in lateral side or lower side of the upper arm. Under this constraint, the concept design is carried out. Through this work, overall layout of system will be discussed and determined.



Concept 1 Concept 2 Concept 3

Figure 5-2. Concept design for location selection of driving part

In concept 1, all driving parts are arranged in a rows simply. Simplicity of mechanism has the advantage of no friction loss. However, the problem is that the length in the lateral side is so long (about 200mm). Concept 2 utilized bevel gear and put the motor on the lateral side next to upper arm. By using bevel gear, it was tried to make up for the weakness, but it didn’t also be a good alternative as the bevel gear’s own weight and volume are heavy and occupies much space. Moreover, Bevel gear has big backlash. Thus, concept 3 is suggested. Concept 3 makes the best use of its space that is lower and lateral side of upper arm. Motor is placed under the upper arm that is lower side of upper arm, and harmonic drive is located in the lateral side of elbow joint. These two elements are connected by belt.

### 5.1.2 Practical Design

In this section, it’s going to explain how to design the robot modular for practical use while explaining the process continuously.

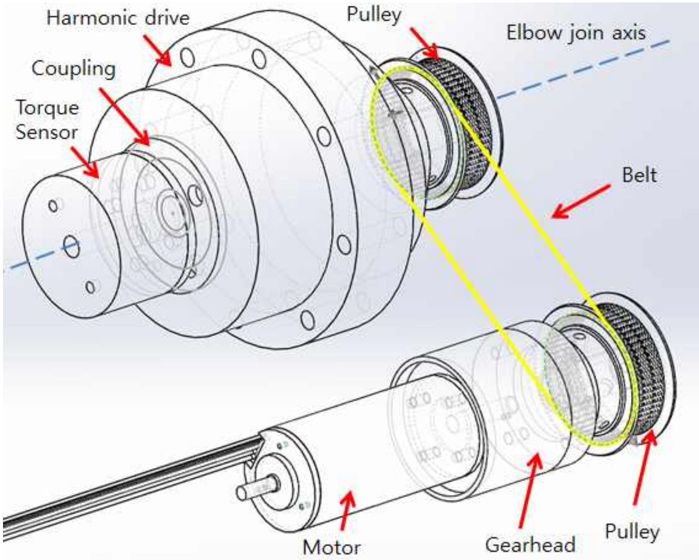


Figure 5-3. Arrangement of driving elements

Continuously, the arrangement of driving elements is implemented in 3D CAD tool (Solidworks), as shown in figure 5-3. By using a timing belt and pulleys, two mechanical devices (motor and harmonic drive) are accurately interlocked. The pulley is high torque timing pulley (HTPA60S2M100-B-N12) of MISUMI. The material is duralumin (A2024) processed by alumite, and the number of teeth is 60. Outer diameter is 37.69mm, and the diameter for hole of axis is 12mm (key way: 4mm).

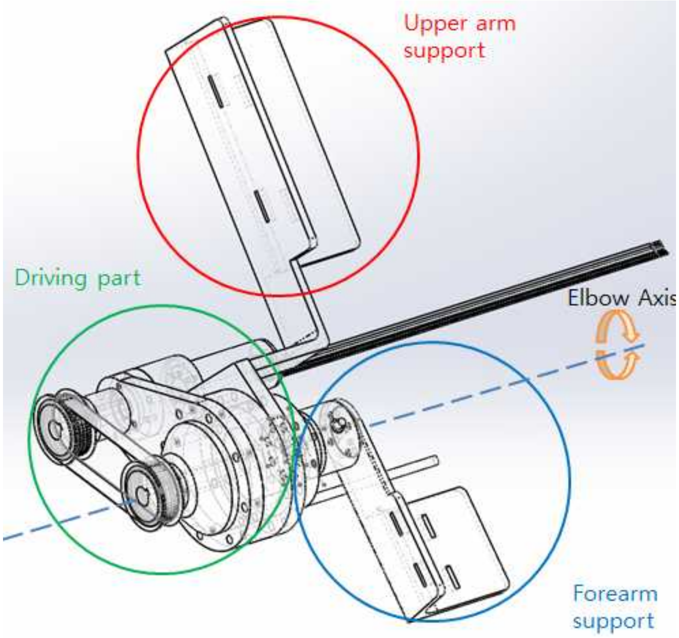


Figure 5-4. 3D CAD drawing based on the concept design

Based on the position of driving part, upper arm support and forearm support are designed sequentially, as shown in figure 5-4. Upper arm support will serve as immobilizing the upper arm during elbow therapeutic exercise. Forearm support acts a part in moving the elbow joint actually. The dotted line in figure 5-4 represent rotation axis of the robot as well as elbow joint axis. The three parts (driving part, upper arm support, forearm support) coupled with one another as follows.

Above all, bodies of motor and harmonic drive are fastened so that only power transmission shaft is rotated when it start a motor, as shown in figure 5-5.

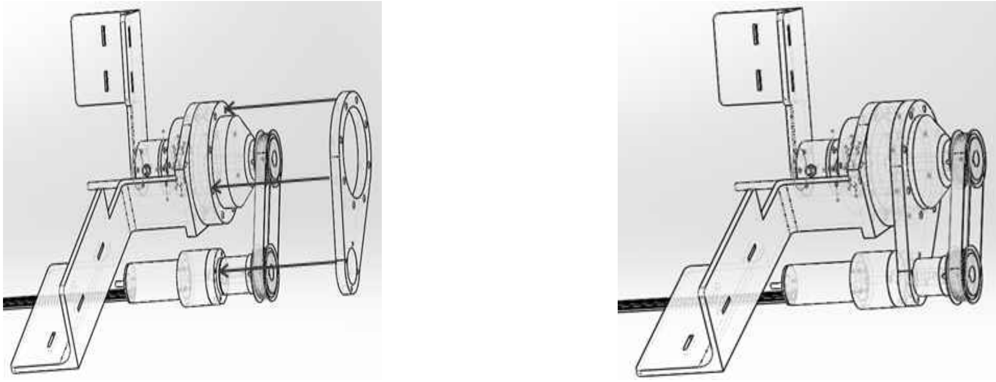


Figure 5-5. Fixation between motor head and harmonic drive

Figure 5-6 and figure 5-7 represent that the support parts how to combine with driving part.

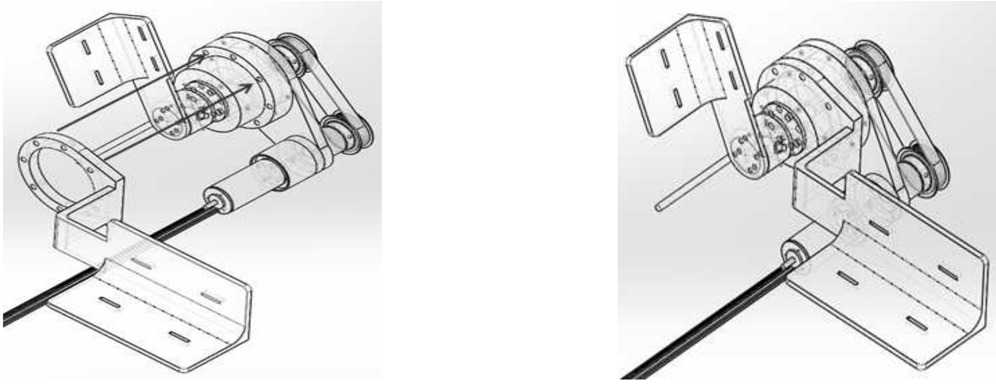


Figure 5-6. Fixation between upper arm support and harmonic drive

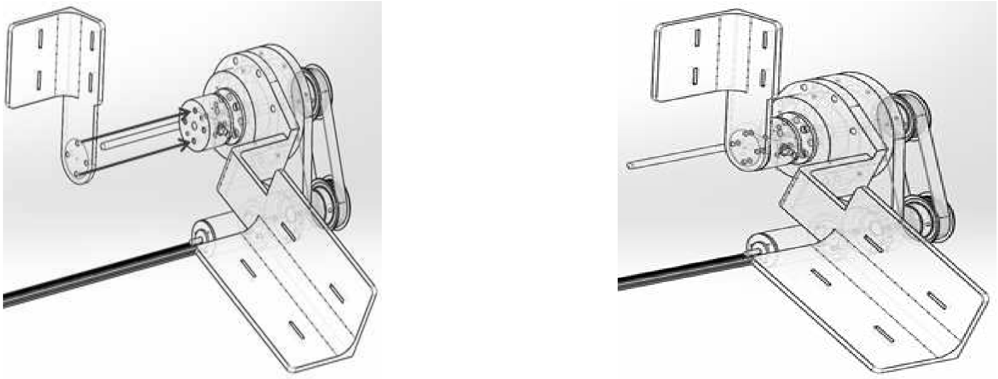


Figure 5-7. Fixation between forearm support and torque sensor

After basic framework is constructed, the combination of existing hand robot and forearm support (forearm link) is considered. But if the elbow exoskeleton has to consider the coupling with hand robot, it should think about length adjustment because hand robot will limit the users by fixing the location itself.

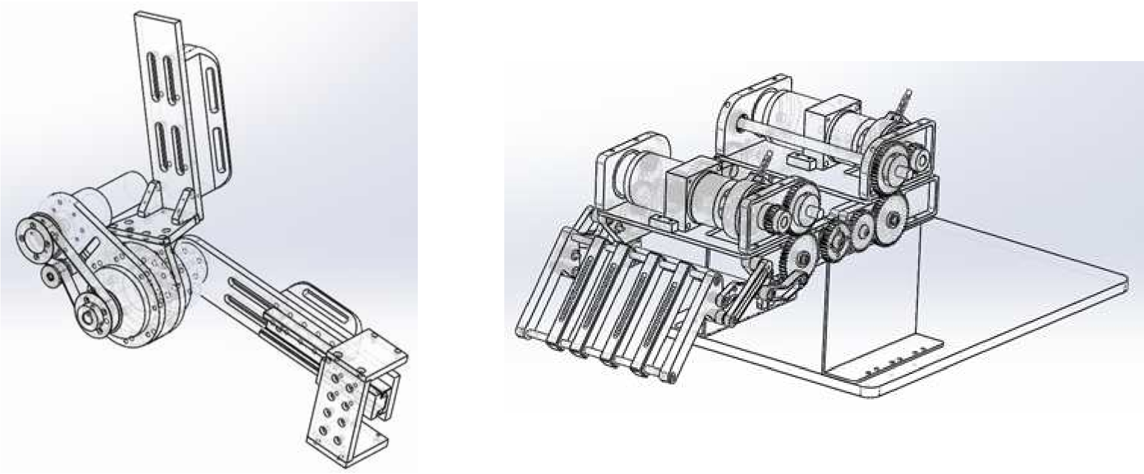


Figure 5-8. Elbow robot and existing hand-wrist robot

Figure 5-8 represents proposed elbow robot and existing hand-wrist robot, respectively. The detail design of the elbow robot was continued until manufacturing and the left one in figure 5-8 shows modified version of the elbow robot. Both of them should be able to be used in actual clinical practice depending on the situation. For example, each robot needs to be moved not only together in order to promote cooperative movement in occupational therapy, but also independently for separate use in certain lesion side.

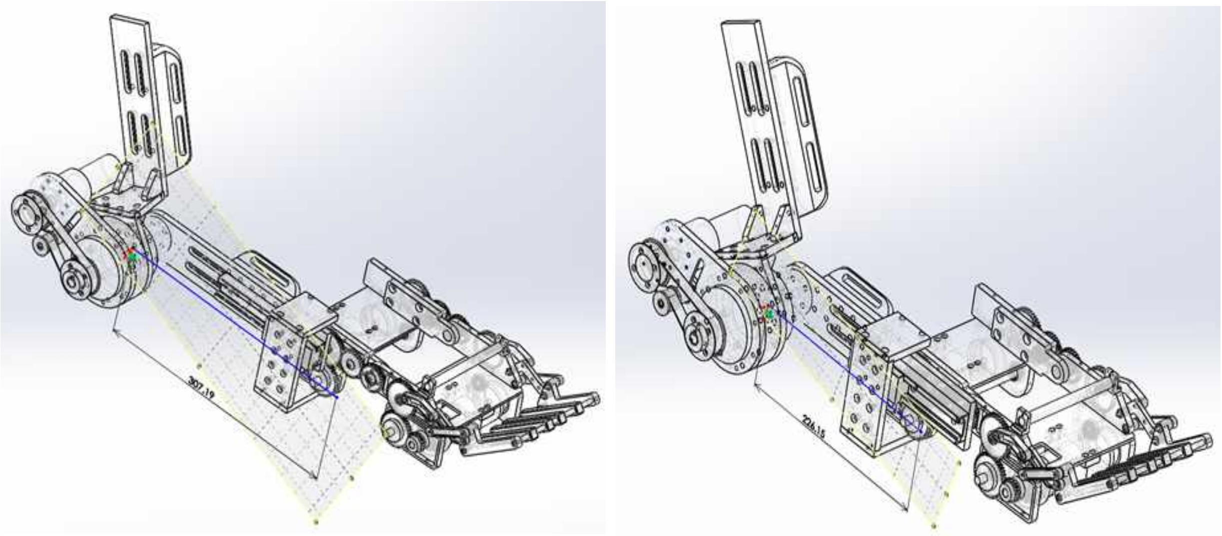


Figure 5-9. Combination of elbow robot and hand robot. Left: maximum length; Right: minimum length

To apply this robot to as much people as possible, length adjustment mechanism is designed as shown in figure 5-9. According to statistical data of table 5-2, the maximum length and the minimum length of forearm link were set. The minimum length (226.15mm) satisfies the lower 5% of female (226.5mm) and the minimum length (307.19mm) satisfies the upper 5% of male (293.5mm).

### 5.1.3 Safety Design

Proposed robot is necessary to consider safety for post-stroke patients with spasticity as well as sufficient force for spasticity. Spasticity can be defined as a motor disorder characterized by a velocity-dependent increase of resistance in stretch reflexes with exaggerated tendon jerks.[8] According to Modified Ashworth Score (MAS), the position that spastic catch or jerks is arising can be different from individual to individual. In the robot-aided therapy, that situation can have an adverse effect by force patient's arm to move. Thus, robot should be able to prevent that situation.

As the solution to the problem, catch detection was proposed. No matter what angle is, when unexpected catch is arising, safety of patients must be guaranteed by preventing the excessive movement. Upon investigation, it was found that spastic catch can be reflected in the changes of torque and instantaneous velocity.[20] In the case of a healthy person who has no catch, the change of torque has no difference during passive exercising. To know the change of torque and velocity, it requires sensors. In this system, two sensors are used: torque sensor and encoder.

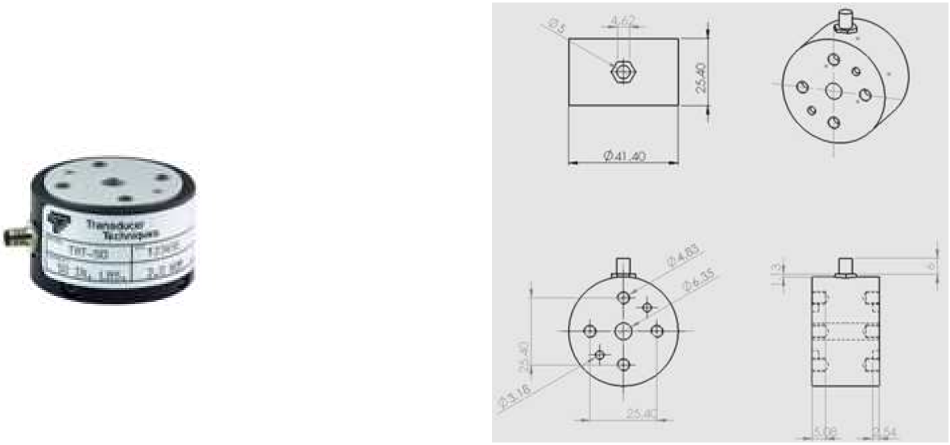


Figure 5-10. Torque sensor (TRT-500)

Torque sensor is TRT-500 reaction torque sensor of Transducer Techniques. The capacity range is 500in-lb and it can express 56.49Nm in newton meter. Although the torque range is a little smaller than the output torque (59.78Nm) of motor, there will be no serious problems for detect the catch. As an encoder, Encoder MR of Maxon motor is used, and the counts per turn are 500 and the maximum speed is 24000rpm. It covers the maximum speed of motor.

Next, a catch detection algorism was designed on the basis of literature investigation and opinion of clinical specialists. At first, the joint degree and the reaction torque must not be exceeded the maximum ROM and torque that requires to care patients with spasticity (MAS grade 3). Therefore, if the measured torque exceeds the maximum torque, it should allow robot to be stopped by measuring real-time torque from sensor. Otherwise, the algorism will continue.

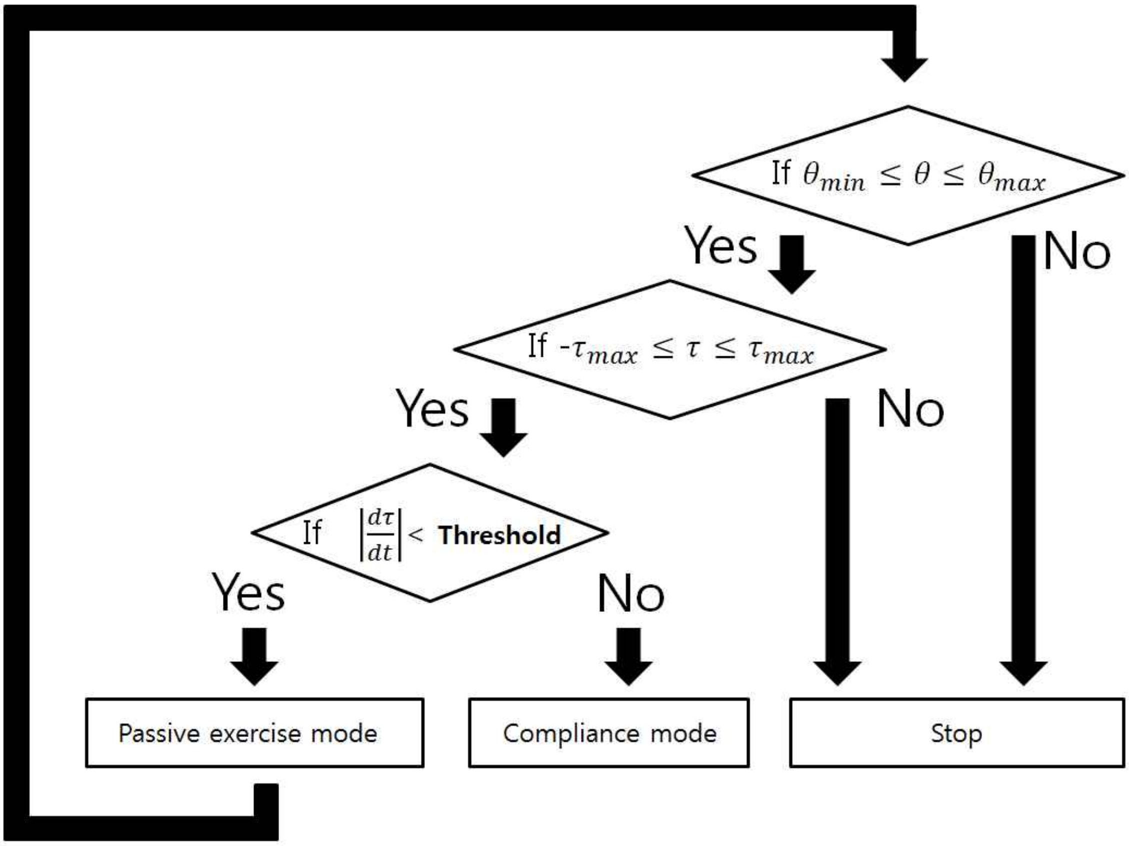


Figure 5-11. Safety algorism

Secondly, based on the torque profile from sensors, the detection is carried out whether catch is or not. If the change of torque is greater than its threshold, robot will be discontinued. If the change of torque is less than the threshold, the algorism of the robot will continue action.

## 5.2 Programmatic Simulation

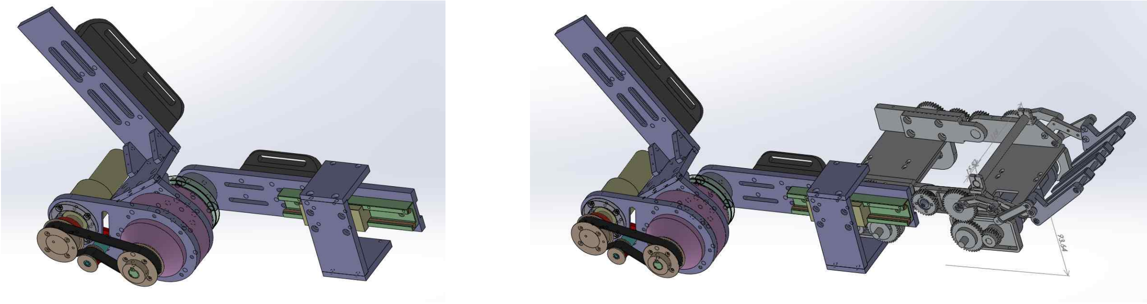


Figure 5-12. Final detail drawing

Figure 5-12 shows the final drawing of the proposed elbow exoskeleton robot. The left one is the elbow robot itself and the right one expresses the combined figure with hand exoskeleton. This detailed drawing was conducted with the assistance of KUNYOUNG Engineering in Daejeon, so that actual machining is possible.

Before the prototyping, a simulation using Solidworks 2012 was also conducted for confirmation. To realize the actual situation, a virtual dummy was used to play a role of a patient. Figure 5-13 appears the proposed elbow robot equipped by the virtual dummy.

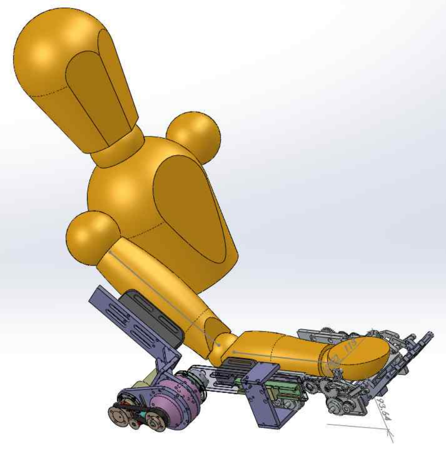


Figure 5-13. Elbow robot equipped by dummy

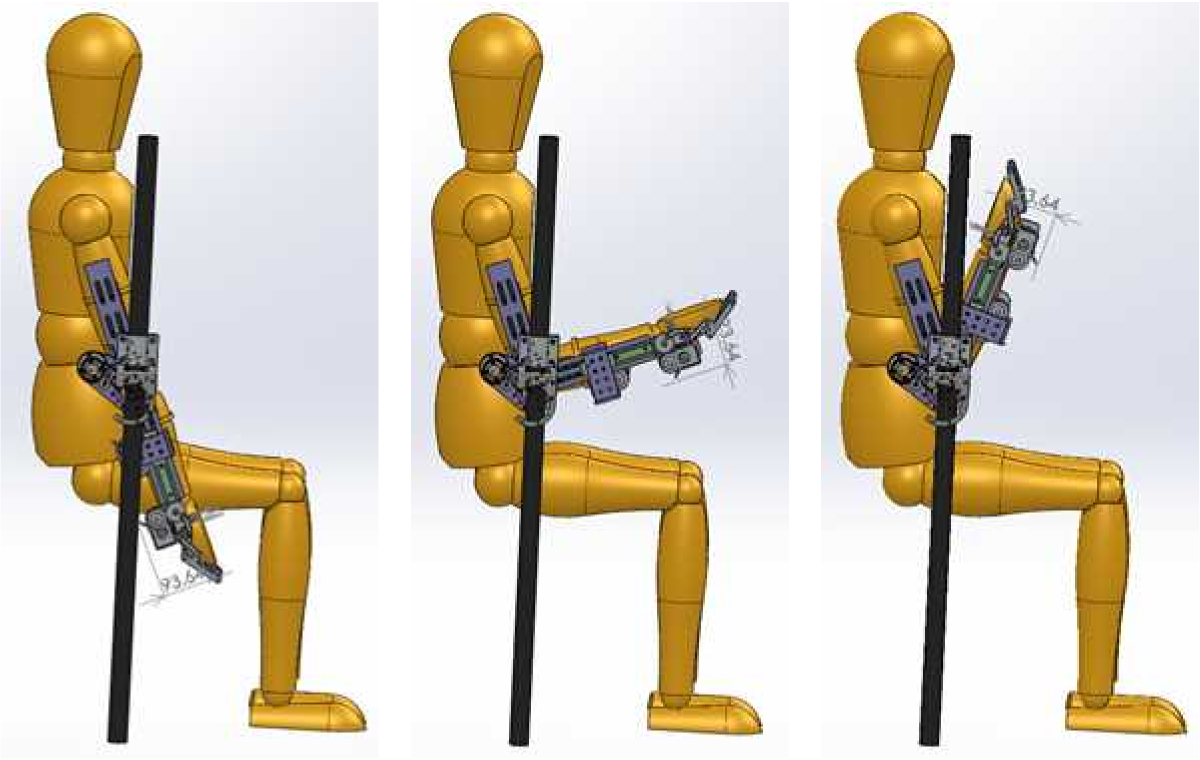


Figure 5-14. Simulation with dummy

## 5.3 Prototyping

After detail design work and virtual simulation through 3D CAD, implementation of the design is started. In this section, the production process will be explained. With the exception of electrical components, linkage frame of the elbow robot is made of duralumin (7075-T6), a kind of aluminum alloy, as shown in figure 5-15.

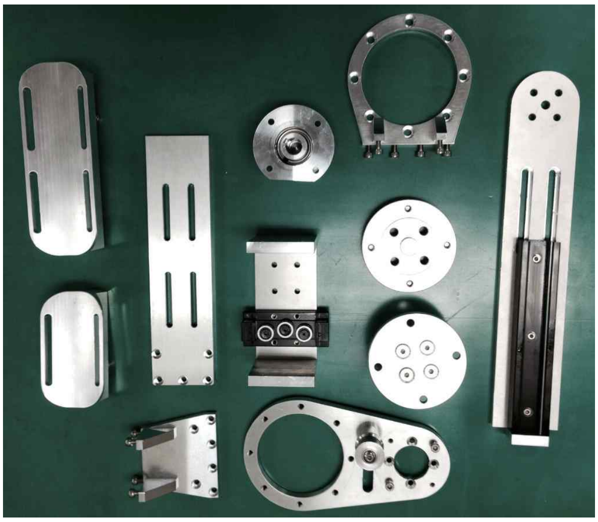


Figure 5-15. Processed components

For assembling of all components, a two days business trip to a manufacturing plant was arranged and the assembly could be finished as shown in figure 5-16.

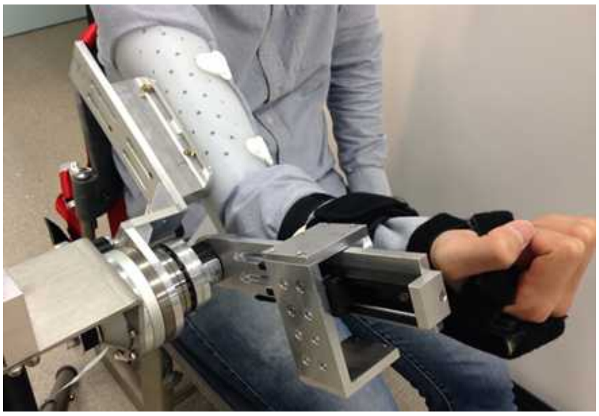


Figure 5-16. Assembled appearance of elbow robot

As mentioned in page 48 of section 5.2.2, the assembled elbow robot is able to combine with an existing hand robot as shown in figure 5-17.

Figure 5-17. Assembled appearance of elbow robot with hand robot

## 5.4 System Architecture

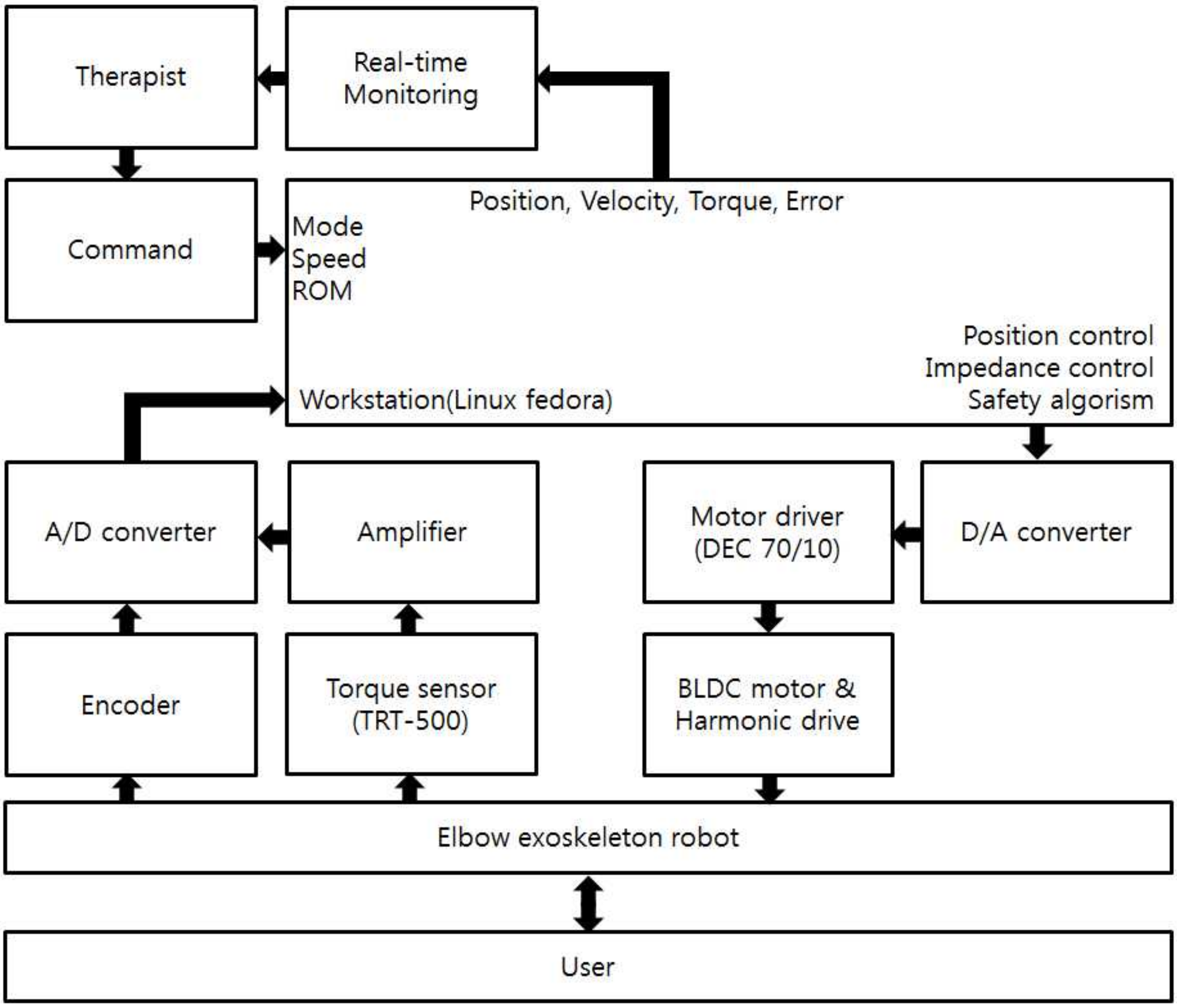


Figure 5-18. System architecture

Overall system architecture is as shown in figure 5-18.

## 5.5 Experiments

For verification of the usability, two experiments were carried out. The first one is an experiment to identify how well the robot works under the maximum torque. And the second one is an experiment to verify whether the robot is able to detect a catch and guarantee patient's safety or not.

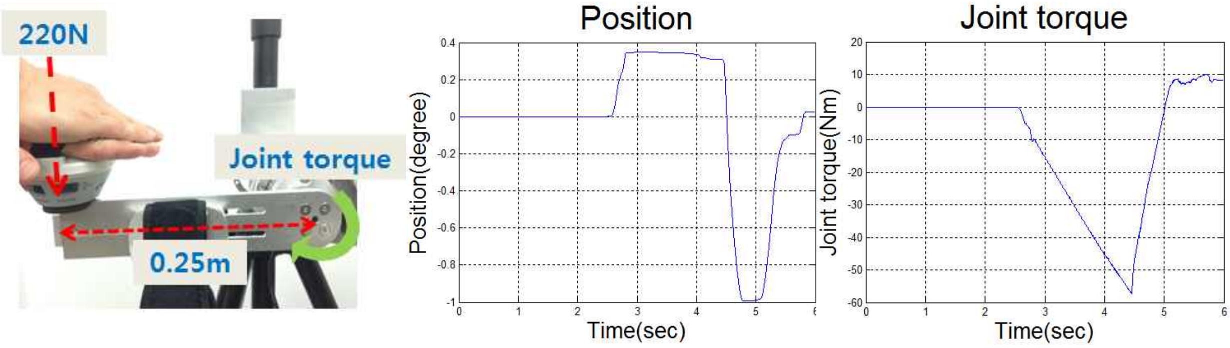


Figure 5-19. Actual test for designed robot's torque capacity

The first experiment was performed under the situation like the left one of figure 5-19. Robot maintains the joint angle in zero degree. And an external force of about 220N was applied at the end of forearm link. The force could be transformed into 55Nm as the length of forearm link is 0.25m. As the result, the position error was about 0.4° under the maximum torque and -1.0° when the force is released suddenly. The right graph of figure 5-19 shows that joint torque was increased until 57.23Nm and it means that the motor capacity of the designed robot is able to cover the maximum torque situation.

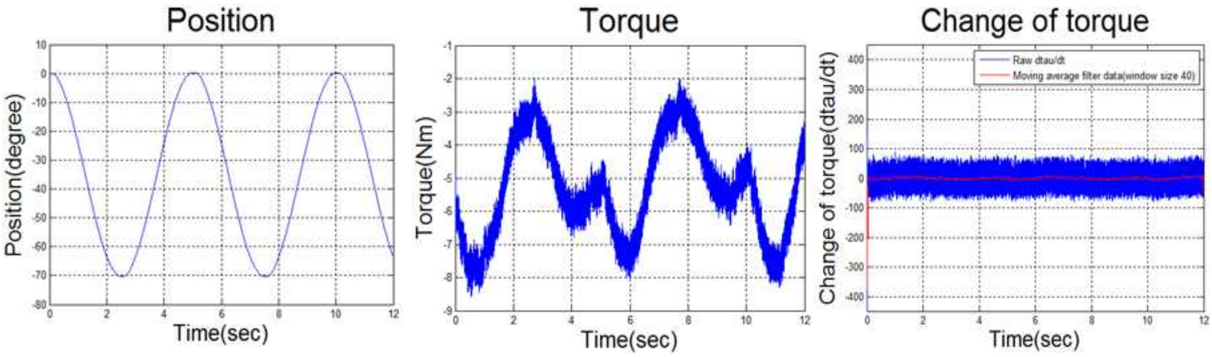


Figure 5-20. Experimental result in passive training without spastic catch situation

Before the verification of catch detection and safety, an experiment was conducted in passive mode without any disturbance (catch) situation. The result is shown in figure 5-20. In this situation, the change of torque (differential value of torque) remains zero although the torque was fluctuated during passive training.

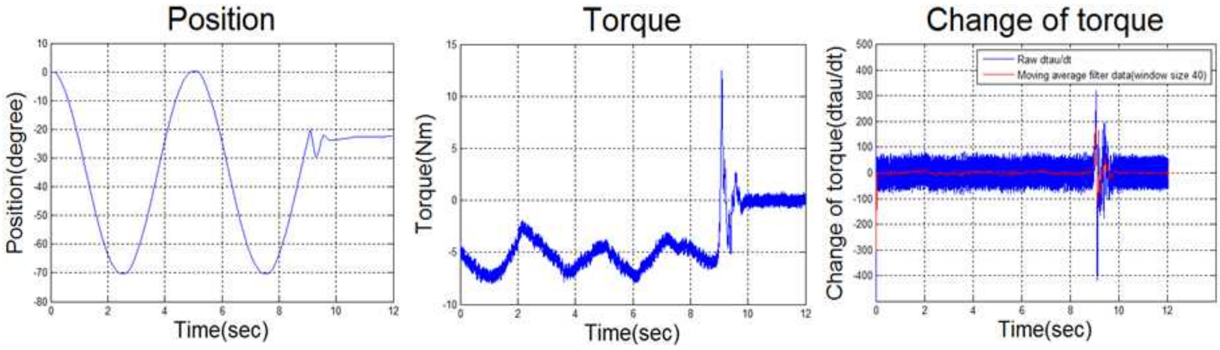


Figure 5-21. Experimental result in passive training with spastic catch situation

Figure 5-21 is an experimental result that represents catch detection and mode change from passive exercising mode to compliance mode for safety. During passive exercising by exoskeleton robot, healthy subject made the sudden disturbance by stopping their arm as shown at 9 seconds in figure 5-21. Accordingly, robot recognizes the moment as catch and changes the mode from forceful passive mode to compliant impedance mode.

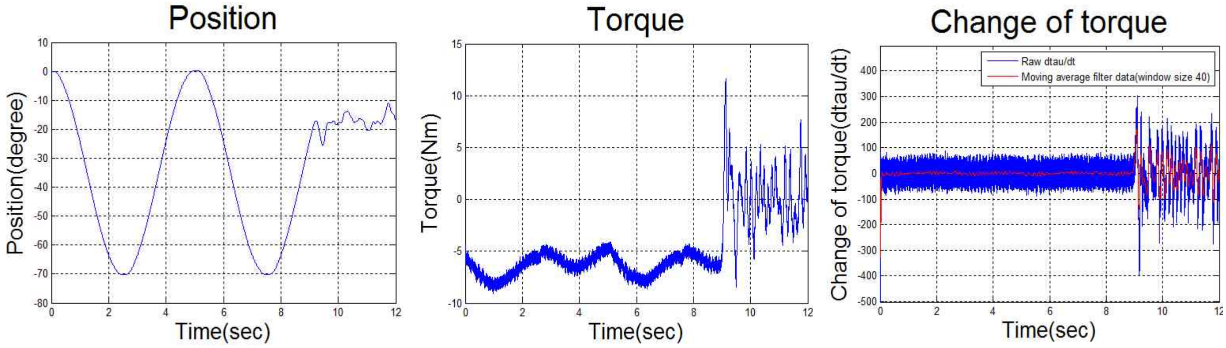


Figure 5-22. Experimental result in passive training with spastic catch and tonic spasm

Another experiment was performed with muscle spasm that continues the contraction of muscle in addition to spastic catch. At 9 seconds, subject who acts the part in stroke patient with spasticity made the sudden disturbance and generated the tremor. Through this result, it indicates that the designed robot is compliable to unexpected situation and it is safe.

# Ⅵ. CONCLUSION

## 6.1 Study Summary

This study was conducted with the aim of trying to help post-stroke patients with spasticity and designed a clinically relevant elbow exoskeleton robot. Based on the field study and literature study, actual problems and the requirements in clinical practice were identified and understood. Accordingly, three main development strategies have been set. Firstly, the proposed robot was developed to help therapies for patients with spasticity. To know the required torque for therapy of spastic arm, an experiment was carried out and the specific design is processed according to required specification. Consequentially, the output torque of the designed robot is sufficient enough. Secondly, the proposed robot was designed to have structural features of modular for useful clinical application. For this function, specific requirements are arranged and the detail design was continued. Lastly, the proposed robot was created to guarantee the safety for robot-aided therapy of patients with spasticity. Spasticity as a movement disorder varies from mild cases to severe. Also, the symptoms may include spastic catch, exaggerated tendon jerks, and muscle spasms. During passive exercising of patients with spasticity, if the symptom like catch is arising, it can adversely affect the elbow joint. Thus, a detection algorism was applied in the designed robot to sense any spastic catch situation during therapy and guarantee the safety.

In this thesis, the whole process was described in accordance with production procedures from development strategy and concept design to simulation, prototyping, and experiments. And table 6-1 is a comparing table with existing exoskeleton robots. Each row means strategy points respectively and it represents that the proposed robot is clinically relevant compared with other exoskeleton robots.

| Criteria | Assembled type robots | | | proposed robot | Stand-alone type robots | | |
|---|---|---|---|---|---|---|---|
| | MGA | IntelliArm | ARMin III | | WOTAS | MyoPro | MAHI exo II |
| Maximum torque* | 69Nm | 32Nm | 32Nm | 59.78Nm | 8Nm | 7Nm | 11.61Nm |
| Consideration about Spasticity** | X | X | X | O | X | X | X |
| Modularity*** | X | X | X | O | X | X | X |

Table 6-1. Comparison with existing robots

## 6.2 Future Directions

The proposed robot has sufficient torque but it is quite heavy for wearable use. To highlight the advantages of exoskeleton type, weight reduction will be necessary. Cable mechanism can be a viable alternative by placing heavy parts in other positions, such as the back. This system also considered the patients with MAS grade 3 as target, but there may be better management for MAS grade 1 or 2. Thus, the motion of robot according to the spasticity level needs to be studied more. In addition, the design plan of the next version will include consideration about carrying angle and structure of support that would be placed between arm and robot so that the force will be transmitted better and for more comfortable feel for the user.

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# 요 약 문

## 뇌졸중 환자를 위한 임상적으로 적절한 외골격 팔 재활로봇의 설계

현재 뇌졸중 환자의 수는 매년 증가하고 있다. 이러한 상황과 장애인들에 대한 삶의 질을 향상시키고자 하는 관심이 높아지고 있는 가운데, 재활 로봇은 점점 그 중요성을 더하고 있다. 그 중 외골격 로봇은 많은 장애인들과 노인들이 정상적인 삶을 살 수 있도록 도울 것이다. 또한 이 재활로봇은 병원에서 물리치료와 작업치료에 활용될 수 있다.

본 논문은 임상적인 요구들을 충족시키는 임상적으로 의의가 있는 새로운 전완부 재활로봇을 설계하는 것이 목표이다. 먼저, 제안하는 로봇은 임상에서 실제로 환자의 경직된 팔을 치료하기 위한 충분한 토크를 가지도록 설계되었다. 그 이유는 경직도가 높아 상당한 뻣뻣함을 가진 환자들의 경우, 치료사들에게 부담이 될 수 있으며, 그에 따라 환자들은 치료를 충분히 받지 못할 수 있기 때문이다.

둘째로, 제안하는 로봇은 경직을 가진 환자의 로봇 재활 치료에 있어서 안전을 보장하도록 설계 되었다. 로봇 재활 치료는 힘이나 반복적인 동작 면에서는 장점이 있지만, 환자의 안전 문제에 있어서는 사람에 비해 믿을 만하지 못하다. 따라서 제안하는 로봇의 시스템에는 갑작스런 근육의 수축 등을 감지하여 환자의 팔에 로봇이 순응하도록 하는 안전 알고리즘이 적용되었다.

셋째로, 의료 로봇은 임상에서의 요구사항들을 충족시킬 필요가 있다. 따라서 제안하는 로봇은 병원에서의 실용적인 사용을 위하여, 모듈 식으로 기존의 손 로봇과 결합과 분리가 용이하도록 설계되었다. 이는 병원에서 치료사들이 사용할 때 유용한 점이 될 수 있으며, 저가로 공급할 수 있는 장점이 된다.

이 외에도 이 로봇은 한국인 인체 치수 측정 자료를 기초로 거의 모든 사람(90%)의 팔 길이에 따라 조절이 될 수 있도록 하였다. 또한 외골격 로봇을 설계하는데 있어서 물리치료사들의 사용의 편리성과 환자들이 편안함을 느낄 수 있도록 인간 공학적인 측면이 고려되었으며, 오른팔과 왼팔 둘 다에 적용 될 수 있다는 것이 특징이다.

마지막으로, 임상적으로 좀 더 실용적인 사용을 위해, 이 로봇이 가진 센서들을 통하여 환자의 상태를 평가하기 위한 특정한 지표를 치료사들에게 제공할 수 도 있다면 이 또한 장점이 될 수 있을 것이라 생각한다.

핵심어: 외골격 로봇, 팔꿈치 재활, 인간공학적 설계, 뇌졸중, 경직