A task-oriented robotic hand rehabilitation system for post-stroke recovery

Toh, Chen Koon

2015

Toh, C. K. (2015). A task-oriented robotic hand rehabilitation system for post-stroke recovery. Master's thesis, Nanyang Technological University, Singapore.

<https://hdl.handle.net/10356/65032>

<https://doi.org/10.32657/10356/65032>

**NANYANG
TECHNOLOGICAL
UNIVERSITY**

**A TASK-ORIENTED ROBOTIC HAND
REHABILITATION SYSTEM FOR POST-STROKE
RECOVERY**

TOH CHEN KOON

School of Mechanical and Aerospace Engineering

2015

**A TASK-ORIENTED ROBOTIC HAND
REHABILITATION SYSTEM FOR POST-STROKE
RECOVERY**

TOH CHEN KOON

School of Mechanical and Aerospace Engineering

A thesis submitted to the Nanyang Technological University
in partial fulfilment of the requirement for the degree of
Master of Engineering

2015

Acknowledgement

I would like to extend my sincere thanks to Prof. Low Kin Huat for giving me the opportunity to carry out the research work. His continuous guidance, support and valuable advice have always inspired me throughout the course of my master's project. His constructive advice have been imperative for improving my knowledge in the field of rehabilitation robotics.

My deep gratitude goes to Li Lei, for the many fruitful discussions and exchanges, not only in solving the technical challenges in the project, but also on the general topics in robotics. I thank him for the friendship, support and the great moments we shared in the Robotics Research Center. I would also like to thank him for patiently reviewing and proof-reading my thesis.

I must also include the friendly and helpful Mr. Lim Eng Cheng in my acknowledgement, for his coordination and assistance with the procurement and logistics issues. The clean laboratory and neat workshop maintained by him and Ms. Agnes Tan provided me an enjoyable working experience throughout the project.

Lastly, I am especially thankful to my fiancée and family for their sacrifices, understanding, and support during this busy period, while I was trying to balance my time between work, research and family.

Abstract

In emulating physical therapists' role in occupational therapy, the methodology of exoskeleton based rehabilitation robot is widely researched in facilitating the rehabilitation and motion re-learning of post stroke patients. The research focuses on the design and simulation of a hand rehabilitation exoskeleton robot. Unlike the exoskeleton robots for arm and shoulder rehabilitation, hand exoskeleton systems are required to handle the multiple joints on hand with four times the degree of freedom in a confined space. In addition, exoskeleton robot as a physical wearable system requires careful design of human machine interface, in order to ensure the patient's safety and to avoid discomfort or injuries on his hand.

After reviewing different rehabilitation techniques used in post-stroke recovery, the rehabilitation exoskeleton is designed to provide task oriented training guided with Bobath's rehabilitation technique. The robot is designed to actuate and drive the patient's hand in natural motion, while preventing the patient from developing wrong muscle tone. In order to better prepare the patient to regain his self-care abilities, the rehabilitation training with the robot is based on activities of daily living (ADL) exercise, which revolves around manipulation of daily objects.

With reference to the anatomy and kinematic model of human hand, a hand rehabilitation robot utilizing an innovative arc-gear mechanism is designed and built. As the exoskeleton has to be designed at the dorsal side of hand due to space constraint, it is essential for the exoskeleton structure to provide a guided movement which is concentric to the human joints. The arc-gear mechanisms driven by DC motors aimed to replicate an accurate and natural hand movement to exercise patients' hand. State of the art from other institutions will also be discussed to justify the strength of the designed machine. The workspace of the human hand is plotted in the 3D CAD software to verify the working range of the exoskeleton. Amplifiers for the DC motors have been designed and built by utilizing the control signal from NI motion control hardware.

The ADL training chosen for the research is reach-to-grasp. The user is required to reach for a mug and grasp it, before retrieving it back to the original position. The trajectories for the reaching and grasping movements are carefully designed to

provide the natural motion profile. Position control is introduced at task space and joint space level to monitor the motion of exoskeleton. As conclusion to the research, the model is simulated with the NI Softmotion, whereby the motion command is generated from the Labview software to move the 3D model of the hand exoskeleton in Solidworks software. The results from the motion are then compared to the actual reach-to-grasp trajectories performed by healthy persons as reported in various literatures. The motion profile of the planned trajectories actuated by the designed exoskeleton is verified to be similar to the natural reach-to-grasp trajectories.

Table of Contents

Acknowledgement.....	i
Abstract.....	ii
List of Figures	vii
List of tables	x
Chapter 1.....	1
Introduction	1
1.1 Motivation.....	1
1.1.1 Demand and Limited Resources	1
1.1.2 Time Course of Recovery	2
1.2 Objectives.....	3
1.3 Thesis Contribution	3
1.4 Thesis Overview	4
Chapter 2.....	5
Literature Review on Rehabilitation Treatments.....	5
2.1 Introduction	5
2.2 Bobath Approach	6
2.3 Motor Relearning Programme	7
2.4 Discussion and Conclusion	8
Chapter 3.....	10
Review of Hand Rehabilitation Devices.....	10
3.1 Finger Rehabilitation Mechanism	10
3.1.1 Coaxial Driving.....	11
3.1.2 Gliding Joint.....	12
3.1.3 Remote Centre of Motion (RCM) Approach	12
3.1.4 Ventral Driving Mechanism.....	15
3.2 Wrist Rehabilitation Mechanism	17
3.3 Conclusion.....	20
Chapter 4.....	22
Human Hand Anatomy and Modeling	22
4.1 Terminology	22
4.2 Degree of Freedoms.....	24

4.2.1	Fingers	24
4.2.2	Thumb	24
4.2.3	Wrist	25
4.3	Range of Motion (ROM)	26
4.4	Kinematic Modeling of Hand	27
4.4.1	D-H Representation	31
4.4.2	Workspace Analysis	32
4.5	Discrepancies from Real Life Model	38
4.5.1	Intersection of Thumb Joints	38
4.5.2	Hollowing of the Palm	38
4.6	Discussion	40
Chapter 5		41
Design and Realization of Rehabilitation Device		41
5.1	Finger Module	41
5.1.1	Design Concept	41
5.1.2	Mechanical Model and Assembly	42
5.2	Thumb Module	45
5.2.1	Initial Design Concepts	46
5.2.2	Final Design Concept	48
5.2.3	Mechanical Model and Assembly	50
5.3	Wrist Module	53
5.3.1	Design Concept	53
5.3.2	Mechanical Model and Assembly	53
5.4	Assembled Prototype	56
5.4.1	Kinematic Model of the Rehabilitation Robot	56
5.4.2	Verification of the Workspace	57
5.5	Motor Sizing and Calculation	58
5.5.1	Thumb and Index Finger	58
5.5.2	Wrist	60
5.5	Electronics Interface	63
5.5.1	Motion Controller and Software	64
5.5.2	Motor Driver	64
5.5.3	Encoder	66
5.6	Discussion	67

Chapter 6.....	69
Trajectory Planning.....	69
6.1 Stages in Reach-to-grasp.....	69
6.2 Preshaping.....	70
6.2.1 Preshape Posture Determination	70
6.2.2 Determination of Wrist Joint Location for Optimized Grasping Posture	72
6.3 Grasping Tracjectory	77
6.3.1 Logarithmic Spiral Trajectory.....	78
6.3.2 Task Space Control	81
6.4 Reach Trajectory	83
6.4.1 Minimum Angular Jerk.....	83
6.4.2 Joint-based Control.....	84
6.5 Simulation	85
6.5.1 Velocity and Acceleration Profiles	85
6.5.2 Reaching and Grasping Trajectory	88
6.5.3 Grip Size	91
Chapter 7.....	93
Epilogue	93
7.1 Conclusion.....	93
7.2 Future Work	94
Bibliography	96
Appendix	104

List of Figures

Figure 2.1: Bobath technique applied by therapist to guide the correct postural movement.	6
Figure 3.1: Shear force induced by non-coaxial rotation	11
Figure 3.2: Coaxial driving at the side of finger.	11
Figure 3.3: Shifting of joint axis during rotation	12
Figure 3.4: Four-bar linkage driving mechanism.....	13
Figure 3.5: Six-bar linkage driving mechanism.....	13
Figure 3.6: Arc-shape linkage with bearing support.....	14
Figure 3.7: Arc shape linkage with rack and pinion method.	15
Figure 3.8: Arc shape linkage with direct contact.....	15
Figure 3.9: HIFE machine.....	16
Figure 3.10: GIFU hand rehabilitation robot.	16
Figure 3.11: Wrist mechanism of MIT MANUS robot.....	17
Figure 3.12: (a) ARMIN II arm rehabilitation robot (b) Wrist mechanism of ARMIN II.	18
Figure 3.13: The wrist rehabilitation robot with linear actuator in universal joint locked and unlocked mode.	18
Figure 3.14: RiceWrist uses 3-RPS parallel robot for wrist rehabilitation.	19
Figure 3.15: Stewart platform built to provide precise motion for wrist rehabilitation.	20
Figure 4.1: Bones and joints of human hand	23
Figure 1.2: Range of motion (ROM) of human hand.....	23
Figure 4.3: Shape of (a) hinge joint (b) ellipsoid joint (c) saddle joint (d) gliding joint.....	24
Figure 4.4: (a) Center of wrist deviation (b) Axe of wrist flexion and extension	25
Figure 4.5: Hand structure and the annotations used	27
Figure 4.6: (a) Coordinate frame assigned for thumb and index finger model (b) D-H representation for the thumb (c) D-H representation for the index finger	29
Figure 4.7: (a) Isometric view (b) Top view (c) Front view (d) Side view of the workspace for Index finger.	36
Figure 4.8: (a) Isometric view (b) Top view (c) Front view (d) Side view of the workspace for thumb.....	36
Figure 4.9: Combined workspace of the thumb and index finger.....	36
Figure 4.10: Five link thumb model proposed by Giurintano.....	37
Figure 4.11: Arc of palm during hollowing	38
Figure 4.12: Focal point of fingers during certain orientation	38
Figure 5.1: (a) Transmission system of the module (b) Center of rotation at the finger joints.....	41
Figure 5.2: (a) Constraint for the arc gear (b) Torsional constant for the arc gear	42
Figure 5.3: The mounting of finger onto rehabilitation module.	44
Figure 5.4: Failsafe mechanical stopper at the arc gear to prevent overstraining finger joints.....	43
Figure 5.5: The index finger attached to the rehabilitation module.....	45
Figure 5.6: Two variations of thumb module explored and designed.....	46
Figure 5.7: Cross sectional views of hand.	48
Figure 5.8: (a) The palmar abducted position. (b) The radial abducted position.....	47

Figure 5.9: The amount of thumb pronation is 90° which define the center and size of the circle.....	47
Figure 5.10: Section view of the thumb CMC module and the constraints on the arc-gear	48
Figure 5.11: Actuator and transmission system for the thumb CMC module.....	51
Figure 5.12: A passive DOF for thumb pronation compensated with constant force spring ...	50
Figure 5.13: (a) Rest position of thumb MP and DP modules. (b) Flexed orientation of thumb MP and DP modules	50
Figure 5.14: Thumb is overstrained when the pronation motion is not designed into the module.	52
Figure 5.15: (a) Handle-grasping type of wrist rehabilitation robot from the Newman Lab, MIT (b) Splinting on wrist.....	51
Figure 5.16: Wrist module with the arm rest and palm brace	52
Figure 5.17: Wrist flexion module.....	52
Figure 5.18: Arm supination/pronation module.....	53
Figure 5.19: Wrist advance/retract module.....	53
Figure 5.20: Assembled system of fingers and wrist modules.....	54
Figure 5.21: Kinematics representation of the rehabilitation robot	54
Figure 5.22: Workspace of thumb and index finger and their use in verifying rehabilitation robot workspace in CAD design	56
Figure 5.23: Torque calculation for the finger module	57
Figure 5.24: Torque calculation for wrist flexion module	59
Figure 5.25: Torque calculation for arm supination/pronation module.	61
Figure 5.26: Electrical system for servomechanism	61
Figure 5.27: Motion interface and motion controller card from National Instruments.....	62
Figure 5.28: H-bridge motor driver.....	63
Figure 5.29: Direct amplification motor driver.....	64
Figure 5.30: Voltage follower op-amp configuration	64
Figure 5.31: Arm rehabilitation robots	66
Figure 6.1: Preshapes configuration for grasping action	69
Figure 6.2: User's hand is brought into preshapes position by the rehabilitation robot	70
Figure 6.3: During power grasp, the hand grasping axis is not parallel to the object rotation axis, but is inclined to an angle.	73
Figure 6.4: Geometrical analysis for the optimum wrist position to provide a stable grasping.....	72
Figure 6.5: The projection of fingers position and orientation onto the plane that is perpendicular to object axis	74
Figure 6.6: Logarithmic spiral curve in 2D.....	76
Figure 6.7: The projection from grasping frame onto original frame	77
Figure 6.8: The logarithmic spiral trajectory in 3D showing the start position and final position.....	79
Figure 6.9: The control diagram for grasping action	80
Figure 6.10: The joint space control for the wrist module.....	82
Figure 6.11: The kinematic performance of the reaching task.....	84
Figure 6.12: The velocity and acceleration profile of wrist joint during reach-to-grasp	87

Figure 6.13: The trajectories of thumb tip, index fingertip and wrist joint in Cartesian during reach-to-grasp	86
Figure 6.14: Motion trajectories of thumb tip, index fingertip and wrist joint in 2D plane.....	89
Figure 6.15: From left to right, top to bottom are the sequence of animated reaching and grasping action performed by the hand rehabilitation robot	89
Figure 6.16: The plot of wrist velocity and grip size over time for reach-to-grasp training....	91
Figure 6.17: Top image shows the moving velocity of hand in reach-to-grasp exercise, while the bottom image shows the change of grip size during the exercise. NV: normal vision, PV: peripheral vision.....	92

List of tables

Table 3.1: Different categories of attributes and the references	20
Table 4.1: ROM of hand joints	26
Table 4.2: Functional ROM of fingers from Hume	26
Table 4.3: Approximation of segment Length for fingers proposed by Buchholz	28
Table 4.4: Calculated finger length using Buchholz's method	30
Table 4.5: Calculated D-H parameters for four fingers	30
Table 4.6: Calculated D-H parameters for thumb.....	31
Table 5.1: ROMs of prototype.....	55
Table 5.2: Joint torque required on human fingers	56
Table 5.3: Total torque required on each joints	57
Table 5.4: Motor selected for finger modules.....	58
Table 5.5: Maximum torque values applied by wrist joint for 19 activities of daily living (ADL).....	58
Table 6.1 : Angular displacement for each joints at grasping preshapes orientation.....	70

Chapter 1

Introduction

Stroke is the second leading cause of death in the world behind heart disease with 15 million sufferers each year. The rate of stroke worldwide is significant as shown in various literature despite the declining trend in developed countries. In Singapore, cerebrovascular disease was the fourth leading cause of death (8%) and seventh leading cause of hospitalization (2.1%) during year 2009 [1]. The total number of stroke patients is rising over the years due to the ageing of Singapore population, with 4064 cases of hospital admission for stroke in the period 1st July 2010 to 30th June 2011. [2]

1.1 Motivation

1.1.1 Demand and Limited Resources

In Singapore, 63% of the stroke survivors are still moderately or severely disabled three months after the stroke [3]. Most of them need to undertake a period of rehabilitation program in day rehabilitation centers after being discharged from hospital, sharing the facilities with patients suffering from fractures, lower limb amputations and other conditions that impair functional abilities. The number of day rehabilitation centers in Singapore decreased from 29 in year 2007 to 28 in year 2008 [4], while the figure of outpatient attendances rises from 223262 cases in year 2007 to 235229 cases in year 2008 [5]. Not all stroke patients are enrolled into a formal rehabilitation program due to its resource-intensive nature.

According to statistics reported by Tran et al. in a Toronto hospital, 56% of stroke survivors were discharged home in year 1999 (compared to 33% in 1993), 32% to rehabilitation (41% in year 1993), and 11% directly to nursing home or long-term care (26% in 1993) [6]. For local statistics, two to three rehabilitation physicians were managing a maximum of 60 inpatients in year 1983, compared to seven to eight physicians managing up to 100 patients in year 1996. The scarcity in resources has resulted in more stringent selection criteria, focusing on patients with higher positive rehabilitation potential for inpatient rehabilitation.

1.1.2 Time Course of Recovery

In general, post-stroke recovery can be categorized into neurological or functional recovery. Neurological impairments are usually classified using Scandinavian Neurological Stroke Scale (SSS) and its recovery involves the reorganization of brain cells and often associated with the resolution of edema. Functional or adaptive recovery corresponds to the improvement of independency in mobility and self-care and can be measured by Barthel Index (BI).

In the Copenhagen Stroke Study where 1197 acute stroke patients were assessed, 95% of the patients reached the best neurological improvement within 11 weeks and best activities of daily living function within 12.5 weeks [7]. Dobkin reported that 95% of stroke patients achieved best upper extremity strength and function with Barthel Index subscores for grooming and feeding in a community study. Patients who are able to flex and extend their affected fingers and wrist within three months, showed continual improvement for more than a year in specific practiced tasks [8].

The neurological recovery is most effective during the first three months post-stroke while the functional recovery can extend to months after neurological recovery is completed. Hence, it is important to enroll stroke patients in rehabilitation program as early as possible, although this is often met with challenges from increasing number of patients and the limited rehabilitation resources.

1.2 Objectives

The aim of the research is to investigate the role and effective application of robotics technology into stroke rehabilitation, particularly on the rehabilitation of upper extremity which includes fingers and wrist. The rehabilitation robot is not intended to totally replace the doctors' or therapists' role in the rehabilitation program, but serves as a tool to improve the efficiency and effectiveness of the session. With the use of this rehabilitation platform, it is aimed to increase the number of patients attended to by a single physician, so that the patients will not miss the golden time of recovery caused by the congestion in rehabilitation centers.

The scope of the research is to examine the needs of stroke patients and occupational therapists, and to address the barriers confronted by them. Subsequently, the research explores the engineering feasibility of building a hand robotic assistive platform to assist and improve the rehabilitation process. The hand rehabilitation robot will be simulated in software to investigate the robot trajectory in performing the designated actions.

1.3 Thesis Contribution

The main contributions reported in this thesis are:

1. The finger rehabilitation module design that works based on the remote centre motion mechanism.
2. The thumb rehabilitation module design that follows the anatomy of human thumb, which provides the degree of freedom on the pronation of thumb.
3. The workspace verification method. Cartesian coordinates for the boundary surfaces of finger workplace are calculated in Matlab and converted into surfaces in Solidworks with "Scanto3D" function. The workspace is used as a visual reference in CAD software to assist the design of rehabilitation robot.
4. Incorporation of pre-shaping and logarithmic spiral trajectory into the reach-to-grasp motion planning of rehabilitation robot.

1.4 Thesis Overview

The thesis is organized into 6 chapters. In Chapter 1, an overview of the stroke rehabilitation and its rising demands is introduced. Next, Chapter 2 compares two rehabilitation methods and explains the effectiveness of task-oriented training in post-stroke recovery. Various mechanisms and designs of hand rehabilitation robots are analyzed in Chapter 3. Kinematics model of human hand and its workspace are defined in Chapter 4. In Chapter 5, the design of hand rehabilitation device is discussed in details. Chapter 6 shows the trajectory planning and simulation of a reach-to-grasp action in retrieving a mug. Finally, Chapter 7 concludes the work done in the research and discusses the further improvements for future research.

Chapter 2

Literature Review on Rehabilitation Treatments

2.1 Introduction

Stroke rehabilitation is a combined effort from a multi-disciplinary team, which consists of the stroke survivors and their families, the nurses and doctors, the physiotherapists, the occupational therapists and the speech therapists. Stroke rehabilitation is built on the theory of neural plasticity, in which the stroke patients can regain control of affected limbs by participating in structural and progressive rehabilitation exercises.

A typical rehabilitation program starts with an evaluation of the condition of post-stroke survivors. In this stage, various tools are used to measure and evaluate the capability of motor, joint range, sensibility and any retained volitional motion. If the case is serious, a surgery has to be carried out to help proper positioning and to relieve pain or pressure sore of the affected limbs. If the patient has good potential for rehabilitation, he will then sent to physiotherapy program for functional re-training. Coupled with other rehabilitative approaches such as mobilization using splints and orthoses, sensorimotor and somatosensory stimulation with thermal or electric stimulants and medication, the rehabilitation program can improve the functionality of limbs and prevent the re-occurring stroke.

In this chapter, two popular methods in early post-stroke rehabilitation: Bobath approach and Motor Relearning Programme are discussed in details.

2.2 Bobath Approach

Bobath concept is the most commonly used method in stroke rehabilitation. It is not considered a treatment or technique in stroke rehabilitation, but a clinical reasoning process to assess and treat patients with functional and postural problems. The method emphasizes on postural control in which the natural body movement patterns should be used in functional and voluntary movements. In the treatment, the therapist will facilitate automatic and voluntary movement through specific handling of some key-points such as pelvis, hands, feet, etc. to achieve motor goals. Abnormal muscle tone and mass movement patterns will be assessed as the patient attempts to move. Motor-relearning is then done by specific handling from the therapist to select the correct posture and movement patterns [9]. In summary, Bobath concept is a problem-solving approach which observes, analyzes and interprets the patient's task performance and uses inhibitory postures and movements with to reduce spasticity and synergies [10].

In the treatment, the therapist uses his hand on the patient's body to produce therapeutic changes in tone and movement. This handling method can be divided into two types of techniques: inhibition and facilitation. Inhibition is used to decrease abnormal muscle tone by interfering passive or active movement, while facilitation technique guides the correct patterns of movement and provide compensation to the weak muscle [11].

Figure 2.1: Bobath technique applied by therapist to guide the correct postural movement [11].

2.3 Motor Relearning Programme

Motor Relearning Programme is a top-down model of rehabilitation, which focuses on tests related to participation instead of specific motor kinematics. This includes task-oriented training and environment specific training with exercises designed to improve the quality of patients' lives. This task-oriented training presents challenging tasks to patients who suppose to act as active problem-solvers. Patients are required to interact and handle daily instruments to acquire real-life useful skill in this training with clear functional task goals [12, 13].

The Motor Relearning Programme works on the theory that adjustments in posture are continuous and anticipatory [14]. The motor behavior can only be developed and learned through environment and task performance. Trained and skilled motors can adapt and function differently according to the variation in environmental demands. This approach is divided into four steps: the analysis of task, the practice of missing components, the practice of task and the transference of learning [14]. The analysis of task is done by observing the activities performed by the patient. Abnormality in the muscle tone like missing activity, excessive tone, incorrect timing or incorrect behavior will be recorded. Then, the most essential components which are missing will be selected by therapist to be practiced on for thirty minutes twice daily. The next phase of training will be converted from cognitive to automatic stage of learning, before the learning is transferred into tasks performed during daily routines.

The tasks presented to patients in task-oriented training are usually challenging, progressive and optimally adapted, yet exciting enough to invoke active participation from patients [15]. Focusing on the practice of problem-solving, the tasks are to be carried out in a real-life setting with real objects encountered in daily life. For instance, in order to provide an contextual exercise, patient can be trained to reach for a ringing telephone instead of a training repetitively in a reaching action in the air that focuses on the correct posture. This task-oriented training is found to improve the transfer of skill learnt from training into activities of daily life as the training is focused on familiar daily tasks.

An important factor in ensuring effective implementation of this technique is to select tasks that are meaningful and relevant to the patient. Emphasis should be

placed on the life satisfaction of that particular patient during the setting of goals, which varies according to their roles in life (for example parents, artists, engineers and etc). Next, specific task which is discrete, serial and continuous will be chosen and analyzed to prepare the optimal movement patterns for the training [16].

2.4 Discussion and Conclusion

These rehabilitation methods are two fundamentally distinct disciplines which have been the subject of post stroke research for years. Bobath therapy is a problem-solving approach to facilitate post-stroke rehabilitation based on neurodevelopmental model, while Motor Relearning Programme is a system level approach to strengthen muscle through context specific training.

Studies have shown that Motor Relearning Programme is more effective than Bobath therapy in early post-stroke therapy [17-18]. Instead of focusing on non-task specific movement and motor control of movement in Bobath therapy, the Motor Relearning Programme has successfully improves the patients' performance in Barthel Index through early intervention and introduction of normal daily lives routine into the rehabilitation training. Besides that, it is also more effective in improving the daily lives' activities and ambulation during early stage of recovery [17]. With a sequential and function-based training regime, rehabilitation exercises involving activities of daily living (ADL) tasks are effective in regaining patients' functional recovery in self-care and community re-integration [18]. Various literatures in task orientated training [19-22] further verified the clinical performance of task-oriented training in post-stroke rehabilitation.

In view of increasing demand in physical therapy for post-stroke rehabilitation as discussed in previous chapter, we intend to address the issue with a robotics system that is able to train patients' hands in task-based rehabilitation exercise. The robotic system is able to guide and exercise each segment of the patient's fingers and wrist in the correct synergies while performing various movement patterns required to complete daily life activities. The rehabilitation robot functions as the role of therapists to hold and move the patient's finger, while the rehabilitation routine involving ADL activities keeps the motivation high.

According to the established clinical stroke scales in assessment of ADL performance such as Barthel Index, Katz index, Functional Independence Measure [23-25], activities of daily living include feeding, bathing, grooming, dressing, continence (control over urination and defecation), toilet use, transfer (move in and out bed or chair) and mobility on level surfaces. In this thesis, we focus on a hand rehabilitation robot to perform the ADL based task rehabilitation exercise. The task chosen in the thesis is reach-to-grasp action to retrieve a water mug. In this research, we start with an individual's reaching and grasping motion of fingers before further developing it into a whole task itself. Besides that, the machine can also be further developed into or combined with existing upper extremity rehabilitation robot to perform a fully functional ADL task-oriented training in the future.

Chapter 3

Review of Hand Rehabilitation Devices

Designing a rehabilitative structure to interface with human hand is not a simple task, as there are challenges such as space constraint, complex anatomy and the design ergonomics. The human hand consists of more than 20 degrees of freedom, in which the distance between each degree of freedom can be less than a centimeter. It is very challenging to accommodate a rehabilitation robot with the same flexibility within the limited space. Furthermore, human hand is a sensitive body limb that can detect minute change in force and displacement. If the robot is not driving the hand and fingers at their natural motion patterns, the user wearing the exoskeleton would experience irritation, discomfort and pain during the rehabilitation.

3.1 Finger Rehabilitation Mechanism

The hand anatomy and the size of its actuators cause the space for exoskeleton structure to be limited, and most of them have to be installed on the dorsal side of the hand. The exoskeletal structure driving the finger from the dorsal side results in a non-coaxial rotation of the robot and finger. This results to a non-normal, directional force which is applied onto the finger by the exoskeletal link. As shown in Figure 3.1, the directional force will induce a shear force inwards during flexion, and outwards during extension. The shear force will generate discomfort and sometimes pain to the user's fingers if the friction is high at the point of contact.

Figure 3.1: Shear force induced by non-coaxial rotation.

In order to avoid sliding friction, the exoskeleton has to move coaxially with the axes of finger joints. The actuation structure is preferred to be placed at the side of finger, to align the axes of rotation between the finger joint and the actuator. The following section will take a deeper investigation into the different mechanism designs to overcome this issue and provide a smooth rehabilitation experience.

3.1.1 Coaxial Driving

For coaxial driving mechanism, the rotating joints for the rehabilitation robot are installed at the side of the fingers. HANDEXOS developed by Chiri et al. [35] in Figure 3.2 best illustrates this idea. The golden-colored rotating joints at the side are pulleys which carry the Bowden cables to act as transmitter of actuation force. The cable driving system permits a space efficient exoskeleton design that is able to fit into the finger space without occupying much space.

Figure 3.2: Coaxial driving at the side of finger [35].

However, this coaxial design faces the implementation challenge of building a structure that is space efficient without sacrificing the rigidity and strength of the exoskeleton structure.

3.1.2 Gliding Joint

In the Gliding Joint mechanism, the exoskeleton structure does not have a fixed length with varying length which increases with the flexion of finger and decreases with extension of finger. As shown in Figure 3.3, the rotation axis shifts clockwise during the flexion of the finger while the outer link glides outwards along with the finger. The extension or retraction of the robotic link acts as a linkage system to join the rotation axes between the finger and robot. This ensures a normal actuation force is exerted by the rehabilitation robot on users' fingers, and avoids the painful shearing force. Extension and retraction of the link in the rehabilitation robots built by Fu [37] and Nakagawara [47] are achieved by rack and pinion mechanism in which the rotation and extension of the links are coupled and move in a fixed trajectory.

Figure 3.3: Shifting of joint axis during flexion [47].

3.1.3 Remote Centre of Motion (RCM) Approach

A RCM mechanism is a structure that is able to rotate around a distant axis without having any physical revolute joint present at the axis. This mechanism is widely used in robot-assisted surgery applications and is suitable to solve the coaxiality problem in hand exoskeleton design.

3.1.3.1 Linkage Mechanism

For the RCM linkage-type of hand exoskeleton, Li et al. [31] used a four-bar linkage as the driving structure to actuate the fingers. By rotating the joint at the upper link, the blue links attached to the finger will follow the rotation (Refer to Figure 3.4).

Figure 3.4: Four-bar linkage driving mechanism [31].

However, this structure is not the best RCM linkage mechanism as compared to the six-bar linkage proposed by Fontana [33]. The six-bar linkage composed by two parallelograms is able to induce a remote centre rotation at link j_{H3} where a finger holder can be installed to actuate the finger (Figure 3.5).

Figure 3.5: Six-bar linkage driving mechanism [33].

The different variables in the linkage system have to be designed carefully to generate the linkage trajectory which is coaxial and natural to the finger movement.

3.1.3.2 Arc-shaped Structure

Other than using a straight link which produces a non-coaxial rotation, the RCM can be achieved with an arc-shaped link which has its center at the rotation axis of finger joint.

In Figure 3.6, MCP joint of the arc-shaped links is supported by slider bearings to facilitate the rotation of the links. The PIP and DIP joints are operated by the miniature bearings installed at the lateral side of the fingers [27]. The extension and flexion of the supported arc-shaped structure is achieved by a pneumatic powered cable system.

Figure 3.6: Arc-shape linkage with bearing support [27].

In the device designed by Fu [28], a circular rack driven by spur gear is used to perform RCM. The spur gear is directly connected to a pulley which is actuated by Bowden cable. The rack and pinion mechanism on the linkage provides a higher joint rigidity than the sliding linkages mechanism shown in Figure 3.6.

Figure 3.7: Arc shape linkage with rack and pinion method [28].

Another exoskeleton design aimed to provide haptic force feedback is shown in Figure 3.8. The force applied is one directional, whereby the exoskeleton freezes and stops the movement of the finger when it hits an object in a virtual environment [26]. Utilizing rolling links mechanism, the rotation of arc-shaped link is actuated by frictional contact of the cable drum mounted on top of each link. The drum is connected to a cable system which is driven by DC motors.

Figure 3.8: Arc shape linkage with direct contact [26].

3.1.4 Ventral Driving Mechanism

While most exoskeleton designs that position the actuators at the dorsal side of the hand, there are also hand rehabilitation machines which are designed to drive from the ventral side by guiding the distal phalanges of the fingers. As illustrated in the finger exercising machine (HIFE) in Figure 3.9, the design removes the heavy machine weights applied on user's hand and bypasses the space constraint for complex mechanism design.

Figure 3.9: HIFE machine [45].

Guiding only the distal phalanges, modeling of complex hand joints can be avoided and multi-DOF adaptation n-structure is not needed. The rehabilitation device only needs to ensure the final position of each user's finger is in the range of the robot motion.

In the multi-fingered haptic interface robot from Gifu University shown in Figure 3.10, the robotic device is installed using the mirror image of the user's hand. The finger-holder mounted on the distal end of each robotic finger is installed with a passive ball joint in order to adapt to the different finger postures and orientations.

Figure 3.10: GIFU hand rehabilitation robot [47].

Nevertheless, there are drawbacks in this ventral driving method. The machine is more suited for repetitive training because it consumes greater space at the ventral side of the user's hand. Interaction with external objects such as grasping the door knob or pinching of door key laterally will be blocked by the rehabilitation robot. This type of robot is also more cumbersome and static.

3.2 Wrist Rehabilitation Mechanism

The wrist rehabilitation mechanism can be categorized into two groups; direct serial driven and parallel-driven. Direct-driven mechanism is similar to a serial robot by which the exoskeletal mechanisms are built on top of one another. Parallel driven mechanism adopts a structure similar to Stewart platform, and the orientation of the wrist platform and multiple DOF can be controlled simultaneously by linear actuators.

MIT-Manus is a direct-driven five-bar linkage mechanism which provides two translational degrees of freedom for the hand and arm motions. On top of the linkage, there is a 3-DOF wrist robot which provides flexion-extension, abduction-adduction and pronation-supination motions. The pronation-supination module rotates on a curve slide ring which carries the motors and mechanisms for flexion-extension and abduction-adduction motions.

Figure 3.11: Wrist mechanism of MIT MANUS robot. (a) 3D model of wrist mechanism showing the working principle (b) Curved rail and carriage for wrist pronation/supination (c) User using the rehabilitation robot [54].

ARMin II is a full-arm exoskeleton robot that guides rehabilitation routines through the end-effector, where users' hands are strapped onto the hand cuffs [55].

This design only permits wrist pronation/supination and flexion/extension since wrist abduction/adduction is viewed as lack of functional importance. Similar to MIT-Manus, the pronation/supination is achieved with a semi-circular gear and a moving cart. A lever system at the wrist is actuated by a ball spindle that is coupled to a DC- motor to provide the flexion/extension motion.

Figure 3.12: (a) ARMIN II arm rehabilitation robot (b) Wrist mechanism of ARMIN II [55].

Universal haptic drive (UHD) developed by Oblak [56] adopts a linear actuated bar with a spherical joint to create different configurations for rehabilitation. Using the locking and unlocking of the spherical joint, two modes called “arm” mode and wrist” mode can be applied in the rehabilitation exercise. When the joint is locked, extension of the linear actuator will move the whole arm of the patient. In the “wrist” mode when the spherical joint is unlocked, the motion of linear actuator tilts and flexes the patient’s wrist into various orientations.

Figure 3.13: The wrist rehabilitation robot with linear actuator in universal joint locked and unlocked mode [56].

For parallel-driven mechanism, RiceWrist [57] adopts the principle of 3-RPS (revolute-prismatic-spherical) serial-in-parallel platform. This mechanism allows abduction/adduction and flexion/extension motion, but has limited translational motion which is restricted by the ROM of the spherical joints. However, the mechanism possesses the advantages of being compact, lightweight-structured and having high torque output.

Figure 3.14: RiceWrist uses 3-RPS parallel robot for wrist rehabilitation [57].

Takaiwa designed and built a pneumatic parallel wrist platform supported by 6 cylinders in his article [58]. In his work, the Stewart platform is able to move the wrist module in 6-DOF, and to define a precise wrist position and orientation. Pneumatic powered cylinders are used as the actuators to provide minute force control to perform complex motion of human wrist joint.

Figure 3.15: Stewart platform built to provide precise motion for wrist rehabilitation [58].

3.3 Conclusion

Apart from exoskeletal-based machine, there are also other types of devices that are inspired by the specific tasks performed in hand rehabilitation programs such as handle [50] and knob [51] to practice the opening and closing of the grasping action, devices that train grasping and forearm pronation/supination [52], and an index finger training mechanism that combines different sensorimotor stimulation [53].

Generally, hand rehabilitation devices can be categorized based on three attributes. These attributes are (1) the motion covered, (2) the actuation method, and (3) the mechanism for co-axial movement with joints of hand.

For the coverage of motion, there are devices that are able to provide exercises targeting only one or two fingers, exercises with partial independence (some fingers tied together and moved as one module) and exercises with full independence (all fingers moved separately). There are also devices that guide the distal phalanges for exercise (end effector guided). As for the actuation method, there are four types reported; motor direct driven, cable-driven, pneumatic powered, and flexi-shaft driven. There are four mechanisms to achieve coaxial movement which is the third attribute. These are linkage mechanism, side/coaxial driving, arc-shaped driving links, and gliding joint (mobile joint origin).

Table 3.1: Different categories of attributes and the references.

Attributes		
Motion covered	Actuation methods	Mechanisms
Exercise one or two fingers [38,41,42]	Direct driven [29,39,43,45,46,48]	Linkage mechanism [28-33,36,39,41,42,45]
Partial independence [39,43,44]	Cable driven [28,30-38,47]	Coaxial driving [35,43,44]
Full independence [27,35]	Pneumatic powered [27,40,42,44]	Arc-shaped link [27,28,38]
End-effector guided [33,34,40,45,46,48]	Flexi-shaft driven [41]	Gliding joint [37,47]

Table 3.1 shows that most of the hand rehabilitation machines which are designed to exercise individual fingers are mainly cable-driven with linkage mechanism and not many are able to tackle the full degree of freedom (DOF) of a human hand. It is apparent that the trend of the research focuses on minimizing the weight while using complex linkage system to achieve the coaxial rotation on hand finger joints. There is also an approach aimed at solving the limited space problem by driving two or more fingers as one module and sacrificing the full DOF available on the human hand. For wrist exoskeleton, parallel driven mechanism is complex and carries limited workspace. The serial mechanism that decouples each degree of freedom is more advantageous for its simplicity in the control mechanism.

Chapter 4

Human Hand Anatomy and Modeling

Since rehabilitation robots apply direct force onto the hand and wrist, it is important to analyze and understand the anatomy and synergy of the human hand. The robot has to adhere to the natural motion trajectory of the hand while correcting the wrong muscle tone used in the movement.

Human hand is an important body instrument for its ability of prehension which varies from fine manipulation of tiny objects to strong gripping of sturdy handles. Human hand is also a sensitive and accurate sensory receptor which aids the development of visual appreciation. The human hand is a complex structure formed by 27 bone segments which carries a total of more than 20 degrees of freedom.

4.1 Terminology

The major bones and joints of human hand are shown in Figure 4.1. The segments of hand involved in the rehabilitation exercise are distal interphalangeal (DIP) joints, proximal interphalangeal (PIP) joints, and metacarpophalangeal (MCP) joints on fingers; and interphalanges (IP) joint, metacarpophalangeal (MCP) joint and carpometacarpal (CMC) joint on thumb.

Figure 4.1: Bones and joints of human hand [63].

The active motions of human hand are summarized in Figure 4.2.

Figure 2.2: Range of motion (ROM) of human hand [63].

4.2 Degree of Freedoms

4.2.1 Fingers

In human fingers, there are 4 degrees of freedom consisting of 3 flexion/extension motions and 1 abduction/adduction motion. The metacarpophalangeal (MCP) joint on each finger is an ellipsoid/condyloid joint that is able to perform biaxial movement. It can be presumed as a universal joint with a limited axial rotation of 60°. For the interphalangeal joints (DIP and PIP), they are hinge joints that allow only uniaxial movement (flexion/extension).

4.2.2 Thumb

There are 5 degrees of freedom in the thumb, with 1 degree of freedom at the interphalangeal (IP) joint, 2 degree of freedom at the MCP joint and 2 degree of freedom at the CMC joint. Similar to human fingers, the MCP joint of thumb is an ellipsoid joint while the IP joint is a hinge joint. CMC joint serves as a saddle joint that provide biaxial movement. The shape of the two concave bones in the thumb is similar to a rider sitting on saddle providing unique movements to the thumb [64].

Combination of the abduction and adduction actions by the MP and CMC joints forms a palmar abduction movement, while combination of flexion and extension actions on the same joints results in a radial abduction. In Figure 4.2, the opposition movement is formed by the flexion and abduction of the CMC joint while reposition movement is created from the extension and adduction of the same joint.

Figure 4.3: Shape of (a) hinge joint (b) ellipsoid joint (c) saddle joint (d) gliding joint [64].

4.2.3 Wrist

For the wrist, the movement between 8 intercarpal bones is achieved by gliding joints which are non-axial and permit only limited planar movements. The radiocarpal joints connected to the radius and ulna bones are ellipsoid joints with bi-axial motions.

There are two types of motions that human wrists can perform; flexion/extension and ulnar/radial deviation. Scaphoid/lunate bones roll anteriorly and glide posteriorly during flexion motion and move in the opposite direction during the extension motion. In ulnar deviation, scaphoid/lunate bones roll toward the ulna and glide towards radius. Similarly, the movement is opposite in radial deviation.

The axes of both motions are also not intersecting. In the case of flexion/extension, the axis of flexion is situated around the radiocarpal joint's lateral axis while the axis of extension happened at the midcarpal joint's lateral axis [65]. For ulnar and radial deviation, the centre of rolling occurred at the axis that passes through the capitate bone (marked x in Figure 4.4).

Figure 4.4: (a) Center of wrist deviation (b) Axe of wrist flexion and extension [65].

4.3 Range of Motion (ROM)

In a laboratory or clinic, the range of motion is commonly measured by researchers and therapists with a goniometer. There are two types of range of motion; active and passive. Passive ROM is usually slightly bigger than active ROM due to the elastic stretch of muscle tissues. However, only active ROM will be considered in this research as the ADL oriented exercises adopted in the design emphasize more on functional rehabilitation. The range of motion for each joint is compiled from the academic literature [66]-[72] and summarized in table [2].

Table 4.1: ROM of hand joints.

Joint	Motion	Range of Motion (°)
		Active
Finger (MCP)	Flexion/Extension	90/45
	Abduction/Adduction	30/30
Finger (PIP)	Flexion/Extension	100/0
Finger (DIP)	Flexion/Extension	90/0
Thumb (CMC)	Flexion/Extension	20/0
	Abduction/Adduction	70/0
Thumb (MCP)	Flexion/Extension	55/20
	Abduction/Adduction	20/20
Thumb(IP)	Flexion/Extension	90/20
Wrist	Flexion/Extension	80/70
	Radial/Ulnar Deviation	20/30

*Flexion of MCP joints increase linearly from the index to little finger [66].

*Index finger has the biggest range of abduction/adduction motion.

For the minimum ROM required for our machine, we adopt the functional ROM reported by Hume *et al.* [73] which records the joint motion required to accomplish a designated task. The data is shown in Table 4.2. Hence, the workspace of rehabilitation machine must lie between the maximum and minimum ROM presented in the table.

Table 4.2: Functional ROM of fingers from Hume [91].

Joints		Task specific positions (°)			
		Key	Pinch	Grasp	Grip
Thumb	MCP	20	22	10	23
	IP	16	25	28	36
Index finger	MP	62	58	33	72
	PIP	76	76	39	78
	DIP	46	33	26	50

4.4 Kinematic Modeling of Hand

As a way to translate the data and findings from hand kinesiology research into a kinematic model that is suitable for robotic application, the human hand is to be treated as five serial-links robotic manipulators and can be defined by Denavit-Hartenberg (D-H) convention.

The model of the human hand is presented in Figure 4.5 with origin at the capitate bone. The straight lines for fingers are the phalanges and metacarpal bones, while the straight lines at thumb are phalanges, metacarpal, trapezium bones. The dots are the joints to be modeled, which include CMC, MCP and IP joints of thumb and MCP, PIP and DIP joints of four fingers.

Figure 4.5: Hand structure and the annotations used [74].

There is a vast amount of literature published on the anthropometric data of human hands across different countries, races, professions and age ranges. For an accurate generalization on the diverse statistical data, we adopt the Buchholz's work reported by Huang and Low [74] where the variation of bone lengths and joint centre are standardized by using approximation of external hand measurements. As shown in Table 4.3, the adopted work estimates these bone and joint parameters by measuring hand length, l_h (distance from distal wrist crease to the tip of middle finger) and hand breadth, b_h (distance between MCP joints of index and little fingers). The bone segments are assumed to be parallel and lie in coronal plane during rest position.

Table 4.3: Approximation of segment Length for fingers proposed by Buchholz.

Finger	l_c	l_p	l_m	l_d
Thumb	$0.5(0.118 l_h + \sqrt{(0.073l_h)^2 + (0.196b_h)^2})$	$0.196l_h$	$0.251l_h$	$0.158l_h$
Index	$0.5(0.463 l_h + \sqrt{(0.447l_h)^2 + (0.251b_h)^2})$	$0.245l_h$	$0.143l_h$	$0.097l_h$
Middle	$0.446l_h$	$0.266l_h$	$0.170l_h$	$0.108l_h$
Ring	$0.5(0.421 l_h + \sqrt{(0.409l_h)^2 + (0.206b_h)^2})$	$0.244l_h$	$0.165l_h$	$0.107l_h$
Little	$0.5(0.414 l_h + \sqrt{(0.368l_h)^2 + (0.402b_h)^2})$	$0.204l_h$	$0.117l_h$	$0.093l_h$

*Notation l_c, l_p, l_m, l_d , are referred in Figure 4.5.

The coordinate system is defined in Figure 4.6. Homogeneous transformation matrix T can be defined by four D-H parameters (joint angle θ , link twist a , link offset d , link twist α). It is represented as a product of four basic transformations from frames i to frame $i-1$.

$$\begin{aligned}
 {}^{i-1}T_i &= \text{Rot}_{z,\theta_i} \text{Trans}_{z,d_i} \text{Trans}_{x,a_i} \text{Rot}_{x,\alpha_i} \\
 &= \begin{bmatrix} \cos \theta_i & -\cos \alpha_i \sin \theta_i & \sin \alpha_i \sin \theta_i & a_i \cos \theta_i \\ \sin \theta_i & \cos \alpha_i \cos \theta_i & -\sin \alpha_i \cos \theta_i & a_i \sin \theta_i \\ 0 & \sin \alpha_i & \cos \alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \\
 &= \begin{bmatrix} {}^{i-1}R_i & {}^{i-1}P_i \\ 0 & 1 \end{bmatrix} \\
 (4.1)
 \end{aligned}$$

where ${}^{i-1}R_i$ = Orientation vector of frame i with respect to frame $i-1$.

${}^{i-1}P_i$ = Position vector of frame i with respect to frame $i-1$.

The forward kinematics that relates the coordinates of end effector to the coordinates of origin can be determined by the following formula (4.2).

$$\begin{aligned}
 {}^0T &= \prod_{j=1}^i {}^{j-1}T_j \\
 &= {}^0T_1 {}^1T_2 \dots {}^{i-2}T_{i-1} {}^{i-1}T_i
 \end{aligned} \tag{4.2}$$

Figure 4.6: (a) Coordinate frame assigned for thumb and index finger model (b) D-H representation for the thumb (joint 1&2, 3&4 have the same origin) (c) D-H representation for the index finger (joint 1&2 have the same origin) on for the index finger (joint 1&2 have the same origin)

In the design of the hand rehabilitation robot, we refer the dimension of a healthy subject's right hand, which has hand length of $l_h = 18.3\text{cm}$ and hand breath of $b_h = 6.8\text{cm}$. We also obtain the bone lengths of each segment as shown in Table 4.4.

Table 4.4: Calculated finger length using Buchholz's method.

Finger	l_c (mm)	l_p (mm)	l_m (mm)	l_d (mm)
Thumb	20.23	35.87	45.93	28.91
Index	84.15	44.84	26.17	17.75
Middle	81.62	48.68	31.11	19.76
Ring	76.59	44.65	30.2	19.58
Little	74.22	37.33	21.41	17.02

The results are cross-checked with the direct measurements on the user's hand and it is found that the approximation method gives estimates close to the real bone lengths.

4.4.1 D-H Representation

The D-H parameters for fingers model are presented in Table 4.5. The Euler angles between metacarpal bones pictured in Figure 4.5 that are measured from the user's hand are $\gamma_i = 26.6^\circ$, $\gamma_r = 28.2^\circ$, $\gamma_s = 42.2^\circ$.

Table 4.5: Calculated D-H parameters for four fingers.

<i>Frame</i>	Index					
	$\theta (^\circ)$	d (mm)	a (mm)	$\alpha (^\circ)$	<i>Lower limit</i> (rad)	<i>Upper limit</i> (rad)
1	0	37.68	75.24	$\pi/2$	-	-
2	θ_1	0	0	$-\pi/2$	$-\pi/6$	$\pi/6$
3	θ_2	0	44.84	0	$-\pi/4$	$\pi/2$
4	θ_3	0	26.17	0	0	$5\pi/9$
5	θ_4	0	17.75	0	0	$\pi/2$

The D-H parameters for the thumb model are tabulated in Table 4.6. The Euler angles between the CMC joints and middle metacarpal bone shown in Figure 4.5 are measured to be $\gamma_t = 54.1^\circ$, $\beta = 32.3^\circ$.

Table 4.6: Calculated D-H parameters for thumb.

<i>Frame</i>	Thumb					
	θ (rad)	d (mm)	a (mm)	α (rad)	<i>Lower limit</i> (rad)	<i>Upper limit</i> (rad)
1	0	19.93	3.48	$\pi/2$	—	—
2	θ_1	0	0	$-\pi/2$	$8\pi/45$	$17\pi/30$
3	$\theta_2 + \frac{8}{45}\pi$	0	45.93	$\pi/2$	0	$\pi/9$
4	θ_3	0	0	$-\pi/2$	$-\pi/9$	$\pi/9$
5	θ_4	0	35.87	0	$-\pi/9$	$11\pi/36$
6	θ_5	0	28.91	0	$-\pi/9$	$\pi/2$

4.4.2 Workspace Analysis

Workspace is a reachable region in space where the end effector of the robot can maneuver and operate. It is a series of points which define the volume and boundaries of the working space to perform the task of interest. The workspace analysis is important for rehabilitation robots as it ensures a realistic and safe operation. Knowing the workspace and limits of hand facilitates the designing of the robot to perform the required task in a safe working space.

The boundaries of the surfaces and curves in the workspace represent the singularity orientations of the robot. Singularity orientations can cause control difficulties and motion impediments to the robot, and this will then inhibit further operation and injure the user's hand.

As the workspace for a robot represents the reachability region of its end effector, it is characterized by the position vector for the end effector. This can be described by the multiplication of rotation matrices and position vectors:

$$P(\theta) = \sum_{i=1}^n [\prod_{j=1}^{i-1} R_j]^{i-1} p_i = \begin{bmatrix} x(\theta) \\ y(\theta) \\ z(\theta) \end{bmatrix} \quad (4.3)$$

where n is the number of link, θ is the joint angle, R is the rotation matrix and p is the position vector. (Note: refer to equation in section 4.4 for D-H representation method)

This position vector specifies all the set of points inside and on the boundary of the workspace envelope in which a constraint function can be generated for a specific position, (x_p, y_p, z_p) in the envelope using the equation below.

$$\begin{bmatrix} x(\theta) - x_p \\ y(\theta) - y_p \\ z(\theta) - z_p \end{bmatrix} = 0 \quad (4.4)$$

Malek, Yang and the team [75] have formulated an analytical method to determine the singular geometric entities inside the workspace. In order to introduce more constraints to solve the manifold equation, the formulation is extended by introducing joint limits in terms of inequality constraints:

$$\theta_i^{min} \leq \theta_i \leq \theta_i^{max} \quad (4.5)$$

where θ_i^{min} and θ_i^{max} are the lower and upper limits, $i = 1, 2, \dots, n$ where n is the number of degree of freedom.

The inequality constraints in the equation above can be transformed into equality by introducing a new set of generalized coordinates λ_i , such that

$$\theta_i = a_i + b_i \sin \lambda_i \quad (4.6)$$

where $a_i = \frac{\theta_i^{min} + \theta_i^{max}}{2}$ and $b_i = \frac{\theta_i^{max} - \theta_i^{min}}{2}$ are the mid point and half range of the inequality constraint and λ_i is a slack variable that converts the inequality constraints into equality constraint.

The slack variable does not change the dimension of the problem since it is inherently constrained by the sine function. With this additional constraint introduced, the constraint function for position vector is transformed into a manifold:

$$H(\theta^*) = \begin{bmatrix} x(\theta) - x_p \\ y(\theta) - y_p \\ z(\theta) - z_p \\ \theta_i - a_i - b_i \sin \lambda_i \end{bmatrix} \quad (4.7)$$

where $\theta^* = \begin{bmatrix} \theta^T \\ \lambda^T \end{bmatrix}$ is the vector of all generalized coordinates.

The Jacobian of the constraint function is then introduced to determine the singular behavior of the manifold. Jacobian matrix relates the velocity of the end effector to the angular velocities of the individual joints. At a singular position, the joint velocities cannot be calculated and there is no inverse for the Jacobian matrix.

The Jacobian of the constraint function is a $(3+n) \times 2n$ matrix:

$$\begin{aligned} H_{\theta^*} &= \frac{\partial H}{\partial \theta^*} \\ &= \begin{bmatrix} x_{\theta} & 0 \\ I & \theta_{\lambda} \end{bmatrix} \end{aligned} \quad (4.8)$$

where $x_\theta = \frac{\partial x}{\partial \theta}$, $\theta_\lambda = \frac{\partial \theta}{\partial \lambda}$, 0 is (3 x n) zero matrix, I is the identity matrix, and

$$x_\theta = \begin{bmatrix} x_{\theta 1} & x_{\theta 2} & \dots & x_{\theta n} \\ y_{\theta 1} & y_{\theta 2} & \dots & y_{\theta n} \\ z_{\theta 1} & z_{\theta 2} & \dots & z_{\theta n} \end{bmatrix}$$

$$\theta_\lambda = \begin{bmatrix} -\left(\frac{\theta_1^{max}-\theta_1^{min}}{2}\right) \cos \lambda_1 & 0 & \dots & 0 \\ 0 & -\left(\frac{\theta_1^{max}-\theta_1^{min}}{2}\right) \cos \lambda_2 & \dots & 0 \\ 0 & 0 & \dots & 0 \\ 0 & 0 & \dots & -\left(\frac{\theta_1^{max}-\theta_1^{min}}{2}\right) \cos \lambda_n \end{bmatrix} \quad (4.9)$$

Since the Jacobian is not a square matrix, it is rank deficient where the manifold is defined by ∂W and characterized by

$$\partial W \subset \{Rank H_{\theta^*} < k, \text{ for some } \theta^* \text{ with } H(\theta^*) = 0\} \quad (4.10)$$

where $k \geq n + 3$

In order to solve the rank deficient Jacobian matrix, three types of singularities are exploited:

Type I singularities set:

When all joints are not at their limits, the sub-matrix θ_λ is a full rank matrix. Hence, for the Jacobian of constraint function, H_{θ^*} to be rank deficient, the block matrix x_θ must be rank deficient. It is thus defined as:

$$S^{(1)} \equiv \{p \in \theta: Rank[x_\theta] < 3, \text{ for some constant subset of } \theta^*\} \quad (4.11)$$

where p is within the specific joint limit constraints and may contain joints that are the functions of others or constant values.

Type II singularity sets:

When some of the joints are at their limits, the corresponding diagonal elements in the matrix θ_λ will be equal to zero. By removing the corresponding columns with the joints at limit in matrix x_θ , the rank deficient criteria is applied on the matrix. This will be repeated for all the possible combination of joints, until the remaining of matrix x_θ becomes a square matrix. It is defined as:

$$S^{(2)} \equiv \{p = [\hat{p} \cup \partial\theta^{limit}]: Rank[x_\theta(w, \partial q^{limit})] < 3, \text{ for some } \hat{p} \in \theta^*, \dim(\partial\theta^{limit}) \leq (n - 3)\} \quad (4.12)$$

where $\hat{p}$ is the singular set as a result of applying the rank deficiency criteria to the matrix x_θ with column of joints at limits removed.

Type III singularity sets:

When all the joints are at their limits, the singular sets can be found by solving the equation $|\theta_\lambda| = 0$. The definition is given by:

$$S^{(3)} \equiv \{p \in R^{(n-2)}: p \equiv \partial\theta^{limit} = [\theta_i^{limit}, \theta_j^{limit}, \dots]\}; \text{ where } i \neq j \quad (4.13)$$

With the sets of θ_i determined from the above three singularity conditions, they can be substituted into the accessible set $x(q)$ to identify the manifold of the workspace. Each set of θ_i will produce a specific singular region bounded by certain conditions. Combining all the manifolds calculated from the three singularity conditions, the total singularity set S generated by the robot is hence:

$$S = S^{(1)} \cup S^{(2)} \cup S^{(3)} \quad (4.14)$$

where $S^{(1)}$, $S^{(2)}$ and $S^{(3)}$ are determined from the three singularities sets respectively.

The workspace of the end effector can hence be visualized by plotting the manifold equations in a Cartesian space.

(a)

(b)

(c)

(d)

Figure 4.7: (a) Isometric view (b) Top view (c) Front view (d) Side view of the workspace for Index finger.

Figure 4.8: (a) Isometric view (b) Top view (c) Front view (d) Side view of the workspace for thumb.

The Fig. 4.9 below shows the intersection of workspace between thumb and index finger:

Figure 4.9: Combined workspace of the thumb and index finger.

4.5 Discrepancies from Real Life Model

Due to the absence of a translation from anatomical research findings to a readily applicable model in the robotics research community, the hand model proposed above is only a simplified version that is not considering the movement of the metacarpals and carpal bones. The real human hand is more complicated with greater complexity in movements involved. The following sections describe some of the complex scenarios not presented in our model above.

4.5.1 Intersection of Thumb Joints

In human thumb, Santos [76] reported that the kinematic modeling on MCP and CMC joints with intersecting axes of rotation is not realistic. There is an average distance of 1.42cm between flexion-extension (FE) axis and abduction-adduction (AA) axis on CMC joint and 1.56cm between FE axis and AA axis on MCP joint. Besides proposing the D-H parameters for his thumb model, he further suggested to include the translational degree of freedom at trapezium bone to complete the whole model.

Figure 4.10: Five link thumb model proposed by Giurintano [76].

4.5.2 Hollowing of the Palm

Our hand model presented above assumes a flat and rigid planar surface of the palm in the coronary plane, with non-moving metacarpal bones. However, during the grasping of an object, the human hand will become hollow and its palm distorted to form arches in three directions (Fig 4.11). As shown in the same picture, the MCP joints of the four fingers displace latero-medially during hollowing from negligible movement at the index finger to the most significant

one at little finger. The movements of MCP joints is not only in anterior direction, but also slightly curved laterally.

Figure 4.11: Arc of palm during hollowing.

The movement at the metacarpal joints also induces the convergence of finger axes into a focal point (marked as star in Fig 4.12) during clenching of fist with distal joints extended. This implies that the parallel flexing of four fingers in the fist-making action is not natural. The opposition of thumb is also difficult to achieve without the hollowing of palm.

When the fingers are actively stretched and extended out, the axes of five fingers converge at the scaphoid bone as shown in Fig 4.12. In addition, the center of abduction/adduction action lies at the plane of the third metacarpal bone and middle finger. Hence, the middle finger movement is insignificant during the abduction/adduction movement although it can be moved voluntarily if required.

Figure 4.12: Focal point of fingers during certain orientation.

4.6 Discussion

A quick review on hand physiology research reveals many complex structures and issues not common to the robotics community. It is debatable whether a complicated model is needed to achieve a full functional rehabilitation robot or a good simplified model is sufficient to achieve our objectives of rehabilitation training. Besides that, the stringent rules applicable to healthcare products have to be taken into consideration as a simplified model might obstruct the rehabilitation model or injured the patient.

For this research, we will start with the proposed kinematic model as the first exploration into hand rehabilitation exercise. Then after, further complexity in the hand structure will be reviewed together with the performance of rehabilitation devices and patients feedbacks.

Chapter 5

Design and Realization of Rehabilitation Device

5.1 Finger Module

5.1.1 Design Concept

The Bobath method is selected as the rehabilitation technique for our machine where the patients' fingers are guided to the correct postures while performing tasks. The method of driving distal phalanges (either at dorsal or ventral side of palm) was initially considered for its advantage of minimal actuators and simpler motion control. However, it is discovered that the mechanism will not be able to control the position and orientation of middle and proximal phalanges of the patients' fingers. Although the fingers follow the robot-guided trajectory to the desired position, the fingers might move in an abnormal pattern and orientation which is a prominent problem for patients with spasticity and contracture. Exercises with this under-actuated system might thus result in an unnatural muscle tone and excessive compensation of the healthy muscle which is undesirable and might worsen the rehabilitation progress. The linkage driven mechanism is also not adopted as its velocity and torque outputs are not linear to the inputs from motors. Moreover, linkage mechanism requires additional analysis in control system to generate a smooth trajectory and motion.

In the consideration of the actuation system, the initial concept explored a cable-driven system which has the advantages of being lightweight, having back-drivability, and space-efficient at the fingers aspect. Nevertheless, there are drawbacks in the working principle for cable-driven mechanism. Due to the pure frictional contact between cable and pulley/drum, slippage of the cable can happen if force stabilization is not designed properly. Besides that, the pulley can degenerate and fail without warning over its life cycle [61]. Control schemes for cable driven system is also more complex with two times the number of generalized coordinates needed in the dynamic model as compared to a rigid system [62]. Past experience in designing MIT Hand Robot Alpha-Prototype I [50] also demonstrates the challenges of low bandwidth, presence of significant friction and lack of full back-drivability in the cable driven system.

In order to avoid a complex mechanical structure and control system design, we have adopted the arc-shaped links mechanism to provide co-axial rotation at the finger joints. Unlike the four-bar or six-bar linkages mechanisms that produce non-linear motion and torque output, an arc-shaped link system has a simpler kinematic model with fewer parts that actuate the finger joints directly at the coaxial axis. Combining it with the direct torque transmission from DC motor, the mechanism is more rigid with faster response, making it suitable for a safe rehabilitation routine while minimizing the online and offline computational cost.

5.1.2 Mechanical Model and Assembly

The finger module of the rehabilitation robot can be separated into three sub-modules for the three phalanges. Each sub-module consists of a DC motor as the driver, a timing pulley and belts for transmission, and a spur gear as further transmission of the motion to the arc gear.

Figure 5.1: (a) Transmission system of the module (b) Center of rotation at the finger joints.

The arc gear joins the three sub-modules and defines the angle of flexion as illustrated in Figure 5.1. The DIP module sits on the arc-gear of the PIP module, and both the DIP and PIP modules are carried by the arc-gear on the MCP module. The center of rotation is vertically below each arc gear which coincides with the joint axes of the phalanges.

The arc gear is supported by a roller and two bearings to simulate the constraint of a circular track. By providing support at these three points instead of the surface constraint in circular track, the efficiency of the mechanism is greatly improved since there is only rolling friction involved during the rotation. The constraints are completed with the addition of flanges at the roller, which limit the sideways motion and support the torsion loading on the arc gear. Thus, the only degree of freedom left is the desired concentric rotation upon actuation by the spur gear.

Figure 5.2: (a) Constraint for the arc gear (b) Torsional constant for the arc gear.

A U-shape brace casted out from medical grade polyurethane foam is mounted at the end of each arc gear. The user's finger can be strapped onto the braces with elastic bands that secure the phalanges with Velcro fasteners. The structure interfacing with user's finger is designed to be firm but deformable, in order to avoid excessive stress applied that might cause injuries during the rehabilitation process.

Figure 5.3: The mounting of finger onto rehabilitation module.

The range of motion for the mechanism is determined by the arc length of the arc gear, where the spur gear and arc gear have to remain engaged throughout the motion. A hard stopper is installed at the end of arc gear to limit the range of motion such that it does not travel out of limit and overstrain the user's finger.

Figure 5.4: Failsafe mechanical stopper at the arc gear to prevent overstraining finger joints.

Figure 5.5: The index finger attached to the rehabilitation module at (a) rest position (b) Flexed position.

5.2 Thumb Module

The designing of a thumb exoskeleton poses various considerations into the approaches as compared to the rest of the fingers. Firstly, the thumb is not parallel to the other four fingers with the metacarpal bones connected to the trapezium bone at an angle with respect to coronary plane. Furthermore, the thumb has more degrees of freedom with less visible phalange joints as compared to the other fingers. This results in difficulties in locating the correct rotation axes for the joints and complicates the design for a coaxial-driven exoskeleton structure.

However as the first digit of the hand, there is more free space at the lateral side of the thumb to accommodate mechanical structure and its mechanism. Thus, there is more freedom in selecting an appropriate driving mechanism for optimal performance.

5.2.1 Initial Design Concepts

The initial concept was designed with the end effector driving approach where the distal phalange was actuated by a crane structure with 4 DOFs. As shown in Fig 5.6(a), the approach used in version 1 of the thumb module is analogous to a manipulator holding the thumb tip and moving it to the desired position in the right orientation. This method bypasses the needs of the mechanical structure to comply with the complex thumb joints while still controlling the thumb from the dorsal side of the hand.

The next proposal in version 2 of the thumb module design utilizes the principle of direct driving, where the drives are attached to the side of the thumb and rotating concentrically to the thumb joints. The design is shown in Fig 5.6(b). This method breaks down the thumb motion into individual components and drives it from the side.

Since the flexion/extension axis and abduction/adduction axis of the CMC joint are not perpendicular to each other and the angle between the two axes is reported to be in the range of 72.7° to 114.92° [77], the thumb phalanges are not parallel to the coronal plane of human hand, but inclined at an angle to provide the opposition motion. Hence, the CMC joint in version 2 of thumb module is designed to be adjustable in position and orientation to place the IP and MCP link in the correct inclination.

Figure 5.6: Two variations of thumb module explored and designed (a) Version 1 (b) Version 2.

However, after further analysis, it is difficult and impractical for an external crane structure in version 1 design to replicate the workspace of the thumb. Checking the

design with the workspace modeled in section 4.4.2, the exoskeleton motion covers only about 50% of the thumb workspace. The exoskeleton fails to push the thumb into flexed and opposed position.

For the thumb module design in version 2, the thumb workspace can be covered fully by the exoskeleton. However, upon verification in CAD model, the thumb orientation driven by the exoskeleton is not correct in the opposition configuration. This is further discovered to be caused by a minor passive axial rotation during the thumb opposition.

Due to the ligamentous laxity of the thumb joint which allows rotation of CMC joint along the axis of metacarpal bone, thumb movement involves multiple degrees of freedom where the flexion/extension and abduction/adduction of CMC joint consist of certain degree of passive pronation/supination. For example, thumb opposition is a combination of trapeziometacarpal and metacarpophalangeal joint abduction, flexion and pronation.

Although it is possible for the design concepts explored above to cover the workspace of thumb motion, the change in thumb phalanges orientation during the course of motion is not considered and provided for. Using the thumb exoskeleton design without pronation/supination does not only restricts the workspace of the exoskeleton device but the pronation/supination of thumb within the braces will also create the sliding motion and friction causing potential discomfort and injuries to the users.

Figure 5.70-3: Cross sectional views of hand. (a) Metacarpal bone in thumb rotates axially during opposition. (b) If the finger holder is designed to have a constant orientation during opposition, metacarpal bone can slide in the holder and cause discomfort. (c) Holder should rotate along with the metacarpal bone.

Another challenge in thumb exoskeleton design is the close proximity between the thumb CMC joint and the wrist joint. An individual functioning thumb exoskeleton has no space constraint in accommodating the driving mechanism as long as it does not interfere and block the movement. After the integration and mounting of thumb module onto the wrist platform, the distance of less than 3cm between the thumb CMC joint and wrist joint creates a fight for space to fit structures from both joints. The available design envelope is further constrained by the workspace and range of motion for the thumb and wrist.

5.2.2 Final Design Concept

Due to the aforementioned issues, the design had been simplified by re-examining the functionality and movement of the thumb to identify the key motion characteristics. Activities of daily living (ADLs) refers to the self-care activities that patients carry out at home, including feeding, dressing, housekeeping,

grooming and taking medicine. Thus, the prominent motor skill required to complete the activities is grasping, which involves the thumb motion of opposition between the radial abducted position and the palmar abducted position.

Figure 5.8: (a) The palmar abducted position. (b) The radial abducted position.

The trajectory of thumb opposition within these two postures forms an arc at the base of an imaginary cone, which has its tip at the CMC joint. The cone orientation is defined by three points: the CMC joint, MCP joint at radial abduction posture and MCP joint at palmar abduction posture. The arc length can be determined by the amount of thumb axial pronation within this trajectory, which then provides the size of the cone. With the cone, thus the correct opposition trajectory is constructed and the actuation can be designed with the principle of RCM by following the shape of the base circle of the cone.

Figure 5.9: The amount of thumb pronation is 90° which define the center and size of the circle.

5.2.3 Mechanical Model and Assembly

Similar to the actuation mechanism of finger module, an arc gear is designed to be concentric to the base circle defined in the previous section. The size and orientation of the arc gear follow the circumference of the cone drawn by the thumb pronation. Differing from the finger design, the thumb arc gear is supported by 2 rollers and 4 bearings with a more rigid structure since the load acting on the module is larger.

Figure 5.10: Section view of the thumb CMC module and the constraints on the arc-gear.

Because of the orientation of the structure and space allocation, worm gear is chosen as the force transmission mechanism. The DC motor is placed at the right angle to the rotation axis, and transmits the torque to a spur gear through the worm gear mechanism to drive the arc gear. The high gear ratio of worm gear permits a relatively smaller DC motor to be used at the expense of output speed.

Figure 5.11: Actuator and transmission system for the thumb CMC module.

The arc gear is then driven to move along the opposition trajectory as designed and to carry the metacarpal phalange of the user's thumb from the radial abducted position to the palmar abducted position.

As the thumb CMC joint moves in a cone path instead of a cylindrical path, the thumb is not perpendicular to the circle as shown in Fig. 5.9. As a result, the actual pronation is slightly bigger than the angle defined in the previous section. An additional degree of freedom has to be added for the thumb pronation to accommodate this extra degree of rotation. Due to the space constraint, it is designed to be a passive mechanism where it follows the pronation of the thumb metacarpal bone along the motion of the thumb opposition. As shown in Figure 5.12, the pronation mechanism is designed as an arc structure that slides along the dorsal side of the thumb CMC housing. It is guided by two screws that move in the track of thumb CMC housing.

In order to compensate for the weight of the pronation mechanism, a constant force spring is installed at the thumb CMC housing as a counterbalance. The spring applies an upwards pulling force on the load to cancel the effect of gravity. It provides a fixed amount of pulling force over the range of motion.

Figure 5.12: A passive DOF for thumb pronation compensated with constant force spring.

Mounting on this thumb pronation module are the remains of the thumb module: the flexion/extension of the thumb MP and DP modules. The direct driving method is adopted in these modules where the actuator is driving the motion concentrically to the finger joints.

Figure 5.13: (a) Rest position of thumb MP and DP modules. (b) Flexed orientation of thumb MP and DP modules.

Figure 5.14: Thumb is overstrained when the pronation motion is not designed into the module.

5.3 Wrist Module

5.3.1 Design Concept

In order to complete the tasks in the activities of daily living, a wrist joint mechanism is added to bring the patient's hand towards the location of interest for further actions like grasping, manipulation, pushing and etc. Three degrees of freedom are introduced in the wrist joint module, namely wrist flexion/extension, forearm pronation/supination and forearm forward/backward.

In order to free up the hand's palmar space for further action like grasping, the widely adopted palmar handle design in actuation of wrist flexion/extension joint is not used in the design (Figure 5.15a). Grasping of handle constraints the fingers movement and couples the degree of freedom between wrist and fingers. Furthermore, holding on to a handle when moving the wrist limits the usable task for fingers rehabilitation. Hence, the patient's palm is designed to be wrapped externally at the dorsal side of the palm, which is similar to a hand splint (Figure 5.15b).

Figure 5.15: (a) Handle-grasping type of wrist rehabilitation robot from the Newman Lab, MIT (b) Splinting on wrist.

5.3.2 Mechanical Model and Assembly

The wrist mechanism consists of three modules: wrist flexion/extension module, arm pronation/supination module and wrist advance/retract module. The main mounting interface for user is the arm rest and palm brace. The patients' forearm can be positioned on the arm rest and secured with a strap, while the patients' hand will be fixed to the palm brace at the dorsal side.

Figure 5.16: Wrist module with the arm rest and palm brace.

After the user strapped his hand to the palm brace, the brace will be driven by a DC motor placed beneath the wrist joint through a belt-pulley transmission system. This module is mounted onto the arm rest and follows the motion of arm supination/pronation.

Figure 5.17: Wrist flexion module.

For arm supination/pronation module, the arm rest is actuated by the spur gear in contact with the internal gear. The internal gear is mounted stationary to the main platform, while the spur gear is attached to the supination/pronation motor. The arm rest is supported by three cam followers that move along the customized track, which provide structural constraints in twisting along the Y and Z axes. The internal gear and tracks are designed with an opening to ease the placement of user hand onto the machine.

Figure 5.18: Arm supination/pronation module.

In the wrist advance/retract module, the main platform is actuated by a lead screw system driven by DC motor. The lead screw system is selected due to its high mechanical advantage and stability (self-locking due to the high stiction). Furthermore, high linear speed is not required for the platform movement which suits lead screw application. Besides the actuator, two linear guides installed at both sides of the lead screw serve as the main support of the machine weight to guide the linear motion.

The assembled wrist module serves as a platform for the arm and hand of user to perform pitch and roll motion.

Figure 5.19: Wrist advance/retract module.

5.4 Assembled Prototype

The assembled thumb and index finger modules, mounted onto the wrist platform are shown in Figure 5.20. An arm with hand model is inserted to the module to illustrate the use case.

Figure 5.20: Assembled system of fingers and wrist modules.

5.4.1 Kinematic Model of the Rehabilitation Robot

The kinematic model and the ROM of the designed rehabilitation module are shown in Figure 5.21 and Table 5.1 respectively.

Figure 5.21: Kinematics representation of the rehabilitation robot.

Table 5.1: ROMs of prototype.

Joint			ROM
Thumb Module	θ_{81}	CMC joint	-10° to 60°
	θ_{92}	MP joint	-30° to -50°
	θ_{103}	DP joint	-45° to 80°
Index Finger Module	θ_{47}	MCP abduction/adduction	-57° to 63°
	θ_{58}	MCP flexion/extension	-57.5° to 75.8°
	θ_{69}	PIP joint	-55° to 72.5°
	θ_{710}	DIP joint	-48° to 65°
Wrist module	θ_{37}	Wrist flexion/extension	-16° to 50°
	θ_{28}	Wrist pronation/supination	0° to 180°
	S_{110}	Wrist advance/retract	0mm to 200mm

5.4.2 Verification of the Workspace

From the workspace analysis calculated through singularities rank deficient criteria in Section 3.6, the workspace of the thumb and index finger is modelled in the CAD software. The purpose of the conversion is to verify the range of motion of hand rehabilitation exoskeleton, as compared to the workspace of the user's thumb and finger. By placing the calculated finger workspace at the same origin with the design hand exoskeleton, the verification can be performed by checking the overlapping of workspace and exoskeleton modules while moving them live in the CAD software.

Figure 5.22: Workspace of thumb and index finger and their use in verifying rehabilitation robot workspace in CAD design.

Whenever there was a major discrepancy between the motion of exoskeleton modules and the workspace of user's fingers, the exoskeleton design would be revised to identify the mistake and refined to achieve the desired application.

5.5 Motor Sizing and Calculation

5.5.1 Thumb and Index Finger

Using torque gauge to measure the assistance force applied by therapists during rehabilitation session, Ueki [29] determined the reliable joint torque to be applied by the robot onto the patient's finger. The measurements are presented in Table 5.2.

Table 5.2: Joint torque required on human fingers [29].

Joint		Thumb (Ncm)	Index (Ncm)
CMC	Extension	29.3	-
	Flexion	29.0	-
	Abduction	32.8	-
MCP	Extension	13.0	24.7
	Flexion	26.0	29.3
	Abduction	-	16.7
PIP	Extension	-	28.7
IP/DIP	Extension	22.3	17.7
	Flexion	24.8	19.7

Besides the functional movement required by the finger presented in Table 5.2, the motors have provided additional torque to support and move the structures of mechanisms. For example the MCP joint in index finger module, the motor should

be able to drive the structures of DIP and PIP modules besides providing the functional requirements of 29.3Ncm for MCP joint flexion. Including the torque resulted by the weight of the modules, which is $2.9\text{N} \times 5.9\text{cm} = 17.11\text{Ncm}$, the total torque required for the MCP joint driver is 46.41Ncm. This calculation is illustrated in Figure 5.23.

Figure 5.23: Torque calculation for the finger module.

Motor selection for all the finger joints are calculated in the table below:

Table 5.3: Total torque required on each joints.

Joints		Joint torque (Ncm)	Required torque to offset robot weight (Ncm)	Total torque required (Ncm)
Index Finger	MCP flexion/extension	29.3	17.11	46.41
	MCP abduction	24.7	14.93 (flexed wrist)	39.63
	PIP	28.7	3.79	32.49
	DIP	19.7	0.03	19.73
Thumb	CMC flexion/extension	29.3	9.45	38.75
	CMC abduction	32.8	4.69 (flexed wrist)	37.49
	MP	26	2.54	28.54
	IP	24.8	0.05	24.85

Factor in the gear ratio and transmission efficiency, the selected motors are:

Table 5.4: Motor selected for finger modules.

Joints		Arc-gear		Timing belt	Required torque (Ncm)	Motor selected			Torque output (Ncm)	Safety factor
		Gear ratio	Efficiency	Drive ratio		Motor	Gear-head	Encoder		
Index finger	MCP flexion	17:4	0.98	1:1	11.14	A-max19 110092	Planetary 149044	MR 228177	22.2	1.99
	MCP abduc	-	-	-	39.63	A-max19 110092	Planetary 149047	MR 228177	41.49	1.05
	PIP	7:2	0.98	1:1	9.47	A-max19 110092	Planetary 149044	MR 228177	22.2	2.34
	DIP	20:7	0.98	1:1	7.05	A-max19 110092	Planetary 149043	MR 228177	8.50	1.21
Thumb	CMC flexion	-	-	-	38.75	A-max19 110092	Planetary 149047	MR 228177	41.49	1.07
	CMC abduc	-	-	-	37.49	A-max19 110092	Planetary 149047	MR 228177	41.49	1.11
	MP	-	-	-	28.54	A-max19 110092	Planetary 149046	MR 228177	33.83	1.19
	IP	-	-	-	24.85	A-max19 110092	Planetary 149046	MR 228177	33.83	1.36

5.5.2 Wrist

The sizing for wrist motor is determined based on the findings of continuous wrist torque exerted in 19 activities of daily living as reported in [78]. Table 5.5 shows the torque values needed.

Table 5.5: Maximum torque values applied by wrist joint for 19 activities of daily living (ADL).

Joint	Torque (Nm)
Forearm pronation/supination	0.06
Wrist flexion/extension	0.35
Wrist abduction/adduction	0.35

Similarly, the weight of the robot is factored into the calculation to provide sufficient operating torque at the wrist joint:

Figure 5.24: Torque calculation for wrist flexion module.

For wrist flexion as illustrated in the picture above, the maximum torque generated by the weight of finger modules occurs at the horizontal position, with a magnitude of $10.47\text{N} \times 0.087\text{m} = 0.911\text{Nm}$. Combining the functional torque of 0.35Nm , the total torque provided by the wrist flexion/extension motor should be 1.26Nm . Hence, the suitable motor selected is Maxon motor A-max26 110963 with gear-head 144044 that produces total nominal torque of 2.7Nm , including a safety factor of 2.14.

Figure 5.25: Torque calculation for arm supination/pronation module.

In the case of wrist pronation/supination joint, the maximum torque generated by the finger modules is $15.13\text{N} \cdot 0.036\text{m} = 0.543\text{Nm}$. The total motor torque needed is hence 0.6Nm , after adding in the functional wrist pronation/supination torque of 0.06Nm . The motor selected is thus Maxon A-max26 110963 with gear-head 144040 which provides nominal torque of 1.53Nm and gives a safety margin of 2.5.

With lead screw-nut pair adopted in the wrist advance/retract mechanism, a relatively smaller DC motor can be used to drive the rehabilitation platform. Lead screw system is an economical, compact and precise mechanism that produces a high mechanical advantage at the expense of linear speed.

For an arm weight of 4.5kg (5% of total human weight), hand weight of 0.5kg and rehabilitation robot of 3.5kg , the total thrust force required to drive the machine along the lead screw is

$$F_T = F_f + F_i + F_A \quad (5.1)$$

where F_f is the frictional force, F_i is the inertial force and F_A is the application force. The total thrust force required is $41.69 + 8.5 + 56 = 106.19\text{N}$, assuming a coefficient of friction of 0.5, maximum acceleration of 1ms^{-2} and the required applied force is 50% of the maximum pushing force in healthy human.

As the chosen lead screw and lead nut is made from steel and brass respectively, the lead angle L_A and screw efficiency η can be determined via

$$L_A = \tan^{-1} \left(\frac{L}{\pi d_m} \right) \quad (5.2)$$

$$\eta = \frac{1 - \mu \tan(L_A)}{1 + \frac{\mu}{\tan(L_A)}} \quad (5.3)$$

where L is the screw lead, d_m is the mean screw diameter, and μ is the coefficient of dynamic friction. For the chosen lead screw, $L_A = 3.42^\circ$ and $\eta = 21.85\%$ with coefficient of dynamic friction of 0.21 between steel and brass.

With the calculated information above, the torque, T required at the lead screw to produce the thrust force for the rehabilitation robot is 0.116Nm .

$$T = \frac{F_T L}{2\pi\eta} \quad (5.4)$$

where F_T is the total thrust force, L is the screw lead and η is the screw efficiency

The motor selected is Maxon motor A-max22 110164 with gear-head 134767 that produces total nominal torque of 0.135Nm. The maximum advance/retract speed of the rehabilitation robot is hence 0.464ms^{-1} , which is sufficient for most of the tasks.

5.5 Electronics Interface

Considering the payload requirement for fingers and wrist rehabilitation is less demanding, DC brushed motors are selected over DC brushless motors for its simplicity of electrical control. Planetary gear head is attached coaxially to the motor to provide large reduction ratio and high power density.

In general, DC brushed motor can be installed and controlled through the following interfaces:

Figure 5.26: Electrical system for servomechanism.

In a motion control system, the motion controller is the brain of the system where it coordinates between the high level software, motor driver and system feedback. Firstly, the software creates the motion profiles for the motor and delivers the desired target position to the motion controller at a fixed interval. The motion controller then calculates the motor speed required based on the given target

position, and outputs analog control signal to the amplifier. Next, based on the received control signal, the motor driver or amplifier will then regulate the current supply it receives from the power supply, to turn the motor at the specified speed. The motor then turns the electrical energy into mechanical energy and moves the payload into the target position. This control cycle ends when the motor encoder coupled to the motor shaft sends the motor position back to the motion controller, to close the control loop. With the position feedback, motion controller can determine the motion error and factor it in the planning of motor speed for the next cycle.

5.5.1 Motion Controller and Software

The control software used in the hand rehabilitation robot is Labview, which has a graphical programming interface with various built ready toolboxes and libraries suitable for rapid prototyping. The software is implemented with the hardware from National Instruments, including the universal motion interface UMI-7774, and motion controller cards PXI-7344.

Figure 5.27: Motion interface and motion controller card from National Instruments.

5.5.2 Motor Driver

Maxon DC brushed motors are implemented in the hand rehabilitation robot. These motors require nominal voltage of 2.4V and starting current of 2.09A for optimum motor torque performance. The motion controller used is the National Instrument system with motion card PXI-7344 which output analog control signal of $\pm 10V$. In order to convert the control signal into suitable motor current, two amplifier systems, namely H-bridge motor driver and direct signal amplification method were designed and tested.

The H-bridge integrated circuit (IC) used is drv8833 from Texas Instruments which can drive two DC brushed motors in both directions at the same time. Since this IC chip requires pulse-width modulation (PWM) input, a microcontroller is used to interpret the control signal from the NI motion card and convert them into PWM signal of corresponding duty cycle. The PWM signal is then channeled to the H-bridge IC as current control of the motor power. The power supply of 2.7V is regulated by H-bridge to drive the motor at different speeds and directions. There is a reverse polarity protection circuit built into the system to prevent a mistake in power supply installation from damaging the circuit.

Figure 5.28: H-bridge motor driver.

The circuit was built and tested with the prototype. However, the resultant system bandwidth was found to be low due to the multiple layers of signal conversion between motion controller and motor. There is a noticeable latency between command and execution of the rehabilitation device.

The method of direct amplification of control signal from NI motion card is explored in lieu of the effort to remove the conversion circuits between control module and dc motors. The amplification is done through the operational amplifier chip OPA544T from Texas Instruments.

Figure 5.29: Direct amplification motor driver.

In this method, the control signal output from NI motion card is adjusted from $\pm 10V$ to $\pm 3V$. The op-amp is arranged in a unity buffer or voltage follower configuration with the gain of 1 to eliminate the loading effects.

Figure 5.30: Voltage follower op-amp configuration.

Since the amplifier in the designed circuit has unity gain, the output voltage from OPA544T has the same voltage value but with a higher current supply up to 2A. The current supply provided is sufficient to meet the starting current required for the motors. The direct amplification method also eliminated the significant control delay observed in the H-bridge circuit, and thus suitable for the application.

5.5.3 Encoder

The magnetic encoder with quadrature signal output is adopted for the position feedback of the motor. Magnetic encoder is a compact solution that comes with magnetic poles to generate encoder position on a magnetic sensor. As the motion between sensor and poles is contactless, mechanical friction, wear and tear is absent, which prolongs the service life of the encoder.

The quadrature detection method consists of two output channels (A and B) and one index channel. Through tracking the edges of channel A and B which are designed to be 90° out of phase, the position and direction of the motor rotation can be determined. The detection method also permits an option to increase the encoder's resolution, where users can switch between different counting methods: leading edges, trailing edges or both edges. This method provides an increase of up to four times of the encoder specified resolution, which is deemed useful in robotics applications which require high bandwidth.

The electrical interface used to transfer the quadrature output to the motion controller is line driver. Line driver has low output impedance and high signal to noise ratio which can minimize the noise in long cable lengths. Its immunity to electromagnetic interference makes it an ideal candidate to be implemented in this electro-mechanical prototype.

5.6 Discussion

The hand rehabilitation system discussed in this chapter is designed for a reach-to-grasp motion to grasp and retrieve a mug. The index finger, thumb and palm modules are carried by a linear stage in forward and backward motions of the reaching motion. However, the adoption of a linear stage is a simplified system to validate the finger and thumb robots design. The forward/backward motion works in planar space and does not represent the real life upper arm application. For example, in order to complete the ADL task of grooming, the robot should be able to retrieve the comb and reach for the patient's hair. The patient's arm moves in a more complex trajectory instead of a planar space.

Due to the limitation of the linear stage in providing the patient's arm motion, the index finger, thumb and palm mechanisms are designed as a functional independent module which can be mounted and integrated with other arm rehabilitation robot. Some examples of the arm rehabilitation robots includes Dampace from University of Twente [79], ARMin from ETH Zurich [55] and T-WREX from University of California, Irvine [80].

(a)

(b)

(c)

Figure 5.31: Arm rehabilitation robots: (a) Dampace [79] (b) T-WREX [80] (c) ARMin [55].

Chapter 6

Trajectory Planning

The ADL task to be performed is reach-to-grasp action to retrieve a mug placed on a platform. Based on the degree of freedom in our machine, the tasks to be performed will be limited to pick and place of the mug in one direction.

6.1 Stages in Reach-to-grasp

Generally, the grasping action in human can be observed in two phases: reaching and grasping. In the reaching phase, the arm moves towards the target while the hand opens up and fingers extend simultaneously. When the hand reaches a suitable location, the fingers flex and press firmly onto the target, which complete the grasping action.

These two phases of grasping action decouple the movement of arm and fingers and reduce the complexity in grasping planning. Instead of designing complex trajectories for multiple serial robots with end effectors at each finger tip, the grasping action can be broken down into three simpler independent actions: extension of fingers (preshape), hand and arm motion approaching the target (reaching), flexion of fingers to grip the object (grasping).

6.2 Preshaping

Preshaping is the concept of preparing the hand shape before approaching the object to be grasped. With pre-shaping, the fingers assume appropriate configurations to match the shape of the target object for a stable and firm grip. Based on the physical properties (i.e. size, form, center of mass, etc.) of the objects, the fingers form the most suitable contour before grasping, such that the fingers follow a realistic trajectory and place the contact at optimum points for a firm grip of objects.

The idea of preshaping is supported by the research from Santello and Soechting, where hand shape is found to adapt gradually to objects contour along the reach-to-grasp action [81]. They found that at the 50% movement time where the hand aperture is at the maximum, the hand shapes are noticeably distinct for different object shapes. The distinction of the hand shape becomes more obvious as the aperture decreases and finally mould around the objects.

It is found that in grasp planning and generation, the pre-shapes can be categorized into different categories. Miller, Knoop et. al. proposed four different preshapes for four different basic shapes: spherical, cylindrical, boxes and conical preshapes [82]. Wren and Fisher suggested the precision, lateral, manipulation, and hook preshapes for different applications [83]. Different rules can then be applied to the pre-shapes and their strategies to constrain and define the best orientation and positions for the starting points of grasping.

In this thesis, the focus is placed on grasp planning of a mug (cylindrical objects), with power grasp. The grasp planning is divided into three parts: preshapes selection to determine the posture of the fingers, calculation and move to optimum location of wrist joint upon grasping, and the trajectory of finger motion to the grasping posture.

6.2.1 Preshape Posture Determination

For the pre-shapes, the cylinder shape primitive is chosen as the grasp approach since the mug is considered to be a cylindrical shape. For power grasping where the fingers wrap around the cylinder, the approaching direction should be

perpendicular to the side surface of the cylinder, and the thumb should be perpendicular to the central axis of the cylinder.

Resulting from the definition, three constraints provided for this cylinder pre-shapes are illustrated in Fig. 6.1:

1. The IP and MP links of thumb form a straight line.
2. The fingers and palm forms a straight line.
3. The IP and MP links of thumb are perpendicular and form a right angle with the palm.

Figure 6.1: Preshapes configuration for grasping action.

As our exoskeleton machine is built without abduction/adduction at thumb MP joint, the IP and MP links of thumb are not able to form a right angle with the palm. Hence, the third constraint is translated to the maximum angle of abduction of thumb CMC joint, which is 70° .

The configuration for preshape which fully formed at 50% of the reaching distance is hence defined by the joint angles as shown in Table 6.1.

Figure 6.2: User's hand is brought into preshapes position by the rehabilitation robot.

Table 6.1 : Angular displacement for each joints at grasping preshapes orientation.

Fingers	Joint	Joint angle (°)
Index	MCP abduction/adduction, θ_4	0
	MCP flexion/extension, θ_5	0
	PIP flexion/extension, θ_6	0
	DIP flexion/extension, θ_7	0
Thumb	CMC abduction/adduction, θ_8	90
	MP flexion/extension, θ_9	0
	IP flexion/extension, θ_{10}	0
Wrist	Pronation/supination, θ_2	90
	Flexion/ extension, θ_3	0
	Advance/ retract, S_1	1240

6.2.2 Determination of Wrist Joint Location for Optimized Grasping Posture

As illustrated by Lee and Zhang [84], a stable power grasp is defined when the grip force is maximum while the inflicted stress is minimum. This happens when the soft tissues of the hand and fingers are most expanded and the forces exerted are evenly distributed. Thus, this biomechanical model can be accomplished by minimizing the distance between finger joints and object surface to spread out the contact stresses of each segment. In mathematical term, the function to be minimized is:

$$f = \sum_{i=1}^3 dist_i(x, z, \gamma) + \sum_{j=1}^2 dist_j(x, z, \gamma) \quad (6.1)$$

where

i is the joint index for index finger, from 1 (MCP joint) to 3 (DIP joint),

j is the joint index for thumb, from 1 (MP joint) to 2 (IP joint)

$dist(x, z, \gamma)$ is the distance of joint from the object surface as a function of x and z , which are the coordinate of capacitance bone (origin in the hand model); and function of γ , the inclination angle of object rotation axis and hand grasping axis.

Figure 6.3: During power grasp, the hand grasping axis is not parallel to the object rotation axis, but is inclined to an angle.

The power grasp model with its parameters is shown in Fig 6.4 to describe the optimization procedure. The parameters in the model are calculated with respect to the reference frame of the hand model as explained in Chapter 4, where the origin is at the capitatum bone. The grasping action is the flexing of fingers starting from the pre-shape posture to a stable gripping posture, with the assumption that links l_0 , T_0 and T_{00} are stationary during the grasping process.

Figure 6.4: Geometrical analysis for the optimum wrist position to provide a stable grasping.

As shown in Fig. 6.4, the parameters:

T_i is the length of the thumb segments,

l_i is the length of index finger segments

t_i^n is the segment thickness at contact with the object, which is the shortest distance between a segment and the object surface during a stable grip posture as empirically determined by Zhang and Lee [82]

D_i^n is the distance between the joints and object surface

For the simple case without considering the grasping angle γ , the distances between the joints and the object surface can be calculated via geometry analysis:

Index finger

$$D_1^I = \left[\sqrt{(x_{MCP} - x_{object})^2 + z_{object}^2} \right] - r_{object} \quad (6.2)$$

$$D_2^I = \left\{ \sqrt{\left[l_1 - \sqrt{(r_{object} + D_1^I)^2 - (r_{object} + t_1^I)^2} \right]^2 + (r_{object} + t_1^I)^2} \right\} - r_{object} \quad (6.3)$$

$$D_3^I = \left\{ \sqrt{\left[l_2 - \sqrt{(r_{object} + D_2^I)^2 - (r_{object} + t_2^I)^2} \right]^2 + (r_{object} + t_2^I)^2} \right\} - r_{object} \quad (6.4)$$

Thumb

$$D_1^t = \left[\sqrt{(x_{object} - x_{MP})^2 + (z_{MP} - z_{object})^2} \right] - r_{object} \quad (6.4)$$

$$D_2^t = \left\{ \sqrt{\left[T_1 - \sqrt{(r_{object} + D_1^t)^2 - (r_{object} + t_1^t)^2} \right]^2 + (r_{object} + t_1^t)^2} \right\} - r_{object} \quad (6.5)$$

where r_{object} is the radius of the cylindrical object.

When there is a grasping angle of γ , vector projection of the joint length from the finger plane to the perpendicular plane should be considered. The projected link length l_{pi} can be calculated as

$$l_{pi} = \sqrt{\left(l_{oi}^2 - \|l_{oi} \cdot (n_p \times n_o)\|^2 \right) \cdot (n_p \cdot n_o)^2 + \|l_{oi} \cdot (n_p \times n_o)\|^2} \quad (6.6)$$

where

l_{oi} is the link length of the finger segment i in the original plane

n_p is the normal vector for the projected plane

n_o is the normal vector for the original plane.

Figure 6.5: The projection of fingers position and orientation onto the plane that is perpendicular to object axis.

Let the capacitate bone be the origin with coordinate $(0, 0, 0)$, the normal vector for projected plane, $n_p = (0, 0, -1)$ and the normal vector for original plane, $n_o = (0.5, 0, 0.866)$.

With the calculated projected link l_{pi} replacing the original link length l_{oi} , the sum of distance between each finger joint and object surface will be minimized to provide the optimum value for $D_1^I, D_2^I, D_3^I, D_1^t$ and D_2^t .

After that, with reference to the centroid of the object, $P_{object}(x_{obj}, y_{obj}, z_{obj})$, the position for capacitance bone, P_{CB} and thus the wrist joint location, $P_{wrist}(x_{wrist}, y_{wrist}, z_{wrist})$ can be calculated

$$P_{CB}(x_{CB}, y_{CB}, z_{CB}) = (x_{obj} - l_0 \cos \gamma, y_{obj} - l_0 \sin \gamma, z_{obj} + r_{object} + D_1^i) \quad (6.7)$$

$$[x_{wrist} \ y_{wrist} \ z_{wrist} \ 1]^T = {}^{CB}T_{wrist} [x_{CB} \ y_{CB} \ z_{CB} \ 1]^T. \quad (6.8)$$

With the optimized wrist joint position P_{wrist} thus the distance between joints and object surfaces D_i^n calculated from the algorithm, the final grasping posture can be determined. The joint angles in projected plane θ_p can be found via geometry analysis:

$$\theta_{pi}^n = \sin^{-1} \left(\frac{r_{object} + t_{i-1}^n}{r_{object} + D_i^n} \right) + \sin^{-1} \left(\frac{r_{object} + t_i^n}{r_{object} + D_i^n} \right) \quad (6.9)$$

The final grasping position for joint space can then be determined by finding the joint angle in the original plane:

$$\theta_{oi}^n = \cos^{-1} \left\{ \frac{(l_{oi}^n)^2 + (l_{o(i+1)}^n)^2 - [(l_{pi}^n)^2 (l_{p(i+1)}^n)^2 - 2(l_{pi}^n)^2 (l_{p(i+1)}^n)^2 \cos \theta_{pi}^n - (\sqrt{(l_{oi}^n)^2 - (l_{pi}^n)^2} - \sqrt{(l_{o(i+1)}^n)^2 - (l_{p(i+1)}^n)^2})^2]}{2l_{oi}^n l_{o(i+1)}^n} \right\} \quad (6.10)$$

6.3 Grasping Tracjectory

There are limited literature and studies done in investigating the model of human fingers trajectory during grasping motion. The minimum jerk trajectory approach proposed by Secco [85] in prosthetic fingers motion planning aimed to provide a natural movement while minimizing the mechanical vibration of the structure. In this method, the fingertip of the prosthetic moves in a straight line trajectory while providing a low jerk motion at joint level. However, according to the empirical observation and experiment data collected by Kamper [86], the straight line trajectory proposed by Secco doesn't fit the velocity profile of grasping action. Instead, the data produced by Gupta [85] and Kamper [86] through motion capture system, suggested that the fingertips paths follow a logarithmic spiral trajectory during grasping action.

In addition to that, there are more studies in reach and grasp motion to determine an appropriate trajectory model for the arm movement. Energetic optimization models were proposed for arm motion where human arms follow trajectories of minimum kinetic energy [88] and minimum torque change [89]. In an effort to model sequential movement of human arm, Okadome and Honda introduced a minimum angular jerk model [90] based on their experiment data. Besides that, based on biomechanical model, Flash [91] believed that the arm motion follows an equilibrium trajectory guided by the joint stiffness and viscosity.

In his study of grasping motions, Friedman [92] compared four different trajectory models (Minimum kinetic energy, minimum angular jerk, minimum torque change and logarithmic spiral model) to determine the best fit to the experimental data. Logarithmic spiral model was found best in describing the fingertips trajectory.

This trajectory is found to be consistent and not affected by the initial finger posture, which is deemed useful for our application.

6.3.1 Logarithmic Spiral Trajectory

Logarithmic spiral is a spiral curve that grows exponentially with its angle. It has a constant angle between the tangent and radial line. It is described in polar coordinate as

$$r = ae^{b\theta} \quad (6.11)$$

where

r is the spiral radius

θ is the angular displacement of rotation

e is the base of natural logarithms

a and b are arbitrary positive real constants.

Figure 6.6: Logarithmic spiral curve in 2D.

In two-dimensional Cartesian frame, the spiral curve can be expressed parametrically as

$$x = ae^{b\theta} \cos \theta \quad (6.12)$$

$$y = ae^{b\theta} \sin \theta \quad (6.13)$$

In order to project the 2D logarithmic spiral trajectory into a 3D space for the finger closure action in grasping, the spiral trajectory is designed to be located in the X-Z plane of a Cartesian space. In this setting, the human palm is designed to be parallel with the X-Y plane and the finger is co-linear with the x-axis at the rest position. The flexion of finger is assumed to be perpendicular to the palm and abduction or adduction does not happen during the motion. The 3D trajectory for logarithmic spiral can be expressed as

$$x_g = ae^{b\theta} \sin \theta \quad (6.14)$$

$$y_g = 0 \quad (6.15)$$

$$z_g = -ae^{b\theta} \cos \theta \quad (6.16)$$

Due to the tilt angle of the grasping plane, the trajectory has to be projected back to the original plan. A z-axis rotation matrix with angle γ° is introduced to relate the grasping frame with the original frame. The final trajectory in original frame is thus

$$\begin{aligned} \begin{pmatrix} x_o \\ y_o \\ z_o \end{pmatrix} &= \begin{pmatrix} \cos \gamma & \sin \gamma & 0 \\ -\sin \gamma & \cos \gamma & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} ae^{b\theta} \sin \theta \\ 0 \\ -ae^{b\theta} \cos \theta \end{pmatrix} \\ &= \begin{pmatrix} ae^{b\theta} \sin \theta \cos \gamma \\ -ae^{b\theta} \sin \theta \sin \gamma \\ -ae^{b\theta} \cos \theta \end{pmatrix} \end{aligned} \quad (6.17)$$

Figure 6.7: The projection from grasping frame onto original frame.

Note that the Cartesian frame for the logarithmic spiral trajectory specifies the position of fingertip with respect to the MCP joint, where the origin of the coordinate frame is situated at MCP joint.

With the joint angle for the fingers in final grasping posture determined previously, the Cartesian coordinate for the pre-grasp position $P_{Fingertip0}(x_o, y_o, z_o)$ and the post-grasp position $P_{FingertipF}(x_f, y_f, z_f)$ of the fingertip can be calculated through forward kinematics.

At the pre-grasp position $P_{Fingertip0}(x_o, y_o, z_o)$, the finger lies in the X-Y plane which gives $z_o = 0$. As the origin of the logarithmic spiral starts from the z axis, the angular displacement, $\theta = 90^\circ$ when the finger is in preshapes orientation. The coordinate of $P_{Fingertip0}(x_o, y_o, z_o)$ can thus be represented by

$$x_o = ae^{1.57b} \cos(30^\circ) \quad (6.18)$$

$$y_o = ae^{1.57b} \sin(30^\circ) \quad (6.19)$$

$$z_o = 0 \quad (6.20)$$

At the post-grasp position $P_{FingertipF}(x_f, y_f, z_f)$, the location of the fingertip is

$$x_f = ae^{b\theta_f} \sin \theta_f \cos(30^\circ) \quad (6.21)$$

$$y_f = -ae^{b\theta_f} \sin \theta_f \sin(30^\circ) \quad (6.22)$$

$$z_f = -ae^{b\theta_f} \cos \theta_f \quad (6.23)$$

With the pre-grasp position and post-grasp position of the fingertip known, there are three unknowns (a, b, θ_f) with three equations (interdependence in expression x_o and y_o , x_f and y_f) to be solved. After solving the system of equations, the parameters are

$$\theta_f = \tan^{-1} \left(\frac{-x_f}{z_f \cos \gamma} \right) \quad (6.24)$$

$$b = \frac{\ln(x_o / \sin \theta_f)}{90^\circ - \theta_f} \quad (6.25)$$

$$a = \frac{x_o}{e^{1.57b} \cos \gamma} \quad (6.26)$$

Figure 6.8: The logarithmic spiral trajectory in 3D showing the start position and final position.

6.3.2 Task Space Control

The control architecture for the grasping action is divided into two parts, the outer loop and inner loops. The inner loop with a shorter cycle time takes care of the position control of individual joints; while the outer loop in smaller frequency controls the Cartesian position of the end effector, which is the fingertip used in closing and grasping the object.

The logarithmic spiral trajectory is first generated in the task space for the tip of the finger, where the individual joint angle for each joint are calculated through inverse kinematics. The respective target joint angles are then passed to the inner control loops and the individual controllers of each joint. Next, the target angles are converted into analog control signal which is then converted into amplified current to drive the DC motors. Due to the actuators and mechanical system dynamics, the resultant joint movement is biased from the target position. The actual joint angles moved are recorded by the encoders, and the errors in angular positions are feedback into the DIP controllers. The controllers then determine the

compensation value and deliver the corrected target angle back to the subsequent cycle of the loop.

Figure 6.9: The control diagram for grasping action.

P_T is the target position of the fingertip in Cartesian coordinate,

P_A is the actual position of fingertip,

P_E is the position error of the fingertip,

P_C is the controlled position of fingertip,

θ_i is the target joint angle,

θ_{Ai} is the actual joint angle moved,

θ_{Ei} is the error of joint angle,

V_i is the control signal in voltage,

I_i is the amplified current drive for the motor,

C_i is the encoder count measured at each joint.

In the outer loop, the actual position of the fingertip travelled will be calculated using forward kinematics with the joint angles collected from the encoders at each joint. The error between the target position and the actual position in Cartesian coordinate is then passed into a PI controller to generate the controlled target

position for the subsequent control cycle. The controlled position of fingertip is then segregated into individual target joint position again and passed to the inner control loop.

6.4 Reach Trajectory

6.4.1 Minimum Angular Jerk

For the reaching motion of the arm from the origin to the mug, the minimum angular jerk approach is adopted [91]. The minimum angular jerk trajectory is important in minimizing the vibration, wear and tear of the mechanical components, which is significant for the movement of the wrist joint with high inertia. The angular jerk is defined by the third time derivative of the angular displacement:

$$\ddot{\theta}(t) = \frac{d^3\theta(t)}{dt^3} \quad (6.27)$$

Through minimizing the jerk cost, a smooth trajectory function can be generated without a sharp change in angular acceleration. The function of the jerk cost to be minimized is

$$H(\theta(t)) = \frac{1}{2} \int_0^{t_f} \ddot{\theta}^2 dt \quad (6.28)$$

The general solution to the minimum jerk function is a fifth order polynomial:

$$x^{(6)} = a_0 + a_1 t + a_2 t^2 + a_3 t^3 + a_4 t^4 + a_5 t^5 = 0 \quad (6.29)$$

For the reaching action, the human hand starts from a resting position, forming the pre-shape posture at the middle point and reaching the optimum position at the end of the travel. The joint angles involved in the process are θ_5 and θ_6 .

For θ_5 , the initial joint angle $\theta_{5_0} = 0$ and the final joint angle $\theta_{5_f} = 1.2217 \text{ rad}$.

Solving the fifth order polynomial gives

$$a_0 = a_1 = a_2 = 0 \quad (6.30)$$

$$a_3 = \frac{12.22}{t_f^3} \quad (6.31)$$

$$a_4 = -\frac{18.33}{t_f^4} \quad (6.32)$$

$$a_5 = \frac{7.33}{t_f^5} \quad (6.33)$$

For θ_6 , the initial joint angle $\theta_{6_0} = 0$ and the final joint angle $\theta_{6_f} = 1.571rad$.

Solving the fifth order polynomial gives

$$a_0 = a_1 = a_2 = 0 \quad (6.34)$$

$$a_3 = \frac{15.71}{t_f^3} \quad (6.35)$$

$$a_4 = -\frac{23.57}{t_f^4} \quad (6.36)$$

$$a_5 = \frac{9.43}{t_f^5} \quad (6.37)$$

Together with the forward actuation of the base, the above trajectories bring the user's hand to the optimum wrist position in pre-shape grasping posture.

6.4.2 Joint-based Control

For the reaching action, the control architecture is relatively simpler. The action involves the movement from the original posture to the preshape posture, where the action can be decoupled into individual joint action. This is due to the movement axes of the wrist module that are located at the same origin. The degrees of freedom at the wrist module are not dependent on each other, and any movement in the machine does not change the position but orientation of the hand. Hence, only joint based control is required and implemented, to change the orientation of the hand from the original posture to the preshapes posture.

Similar to the inner loop of the task-based control, a PID controller is designed in each joint of the wrist: wrist roll, wrist pitch and wrist advance modules.

Figure 6.10: The joint space control for the wrist module.

6.5 Simulation

The reaching and grasping action is validated through the Labview and Solidworks software. Using the NI SoftMotion in Labview, each motor output is mapped into a motor axis in the CAD model in Solidworks. Through integration of the motion simulation in Labview and Solidworks, the motion profiles defined in Labview can be applied real time to hand rehabilitation robot assembly in Solidworks. The motion pattern and timing sequence can be visualized in the Solidworks animation, in order to validate and verify the motion trajectory and control system designed. Besides that, the material and mass properties of the CAD models can provide a reference for the motion analysis of the planned trajectory.

Based on the equations discussed in the previous sections, trajectories for reaching and grasping actions are generated offline through the Matlab software. The trajectories are stored in arrays of position data which is sampled at a fixed interval. The data is then imported into Labview which converts the individual data into a continuous spline motion. The splines created connect all the points while maintains a smooth motion profile.

6.5.1 Velocity and Acceleration Profiles

The motion profile including angular displacement, angular velocity and angular acceleration of each moving joints are generated as the result of simulation. The plots for each joint are shown in the Fig 6.11.

Figure 6.11: The kinematic performance of the reaching task of (a) thumb CMC module (b) wrist supination/pronation module (c) wrist advance/retract module.

From the simulated motion profiles, the reaching trajectory designed can be verified by checking the specification required to provide the system performance. Firstly, the peak angular velocity output from the servo system is checked against the velocity profiles in the three trajectories. The peak velocity required in the motion profile for thumb CMC module, wrist pronation/supination module and wrist advance/retract module are 11.46rpm, 11.46rpm and 381.97rpm respectively, which is sufficiently provided by the DC motors.

The other criterion to be examined is the peak torque required for the motion profile. The peak torque can be determined from the product of peak angular acceleration and the moment of inertia of driven loads, as expressed by equation $\tau = I\alpha$. The peak torque requirements for the motion profile of thumb CMC module is 5.38×10^{-4} Nm and for wrist supination/pronation module is 3.21×10^{-3}

Nm. The peak torque required by the motion profiles is acceptable for the designed servo system.

Figure 6.12: The velocity and acceleration profile of wrist joint during reach-to-grasp in: (a) & (b) Hand exoskeleton simulation (c) & (d) Actual healthy subjects [90] (e) Stroke patient [91].

In the reach to grasp movement study conducted by Castiello [92], the natural hand posture and motion pattern was investigated using 3D motion capture system. Data was collected on subjects performing reaching and grasping of cylinders of different sizes. The wrist velocity and acceleration in reach-to-grasp of two cylinders of different diameter are shown in Fig 6.12(c) and (d).

Compared to the result from Castiello, the motion profile designed in our system produces similar wrist velocity and acceleration profiles, where the peaks and valleys of the curves are symmetric over the course of action. It is close to the constant and balanced motion profile of healthy subjects' wrist during reach-to-grasp action, unlike the jerky and lopsided profile [93] as demonstrated by stroke patient in Fig 6.12(e).

Besides that, the peak velocity and acceleration in our designed motion, which is about 40mm/s^{-1} and 12mm/s^{-2} , are very small as compared to 900mm/s^{-1} and 6000mm/s^{-2} in the actual speed of wrist motion during reaching and grasping,

6.5.2 Reaching and Grasping Trajectory

The reach-to-grasp trajectory is illustrated in Fig 6.13, showing the paths of three key end effectors: thumb tip, index fingertip, and wrist joint. The green color cylinder in the graph represents the mug used in the grasping exercise. The three different stages of reach-to-grasp motion which includes preshaping, moving into optimum position, and finger closure for grasping can be clearly identified in the graph.

Figure 6.13: The trajectories of thumb tip, index fingertip and wrist joint in Cartesian during reach-to-grasp.

In Fig 6.14, the 2D plots of the motion trajectory are illustrated with the Y axis is the reaching direction towards the mug. As shown in the Fig 6.14(b), the natural

reach-to-grasp motion is a blend of preshaping, reaching, and grasping actions where the three stages are performed at the same time. Unlike the trajectory exhibited by the hand exoskeleton, the actual grasping motions performed by healthy subjects do not portray any distinct stages. The actual trajectory is advantageous as the duration of reach-to-grasp action is shorter. However, in order to safeguard the user's safety in using the rehabilitation robot for training, the efficiency in time is sacrificed for a stage-by-stage motion. Preshaping is initiated from the start of reaching and ends about halfway of reaching to ensure a collision free movement. After that, flexion of fingers for grasping starts only at the end of reaching, where the hand has reached the optimum position for a firm grasp.

The actual reaching trajectory of wrist joint shown in Fig 6.14(b) is comparable to the straight line trajectory profile designed for hand exoskeleton robot. Thus, a perfectly straight reaching motion at the wrist joint of the exoskeleton robot will not impose excessive strain or abnormal tone to the user's muscles during training.

Figure 6.14: Motion trajectories of thumb tip, index fingertip and wrist joint in 2D plane (a) Planned trajectories for exoskeleton robot (b) actual trajectories by healthy subjects [92].

The actual reach-to-grasp action is simulated in Solidworks and illustrated in Fig 6.15.

Figure 6.15: From left to right, top to bottom are the sequence of animated reaching and grasping action performed by the hand rehabilitation robot.

6.5.3 Grip Size

Another important behavioral kinematic data in reach-to-grasp action is the grip size or hand aperture. The grip size usually reaches the maximum during 60-70% of the duration of reaching, as shown in Fig 6.16(a). The maximum grip size also increases with the speed of the movement.

Figure 6.16: The plot of wrist velocity and grip size over time for reach-to-grasp training for (a) healthy subjects [92] (b) hand exoskeleton robot designed.

In the designed motion profile of the hand exoskeleton robot shown in Fig 6.16(b), the grip aperture opens to the maximum size before the wrist joint reaches the

maximum velocity, or the midpoint of the reaching path. This is due to the strategy of forming grasp preshape at 50% of the reaching journey, in order to create a stable posture before moving close to the grasping position. The grip size maintains at the maximum aperture until the end of the reaching stage, where the fingers start to close for grasping.

This design of grip size pattern in our rehabilitation robot corresponds to the reach-to-grasp motion profile observed in grasping without aid of vision. In the research by Sivak [94], wider grip size and lower movement speed is observed when the patients had limited vision and information about the size and spatial information about the object. Their grip size reached the maximum before the peak velocity of wrist joint motion, which signifies a more cautious reaching strategy due to the lack of visual information.

Figure 6.17: Top image shows the moving velocity of hand in reach-to-grasp exercise, while the bottom image shows the change of grip size during the exercise. NV: normal vision, PV: peripheral vision [92].

Chapter 7

Epilogue

7.1 Conclusion

A hand rehabilitation system consists of thumb, index finger and wrist modules has been designed with the objective to provide task-oriented trainings for post-stroke recovery exercises. The anatomy of human fingers and wrist is studied in detail to understand its ranges of motion and limitations, before using it as the reference in the design of the hand exoskeleton. In order to ensure the safety of using the exoskeleton, the workspaces of finger and thumb have been cross-checked with the hand exoskeleton model in the CAD software.

The rehabilitation robot adopts the principle of task-oriented training to improve the functional performance of patients' hand. Reach-to-grasp exercise with a mug has been chosen as the primary activities of daily living (ADL) exercise to be performed using the hand exoskeleton. The reach-to-grasp exercise is split into three stages: preshaping, reaching, and grasping. The cylinder preshape is adopted for the grasping of a mug, where the thumb and index finger form a right angled L shape before grasping of the mug. Then, the exoskeleton moves to the optimum position between hand and mug which has been pre-determined offline. Lastly, the thumb and finger follows a logarithmic spiral trajectory to form the grip. The final position of the firm grasp is defined by a minimal distance between all finger joints with the centroid of the object. The motion trajectories are carefully planned to provide a natural motion profile to the rehabilitation exercise.

The control structure is divided into task space control and joint space control. For the simpler task of reaching, joint space PID position control is sufficient to control the reaching motion, as the joints motion can be decoupled and moved independently. For the grasping action, a task space PI controller is designed to control the logarithmic spiral trajectory of grasping.

Simulation of the reach-to-grasp motion for hand exoskeleton robot is achieved with the synchronization between Labview and Solidworks. Motion commands from Labview are transferred to Solidworks in real time through the bridging plug-in, NI Softmotion. The simulation results are compared and verified with the actual reach-to-grasp trajectories recorded in various literatures. The motion designed is similar to the motion profile in actual human reach-to-grasp action, but the exoskeleton moves at a slower speed with a more cautious approach.

7.2 Future Work

As further improvement and extension of the project, the hand exoskeleton robot can be completed with the installation of three other finger modules: middle finger, fourth finger and little finger modules. These finger modules can have a design similar to the index finger module, with the arc gear actuating finger joint from the remote center. The same DC motors and electronics system can be installed to drive the motor.

On top of that, force sensor can be installed onto each finger joint to provide force feedback during the grasping of object. The sensors are important apparatus to monitor and limit the force and pressure exerted by the exoskeleton robot on the user's fingers. The force feedback serves as a limit switch to prevent the robot from hurting user's finger or damaging the object in manipulation. Two commonly applied force sensors are force sensing resistor and strain gauge. Force sensing resistor is a conductive polymer that comes in sheet form that changes resistance upon application of force. Strain gauge is a sensitive device that measures the deformation or strain of a structure through resistive change. The amount of stress applied to the structure can then be determined from the exerted strain. In order to capture a reliable reading, it is important to place the force sensor at the location where most forces pass through, such as the mounting for finger phalanges. With this additional information of force measurement on top of the existing positional

feedback, high level control algorithms such as sliding mode control [32], impedance control [57] and admittance control [95] can be introduced to improve the robot motion. With a more robust control system, ADL exercises that require complex object manipulation by the exoskeleton can be achieved.

Bibliography

- [1] Ministry of Health Singapore. (2011, October 14) *Singapore Health Facts*. [Online]. Available: http://www.moh.gov.sg/content/moh_web/home/statistics/Health_Facts_Singapore.html
- [2] Ministry of Health Singapore. (2011, October 14) *Stroke with complications*. [Online]. Available: http://www.moh.gov.sg/content/moh_web/home/costs_and_financing/HospitalBillSize/stroke_with_complications.html
- [3] W. L. Chow. (2011, October 15) Review of stroke caregiver's health and needs. [Online]. Available: <http://www.singhealth.com.sg/Research/HealthServicesResearch/NewsEvents/PastEvents/Documents/Stroke%20caregiving%20-%20NUS%20Health%20Cluster%20Presentation%20101109.pdf>
- [4] Ministry of Health Singapore. (2011, October 14) *Health Facilities*. [Online]. Available: http://www.moh.gov.sg/content/moh_web/home/statistics/Health_Facts_Singapore/Health_Facilities.html
- [5] Ministry of Health Singapore. (2011, October 14) *Admissions and Outpatient Attendances*. [Online]. Available: http://www.moh.gov.sg/content/moh_web/home/statistics/Health_Facts_Singapore/Admissions_and_Outpatient_Attendances.html
- [6] C. Tran, Z. Nadareishvili, L. Smurawska, P. I. T. Oh, J. W. Norris, "Decreasing Costs of Stroke Hospitalization in Toronto," *Stroke*, vol. 30, pp. 185-186, Jan. 1999.
- [7] R. Teasell, N. Bayona, J. Bitensky. (2011, October 20) Background Concepts in Stroke Rehabilitation. [Online]. Available: http://www.ebrsr.com/uploads/Module-3_background.pdf
- [8] B. H. Dobkin, "Impairments, Disabilities, and Bases for Neurological Rehabilitation after Stroke," *J. Stroke and Cerebrovascular Diseases*, vol 6(4), pp. 221-226, Apr. 1997.
- [9] C. Luke, K. J. Dodd, K. Brock, "Outcomes of the Bobath Concept on upper limb recovery following stroke," *Clinical Rehabilitation*, vol. 18(8), pp.888-898, Aug. 2004.
- [10] N. Foley, R. Teasell, J. Jutai, S. Bhogal, E. Kruger (2011, October 20) *Upper Extremity Interventions*. [Online]. Available: www.ebrsr.com/uploads/Module-10_upper-extremity_001.pdf
- [11] M. V. Radomski, C. A. T. Latham, "Optimizing Motor Behavior Using the Bobath Approach," in *Occupational Therapy for Physical Dysfunction*, 5th ed. Riverwoods, IL: Lippincott Williams & Wilkins, 2001, ch. 24, sec. 5, pp. 644-647.

- [12] A. Kagan, C. Richards, N. Korner-Bitensky. (2011, November 17) *Task-Oriented Training Upper Extremity*. [Online]. Available: <http://strokengine.ca/intervention/index.php?page=topic&id=77>
- [13] C. J. Winstein, S. L. Wolf, "Task-Oriented Training to Promote Upper Extremity Recovery," in *Stroke recovery and rehabilitation*, 1st ed. New York, NY: Demos Medical, 2008, ch. 17, sec. 4, pp. 267-290.
- [14] Carr, J. H. & Shepherd, R. B., *A motor relearning programme for stroke*, 2nd ed. Oxford: Butterworth-Heinemann, 1987.
- [15] M. V. Radomski, C. A. T. Latham, "Optimizing Motor Behavior Using the Occupational Therapy Task-Oriented Approach," in *Occupational Therapy for Physical Dysfunction*, 5th ed. Riverworrd, IL: Lippincott Williams & Wilkins, 2001, ch. 22, sec. 5, pp. 600-604.
- [16] P. S. Lum, C. G. Burgar, P. C. Shor, M. Majmundar, M. V. Loos, "Robot assisted movement training compared with conventional therapy techniques for the rehabilitation of upper-limb motor function after stroke," *Archives of Physical Medicine and Rehabilitation*, vol. 83(7), pp. 952-959, Jul. 2002.
- [17] G. Bhalerao, V. Kulkarni, C. Doshi, S. Rairikar, A. Shyam, P. Sancheti, "Comparison of motor relearning program versus bobath approach at every two weeks interval for improving activities of daily living and ambulation in acute stroke rehabilitation," *Int. J. Basic and Applied Medicinal Sciences*, vol. 3, pp. 70-77, Sept. 2013.
- [18] D. YL Chan, C. CH Chan, D. KS Au, "Motor relearning programme for stroke patients: a randomized controlled trial," *Clinical Rehabilitation*, vol. 20, pp. 191-200, Mar. 2006.
- [19] M. Rensink, M. Schuurmans, E. Lindeman, T. Hafsteinsdottir, "Task-oriented training in rehabilitation after stroke: systematic review," *Journal of Advanced Nursing*, vol. 65(4), pp. 737-754, Apr. 2009.
- [20] L. A. Boyd, E. D. Vidoni, B. D. Wessel, "Motor learning after stroke: is skill acquisition a prerequisite for contralesional neuroplastic change?," *Neuroscience Letters*, vol. 482(1), pp. 21-25, Sep. 2010.
- [21] M. N. McDonnell, S. L. Hillier, T. S. Miles, P. D. Thompson, M. C. Ridding, "Influence of combined afferent stimulation and task-specific training following stroke: a pilot randomized controlled trial," *Neurorehabilitation and neural repair*, vol. 21(5), pp. 435-443, Sep. 2007.
- [22] J. Blennerhassett, W. Dite, "Additional task-related practice improves mobility and upper limb function early after stroke: a randomised controlled trial," *The Australian Journal of Physiotherapy*, vol. 50(4), pp. 219-224, 2004.
- [23] R. M. Herndon, "Clinical Stroke Scales" in *Handbook of neurological rating scales*, 2nd ed. New York, NY: Demos Medical, 2005, ch. 9, pp. 277-281.

- [24] F. I. Mahoney, D. Barthel, "Functional evaluation: the Barthel Index," *Maryland State Med. Journal*, vol. 14, pp. 56-61, Feb. 1965 .
- [25] S. Katz, T. D. Downs, H. R. Cash, R. C. Grotz, "Progress in development of the index of ADL," *Gerontologist*, vol. 10(1), pp. 20-30, 1970.
- [26] M. J. Lelieveld, T. Maeno, "Design and development of a 4 DOF portable haptic interface with multi-point passive force feedback for the index finger," in *Proc. 2006 Int. Conf. Robotics and Automation*, Orlando, FL, 2006, pp. 3134-3139.[27] T.
- [27] M. W. Burton, R. Vaidyanathan, S. C. Burgess, A. J. Turton, C. Melhuish, "Development of a parametric kinematic model of the human hand and a novel robotic exoskeleton," in *2011 IEEE Int. Conf. Rehabilitation Robotics*, Zurich, 2011, pp. 1-7.
- [28] Y. Fu, P. Wang, S. Wang, "Development of a multi-DOF exoskeleton based machine for injured fingers," in *2008 IEEE/RSJ Int. Conf. Intelligent Robots and Systems*, Nice, 2008, pp. 1946-1951.
- [29] S. Ueki *et al.*, "Development of a hand-assist robot with multi-degrees-of-freedom for rehabilitation therapy," *IEEE/ASME Trans. Mechatron.*, vol. 99, pp. 1-11, Dec. 2010.
- [30] H. Yamaura, K. Matsushita, R. Kato, H. Yokoi, "Development of hand rehabilitation system for paralysis patient – universal design using wire-driven mechanism," in *31st Annual Int. Conf. IEEE EMBS*, Minneapolis, MN, 2009, pp. 7122-7125.
- [31] J. Li, R. Zheng, Y. Zhang, J. Yao, "iHandRehab: an interactive hand exoskeleton for active and passive rehabilitation," in *IEEE Int. Conf. Rehabilitation Robotics, Zurich*, 2011, pp. 1-6.
- [32] A. Wege, K. Kondak, G. Hommel, "Mechanical design and motion control of a hand exoskeleton for rehabilitation," in *Proc. IEEE Int. Conf. Mechatronics & Automation*, Niagara Falls, 2005, pp. 155-159.
- [33] M. Fontana, A. Dettori, F. Salsedo, M. Bergamasco, "Mechanical design of a novel hand exoskeleton for accurate force displaying," in *IEEE Int. Conf. Robotics and Automation*, Kobe, 2009, pp. 1704-1709.
- [34] L. Dovat, O. Lambercy, R. Gassert, T. Maeder, T. Milner, C. L. Teo, E. Burdet, "HandCARE: a cable-actuated rehabilitation system to train hand function after stroke," *IEEE Trans. Neural Systems and Rehabilitation Engineering*, vol. 16, no. 6, pp. 582-591, Dec. 2008.
- [35] A. Chiri *et al.* "HANDEXOS: towards an exoskeleton device for the rehabilitation of the hand," in *IEEE/RSJ Int. Conf. Intelligent Robots and Systems*, St. Louis, MO, 2009, pp. 1106-1111.

- [36] J. Li, R. Zheng, Y. Zhang, J. Yao, "iHandRehab: an interactive hand exoskeleton for active and passive rehabilitation," in *IEEE Int. Conf. Rehabilitation Robotics*, Zurich, 2011, pp. 1-6.
- [37] Y. Fu, Q. Zhang, F. Zhang, Z. Gan, "Design and development of a hand rehabilitation robot for patient-cooperative therapy following stroke," in *IEEE Int. Conf. Mechatronics and Automation*, Beijing, 2011, pp. 112-117.
- [38] T. T. Worsnopp, M. A. Peshkin, J. E. Colgate, D. G. Kamper, "An actuated finger exoskeleton for hand rehabilitation following stroke," in *IEEE 10th Int. Conf. Rehabilitation Robotics*, Noordwijk, 2007, pp. 896-901.
- [39] B. L. Shields, J. A. Main, S. W. Peterson, A. M. Strauss, "An anthropomorphic hand exoskeleton to prevent astronaut hand fatigue during extravehicular activities," *IEEE Trans. Systems, man, and cybernetics, Part A: Systems and Humans*, vol. 27, no. 5, pp. 668-673, Sep. 1997.
- [40] M. Bouzit, G. Burdea, G. Popescu, R. Boian, "The Rutgers Master II – New design force-feedback glove," *IEEE/ASME Tran. Mechatronics*, vol. 7, no. 2, pp. 256-263, Jun. 2002.
- [41] F. Wang et al. 'Design and control of an actuated thumb exoskeleton for hand rehabilitation following stroke," in *IEEE Int. Conf. Robotics and Automation*, Shanghai, 2011, pp. 3688-3693.
- [42] L. Lucas, M. DiCicco, Y. Matsuoka, "An EMG-controlled hand exoskeleton for natural pinching," in *IEEE Int. Conf. Robotics and Automation*, 2004, pp. 1622-1627.
- [43] R. C. V. Loureiro, W. S. Harwin, "Reach & Grasp therapy: Design and control of a 9-DOF robotic neuro-rehabilitation system," in *IEEE 10th Int. Conf. Rehabilitation Robotics*, Noordwijk, 2007, pp. 758-763.
- [44] C. D. Takahashi, L. Der-Yeghiaian, V. H. Le, S. C. Cramer, "A robotic device for hand motor therapy after stroke," in *IEEE 9th Int. Conf. Rehabilitation Robotics*, Chicago, IL, 2005, pp. 17-20.
- [45] U. mali, M. Munih, "HIFE- Haptic Interface for finger exercise," in *IEEE/ASME Trans. Mechatronics*, vol. 11, no. 1, pp. 93-102, Feb. 2006.
- [46] M. Chen et al. "Interactive rehabilitation robot for hand function training," in *IEEE 11th Int. Conf. Rehabilitation Robotics*, Kyoto, 2009, pp. 777-780.
- [47] S. Nakagawara, H. Kajimoto, N. Kawakami, S. Tachi, I. Kawabuchi, "An encounter-type multi-fingered master hand using circuitous joints," in *Proc. of the 2005 IEEE Int. Conf. Robotics and Automation*, Barcelona, 2005, pp. 2667-2672.
- [48] J. Iqbal, N. G. Tsagarakis, D. G. Caldwell, "A multi-DOF robotic exoskeleton interface for hand motion assistance," in *33rd Annual Int. Conf. IEEE EMBS*, Boston, MA, 2011, pp. 1575-1578.

- [49] E. B. Brokaw, I. Black, R. J. Holley, P. S. Lum, "Hand spring operated movement enhancer (HandSOME): A portable, passive hand exoskeleton for stroke rehabilitation," in *IEEE Trans. Neural Systems and Rehabilitation Engineering*, vol. 19, no. 4, pp. 391-399, Aug. 2011.
- [50] L. Masia, H. I. Krebs, P. Cappa, N. Hogan, "Design and characterization of hand module for whole-arm rehabilitation following stroke," *IEEE/ASME Trans. Mechatronics*, vol. 12, no. 4, pp. 399-407, Aug. 2007.
- [51] O. Lamercy et al. "Rehabilitation of grasping and forearm pronation/supination with the haptic knob," in *IEEE 11th Int. Conf. Rehabilitation Robotics*, Kyoto, 2009, pp. 22-27.
- [52] J. Metzger, O. Lamercy, D. Chapuis, R. Gassert, "Design and characterization of the ReHapticKnob, a robot for assessment and therapy of hand function," in *IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, San Francisco, CA, 2011, pp. 3074-3080.
- [53] O. Lamercy, A. J. Robles, Y. Kim, R. Gassert, "Design of a robotic device for assessment and rehabilitation of hand sensory function," in *IEEE Int. Conf. Rehabilitation Robotics*, Zurich, 2011, pp. 1-6.
- [54] H. I. Krebs et al. "A wrist extension for MIT-MANUS," *Advance in Rehabilitation Robotics*, vol. 306, pp. 377-390, 2004.
- [55] M. Mihelj, T. Nef, R. Riener, "ARMIN II – 7 DoF rehabilitation robot: mechanics and kinematics," in *IEEE Int. Conf. Robotics and Automation*, Roma, 2007, pp. 4120-4125.
- [56] J. Oblak, I. Cikajlo, Z. Matjacic, "Universal haptic drive: a robot for arm and wrist rehabilitation," *IEEE Trans. on Neural Systems and Rehabilitation Engineering*, vol. 18, no. 3, pp. 293-302, June 2010.
- [57] A. Gupta, M. K. O'Malley, V. Patoglu, C. Burgar, "Design, control and performance of RiceWrist: a force feedback wrist exoskeleton for rehabilitation and training," *The International Journal of Robotics Research*, vol. 27, No. 2, pp. 233-251, February 2008.
- [58] M. Takaiwa, T. Noritsugu, "Development of wrist rehabilitation equipment using pneumatic parallel manipulator," *IEEE Int. Conf. Robotics and Automation*, Barcelona, 2005, pp. 2302-2307.
- [59] G. Zong, X. Pei, J. Yu, S. Bi, "Classification and type synthesis of 1-DOF remote center of motion mechanisms," *Mechanism and Machine Theory*, vol. 43, no. 12, pp. 1585-1595, Dec. 2008.
- [60] M. Hioki, H. Kawaaki, H. Sakaeda, Y. Nishimoto, T. Mouri, "Finger rehabilitation system using multi-fingered haptic interface robot controlled by surface electromyogram," in *Proc. 2010 3rd IEEE RAS & EMB Int. Conf. Biomedical Robotics and Biomechatronics*, Tokyo, 2010, pp. 276-281.

- [61] S. Gibilisco, "Cable drive," in *Concise encyclopedia of robotics*, 1st ed. New York, NY: McGraw-Hill, 2003, pp. 39.
- [62] A. D. Luca, W. Book, "Robots with flexible elements," in *Springer Handbook of Robotics*, 1st ed. Berlin, Germany: Springer, 2008, ch. 13, sec. B, pp. 287-290.
- [63] American Society for Surgery of the Hand. (2011, December 25) *Hand Anatomy*. [Online].
Available: <http://www.assh.org/Public/HandAnatomy/Pages/default.aspx>
- [64] C. Cael, "Osteology and Arthrology," in *Functional anatomy: musculoskeletal anatomy, kinesiology, and palpation for manual therapist*, 1st ed. Riverworrrds, IL: Lippincott Williams & Wilkins, 2010, ch. 2 ,pp. 40-43.
- [65] D. Thompson. (2011, December 26) *Wrist joint complex*. [Online].
Available: <http://moon.ouhsc.edu/dthompsso/namics/wrist.htm#apaxis>
- [66] L. A. Jones, S. J. Lederman, "Evolutionary development and anatomy of the hand," in *Human hand function*, 1st ed. Oxford, United Kingdom: Oxford University Press, 2006, ch.2, pp. 14-16.
- [67] C. Cael, "The elbow, forearm, wrist, and hand," in *Functional anatomy: musculoskeletal anatomy, kinesiology, and palpation for manual therapist*, 1st ed. Riverworrrds, IL: Lippincott Williams & Wilkins, 2010, ch. 5 ,pp. 140-149.
- [68] V. M. Zatsiorsky, "Kinematics of individual joints," in *Kinematics of human motion*, 1st ed. Champaign, IL: Human Kinetics, 1997, ch. 5, pp. 361-365.
- [69] W. Lowe, "Elbow, forearm, wrist, & hand," in *Orthopedic assessment in massage therapy*, 1st ed. Sisters, OR: David Scott, 2006, ch. 11, pp. 37-38.
- [70] C. Eaton. (2011, December 26) *Normal range of motion reference value*. [Online].
Available: <http://www.eatonhand.com/nor/nor002.htm>
- [71] E. Y. S. Chao, "Hand joint orientation and range of motion," in *Biomechanics of the hand: a basic research study*, Singapore: World Scientific Publishing, 1989, ch. 4 ,pp. 87-91.
- [72] H. M. Clarkson, "Wrist and hand," in *Musculoskeletal assessment: joint range of motion and manual muscle strength*, 2nd ed. Riverworrrds, IL: Lippincott Williams & Wilkins, 2000, ch. 5, pp. 255-257.
- [73] M. C. Hume, H. Gellman, H. McKellop, R. H. Brumfield, "Functional range of motion of the joints of the hand," *The journal of hand surgery*, vol. 15A, no. 2, pp. 240-243, Mar. 1990.
- [74] Y. Y. Huang, K. H. Low, "Initial analysis and design of an assistive rehabilitation hand device with free loading and fingers motion visible to subjects," in *IEEE Int. Conf. Systems, Man and Cybernetics*, Singapore, 2008, pp. 2584-2590.

- [75] K. Abdel-Malek, J. Yang, R. Brand, E. Tanbour, "Towards understanding the workspace of human limbs," *Ergonomics*, vol. 47, no. 13, pp. 1386-1405, October 2004.
- [76] V. J. Santos, F. J. Valero-Cuevas, "Reported anatomical variability naturally leads to multimodal distributions of Denavit-Hartenberg parameters for the human thumb," *IEEE Trans. Biomedical Engineering*, vol. 53, no. 2, pp. 155-163, Feb. 2006.
- [77] L. Y. Chang, N. S. Pollard, "Method for determining kinematic parameters of the In Vivo thumb carpometacarpal joint," *IEEE Trans. Biomedical Engineering*, vol. 55, no. 7, pp. 1897-1906, July 2008.
- [78] S. M. Michaelsen, A. Luta, A. Roby-Brami, M. F. Levin, "Effect of Trunk Restraint on the Recovery of Reaching Movements in Hemiparetic Patients," *Stroke*, vol 32(8), pp. 1875-1883, Aug. 2001.
- [79] A. H. A. Stinen, E. G. Hekman, etc., "Dampace: dynamic force-coordination trainer for the upper extremities," *IEEE Int. Conf. Rehabilitation Robotics*, Noordwijk, June 2007, pp. 820-826.
- [80] S. J. Housman, V. Le, T. Rahman, R. J. Sanchez, D. J. Reinkensmeyer, "Arm-training with T-WREX after chronic stroke: preliminary results of a randomized controlled trial," *IEEE Int. Conf Rehabilitation Robotics*, Noordwijk, June 2007, pp. 562-568.
- [81] M. Santello, J. F. Soechting, "Gradual molding of the hand to object contours," *Journal of Neurophysiology*, vol. 79, no. 3, pp. 1307-1320, March 1998.
- [82] A. T. Miller, S. Knoop, H. I. Christensen, P. K. Allen, "Automatic grasp planning using shape primitives," in *IEEE Int. Conf. Robotics and Automation*, Taipei, 2003, pp. 1824-1829.
- [83] D. Wren, R. B. Fisher, "Dextrous hand grasping strategies using preshapes and digit trajectories," *IEEE Int. Conf. Systems, Man and Cybernetics*, Vancouver, 1995, pp. 910-915.
- [84] S. Lee, X. Zhang, "Development and evaluation of an optimization-based model for power-grip posture prediction," *Journal of Biomechanics*, vol. 38, no. 8, pp. 1591-1597, Aug 2005.
- [85] E. L. Secco, A. Visioli, G. Magenes, "Minimum jerk motion planning for a prosthetic finger," *Journal of Robotic Systems*, vol. 21, no. 7, pp. 361-368. July 2004.
- [86] D. G. Kamper, E. G. Cruz, M. P. Siegel, "Stereotypical fingertip trajectories during grasp," *J. Neurophysiology*, vol. 90, no. 6, pp. 3702-3710, Dec. 2003.
- [87] A. Gupta, G. S. Rash, N. N. Somia, M. P. Wachowiak, J. Jones, A. Desoky, "The motion path of the digits," *J. Hand Surgery Am.*, vol. 23, no. 6, pp. 1038-1042, Nov. 1998.

- [88] R. M. Alexander, "A minimum energy cost hypothesis for human arm trajectories," *Biol. Cybern.*, vol. 76, no. 2, pp. 97-105, Feb. 1997.
- [89] Y. Uno, M. Kawato, R. Suzuki, "Formation and control of optimal trajectory in human multijoint arm movement," *Biol. Cybern.* vol. 61, no. 2, pp. 89-101, June 1989.
- [90] T. Okadome, M. Honda, "Kinematic construction of the trajectory of sequential arm movements," *Biol. Cybern.*, vol. 80, no. 3, pp. 157-169, Mar. 1999.
- [91] T. Flash, "The control of hand equilibrium trajectories in multi-joint arm movements," *Biol. Cybern.*, vol. 57, no. 4-5, pp. 257-274, Nov. 1987.
- [92] U. Castiello, K. M. B. Bennett, G. E. Stelmach, "Reach to grasp: the natural response to perturbation of object size," *Exp Brain Res*, vol. 94, no. 1, pp. 163-178, May 1993.
- [93] J. Chang, Y. Yang, L. Guo, W. Wu, F. Su, "Differences in reaching performance between normal adults and patients post stroke – a kinematic analysis," *J. Medical and Biological Engineering*, vol. 28, no. 1, pp. 53-58, Jan 2008.
- [94] C. L. Mackenzie, T. Iberall, "Movement before contact," in *The grasping hand*, 1st ed. Amsterdam: Elsevier Science, 1994, ch. 5, sec. 4, pp. 160.
- [95] L. M. Miller, J. Rosem, "Comparison of multi-sensor admittance control in joint space and task space for a seven degree of freedom upper limb exoskeleton," *IEEE Int. Conf. on Biomedical Robotics and Biomechatronics*, Tokyo, 2010, pp. 70-75.

Appendix

Level	Description	BOM .Qty	Unit Cost	Extended Cost	Type	Manufacturer Name	Manufacturers Part Number
1	ASSY, HAND EXOSKELETON	1			ASSEMBLY		
2	ASSY, WRIST MODULE	1			ASSY		
3	ASSY, WRIST ROLL MODULE	1			ASSY		
4	FRONT GUIDE, WRIST ROLL	1	200.0000	200.0000	MACHINED		
4	REAR GUIDE, WRIST ROLL	1	250.0000	250.0000	MACHINED		
4	RACK GEAR, WRIST ROLL	1	340.0000	340.0000	MACHINED		
4	SPACER, WRIST ROLL L11	9	6.1000	54.9000	STANDARD	MISUMI	DWSSB-D10-V4.5-L11
4	SPACER, WRIST ROLL L37	4	8.2000	32.8000	STANDARD	MISUMI	SFJW10-37-M4-N4
4	SCREW, SOCKET HEAD M4 L20	9	0.2000	1.8000	FASTENER	BOSSARD	
4	SCREW, SOCKET HEAD M4 L15	8	0.2000	1.6000	FASTENER	BOSSARD	
3	ASSY, WRIST FLEX MODULE	1			ASSY		
4	LEFT BRACKET, WRIST ROLL	1	63.0000	63.0000	MACHINED		
4	RIGHT BRACKET, WRIST ROLL	1	71.0000	71.0000	MACHINED		
4	LINK, WRIST ROLL BRACKET	1	47.0000	47.0000	MACHINED		
4	MOUNT, WRIST ROLL MOTOR	1	20.0000	20.0000	MACHINED		
4	BRACE, WRIST ROLL	1	5.0000	5.0000	DIE CUT		
4	STRAP, WRIST ROLL	1	3.0000	3.0000	DIE CUT		
4	MOTOR, WRIST FLEX	1	970.0000	680.0000	ACTAUTOR	MAXON	
4	BELT, WRIST FLEX	1	14.0000	14.0000	STANDARD	MISUMI	
4	INPUT PULLEY, WRIST FLEX	1	16.0000	16.0000	STANDARD	MISUMI	HTPA15S3M100-K-P5
4	OUTPUT PULLEY, WRIST FLEX	1	15.0000	15.0000	STANDARD	MISUMI	HTPB25S3M100-A-P6
4	MOTOR, WRIST ROLL	1	970.0000	680.0000	ACTAUTOR	MAXON	
4	ROLLER, WRIST ROLL	3	29.0000	87.0000	STANDARD	MISUMI	CFUAG6-16
4	LEFT BEARING, WRIST FLEX	1	3.6000	3.6000	STANDARD	MISUMI	SB695ZZ
4	RIGHT BEARING, WRIST FLEX	1	3.6000	3.6000	STANDARD	MISUMI	SB6800ZZ

4	RACK GEAR, WRIST ROLL	1	32.0000	32.0000	STANDARD	KHK	SS1.5-20C
4	MOTOR SHAFT, WRIST ROLL	1	18.0000	18.0000	MACHINED		
4	SCREW, SOCKET HEAD M4 L10	8	0.2000	1.6000	FASTENER	BOSSARD	
4	SCREW, SOCKET HEAD M3 L10	8	0.2000	1.6000	FASTENER	BOSSARD	
3	ASSY, PALM MODULE	1			ASSY		
4	LEFT PILLAR, PALM MODULE	1	42.0000	42.0000	MACHINED		
4	RIGHT PILLAR, PALM MODULE	1	45.0000	45.0000	MACHINED		
4	PLATE, PALM MODULE	1	36.0000	36.0000	MACHINED		
4	BRACE, PALM MODULE	1	6.0000	6.0000	DIE CUT		
4	STRAP, PALM MODULE	1	5.0000	5.0000	DIE CUT		
4	BOTTOM BLOCK, PALM MODULE	2	6.0000	12.0000	STANDARD	MISUMI	HFSB5-2020-40
4	TOP BLOCK, PALM MODULE	1	6.0000	6.0000	STANDARD	MISUMI	HFSB5-2020-59
4	SCREW, SOCKET HEAD M3 L15	4	0.2000	0.8000	FASTENER	BOSSARD	
4	SCREW, SOCKET HEAD M5 L20	4	0.2000	0.8000	FASTENER	BOSSARD	
4	ASSY, INDEX FINGER MODULE	1			ASSY		
5	MOUNT, INDEX FINGER MODULE	1	42.0000	42.0000	MACHINED		
5	COVER, INDEX FINGER MODULE	1	16.0000	16.0000	MACHINED		
5	SHAFT, INDEX FINGER MODULE	1	18.0000	18.0000	MACHINED		
5	BEARING, INDEX FINGER MODULE	2	3.5000	7.0000	STANDARD	MISUMI	B685ZZ
5	SCREW, SOCKET HEAD M5 L15	1	0.2000	0.2000	FASTENER	BOSSARD	
5	SCREW, SOCKET HEAD M3 L10	4	0.2000	0.8000	FASTENER	BOSSARD	
5	ASSY, MCP MODULE	1			ASSY		
6	MOUNT, MCP MODULE	1	65.0000	65.0000	MACHINED		
6	COVER, MCP MODULE	1	55.0000	55.0000	MACHINED		
6	MOUNT, MOTOR MCP MODULE	1	26.0000	26.0000	MACHINED		
6	MOTOR, MCP MODULE	1	240.0000	240.0000	ACTUATOR	MAXON	
6	HOUSING, GEAR MCP MODULE	1	92.0000	92.0000	MACHINED		
6	PLATE, MCP MODULE	1	82.0000	82.0000	MACHINED		
6	ROLLER, MCP MODULE	1	42.0000	42.0000	MACHINED		
6	PULLEY, MCP MODULE	2	13.4000	26.8000	STANDARD	MISUMI	HTPA16S2M040-A-H3

6	BELT, MCP MODULE	1	5.2000	5.2000	STANDARD	MISUMI	HTBN144S2M-40
6	SPUR GEAR, MCP MODULE	1	16.2000	16.2000	STANDARD	KHK	S1S14A - 0805F
6	ARC GEAR, MCP MODULE	1	120.0000	120.0000	MACHIEND		
6	BEARING SHAFT, MCP MODULE	2	22.0000	44.0000	MACHINED		
6	ROLLER SHAFT, MCP MODULE	1	26.0000	26.0000	MACHINED		
6	BEARING, ROLLER MCP MODULE	2	4.8000	9.6000	STANDARD	MISUMI	B684ZZ
6	BEARING, GEAR MCP MODULE	1	3.8000	3.8000	STANDARD	MISUMI	B675ZZ
6	BEARING, PULLEY MCP MODULE	1	3.5000	3.5000	STANDARD	MISUMI	B674ZZ
6	SUPPORT, ARC GEAR MCP MODULE	2	3.1000	6.2000	STANDARD	MISUMI	B604ZZ
6	RETAINING RING, BEARING MCP MODULE	4	0.8000	3.2000	STANDARD	MISUMI	STWS4
6	MOUNT, PIP MODULE	1	82.0000	82.0000	MACHINED		
6	MOUNT, MCP FINGER	1	60.0000	60.0000	MACHINED		
6	BRACE, MCP FINGER	1	2.0000	2.0000	DIE CUT		
6	SCREW, SOCKET HEAD M2 L5	2	0.2000	0.4000	FASTENER	BOSSARD	
6	SCREW, SOCKET HEAD M2.5 L8	12	0.2000	2.4000	FASTENER	BOSSARD	
6	SCREW, SOCKET HEAD M3 L5	2	0.2000	0.4000	FASTENER	BOSSARD	
5	ASSY, PIP MODULE	1			ASSY		
6	COVER, PIP MODULE	1	55.0000	55.0000	MACHINED		
6	MOUNT, MOTOR PIP MODULE	1	26.0000	26.0000	MACHINED		
6	MOTOR, PIP MODULE	1	240.0000	240.0000	ACTUATOR	MAXON	
6	HOUSING, GEAR PIP MODULE	1	88.0000	88.0000	MACHINED		
6	PLATE, PIP MODULE	1	74.0000	74.0000	MACHINED		
6	ROLLER, PIP MODULE	1	30.0000	30.0000	MACHINED		
6	PULLEY, PIP MODULE	2	13.4000	26.8000	STANDARD	MISUMI	HTPA16S2M040-A-H3
6	BELT, PIP MODULE	1	5.2000	5.2000	STANDARD	MISUMI	HTBN124S2M-40
6	SPUR GEAR, PIP MODULE	1	14.5000	14.5000	STANDARD	KHK	S80SU16B + 0704
6	ARC GEAR, PIP MODULE	1	88.0000	88.0000	MACHIEND		
6	BEARING SHAFT, PIP MODULE	2	20.0000	40.0000	MACHINED		
6	ROLLER SHAFT, PIP MODULE	1	22.0000	22.0000	MACHINED		

6	BEARING, ROLLER PIP MODULE	2	4.8000	9.6000	STANDARD	MISUMI	B684ZZ
6	BEARING, GEAR PIP MODULE	1	3.5000	3.5000	STANDARD	MISUMI	B674ZZ
6	BEARING, PULLEY PIP MODULE	1	3.5000	3.5000	STANDARD	MISUMI	B674ZZ
6	SUPPORT, ARC GEAR PIP MODULE	2	3.5000	7.0000	STANDARD	MISUMI	B674ZZ
6	RETAINING RING, BEARING PIP MODULE	4	0.8000	3.2000	STANDARD	MISUMI	STWS4
6	MOUNT, DIP MODULE	1	74.0000	74.0000	MACHINED		
6	MOUNT, PIP FINGER	1	51.0000	51.0000	MACHINED		
6	BRACE, PIP FINGER	1	2.0000	2.0000	DIE CUT		
6	SCREW, SOCKET HEAD M2 L5	2	0.2000	0.4000	FASTENER	BOSSARD	
6	SCREW, SOCKET HEAD M2.5 L8	9	0.2000	1.8000	FASTENER	BOSSARD	
6	SCREW, SOCKET HEAD M3 L5	2	0.2000	0.4000	FASTENER	BOSSARD	
5	ASSY, DIP MODULE	1			ASSY		
6	COVER, DIP MODULE	1	55.0000	55.0000	MACHINED		
6	MOUNT, MOTOR DIP MODULE	1	26.0000	26.0000	MACHINED		
6	MOTOR, DIP MODULE	1	240.0000	240.0000	ACTUATOR	MAXON	
6	HOUSING, GEAR DIP MODULE	1	76.0000	76.0000	MACHINED		
6	PLATE, DIP MODULE	1	65.0000	65.0000	MACHINED		
6	ROLLER, DIP MODULE	1	18.0000	18.0000	MACHINED		
6	PULLEY, DIP MODULE	2	13.4000	26.8000	STANDARD	MISUMI	HTPA16S2M040-A-H3
6	BELT, DIP MODULE	1	5.2000	5.2000	STANDARD	MISUMI	HTBN118S2M-40
6	SPUR GEAR, DIP MODULE	1	14.5000	14.5000	STANDARD	KHK	S80SU16B + 0704
6	ARC GEAR, DIP MODULE	1	78.0000	78.0000	MACHIEND		
6	BEARING SHAFT, DIP MODULE	2	18.0000	36.0000	MACHINED		
6	ROLLER SHAFT, DIP MODULE	1	20.0000	20.0000	MACHINED		
6	BEARING, GEAR DIP MODULE	1	3.8000	3.8000	STANDARD	MISUMI	B675ZZ
6	BEARING, PULLEY DIP MODULE	1	3.5000	3.5000	STANDARD	MISUMI	B674ZZ
6	SUPPORT, ARC GEAR DIP MODULE	2	3.2000	6.4000	STANDARD	MISUMI	B673ZZ
6	RETAINING RING, BEARING DIP MODULE	3	0.7000	2.1000	STANDARD	MISUMI	STWN3
6	MOUNT, DIP FINGER	1	48.0000	48.0000	MACHINED		

6	BRACE, DIP FINGER	1	2.0000	2.0000	DIE CUT		
6	SCREW, SOCKET HEAD M2 L5	2	0.2000	0.4000	FASTENER	BOSSARD	
6	SCREW, SOCKET HEAD M2.5 L8	9	0.2000	1.8000	FASTENER	BOSSARD	
6	SCREW, SOCKET HEAD M3 L5	2	0.2000	0.4000	FASTENER	BOSSARD	
5	SCREW, SOCKET HEAD M2.5 L8	6	0.2000	1.2000	FASTENER	BOSSARD	
5	SCREW, SOCKET HEAD M3 L8	4	0.2000	0.8000	FASTENER	BOSSARD	
5	ASSY, THUMB MODULE	1			ASSY		
6	MOUNT, MOTOR THUMB PRONATION	1	35.0000	35.0000	MACHINED		
6	MOTOR, THUMB PRONATION	1	240.0000	240.0000	ACTUATOR	MAXON	
6	MOUNT, WORM GEAR THUMB PRONATION	1	21.0000	21.0000	MACHINED		
6	WORM GEAR, THUMB PRONATION	1	7.8000	7.8000	STANDARD	MISUMI	KWG0.8-R2
6	WORM WHEEL, THUMB PRONATION	1	11.1000	11.1000	STANDARD	MISUMI	AG0.8-20R2
6	SHAFT, THUMB PRONATION	1	52.0000	52.0000	MACHINED		
6	BEARING, SHAFT THUMB PRONATION	6	4.0000	24.0000	STANDARD	MISUMI	B676ZZ
6	BEARING, SUPPORT THUMB PRONATION	4	3.6000	14.4000	STANDARD	MISUMI	B686ZZ
6	ROLLER, THUMB PRONATION	2	42.0000	84.0000	MACHINED		
6	SHAFT, SUPPORT THUMB PRONATION	2	30.0000	60.0000	MACHINED		
6	SPUR GEAR, THUMB PRONATION	1	18.0000	18.0000	STANDARD	MISUMI	SSA1-25
6	FRONT PLATE, THUMB PRONATION	1	60.0000	60.0000	MACHINED		
6	REAR PLATE, THUMB PRONATION	1	60.0000	60.0000	MACHINED		
6	SPACER, THUMB PRONATION	4	4.2000	16.8000	STANDARD		
6	SCREW, SOCKET HEAD M2.5 L8	4	0.2000	0.8000	FASTENER	BOSSARD	
6	SCREW, SOCKET HEAD M3 L8	4	0.2000	0.8000	FASTENER	BOSSARD	
6	SCREW, SOCKET HEAD M2 L5	8	0.2000	1.6000	FASTENER	BOSSARD	
6	ARC GEAR, THUMB PRONATION	1	135.0000	135.0000	MACHINED		
6	MOUNT, THUMB CMC	1	82.0000	82.0000	MACHINED		
6	BRACE, THUMB CMC	2	2.0000	4.0000	DIE CUT		
6	REAR SLIDER, THUMB CMC	1	52.0000	52.0000	MACHINED		

6	FRONT SLIDER, THUMB CMC	1	70.0000	70.0000	MACHINED		
6	SPRING, LINEAR THUMB CMC	1	24.7000	24.7000	STANDARD	MISUMI	CFS0.6
6	BEARING, THUMB CMC	1	3.4000	3.4000	STANDARD	MISUMI	SB684ZZ
6	MOUNT, MOTOR THUMB CMC	1	35.0000	35.0000	MACHINED		
6	MOTOR, THUMB CMC	1	240.0000	240.0000	ACTUATOR	MAXON	
6	BRACKET, THUMB MP	1	65.0000	65.0000	MACHINED		
6	MOUNT, MOTOR THUMB MP	1	35.0000	35.0000	MACHINED		
6	BEARING, THUMB MP	1	3.4000	3.4000	STANDARD	MISUMI	SB684ZZ
6	MOTOR, THUMB MP	1	240.0000	240.0000	ACTUATOR	MAXON	
6	BRACE, THUMB MP	1	2.0000	2.0000	DIE CUT		
6	BRACKET, THUMB IP	1	55.0000	55.0000	MACHINED		
6	BRACE, THUMB IP	1	2.0000	2.0000	DIE CUT		
2	ASSY, BASE MODULE	1			ASSY		
3	PLATE, BASE MODULE	1	25.0000	25.0000	MACHINED		
3	BRACKET, PILLAR BASE MODULE	8	1.8000	14.4000	STANDARD	MISUMI	HBLSSB5
3	PILLAR, BASE MODULE	4	5.5000	22.0000	STANDARD	MISUMI	HFSB5-2020-50-LTP
3	HOUSING, LEAD NUT	1	36.0000	36.0000	STANDARD	MISUMI	
3	LEAD NUT, BASE MODULE	1	14.7000	14.7000	STANDARD	MISUMI	MTSFR8
3	LINEAR GUIDE, BASE MODULE	2	117.2000	234.4000	STANDARD	MISUMI	SXR28-280
3	MOTOR, BASE MODULE	1	680.0000	680.0000	ACTUATOR	MAXON	
3	MOUNT, MOTOR BASE MODULE	1	16.0000	16.0000	MACHINED		
3	COUPLING, BASE MODULE	1	61.5000	61.5000	STANDARD	MISUMI	SCXW21-4
3	BEARING, BASE MODULE	2	27.9000	55.8000	STANDARD	MISUMI	BGHKB626ZZ-20
3	LEAD SCREW, BASE MODULE	1	46.2000	46.2000	STANDARD	MISUMI	MTSBRW8-350-F8-V6-S20-Q6
3	PLATFORM, BASE MODULE	1	35.0000	35.0000	STANDARD	MISUMI	
3	SCREW, SOCKET HEAD M2 L5	2	0.2000	0.4000	FASTENER	BOSSARD	
3	SCREW, SOCKET HEAD M3 L8	2	0.2000	0.4000	FASTENER	BOSSARD	
3	SCREW, SOCKET HEAD M4 L8	4	0.3000	1.2000	FASTENER	BOSSARD	
3	SCREW, SOCKET HEAD M5 L8	38	0.4	15.2000	FASTENER	BOSSARD	
TOTAL COST				8504.6000			