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TASK-ORIENTED METHODOLOGY FOR OBJECTIVE ASSESSMENT OF HAND REHABILITATION WITH ROBOTICS THERAPY

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Abstract

Impairments such as muscle weakness, loss of range of motion, decreased reaction times and disordered movement organization create deficits in motor control, which affect independent living of patients. Rehabilitation robotic systems are then suggested to help the patients in maintaining or improving their independence and to reduce the burden of care on institutions and caregivers.

Many clinical methods used are based on subjective and qualitative assessments made by therapists, which highly depends on their experience. Small changes or variations following injury are often undetected. Useful results obtained by clinical groups are not widely-received in the robotics community. The lack of an effective means of communication between the clinical and engineering groups is a major hindrance to any effective rehabilitation process.

The main aim of this research is to develop task-oriented methodology for objective assessment of hand rehabilitation with robotics therapy to aid the restoration of hand function of patients experiencing motor weakness and loss of function in the hand. Target users are the elderly and people with an upper-limb motor disability, such as post-stroke and Spinal Cord Injury (SCI) patients.

For successful and effective rehabilitation outcomes, it is important to apply engineering knowledge and technology to the improvement and delivery of health services. The research work aims to apply engineering knowledge and technology for improvement and delivery of the clinical application – the hand rehabilitation in this research. It will contribute in closing the knowledge gap of clinical and engineering groups. By adopt an objective approach, the proposed rehabilitation methodology for robotic hand rehabilitation should enhance the programme planning and assessment of hand functionality for effective hand rehabilitation through clinical trials.

The work presented in this thesis focuses on the biomechanical model of human hand suitable for targeted patient subjects, the study & analysis of tasks-oriented hand rehabilitation for the key hand movements that are essential for hand functioning in activities of daily living (ADL), and the task-oriented assessment methodology for robotic therapy. The proposed robotic device with "load-free" concept of mechanism design is only one of the solutions for hand-fingers rehabilitation in order to achieve our goal. However, the biomechanical model, analysis of task-specific hand rehabilitation and the task-oriented assessment methodology are also applicable to other robotics devices for hand rehabilitation.

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List of Abbreviations

ADL	Activities of Daily Living
APB	Abductor Pollicis Brevis
APL	Abductor Pollicis Longus
ASIA	American Spinal Injury Association
CMC	Carpometacarpal
DIP	Distal Interphalangeal
DOE	Design of Experiment
DOF	Degrees of Freedom
ECR	Extensor Carpi Radialis
ECU	Extensor Carpi Ulnaris
ED	Extensor Digitorum
EMG	Electromyography
EPL	Extensor Pollicis Longus
FCR	Flexor Carpi Radialis
FCU	Flexor Carpi Ulnaris
FDI	First Dorsal Interosseus
FDS	Flexor Digitorum Superficialis
FIM	Functional Independence Measure
FMA	Fugl-Meyer Assessment
FPB	Flexor Pollicis Brevis
FPL	Flexor Pollicis Longus
IP	Interphalangeal
MCP	Metacarpophalangeal
MVA	Multivariate Analysis
PCA	Principal Component Analysis
PIP	Proximal Interphalangeal
PLS	Projections to Latent Structures
QFD	Quality Function Deployment
ROM	Range of Motion
SCI	Spinal Cord Injury

Chapter 1 INTRODUCTION

1.1 Background

In the next 50 years, the world, especially the Asian region, will experience a dramatic increase in their aged population [1]. It is expected that the demand for facilitation and maintenance of healthy aging in this region is likely to escalate in the future. It is well known that stroke is one of the leading causes of serious and long-term disabilities. Stroke is Singapore's fourth leading cause of death, comprising 9% of all deaths, a crude death rate of 40.4/100,000, an age- and sex-standardized prevalence of 3.65% among adults aged more than 50 years, and an incidence of 1.8/1000 patient-years [2]. It is among our top 10 causes of hospitalization [3] and remains the most common cause of disability in the adult population. One of the sequelae of stroke is weakness of the upper limb, especially of the hand, and this can occur in up to 89% of patients [4].

Loss of hand function prevents patients from performing activities of daily living and also limits employment opportunities. The current treatment for patients with impaired hand function after a stroke is rehabilitation exercises, usually performed by an occupational therapist. Studies have consistently shown that exercises which are intensive and task-specific give rise to better outcome than those that are not [5-7]. For many patients, especially those with more severe weaknesses, these rehabilitation exercises have to be performed consistently and regularly over a period of weeks and months.

Unfortunately, practical and other considerations, e.g. high demand and manpower shortage, usually mean that most stroke patients do not receive the necessary intensive exercises. For example, the average stroke patient undergoing inpatient rehabilitation is likely to receive an hour of supervised occupational therapy daily, which can inhibit recovery and progression. One solution is to provide more intensive exercises through the use of robotics-facilitated therapy. Therefore, effective and productive therapeutic training devices for assisting the elderly and people with a motor disability (e.g., survivors of post-stroke) are currently in high demand and this demand will only increase. The availability of such devices will not only help to maintain or improve patient independence, but have the ability to reduce the burden of care on institutions and caregivers, including family members. Impairments such as muscle weakness, loss of range of motion, increased reaction times, and disordered movement coordination create deficits in motor control, which affect the patient's independent living and provide a cause of great frustration and depression to the patient.

In recent years, the use of exoskeleton robots has expanded in the area of rehabilitation. Many research groups have focused on retraining the upper limb to guide the reaching movement (see Figure 1.1). The reaching component is concerned with bringing the hand to the object to be grasped, which involve the shoulder, elbow, and wrist movements, whereas the grasping component refers to the opening and closing of the hand. Note that the shoulder and upper arm of the patient needs to be stabilized prior to or during the use of the robot otherwise it will be impossible to attain a control or good motor patterning in the hand due to the presence of enhanced spasticity as a result of poor scapular patterning. Grasping tasks involve finger movement, strength and power, hand dexterity, etc. Clearly, the motion of upper limb is insufficient to perform any useful functional task, without good hand function. It is known that the recovery of the upper limb is from proximal (shoulder, elbow and forearm) to distal (wrist and hand/fingers). A study [8] also found that active finger muscle exercises improved how quickly the stroke survivor could recover in order to be able to grip or release an object.

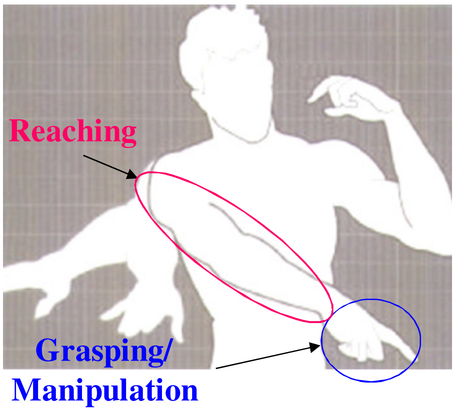


Figure 1.1: ADL-related Function of Upper Limb (Arm and Hand) Focusing Mostly on Finger Motion

The human hand is vital for performing activities of daily living, and the loss of hand function severely restricts independent living and limits employment opportunities. It is not surprising therefore that great attention in the field of rehabilitation has focused on understanding and restoring hand motor function after stroke [6]. These patients need timely and persistent rehabilitation to recover their lost abilities and regain their normal daily lives. It is believed that restoration of hand function can greatly improve activities of daily living, and thus enhance their overall independence and quality of life. The restoration or maintenance of hand function is associated with intensive voluntary practice of the affected hands.

There is a general consensus that early intervention is ideal (commencing within one week following a stroke) to promote neuro-plasticity and should include repetitive hand and finger motion [5]. There is also ample evidence that shows that the incorporation of functional tasks in rehabilitation protocols will translate into far better outcomes [9] in comparison to uni-planar experimental tasks or tasks practiced in their component parts. One of the important components of hand function is the ability grasp during static conditions (holding objects without letting them slip) and under dynamic conditions (opening jars, key turning, picking tiny items). Functionally relevant tasks have been shown to be of greater benefit for the recovery after stroke [9].

Robots hold great promise over traditional therapy. Specifically, robots can provide therapy over long time periods, in a consistent and precise manner, whilst accounting and adjusting for fatigue. It also has the potential to enhance the therapy beyond the abilities of the practitioner. Some unique contributions of robotic therapy versus conventional therapies are that robots can be used as valuable adjuncts to save time and energy for the therapist, making rehabilitation sessions more efficient; or to gain insights into the rehabilitation recovery process, and that rehabilitation protocols can be very precisely tailored to individual patients with only as much assistance provided as needed.

1.2 Motivations

Upper limb is very important because it is able to execute cognitive expression, and manipulation activities, it takes a crucial role when exploring the environment and in all reflex motor acts. Consequently, any alteration or pathology that affects the upper limb motion range, muscle power, sensibility, skin integrity, will alter its operation [10]. Individuals with paralysis rely on the use of their hands and upper limbs in order to complete basic activities of daily living such as self-feeding, dressing, bathing and toileting. Mobility needs such as transfers from surface to surface, transitional movements such as rolling, bridging and sit to lying down, crutch walking and wheeled mobility is also completed by using their arms [11]. This greater reliance on the arms can lead to pain and injury, which can have an impact not only on mobility, but also on the ability to complete activities of daily living (ADL) [12].

The analysis of lower limb movements has been well established in kinesiological research and in the rehabilitation environment for a long time [13]. While human walking can be assessed by analyzing the repeating nature of hip, knee, and ankle joint angles and by measuring the ground reaction forces, it is impossible to apply the same methods to upper limb kinematics and dynamics, which are determined by the task and characterized by much more complex movements that are normally not cyclical. Therefore, the introduction of the assessment of arm and hand movements in clinical practice is of importance for improved evaluation of various therapeutically procedures [14].

At present, most rehabilitation exercises are performed manually by physical or occupational therapists. The manually assisted movement training by therapists has several major limitations. The training is labor-intensive, and, therefore, training duration is usually limited by personnel shortage and fatigue of the therapist, not by that of the patient. The disadvantage is that the training sessions may be shorter than required to gain an optimal therapeutic outcome. Finally, manually-assisted movement training lacks repeatability and objective measures of patient performance and progress [15]. Many clinical methods used are based on subjective and qualitative assessments made by therapists, which highly depends on their experience. Small changes or variations following injury are often undetected.

With an automated robot-assisted device, the duration and number of training sessions can be increased, while reducing the number of therapists required per patient. One therapist may be able to train two or more patients in the future. Thus, personnel costs can be significantly reduced. Furthermore, the robotic device provides quantitative measures, thus, allowing the observation and evaluation of the rehabilitation process [15]. The automated process relieves therapists of the manual labor. Therefore, the training sessions can be longer and repeatable. As a result, the therapy is more efficient and the patients achieve their goals faster.

In recent years, the use of exoskeleton robots has expanded in the area of rehabilitation. Many research groups have focused on retraining the upper limb to guide the reaching movement. The reaching component is concerned with bringing the hand to the object to be grasped, which involve the shoulder, elbow, and wrist movements, whereas the grasping component refers to the opening and closing of the hand. Note that the shoulder and upper arm of the patient needs to be stabilized prior to or during the use of the robot otherwise it will be impossible to attain a control or good motor patterning in the hand due to the presence of enhanced spasticity as a result of poor scapular patterning. Grasping tasks involve finger movement, strength and power, hand dexterity, etc. Clearly, the motion of upper limb is insufficient to perform any useful functional task, without good hand function. It is known that the recovery of the upper limb is from proximal (shoulder, elbow and forearm) to distal (wrist and hand/fingers). A new study [8] also found that active finger muscle exercises improved how quickly the stroke survivor could recover in order to be able to grip or release an object.

Hand functioning can be compromised by a series of conditions including trauma from injury to the tendon and nerves in the wrist, burns and from two key common conditions affecting our ageing population namely, stroke and arthritis. Due to the complex nature of hand function, rehabilitation is time consuming, slow for the patient and often frustrating. Thus a device to assist and guide this process will be invaluable; in addition the ability to comprehensively quantify function to measure improvement and the potential for real time biofeedback to the patient.

Hand rehabilitation is somewhat difficult because the hand possesses more than 20 degrees of freedom of motion, and a hand motion assistive device will need to be small, and capable of precise complex movements. Research on the function of the fingers by functional electrical stimulation (FES) [16-18], robotic devices [19-22], exoskeleton [23-25], and virtual reality-based stroke rehabilitation [26-28] have been presented. Therapies using previously proposed robotic devices for hand rehabilitation provide self-controlled rehabilitation, but these therapies are limited to simple hand tasks such as gripping and tapping. Furthermore, one inherent limitation of biofeedback therapy (e.g. the HandTutor [29]) is that patients with more severe motor deficits cannot participate due to an inability to initiate any functional movement, thus preventing utilization of biofeedback for improving performance. Rehabilitation robots or other devices could solve the problem by providing mechanical assistance for movement [30].

Recent encouraging research has reported [31, 32] on the control of myoelectric prostheses in high-level upper-limb amputation and the use of intelligent control for robotic rehabilitation after stroke [33]. On the other hand, many active upper-limb exoskeleton robot systems have been developed for rehabilitation (for good example see ARMin [34], MIME [35], WREX [36], MAHI [37] and powered exoskeleton [38]), but few have focused on finger motion [39, 40]. The well-designed hand devices [39, 40] attach and move the fingers' tip in performing the hand rehabilitation training. Therefore, in this research, we will focus on hand/finger rehabilitation during grasping/manipulation tasks. The proposed hand rehabilitation device provides task-oriented motion by creating flexion/extension the finger joints of each finger, rather than through the fingertip actuation only.

Design Issues for Effective Hand Rehabilitation (involving fingers)

Our literature review identified several limitations in the current systems available. First of all, most of the robots were only able to provide simple grasping/releasing actions. As presented in [34, 37, 41, 42], the devices are designed for one or two fingers only or all four fingers are combined and preformed together as one single unit, but not as individual fingers with wrist motion. Therefore, these devices would not perform a normal/natural hand function as they do not allow the motion of individual fingers. Secondly, the motors and mechanisms of most of the hand devices are placed on the hand or forearm which in itself can limit their usability. This arrangement is undesirable and uncomfortable to the patients (they may have little or no strength and muscle control), as they need to bear the weight through the rehabilitation training. Lastly, most of the robots cannot support functional activities of daily living (ADL) tasks, which are important for improvements in ADL of real life and reduction of impairments as task-specific practice is required for motor learning to occur [43, 44].

Issues for Assessment/Evaluation Methods

Intensive rehabilitation that involves several components, such as physical therapy, occupational therapy, and speech therapy, usually requires continued sessions of one-on-one training for weeks so as to be of benefit [45]. However, the manually-assisted movement training lacks repeatability and objective measures of patient's performance and progress [15]. Many clinical methods used are based on qualitative assessments made by therapists, which is dependent on their experience and is very subjective. Small changes or variations following injury are often undetected. However, the therapist's experience remains extremely important over the machine/robot in regards to gauging the subject's ability on a step-to-step basis [46]. The physical therapists' distinctive view of the body and its movement needs and potential are central to determining a diagnosis and an intervention strategy is consistent whatever the setting in which practice is undertaken [47]. Occupational therapy practice may be directed to changing certain aspects of the environment to enhance participation. Subjective evaluation is often based upon clinical ordinal scales (e.g., Fugl-Meyer Assessment and Functional Independence Measure), are still preferred and widely used in rehabilitation centers. The main limitations of these assessments are low reliability and sensitivity [48, 49]. Objective and accurate assessment of hand function are needed to monitor and quantify patients' progress during therapy and to validate the outcome of the rehabilitation treatment, this assessment methodology is able to enhance the hand rehabilitation training rather than inhibiting conventional rehabilitation.

There is mounting evidence that more clinicians are recording their findings using ordinal or quantifiable outcome tools. Beyond the administrative push to use datasets to track patient outcomes in relation to health care costs, clinical investigators recognize that using an appropriate outcome tool, to determine the validity of a therapeutic intervention, is the key to establishing or changing the models of best practice [50]. The accuracy and objectivity of hand function evaluation can be increased by introducing simple quantitative methods based on different parameters, such as range of motion, gripping or pinch force, hand dexterity and posture, position and velocity of object grasped, contact distribution of the hand, etc. However, the relationship between these parameters is yet to be investigated. This necessitates a systematic method for the objective and quantitative assessment of hand function to correctly diagnose patients' functional state and to evaluate the progress of therapy. Therefore, there is need to develop a systematic approach to receive data from the occupational therapists as the input to the robotics system, together with the measurement results (sEMG, grip/pinch force, joint angle, etc.) based on the assessment and evaluation of hand function at each progress interval.

Grip and pinch strength have been shown to be two of the most important factors related to hand function. It is noted that pinch and grip strength along with ROM (range of motion) measurements are able to provide a robust alternative to detailed biomechanical measures with the additional benefit of being efficient in terms of cost and time [51]. Tests of grip force, either of whole hand grip or pinch grip between thumb and index finger, may be particularly useful. This is because the control of grip force is a critical feature of all actions between hand and object, and therefore grip force may be a prognostic indicator.

An Objective Approach for Hand Rehabilitation

An implementation of any effective rehabilitation process must consider the issues related to both clinical and engineering aspects (see clinical–engineering approach illustrated in Figure 1.2).

In the clinical aspect, the aim is to ensure maximum recovery and regain early independence of patients with optimal function in their daily activities and return to work. The ASIA score, FIM, and FMA are the most commonly used assessments and the outcome tools for the post-stroke and SCI patients. These measures are based on subjective and qualitative assessments made by therapists, which are highly dependent on their experience. Moreover, the clinical assessment, condition, and progress of a subject are indicated in terms of ordinal scales (e.g., 0-5, 1-7).

As for the engineering aspects, the proposed work is concerned with the study, design, and control of a robotic assisted hand rehabilitation system. The system is considered as a therapeutic tool for people with motor weakness, such as post-stroke patients. By making use of the developed systematic approach, data collected from the therapists will be used as an input data for the robotics system; together with the objective measures (e.g. sEMG, ROM, gripping/pinch force, etc. see the blue boxes in Figure 1.2). These results will then be used as control parameters for the hand rehabilitation device. By monitoring the patient progress and providing objective feedback we hope to enhance patient compliance and increase patient motivation. This will also serve as a tool for therapists and doctors to monitor progression and response to the intervention (see the yellow boxes in Figure 1.2).

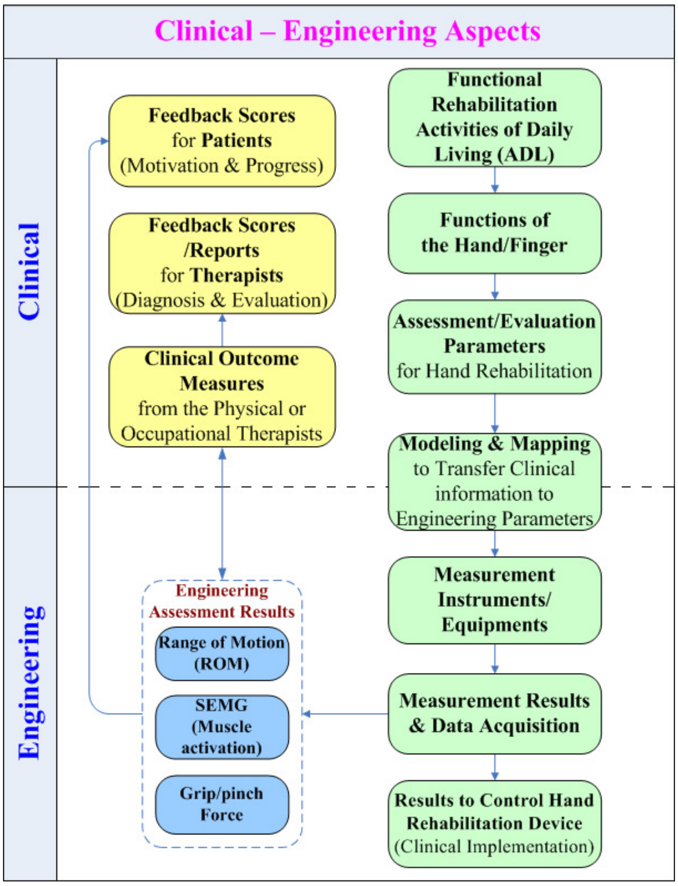


Figure 1.2: An Objective Approach for Hand Rehabilitation

Unfortunately, useful results obtained by clinical groups are not widely-received in the robotics community. Parts of the reason might lie with the complexity of the unfamiliar clinical topics and practical issues to engineers. On the other hand, many engineering works documented do not seem to focus on the crucial clinical problems. The lack of an effective means of communication between the clinical and engineering groups is a major hindrance to any effective rehabilitation process. Whilst technical solutions are being achieved in the field of robotics and knowledge is developing in clinical rehabilitation engineering, to date, the two fields have not merged despite mutual interest. Therefore, our aim is first to build a bridge linking between the clinical and engineering aspects in rehabilitation research; next, to design, develop, adapt, test, evaluate (see the green boxes in Figure 1.2), and provide engineering solutions to clinical problems confronted by individuals with disabilities.

We believe that the accuracy and objectivity of hand function evaluation can be improved by introducing a quantitative assessment method. The quantified parameters include sEMG, gripping/pinch force, ROM together with the clinical input data from the physical or occupational therapists.

In order for the clinical and engineering groups to share their useful and important results, a common assessment/outcome method or even language that is understood and agreed by all parties must be introduced. Therefore, besides the three assessment parameters, the evaluation and outcome from clinical are important. The ASIA score, FIM, and FMA are the most commonly used outcome to measure the SCI and post-stroke patients. However, the clinical assessment, condition, and the progress of a subject are indicated in terms of ordinal scales. Any small changes or variations are often undetectable. Hence, the mapping between the engineering numerical parameters and clinical outcome measures are important to provide a more detailed assessment in terms of quantifiable numerical values.

1.3 Objectives and Scope

The main aim of this research is to develop task-oriented methodology for objective assessment of hand rehabilitation with robotics therapy to aid the restoration of hand function of patients experiencing motor weakness and loss of function in the hand following stroke or other neurological or even musculoskeletal diseases (e.g. tendon injury, nerve injury, etc). The proposed hand rehabilitation system would be (i) load-free (i.e. payload-free), (ii) capable of training key hand movements that are essential for hand functioning in activities of daily living (ADL), e.g. five-pulp pinch, tripod pinch and lateral pinch, and (iii) capable of capturing useful clinical data that can then be used to chart progress and provide biofeedback (e.g. sEMG signals) to the patient.

The hand rehabilitation device will be used in combination with pre-programmed finger motion based on a systematic methodology for objective and quantitative assessment of hand function to correctly diagnose patients' functional state and to evaluate the progress of therapy. With the data provided by the therapists that will serve as the data input to the robotics system, together with the pre-measurement results (sEMG, gripping or pinch force, joint angle, etc.) based on assessment and evaluation of hand function at each progress interval, through an interactive control, the system is able to assist the patient to perform activities of daily living (ADL) rehabilitation on the impaired hand.

The goal of the present engineering research project for clinical application is to develop the assessment methodology of hand rehabilitation, so that the key hand movements that are essential for hand functioning in activities of daily living (ADL) and rehabilitation exercises are effectively performed by using a robotics hand rehabilitation device. The multi-disciplinary approach for the proposed research work of hand rehabilitation is identified and summarized in Figure 1.3. The approach should serve as a general guidance of hand rehabilitation. The approach can be divided into six steps (see the left boxes in Figure 1.3). The individual components and their inter-relationships are described next.

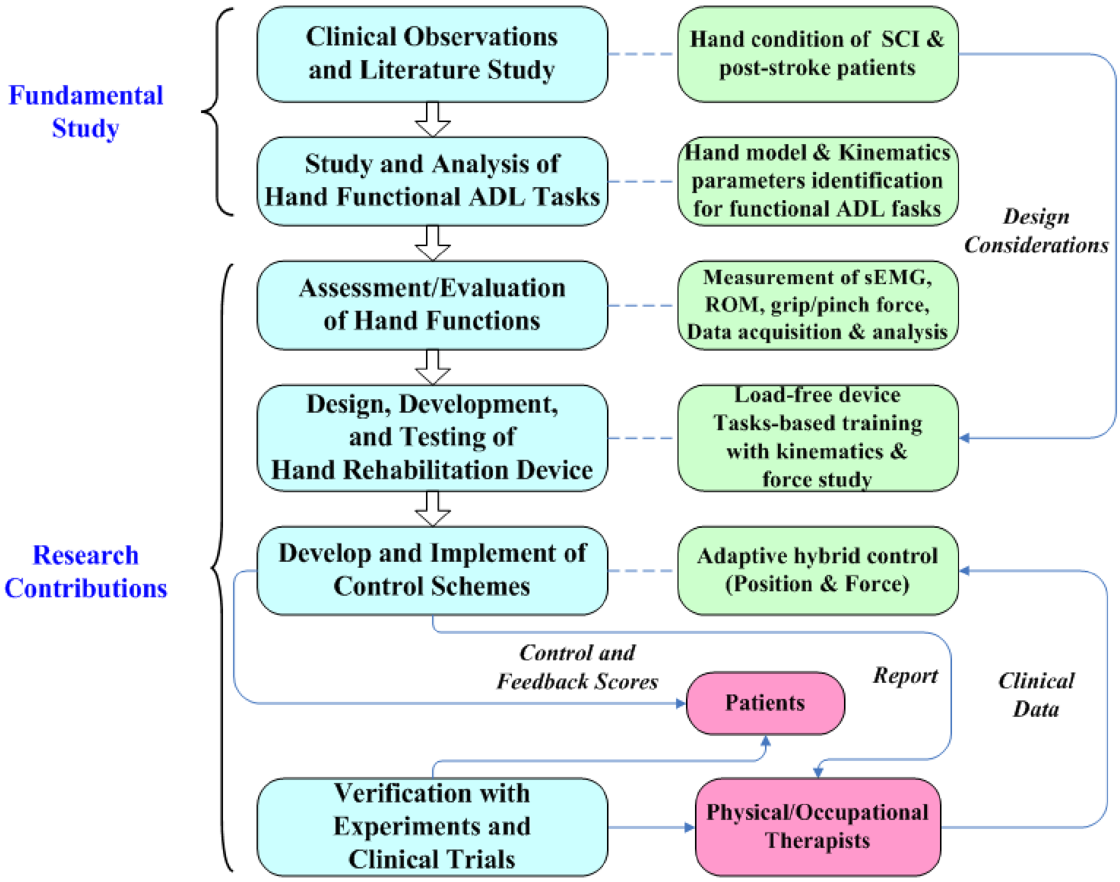


Figure 1.3: Multi-disciplinary Approach of Hand Rehabilitation

1) Fundamental Study:

a) *Clinical observation and literature study:* The principles and techniques that are used in post-stroke patients during hand rehabilitation have been reviewed. In order to have a better understanding of the condition and rehabilitation process of post-stroke patients, clinical observations and discussions with doctors and therapists are carried out in Tan Tock Seng Hospital (TTSH)

Rehabilitation Centre, the largest rehabilitation centre in Singapore. The literature studies and clinical observation helped us in understanding the problems experienced by post-stroke patients, and will be subsequently used in the analysis of functional tasks and the design requirements of a hand rehabilitation device in the later research phases.

b) *Study and analysis of hand functional ADL tasks:* An objective and quantitative assessment of hand function will enable us to correctly diagnose patients' functional state and to evaluate the progress of therapy. The kinematics analysis of human hand and functional grips, with their muscle groups and joint motion in performing the ADL and rehabilitation exercises, will be carried out in a systematic way together with other important parameters, such as gripping/pinch strength along with range of motion, etc. The identification of kinematics parameters has been done for different functional ADL tasks [52].

2) **Research Contributions by Multi-disciplinary Approach:**

a) *Assessment/evaluation of hand function:* Based on the preliminary study and analysis, the accuracy and objectivity of hand function evaluation can be improved by introducing quantitative methods based on different parameters, such as the surface electromyography (sEMG), functional gripping/pinch force, hand posture, position and velocity of object grasped. The sEMG signals obtained off-line are analyzed based on hand motion for specified tasks and different gripping conditions. The sEMG measurement and recordings of muscle actions for each respective movement are useful for analyzing which muscles and at what times they are active. This is the information required for the control of the hand rehabilitation device. As for sEMG pattern recognition, the hand motion-strength relationship will be explored, as stroke survivors tend to regain the independent of intended direction of movement by co-contraction of hand muscles.

b) *Design, development, and testing of hand rehabilitation device:* The hand rehabilitation system should be designed to integrate robotics, mechatronics and information technology to overcome the limitations of the existing rehabilitation systems. For example, most of the existing devices can only provide simple grasping, and are unable to support individual finger motion;

their devices are not load-free. Instead, the motors and mechanical components are placed on the hand or forearm in their design, the device assisted by position control only, which lacks bio-feedback to provide force control, and the device cannot support functional ADL tasks. In this proposed research project, the hand rehabilitation device will consist of several modular components, which is designed to be load-free (i.e. the payload is not loaded on the subject's hand) and the hand motion is visible to the patient/therapist for tasks-oriented rehabilitation training.

c) *Development and implementation of patient-oriented control schemes:* Having discussed with several therapists at several local hospitals, it is noted that for the post-stroke patients, the progress of therapy and its recovery is usually slow in regaining functional use of their impaired arm and hand. Therefore, it is possible to develop a control scheme that uses the clinical data from the occupational therapists as the input to the robotics system, together with the measurement results based on assessment and evaluation of hand function in each progress stage. The control strategy will be provided in the same manner as that by a qualified therapist. It will also assist the patient's movement only as needed. This will then allow the patient to actively learn the spatiotemporal patterns of muscle activation associated with normal hand function. There are four types of assistance considered in the present work: passive, active-assist, active-unassisted and active-constrained. These types can be provided by the hand rehabilitation device by virtue of our carefully designed control schemes and algorithms. It is worth mentioning that the control schemes should be in hybrid manner, which integrate position and force control of the hand rehabilitation system.

d) *Validation with experiments and feasibility test:* The feasibility and benefit of the robotic, assistive hand rehabilitation need to be verified in experiments and clinical studies as well. The mechatronic capability developed should facilitate patient's understanding and therapist's assessment of the rehabilitation stages. It is hoped that the results will not only be used as the control parameters of the hand rehabilitation device, but also serve as feedback scores for patients. The feedback scores provide a means of monitoring and motivating the patient progress. A comprehensive report card for therapists can also be produced by means of diagnosis and evaluation of the therapy progress of a subject.

This thesis addresses the need of a systematic methodology for objective and quantitative assessment of hand function to correctly diagnose patients' functional state and to evaluate the progress of therapy. There is a possibility to develop a systematic approach to receive data from the physical or occupational therapists as the input to the robotics system, together with the measurement results based on assessment and evaluation of hand function at each progress interval.

To achieve the goal, it is important to address the fundamental issues first so as to establish a research basis in this area. The overall objective of this research work is therefore the study and analysis of the fundamental issues that constitute the development of systematic methodology for objective and quantitative assessment for patients with motor weakness, such as post-stroke and spinal cord injury (SCI), to improve their functional ability of hand through the identified functional activities of daily living (ADL) and rehabilitation exercises.

1.4 Thesis Outline

The thesis consists of seven chapters and four appendices. This chapter provides the background and introduction to the motivation of this research, the objectives, scope, challenges of this research, and future research contribution. The outline of the thesis is structured as follows.

Chapter 2 Literature Review provides the literature review on the related topics of hand rehabilitation, which includes hand movement and functions, hand rehabilitation by robotic therapy, State-of-the-art of hand rehabilitation devices and clinical evaluation of hand function.

Chapter 3 Study of Clinical Issues and Requirements presents the several clinical issues are studied during the clinical attachment at rehabilitation centers of the local hospitals (TTSH and SGH). Some key clinical requirements for task-oriented hand rehabilitation system are summarized, which are useful for design of the hand rehabilitation device and the robotics rehabilitation training.

The literature study in both engineering aspects and clinical aspects provide valuable background information, forms the basis of the research methodology proposed in this research work.

Chapter 4 Hand Modeling and Analysis of ADL Tasks presents the skeletal of human hand, the kinematics model of the fingers (Index, Middle, Ring and Small Fingers) and the thumb using D-H method and throughout its workspace analysis., and the study on hand rehabilitation tasks and their motion sequences, the kinematics identification and workspace analysis of ADL functional tasks and 23-DOF virtual model of task-specific hand motion. The chapter also shows the study, analysis, and results.

Chapter 5 Design of a Hand-Fingers Rehabilitation Device has the details on the engineering realization for the features of robotic assisted hand rehabilitation proposed in this research work. Based on the findings of literature reviewed and the suggestion provided by doctors and therapists from local hospitals, several features for robotic assisted hand rehabilitation are proposed. It presents the analysis and hand mechanism design, which covers design considerations, design for reduced DOFs, and design, analysis and the key features of various modules of the robotics device for hand rehabilitation. After several design proposals on the design of the mechanism to cover most movements of the hand model, the concentric design of the finger module, simplified thumb module, and wrist support module and force analysis on the load-free concept are presented in detail. The assembled robotics device for hand rehabilitation and the analysis on force required for flexion and effect of materials is also discussed.

Chapter 6 Study of Hand Strength Measurement on ADL Tasks presents the study of hand strength measurement to investigate the sEMG signals and gripping/pinch force for post-stroke and SCI patients based on the five ADL functional tasks. The analysis using DOE and MVA provide useful data (both statistical data and graphic information) for objective and quantitative assessment towards control applications on a hand rehabilitation device being developed.

Chapter 7 Conclusion and Future Work concludes the work done and provides a general outline of the proposed research approach, research contributions, and recommendation for future research in three areas.

Chapter 2 LITERATURE REVIEW

In Chapter 1, the need to study, analysis, design and develop a robotic assisted device, which served as a therapeutic tool for hand rehabilitation by making use of mechanisms with systematic methodology is identified and defined. The purpose is to improve the functional ability of people with motor weakness, with objective and quantitative assessment to correctly diagnose patient's functional state and evaluate the progress of therapy.

The purpose of this chapter is to present a review of the related topics of hand rehabilitation. In order to give the reader for a better understanding of human hand, a brief introduction of hand movement and its functional activities is provided. General principles of hand rehabilitation, existing hand rehabilitation devices and clinical evaluation of hand function are also reviewed and discussed here.

The review is important as it can be used to assess the need to develop a hand rehabilitation system, which should be developed for assessment and evaluation of hand function and also served as a therapeutic tool for hand rehabilitation.

2.1 Hand Movement and Functions

The hand is a versatile "tool" capable for tasks ranging from fine precision (playing piano, threading a needle) to great strength (swinging a sledgehammer, unscrewing a stubborn jar lid). The success of humans as a species is mainly due to our capability to grasp and manipulate objects. The strong, opposable thumb is crucial in this respect, and is one adaptation that allows humans to take the evolutionary "quantum leap" beyond their primate ancestors [53].

2.1.1 Hand Anatomy and Movement

The hand comprises the wrist, palm and fingers. It has 27 bones divided into three groups: 8 carpal bones in the wrist, 5 metacarpal bones and 14 phalanges of the fingers (see Figure 2.1).

There are three joints in each finger, in sequence from the proximal to distal: Carpometacarpal (CMC), Metacarpophalangeal (MCP) and Interphalangeal (IP) joints. Each finger has two IP joints, the Proximal Interphalangeal (PIP) and Distal Interphalangeal (DIP) joints, except the thumb, which has only one.

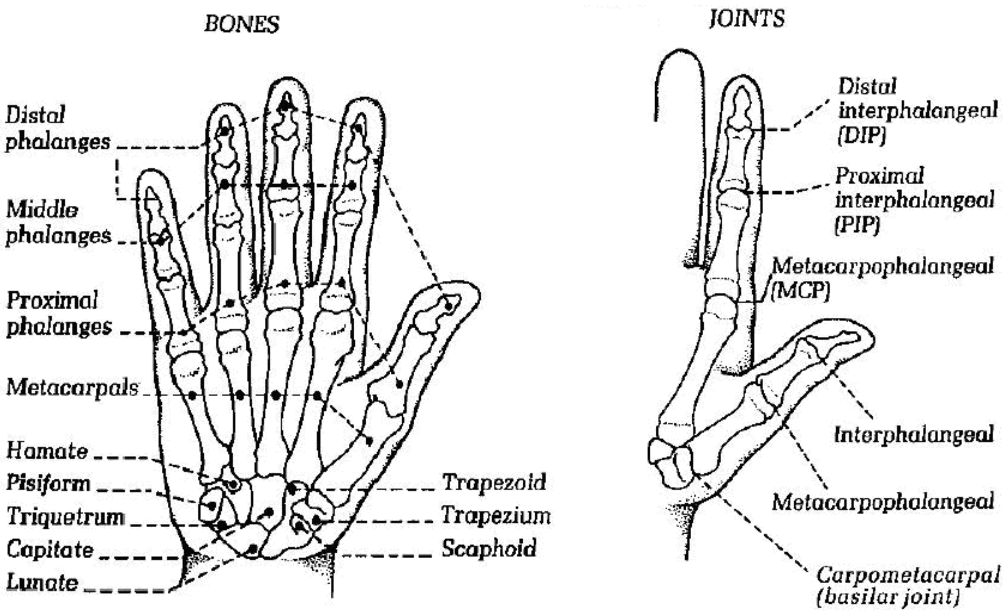
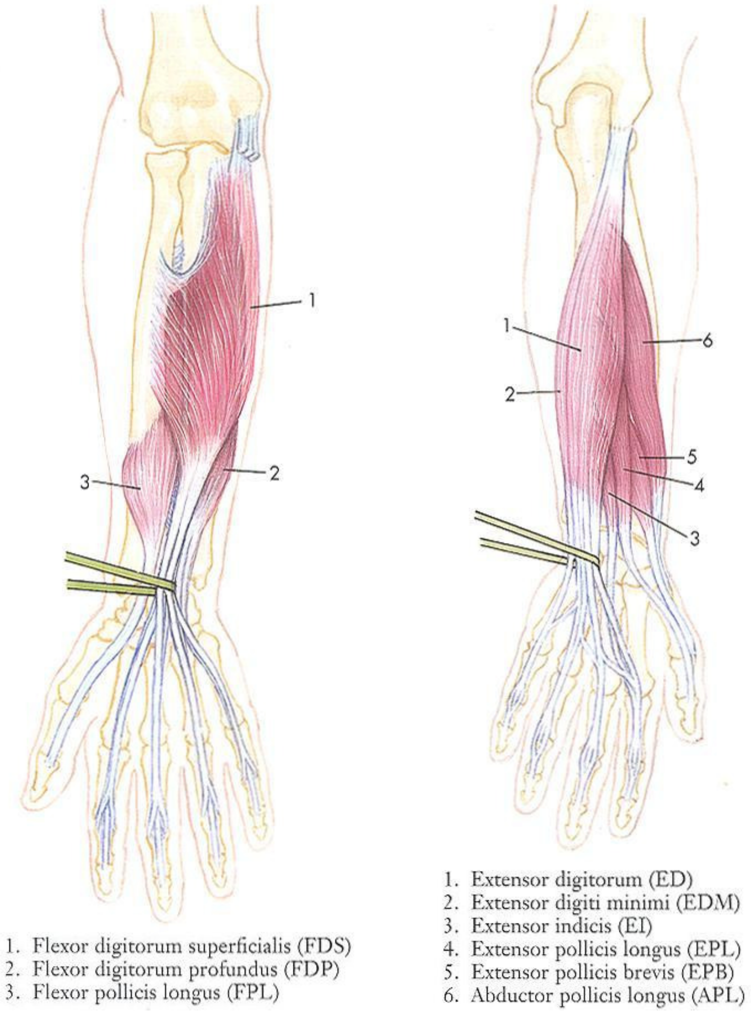


Figure 2.1: Hand Anatomy (Modified from [54])

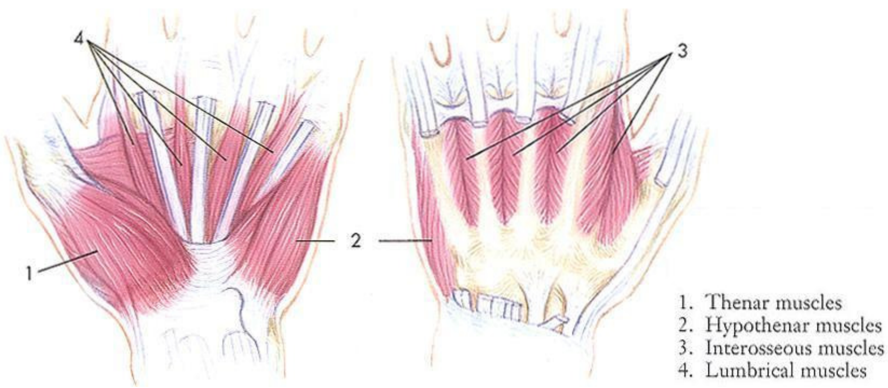
Optimal hand function is the result of mobile balance of the wrist and fingers with their respective muscles. Motions occur around variable axes to facilitate precise positioning of the digits for prehension. Optimal hand function thus requires a complex interaction between the wrist, thumb, and fingers [55].

The movement of hand is controlled by 34 muscles which consist of extrinsic and intrinsic muscles based on the origin of the muscles. Most muscles in the forearm move the hand at wrist and/or the fingers. These muscles are called extrinsic muscles (see Figure 2.2) of the wrist and hand, because the muscles originate from the forearm, not the wrist or hand. The intrinsic muscles (see Figure 2.3) of the hand are small muscles that both originate and insert on the hand; they are housed entirely within the palm.



(a) Extrinsic Digital Flexors (b) Extrinsic Digital Extensor

Figure 2.2: Extrinsic Muscles of the Hand at the Forearm [56]



(a) Palmar view (b) Dorsal view

Figure 2.3: Intrinsic Muscles of the Hand [56]

Tables 2.1-2.5 provide an overview on the anatomy of the hand and its functions as well as maps the muscles onto different hand movements and its corresponding range of motion (ROM).

Table 2.1: Extrinsic Muscles of the Fingers (Modified from [56, 57])

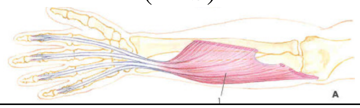
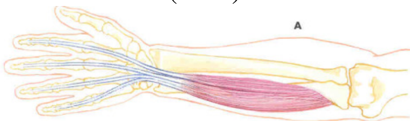
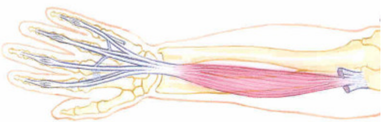
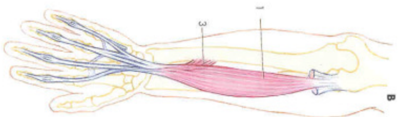
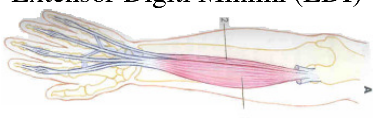
No	**Muscle**	**Location**	**Action**	**ROM**
1.	Flexor Digitorum Superficialis (FDS) 	Originates from both elbow joint capsule, coronoid process of the ulna and anterior surface of the radius.	Flexes the MCP and PIP joints of second through fifth fingers.	MCP: -45 to +90 degrees flexion. PIP: 0 to 100 degrees
2.	Flexor Digitorum Profundus (FDP) 	Broad origin on the anterior and medial ulna. Splits into 4 tendons, which pass through the carpal tunnel and inserts on the distal phalanges of fingers II to V.	Flexes all interphalangeal joints of second through fifth fingers. 	MCP and PIP: As above. DIP: 0 to 60 degrees.
3.	Extensor Digitorum (ED) 	From common extensor origin and deep fascia of the forearm. Splits into 4 tendons, each tendon splits into 3 bands.	Extends all interphalangeal joints of second through fifth fingers. 	0 degrees neutral position. -45 degrees for MCP during hyperextension
4.	Extensor Indicis (EI) 	From the posterior ulna and interossous membrane.	Assist the Extensor Digitorum Muscle in extension of all interphalangeal joints of the second finger only.	As above in (3)
5.	Extensor Digiti Minimi (EDI) 	Deep to the extensor digitorum.	Assist the Extensor Digitorum Muscle in extension of all interphalangeal joints of the fifth finger only.	As above in (3)

Table 2.2: Extrinsic Muscles of the Thumb (Modified from [56, 57])

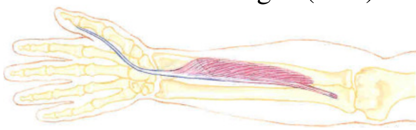
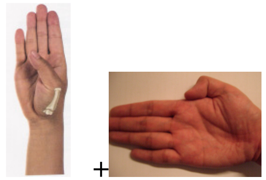
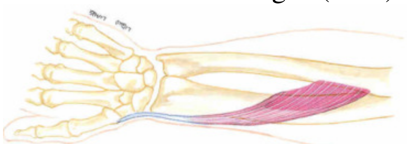
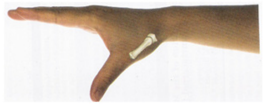
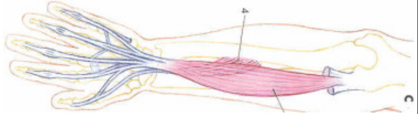
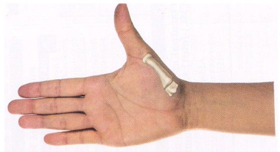
No	Muscle	Location	Action	ROM
1.	Flexor Pollicis Longus (FPL) 	Originates from the anterior radius and lateral part of the interosseous membrane.	Flexes the CMC, MCP and IP joints of the thumb. 	CMC: 0 to 15 degrees. MCP: 0 to 50 degrees. IP: 0 to 80 degrees.
2.	Abductor Pollicis Longus (APL) 	Arises from the posterior surface of the ulna, radius, and interrossous ligament, inferior to supinator.	Abduction and extension of CMC joint of the thumb. 	Abduction: 0 to 70 degrees. Extension: 0 to 20 degrees.
3.	Extensor Pollicis Brevis (EPB) 	Originates on the posterior radius and interossous membrane inferior to abductor pollicis longus.	Extension of MCP joint of the thumb.	Extension of MCP: 0 to 20 degrees.
4.	Extensor Pollicis Longus (EPL) 	Originates on the posterior ulna and interossous membrane inferior to abductor pollicis longus and superior to extensor indicis.	Extension of CMC, MCP and IP joints of the thumb. This is the only muscle that can extend the interphalangeal joint of the thumb. 	As above in (3)

Table 2.3: Intrinsic Muscles of the Hand-Thenar (Modified from [56, 57])

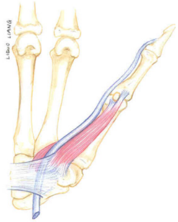
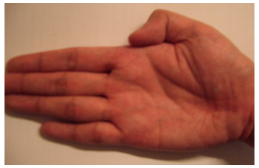
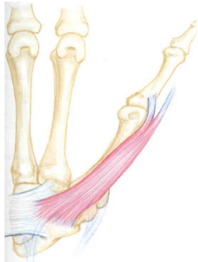
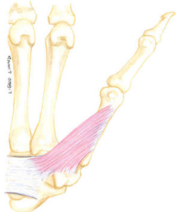
No	Muscle	Location	Action	ROM
1.	Flexor Pollicis Brevis (FPB) 	Originates from the trapezium and flexor retinaculum and attaches to the base of the proximal phalanx of the thumb.	Flexes the CMC and MCP joints of the thumb. 	CMC: 0 to 15 degrees. MCP: 0 to 50 degrees.
2.	Abductor Pollicis Brevis (APB) 	Arises from the flexor retinaculum, schaphoid, and trapezium. Inserts on the lateral base of the proximal phalanx of the thumb next to flexor pollicis brevis.	Abduction of CMC joint of the thumb. 	Abduction: 0 to 70 degrees
3.	Opponens Pollicis (OP) 	Origin similar to flexor pollicis brevis, lies deep to this muscle. Inserts on the lateral shaft of metacarpal I.	Opposition of CMC joint of the thumb. 	Opposition: 0 to 15 degrees.

Table 2.4: Intrinsic Muscles of the Hand-Hypothenar (Modified from [56, 57])

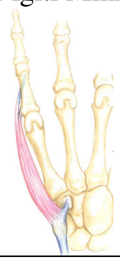
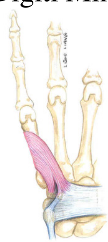
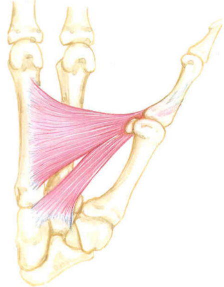
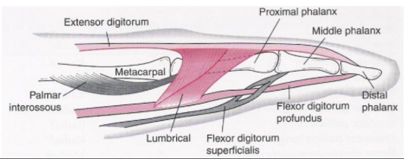
No	Muscle	Location	Action	ROM
1.	Flexor Digiti Minimi (FDM) 	Same origin as opponens pollicis, insert on the base of the proximal phalanx of fifth finger.	Flex MCP joint of the fifth finger.	MCP: 0 to 90 degrees.
2.	Abductor Digiti Minimi (ADM) 	Arises from pisiform and flexor retinaculum, inserts on the base of the proximal phalanx of fifth finger.	Abduction of MCP joint of the fifth finger.	Abduction: 0 to 20 degrees
3.	Opponens Digiti Minimi (ODM) 	From the flexor or retinaculum and hook of hamate, inserts on the medial surface of the fifth metacarpal.	Opposition of the fifth finger i.e. Help move the little finger toward the thumb (for grasping) and create the curvature of the palm.	

Table 2.5: Intrinsic Muscles of the Hand-Deep Palm (Modified from [56, 57])

<table>
<tr><th>No</th><th colspan="2">Muscle</th><th>Location</th><th colspan="2">Action</th><th>ROM</th></tr>
<tr><td>1.</td><td colspan="2">Adductor Pollicis (AP)
</td><td>Lies deep to the flexor tendons in the palm and has 2 origins, from the shaft of metacarpal 3 and the other from the capitate bone and adjacent ligaments.</td><td colspan="2">Adduction of the thumb.
</td><td>0 degrees in neutral position</td></tr>
<tr><td rowspan="2">2.</td><td colspan="2">Interossei</td><td rowspan="2">From the metacarpals and inserting on the phalanges. 4 dorsal and 4 palmar interossei.</td><td>Dorsal</td><td>Dorsal</td><td></td></tr>
<tr><td>Dorsal
</td><td>Palmar
</td><td>Abduct second through fifth fingers.
</td><td>Adduct all fingers except the third.
</td><td>Fingers:
0 to 20 degrees.

Thumb:
0 to 20 degrees.</td></tr>
<tr><td>3.</td><td colspan="2">Lumbricales
</td><td>From the tendons of flexor digitorum profundus, insert on the tendon of extensor digitorum.</td><td colspan="2">Flex MCP joint and extend the PIP and DIP joints of the second through fifth fingers.</td><td>MCP:
0 to 90 degrees.</td></tr>
</table>

(a) Wrist Movement

The wrist is not a single joint, but consists of multiple joints. The wrist or carpus provides a stable support for the hand, allowing the transmission of grip forces as well as positioning of the hand and digits for fine movements. The main function of the wrist is to fine-tune grasp by controlling the length-tension relationship in the extrinsic muscles to the hand. Its combination of movements occurs in the radiocarpal joint, intercarpal joint and carpometacarpal (CMC) joint.

In flexion of the wrist (see Figure 2.4), the palm moves closer to the anterior surface of the forearm. The fingers tend to elongate during this movement, due to tightening of the extensor tendons. They can feel this tightening on the back of the hand when flexing the fingers. In extension of the wrist, the posterior surfaces of the hand and forearm move closer together.

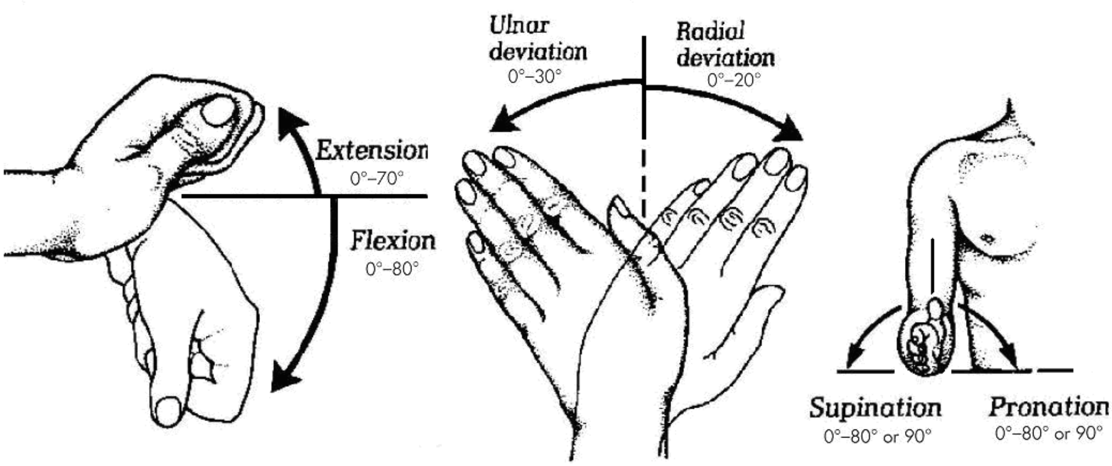


Figure 2.4: Wrist Movements with ROM (Modified from [54])

(b) Fingers Movements

There are three joints involved in the movement of each finger: the metacarpophalangeal (MP), proximal inter-phalangeal (PIP) and distal inter-phalangeal (DIP) joints. The ranges of motion of these three joints account for the functional movement of each finger. The movement of flexion and extension and abduction and adduction is shown in Figure 2.5.

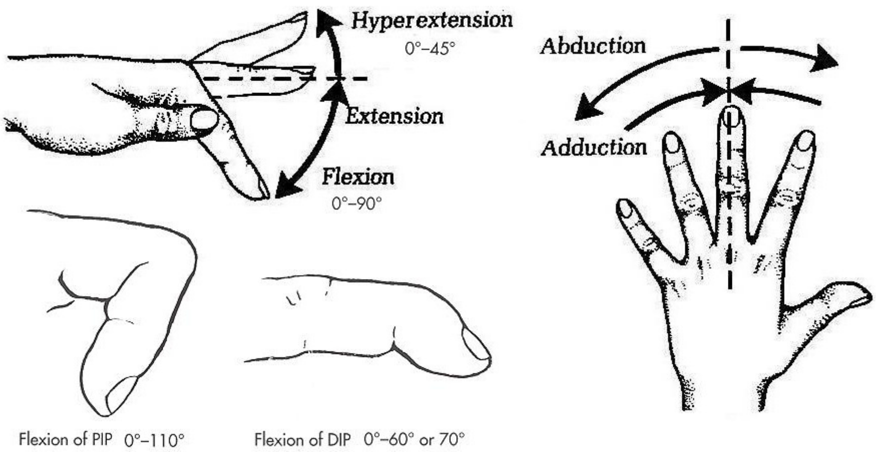
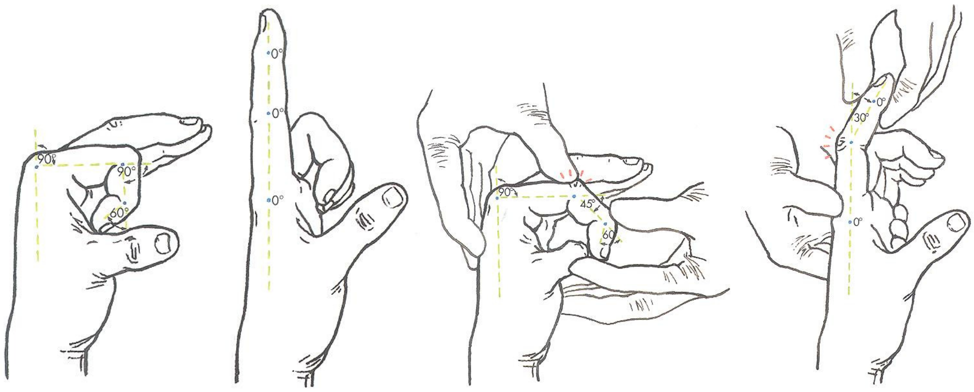


Figure 2.5: Finger Movements with ROM (Modified from [54])



(a) Total Active Motion (b) Total Passive Motion

Figure 2.6: Total Active Motion and Total Passive Motion Measurement [56]

These measurements depicted in Figure 2.6 can be used for assessing the general condition of the range of motion in a diseased finger with limited mobility. TPM represents the condition of the three small joints of the finger, and it may be affected by the problems of bone or soft tissue. TAM, in addition to TPM, also represents the condition of nerves and muscles.

(b) Thumb Movements

The thumb is the most important digit of the hand because of its ability to oppose the fingers as a result of its movable metacarpal. It is used in virtually all hand activities and constitutes an active half of the prehensile hand, playing a part in both power and precision grips. Its movements, its versatility and its stability are concerned in almost all skilled movements of the hand. It is controlled by 9 muscles, 5 intrinsic and 4 extrinsic, which adds to the versatility of its function [58].

The movements of the thumb comprise its carpometacarpal (CMC), metacarpophalangeal (MP) and interphalangeal (IP) joints. The human hand develops into a precise, nimble, and highly functional tool owing mainly to the CMC joint, which has a much more mobile range than other animal. The joint position is unique, and its movements are extremely complex [56].

Opposition, which is an essential function of the hand, is the combined movements of the thumb and fingers and increases the cup shape of the hand and adds precision, strength and stability to the grip. Figure 2.7 summarizes the different types of thumb movement.

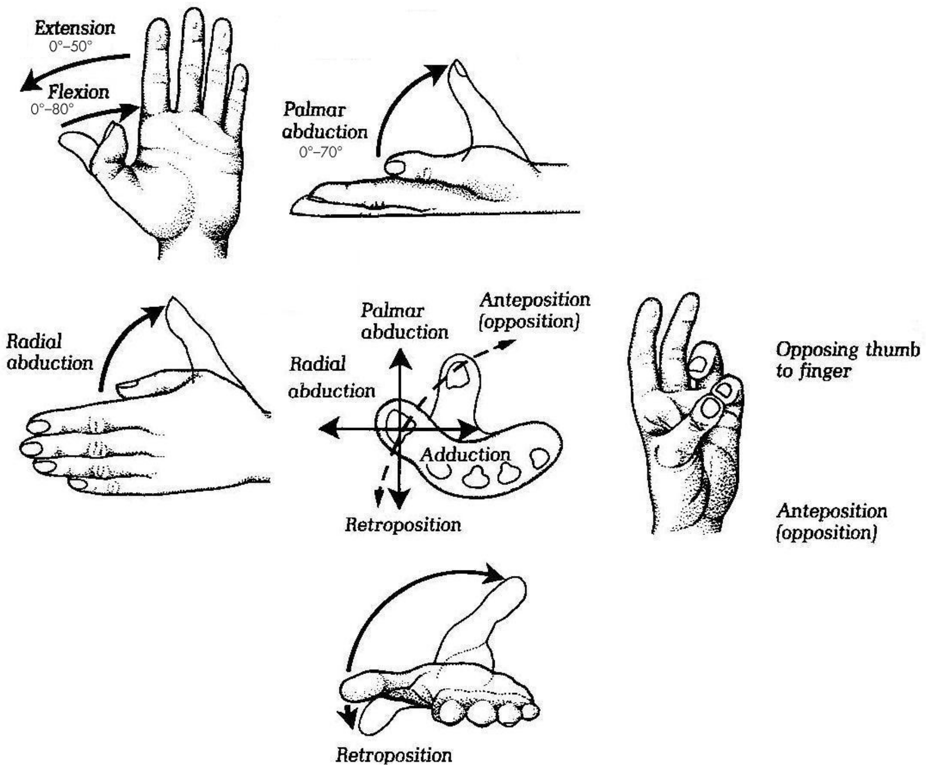


Figure 2.7: Thumb Movements (Modified from [54])

2.1.2 Functional Activities of the Hand

Human hand has 16 joints with more than 20 degrees of freedom (DOF). Therefore, it is necessary to determine how many DOF are necessary for a patient to perform the majority of everyday functional tasks.

The hand has a broad spectrum of functional activities associated with its musculoskeletal and sensory capabilities. According to daily life activities, social interactions, occupation, and psychology, the hand functions can be categorized into six headings [56]:

1) *Self-care*: includes self-feeding, dressing, and personal hygiene such as tooth brushing, hair combing, body bathing, and so forth. Independent patients are spared the intervention of other people in their daily life care.
2) *Occupational skills:* usually require some training and ensure a basic livelihood in society. For example, a secretary may operate a computer, workers use specialized tools, musicians play their instruments, and so forth. The recovery of occupational skills and resumption of work are important goals in functional reconstruction.
3) *Perception and processing of information:* in addition to being able to sense pain, temperature, touch and pressure, the upper limb and hand are exquisitely perceptive of position, sense and stereognosis, by which the form, texture, and solidity of objects can be discriminatory in the palmar digit tips.
4) *Defense and offense:* the hand can be shaped into a fist or a claw, as an aggressive tool. Alternatively, physical attacks may be countered with the ulnar border of the hand. In a broader sense, the hand can also hold a sword, spear, or gun, for offense or defense.
5) *Gestural expression:* the hand may make signals or symbolic gestures to express significance without speaking.
6) *Emotive touch:* the hand may caress with a gentle touch to fondle or express affection and love.

2.1.3 Functional Zones of the Hand

The five rays of the hand have individual importance for the entire functional hand repertoire, according to their strength, mobility, and relationship to the other fingers. In various functional activities, the five rays can be divided into three functional zones (see Figure 2.8), each of which customarily has a synergistic role stemming from the actions involved in handing objects.

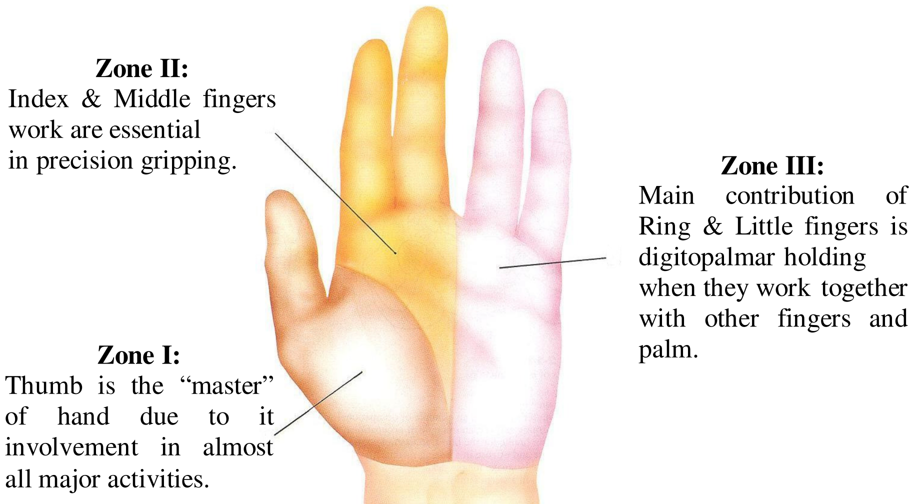


Figure 2.8: Functional Zones of the Hand [56]

1) *Functional zone I:* the first ray, the thumb with its metacarpal, is the "master" of the hand. It participates in almost all of the major hand activities, especially in the precision, power, and complexity of function, in cooperation with the other fingers.
2) *Functional zone II:* the second and third rays, the index and middle fingers with their metacarpals, are essential in precision gripping, separately or in conjunction with the thumb, owing to their dexterity and mobility. The thumb, index, and middle fingers, cooperating in precision gripping, are also called the dynamic tripod.
3) *Functional zone III:* the fourth and fifth rays, the little and ring fingers with their metacarpals, are major elements in digitopalmar holding, when cooperating with the other fingers and the palm. Together with the thumb and index finger, an adaptive power grip can be formed. Owing to this action, the little finger is important, and it should be functionally ranked next to the index finger.

In consideration of dynamic hand functions in regard to complexity, precision, and strength in holding and manipulating, classification under four major categories [56]: (1) simple handling, (2) precision grip, (3) digitoplalmar holding, and (4) complex manipulation.

1) Simple Handling

Simple handling activities are accomplished with only a simple motion of a finger or fingers, usually without the involvement of thumb opposition. Examples of patterns of simple handling include:

a) *Static Hook:* the muscles of the flexor digitorum superficialis and flexor digitorum profundus are kept in a contracted state, as when carrying a bag.

b) *Dynamic Hook:* an action involving only finger flexion, such as pressing a gun trigger.

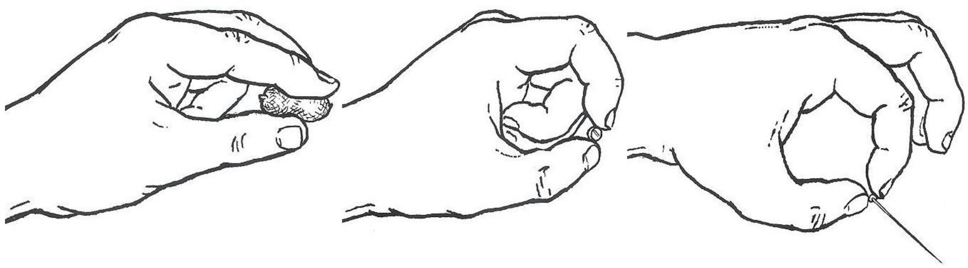
c) *Clamping:* an object such as a syringe is held by two adjacent fingers, closing with adduction and abduction toward each other.

2) Precision Grip

Characteristics of precision grip include the following: (1) the thumb is always involved, usually with opposition, (2) the object is relatively small and is held between the thumb and other finger or fingers (commonly, the index or middle finger or both are involved, and usually without use of the palm), (3) the action is generally precise and accurate rather than powerful.

According to the number and location of the fingers involved in opposition to the thumb in handling an object, precision grip can be considered under following categories:

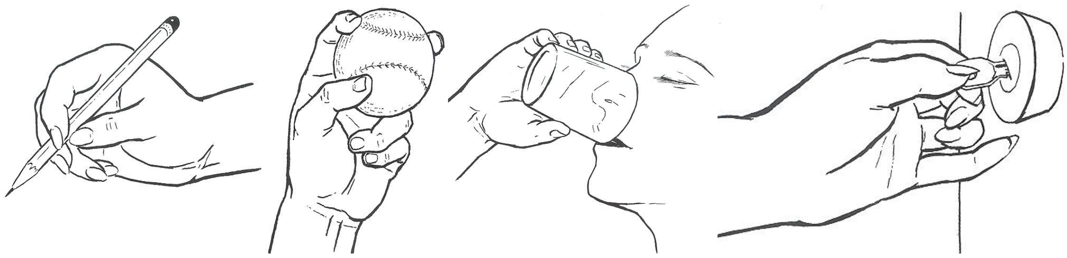
a) *Pulp-to-Pulp Pinch:* an object is held between the pulps of the thumb and one finger, in opposition to each other. In this pattern, the index or middle finger is most commonly used. The tip-to-tip pinch and nail-to-nail pinch should be classified within this category (see Figure 2.9), despite the fact that they may have a greater potential for accuracy and a small difference in pinch position.



(a) Pulp-to-Pulp Pinch (b) Tip-to-Tip Pinch (c) Nail-to-Nail Pinch

Figure 2.9: Examples of Pulp-to-Pulp Pinch [56]

b) *Tripod Pinch:* this pattern occurs with the radial three fingers: thumb, index, and middle, also named the dynamic tripod as shown in Figure 2.10(a). The middle finger joins in this pinch and adds an additional force to the object, forming a tripod, so that both stability and holding are provided, or grasping in preparation for throwing an object.



(a) Tripod Pinch (b) Five-Pulp Pinch (c) Lateral/Key Pinch

Figure 2.10: Examples of Precision Grip [56]

c) *Five-Pulp Pinch:* the ring and little fingers contribute more force and directions, resulting in a more stable and accurate hold as shown in Figure 2.10(b).

d) *Lateral/Key Pinch:* in this pinch pattern, the object is held between the pulp of the thumb and the radial side of the index finger as shown in Figure 2.10(c). The thumb is more adducted and less rotated.

3) Digitopalmar Holding

In digitopalmar holding, the object is placed in the palm and held between the palm and all other fingers, with or without the thumb. This category usually concerns the stable holding of large objects.

Position grip is the simple pattern of digitoplalmar holding. Common examples of the position grip including holding a walking stick or holding a banister as shown in Figure 2.11(a).

Power grip as shown in Figure 2.11(b) is the most specific and useful pattern of digitoplalmar holding. Characteristics of the power grip, which differ from the position grip in digitoplalmar holding, including the following observation:

a) The fingers are flexed tightly, pushing the object toward the palm.

b) The thumb participates in an opposing position with a force from the thenar muscle, to hold the object or, pushing through the phalangles of the index, middle, and ring fingers, to press the object toward the palm.

c) The fourth and fifth rays, especially the fifth ray at the very ulnar margin of the palm, have a principal role in the power grip. The hypothenar muscle provides palmar flexion with the fourth and fifth metacarpals, forming a torque with the thumb for the grip.

d) This action is usually used in handling comparably larger and heavier objects with relatively powerful manipulation.

(a) Position Grip (b) Power Grip

Figure 2.11: Examples of Digitopalmar Holding [56]

4) Complex manipulations

Complex manipulations are a highly developed category of functional activities of the hand, including special kinds of skills for daily life, occupation, or entertainment that are acquired through specific training. In complex manipulations, two or more patterns of activities usually occur at the same time or sequentially. All the patterns generally involve simple handling, precision grip, and digitopalmar holding. Examples may include the manipulation of surgical ties, chopsticks and the composite grip.

2.2 Hand Rehabilitation

Rehabilitation has been defined by the World Health Organization (WHO) as a progressive, dynamic, goal-oriented and often time-limited process, which enables an individual with an impairment to identify and reach his/her optimal mental, physical, cognitive and social functional level [59]. Enhancing quality of life is regarded as an inherent goal of rehabilitation services and programs given their focus on interventions to minimize the impact of pain and physical and cognitive impairment, and on enhancing participation in work and everyday activities. Rehabilitation helps the patient regain muscle strength, joint range of motion (ROM), balance, coordination endurance and functional mobility [60].

2.2.1 General Principles of Hand Rehabilitation

1) Functional Recovery

Functional recovery is more multi-functional and more influenced by rehabilitation [61]. It refers to improvement of independence in areas such as self-care and mobility. Recovery depends on the patient's motivation, ability to learn and family supports as well as the quality and intensity of therapy. Functional deficits are often referred to as disabilities and are measured in terms of functions such as activities of daily living (ADL). ADL should directly trained in order to improve functional recovery after stroke, implying that therapy needs to be focused primary on relearning functional skills that are relevant to individual patients [62].

Brain repair, adaptive reorganization, and compensatory strategies can all contribute to functional recovery of motor systems after brain damage. Animal experiments and human functional imaging studies clearly show that the injured brain changes its function with a complex pattern and variability across subjects and time. It is capable of functional reorganization that promotes functional recovery [63].

Functional recovery is enhanced when, after supervised rehabilitation training resulting in significant functional gains, persons with hemiplegia transfer these skills to their living environments and continue to use their impaired arm away from therapist supervision.

The observable stages of recovery of the hand are flaccidity, followed by little or no active movement, then mass grasping (all the fingers grasping at once), lateral prehension (holding between the side of the index finger and thumb), palmar prehension (holding between the thumb and first two fingers) and finally, individual finger movements [64].

The following scales describe hand function as tested shortly after a stroke [65]:

a) No active motion in digits.

b) Active flexion of all fingers in synergy only.

c) Active flexion and extension of all fingers in synergy.

d) Ability to extend index finger with all other in flexion.

e) Ability to bring thumb in opposition to the tip of the index finger.

f) Ability to oppose thumb to all fingers.

Generally, it can be assumed that the patients will not undergoing hand therapy until they have recovered at least some functionality in the muscles of their upper arm and wrist.

2) Intensity of Physiotherapy and Occupational Therapy

When attempting to determine factors that contribute to the improved functional outcomes that are associated with specialized stroke rehabilitation, the intensity of rehabilitation therapies is often cited as an important element. There is an evidence from neuro-imaging study show that increased intensity of rehabilitation therapies results in greater activation of areas associated with the function towards which this therapy is directed [66]. “Intensity” is usually defined as number of minutes per day of therapy or the number of hours of consecutive therapy. Evidence shows that greater intensity and frequency of focused therapy can improve functional outcomes [67].

However, intensity alone does not account for the differences between traditional stroke and task-specific rehabilitation. For example, it was reported that stroke patients who underwent a 3-week long program that consisted of 45-minute task-specific, upper limb training showed improvements in measures of motor function, dexterity, and increased use of the more affected upper limbs. And task-specific, low-intensity regimens designed to improve use and function of the affected limb have also reported significant improvements [68].

3) Repetitive Task-Specific Training Techniques

Task-specific activities and activities that are meaningful to the person have been shown to produce cortical reorganization and associated functional improvements [69]. It is aimed to improve skill in performing selected movements or functional tasks. Task-oriented training focuses on retraining tasks by taking into account the interplay of many systems, including the musculoskeletal, perceptual, cognitive and neural systems [70]. It is well established that task-specific practice is required for motor learning to occur. Task-specific sessions, e.g. thumb and hand movements, for as short as 15 minutes are also effective in inducing lasting cortical representational changes [43, 44].

Meta-analysis further indicates that physical and occupational therapeutic interventions are task-specific [62]. High-intensity and task-specific upper-limb treatment consisting of active, highly repetitive movements is one of the most effective approaches to arm- and hand function restoration [71, 72].

Optimal restoration of arm and hand motor function is essential for stroke patients to independently perform activities of daily living. Training ADL requires knowledge of the ‘nature’ of co-ordination deficits in functional tasks, and thus about the natural (i.e. physical) laws of coordination and control in the performance of such tasks [62].

4) Active Motor Relearning

Motor Relearning Programme (MRP) [68] focuses on accessing existing ‘motor programmes’, or preplanned patterns of movement, to relearn muscle activity functionally through ‘task-oriented’ goals. The emphasis is placed upon active patient participation, with guidance, instruction and various forms of feedback, until the correct movement is performed to solve the motor problem. The concept is all-encompassing, with an emphasis upon analyzing not only biomechanics, but behavior and lends itself to functionally meaningful environments in which re-learning takes place.

Three main strategies underlying the MRP are: (1) the elimination of unnecessary muscle activity, (2) feedback of information about performance and (3) practice. Initial therapist guidance is later superseded by patient-initiated active movements, which encourage the patient’s volitional movement control.

2.2.2 Robotic Therapy for Hand Rehabilitation

At present, most rehabilitation exercises are performed manually by physical or occupational therapists. The training is labor-intensive, and, therefore, training duration is usually limited by personnel shortage and fatigue of the therapist, not by that of the patient. The training sessions are shorter than required to gain an optimal therapeutic outcome, which is a major burden on both public and private healthcare systems. Standard multidisciplinary stroke rehabilitation requires one-to-one manual interactions with therapists. Treatment protocols entail daily therapy for several weeks, which makes the provision of highly intensive treatment for all patients difficult [73].

It will be beneficial to investigate a more cost-effective system that can take part of the job, perform some of the repetitive tasks in rehabilitation centers and reduce the need for a human attendant. With an automated robot-assisted device, the duration and number of training sessions can be increased, while reducing the number of therapists required per patient. One therapist may be able to train two or more patients in the future. Thus, personnel costs can be significantly reduced.

In the long term, the cost of daily care is reduced as it accelerates the rehabilitation progress and helps them return to work. Furthermore, the robotic device provides quantitative measures, thus, allowing the observation and evaluation of the rehabilitation process [74]. The automated process relieves therapists of the manual labor. Therefore, the training sessions can be longer and repeatable. As a result, the therapy is more efficient and the patients achieve their goals faster.

Robotic therapies show promise in providing safe and intensive rehabilitation to patients who have mild to severe motor impairment. Robotic devices can be used to provide rehabilitation that is of high-intensity, repetitive and task-specific in a manner that is similar to physical therapy.

Initial clinical studies of robotic therapy [26, 75, 76] suggested that additional therapy provided by a robotic device can improve motor recovery. Recent advances in technology have made the robotic therapy become possible. Robotic therapy has the advantages of being reliable, repeatable, and precise. This allows patients to be trained in accurate movement patterns for an unlimited time. Robotic therapy environments are also able to collect quantitative data about patient progress and response to treatment in order to monitor the recovery and help in developing an effective therapy plan [77]. A robotic therapist can eliminate unnecessary exertion by the therapist, deliver highly reproducible motor learning experience, quantitatively monitor and adapt to patient progress, and ensure consistency in planning a therapy program [78].

Robots hold great promise over traditional therapy. Specifically, robots can provide therapy over long time periods, in a consistent and precise manner, whilst accounting and adjusting for fatigue. It also has the potential to enhance the therapy beyond the abilities of the practitioner. Some unique contributions of robotic therapy versus conventional therapies are that robots can be used as valuable adjuncts to save time and energy for the therapist, making rehabilitation sessions more efficient, or to gain insights into the rehabilitation recovery process, and that rehabilitation protocols can be very precisely tailored to individual patients with only as much assistance provided as needed. In addition they can be interactive and if “gaming” technology is incorporated, it can be acted as an incentive for patients to participate more actively in their therapy.

With robotic devices, patients may achieve increased gains from rehabilitation treatment [79]. The clinical relevance of the findings is that robot-aided therapy is a promising new approach to rehabilitation of upper-limb motor control after stroke. For both sub-acute and chronic stroke patients, robot-aided therapy can improve motor control of the hemiparetic upper limb, perhaps even more than conventional therapy [79].

For optimal rehabilitation the exercises need to target four major functional components: finger range of motion, finger speed of motion, degree of independence (of finger fractionation) in coordination, and finger strength to perform a specific task. As well as actively engaging patients in life-like activities, robotic devices also provide the opportunity to quantify and evaluate the patient's performance. Sensors can be attached to the patients to measure the motion, and the sensor readings can be recorded, stored and evaluated by the system, through simple data mining and system programming. Interactive data with robotics can also improve the motivation of the patient towards the therapy by providing an engaging interface to the rehabilitation exercises and provide an important system of biofeedback to the patient.

2.3 State-of-the-Art of Hand Rehabilitation Device

Robotic devices have contributed significantly to automate labor-intensive training techniques, providing new tools for therapists and improved access to therapy for patients [80]. Robotic devices can be used to assist the patient in a number of circumstances. First of all, the robot can aid with passive range of motion to help maintain range and flexibility, to temporarily reduce hypertonia or resistance to passive movement. The robot can also assist when the patient has active movements, but unable to complete a movement independently. Robotics might be most appropriate for patients with dense hemiplegia, although robotics can be used with higher-level patients who wish to increase strength by providing resistance during the movement. Even though unassisted movement may be the most effective technique in patients with mild to moderate impairments, active-assisted movement (with robotic devices) may be beneficial in more severely impaired patients, especially during the acute and sub-acute phases when patients are experiencing spontaneous recovery [81]. The robotic devices rely on the repetition of specific movements to improve functional outcomes. While the majority of robotic devices focus on retraining of the upper extremity, specifically shoulder, elbow and wrist movements, researchers have begun to investigate the potential use of robotic devices for the fingers [82].

The development of robotic technologies in medicine is usually very expensive and needs a close technical/economic cooperation between medicine, engineering and manufacturers. In modern days, computers, smart sensors and actuators as well as many other special robotic devices are successfully used in several medical operations and applications. However, physicians are still resisting new developments because they are not prepared to hand over their specialized skills to automatic devices and/or processes. It should be made clear that the new medical apparatuses will not replace the physician, but assist them to perform more accurately and efficiently his/her jobs [83].

One major technical limitation of robots used for physical therapy is their inability to sense the response of the patient to treatment. Unlike its human counterpart, robots lack the cognitive capacity to prescribe, observe and alter treatment according to patient performance. Electromyography (EMG) biofeedback has been used with some success in traditional rehabilitative settings. However, this type of feedback has not been fully explored as a feedback sensor, which can provide the rehabilitation robot with information so as to improve the objectivity and efficiency of the rehabilitation task. The safety of the patient and the robot arm is another important technical issue in designing and building an intelligent robotic system for physiotherapy [84].

The hand rehabilitation system can also be divided into two groups: Exoskeleton-type and Non-Exoskeleton-type (Robotic Rehabilitation). Exoskeletons are mechatronic systems worn by a person in such a way that the physical interface permits a direct transfer of mechanical power and exchange of information [85]. Devices which are attached to the human and allow moving the hand in several degrees of freedom are called hand exoskeleton [86]. The robotics devices do not have to be worn by the user, so they do not have the same power or size constraints. The Exoskeleton-type system with the motors and mechanisms placed on the hand or forearm which in itself can limit their usability. This arrangement is undesirable and uncomfortable to the patients (they may have little or no strength and muscle control), as they need to bear the weight through the rehabilitation training.

2.3.1 Exoskeleton Systems

1) Hand Exoskeleton

The hand exoskeleton as shown in Figure 2.12 was developed for hand injuries at the University clinic of Ulm to improve therapy results and reduce cost of rehabilitation. It can be easily attached and also be adjusted to deformed and scarred hands. Four degrees of freedom are actuated bidirectional by the use of two Bowden cables and levers for each finger joint. The leverage of the exoskeleton supports independent flexion & extension in the MCP, PIP, and DIP joints and abduction & adduction in MCP joint. The force is transmitted through pull cables to the finger joints. The palm is free of mechanical elements and active bidirectional movement is possible. A sliding mode controller and sensor were incorporated to control the motion of the hand and measure the variation in forces applied respectively, which allows a fast and stable position control; trajectories can be followed with good accuracy.

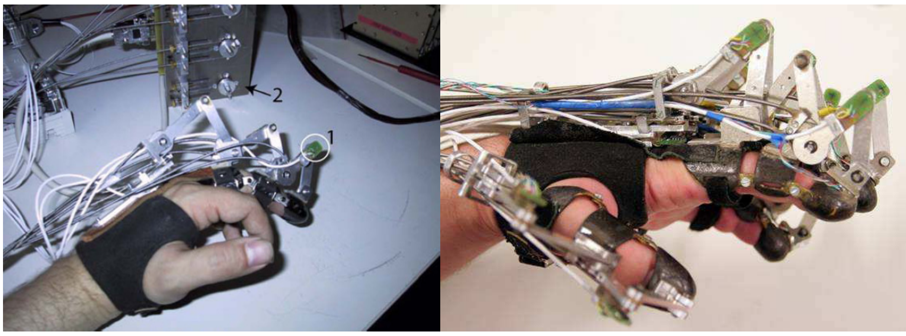


Figure 2.12: Hand Exoskeleton [86-89]

2) Gentle/G Grasp Robot Exoskeleton

The Gentle/G grasp assist unit as shown in Figure 2.13 is intended to work with the hardware and software of the Gentle/G robot for reach & grasp therapy retraining. The Gentle/G system shares the same frame, chair, shoulder support mechanism, elbow orthosis, exercise table, a large computer screen with speakers, a keypad and the Haptic Master robot. In addition the system incorporates a newly developed grasp robot exoskeleton with a connection mechanism to attach the user hand/arm to the Haptic Master. When used with the Gentle/G robot 3 active and 3 passive degrees of freedom are available to provide active, active assist or passive grasp retraining in combination with reaching movements in a reach-grasp-transfer-release sequence.

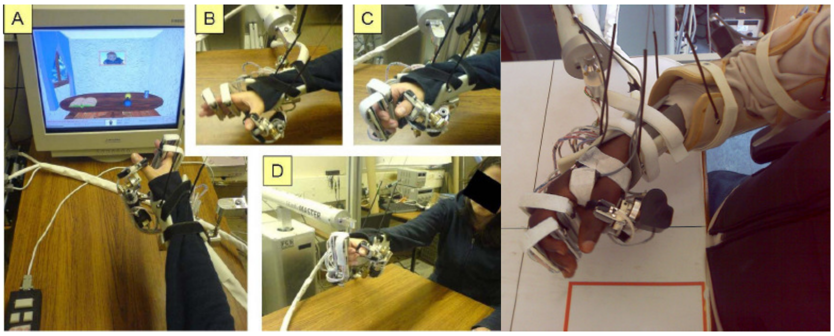


Figure 2.13: Gentle/G Grasp Assistance Robot [90-92]

3) EMG-controlled Exoskeleton

The EMG-controlled exoskeleton as shown in Figure 2.14 is designed to be adaptable and it is actuated by two servomotors. Flexion and extension motions are achieved with the presence of wires and springs. Based on EMG signals the system can "understand" the subject volition to move the hand and thanks to its actuators which can help the fingers movement in order to perform the task. However, the exoskeleton did not turn out to be easily wearable, adaptability of the plastic structure is hardly sufficient for the four fingers, and the exoskeleton does not allow a natural grasp movement.

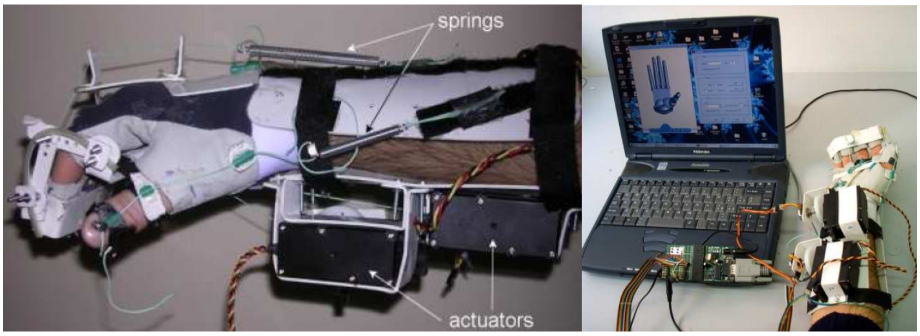


Figure 2.14: EMG-controlled Exoskeleton [93]

4) Orthotic Exoskeleton

The EMG controlled orthotic exoskeleton for the hand as shown in Figure 2.15 was developed at Carnegie Mellon University. It is actuated by pneumatic pistons which can provide assistive force to the user's fingers. The device has two actuators controlling the index finger flexion that can be used to perform a pinching motion against a fixed thumb.

The flexion of the PIP and DIP joints was produced by steel cable running along the front of each finger band and through to the backside of the hand. These cables were pulled by pneumatic cylinder acting in compression. The MCP flexion was achieved by a linkage mechanism. When the extension pneumatic piston pushed this link mechanism forward (distal), the MCP joint resulted in flexion. To achieve smooth repeatable motion and the passive abduction/adduction motion, a flexible coupling between the base-plate and first finger band made from a canvas-like cloth material was added. Small springs were used at all three joints to extend them passively. When the finger was at rest, the springs kept the finger at full extension, and the pistons worked against the spring forces during flexion.

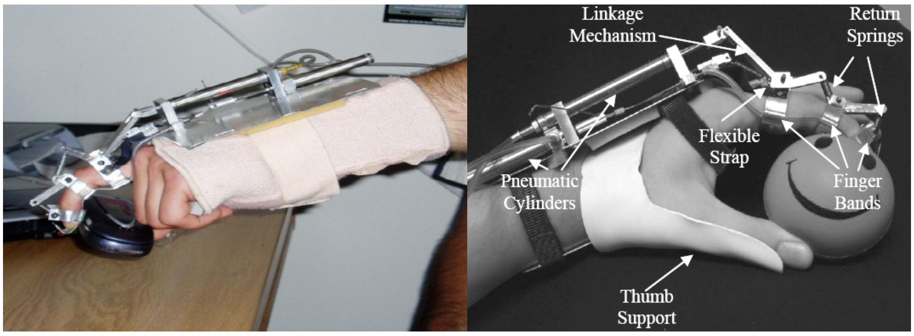


Figure 2.15: EMG Controlled Orthotic Exoskeleton [24, 94]

5) Rutgers Master II-ND Haptic Glove

The Rutgers Master II as shown in Figure 2.16 is a haptic interface for dexterous interaction with virtual environments, which is capable of controlling four fingers with one degree of freedom each. The glove provides force feedback up to 16 N each to the thumb, index, middle, and ring fingertips. Unlike CyberGrasp commercial haptic gloves, the direct-drive actuators make unnecessary cables and pulleys, resulting in a much more compact and light structure. Four pneumatic pistons inside the palm are actuating the fingers, which allow a simpler construction but prevent interaction with real objects.

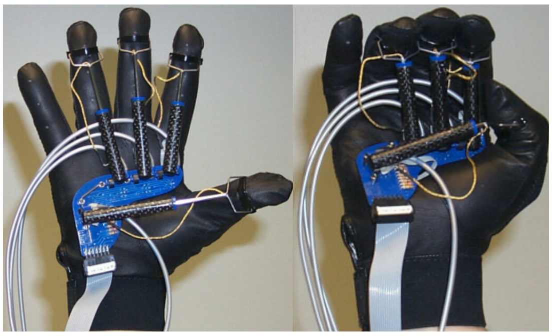


Figure 2.16: The Rutgers Master II [95-97]

2.3.2 Robotics Systems

1) Hand Motion Assist Robot

The hand motion assist robot as shown in Figure 2.17 is a virtual reality-enhanced hand rehabilitation support system with a symmetric master-slave motion assistant for independent rehabilitation therapies, which allows the impaired hand of a patient to be driven by his or her healthy hand on the opposite side. The hand motion assist robot is designed to support the flexion/extension and abduction/adduction motions of fingers and thumb independently as well as the opposability of the thumb. Moreover, it is designed to support a combination motion of the hand and the wrist. This system consists of 18 DOFs and a lateral symmetric master-slave motion assistant system joined with a virtual reality (VR) environment. It is designed to support a combination motion of the hand and the wrist, and train the opposition between the thumb and index finger for pinching.

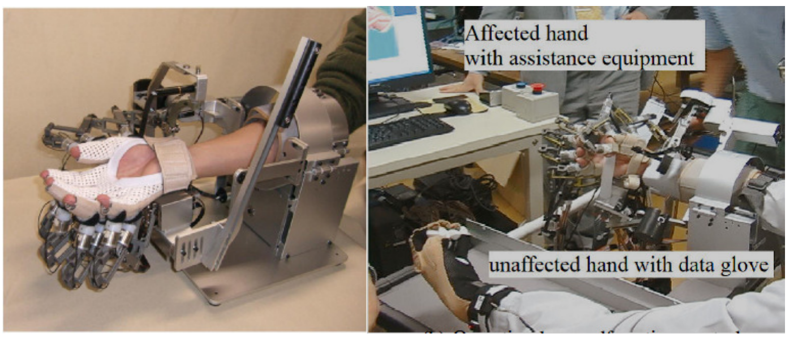


Figure 2.17: Hand Motion Assist Robot [28, 98-100]

2) Hand-Wrist Assisting Robotic Device (HWARD)

The Hand-Wrist Assisting Robotic Device (HWARD) as shown in Figure 2.18, was guided by neurobiological principles of motor learning, which is a robotic therapy device may help people regain strength and normal use of affected hands long after a stroke. HWARD can assist grasping and releasing movements while simultaneously allowing the subject to feel real objects during therapy. This feature is achieved by keeping the palmar surface of the hand unobstructed so that objects may be placed into the hand.

HWARD provides assistance in a pattern that combines wrist extension with hand grasping, and wrist flexion with hand release. This combination of joint movement serves to increase grasping force. The 3 DOFs device is pneumatically-actuated and backdrivable. It sites actuators alongside the little finger which has the advantage of not giving any visual obstruction in normal reach and grasp movements. However, it is not possible to train each finger independently.

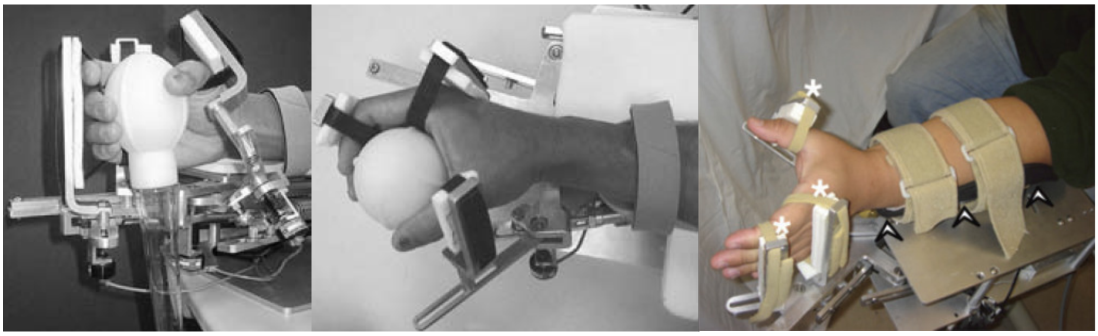


Figure 2.18: The Hand-Wrist Assisting Robotic Device (HWARD) [101, 102]

3) Haptic Knob

The Haptic Knob as shown in Figure 2.19 is a two degree-of-freedom (DOF) device to train opening and closing movement of the hand as well as the interaction with knobs. This design consists of two parallelogram structures, was developed to train basic hand functions, such as opening and closing of the hand and coordination between grasping and wrist rotation, which are necessary for most activities performed with the hand. The mechanical design offers the possibility to adapt the interface to various hand sizes and finger orientations, and to right or left-handed subjects. The interaction with the subject is measured by means of position encoders and four force sensors located close to the output measuring grasping and insertion forces. Various knobs can be mounted on the interface, including a cone mechanism to train a complete opening movement from a strongly contracted and closed hand to a large opened position.

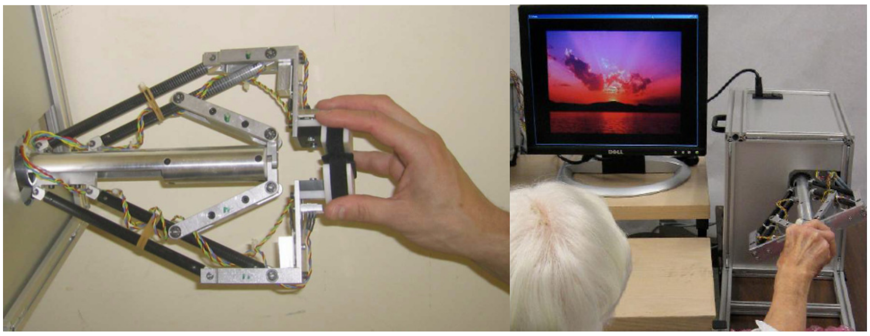


Figure 2.19: Haptic Knob [103-106]

4) Haptic Interface for Finger Exercise (HIFE)

The Haptic Interface for Finger Exercise (HIFE) as shown in Figure 2.20 is based on a tendon-driven transmission system, has been developed to train extension/flexion movements of one finger, suitable for finger exercise. However, the use of this system is limited to one finger only. Mechanism has two active DOFs and two passive DOFs at the finger attachment, which is actuated by two ironless-rotor brushed dc motors. It was constructed as a lightweight mechanism with a small workspace that wraps a finger and can generate forces up to 10N suitable for finger exercise. This device can exert forces only at the finger tip and may not ensure coordinated motion of the fingers.

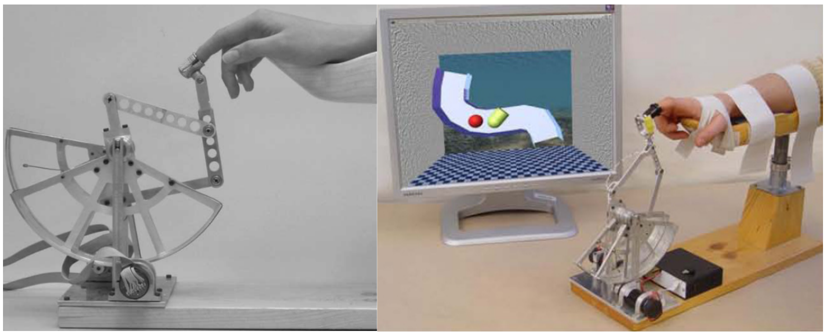


Figure 2.20: Haptic Interface for Finger Exercise (HIFE) [107-110]

5) HandCARE

HandCARE as shown in Figure 2.21 is a cable-actuated rehabilitation system, in which each finger is attached to an instrumented cable loop allowing force control and a predominantly linear displacement. The device can help patients train functions such as finger flexion and extension, coordination between the fingers, and independence of each finger, which are necessary for most activities performed with the hand. The device is designed based on biomechanical measurements, can assist the subject in opening and closing movements and can be adapted to accommodate various hand shapes and finger sizes. Main features of the interface include a differential sensing system, and a clutch system which allow independent movement of the five fingers with only one actuator.

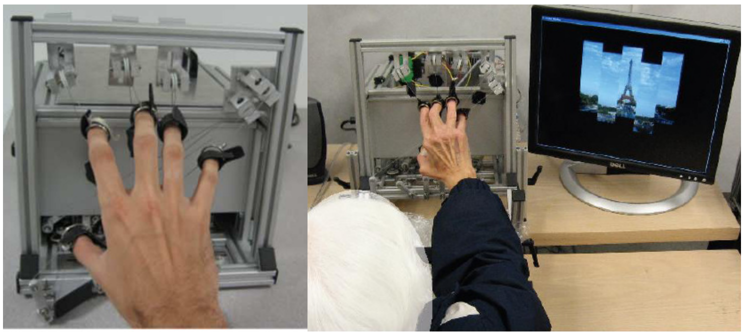


Figure 2.21: HandCARE [40, 111, 112]

6) Interactive Robot

As shown in Figure 2.22, the interactive rehabilitation robot for hand function training on persons after stroke could provide continuous passive training, continuous and interactive EMG-driven training, and EMG-triggered trainings for thumb movements. The robot was designed to help subjects to practice finger flexion and extension to simulate hand opening and grasp. The robot also can quantitatively record the parameters for monitoring the task performance, such as the finger force, finger positions, EMG signals from the muscle of interest.

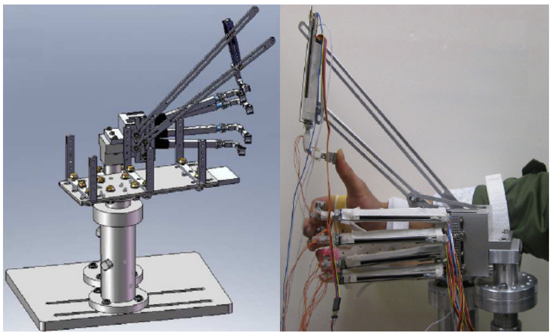


Figure 2.22: The Interactive Rehabilitation Robot [113]

Based on the review of the existing hand rehabilitation devices, a comparison of different systems have been shown in Table 2.6. It summarizes the main characteristics of the hand rehabilitation systems, namely the DOF (active + passive), location of the hand, actuators/power transmission method, the target group of patients, performance and its limitations.

Table 2.6: Overview of the Hand Rehabilitation Systems

Active Finger Movements	Name	DOF (Active+ Passive)	Locations	Actuators/ Power Transmission	Target Group	Performance	Limitations
Fingers move individually	Hand Exoskeleton [86-89]	20	Thumb (4) Fingers (4 each)	DC motors/ Bowden cable and gear drive	Hand injury and/or post-stroke	Control the movement of fingers following the recorded trajectories	Bulky and heavy
	Hand Motion Assist Robot [28, 98-100]	18	Wrist (2) Thumb (4) Fingers (3 each)	Servo motors/ Linkage mechanism and gear drive	Post-stroke	Virtual reality enhanced teleoperation by patient self-motion control	Does not allow a natural grasp movement due to the orientation of the device
Fingers move together	Gentle/G Grasp Robot Exoskeleton [90-92]	3+3	Thumb (1) 4 fingers (2)	DC motors/ Worm and pinion drive	Post-stroke & Brain injury	Retrain hand movement thru reach & grasp therapy in combination with reaching movements in a reach-grasp-transfer-release sequence	Does not support individual finger motion. Impossible to train each finger independently.
	HWARD [101, 102]	3	Wrist (1) Thumb (1) 4 fingers (1)	Pneumatic actuator/ Pneumatic	Post-stroke	Hand motor therapy to retrain grasping and releasing of real objects	
	EMG-controlled Exoskeleton [93]	2	Thumb (1) 4 fingers (1)	Servo motors/ Wire	Post-stroke and SCI	Based on EMG signals to "understand" the subject volition and move the fingers to perform the task	
	Haptic Knob [103-106, 114]	2	Wrist (1) 5 fingers (1)	DC motors/ Belt and pulley	Post-stroke	Gradually recover the ability to open and close the hand and manipulate knobs	
One Finger	Orthotic Exoskeleton [24, 94]	2+1	Index finger (2+1)	Pneumatic actuator/ Cable drive & linkage mechanism	SCI	Perform a pinching motion against a fixed thumb controlled by the user's EMG signals	Limited to one finger only. Does not support individual finger motion. Does not allow a natural grasp movement.
	HIFE [107-110]	2	Index finger (1)	DC motors/ Tendon-driven	Post-stroke	Haptic interface for finger exercise and virtual rehabilitation	
Fingertip	HandCARE [40, 111, 112]	5	Thumb (1) Fingers (1 each)	DC motors/ Cable drive and belt	Post-stroke	Virtual reality training on functions of finger flexion/extension, coordination between the fingers, and independence of each finger	No interaction with real objects. Does not support individual joints of each finger. No coordinated motion of the fingers
	Interactive Robot [113]	5	Thumb(1) Fingers (1 each)	Linear actuators/ Direct-drive	Post-stroke	Provide continuous passive training, continuous and interactive EMG-driven training, and EMG-triggered trainings to simulation the hand opening and grasps	
	Rutgers Master II-ND Haptic Glove [95, 96, 115]	4	Thumb (1) Fingers (1 each, except small finger)	Pneumatic actuator/ Direct-drive	Post-stroke	Virtual reality based exercises train finger range of motion, finger flexion speed, independence of finger motion and finger strength	

These devices can be divided into four groups based on the active finger movements. The first type of device is designed to train the fingers individually as they support individual joints of each finger, so they consist of large number of DOFs. The hand exoskeleton [86-89] with 20 DOFs focuses on support of the rehabilitation process after hand injuries or strokes. Four degrees of freedom are actuated bidirectional by the use of two Bowden cables and levers for each finger joint. The force is transmitted through pull cables to the finger joints. The palm is free of mechanical elements and active bidirectional movement is possible. The hand motion assist robot [28, 98-100] with 18 DOFs is a virtual reality-enhanced hand rehabilitation support system with a symmetric master-slave motion assistant for independent rehabilitation therapies, which allows the impaired hand of a patient to be driven by his or her healthy hand on the opposite side. It is designed to support a combination motion of the hand and the wrist, and train the opposition between the thumb and index finger for pinching. However, it does not allow a natural grasp movement due to the orientation of the device.

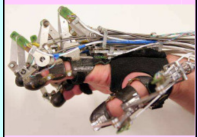
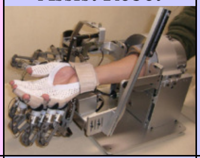
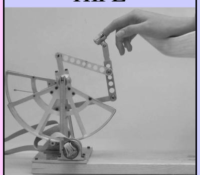
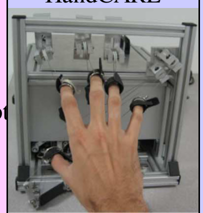
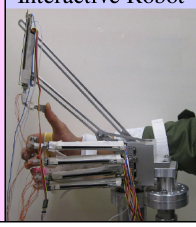
The second group of device is designed for all four fingers combined and preformed together as one single unit, so they usually consist of small number of DOFs. Therefore, these devices would not perform a normal/natural hand function as they do not allow the motion of individual fingers. The Gentle/G grasp assist robot [90-92] with 3 active and 3 passive DOFs are available to provide active, active assist or passive grasp retraining in combination with reaching movements in a reach-grasp-transfer-release sequence. The system incorporates a newly developed grasp robot exoskeleton with a connection mechanism to attach the user hand/arm to the Haptic Master. The Hand-Wrist Assisting Robotic Device (HWARD) [101, 102] with 3 DOFs can assist functional grasping and releasing movements of the stroke-impaired hand. HWARD can assist repetitive grasping and releasing movements while allowing the subject to feel real objects during therapy. The device HWARD sites actuators alongside the little finger which has the advantage of not giving any visual obstruction in normal reach and grasp movements. However, it is not possible to train each finger independently. The EMG-controlled exoskeleton [93] with two DOFs is designed to be adaptable and it is actuated by two servomotors. Based on EMG signals the system can "understand" the subject volition to move the hand and thanks to its actuators can help the fingers movement in order to perform the task. The Haptic Knob [103-106] is a two DOFs device to train opening and closing movement of the hand as well as the interaction with knobs. This design consists of two parallelogram structures, was developed to train basic hand functions, such as opening and closing of the hand and coordination between grasping and wrist rotation, which are necessary for most activities performed with the hand.

The third group of devices is designed for one or two finger only, it neither supports individual finger motion nor allows a natural grasp movement. The EMG controlled orthotic exoskeleton [24, 94] is actuated by pneumatic piston which can provide assistive force to the user's fingers. It has two actuators controlling the index finger flexion that can be used to perform a pinching motion against a fixed thumb. The Haptic Interface for Finger Exercise (HIFE) [107-110] is based on a tendon-driven transmission system, has been developed to train extension/flexion movements of one finger, suitable for finger exercise. However, the use of this system is limited to one finger only. This device can exert forces only at the finger tip and may not ensure coordinated motion of the fingers.

For the fourth group of device, their mechanisms are attached to the fingertips, so the device is capable of controlling four fingers with one degree of freedom each. Therefore, these devices do not allow the motion of individual fingers, and it can exert forces only at the finger tip and may not ensure coordinated motion of the fingers. HandCARE [40, 111, 112] is a cable-actuated rehabilitation system with 5 DOFs, in which each finger is attached to an instrumented cable loop allowing force control and a predominantly linear displacement. The device can help patients train functions such as finger flexion and extension, coordination between the fingers, and independence of each finger, which are necessary for most activities performed with the hand. The interactive rehabilitation robot [113] (with 5 DOFs) for hand function training on persons after stroke could help subjects to practice finger flexion and extension to simulate hand opening and grasp. The Rutgers Master II [95-97] is a haptic interface for dexterous interaction with virtual environments, which is capable of controlling four fingers with one degree of freedom each. Four pneumatic pistons inside the palm are actuating the fingers, which allows a simpler construction but prevent interaction with real objects.

As shown in Table 2.7, current hand exoskeletons are not based on load-free design, with the motors and mechanisms placed on the hand or forearm which in itself can limit their usability. This arrangement is undesirable and uncomfortable to the patients (they may have little or no strength and muscle control), as they need to bear the weight through the rehabilitation training. Compared with the exoskeleton-type devices, the robotic rehabilitation device (non-exoskeleton-type) do not have to be worn by the subject and the robotic devices do not have the same power or size constraints.

Table 2.7: Hand Exoskeleton Vs Robotic Rehabilitation

Active Finger Movements	**Name /Device**	**DOF (Active + Passive)**	**Locations**	**Name [Ref] /Figure**	**DOF (Active + Passive)**	**Locations**
	Exoskeleton-type			**Robotic Rehabilitation (Non-Exoskeleton-type)**		
Fingers move individually	Hand Exoskeleton 	20	Thumb (4) Fingers (4 each)	Hand Motion Assist Robot 	18	Wrist (2) Thumb (4) Fingers (3 each)
Fingers move together	Gentle/G Grasp Robot Exoskeleton 	3+3	Thumb (1) 4 fingers (2)	HWARD 	3	Wrist (1) Thumb (1) 4 fingers (1)
	EMG-controlled Exoskeleton 	2	Thumb (1) 4 fingers (1)	Haptic Knob 	2	Wrist (1) 5 fingers (1)
One Finger	Orthotic Exoskeleton 	2+1	Index finger (2+1)	HIFE 	2	Index finger (1)
Fingertip	Rutgers Master II-ND Haptic Glove 	4	Thumb (1) Fingers (1 each, except small finger)	HandCARE 	5	Thumb (1) Fingers (1 each)
				Interactive Robot 	5	Thumb (1) Fingers (1 each)

2.4 Clinical Evaluation of Hand Function

2.4.1 Evaluation of Hand Functionality

Hand functionality is defined as the level of the functional ability to grasp and manipulate different objects (e.g. grasping a glass of water for drinking, grasping and turning the key to open the door, and grasping and holding a pen to write) [116]. Grasping and manipulation tasks involve finger motion, strength/force, hand dexterity and so on.

Grasping requires an exquisite coordination of finger motion and forces. Due to the complex biomechanical and neural architecture of the hand, several complementary approaches have been used to improve our understanding of how the hand is controlled [117]. The coordination of finger motion and forces has been studied directly using behavioral tasks such as object hold [118-121].

When manipulating a handheld object, for example when drinking from a glass, one needs to apply sufficient grip force to prevent the glass from slipping out of the hand. In addition, one need to control the total torque exerted by all fingers such that the glass remains either vertical (in this case the torque magnitude about the point of thumb contact should equal zero) or at a controlled angle that is suitable for drinking and preventing the liquid from being spilled. Usually, the requirements for grip force stabilization allow for some laxity, while the requirements for total torque production are highly specified. As in the example of drinking from a glass, the grip force needs only to be larger than the slip threshold and smaller than the force that would break the glass. In contrast, the torque applied to the glass needs to be precisely controlled since any error will lead to rotation of the glass and spilling of the liquid [122].

During precision grip in which a load is held by adduction of the tips of the forefinger and thumb, grip force is accurately scaled to prevent slip without crushing the object or using a force that is unnecessarily high and may lead to accelerated muscle fatigue [123]. When a load is to be lifted, the motor program for the grip force estimates the load force needed on the basis of previous experience, and the grip force then becomes closely coupled temporally with the load force [124]. Knowledge of the grip force distribution during grasping with functional force is needed for biomechanical research [125], and also for evaluating hand function [126].

The ability to produce, maintain, and regulate finger force is necessary in the performance of many everyday activities, such as lifting a glass or grasping a doorknob. Successful object manipulations are based on the application of forces that are sufficiently large to prevent slips but are not excessive, preventing fatigue and damage of the lifted object [127]. For accurate manipulation, both the force magnitude and the force direction have to be specified and stabilized against possible internal and external perturbations [128].

Pressing and gripping tasks with several fingers have been studied to a much larger extent than torque-production tasks. In these tasks, however, the fingers act as agonists; i.e., the mechanical effects of their actions are simply summed up. The following three main phenomena have been observed: 1) force sharing – the total force is shared among the fingers in a specific manner [129-131]; 2) force deficit – the maximal force produced by a given finger in a multi-finger task is smaller than the force generated by this finger in a single-finger task [131-133]; and 3) enslaving – fingers that are not required to produce any force by instruction are involuntarily activated [131, 134-136].

Hand functionality also depends on the ability to perform different grips. The ability to grasp an object precisely between the tips of the index finger and thumb is an integral part of our motor repertoire and enables us to perform a wide range of complex manipulative movements when using tools [137]. Impairments in fine motor performance of the hand are often characterized by a diminished ability to perform a precision grip with the thumb and the index finger [138]. Manual tasks are organized and controlled by the nervous system. Successful manipulation requires the ability both to predict the motor commands required to grasp, lift, and move objects and to predict the sensory events that arise as a consequence of these commands [139].

The information on the properties of the object itself (shape, size, texture, etc.) and on the object's relationship to the body (its orientation and position in the workspace), but also on the current configuration of the body; and information derived from former experience and the context of the action may also be important [140]. Investigate function recovery in terms of joint range of motion, timing (phases), angular velocity, acceleration and dexterity in the execution of tests reproducing real life demands.

2.4.2 Measurement of Hand Strength

1) Electromyography (EMG)

Electromyography (EMG) is an experimental technique concerned with the development, recording and analysis of myoelectric signals. Myoelectric signals are formed by physiological variations in the state of muscle fiber membranes [141].

Recordings of muscle action during movement are useful for analyzing which muscles and at what times they are active. EMG recordings can be obtained with either surface mounted electrodes or indwelling fine-wire electrodes. Surface electrodes are commercially available in various sizes and are used to gather muscle group activity or information from larger superficial muscles. When information about a specific muscle, a small superficial muscle, or a deep muscle is desired, indwelling fine-wire electrodes must be used.

The EMG signals are very small, and the interference from noise is large. Motion artifacts are specifically problematic because the wires are moving in the variable electromagnetic field. In order to minimize motion artifacts preamplifiers, being very small, to amplify the signal for about two to three orders of magnitude should be used as close as possible to recording electrodes. The frequency content of EMG signals is up to about 1500 Hz; however, the maximum power is at much lower frequencies (≈ 200Hz). This information is relevant for selection of the sampling rate when collecting EMG. Typical cut-off frequency for EMG is at 1 kHz, but the actual decision based on the analysis required.

EMG signals can be transmitted from electrodes to a computer for storing and analysis by using wires or radio-frequency wireless communication. Electrodes and preamplifiers can be directly connected to amplifiers and recording devices by cable. Cabled systems provide reliable data and clean signals. Mechanically, cabled systems are simple. It is important to use shielded cables to reduce movement artifacts. Cabled EMG amplifiers should have optical or transformer isolation as a safety precaution, to ensure those subjects cannot be injured from the EMG testing device [142].

Surface electromyography (sEMG) signals from flexor digitorum superficialis (FDS) and flexor carpi ulnaris (FCU) were successfully measured and were used in real time as a direct biocontrol to manipulate a simple geometric computer model of the finger and wrist joints. A direct relationship was observed between the RMS sEMG and the motion of the finger and wrist of the computer models. sEMG signals from FDS and FCU can be used as a direct biocontrol to control the motion of the finger and wrist joints in applications, which do not require a very high accuracy [143].

Surface electrodes are less invasive and provide diffused but more global signals. With the current level of understanding in neuroscience, it is easier to understand the "intent" of the signals recorded from muscles (the neural signals arriving at muscles must be used to contract muscle fibers) than to decode the "intent" of individual neurons in the cortex. For these reasons, surface muscle electrodes have been one of the most popular techniques used thus far as the control signals for exoskeletons and prosthetics. Muscle signals from weakened muscles or from the stump are ideally gathered and amplified for control.

However, the relationship between the neural signal arriving at the muscle (called muscle activation) and the muscle force or position is not known. One of the common approaches is to simply set a linear (or other simple) mapping between the muscle activation and the force of the robotic joints and have the user learn this mapping. This is a reasonable task for healthy subjects to complete for a small number of degrees of freedom. However, it is difficult to learn this unnatural mapping and to control any more than one or two degrees of freedom. Thus, the biggest challenge lies in achieving the control of high DOFs (such as in the human hand) in an easily learnable format [144].

There are various ways of gaining information on grip strength; they can be classified in different groups: Data can be obtained indirectly from surface electrodes applied to the muscles in the forearm responsible for finger actuation. The results obtained in this way are limited by several factors: The electrodes can slide with the skin relative to the muscle, and the resultant electromyographic signals depend on the posture of the upper extremity [145].

There are many benefits in using sEMG signals in therapy and rehabilitation robotics.

Firstly, sEMG signals allow for measurements of muscular performance or atrophy, hence it is a direct representation of the health of a muscle. This allows therapists to compare motor patterns between a normal person and a patient, allowing better diagnosis and hence, choice of training or rehabilitation methods, activities or exercises for the patient to perform.

Secondly, the speed and continuity with which the information about muscle activation and relaxation through sEMG signals is provided to the therapist and patient is a huge advantage over just visual and physical inspection of the muscles. sEMG biofeedback can be instantaneous while manual inspection by the therapist can take at least a few seconds.

Thirdly, sEMG signals can give the intention of movement of a patient, even though the external load is too heavy for the patient to move his limbs or when his muscles are not strong enough to do so. This has been used extensively in control of prostheses, where a prosthetic hand device detects the intention of the user to perform a certain motion and performs trajectorial motions to form the task. However, sometimes, the signal acquired may not be from the corresponding muscle related to that motion due to amputation and the motion is based on another muscle. Hence, training is required for the patient to effectively use the prostheses.

Lastly, sEMG signals can be used to improve the efficiency of rehabilitation robotics [9]. For example, the signals can be used as a control input to adjust the amount of assistance or resistance necessary to enable a patient to perform a certain motion. Literature states that passive movement is useful when the patient has not yet been able to generate enough force in the muscles to cause movement of the limb, but that it will not restore strength as effectively as when a patient is performing active or resisted movement.

However, the sEMG signals derived from the muscle may be masked by activity from neighboring muscles which are responsible for other functions. For example, if a patient is performing exercises on finger flexion, flexion or rotation of the wrist will cause sEMG activity to be detected even if the patient is unable to activate his flexor digitorum superficialis muscles to flex his fingers. This will give a false representation of muscle strength which is a disadvantage and limitation of sEMG.

2) Grip Strength Measurement [51]

Grip and pinch strength have been shown as the most important factors related to hand function. It is noted that grip and pinch strength along with ROM measurements are able to provide a robust alternative to detailed biomechanical measures with the additional benefit in terms of cost and time [51].

Testing of grip force (either on the whole hand grip or pinch grip between thumb and index finger) may be particularly useful, because the control of grip force is a critical feature of all actions between the hand and the object, and hence grip force may become a prognostic indicator.

Individuals with stroke compared to healthy individuals commonly produce inefficiently elevated grip forces while performing simple daily tasks [123].

a) Power grip

Power grip strength can be reliably assessed with the dynamometer on the condition that calibration of the instrument is maintained. The dynamometer has five handle positions, each of which influences the strength of grip.

The testing position is as follows: shoulder adducted, elbow flexed to 90 degrees, forearm in neutral rotation, and wrist between 0 to 30 degrees of extension and in slight utnar deviation. The, second handle position was recommended as the test position in 1978 by the 'Clinical Assessment Committee of the American Society for Surgery of the Hand'. The test is performed three times with a short rest period allowed between readings so that the result is not affected by fatigue. The average of the readings is then recorded.

b) Pinch grip

Pinch grip strength is assessed with a pinch gauge which assesses (1) tip-to-tip pinch between the thumb and index finger (weakest pinch), (2) lateral pinch where the thumb is clasped against the radial side of the index finger (strongest pinch grip) and (3) three-jaw chuck where the pulp of the thumb is pinched against the pulps of the index and middle fingers. As for power grip, the test is repeated three times and the average reading is recorded.

2.5 Gaps in the Existing Research

Review of the state of the art reveals that there are several issues that needed to be addressed in the field of robotic assisted hand rehabilitation.

2.5.1 Hand Rehabilitation

The understanding of normal hand functions is definitely useful to the proposed research work, as the ultimate goal of the hand rehabilitation is to regain the hand function as normal as possible. Two groups of subjects are of main concern in the present work on hand rehabilitation: patients with spinal cord injury (SCI) and those after stroke.

It is well-known that a SCI at the cervical level results in tetraplegia, the loss of hand and upper limb function with impairment or loss of motor and/or sensory function. Many stroke victims regain their abilities for activities of daily living, but nevertheless have quantitative limitations, such as reduced speed and inaccuracy, and certain limitations in individual finger movements often persist.

Most of the outcome measures after SCI and stroke often based upon clinical ordinal scales, which are still preferred and widely used in rehabilitation centers. Also, many clinical methods used are based on subjective and qualitative assessments made by therapists, which highly depends on their experience. Small changes or variations following injury are often undetected.

The assessment of hand function is therefore important for the diagnosis and evaluation of rehabilitation process in patients suffering from neuromuscular diseases, central nerves system injury, or hand injury. Any objective and reliable measurement is useful to assess and validate the outcome of the rehabilitation treatment. The measured data can be used to monitor and quantify the rehabilitation progress of a patient over a series of therapy stages. To evaluate the effects of a therapeutic method, an appropriate assessment procedure is also needed to provide objective, quantitative and reliable measurements. Therefore, there is a need for systematic methodology for objective and quantitative assessment of hand function to diagnose the functional state of a patient and to evaluate the progress of therapy.

2.5.2 Design of Rehabilitation Device

Many studies have shown that robotic devices can be used to provide rehabilitation that is of high-intensity, repetitive and task-specific in a manner, which is similar to physical and occupational therapy. With the devices, the duration and number of training sessions can be increased, and the number of patients attended by each therapist can be reduced, if compared with the traditional, manually assisted movement training supervised by therapists currently at most rehabilitation centers.

Through the study and review on the existing hand rehabilitation devices outlined in Section 2.4, it is found that the current systems have several limitations. First of all, most of the robots can only provide simple grasping only. All four fingers are combined and preformed as one unit in most of robotics systems, except Hand Exoskeleton for one full finger motion. As for VR-Enhanced Hand Exoskeleton and Two-Finger Hand Exoskeleton, they are designed for one or two fingers only, but not for the all the five fingers and wrist motion. Therefore, these devices would not perform a normal hand function. Secondly, most of the robots are not load-free design. The motors and mechanism are placed on the hand or forearm, which is undesirable and uncomfortable to the patients, as they need to carry the weights through the rehabilitation training. Thirdly, most of the robots are assisted by a position control, which lacks bio-feedback (e.g. EMG signals) to provide any force control, except the EMG-Controlled Exoskeleton (which is based on FDS and FPL only). Lastly, most of the robots cannot support functional activities of daily living (ADL) tasks, which are important for improvements in ADL of real life and reduction of impairments.

In conclusion, there is a need for a hand rehabilitation system that can be designed to integrate robotics, mechatronics and information technology to develop an adaptive robotic system to overcome the limitations mentioned above. It could be a difficult but valuable task.

2.5.3 Assessment/Measurement of Hand Strength and Function

In many works, surface electromyography (sEMG) has been considered as an assessment tool to apply and complement to the clinical evaluation in providing objective and quantifiable measures. Recording data of muscle action during movement are useful for analyzing which muscles and at what times they are active. However, the use of EMG bio-feedback has not been fully explored as a feedback sensor. The EMG signals are often small, and the interference noise can be large. The relationship between the neural signal arriving at the muscle (or the so-called muscle activation) and the muscle strength is not known. A common approach to solve the problem is to set a linear mapping between the muscle activation and the force of the robotic joints. The approach might work well for the system with a single degree of freedom. However, the method becomes tedious for the system with more number of degrees of freedom.

In order to use EMG signals efficiently, the analysis of functional grips with their muscle group and joint motion during the rehabilitation exercises should be performed in a systematic way. The analysis must consider other important parameters, such as pinch and grip strength along with ranges of motion (ROM), etc. In this way, the system will be able to predict the intention to perform certain movement and act on the patient hand in order to perform a specific task. Note that the effectiveness of a hand function evaluation can be increased by introducing different quantitative parameters, such as functional force, grip force; hand posture, position and velocity of object grasped, contact distribution of the hand, etc.

Although the sEMG has advantages in providing information on muscle activation, the EMG study takes approximately 15-20 minutes to complete and the time varies based on the number and complexity of the muscle groups studied. This might be why EMG is seldom used in most rehabilitation centers.

By discussing with several therapists at a local hospital, it is noted that the recovery progress of therapy for the SCI and post-stroke patients is usually slow for regaining functional use of their impaired arm and hand. It is therefore possible to develop a systematic approach to obtain data from the physical or occupational therapists, as the input to the robotics system together with the measurement results (sEMG, grip/pinch force, joint angle, etc.) based on assessment and evaluation of hand function at each progressive interval. The measured results will be used to control the hand rehabilitation device, and also served as feedback scores for patients. The progress diagnosis and evaluation results can then be used as a means for motivating/monitoring patient progress and report card for therapists.

Chapter 3 STUDY OF CLINICAL ISSUES AND REQUIREMENTS

In Chapter 2, the literature review on the related topics of hand rehabilitation is presented and discussed. During the clinical attachment/observation at rehabilitation centers of Tan Tock Seng Hospital (24-28 September 2007) and Singapore General Hospital (18-20 August 2008), several key findings are presented in Chapter 3, these clinical requirements are important and useful for design of the hand rehabilitation device and the development of robotics rehabilitation training.

3.1 Symptoms

There are two common groups of patients at the rehabilitation centers of the local hospitals: post-stroke patients and spinal cord injury (SCI) patients.

1) Stroke

A stroke or cerebrovascular accident (CVA) is caused by reduced blood supply to a part of the brain due to a blocked or damaged arterial blood vessel. If a thrombus forms at a narrowed region of a cerebral artery, it can completely block the lumen of the artery. On occasion, a stroke also result from an embolus that breaks free, travels through the vascular system, and becomes lodged in a cerebral vessel.

The consequences of a stroke depend on the location and duration of vessel blockages. If the obstruction lasts longer than about 10 minutes, brain tissue may die. Depending on the location of the blockage, the person may experience regional sensory loss, motor loss, or both. The first signs that someone has had a stroke are very sudden. Common symptoms of a stroke include numbness, weakness or paralysis on one side of the body (signs of this may be a drooping arm, leg or a dribbling mouth); slurred speech or difficulty finding words or understanding speech; sudden blurred vision or loss of sight; confusion or unsteadiness; and a severe headache.

2) Spinal Cord Injury (SCI)

Spinal cord injury occurs due to traumatic in cause (e.g., motor vehicle accidents, falls, violent incidences, diving) or non-traumatic (e.g., tumors, spinal stenosis, vascular), which results in disruption of transmission of neural signal from the brain to the limbs which has considerable physical and emotion consequences to the individual's life. Paralysis, altered sensation, or weakness in the parts of the body innervated by areas below the injured region almost always occurs.

In addition to a loss of sensation, muscle functioning and movement, individuals with SCI also experience many other changes, which may affect bowel and bladder, presence of pain, sexual functioning, gastrointestinal function, swallowing ability, blood pressure, temperature regulation and breathing ability [59]. Approximately forty percent of the patients in the National Spinal Cord Injury Database were discharged with lesions at C4 (13.6%), C5 (14.9%) or C6 (10.8%) [146]. Injury at the cervical level results in tetraplegia, the loss of hand and upper limb function with impairment or loss of motor and/or sensory function.

The major problems faced by post-stroke and SCI patients are observed and learnt from the rehabilitation doctors and therapists as follows. This information provides a overview of the problems experienced by the patients, and will be subsequently used in the analysis of functional tasks and the design requirements of a hand rehabilitation device in the later research phases.

1) Loss of Power – Muscle weakness and motor impairment
2) Loss of Sensation
3) Cognition problem – not aware of his/her affected body, memory, loss of attention
4) Perception problem –Vision problem
5) Pain (may affect ROM)
6) Spasticity (hyper-tonic) with low sensation on ROM, tight muscle
   more often for stroke patients – flexor is more active than extensor
7) Poor in-hand manipulation and coordination & control
8) Use the wrong muscles (e.g. shoulder muscles) to compensate the hand movement
9) Velocity dependent resistance to passive stretch
10) Every stroke is different; each person will progress at a different rate, and faster at some times than others.
11) SCI patients have longer recovery time than stroke patients

3.2 Hand/Finger Rehabilitation

Many stroke victims regain their abilities for activities of daily living but nevertheless have quantitative limitations, such as reduced speed and inaccuracy and limitations in individual finger movements often persist [123, 147-149]. Clumsy and slow performance may be a considerable handicap to these patients, especially if fine manipulations are required. Individual finger movements are a prerequisite for dexterous motor acts and these recover the least following stroke-induced hemiparesis of the upper limb [150]. After stroke, hand function seems to be the most difficult motor function to restore even with intensive therapy [151]. Limited rehabilitation resources, time constraints, and a lack of early motor recovery in the arm and hand tend to focus therapy on improving balance, gait and general mobility [68].

Rehabilitation helps the patient regain muscle strength, joint range of motion (ROM), balance, coordination endurance and functional mobility [60]. Intensive rehabilitation that involves several components, such as physical therapy, occupational therapy, and speech therapy, usually requires continued sessions of one-on-one training for weeks to be of benefit [45].

The objectives of the hand rehabilitation for the post-stroke and SCI patients are:

1) Preventing contractures and stiffness in joints
2) Regaining range of motion (ROM)
3) Improving strength
4) Managing pain and muscle spasticity/tone management
5) Preventing muscle atrophy
6) Re-educating hand functions
7) Restoring to their greatest potential and maximum independence
8) Increase grasping power for different joints
9) Control quality of movement
10) Delay onset of secondary conditions

3.3 Manual Assisted Therapy vs Robotics Therapy

At present, most rehabilitation exercises are performed manually by physical or occupational therapists. The physiotherapist (PT) focuses on rehabilitation below the waist of the patients, walking, strengthening and transferring to ensure maximum recovery and early independence of clients. The treatment is usually prescribed to relief pain, restore normal function and strength, prevent further injury and promote healthy living and lifestyles. The occupational therapist (OT) focuses on rehabilitation above the waist of the patients, functional activities. The goal is to achieve optimal function of their upper limbs so as to regain independence in their daily activities and return to work. The treatment modalities include splinting, heat application, fluidotherapy, therapeutic laser and ultrasound, muscle stimulation, and mobilisation and exercises to specific joints of the hand and upper limbs. PT and OT of the rehabilitation team work together to provide care and therapy for the patient.

However, the manually assisted movement training by therapists has several major limitations. The training is labour-intensive, and, therefore, training duration is usually limited by personnel shortage and fatigue of the therapist, not by that of the patient. The disadvantageous consequence is that the training sessions are shorter than required to gain an optimal therapeutic outcome. The high demand and manpower shortage usually mean that most stroke patients do not receive the necessary intensive exercises. For example, the average stroke patient undergoing inpatient rehabilitation is likely to receive an hour of supervised occupational therapy daily which can inhibit recovery and progression.

One solution is to provide more intensive exercises through the use of robotics-facilitated therapy. Such devices will not only help to maintain or improve patient independence, but have the ability to reduce the burden of care on institutions and caregivers, including family members. Impairments such as muscle weakness, loss of range of motion, decreased reaction times, and disordered movement organization create deficits in motor control, which affect the patient’s independent living and provide a cause of great frustration and depression to the patient.

Robots hold great promise over traditional therapy. Specifically, robots can provide therapy over long time periods, in a consistent and precise manner, whilst accounting and adjusting for fatigue. Some unique contributions of robotic therapy versus conventional therapies are that robots can be used as valuable adjuncts to save time and energy for the therapist, making rehabilitation sessions more efficient; or to gain insights into the rehabilitation recovery process, and that rehabilitation protocols can be very precisely tailored to individual patients' needs with only as much assistance provided as needed.

With an automated robot-assisted device, the duration and number of training sessions can be increased, while reducing the number of therapists required per patient. One therapist may be able to train two or more patients in the future. Thus, personnel costs can be significantly reduced. The automated process relieves therapists of the manual labor. Therefore, the training sessions can be longer and repeatable. As a result, the therapy is more efficient and the patients achieve their goals faster. It has been suggested that the application of robotic rehabilitation devices enables therapists to carry out automated and with high frequency repeatable movements and to train particular areas of the human musculoskeletal system.

With the use of robotic devices in rehabilitation can provide high-intensity, repetitive, task-specific and interactive treatment of the impaired hand and an objective, reliable means of monitoring patient progress and patients will achieve increased gains from rehabilitation treatment.

3.4 Principles and Techniques for Hand Rehabilitation

There are a number of approaches/techniques used for stroke and SCI rehabilitation, some techniques can be implemented in the hand rehabilitation system:

1) Neurodevelopmental Techniques (NDT)

The concepts of NDT emphasize that abnormal muscle patterns or muscle tone have to be inhibited, and that normal patterns should be used in order to facilitate functional and voluntary movements. Neurofacilitation techniques encompass several approaches aimed at retraining motor control by promoting normal or inhibiting abnormal movement [70]. There are a number of approaches that fall under the heading of neurodevelopmental techniques. These include the Bobath, Brunnstrom, Proprioceptive Neuromuscular Facilitation (PNF), and Motor Relearning Programme (MRP) approaches.

2) Constraint-Induced Movement Therapy (CIMT)

Constraint-Induced Movement Therapy refers to a family of treatments for motor disability that combines constraint of movement, massed practice, and shaping of behavior to improve the amount of use of the targeted limb [152].

3) Muscle Strengthening Exercises

There is increasing clinical research support for repetitive practice of task-related strengthening exercises and for generation into more functional activities. Handgrip strength is critical to many everyday tasks.

4) Orthopedics

The orthopedics for wrist support prevents wrist drop and protect and stabilize the wrist. It positions the wrist in neutral and limits wrist flexion. Unrestricted thumb and finger dexterity, featuring patented open centre stay, removable padded metal stay limits movement.

5) Hand Splinting (Tenodesis splint)

Metal hand splint which bends at the wrist, and it is worn to strengthen the tenodesis movement. When the wrist is extended, the hand naturally becomes fisted, the splint pulls the fingers into a tight pinch, enabling the person to pick up and hold onto small objects, eating and writing utensils. This enables the person without finger movement to pick up and release objects and to be more independent.

The principles of recovery of motor function involves (1) organized, structured program, (2) behavior reinforcement/feedback, (3) repetitive practice/massed practice, (4) task orientated, goal orientated therapy, (5) selection/combine best therapies, and (6) environmental enhancement.

There are three phases in hand rehabilitation training, (1) retraining – regaining ROM, (2) strengthening – regaining muscle power, and (3) refinement – fine motor training. The stretching exercises increase flexibility and joint range of motion, improve circulation, and enhance coordination & stress relief.

In various therapeutic exercises of functional activities of daily living, each part has individual importance for the entire functional hand repertoire:

1) Wrist – flexion & extension of wrist holding object lifting in correct positions
2) Thumb – flexion & extension, abduction & adduction, retroposition and opposition in precision and power grip
3) Index and middle fingers – flexion & extension in precision grip and pinch
4) Little and ring fingers – flexion & extension in power grip

During the grasping, the wrist extension and fingers with abduction and conjoint rotation of the carpometacarpal joint of thumb and fifth finger and closure of fingers and thumb around object.

3.5 Task-specific Training

Task-specific activities and activities that are meaningful to the person have been shown to produce cortical reorganization and associated functional improvements [69]. It is aimed at improving skill in performing selected movements or functional tasks. Task-oriented training focuses on retraining functional tasks by taking into account the interplay of many systems, including the musculoskeletal, perceptual, cognitive and neural systems [70]. It is well established that task-specific practice is required for motor learning to occur. Task-specific sessions, e.g. thumb and hand movements, for as short as 15 minutes are also effective in inducing lasting cortical representational changes [43, 44]. Studies have consistently shown that exercises which are intensive and task-specific give rise to better outcome than those that are not [5-7].

Motivation is very important as patient cooperation and satisfaction with a training device/program is essential to achieve successful rehabilitation results. The rehabilitation's extent will depend on what the person can manage. Tasks should on the whole be challenging but not impossible. Coordination can be improved by practice/specified activities, e.g. repetitive task-specific training, and ADL exercises (self care, household tasks).

At rehabilitation centers, there are different types of graded and repetitive rehabilitation exercises, such as stimulation and fine motor and work hardening, the patients will maintain and improve muscle strength, range of motion and joint mobility, grasping power and manipulation, coordination, hand dexterity and fine motor skills. Some of rehabilitation exercisers are briefly described below and shown in Figure 3.1.

1) Finger Extension Remedial Game

Heavy pressed board with nonskid feet. Two sided: turn over the checkerboard for a solitaire jumping game. 32 square plastic checkers with Velcro® hook and loop playing surface gives desired resistance. Checkers have a soft vinyl loop to engage the finger in position for active extension.

2) E-Z Exer-Board

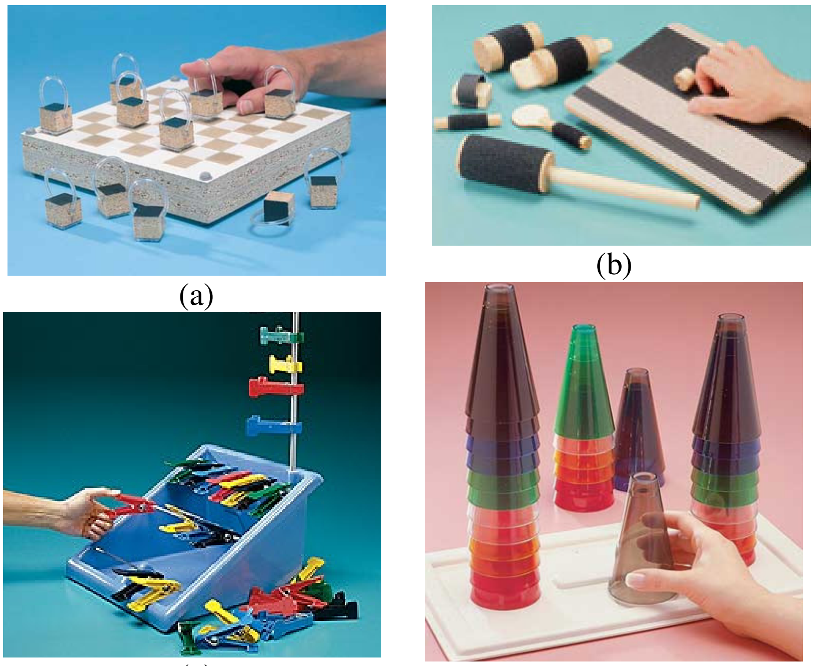
It provides resistive finger flexion, extension and lateral prehension, forearm supination and pronation, and wrist flexion and extension. Use 1" (2.5cm) hook strip and small object for increased resistive motion. Suction-cup base provides stability during exercise.

3) Pinch Exerciser

It features five graded springs in color-coded pinchpins with different resistances. Kit includes three metal rods of different diameters, a vertical metal rod for combining exercises (shoulder ROM with resistive pinch), and 35 graded spring pinch pins, seven of each resistance.

4) Shape Sorting Cube

It develops eye-hand coordination, grasping and cognitive skills. Hardwood box has side and top cut-outs that correspond to each shape.



(a) (b)

(c) (d)

Figure 3.1: Upper Limb Exercisers Used in Local Hospitals (Pictures from [153]) (a) Finger Extension Remedial Game (b) E-Z Exer-Board (c) Pinch Exerciser (d) Shape Sorting Cube

3.6 Assessment Methods

The manually-assisted movement training lacks objective measures of patient performance and progress. The clinical methods used are often based on subjective and qualitative assessments made by therapists, which depends on their experience and unable detection of small changes. Moreover, the assessment tools for each task/exercise are subjective, which lacks of outcome measure for task-based exercise and feedback (muscle activation, etc). Progress will be monitored and goals/functional outcome want to be adjusted over time to meet changing needs. The current assessment tools at the rehabilitation centers of local hospital includes Range of Motion (ROM) testing using goniometers by manual testing, gripping/pinch force testing using hand dynamometers, manual muscle testing, Functional Independence Measure (assessed every week), Fugl-Meyer Assessment (assessed once when admit to rehabilitation centre) and ASIA score (for SCI patients).

1) Strength Testing (Manual muscle testing)

It determines precisely which muscles have been affected following a nerve lesion and help to monitor motor progress during nerve regeneration. The grading of strength is as follows:

0. No evidence of contraction.
1. Evidence of slight muscle contraction; no joint movement.
2. Muscle contraction producing movement with gravity eliminated.
3. Muscle contraction producing movement against gravity.
4. Muscle contraction producing movement against gravity with some resistance.
5. Muscle contraction producing movement against full resistance.

2) Functional Independence Measure (FIM)

The FIM assesses physical and cognitive disability. It consists of 18 items with two subscales; motor and socio-cognitive. The motor subscale includes 13 items: eating, grooming bathing, dressing upper extremity, dressing lower extremity, bowel management, bladder management, transfers to bed, chair or wheelchair, transfer to tub, toilet and shower, walking or wheelchair propulsion and stair climbing. Each item is scored on a 7 point ordinal scale ranging from 1 (total dependence) to a score of 7 (total independence). The FIM is a method for monitoring and evaluating progress associated with treatment. It was developed for a standard measure of disability in six categories of functioning (18 items). It measures daily life activities in the areas of self-care, sphincter control, mobility, locomotion, communication and social cognition. Activities such as eating, toileting, and dressing are rated on a scale which measures dependence / independence. Each category is scored from 1 to 4, 1 indicating complete dependence and 4 indicating complete independence. Table 3.1 shows the Functional Independence Measure.

Table 3.1: Functional Independence Measure (FIM) [154]

LEVELS	7 Complete Independence (timely, safely) 6 Modified Independence (device)	NO HELPER
	Modified Dependence 5 Supervision (subject = 100%) 4 Minimal Assistance (subject = 75%+) 3 Moderate Assistance (subject = 50%+) Complete Dependence 2 Maximal Assistance (subject =25%+) 1 Total Assistance (subject = less than 25%)	HELPER

	ADMISSION	**DISCHARGE**	**FOLLOW-UP**
Self-Care			
A. Eating			
B. Grooming			
C. Bathing			
D. Dressing - Upper Body			
E. Dressing - Lower Body			
F. Toileting			
Sphincter Control			
G. Bladder Management			
H. Bowel Management			
Transfers			
I. Bed, Chair, Wheelchair			
J. Toilet			
K. Tub, Shower			
Locomotion			
L. Walk/Wheelchair	W Walk, C Wheelchair, B Both	W Walk, C Wheelchair, B Both	W Walk, C Wheelchair, B Both
M. Stairs			
Motor Subtotal Score			
Communication			
N. Comprehension	A Auditory, V Visual, B Both	A Auditory, V Visual, B Both	A Auditory, V Visual, B Both
O. Expression	A Auditory, V Visual, B Both	A Auditory, V Visual, B Both	A Auditory, V Visual, B Both
Social Cognition			
P. Social Interaction			
Q. Problem Solving			
R. Memory			
Cognitive Subtotal Score			
TOTAL FIMTM SCORE			

NOTE: Leave no blanks. Enter 1 if patient is not testable due to risk.

3) Fugl-Meyer Assessment

It is a disease-specific impairment index designed to assess motor function, balance, sensation qualities and joint function in hemiplegic post-stroke patients. The scale comprises five domains, motor function (in the upper and lower extremities), sensory function, balance (both standing and sitting), joint range of motion and joint pain. Functional tasks are not incorporated into the evaluation. Table 3.2 shows the upper limb sessions of Fugl-Meyer Assessment.

Table 3.2: Fugl-Meyer Assessment (FMA Upper limb sessions) [155]

		Score	
1 Shoulder / elbow / forearm			
1.1 Reflex activity			
1.1.1 Flexors (biceps and finger flexors)	0	1	2
1.1.2 Extensors (triceps)	0	1	2
1.2 Flexor synergy – volitional movement within synergy			
1.2.1 Shoulder retraction	0	1	2
1.2.2 Shoulder elevation	0	1	2
1.2.3 Shoulder abduction	0	1	2
1.2.4 Shoulder external rotation	0	1	2
1.2.5 Elbow flexion	0	1	2
1.2.6 Forearm supination	0	1	2
1.3 Extensor synergy – volitional movement within synergy			
1.3.1 Shoulder adduction / internal rotation	0	1	2
1.3.2 Elbow extension	0	1	2
1.3.3 Forearm pronation	0	1	2
1.4 Volitional movement mixing the dynamic flexor and extensor strategies			
1.4.1 Hand on lumbar spine	0	1	2
1.4.2 Shoulder flexion	0	1	2
1.4.3 Forearm pronation/supination	0	1	2
1.5 Volitional movements are performed with little or no synergy dependence			
1.5.1 Shoulder abduction	0	1	2
1.5.2 Shoulder flexion	0	1	2
1.5.3 Forearm pronation-supination	0	1	2
1.6 Normal reflex activity	0	1	2
2 Wrist			
2.1 Wrist stability – elbow 90°	0	1	2
2.2 Wrist flexion/extension – elbow 90°	0	1	2
2.3 Wrist stability – elbow 0°	0	1	2
2.4 Wrist flexion/extension – elbow 0°	0	1	2
2.5 Circumduction	0	1	2
3 Hand			
3.1 Mass flexion	0	1	2
3.2 Mass extension	0	1	2
3.3 Grasp A – distal finger grasp	0	1	2
3.4 Grasp B – thumb adduction grasp	0	1	2
3.5 Grasp C – thumb to index finger grasp	0	1	2
3.6 Grasp D – cylinder grasp	0	1	2
3.7 Grasp E – spherical grasp	0	1	2
4 Co-ordination/speed			
4.1 Tremor	0	1	2
4.2 Dysmetria	0	1	2
4.3 Speed	0	1	2
Upper limb score			

4) ASIA score (American Spinal Injury Association)

The International Standards for Neurological Classification of SCI (ASIA 2002 as shown in Figure 3.2) is a multidimensional approach to categorize motor and sensory impairment in individuals with SCI. It identifies sensory and motor levels indicative of the most rostral spinal levels demonstrating “unimpaired” function. Twenty-eight dermatomes are assessed bilaterally using pinprick and light touch sensation and 10 key muscles are assessed bilaterally with manual muscle testing.

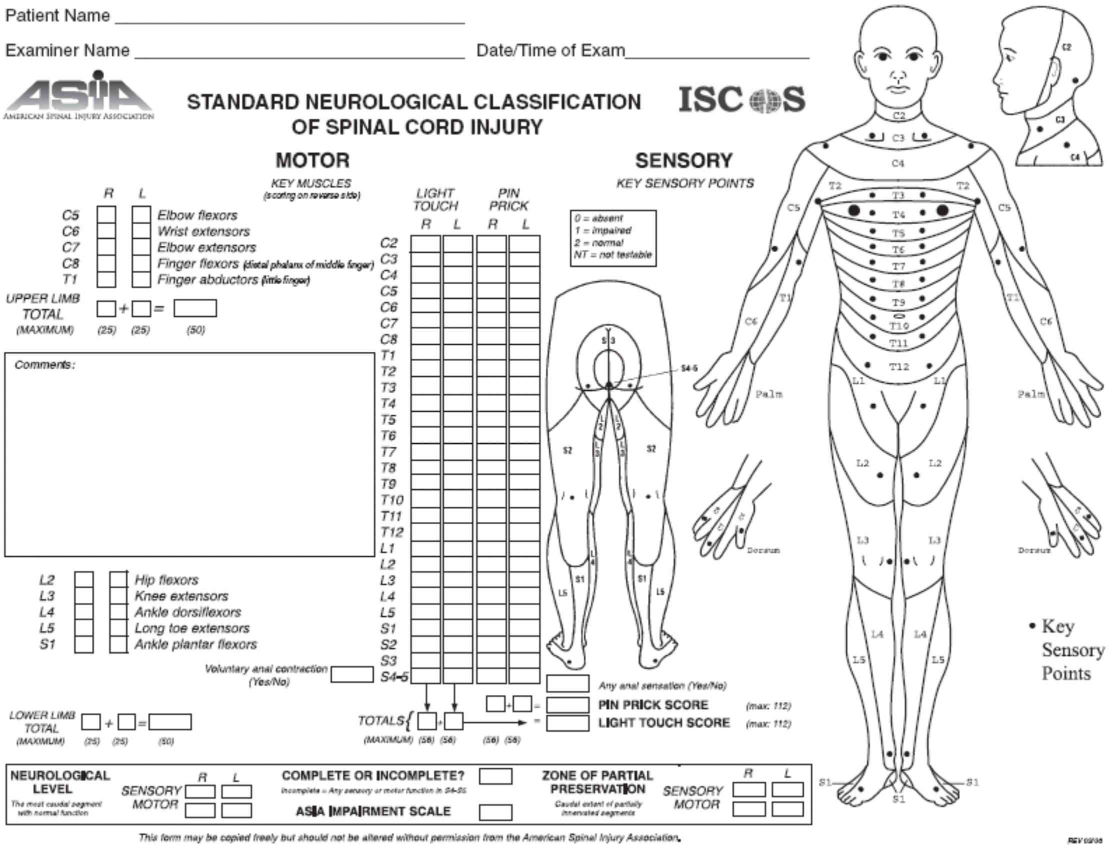


Figure 3.2: ASIA Score [156]

Currently clinical assessments of hand motor function are routinely based on qualitative assessments made by therapists and are as such subjective and dependent on the skills and experience of the therapist. Small changes or variations following injury are often undetected. However, the therapist’s experience remains important in regards to gauging the subject’s ability to progress and improve [46]. The physical therapists' knowledge and experience of the functioning of the body and its response to rehabilitation are central to determining a systematic diagnosis and an intervention strategy irrespective of the setting e.g. robotic or manual [47]. Occupational therapy practice may be directed to changing certain aspects of the environment to enhance participation. These subjective evaluations performed in the clinical setting are often based upon clinical ordinal scales, e.g., Fugl-Meyer Assessment and Functional Independence Measure, but their main limitations are low reliability and sensitivity [48]. As such there is a clear need for an objective and reliable assessment of hand function to monitor and quantify patients' progress during therapy and to validate the outcome of the rehabilitation treatment. These are used to enhance the hand rehabilitation training rather than inhibiting conventional rehabilitation.

With an increasing demand for evidence-based interventions and the mounting use of clinical guidelines, clinicians are increasing required to record their outcomes using ordinal or quantifiable outcome tools with a view to establishing or ascertaining best practice [50]. The accuracy and objectivity of hand function evaluation can be increased by introducing simple quantitative methods based on different parameters, such as ROM (range of motion), gripping/pinch force, hand dexterity and posture, position and velocity of object grasped, etc [157]. However, the relationship between these parameters and their relevance to functional ability remains to be elucidated a systematic method for the objective and quantitative assessment of hand function that is able to reliably diagnose a patients' functional state and to document its response to therapy.

3.7 Clinical Requirements for Robotic Hand Rehabilitation

Based on clinical attachment/observation at the rehabilitation centers, it is found that there is the need for an intelligent robotics hand rehabilitation system to aid the restoration of hand function of patients experiencing weakness and loss of function in the hand following stroke or other neurological or musculoskeletal diseases, although the initial focus is on neurological causes. The proposed hand system would be capable of training key hand movements that are essential for hand functioning in activities of daily living (ADL), to help the therapist to save time and making rehabilitation sessions more efficient.

Since the hand rehabilitation device will be used by therapists to facilitate treatment, the work should focus on the interests and the requirements of the therapists. In fact there are two end users: the patient and the therapist. Furthermore, a system that satisfies the requirements and needs of the therapists will indirectly satisfy those of the patients in terms of the quality of therapy they receive. Based on these principles and techniques used for hand rehabilitation learnt from the doctors and therapists, several findings are summarized.

The design involves the integration of robotics, mechatronic systems, and information technology to develop robotic systems capable of performing some of the tasks involved in physical or occupational rehabilitation. The aim of this hand rehabilitation device is to help patients, who are suffering from stroke or spinal cord injury (SCI), to restore the muscle control, or to help foster muscle control. Therefore, before stating the requirements for the design of this device, it is important to consider some of the patient based requirement of the system.

Firstly, the patient's fingers would have little or no strength and limited if any muscle control, this device must be lightweight and in the manner of "load-free" and able to provide sufficient support to "hold" their fingers. This implies that the patient's elbow should have some forms of arm rest to allow them to rest comfortably with the shoulder and upper limb in a supported position.

Secondly, every patient has their own physical limitations and different presentations and as such they cannot be expected to respond in the same way when using this device. Hence, this device should provide a range of motions to suit the individual patient's needs. Moreover, everyone have different finger length and width, and thus it is essential to make the device adjustable to fit the patient.

Thirdly, in order to achieve the patients' optimal functional ability, the device must be able to support individual finger motion for normal/nature grasp movement and key hand movements that are essential for hand functioning in activities of daily living (ADL) tasks, which is important for improvements in ADL of real life and reduction of impairments, as task-specific practice is required for motor learning to occur. Those therapeutic exercises performed in the rehabilitation centers can be categorized based on their functions and the stages of recovery for the patients as the key/common gripping/pinch exercises for the hand rehabilitation device.

Furthermore, the device should be easily controlled with quantitative feedback. This is to allow the patient to perform rehabilitation, if his condition permits or allow therapist to have easy control while conducting the rehabilitation service. However, subjective evaluations often based upon clinical ordinal scales are still preferred and widely used in rehabilitation centers. The main limitations of these assessments are low reliability and sensitivity. Objective and accurate assessment of hand function is needed to monitor and quantify patients' progress during therapy and to validate the outcome of the rehabilitation treatment. The accuracy and objectively of hand function evaluation can be increased by introducing simple quantitative methods based on different parameters (such as range of motion, functional grip/pinch force, hand dexterity & posture, etc), so that the comprehensive assessment methodology through clinical studies to provide tool to communicate between clinician and engineers can be developed.

Lastly, the device should be robust, reliable, and easy to use/user friendly, simple design, less setting-up time, with safety feature and feedback. The safety of the patient is the most important technical issue in designing and building an intelligent robotic system for hand rehabilitation.

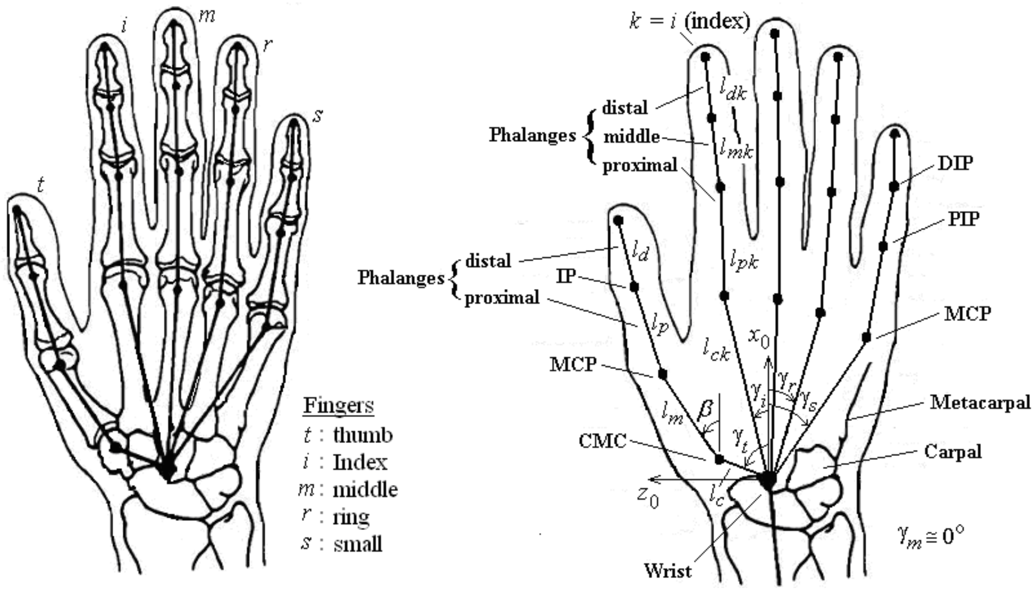
Chapter 4 HAND MODELING AND ANALYSIS OF ADL TASKS

Based on the literature review and discussion in Chapter 2 and clinical issues and requirements discussed in Chapter 3, we knew that the functional activities of daily living (ADL) tasks are important for improvements in ADL of real life and reduction of impairments as task-specific practice is required for motor learning to occur. Chapter 4 presents the modeling of human hand and analysis of ADL tasks, which consists of skeletal of human hand, the kinematics model using D-H method (forward kinematics and workspace analysis), and study of hand rehabilitation tasks and motion sequences, kinematics identification and workspace analysis of ADL functional tasks and virtual modeling of task-specific hand motion.

4.1 Modeling of Human Hand

4.1.1 Skeletal of Human Hand

The human hand is a remarkably complex mechanism. Its skeletal system is composed of 27 bone segments, constituting palm and fingers, as shown in Figure 4.1. The hand movement is produced by the muscles and tendons attached to the bones. Figure 4.1 also depicts the terms and notations used in the present work.



(a) Skeleton (b) Terms and Notations

Figure 4.1: Human Hand (Modified from [158])

The dimension of human hand varies from person to person. Figure 4.2 shows the two basic dimensions that define the size of the hand, where b_h is the breadth of the hand and l_h represents the length of the hand with respect to the wrist.

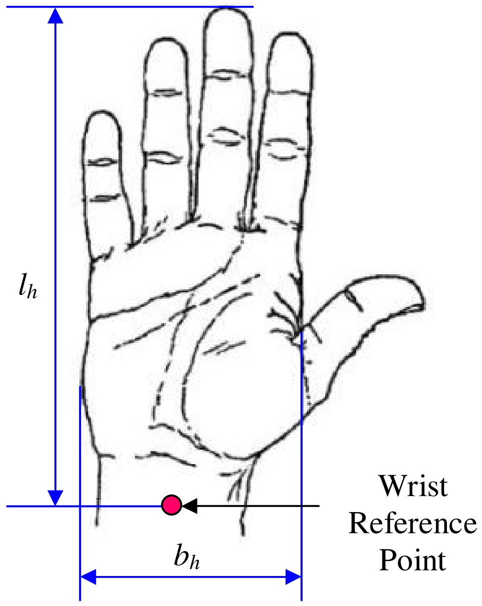


Figure 4.2: Magnitude of Human Hand

The dimension of each finger is important to the study of the hand kinematics and size adjustment of the robotic device. Table 4.1 lists the expression for the segment lengths (l_c, l_p, l_m and l_d in Figure 4.1) of the respective finger, in terms of the hand parameters, l_h and b_h [158].

Table 4.1: Segment Length of Fingers

	l_c	l_p	l_m	l_d
Thumb Finger	$\frac{1}{2}\left(0.118l_h + \sqrt{(0.073l_h)^2 + (0.196b_h)^2}\right)$	0.196 l_h	0.251 l_h	0.158 l_h
Index Finger	$\frac{1}{2}\left(0.463l_h + \sqrt{(0.447l_h)^2 + (0.251b_h)^2}\right)$	0.245 l_h	0.143 l_h	0.097 l_h
Middle Finger	0.446 l_h	0.266 l_h	0.170 l_h	0.108 l_h
Ring Finger	$\frac{1}{2}\left(0.421l_h + \sqrt{(0.409l_h)^2 + (0.2061b_h)^2}\right)$	0.244 l_h	0.165 l_h	0.107 l_h
Small Finger	$\frac{1}{2}\left(0.414l_h + \sqrt{(0.368l_h)^2 + (0.402b_h)^2}\right)$	0.204 l_h	0.117 l_h	0.093 l_h

4.1.2 Kinematics Model of Human Hand

Kinematics modeling of human hand can be obtained using the well-known Denavit-Hartenberg (D-H) method. The general equation describing the coordinate systems is given by the homogeneous equation [159]:

$$\{P\}_{i-1} = \left[H_{(i-1)i}\right]\{P\}_i \tag{4.1}$$

Where

$\{P\}_{i-1}$ the position vector expressed in the i^{th} coordinate system, and $i(i=1,2,3\ldots)$

$\{P\}_i$ the position vector expressed in the $\{i\text{-}1\}^{th}$ coordinate system

$\left[H_{(i-1)i}\right]$ the homogenous matrix transformation from the i^{th} to $\{i\text{-}1\}^{th}$ coordinate systems

and

$$\left[H_{(i-1)i}\right] = \begin{bmatrix} \cos\theta_i & -\cos\alpha_i \sin\theta_i & \sin\alpha_i \sin\theta_i & a_i \cos\theta_i \\ \sin\theta_i & \cos\alpha_i \cos\theta_i & -\sin\alpha_i \cos\theta_i & a_i \sin\theta_i \\ 0 & \sin\alpha_i & \cos\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

For convenience, the kinematics modeling presented in the following section covers only the right hand, although the results obtained could easily be extended for the left hand.

1) Kinematics Model of Fingers (*Index*, *Middle*, *Ring* and *Small* Fingers)

The coordinate systems illustrated in Figure 4.3 are assigned according to D-H method for index finger, while the similar coordinate systems can be assigned for other fingers (except the thumb, which will be considered later). In Figure 4.3, $x_0 y_0 z_0$ is the local coordinate system for the wrist, while θ_j defines the finger's orientation with respect to its own coordinate system. Table 4.2 lists the D-H parameters for all four fingers illustrated in Figure 4.3. The specified ranges of the joint and link parameters are also given in the table. Note that the segment lengths of the respective finger are listed in Table 4.1. The average length of human hand (l_h = 189 mm) and the average breadth of the hand (b_h = 87 mm) is used in our study.

The definitions of the notations in Figure 4.3 and Table 4.2 are:

k Index for fingers (k = i, m, r, s),

where i = *index* finger, m = *middle* finger, r = *ring* finger, s = *small* finger

q_j Generalized coordinates (j = 1 to 5)

θ_{jk} Joint angle of finger k (j = 1 to 5)

γ_k Angle of finger k at the root segment with respect to axis x_0

($\gamma_i = 17^\circ$, $\gamma_m \cong 0^\circ$, $\gamma_r = -15^\circ$, $\gamma_s = -34^\circ$)

l_{ck} Length of **c**arpo-metacarpal segment for finger k

l_{pk} Length of the **p**roximal phalangeal segment

l_{mk} Length of the **m**iddle phalangeal segment for four fingers

l_{dk} Length of the **d**istal phalangeal segment

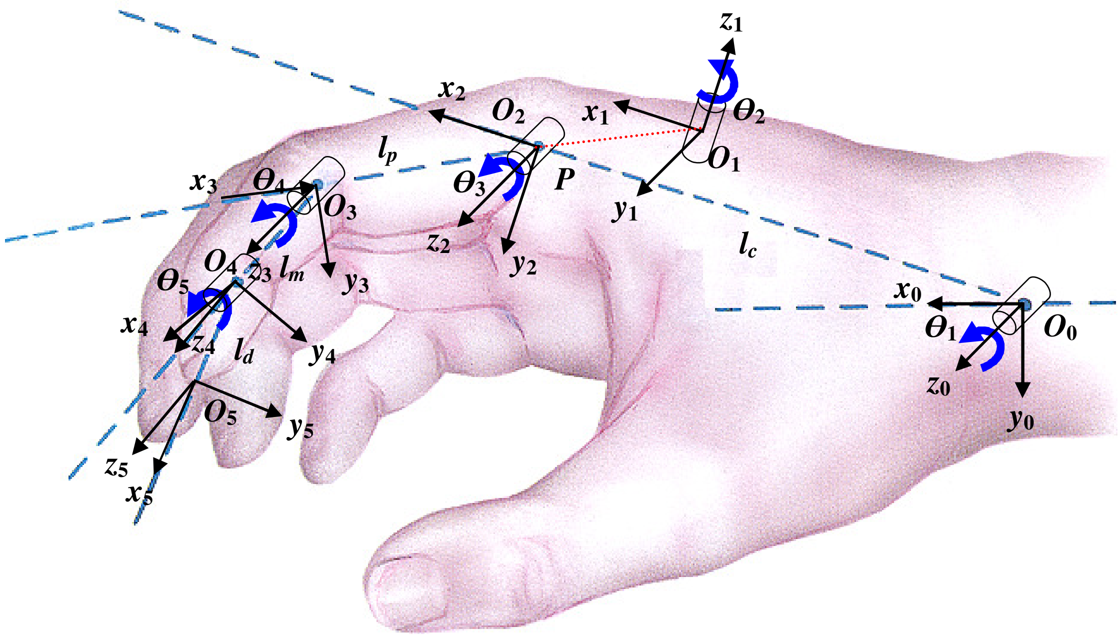


Figure 4.3: D-H Representation of Human Hand (Index finger, k = i)

Table 4.2: D-H Parameters for Fingers (Excluding thumb)

Joint j	θ_j (deg)	α_j (deg)	a_j (mm)	d_j (mm)	Joint Variables#	Range of Joint Angles [55-57] Max. Flexion/ Abduction	Range of Joint Angles [55-57] Max. Extension/ Adduction; *active* (*passive*)	Segment Lengths (Table 4.1) l_h=189 mm; b_h=87 mm
1	q_1	90°	$l_{ck}\cos\gamma_k$	$l_{ck}\sin\gamma_k$	θ_{1k}	80°	-70°	l_{ck}
2	q_2	-90°	0	0	θ_{2k}	20°	-20°	-
3	q_3	0	l_{pk}	0	θ_{3k}	90°	-20° (-70°)	l_{pk}
4	q_4	0	l_{mk}	0	θ_{4k}	100°	0°	l_{mk}
5	q_5	0	l_{dk}	0	θ_{5k}	60°	-5° (-30°)	l_{dk}

k = i, m, r, s (i = *index* finger, m = *middle* finger, r = *ring* finger, s = *small* finger)

a) Forward Kinematics

The coordinate and orientation of the fingertip in the right finger, identified as System 5 in Figure 4.3, can be obtained using the D-H method:

$$\begin{aligned} \{P\}_0 &= [H_{05}]\{P\}_5 \\ [H_{05}] &= [H_{01}][H_{12}][H_{23}][H_{34}][H_{45}] \end{aligned} \tag{4.2}$$

With the individual matrix $\left[H_{(i-1)i}\right]$ for each individual finger *k*,

$$[H_{01}] = \begin{bmatrix} \cos\theta_1 & 0 & \sin\theta_1 & l_{ck}\cos\gamma_k\cos\theta_1 \\ \sin\theta_1 & 0 & -\cos\theta_1 & l_{ck}\cos\gamma_k\sin\theta_1 \\ 0 & 1 & 0 & l_{ck}\sin\gamma_k \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

(4.3)

$$[H_{12}] = \begin{bmatrix} \cos\theta_2 & 0 & -\sin\theta_2 & 0 \\ \sin\theta_2 & 0 & \cos\theta_2 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{4.4}$$

$$[H_{23}] = \begin{bmatrix} \cos\theta_3 & -\sin\theta_3 & 0 & l_{pk}\cos\theta_3 \\ \sin\theta_3 & \cos\theta_3 & 0 & l_{pk}\sin\theta_3 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{4.5}$$

$$[H_{34}] = \begin{bmatrix} \cos\theta_4 & -\sin\theta_4 & 0 & l_{mk}\cos\theta_4 \\ \sin\theta_4 & \cos\theta_4 & 0 & l_{mk}\sin\theta_4 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{4.6}$$

$$[H_{45}] = \begin{bmatrix} \cos\theta_5 & -\sin\theta_5 & 0 & l_{dk}\cos\theta_5 \\ \sin\theta_5 & \cos\theta_5 & 0 & l_{dk}\sin\theta_5 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{4.7}$$

Note that the index *k* of θ_{jk} in [*H*] matrices has been removed, for clarity.

The direct (or forward) kinematics solution, therefore, simply a matter of obtaining the resultant matrix $H = [H_{05}]$ by multiplying the five $\left[H_{(i-1)i}\right]$ matrices as

$$[H_{05}] = \begin{bmatrix} n_X & s_X & a_X & p_X \\ n_Y & s_Y & a_Y & p_Y \\ n_Z & s_Z & a_Z & p_Z \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{4.8}$$

from which the forward kinematics equation is given by

$$\begin{aligned} p_X =& [(\cos\theta_1\cos\theta_2\cos\theta_3 - \sin\theta_1\sin\theta_3)\cos\theta_4 \\ &+ (-\cos\theta_1\cos\theta_2\sin\theta_3 - \sin\theta_1\cos\theta_3)\sin\theta_4]l_{dk}\cos\theta_5 \\ &+ [-(\cos\theta_1\cos\theta_2\cos\theta_3 - \sin\theta_1\sin\theta_3)\sin\theta_4 \\ &+ (-\cos\theta_1\cos\theta_2\sin\theta_3 - \sin\theta_1\cos\theta_3)\cos\theta_4]l_{dk}\sin\theta_5 \\ &+ (\cos\theta_1\cos\theta_2\cos\theta_3 - \sin\theta_1\sin\theta_3)l_{mk}\cos\theta_4 \\ &+ (-\cos\theta_1\cos\theta_2\sin\theta_3 - \sin\theta_1\cos\theta_3)l_{mk}\sin\theta_4 \\ &+ l_{pk}\cos\theta_1\cos\theta_2\cos\theta_3 - l_{pk}\sin\theta_1\sin\theta_3 + l_{ck}\cos\theta_1\cos\gamma_t \end{aligned} \tag{4.9}$$

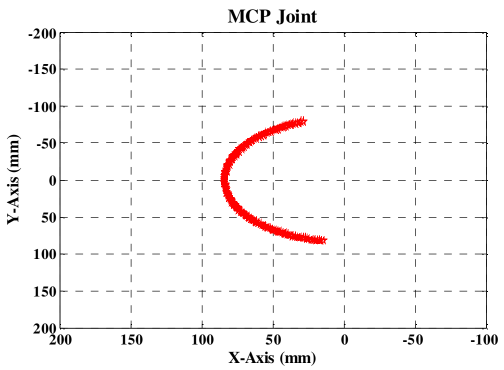
$$\begin{aligned} p_Y =& [(\sin\theta_1\cos\theta_2\cos\theta_3 + \cos\theta_1\sin\theta_3)\cos\theta_4 \\ &+ (-\sin\theta_1\cos\theta_2\sin\theta_3 + \cos\theta_1\cos\theta_3)\sin\theta_4]l_{dk}\cos\theta_5 \\ &+ [-(\sin\theta_1\cos\theta_2\cos\theta_3 + \cos\theta_1\sin\theta_3)\sin\theta_4 \\ &+ (-\sin\theta_1\cos\theta_2\sin\theta_3 + \cos\theta_1\cos\theta_3)\cos\theta_4]l_{dk}\sin\theta_5 \\ &+ (\sin\theta_1\cos\theta_2\cos\theta_3 + \cos\theta_1\sin\theta_3)l_{mk}\cos\theta_4 \\ &+ (-\sin\theta_1\cos\theta_2\sin\theta_3 + \cos\theta_1\cos\theta_3)l_{mk}\sin\theta_4 \\ &+ l_{pk}\sin\theta_1\cos\theta_2\cos\theta_3 + l_{pk}\cos\theta_1\sin\theta_3 + l_{ck}\sin\theta_1\cos\gamma_t \end{aligned} \tag{4.10}$$

$$\begin{aligned} p_Z =& (\sin\theta_2\cos\theta_3\cos\theta_4 - \sin\theta_2\sin\theta_3\sin\theta_4)l_{dk}\cos\theta_5 \\ &+ (-\sin\theta_2\cos\theta_3\sin\theta_4 - \sin\theta_2\sin\theta_3\cos\theta_4)l_{dk}\sin\theta_5 \\ &+ l_{mk}\sin\theta_2(\cos\theta_3\cos\theta_4 - \sin\theta_3\sin\theta_4) + l_{pk}\sin\theta_2\cos\theta_3 + l_{ck}\sin\gamma_t \end{aligned} \tag{4.11}$$

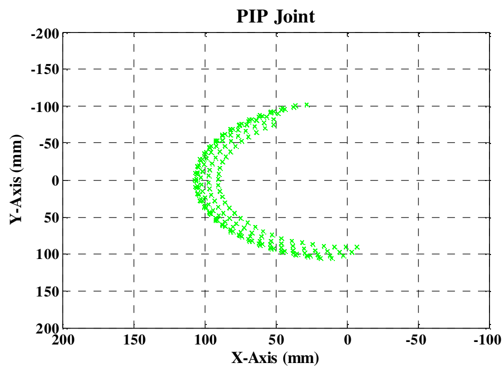
Note that the coordinates $\{p_X, p_Y, p_Z\}$ are written in terms of the joint parameters.

b) Workspace of Index Finger

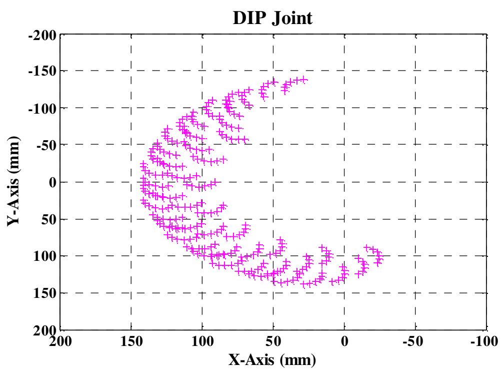
Based on the average length of human hand (l_h = 189 mm) and the ranges of each joints (we assume that θ_2=0 as the abduction/adduction is less significant functionally and it's ROM is small) as defined in Table 4.2, the possible workspace of the MCP joint, PIP joint, DIP joint and fingertip of the index finger is plotted using MATLAB and the result is shown in Figure 4.4, where the X-Axis and Y-Axis in the Figure refer to the $x_0 y_0 z_0$ reference coordinate system located at the wrist. The workspace of each joint will be used to monitor the patient progress and provide objective feedback for the patients with limited ROM compared to healthy subjects.



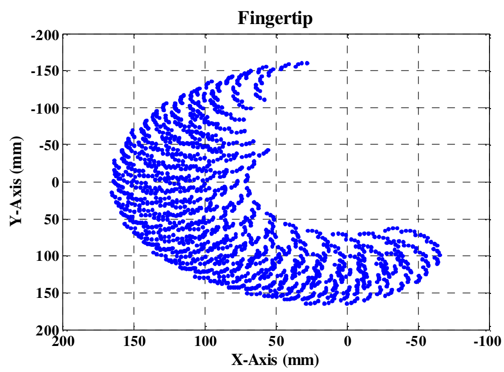
(a) MCP Joint



(b) PIP Joint



(c) DIP Joint



(d) Fingertip

Figure 4.4: Workspace of the Human Index Finger

2) Kinematics Model of the Thumb

In a similar manner, the coordinate systems illustrated in Figure 4.5 are assigned according to D-H method for the thumb, where $x_0y_0z_0$ is the reference coordinate system located at the wrist. Table 4.3 lists the D-H parameters for the thumb with the generalized coordinates (q_j) illustrated in Figure 4.5. Note that six joint parameters are used to describe the kinematics model of the human thumb.

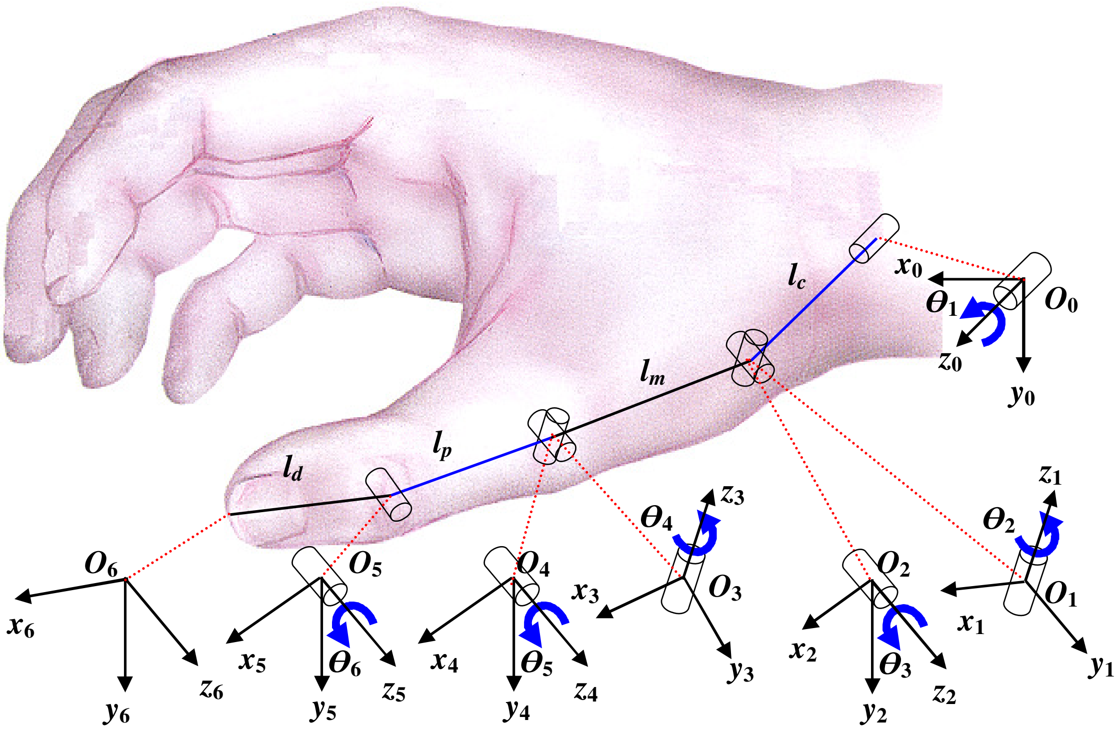


Figure 4.5: D-H Representation of Human Thumb

Table 4.3: D-H Parameters for the Thumb

Joint j	θ_j (deg)	α_j (deg)	a_j (mm)	d_j (mm)	Joint Variables	Range of Joint Angles [55-57]		Segment Lengths (Table 4.1) l_h=189 mm b_h=87 mm
						Max. Flexion/ Abduction	Max. Extension/ Adduction	
1	q_1	90°	$l_c\cos\gamma_t$	$l_c\sin\gamma_t$	θ_1	80°	-70°	l_c=22.3
2	$q_2+\beta$	-90°	0	0	θ_2	50°	-20°	-
3	q_3	90°	l_m	0	θ_3	60°	-20°	l_m=47.4
4	q_4	-90°	0	0	θ_4	30°	-30°	-
5	q_5	0°	l_p	0	θ_5	60°	-10°	l_p=37.0
6	q_6	0°	l_d	0	θ_6	90°	-20°	l_d=29.9

The definitions of the notations in Figure 4.5 and Table 4.3 are:

q_j Generalized coordinates (j = 1 to 6)

θ_j Joint angle at O_j relative its own coordinate system

γ_t Joint angle at CMC of thumb with respect to axis x_0 ($\gamma_t = 73^\circ$)

β Joint angle at MCP of thumb with respect to axis x_0 ($\beta = 41^\circ$)

l_c Length of the **c**arpal segment

l_p Length of the **p**roximal phalangeal segment

l_m Length of the **m**etacarpal segment

l_d Length of the **d**istal phalangeal segment

Having established the coordinate systems and D-H parameters for the links (joints) of the thumb, the individual homogeneous matrix $[H]_{4\times4}$ between the adjacent coordinate systems can be derived.

a) Forward Kinematics

The coordinates of the thumb fingertip, located at the origin of System 5 in Figure 4.5, can be obtained using the D-H method,

$$\begin{aligned} \{P\}_0 &= [H_{06}]\{P\}_6 \\ [H_{06}] &= [H_{01}][H_{12}][H_{23}][H_{34}][H_{45}][H_{56}] \end{aligned} \tag{4.12}$$

With the individual matrix $\left[H_{(i-1)i}\right]$,

$$[H_{01}] = \begin{bmatrix} \cos\theta_1 & 0 & \sin\theta_1 & l_c\cos\gamma_t\cos\theta_1 \\ \sin\theta_1 & 0 & -\cos\theta_1 & l_c\cos\gamma_t\sin\theta_1 \\ 0 & 1 & 0 & l_c\sin\gamma_t \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{4.13}$$

$$[H_{12}] = \begin{bmatrix} \cos(\theta_2+\beta) & 0 & -\sin(\theta_2+\beta) & 0 \\ \sin(\theta_2+\beta) & 0 & \cos(\theta_2+\beta) & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{4.14}$$

$$[H_{23}] = \begin{bmatrix} \cos\theta_3 & 0 & \sin\theta_3 & l_m\cos\theta_3 \\ \sin\theta_3 & 0 & -\cos\theta_3 & l_m\sin\theta_3 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{4.15}$$

$$[H_{34}] = \begin{bmatrix} \cos\theta_4 & 0 & -\sin\theta_4 & 0 \\ \sin\theta_4 & 0 & \cos\theta_4 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{4.16}$$

$$[H_{45}] = \begin{bmatrix} \cos\theta_5 & -\sin\theta_5 & 0 & l_p\cos\theta_5 \\ \sin\theta_5 & \cos\theta_5 & 0 & l_p\sin\theta_5 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{4.17}$$

$$[H_{56}] = \begin{bmatrix} \cos\theta_6 & -\sin\theta_6 & 0 & l_d\cos\theta_6 \\ \sin\theta_6 & \cos\theta_6 & 0 & l_d\sin\theta_6 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{4.18}$$

The direct (or forward) kinematics solution is, therefore, simply the finding of the resultant matrix $\boldsymbol{H} = \boldsymbol{H}_{06}$ by multiplying the six $[H_{(i\text{-}1)i}]$ matrices and evaluating each element in the $\boldsymbol{H}$ matrix given by

$$[H_{06}] = \begin{bmatrix} n_X & s_X & a_X & p_X \\ n_Y & s_Y & a_Y & p_Y \\ n_Z & s_Z & a_Z & p_Z \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{4.19}$$

from which the position vector $\boldsymbol{p}$ is obtained as

$$\begin{aligned} p_X = \{&[(\cos\theta_1\cos(\theta_2+\beta)\cos\theta_3\text{-}\sin\theta_1\sin\theta_3)\cos\theta_4 \\ &\text{-}\cos\theta_1\sin(\theta_2+\beta)\sin\theta_4]\cos\theta_5 \\ &+(\text{-}\cos\theta_1\cos(\theta_2+\beta)\sin\theta_3\text{-}\sin\theta_1\cos\theta_3)\sin\theta_5\}l_d\cos\theta_6 \\ &+\{\text{-}[(\cos\theta_1\cos(\theta_2+\beta)\cos\theta_3\text{-}\sin\theta_1\sin\theta_3)\cos\theta_4\text{-}\cos\theta_1\sin(\theta_2+\beta)\sin\theta_4]\sin\theta_5 \\ &+(\text{-}\cos\theta_1\cos(\theta_2+\beta)\sin\theta_3\text{-}\sin\theta_1\cos\theta_3)\cos\theta_5\}l_d\sin\theta_6 \\ &+[(\cos\theta_1\cos(\theta_2+\beta)\cos\theta_3\text{-}\sin\theta_1\sin\theta_3)\cos\theta_4\text{-}\cos\theta_1\sin(\theta_2+\beta)\sin\theta_4]l_p\cos\theta_5 \\ &+(\text{-}\cos\theta_1\cos(\theta_2+\beta)\sin\theta_3\text{-}\sin\theta_1\cos\theta_3)l_p\sin\theta_5 \\ &+l_m\cos\theta_1\cos(\theta_2+\beta)\cos\theta_3\text{-}l_m\sin\theta_1\sin\theta_3+l_c\cos\theta_1\cos\gamma_t \end{aligned} \tag{4.20}$$

$$\begin{aligned} p_Y = \{&[(\sin\theta_1\cos(\theta_2+\beta)\cos\theta_3+\cos\theta_1\sin\theta_3)\cos\theta_4 \\ &\text{-}\sin\theta_1\sin(\theta_2+\beta)\sin\theta_4]\cos\theta_5 \\ &+(\text{-}\sin\theta_1\cos(\theta_2+\beta)\sin\theta_3+\cos\theta_1\cos\theta_3)\sin\theta_5\}l_d\cos\theta_6 \\ &+\{\text{-}[(\sin\theta_1\cos(\theta_2+\beta)\cos\theta_3+\cos\theta_1\sin\theta_3)\cos\theta_4\text{-}\sin\theta_1\sin(\theta_2+\beta)\sin\theta_4]\sin\theta_5 \\ &+(\text{-}\sin\theta_1\cos(\theta_2+\beta)\sin\theta_3+\cos\theta_1\cos\theta_3)\cos\theta_5\}l_d\sin\theta_6 \\ &+[(\sin\theta_1\cos(\theta_2+\beta)\cos\theta_3+\cos\theta_1\sin\theta_3)\cos\theta_4\text{-}\sin\theta_1\sin(\theta_2+\beta)\sin\theta_4]l_p\cos\theta_5 \\ &+(\text{-}\sin\theta_1\cos(\theta_2+\beta)\sin\theta_3+\cos\theta_1\cos\theta_3)l_p\sin\theta_5 \\ &+l_m\sin\theta_1\cos(\theta_2+\beta)\cos\theta_3+l_m\cos\theta_1\sin\theta_3+l_c\sin\theta_1\cos\gamma_t \end{aligned} \tag{4.21}$$

$$
\begin{aligned}
p_Z = &[(\sin(\theta_2+\beta)\cos\theta_3\cos\theta_4+\cos(\theta_2+\beta)\sin\theta_4)\cos\theta_5 \\
&-\sin(\theta_2+\beta)\sin\theta_3\sin\theta_5]l_d\cos\theta_6 \\
&+[-(\sin(\theta_2+\beta)\cos\theta_3\cos\theta_4+\cos(\theta_2+\beta)\sin\theta_4)\sin\theta_5 \\
&-\sin(\theta_2+\beta)\sin\theta_3\cos\theta_5]l_d\sin\theta_6 \\
&+(\sin(\theta_2+\beta)\cos\theta_3\cos\theta_4+\cos(\theta_2+\beta)\sin\theta_4)l_p\cos\theta_5 \\
&-l_p\sin(\theta_2+\beta)\sin\theta_3\sin\theta_5+l_m\sin(\theta_2+\beta)\cos\theta_3+l_c\sin\gamma_t
\end{aligned}
\tag{4.22}
$$

b) Workspace of Thumb

Based on the average length of human fingers (l_h = 189 mm) and ranges of each joints as specified in Table 4.3, the possible workspace of the thumb fingertip is plotted by using MATLAB as shown in Figure 4.6.

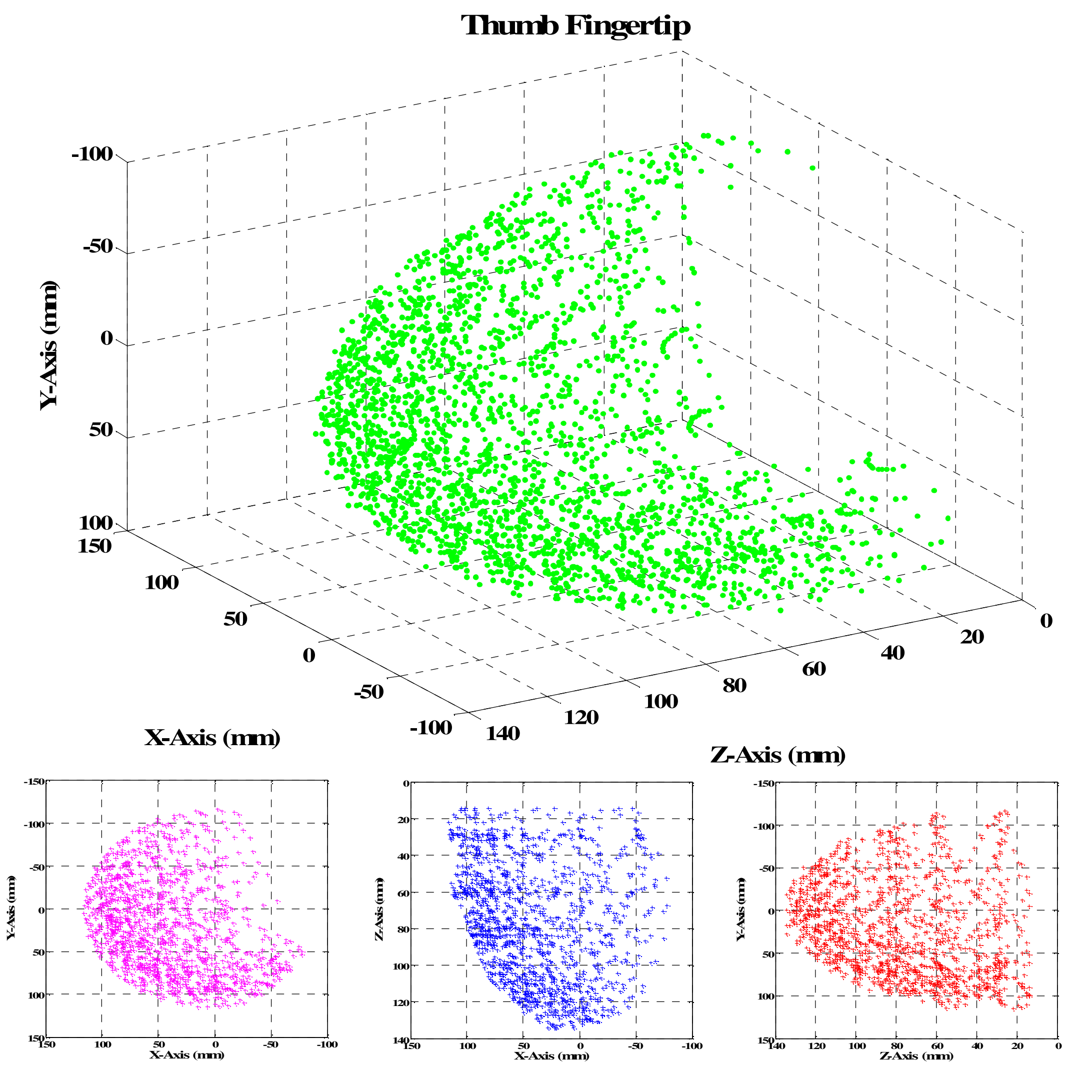


Figure 4.6: Workspace of Human Thumb Fingertip in Various Views

4.2 Study of Hand Rehabilitation Activities

4.2.1 Categorizing of Functional Rehabilitation Activities

In the following, we describe some common types of grips used in activities of daily living (ADL) tasks and rehabilitation exercises, based on the stages of recovery as reviewed in Section 2.2.

1) Five-Pulp Pinch

The five-pulp pinch shown in Figure 4.7 is a precision grip where an object is held in place by the pulps of the fingers and the thumb.

(a) Holding a Cup (b) Stacking Cones

Figure 4.7: Examples of the Five-Pulp Pinch [153]

First, the CMC joint (see Figure 4.7) of the thumb in this grip is abducted. Next, the MCP, PIP, DIP joints of the fingers and the IP joint of the thumb are flexed to secure the object between the pulps.

The muscles used in abduction of the CMC joint of the thumb are the extrinsic abductor pollicis longus and the intrinsic abductor pollicis brevis. For flexion of the MCP, PIP and DIP joints, the extrinsic flexor digitorum superficialis and flexor digitorum profundus are used. Flexion of the IP joint of the thumb is due to the extrinsic flexor pollicis longus.

The five-pulp grip is used mostly to wrap around cylindrical objects. Holding a cup or a bottle utilizes this type of grip. One can imagine this grip as making a letter C with the fingers and thumb. The five-pulp grip is used in many rehabilitation exercises such as stacking cones.

2) Lateral / Key Pinch

The lateral pinch grip is a grip where the pad of the extended thumb is pressing an object against the radial side of the index finger.

First, the MCP, PIP and DIP joints of the fingers are flexed. Next, the CMC, MCP and IP joints of the thumb are extended to make a thumb-up sign. Following this, the CMC joint of the thumb is slightly abducted. Finally, with the object between the lateral side of the index finger and the pulp of the thumb, the CMC, MCP and IP joints of the thumb are flexed to secure the object.

Muscles used in flexion of the fingers are the extrinsic flexor digitorum superficialis and the flexor digitorum profundus. Extension of the thumb uses the extensor pollicis brevis and extensor pollicis longus. Abduction of the CMC joint of the thumb involves the abductor pollicis brevis and abductor pollicis longus. Flexion of the joints of the thumb uses the flexor pollicis longus and flexor pollicis brevis. In addition, the first dorsal interosseus muscle provides an abduction force of the index finger against the adduction force of the thumb to securely grip the object.

The key grip is not frequently used in everyday life as many would prefer the pulp-to-pulp pinch. This grip also allows less fine movements, but is a stronger grip. An added advantage of this grip is that a person who has lost opposition of the thumb, but is still able to adduct the thumb to grasp small objects. For example, this grip is used when holding a card or turning a key into a lock or stirring a beverage with a teaspoon. It is also used during eating, where one has to grip utensils.

3) Pulp-to-Pulp Pinch

The pulp-to-pulp pinch is a precision grip where an object is held between the pulps of the thumb and one finger, usually the index finger or middle finger.

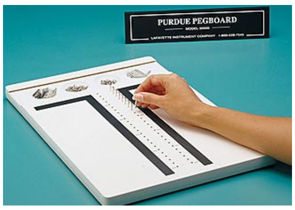
First, the CMC joint of the thumb is abducted so that the thumb is perpendicular to the index finger. The middle, ring and little fingers are not considered here as they have less function in the grip. Next, the MCP joint of the index finger is flexed to bring the pulp of the index finger opposite the pulp of the thumb. At this point, the user positions his hand such that the object is between both pulps. Finally, the PIP joint of the index finger is flexed to secure the object in the pinch. Depending on the size of the object, the PIP and DIP joints of the index finger may be flexed for small objects or extended for larger objects. Depending on the force required to secure the object, the IP joint of the thumb may be in flexion.

For the muscles involved in this grip, it is noted that the major motions of the thumbs and fingers are abduction of the thumb and flexion of the fingers. For abduction of the thumb, the muscles involved are the extrinsic abductor pollicis longus and the intrinsic abductor pollicis brevis. Flexion of the MCP and PIP joints of the index finger involves the use of the extrinsic flexor digitorum superficialis and flexor digitorum profundus.

The pulp-to-pulp pinch grip is used in many activities where a small object needs to be picked up or manipulated. For example, one would use a pulp-to-pulp pinch grip to pick up small objects like coins, medicine pills or pins. Tasks for accurate manipulation, such as threading a needle, also require this grip. When flipping the pages of a book, this grip may also be used although in this case, the other three fingers are extended and the page of the book is gripped between the thumb and index finger before being flipped.

The pulp-to-pulp pinch grip is used in many rehabilitation exercises (see Figure 4.8) such as depth perception pegboard set, easy grip pegs/boards, visual perception assessment program, Purdue pegboard test, pinch exerciser.

(a) Depth Perception Pegboard Set



(b) Purdue Pegboard Test

(c) Pinch Exerciser

Figure 4.8: Placing Tasks during Hand Rehabilitation [153]

For some of the rehabilitation exercises shown in Figure 4.9, such as resistive prehension bench and two-tiered horizontal bolt board and multi-functional work station, besides the pulp-to-pulp pinch, assembly is required.

(a) Resistive Prehension Bench

(b) Two-Tiered Horizontal Bolt Board

Figure 4.9: Assembly Tasks during Hand Rehabilitation [153]

4) Tripod Pinch

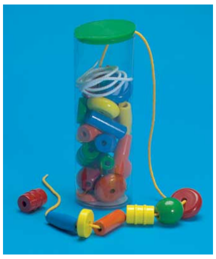
The tripod pinch is a precision grip where the object is held in between the radial or pulp sides of the index finger and middle finger. The thumb supports the object for stability.

First, the MCP joints of the fingers are abducted and the CMC, MCP and IP joints of the thumb is extended. Next, the MCP, PIP and DIP joints of the index and little fingers are in flexion. Finally, the IP joint of the thumb and the PIP and DIP joints of the index and middle fingers are flexed to secure the object.

The muscles involved for abduction of the fingers are the intrinsic interossei muscles while the muscles involved for extension of the CMC, MCP and IP joints of the thumb are the extrinsic extensor pollicis brevis and extensor pollicis longus. The flexor digitorum superficialis and flexor digitorum profundus act to flex the ring and little fingers and subsequently the index and middle fingers. The extrinsic flexor pollicis longus acts to flex the IP joint of the thumb.

The tripod grip is used when both stability and holding are needed. For example, this grip is used in preparation for throwing an object such as a baseball. This grip is also used when one is handling a pen, although variations of this grip exist as different people hold a pen differently. This grip is also used when one is controlling a computer mouse.

The tripod grip is used in many rehabilitation exercises (see Figure 4.10) such as Minnesota spatial relation test, Minnesota manual dexterity test, Jumbo beads and shape sorting cube.



(a) String-a-Lace Jumbo Beads

(b) Shape Sorting Cube

Figure 4.10: Placing Tasks with Stability During Hand Rehabilitation [153]

5) Power Grip

The cylindrical grip is a commonly used power grip. The object is positioned against the palm of the hand. The fingers are then flexed around the object, and the thumb wraps around the object in the opposite direction.

First, the MCP, DIP and PIP joints of the fingers are flexed, pushing the object against the palm of the hand. Then the CMC joint of the thumb is abducted to position the thumb. The IP and MCP joints of the thumb are then flexed so that the pulp of the thumb is in contact with the object.

For flexion of the fingers, the muscles involved are the extrinsic flexor digitorum superficialis and flexor digitorum profundus. For abduction of the CMC joint of the thumb, the muscles involved are the extrinsic abductor pollicis longus and the intrinsic abductor pollicis brevis. For the flexion of the IP joint of the thumb, only the extrinsic flexor pollicis longus muscle is involved. For flexion of the MCP joint, the extrinsic flexor pollicis longus and the intrinsic flexor pollicis brevis are used.

The cylindrical power grip is a commonly used grip in activities where relatively large force needs to be applied to an object. For example, this grip is used when one needs to hold a hammer. A large force needs to be applied to hammer a nail into a piece of wood, for example. This grip is also used in racquet sports, such as tennis and badminton. Because a large force is needed to hit the ball, this grip is necessary to ensure that the racquet does not fly out of the user’s hand. Other daily activities include gripping a door handle to turn it and gripping the handle of a pail.

4.2.2 Motion Sequences of Grips

Tables 4.4-4.8 summarize the sequence of motions for each of the five above-mentioned grips used in activities of daily living, the joints and muscles used in each sequence, and some uses of the grip in daily activities. The ranges of motion of the joints in each sequence are also given to cater to different sizes of objects to be gripped. It should be noted that the use of the grips in daily activities is non-exhaustive and that variations of the grips exist for various functions. This information is used in the measurement of the hand strength in Chapter 5 and also design of the robotics device in Chapter 6.

Table 4.4: Motion Sequences of the Five-Pulp-Pinch

Position	Initial	Intermediate	Final	
Illustration				
Joints in Motion	-	Abduction/adduction of CMC joint of thumb.	Flexion/extension of MCP, DIP, and PIP joints of fingers. Flexion/extension of MCP, IP joint of thumb.	
Range of Motion (Section 4.2)	-	CMC: 0 to 60	<u>Fingers</u> MCP: 0 to 90 PIP: 0 to 100 DIP: 0 to 60	<u>Thumb</u> CMC: 0 to 15 MCP: 0 to 50 IP: 0 to 80
Muscles Activated (Section 4.3)	-	1. APL 2. APB	1. FDS	1. FPB 2. FPL
Use in ADL	Holding cups, bottles and other cylindrical objects.			

Table 4.5: Motion Sequences of the Lateral Pinch

Position	**Initial**	**Intermediate**	**Final**
Illustration			
Joints in Motion	-	Flexion/extension of MCP, DIP, and PIP joints of fingers.	Abduction/adduction of CMC joint of thumb. Flexion/extension of MCP, IP joint of thumb.
Range of Motion (Section 4.2)	-	MCP: 0 to 90 PIP: 0 to 100 DIP: 0 to 60	CMC: 0 to 15 MCP: 0 to 50 IP: 0 to 80
Muscles Activated (Section 4.3)	-	1. FDS	1. FPL 2. FPB 3. FDI
Use in ADL	Holding flat objects such as cards, keys, toothbrush handle, and teaspoon.		

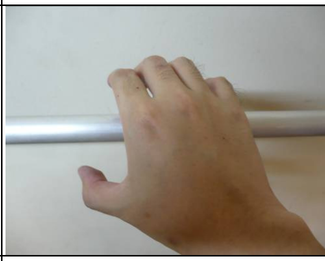
Table 4.6: Motion Sequences of the Pulp-to-Pulp Pinch

Position	**Initial**	**Intermediate**	**Final**	
Illustration				
Joints in Motion	Abduction/adduction of CMC joint of thumb.	Flexion/extension of MCP joint of index finger.	Flexion/extension of MCP, PIP, DIP joints of index finger. Abduction/adduction of CMC joint of thumb. Flexion/extension of MCP, IP joint of thumb.	
Range of Motion (Section 4.2)	CMC: 0 to 60	MCP: 0 to 90	Fingers MCP: 0 to 90 PIP: 0 to 100 DIP: 0 to 60	Thumb CMC: 0 to 60 MCP: 0 to 50 IP: 0 to 80
Muscles Activated (Section 4.3)	1. APB 2. APL	1. FDS	1. FDS	1. FPB 2. FPL 3.APB 4.APL
Use in ADL	Picking up small objects, e.g. Coins, medicine pills, pins. Threading a needle, flipping pages of a book.			

Table 4.7: Motion Sequences of the Tripod Pinch

<table>
<tr><th>Position</th><th>Initial</th><th colspan="2">Intermediate</th><th colspan="2">Final</th></tr>
<tr><td>Illustration</td><td></td><td colspan="2"></td><td colspan="2"></td></tr>
<tr><td>Joints in Motion</td><td>-</td><td colspan="2">Flexion/extension of MCP and IP joint of thumb.</td><td colspan="2">Flexion/extension of MCP, PIP, and DIP joints of ring, little fingers.
Flexion/extension of PIP, DIP joints of index, middle fingers.
Flexion/extension of IP joint of thumb.</td></tr>
<tr><td>Range of Motion (Section 4.2)</td><td>-</td><td><u>Fingers</u>
MCP:
0 to 20</td><td><u>Thumb</u>
CMC:
0 to 15
MCP:
0 to 20
IP:
0 to 80</td><td><u>Fingers</u>
MCP:
-45 to 90
PIP:
0 to 100
DIP:
0 to 60</td><td><u>Thumb</u>
IP:
0 to 80
CMC:
0 to 15</td></tr>
<tr><td>Muscles Activated (Section 4.3)</td><td>-</td><td colspan="2">1. FDI
2. EPL</td><td colspan="2">1. FDS
2. FPL
3. FPB</td></tr>
<tr><td>Use in ADL</td><td colspan="5">Holding small, spherical objects, like tennis ball, baseballs etc. Holding a pen, controlling a mouse.</td></tr>
</table>

Table 4.8: Motion Sequences of the Power Grip

<table>
<tr><th>Position</th><th>Initial</th><th colspan="2">Final</th></tr>
<tr><td>Illustration</td><td></td><td colspan="2"></td></tr>
<tr><td>Joints in Motion</td><td>Abduction/adduction of CMC joint of thumb.</td><td colspan="2">Flexion/extension of MCP, PIP, DIP joint of fingers.
Flexion/extension of IP joint of thumb.</td></tr>
<tr><td>Range of Motion (Section 4.2)</td><td>CMC: 0 to 60</td><td><u>Fingers</u>
MCP: 0 to 90
PIP: 0 to 100
DIP: 0 to 60</td><td><u>Thumb</u>
IP: 0 to 80</td></tr>
<tr><td>Muscles Activated (Section 4.3)</td><td>1. APL
2. APB</td><td>1. FDS</td><td>1. FPL</td></tr>
<tr><td>Use in ADL</td><td colspan="3">Holding a hammer, gripping a door handle, carrying a pail. Sports such as tennis, badminton and squash.</td></tr>
</table>

4.3 Kinematics Identification and Workspace Analysis of ADL Tasks

In order to securely hold an object for a specified task, the required kinematics joints angles are required for control purposes. In this section, the joint parameters associated to three specified tasks are identified. We also derive the required kinematics angles of the finger joints to securely holding an object in the specified task. The coordinates of any interested finger position, (x_p, y_p), can then be obtained by the derived joint angles θ_{nf} for four fingers or θ_{nt} for the thumb, in terms of the dimensions of the fingers and object held. The workspace of the three tasks is also studied to compare with the total workspace of normal hand movement.

4.3.1 Five Pulp Pinch

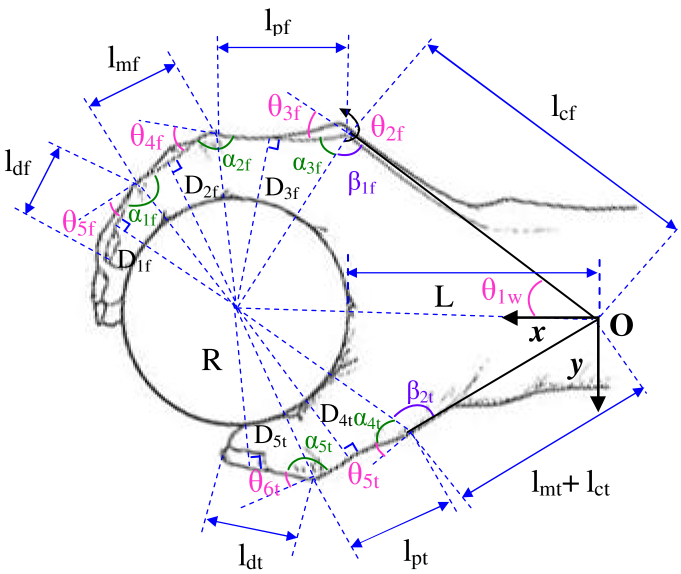


Figure 4.11: Schematic Kinematics Diagram of Five Pulp Pinch with a Holding Cylindrical Object

In Figure 4.11, xy is the local coordinate system located at the wrist origin O, while θ_{nf} and θ_{nt} defines the four fingers and the thumb's orientations with respect to its own coordinate system, and the joint angle θ_{2f} are fixed constant (refer to the θ_2 in Figure 4.3). For easy calibration and systemic control purpose, we assume that the center of the cylindrical object handled is aligned with the x axis and also

R = radius of the cylindrical object handled

L = distance between the wrist reference position to the rim of the object

D_{1f}, D_{2f}, D_{3f} = thickness of distal phalanx, middle phalanx, and proximal phalanx of the four finger respectively

D_{4t}, D_{5t} = thickness of distal phalanx, and proximal phalanx of the thumb respectively

Through trigonometry, the DIP joint angle of finger θ_{5f} then becomes

$$\theta_{5f} = \pi - \alpha_{1f} = \pi - 2\tan^{-1}\left[\frac{2\left(R + D_{1f}\right)}{l_{df}}\right] \tag{4.23}$$

Similarly, the PIP joint angle of finger θ_{4f} then becomes

$$\theta_{4f} = \pi - \alpha_{2f} = \pi - 2\tan^{-1}\left[\frac{2\left(R + D_{2f}\right)}{\left(2l_{pf} - l_{df}\right)}\right] \tag{4.24}$$

By using the law of cosines, the wrist angle θ_{1w} is

$$\theta_{1w} = \cos^{-1}\left\{\frac{(R+L)^2 + l_{cf}^{\ 2} - \left[\left(R + D_{3f}\right)^2 + \left(l_{pf} - l_{mf} + {l_{df}}/{2}\right)^2\right]}{2l_{cf}\left(R+L\right)}\right\} \tag{4.25}$$

By using the law of cosines, the angle β_{1f} is

$$\beta_{1f} = \cos^{-1}\left[\frac{l_{cf}^{\ 2} + \left(R + D_{3f}\right)^2 + \left(l_{mf} - l_{pf} + {l_{df}}/{2}\right)^2 - (R+L)^2}{2l_{cf}\sqrt{\left(R + D_{3f}\right)^2 + \left(l_{mf} - l_{pf} + {l_{df}}/{2}\right)^2}}\right] \tag{4.26}$$

Through trigonometry, the MCP joint angle of finger θ_{3f} then becomes

$$\theta_{3f} = \pi - \alpha_{3f} - \beta_{1f} = \pi - \tan^{-1}\left[\frac{2\left(R+D_{3f}\right)}{\left(2l_{mf} - l_{pf} + l_{df}\right)}\right] - \cos^{-1}\left[\frac{l_{cf}{}^{2} + \left(R+D_{3f}\right)^{2} + \left(l_{mf} - l_{pf} + {l_{df}}/{2}\right)^{2} - \left(R+L\right)^{2}}{2l_{cf}\sqrt{\left(R+D_{3f}\right)^{2} + \left(l_{mf} - l_{pf} + {l_{df}}/{2}\right)^{2}}}\right] \tag{4.27}$$

By using the law of cosines, the angle β_{2t} is

$$\beta_{2t} = \cos^{-1}\left[\frac{\left(l_{mt} + l_{ct}\right)^{2} + \left(R+D_{4t}\right)^{2} + \left(l_{pt} - {l_{dt}}/{2}\right)^{2} - \left(R+L\right)^{2}}{2\left(l_{mt} + l_{ct}\right)\sqrt{\left(R+D_{4t}\right)^{2} + \left(l_{pt} - {l_{dt}}/{2}\right)^{2}}}\right] \tag{4.28}$$

Through trigonometry, the MCP joint angle of the thumb θ_{5t} then becomes

$$\theta_{5t} = \pi - \alpha_{4t} - \beta_{2t} = \pi - \tan^{-1}\left[\frac{2\left(R+D_{4t}\right)}{\left(2l_{pt} - l_{dt}\right)}\right] - \cos^{-1}\left[\frac{\left(l_{mt} + l_{ct}\right)^{2} + \left(R+D_{4t}\right)^{2} + \left(l_{pt} - {l_{dt}}/{2}\right)^{2} - \left(R+L\right)^{2}}{2\left(l_{mt} + l_{ct}\right)\sqrt{\left(R+D_{4t}\right)^{2} + \left(l_{pt} - {l_{dt}}/{2}\right)^{2}}}\right] \tag{4.29}$$

Similarly, the IP joint angle of the thumb θ_{6t} then becomes

$$\theta_{6t} = \pi - \alpha_{5t} = \pi - 2\tan^{-1}\left[\frac{2\left(R+D_{5t}\right)}{l_{dt}}\right] \tag{4.30}$$

Taking the index finger as an example, based on the average length of human hand, the joint angles of the index finger and thumb can be calculated for different radius of the cylindrical object R using above equations.

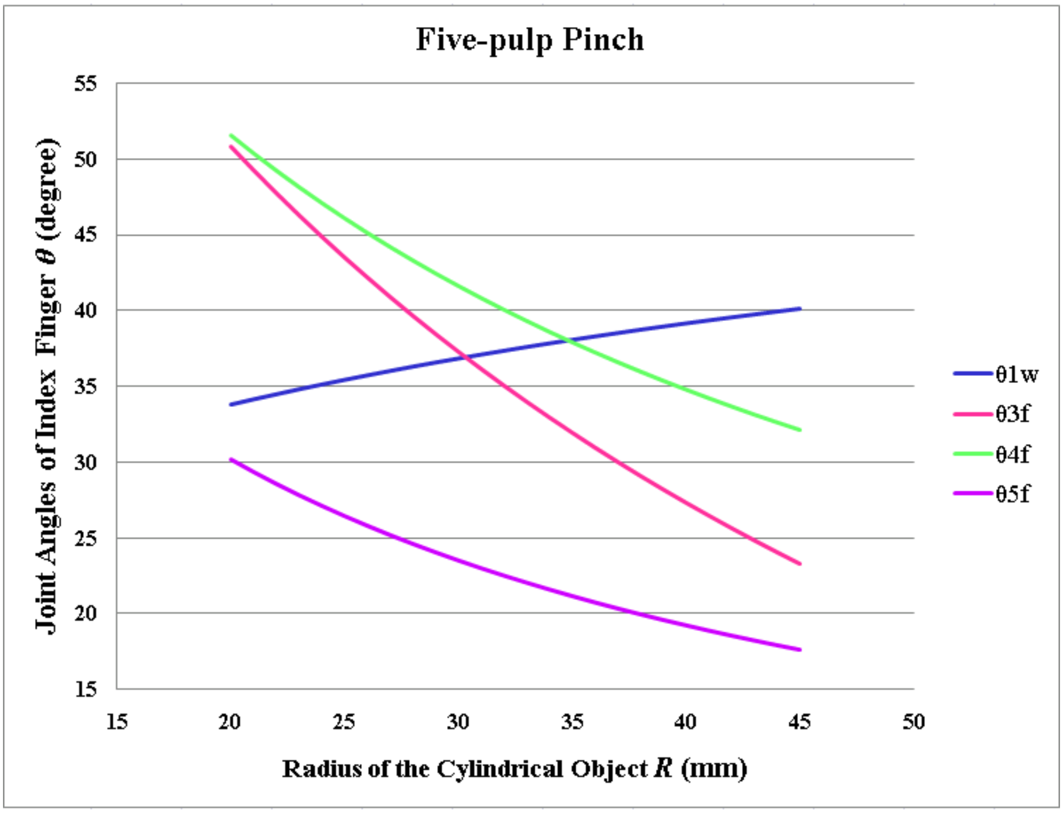


Figure 4.12: Required Joint Angles of Index Finger for Different Object Radius during Five-pulp Pinch

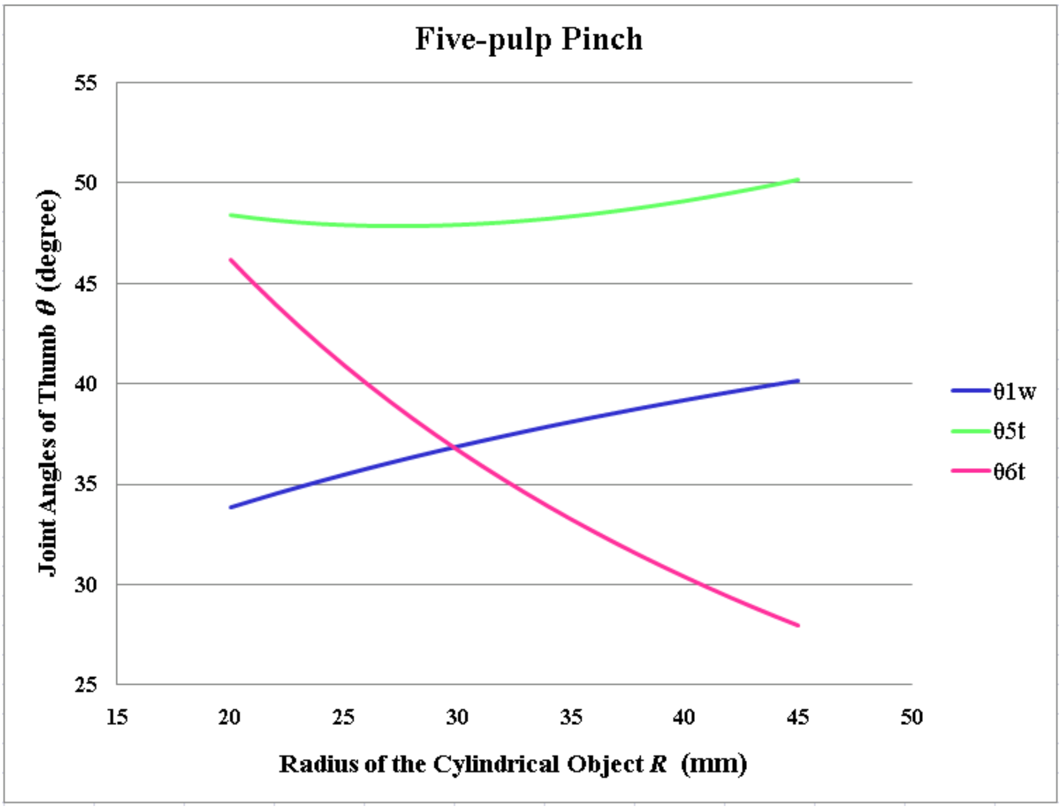


Figure 4.13: Required Joint Angles of Thumb for Different Object Radius during Five-pulp Pinch

Figure 4.12 shows the effects of object radius on the joint angles of index finger during five-pulp pinch, as the radius of the cylindrical object increases, the wrist angle θ_{1w} increases to accomplish this task, and the joint angles of index finger θ_{3f} to θ_{5f} decreases as less movement is required due to the bigger size of cylindrical object being held. Figure 4.13 shows the effects of object radius on the joint angles of the thumb during five-pulp pinch, as the radius of the cylindrical object increases, the joint angles of the thumb θ_{6t} decreases. However, the changes of the joint angle of the thumb θ_{5t} is much less compared to the joint angle of the thumb θ_{6t} .

Figure 4.14 shows the workspaces of five-pulp pinch of the index fingertip based on joint angles kinematics calculations above.

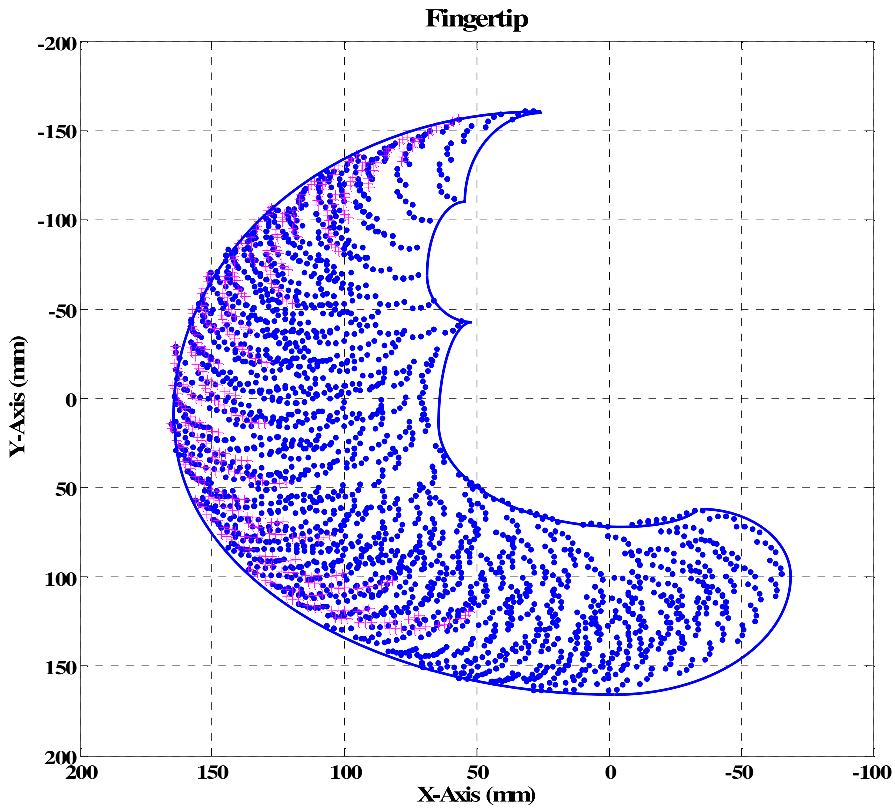


Figure 4.14: Workspace of the Index Finger Fingertip during Five-pulp Pinch (Total Workspace in Blue Colour and Five-pulp Pinch in Magenta Colour)

4.3.2 Lateral/Key Pinch

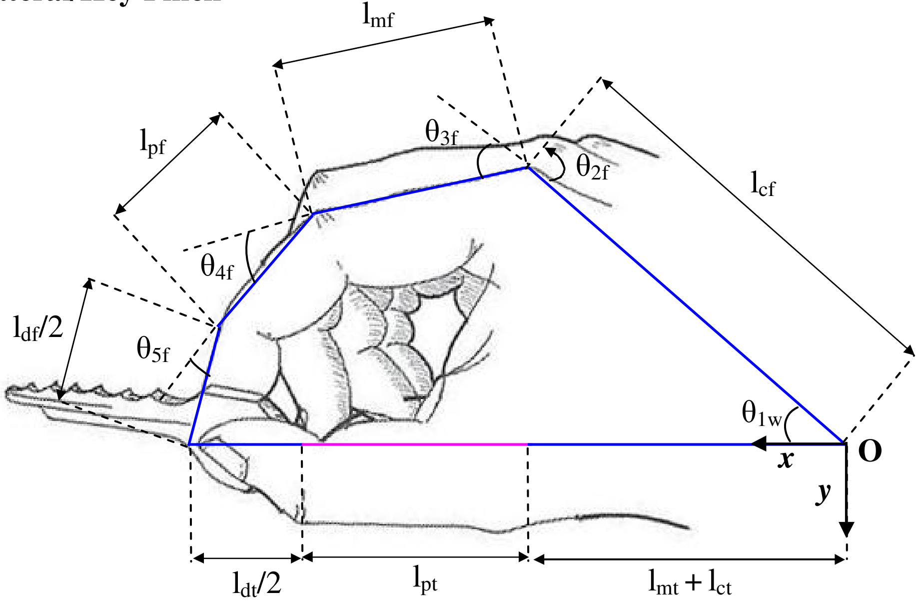


Figure 4.15: Schematic Kinematics Diagram of Lateral/Key Pinch with a Holding Key

In Figure 4.15, xy is the local coordinate system located at the wrist origin O, while θ_{nf} defines the four fingers orientations with respect to its own coordinate system, and the joint angle θ_{2f} are fixed constant (refer to the θ_2 in Figure 4.3). For easy calibration and systemic control purpose, we assume that the fingertip of thumb is aligned with the x axis.

As shown in Figure 4.15, the index finger and the thumb form a closed loop, so we have following equations in x and y directions

$$l_{cf}\cos\theta_{1w}+l_{mf}\cos(\theta_{3f}-\theta_{1w})+l_{pf}\cos(\theta_{3f}-\theta_{1w}+\theta_{4f})+{}^{l_{df}}\!/_{2}\cos(\theta_{3f}-\theta_{1w}+\theta_{4f}+\theta_{5f}) = {}^{l_{dt}}\!/_{2}+l_{pt}+l_{mt}+l_{ct} \quad (4.31)$$

$$l_{cf}\sin\theta_{1w}-l_{mf}\sin(\theta_{3f}-\theta_{1w})-l_{pf}\sin(\theta_{3f}-\theta_{1w}+\theta_{4f})-{}^{l_{df}}\!/_{2}\sin(\theta_{3f}-\theta_{1w}+\theta_{4f}+\theta_{5f})=0 \quad (4.32)$$

As the DIP joint angle of finger θ_{5f} is very small during key pinch, we assume that $\theta_{5f}\approx 0$ as shown in Figure 4.16(a). In order to hold the key in position, the range of the wrist angle θ_{1w} can be calculated.

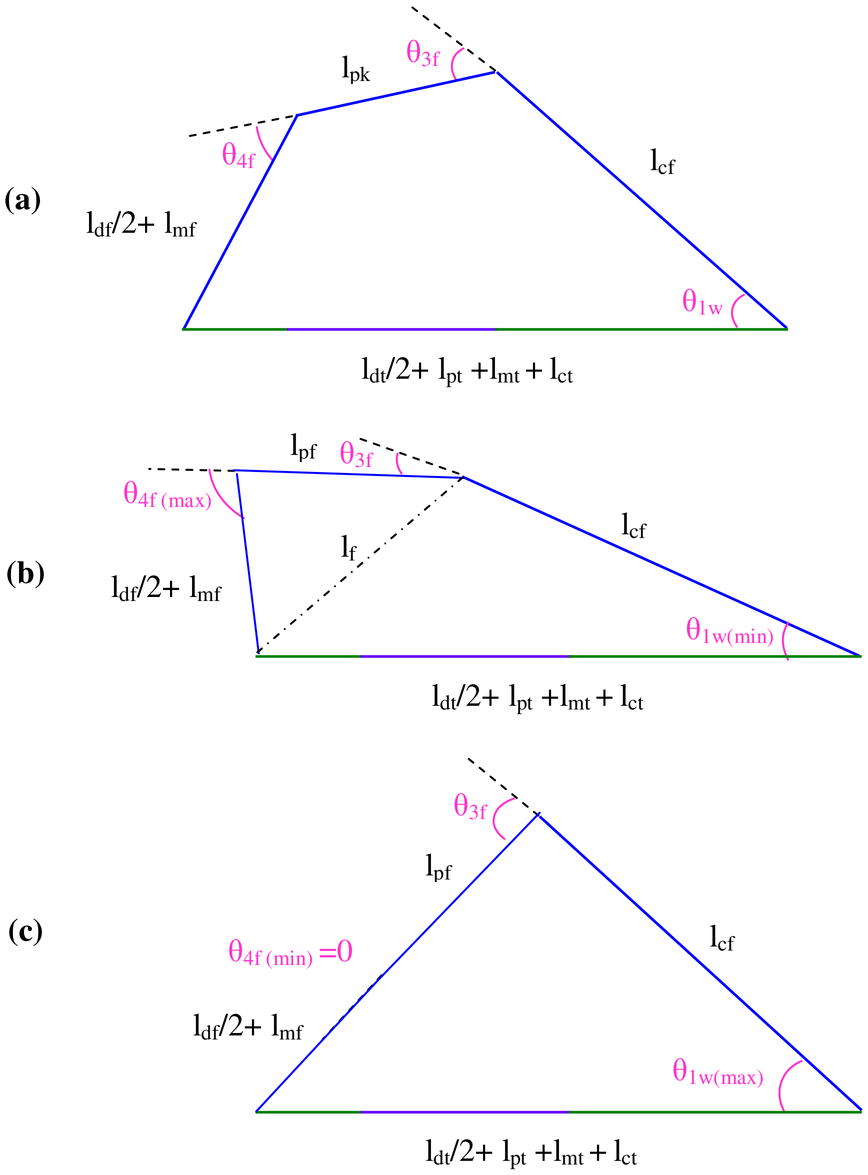


Figure 4.16: Simplified Schematic Kinematics Diagram of Lateral/Key Pinch

As shown in Figure 4.16(b), assuming the PIP joint angle of finger $\theta_{4f} = 100°$ (maximum flexion) based on the range of joint angle in Table 4.2 and by using the law of cosines, the length l_f becomes

$$l_f = \sqrt{l_{mf}^{\ 2} + \left(l_{pf} + {l_{df}}/{2}\right)^2 - 2l_{mf}\left(l_{pf} + {l_{df}}/{2}\right)\cos\left(\pi - \theta_{4f\,\max}\right)} \tag{4.33}$$

Similarly, as shown in Figure 4.16(c), when the PIP joint angle of finger $\theta_{4f} = 0°$ (maximum extension) based on the range of joint angle in Table 4.2, the length l_f then becomes

$$l_f = l_{mf} + \left(l_{pf} + {l_{df}}/{2} \right) \tag{4.34}$$

Based on the average segment lengths of index finger, in order to hold the key in position, the wrist angle θ_{1w} range from

$$23.1° \le \theta_1 \le 42.7°$$

With predefined angle θ_{1w}, the MCP and PIP joint angles of finger θ_{3f} and θ_{4f} can be solved using the above equations. For the patients with limited joint angle movement at a specific joint, the other joint angle required for compensation can be calculated in order to accomplish this key pinch. Figure 4.17 shows the required joint angles of index finger for different wrist angle during lateral/key pinch, as the wrist angle θ_1 increases, the joint angle of index finger θ_{3f} increases (take note that the $\theta_{3f(\max)} = 88.7° < 90°$ is within the limit of maximum flexion) and the joint angle of index finger θ_{4f} decreases.

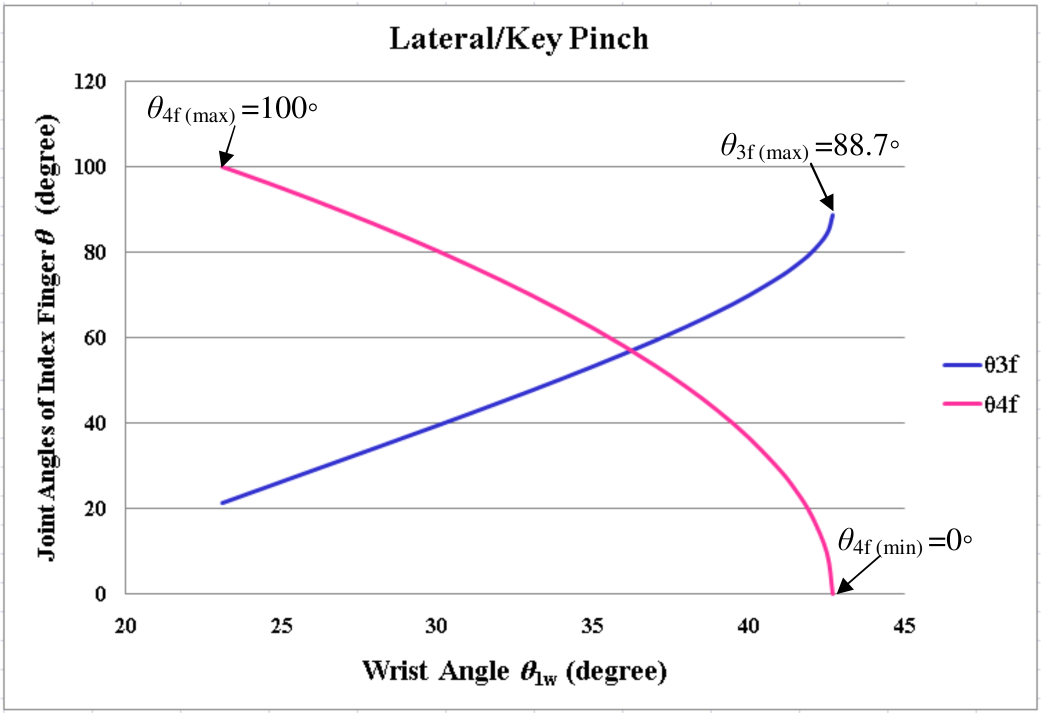


Figure 4.17: Required Joint Angles of Index Finger for Different Wrist Angle during Lateral/Key Pinch

Figure 4.18 shows the workspaces of key pinch of the index fingertip based on joint angles kinematics calculations above.

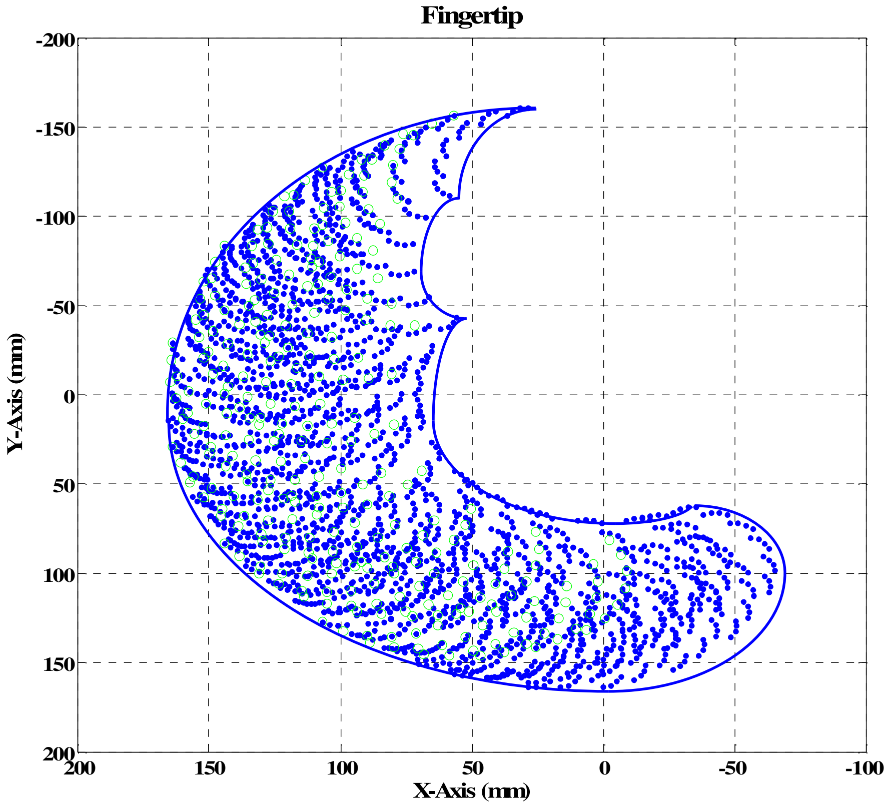


Figure 4.18: Workspace of the Index Finger Fingertip during Key Pinch (Total Workspace in Blue Colour, and Key Pinch in Green Colour)

4.3.3 Pulp-to-Pulp Pinch

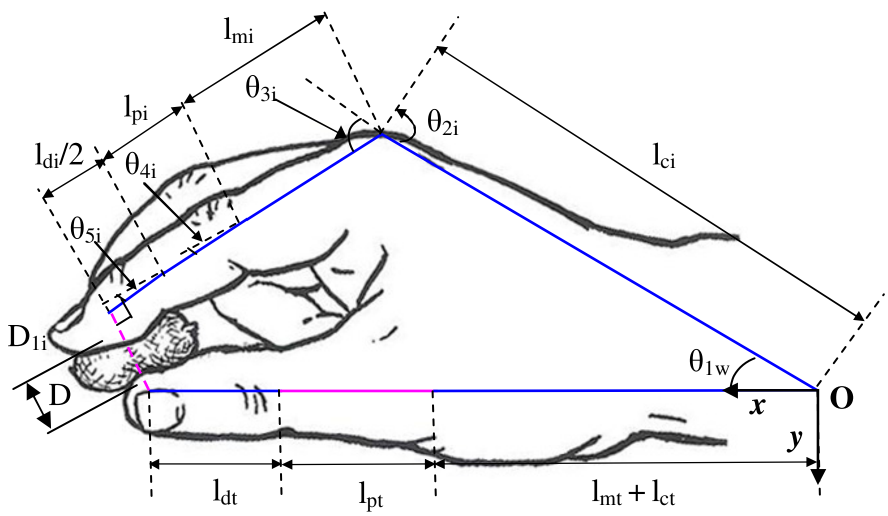


Figure 4.19: Schematic Kinematics Diagram of Pulp-to-Pulp Pinch with a Holding Tiny Object

In Figure 4.19, xy is the local coordinate system located at the wrist origin O, while θ_{ni} defines the index finger's orientations with respect to its own coordinate system, and the joint angle θ_{2f} are fixed constant (refer to the θ_2 in Figure 4.3). For easy calibration and systemic control purpose, we assume that the fingertip of thumb is aligned with the x axis and also

D = thickness of object handled

D_{1i} = thickness of distal phalanx of index finger

As shown in Figure 4.19, the index finger, the thumb and object forms a closed loop, so we have following equations in x and y directions

$$\begin{aligned} &l_{ci}\cos\theta_{1w} + l_{mi}\cos(\theta_{3i}-\theta_{1w}) + l_{pi}\cos(\theta_{3i}-\theta_{1w}+\theta_{4i}) + {}^{l_{di}}\!/_{2}\cos(\theta_{3i}-\theta_{1w}+\theta_{4i}+\theta_{5i}) \\ &-(D_{1i}+D)\sin(\theta_{3i}-\theta_1+\theta_{4i}+\theta_{5i}) = l_{dt}+l_{pt}+l_{mt}+l_{ct} \end{aligned} \tag{4.35}$$

$$\begin{aligned} &l_{ci}\sin\theta_{1w} - l_{mi}\sin(\theta_{3i}-\theta_{1w}) - l_{pi}\sin(\theta_{3i}-\theta_{1w}+\theta_{4i}) - {}^{l_{di}}\!/_{2}\cos(\theta_{3i}-\theta_{1w}+\theta_{4i}+\theta_{5i}) \\ &-(D_{1i}+D)\cos(\theta_{3i}-\theta_{1w}+\theta_{4i}+\theta_{5i}) = 0 \end{aligned} \tag{4.36}$$

As the DIP and PIP joint angles $\theta_{4i} = \theta_{5i} \approx 0$ during the pulp-to-pulp pinch, the equations can be simplified as follows,

$$\begin{aligned} &l_{ci}\cos\theta_{1w} + l_{mi}\cos(\theta_{3i}-\theta_{1w}) + l_{pi}\cos(\theta_{3i}-\theta_{1w}) + {}^{l_{di}}\!/_{2}\cos(\theta_{3i}-\theta_{1w}) - \left({}^{D_{1i}}\!/_{2} + D\right)\sin(\theta_{3i}-\theta_{1w}) \\ &= l_{dt}+l_{pt}+l_{mt}+l_{ct} \end{aligned}$$

$$l_{ci}\sin\theta_{1w} - l_{mi}\sin(\theta_{3i}-\theta_{1w}) - l_{pi}\sin(\theta_{3i}-\theta_{1w}) - {}^{l_{di}}\!/_{2}\sin(\theta_{3i}-\theta_{1w}) - (D_{1i}+D)\cos(\theta_{3i}-\theta_{1w}) = 0$$

With the known object thickness D, the wrist angle θ_{1w} and the MCP joint angle θ_{3i} can be solved using above equation. Figure 4.20 shows the effects of object thickness on the joint angles during pulp-to-pulp pinch, as the object thickness D increases, the wrist angle θ_{1w} increases to accomplish this task, and the MCP joint angle of index finger θ_{3i} decreases as less movement required for pinching larger objects.

Figure 4.21 shows the workspaces of five-pulp pinch, key pinch and pulp-to-pulp pinch of the index fingertip based on joint angles kinematics calculations above.

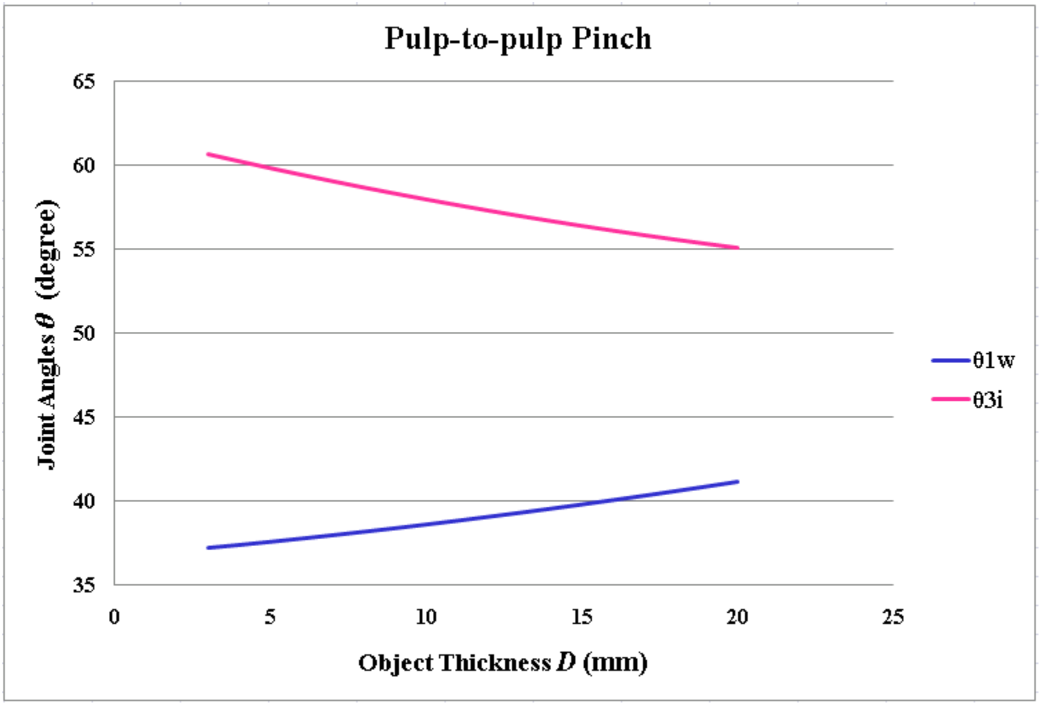


Figure 4.20: Required Joint Angles for Different Object Thickness during Pulp-to-pulp Pinch

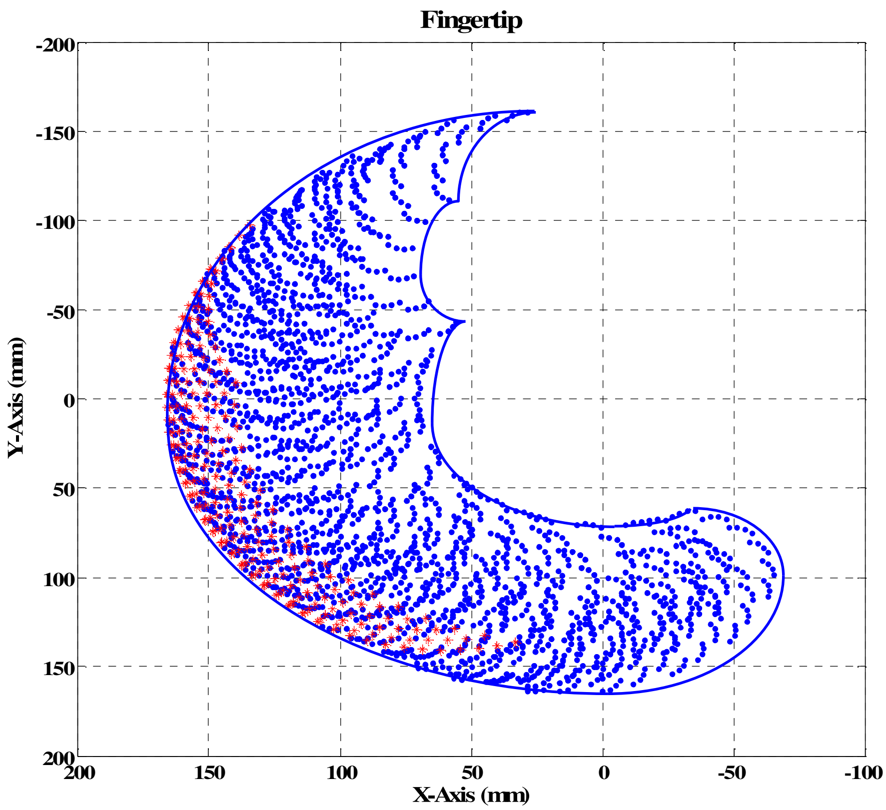


Figure 4.21: Workspace of the Index Finger Fingertip during Pulp-to-pulp Pinch (Total Workspace in Blue Colour and Pulp-to-pulp Pinch in Red Colour)

4.4 Virtual Modeling of Task-Specific Hand Motion

4.4.1 Virtual Modeling of Human Hand

Human hands can be viewed as a collection of rigid bodies, articulately connected by rotational joints with one or two degrees of freedoms (DOF). In this research, the model of human hand is proposed for the use of simulating five prehensile tasks in Section 5.1.1 which are commonly encountered in daily routine. The model is constituted by total 22 articulated rigid bodies, representing the palm, forearm, all phalanges and metacarpals of fingers.

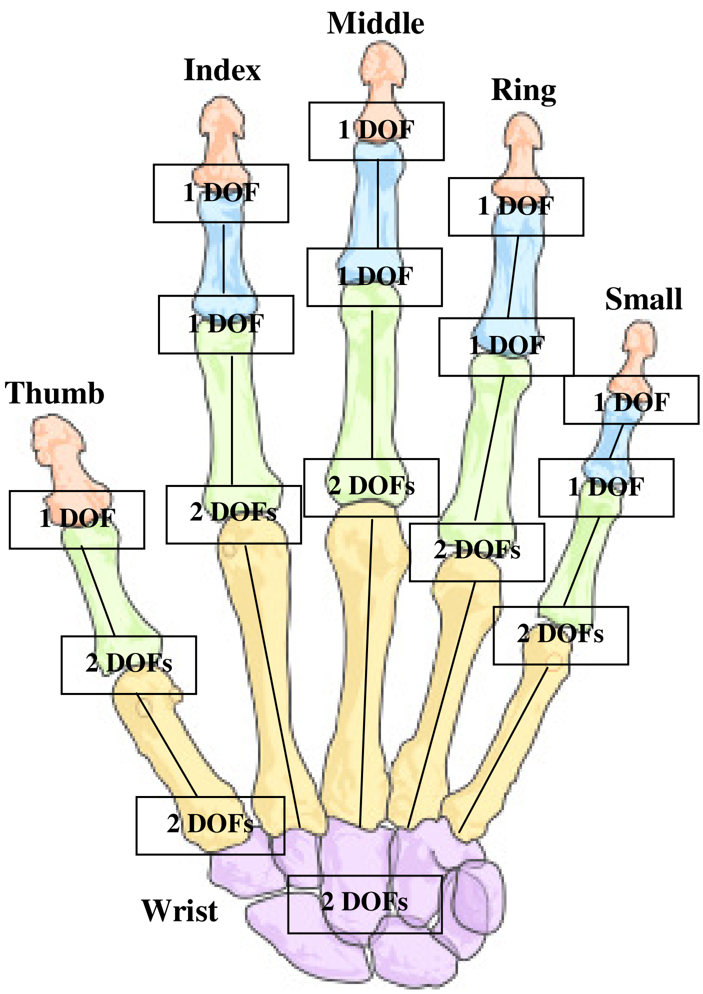


Figure 4.22: Kinematical Structure of Hand Model (modified from [160])

The number of DOFs for each joint is represented in the kinematical structure of hand shown in Figure 4.22. The overall hand model possesses 23 DOFs, which can be divided into 21 DOFs for the fingers and 2 DOFs for flexion/extension and abduction/adduction motions of the wrist joint. Each finger of proposed model has 4 DOFs, except the thumb has 5 DOFs. The DIP and PIP joints of fingers are modeled as revolute joints and capable of flexion/extension movements merely. The MCP joints of all fingers and CMC joint of thumb are modeled as universal joints and capable to perform both flexion/extension and abduction/adduction motions. Figure 4.23 shows the final assembly of the hand model.

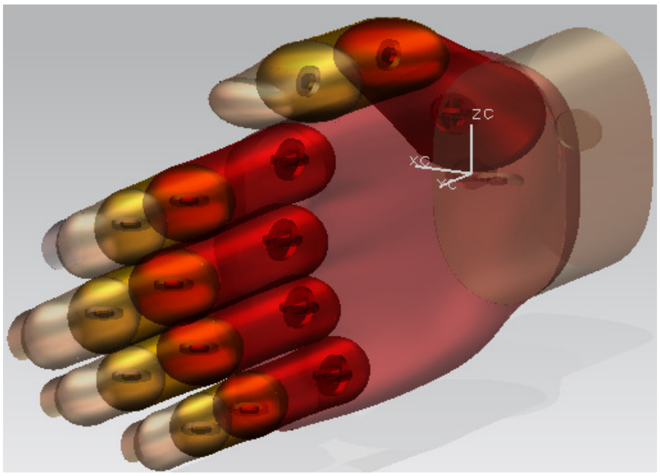
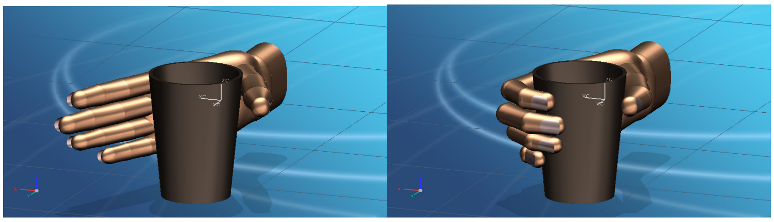


Figure 4.23: Virtual Hand Model using UGNX Software

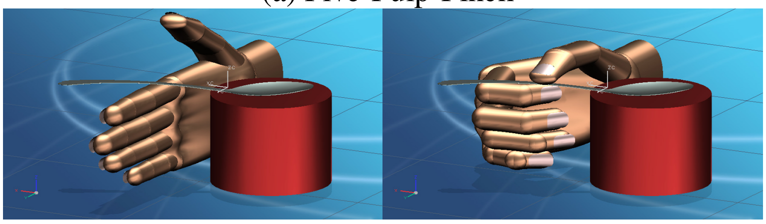
The hand magnitude and dimension of fingers vary for different percentile of people worldwide. Figure 4.1 describes the terms and notations used in the approach of modeling the human hand where l represents the segment length, subscripts d, m, p and c represent distal, middle, proximal phalangeal and carpo-metacarpal segments. The length of each bone segments are determined by two basic parameters only, which are the length of hand and breadth of palm represented by l_h and b_h respectively. In other words, the model is scalable entirely by simply varying the values of these two parameters. Hence, the hand magnitude of different populations and percentile groups can be calculated. The hand length and palm breath of male for the 50th percentile are 189 mm and 87 mm. By substituting l_h = 189 mm and b_h = 87 mm into the expressions listed in Table 4.1, those values are then utilized for setting the length of phalanges and metacarpals for every finger during modeling.

4.4.2 Animations of 5 Functional Tasks

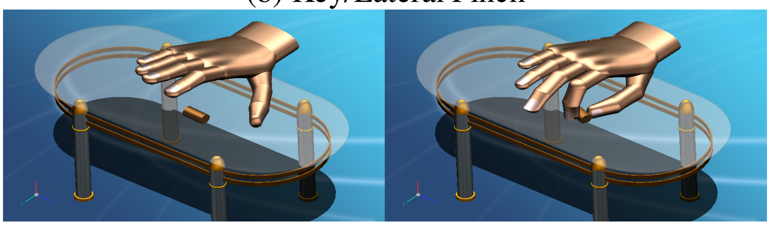
Figure 4.24 shows the snapshot of the initial and final position of the 5 functional tasks simulation. A cup model was used for the five pulp pinch as shown in Figure 4.24(a). A spoon model is used for key/lateral pinch is shown in Figure 4.24(b). A cylindrical object with diameter 15 mm and length 30 mm was built for pulp-to-pulp pinch as shown in Figure 4.24(c). A typical computer mouse was used for the tripod pinch as shown in Figure 4.24(d). A cylindrical bar was built for the power grip as shown in Figure 4.24(e).



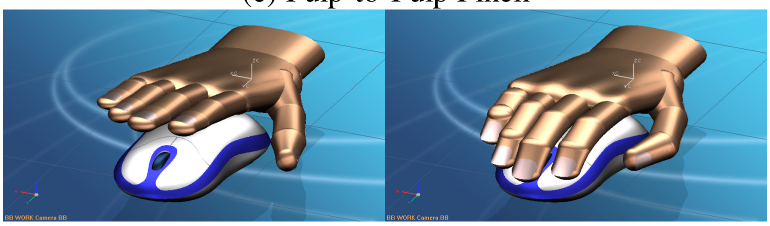
(a) Five-Pulp-Pinch



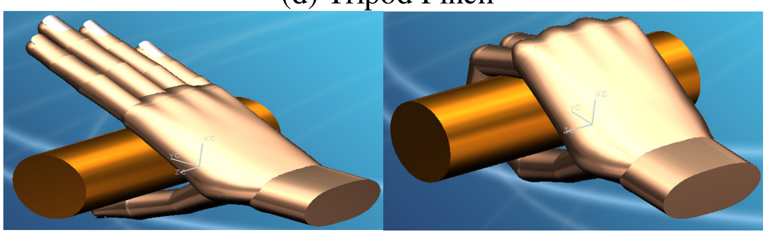
(b) Key/Lateral Pinch



(c) Pulp-to-Pulp Pinch



(d) Tripod Pinch



(e) Power Grip

Figure 4.24: Snapshots of Virtual Model for 5 Functional Tasks

The model is able to simulate and visualize its 3D motion for five ADL tasks under real-world operating conditions. The simulation models for the hand rehabilitation device will be established. Interactive simulations will be performed to demonstrate the control algorithms, which provide useful information for the design and control platform of the hand rehabilitation device being constructed, although an optimum DOF number (13 DOFs including wrist motion) as presented in Section 8.1.1 will be adopted in our hand rehabilitation device.

4.5 Summary

The modeling and analysis of human hand is presented, which consists of skeletal of human hand, the kinematics modeling of the fingers (Index, Middle, Ring and Small Fingers) and the thumb using D-H method and throughout its workspace. The forward kinematics is used to describe the positions and orientation of each finger joints for different anthropometry, which will be used in the kinematics identification of functional tasks.

Workspace analysis based on the kinematics model using D-H method provides workspace for each finger joint and fingertip, which is useful in comparing the patients with limited ROM against healthy subjects for assessment purposes. By knowing the workspace of human hand for healthy subject, the device is designed to provide the sufficient space for hand rehabilitation training.

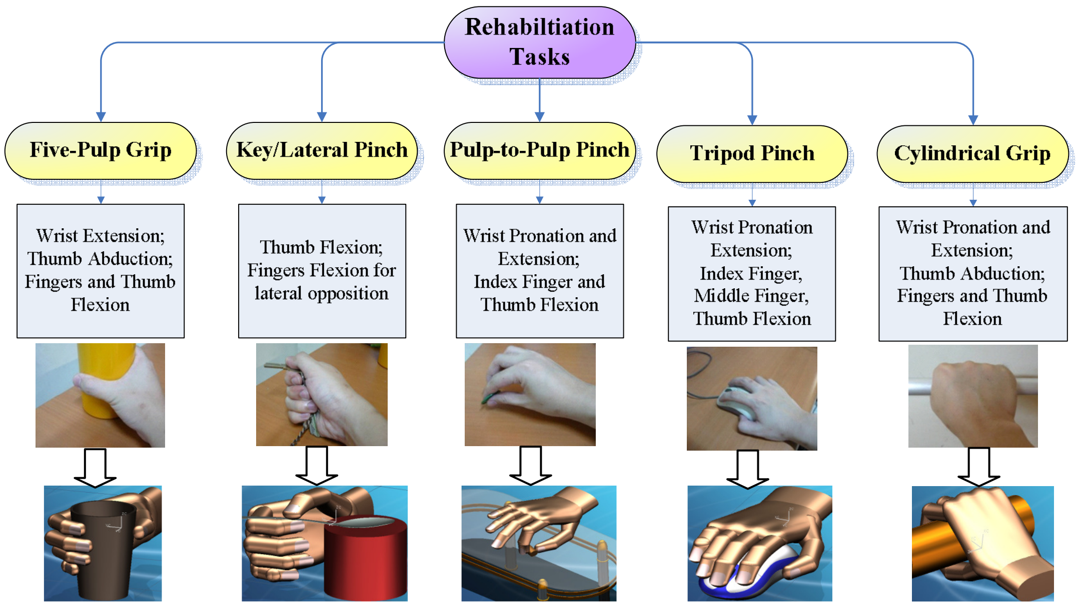


Figure 4.25: Five Selected Functional Tasks for Hand Rehabilitation

Based on the recovery stages of the stroke patients [64], five most common types of grips/pinches used in activities of daily living (ADL) tasks are selected and investigated in this research, as shown in Figure 4.25. In order to securely hold an object for a specified task, the required kinematics joints angles are required for control purposes. The kinematics and workspace analysis of ADL tasks (five pulp pinch, lateral/key pinch and pulp-to-pulp pinch) are also studied and discussed.

The 23-DOF virtual model was established according to the skeletal anatomy of a realistic human hand for performing simulations of the specified functional tasks. It is constituted from 22 articulated rigid bodies, representing palm, forearm, all phalanges and metacarpals of fingers, connected by rotational joints with one or two degrees of freedom. The model is able to simulate and visualize its 3D motion for five ADL tasks.

Chapter 5 DESIGN OF A HAND-FINGERS REHABILITATION DEVICE

Based on the findings of literature reviewed and the suggestion provided by doctors and therapists from local hospitals, several features for robotic assisted hand rehabilitation are proposed. Chapter 5 presents the design of the hand-fingers rehabilitation device, which covers design considerations, design for reduced DOFs, design and analysis of various modules of the robotics device for hand rehabilitation. After several design proposals on the design of the mechanism to cover most movements of the hand model, the concentric design of the finger module, simplified thumb module, wrist support module and assembled CAD model of the robotics device for hand rehabilitation are presented in details. The force analysis on the "load-free" concept, estimation of joint torques from EMG signals and the analysis on force required for flexion and effect of object's materials is also discussed. The supplementary design information can be found in Appendix A.

5.1 Design Considerations

After taken into considerations of the several factors based on the hand anatomy reviewed in Section 2.1 and the clinical requirements obtained in Section 3.7, the following requirements are considered in the design:

1) The device should be able to assist the thumb and the fingers in task-oriented training
2) The device should be able to provide sufficient torque to secure training objects
3) The device should be comfortable to be worn and it does not provide any hindrance while wearing it.
4) The device should be easy to put on and take off (should be less than 2 minutes).
5) The device should be safe for the user and is not hazardous to the user's health.
6) The user should be able to control the device with ease.
7) The length of the linkages should be made adjustable to allow patients with different hand sizes to use the device.

8) The palm should be free of mechanical elements to allow interaction with the environment.
9) The wrist module should provide sufficient support without restricting any hand motion.
10) The device should be as compact as possible. Hence, the overall device should be of good aesthetic that does not look intimidating to the user.
11) The device should be able to provide quantitative feedback (for the assessment for the forces and movements of the patient during rehabilitation).

As the robotic device is designed for rehabilitation purposes, it must be able to support functional ADL tasks. We consider two orientations of the device for different ADL tasks; the horizontal orientation is for pulp-to-pulp pinch tripod pinch, and power grip; the vertical orientation is for five-pulp-pinch and lateral pinch.

5.1.1 Reduced Degrees of Freedom

As shown in Figure 5.1, the human hand has 15 joints with more than 20 degrees of freedom (DOF), which is complex in terms of kinematics. If the joint movements are replicated well by the device, it will not accomplish the necessary therapeutic treatments and the device may injure or cause discomfort to the patients' hand. Therefore, it remains a challenge to optimize the necessary DOFs for a patient to perform the majority of key hand movements that are essential for hand functioning in activities of daily living (ADL).

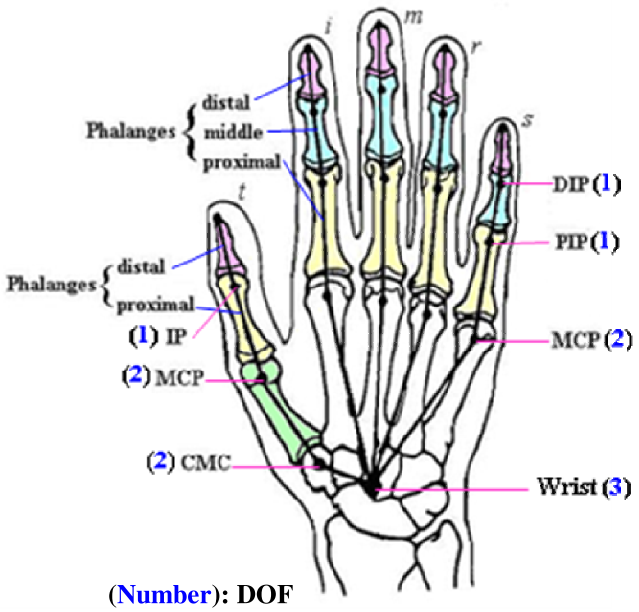


Figure 5.1: Kinematics Skeleton of Hand (Modified from [158])

Based on the study in Section 5.1.2, the required joint for all 5 functional tasks are: MCP, PIP, and DIP joints of the 4 fingers and CMC, MCP, and IP joints of thumb. And as the functional zones of human hand reviewed in Section 2.1.3, the five rays can be divided into three functional zones (see Figure 2.8): (1) the Thumb, (2) Index & Middle fingers, and (3) Ring & Small fingers.

To reduce the numbers of motor for adjacent fingers for specified rehabilitation training, the ring and small fingers are actuated together while the thumb, index & middle fingers are moved separately. Because the thumb is involved in almost all major activities, and index & middle fingers are essential in precision gripping, while the actuation is similar for index and middle fingers. This arrangement allows for gross grasping action of all the fingers and thumb, as well as more precise grasping using the index and/or middle fingers and thumb.

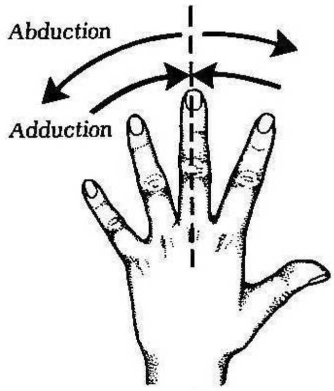


Figure 5.2: Abduction/Adduction of the Fingers [54]

As abduction/adduction shown in Figure 5.2 is less significant functionally than flexion/extension for most joints, these movements are controlled by small intrinsic muscles in the hand, which are difficult to actuate and not usually controllable by the patients. It will not be actively controlled, instead of passive except the CMC of the thumb and passive degrees of freedom for the MCP abduction/adduction are considered. In the thumb, flexion/extension and abduction/adduction are necessary and both degrees of freedom are actuated.

In order to accomplish the five functional tasks in the activities of daily living (ADL), both flexion/extension [161, 162] and supination/pronation [163] of wrist joint are important in completing those tasks, for example, holding cup for drinking in Five-Pulp-Pinch, holding keys for opening door and holding teaspoon for feeding in

Key/Lateral Pinch, flipping pages of a book in Pulp-to-Pulp Pinch, gripping a door handle in Power Grip.

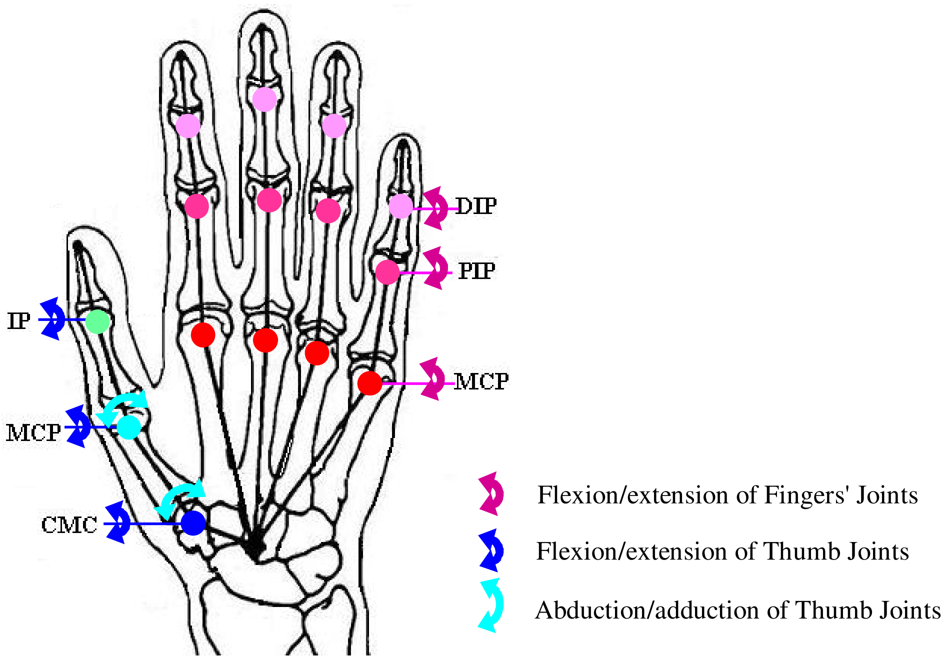


Figure 5.3: Joint Movement of Human Hand

Table 5.1: Required Joints of Motion for Five Functional Tasks

Tasks	Required Joints in Motion for Fingers	Required Joints in Motion for Thumb
Five-Pulp-Pinch	Flexion/extension of MCP, DIP, and PIP joints of fingers.	Abduction/adduction of CMC joint of thumb. Flexion/extension of MCP, IP joint of thumb.
Lateral Pinch	Flexion/extension of MCP, DIP, and PIP joints of fingers.	Abduction/adduction of CMC joint of thumb. Flexion/extension of MCP, IP joint of thumb.
Pulp-to-Pulp Pinch	Flexion/extension of MCP, PIP, DIP joints of index finger.	Abduction/adduction of CMC joint of thumb. Flexion/extension of MCP, IP joint of thumb.
Tripod Pinch	Flexion/extension of MCP, PIP, and DIP joints of ring, little fingers. Flexion/extension of PIP, DIP joints of index, middle fingers.	Flexion/extension of MCP and IP joint of thumb.
Power Grip	Flexion/extension of MCP, PIP, DIP joint of fingers.	Abduction/adduction of CMC joint of thumb. Flexion/extension of IP joint of the thumb.

As studied in Section 4.2.2, the required joints of motion for fingers and thumb is summarized in Table 5.1 with the illustration of joint movement shown in Figure 5.3. And according to the active degrees of freedom (DOF) and functions of the hand, the device consists of four sub-modules as listed in Table 5.2. The Index & Middle Fingers can be divided into two sub-systems, which are the two finger modules similar in design. Note that the whole system consists of 13 DOFs.

Table 5.2: Modules and its Joint Actions versus DOFs

No.	Module	Joints Actions Versus DOFs		
1	Wrist Support Module (1)	Wrist flexion/extension (1 DOF)	Wrist supination/ pronation (1 DOF)	
2	Index & Middle Fingers Module (6)	MCP flexion/extension (1 DOF for each finger)	PIP flexion/extension (1 DOF for each finger)	DIP flexion/extension (1 DOF for each finger)
3	Ring & Small Fingers Module (2)	MCP flexion/extension (1 DOF)	PIP and DIP flexion/extension (1 DOF)	
4	Thumb Module (3)	CMC abduction/adduction (1 DOF)	MCP flexion/extension (1 DOF)	IP flexion/extension (1 DOF)

5.1.2 Required Range of Motion (ROM)

In addition to determining which joints needed to be actuated, it is necessary to determine their range of motion (ROM), which is one of the important parameters. Most of the patients will not have full mobility in the hands, especially at the start of therapy, but it was deemed important for the device to be able to span the entire range. The ranges of motion shown in Table 5.3 are suggested for functional requirements. The hand motions are selected as most critical motion that helps patient to regain their ability on daily activities through rehabilitation.

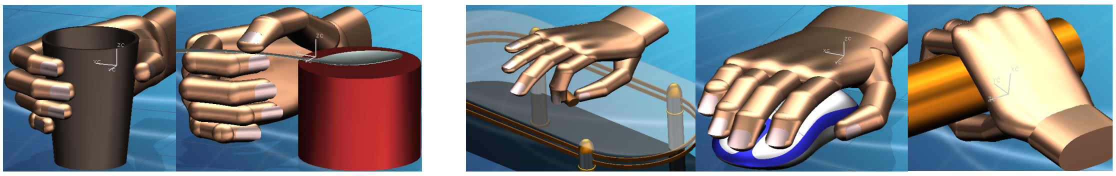
Table 5.3: Individual Joint ROM [55-57]

	Joints	**Flexion**	**Extension**	**Abduction**	**Adduction**	**Supination**	**Pronation**
Wrist	**-**	80°	-70°			90°	-90°
Thumb	CMC	60°	-20°	50°	-20°		
	MP	60°	-10°	30°	-30°		
	IP	90°	-20°				
Fingers	MCP	90°	-30°				
	PIP	100°	0°				
	DIP	60°	-5°				

5.1.3 Dual-configuration of Robotic Device

As the robotic device is designed with two placing configurations in order to train the key hand movements that are essential for hand functioning in activities of daily living (ADL), e.g. the five functional tasks that selected and studied in Chapter 5.

The "Thumb-up" orientation as shown in Figure 5.4(a) is designed for five-pulp-pinch and lateral pinch, for example, holding a cup or a bottle, holding a card or turning a key into a lock or stirring a beverage with a teaspoon. The "Palm-down" orientation as shown in Figure 5.4(b) is designed for pulp-to-pulp pinch, tripod pinch and power grip, for example, pick up small objects like coins, medicine pills or pins, handling a pen or controlling a computer mouse and holding a walking stick or door handle.



(a) "Thumb-up" orientation (b) "Palm-down" orientation

Figure 5.4: Two Placing Configurations of Robotic Device for Hand Rehabilitation

5.2 Concentric Design of Finger Module

Most of the existing robotics devices are not "load-free" design; the motors and mechanism are placed on the hand or forearm, which is neither desirable nor comfortable to the patient as she/he needs to carry the weight. To avoid this, the end points of the mechanisms (which are adjustable and suit for different anthropometry) are attached to each finger segments just like a therapist "holding' his/her hand to do the exercises (as illustrated in Figure 5.5). Using this arrangement, the patient will not feel the weight of the device when attach to it. Also, the patient can clearly visualize his/her hand movement when performing task-specific training with the object held.

The safety of the device can be ensured by the back drivability of the mechanism utilizing direct-drive actuators. For example, motor current limitations and diagnostics routines can also be implemented in software, in addition to emergency stops that are available at the interface.

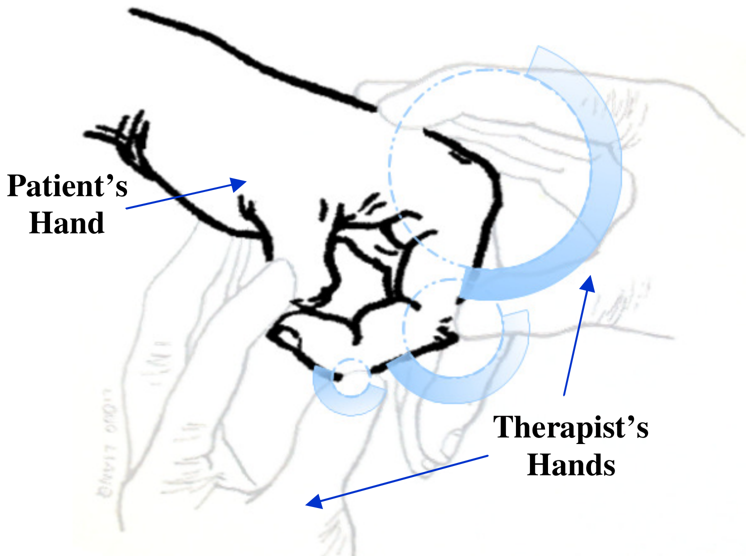


Figure 5.5: Proposed Rehabilitation Device to Imitate Like Therapist "Holding' Patient's Hand

5.2.1 Linear Motion Driven

A conceptual 3D model was developed to simulate the motions of the human finger to visualize and study the feasibility of using linear actuator for driving a finger (see Figure 5.6 the images cropped from the actual animation). The requirement of the simulation was to flex and extend the finger precisely and smoothly with three linear actuators working simultaneously for MCP, PIP and DIP joints of the finger.

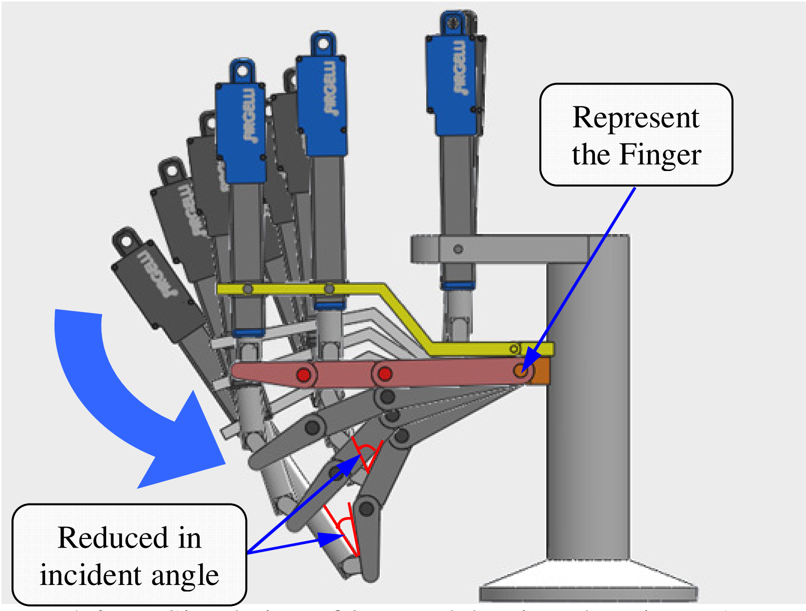


Figure 5.6**:** Simulation of 3D Model Driven by Linear Actuators

Observing from simulations of the 3D model in Figure 5.6, the incident angle to the finger decreased (< 90˚), as a result the apply force exerted on the intended area is reduced. The conditions became worse when the distal phalanx was flex to almost its maximum range where the linear actuator was at its maximum stroke length.

Thus alternative source of the driving actuator was explored; servo motor and DC motor were selected as the next potential actuator driver due to their precision and stability. However, the replacement of the linear actuator must be able to produce the same linear motions. Effort was made to design the mechanism for conversion of rotational motion to linear motion. Figure 5.7 shows the design of the rack and pinion, both of the drivers had undergone several revisions before been finalized for motion study in Solidworks.

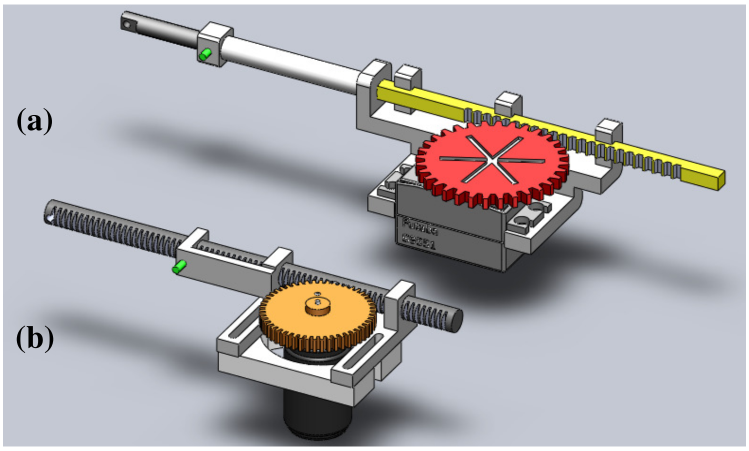


Figure 5.7**:** Drivers for Linear Motions (a) Servo Motor Driven, (b) DC Motor Driven

After having completed the two new drivers as shown in Figure 5.7, the next step was to assembly the driver together with the finger holder to form the finger module. However, a new problem had arisen over assembling the finger module. The new drivers took up a larger width and height, and they needed longer space for the cylinder to retract.

Figure 5.8 shows the physical mockup made for the purpose of testing the design workability. The mockup demonstrated the concept of design was feasible, however further analysis was needed to verity the workability of the device. Several attempts were made to reduce the size of the new drivers, including used of smaller motor and reduced the size of the base, but it was all failed.

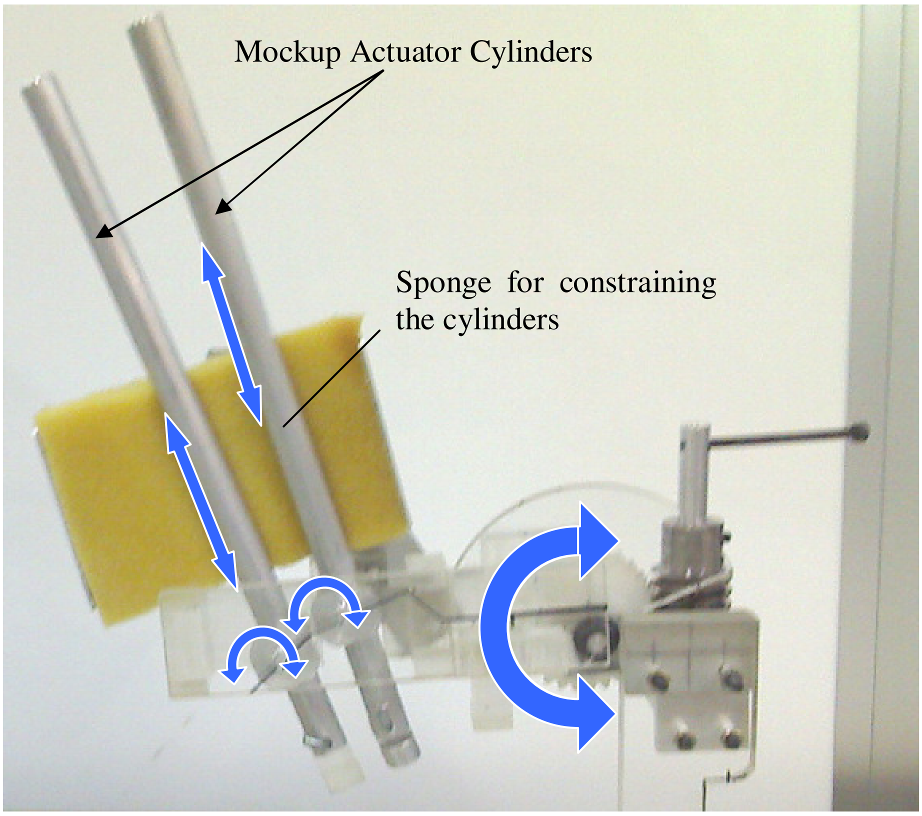


Figure 5.8**:** Physical Mockup of Index Finger Module

The key to the solution was to stagger the assembly, by changing the height of the drivers; the assembly was able to pack in more linear drivers at the same time minimized the potential of collision. Minor design changed was done to turn the protrusion parts away from each other helped space out the nearby drivers, as illustrated in Figure 5.9.

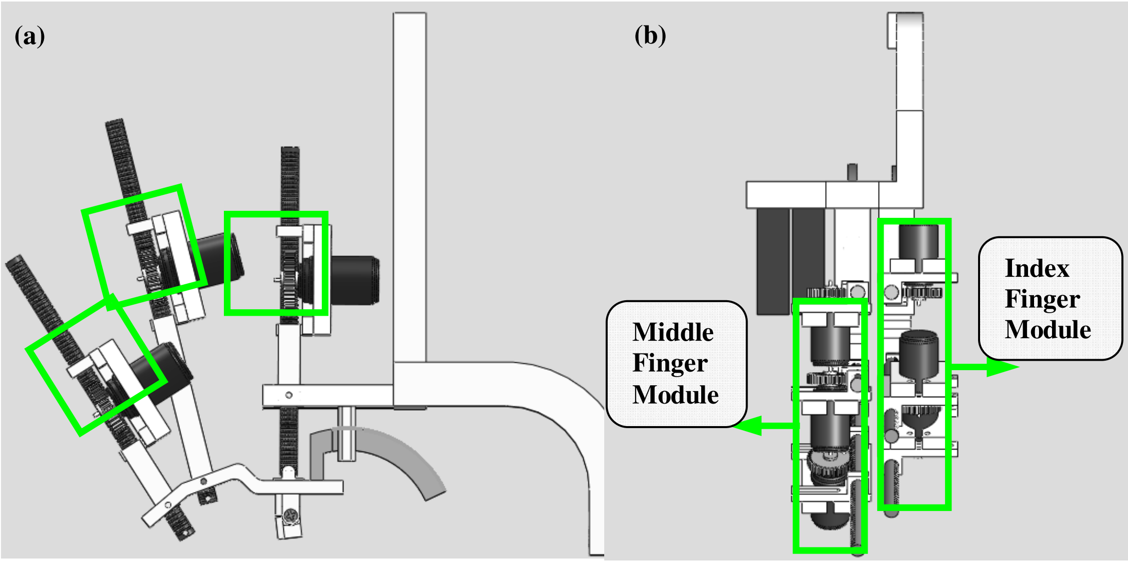


Figure 5.9: Stagger of the Drivers (a) Side view, (b) Top View

However, critical decision was made to drop this model of finger module due to the free dangling linear driver as shown in Figure 5.10 was observed in the finger module, the position of the cylinders at distal and middle phalanx were difficult to control and predict without introducing new limiting factor (more driver, more cost).

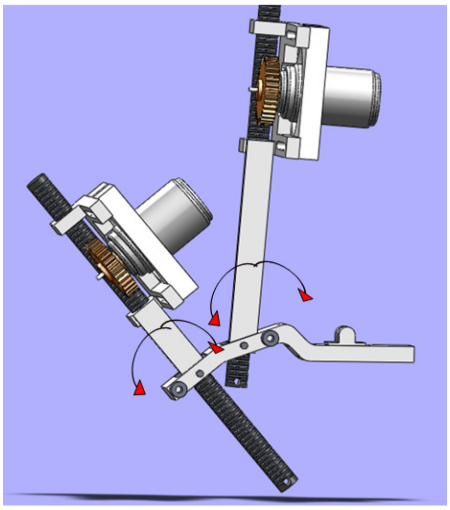


Figure 5.10**:** Free Dangling Motions in Single Plane

Furthermore, an observable safety issue was the potential failure of actuations sequence. If the actuators on the middle phalanx continued to extend while the distal phalanx and proximal phalanx actuators remained at the original position as illustrated in Figure 5.11, it would over extended the DIP and PIP joints and possible rupture of joints may occur.

To fundamentally solve all the problems mentioned above, a more ergonomics design was proposed to replace this model.

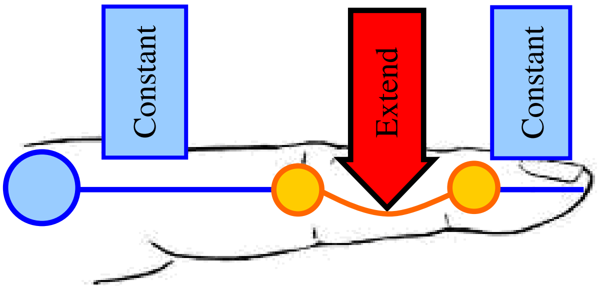


Figure 5.11: Force Exerting on Middle Phalanx

5.2.2 Angular Motion Driven

As shown in Figure 5.12, the rotation joint of the finger attachment linkages was not concentric with the DIP joint of the finger. Such a device would introduce shearing force on the mounting area between the attachment linkages and the patients' fingers due to displacement of the mounting point between the finger and the attachment linkages. So whenever a driving force was applied, the distal phalanx would be compressed toward the DIP joints first due to shear force before the finger bended to compensate the stress exerted on the joints.

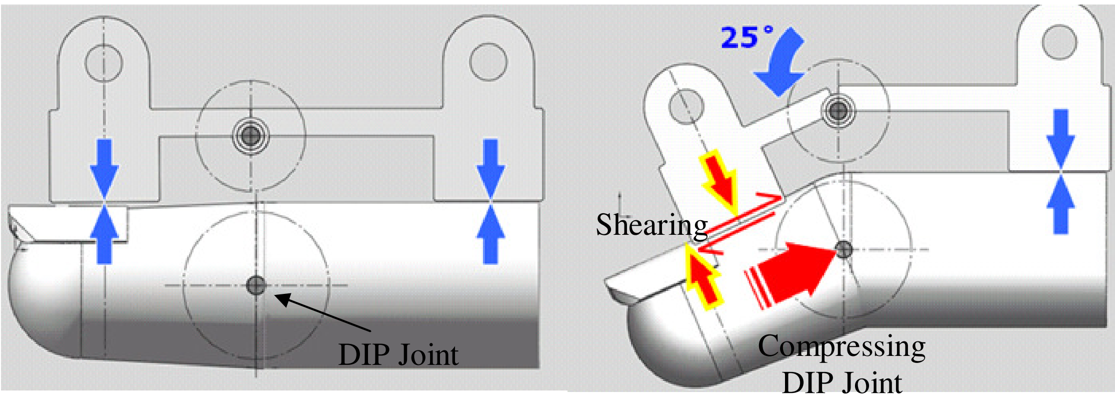


Figure 5.12: Illustration of Shear and Compression Forces Acting on the Mounting Area and Distal Phalanx Respectively for Non-Concentric Design

To prevent the device from shearing as well as achieving natural flexion and extension motions while driving the finger, the device must share the same rotation centre as the joints of the finger. In other words, the actuator should be designed to be concentric with the respective finger joints, as illustrated in Figure 5.13.

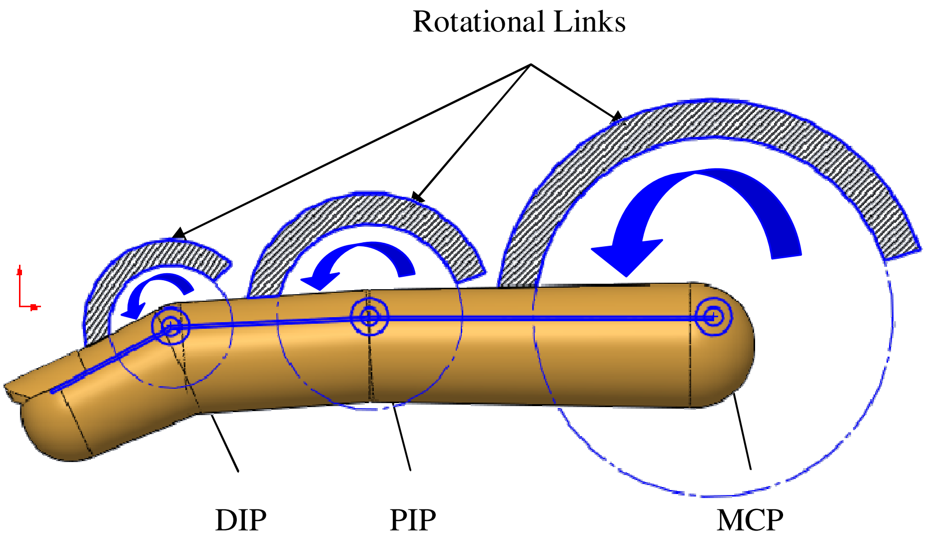


Figure 5.13: Concentric Design of the Finger Module

The model at early development phase was presented in Figure 5.14 with the full implementation of concentric design. The main difference between the two models was the removal of translational motion from the distal and middle phalanx and the finger holder. Angular driver was designed to replace the linear driver. The major advantage of the angular driver over the linear driver was it required less space to perform power transmission, angular driver did not require extra space for rack retraction, and hence it is smaller in design.

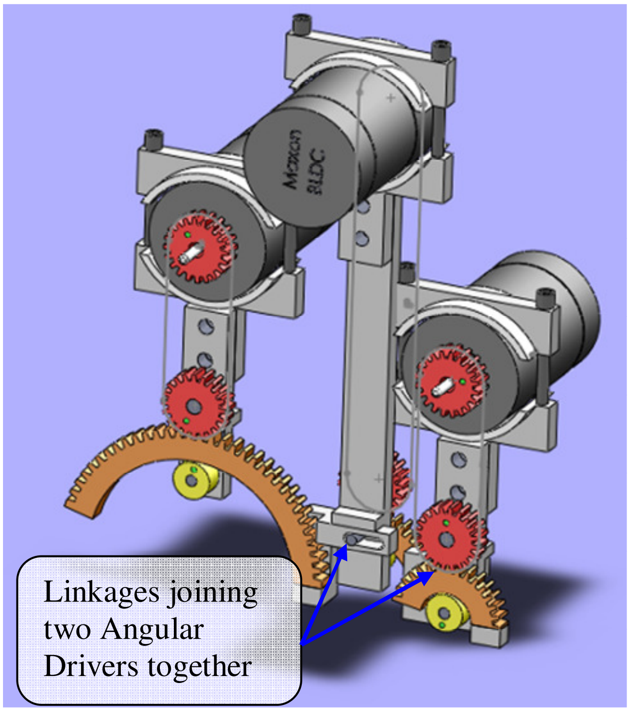


Figure 5.14: Finger Module with Concentric Design

As shown in Figure 5.14, the protrusion parts like the motors were oriented in an alternative manner to avoid potential collision with the neighboring motors and the angular driver for middle phalanx was designed to be higher for the purpose of creating spaces between the distal and proximal angular drivers.

In order to drive the finger, the three angular drivers were later joined together to work simultaneously. As shown in Figure 5.14, to link all three of the angular drivers together, linkages were designed to join the MCP angular driver with PIP angular driver, and PIP angular driver with DIP angular driver.

Each of the driving links (arc gears) is a modified external gear which half of the gear been removed. The arc gears are secured on a driver module by roller and bearings to produce smooth and stable motions. A precision digital servo motor with optical encoder is used to drive the arc gear to achieve rotary motions which will assist the finger joints to rotate simultaneously according the pre-determined angles independently in a task-oriented therapy. The MCP driver is shown in Figure 5.15.

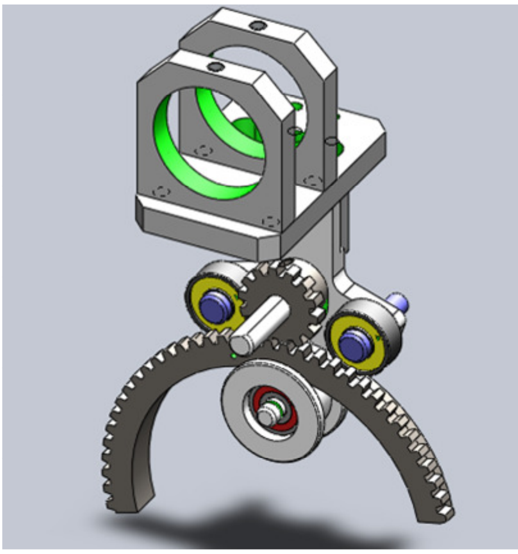


Figure 5.15: MCP Driver without Servo Motor

For a finger to function normally, each finger joint is required to flex and extend independently, hence the device is designed to have three drivers on each fingers providing sufficient torques for the respective fingers to move. Based on the hand anatomy, the PIP and DIP joints are in relative motion with the MCP joint, whenever the MCP flex or extend the two joints will displace in the direction of the MCP flexion or extension. Same for the DIP joint, whenever PIP joint flex or extend it will displace accordingly.

In order to satisfy the motions mentioned above, drivers for the three joints are designed separately with independent motors that are joined together through the yellow linkages (as shown in Figure 5.16) to create a device with three degree of freedoms (DOF) for each finger. The linkage length is adjusted according to the segments length of finger for individual patient (based on the calculation in Table 4.1). The conception design of the index & middle finger module is illustrated in Figure 5.16.

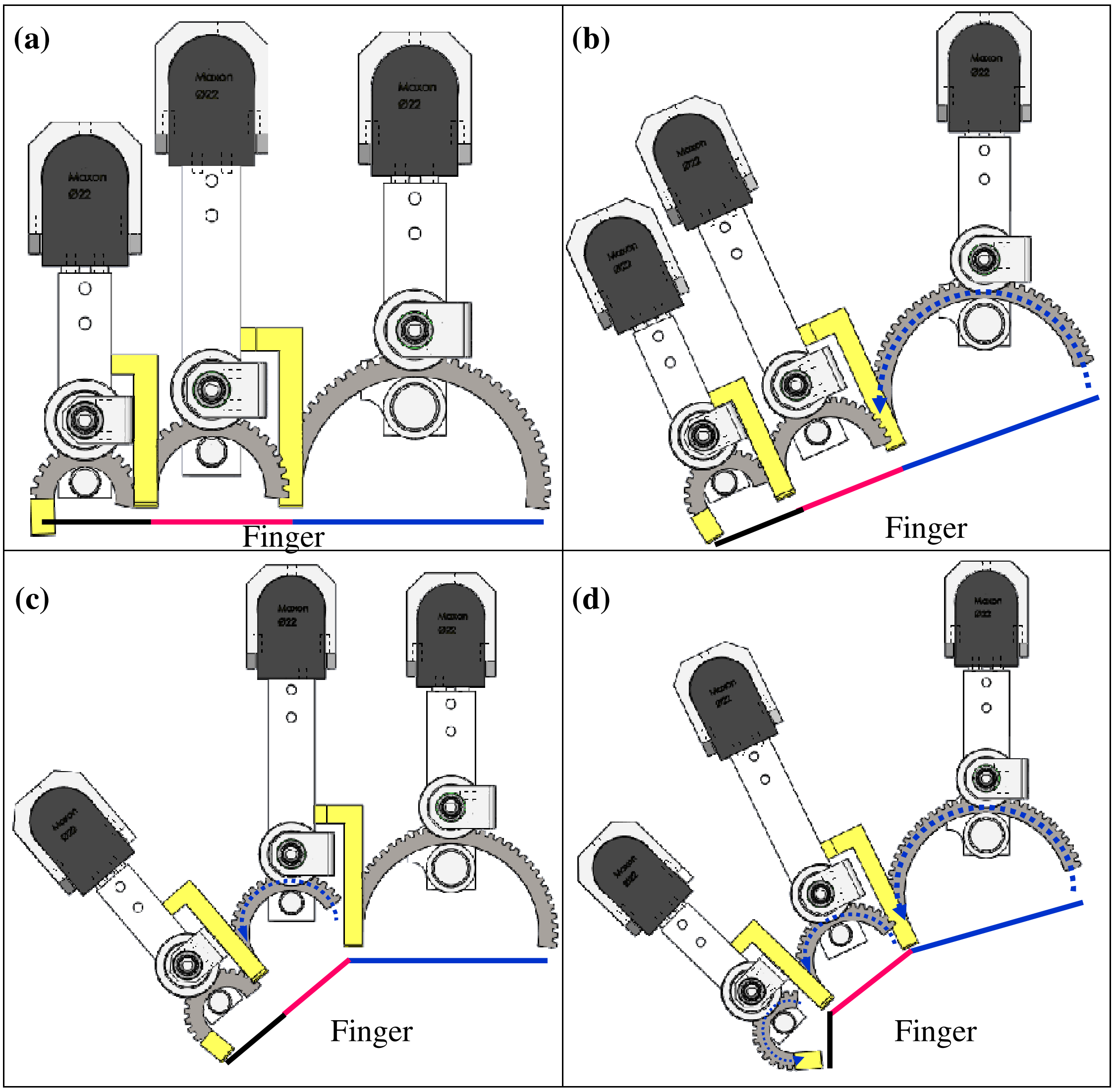


Figure 5.16: (a) Index Module at Neutral Position, (b) MCP Rotated, PIP & DIP Stayed Neutral, (c) DIP Rotated, MCP & PIP Stayed Neutral, and (d) All Three Joints Rotated.

5.2.3 Non-concentric Design Vs Concentric Design

The method using the linear actuator is able to push/pull the finger easily with free of the task workspace. However, as the finger joints rotate, the end point of linear actuator is no longer perpendicular to the finger surface as shown in Figure 5.17(a), which produces the large shear force. And the safety issue is the potential failure of actuations sequence, if the linear actuator on the middle phalanx is over extended compared to the distal phalanx and proximal phalanx actuators.

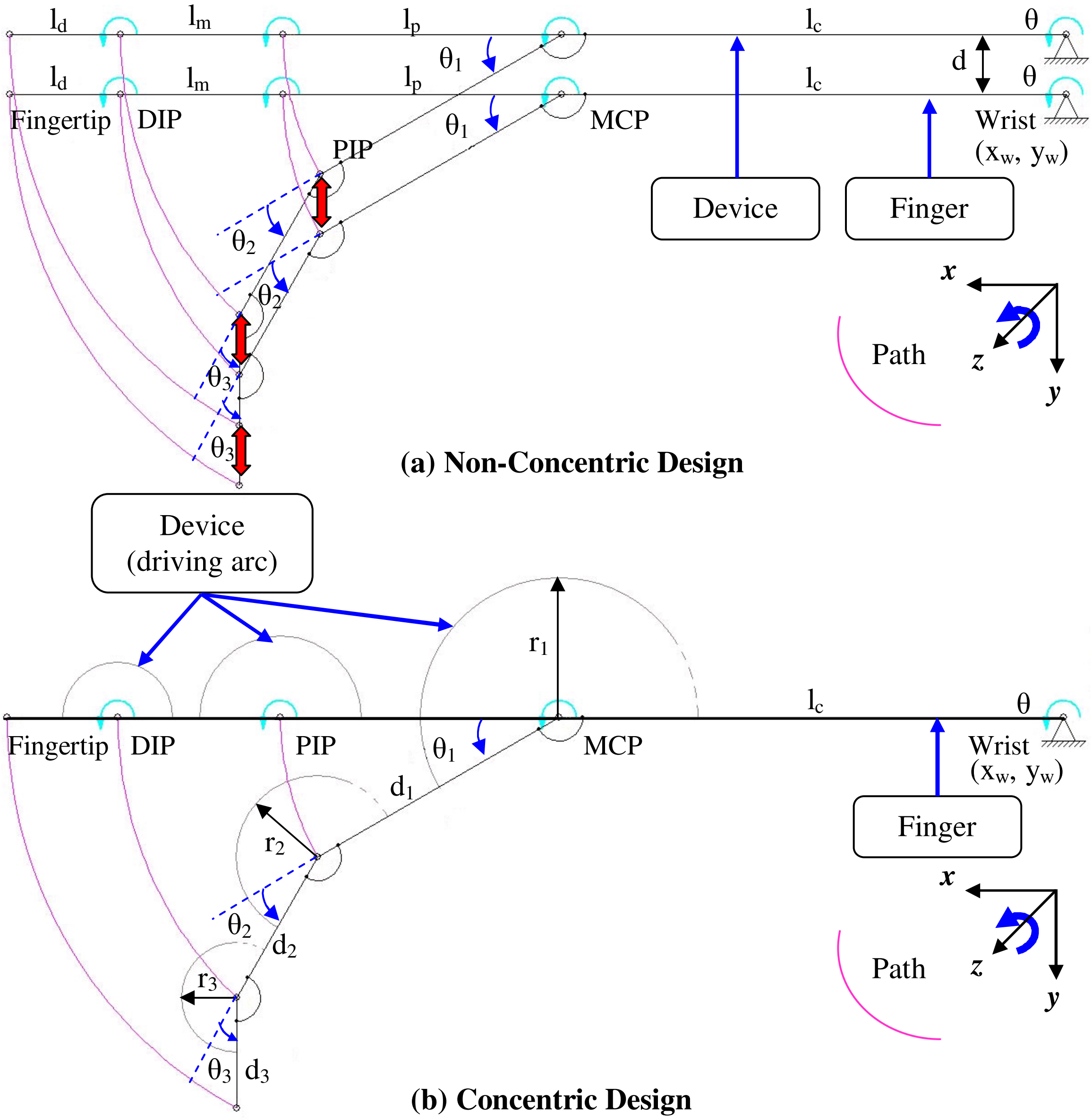


Figure 5.17: Comparison of Path Analysis using SAM Software between the Non-concentric Design and Concentric Design of Finger Module

In order to prevent the device from shearing the finger during flexion and extension, the angular driving method is preferred. However, if the driving mechanism is placed on the finger directly, the path of each finger joint and fingertip are different from the actual finger as shown in Figure 5.17 (a), with shear force induced. The proposed finger module by angular motion driven is designed to share the same rotation centre as the joints of human hand, which is called concentric design shown in Figure 5.17 (b). Figure 5.17 shows the images cropped from the actual animation for comparison.

For concentric design as shown in Figure 5.17(b), the position vector of device located at human fingertip is

$$x_{Concentric\,device,f} = x_w + l_c \cos\theta + (r_1 + d_1 + r_2)\cos\theta_1 + (r_2 + d_2 + r_3)\cos\theta_2 + (r_3 + d_3)\cos\theta_3 \tag{5.1}$$

$$y_{Concentric\,device,f} = y_w + l_c \sin\theta + (r_1 + d_1 + r_2)\sin\theta_1 + (r_2 + d_2 + r_3)\sin\theta_2 + (r_3 + d_3)\sin\theta_3 \tag{5.2}$$

since $\quad r_1 + d_1 + r_2 = l_p; \quad r_2 + d_2 + r_3 = l_m; \quad r_3 + d_3 = l_d$

The position vector of device located at human fingertip becomes the same as the position vector of human fingertip. And they share the same paths for the each joints of fingers (see the paths in pink color in Figure 5.17(b)).

$$x_{Concentric\,device,f} = x_w + l_c \cos\theta + l_p \cos\theta_1 + l_m \cos\theta_2 + l_d \cos\theta_3 = x_{fingertip} \tag{5.3}$$

$$y_{Concentric\,device,f} = y_w + l_c \sin\theta + l_p \sin\theta_1 + l_m \sin\theta_2 + l_d \sin\theta_3 = y_{fingertip} \tag{5.4}$$

The detailed illustration of MCP, PIP and DIP joints rotation is shown in Figure 5.18, where the arc angles for the rings are constant during rotation.

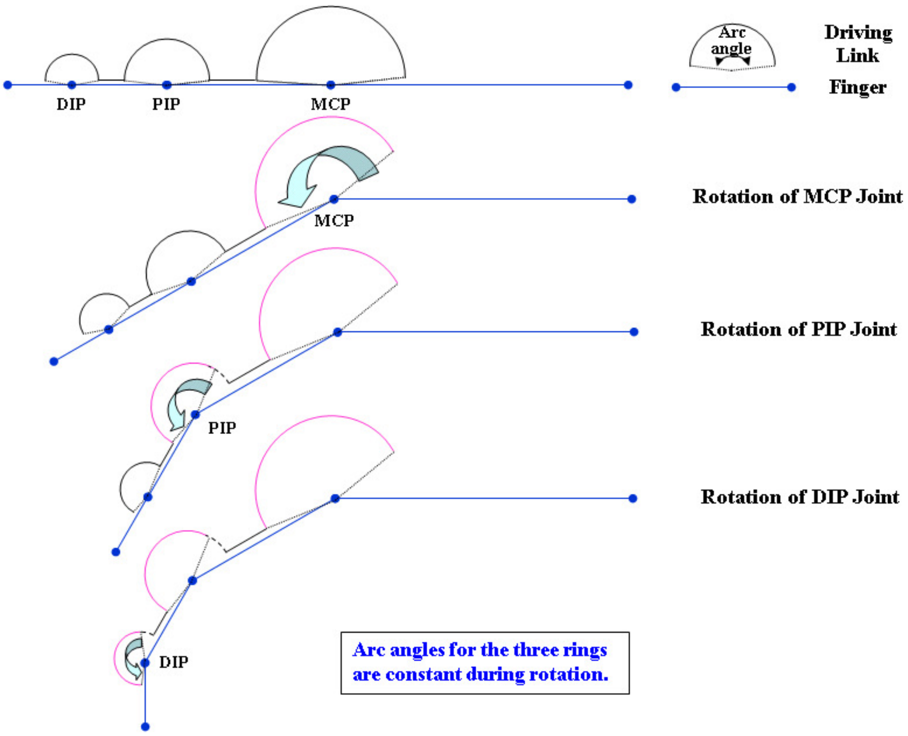


Figure 5.18: Illustrations of MCP, PIP and DIP Joints Rotation by Angular Motion Driven Method of Finger Module

5.2.4 Embodiment Design of Index and Middle Finger Modules

To prevent the device from shearing the finger while driving the finger flexion and extension, the finger module for Index & Middle fingers is designed to share the same rotation centre as the joints of human hand. Each of the driving links is a modified external gear which half of the gear been removed. The arc gears are secured on a driver module by roller and bearings to produce smooth and stable motion. Drivers for the MCP, PIP and DIP joints are designs separately with independent motors are mounted together to provide the three active degree of freedom. The safety features of the device are implemented by two ways: software control and hardware design. Pressure sensors will be installed at where the device and finger mounted together once the pressure on the finger exceeded the pre determined pressure should produce on the mounting area, the power to the device will be cut off immediately by the monitoring software. An emergency stop button will be installed right beside of the device, should the user feel comfortable using the device. For hardware design, hard stopper blocks will be installed to prevent the device from going beyond the normal range/angle each human finger can reach as well as preventing the device from taking the joint into hyper-extension.

The driving mechanism – the angular driver of the Index, and Middle finger modules was identified as the most crucial mechanism in the design. It was noted that the angular driver was lack of constraint. The rotation link was not stable, if subjected to forces coming from the side and perpendicular to the surface of the link, the link would be played and have the tendency of falling off from the roller.

Another potential failure was due to the massive loads the rotation link was subjected to. Reaction forces were accumulated from the distal phalanx angular driver to middle phalanx angular driver, all accumulated at the rotation link of proximal phalanx or the MCP angular driver. Also, the protrusions of the driver were creating an opening for collision of neighboring driver to occur.

1) Improvement in Design

To verify the functionality and feasibility of the design a precision mockup was fabricated for the purpose, the design and its mockup is shown in Figure 5.19. A precision DC motor is mounted on top of the MCP driver; the power from the motor will be transmitted through timing belt and pulleys to the arc gear for actuation. To evaluate the functionality of the design, the driver was driven to move forward and backward repeatedly and observation was made on the motions on the arc gear. The mockup angular driver was tested manually to prove the design concept of this module. However, some minor improvement was required as the frictional force on the running arc gear was relatively high and the arc gear needed to be further stabilized.

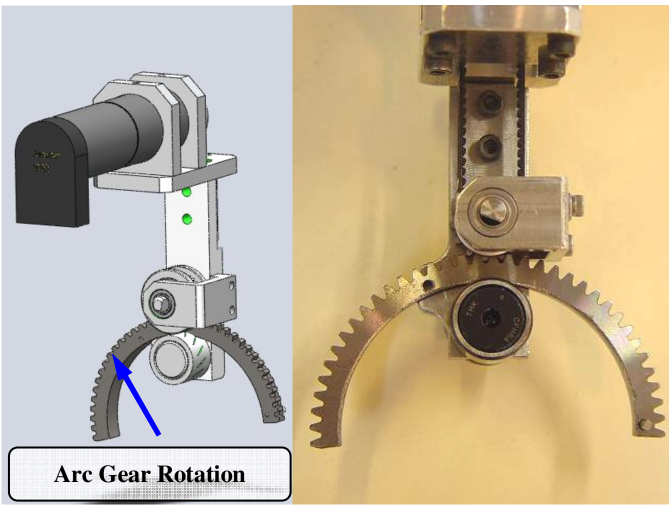


Figure 5.19: 3D Model and Precision Mockups of the MCP Angular Driver

In view of the issues mentioned above, the design is revised with the introduction of more rotational elements for reduction of frictional force and at the same time fully constraint the arc gear. Miniature bearings and flanged roller were amount the rotational elements used for the improvement of the angular driver. Besides that, changes were made on the driver base to widen the constraint area, while the triangular represent the constraint area.

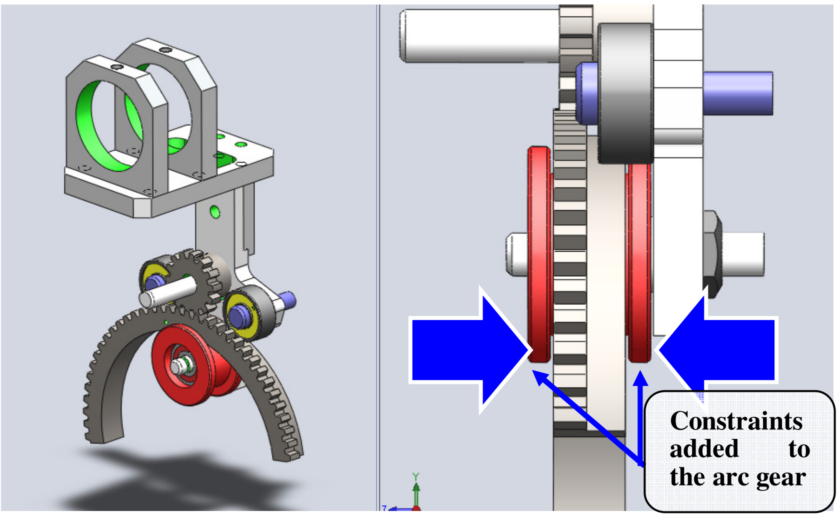


Figure 5.20: Final Revision of MCP Angular Driver

As shown in Figure 5.20, the improved design of the MCP angular driver with the implementation of two bearings and a flanged arc gear was fully constrainted. Physical mockup as shown in Figure 5.21 was fabricated based on the improved design. The performance of the angular driver was satisfactory based the testing and analysis of preliminary results.

Figure 5.21: Precision Mockup of the Improved MCP Angular Driver

2) Stress Analysis and Material Selection

To analyze the arc gear for structural stability, Solidworks Simulation was used. As shown in Figure 5.22, bar added on the arc gear was to simulate the moment arm length. The apply force of 6N, 8N, 8N, was exerted at point 1, 2, and 3 respectively.

Another load of 5N, which was the average weight of a human hand, was added at point 1 for analysis. The setting of the simulations was assuming the arc gear was at its maximum stroke to simulate the extreme stress the gear might subject to.

The structure was analyzed by von Mises criterion, the arc gear was made of carbon steel which has yield strength of 530 MPa. The analysis result is shown in the table of Figure 5.22, which is confirmed that the arc gear would not fail under the normal application. Calculated from the value in Figure 5.22, the MCP arc gear has a safety factor of 1.5.

Similar analysis was done on some other parts of the device which was subjected to high load, precaution like resizing the design, adding of flange, web and altering the material were taken to ensure that the device was stable and safe to operate.

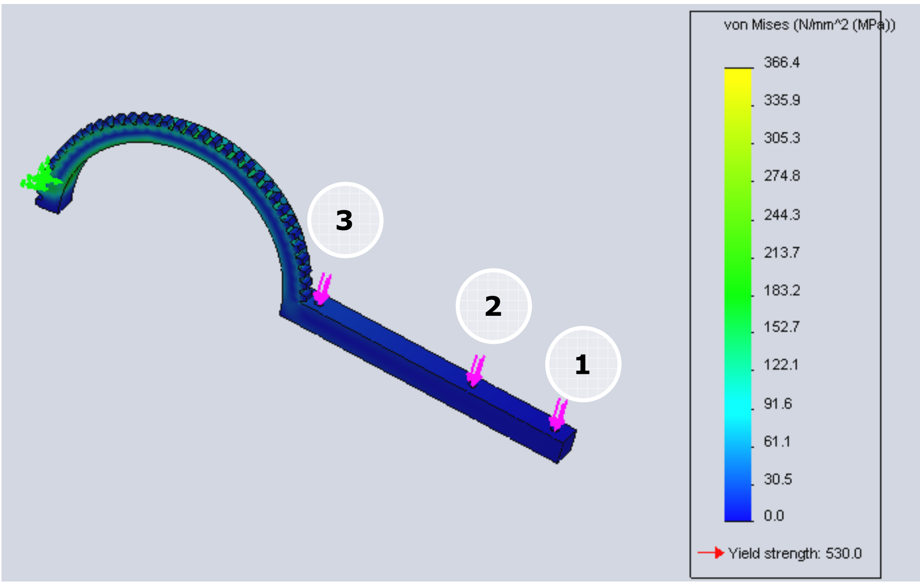


Figure 5.22: Stress Analysis of the MCP Arc gear

3) Safety Features

The safety features of the device were achieved by taking a two-pronged approach: software control and by hardware design.

Pressure sensors are installed at where the device and finger are mounted together once the pressure incurred on the finger exceeded the pre determined forces on the mounting area, the power to the device will be cut off immediately by the monitoring software. An emergency stop button will be installed on the device, should the user feel uncomfortable using the device.

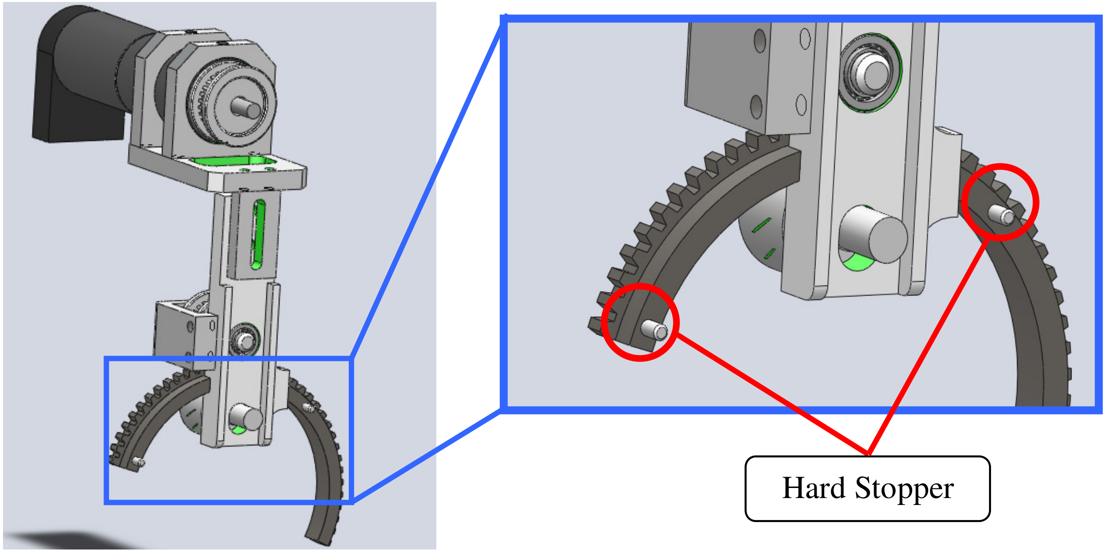


Figure 5.23: Implementation of Hard Stopper

For hardware design, hard stoppers as shown in Figure 5.23 are installed at all arc gears to prevent the device from going beyond the normal range/angle each human fingers could reach in case of controller failure, where all the electronic sensors are disabled, as well as preventing the device from forcing the finger going hyper-extension state (see Figure 5.24).

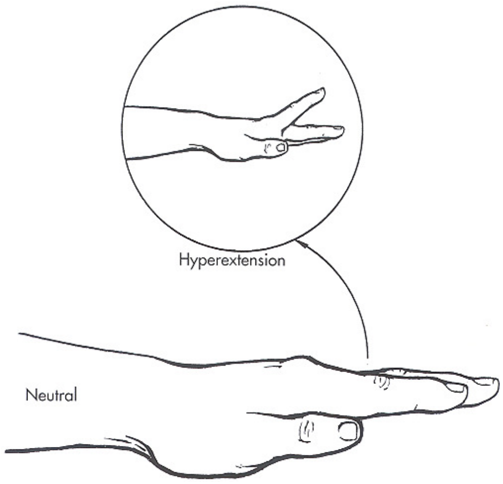


Figure 5.24: Hyper-extension of MCP Joint [56]

The hard stoppers are two protruded pins that hit the driver base and stop the rotation link from moving further whenever the driver exceeded the pre determined range which is 90˚ measure from neutral position during flexion, and extension will be limited at 0˚ (neutral position).

To further ensure the safety of the user, objects made of hard sponge are recommended for the rehabilitation exercise instead of rigid objects. The recommendation is to prevent excessive amount of forces exerting on the finger due to mishandling or failure of device. The excessive force can be absorbed by the sponge; hence protecting the user from injuries.

5.3 Simplified Thumb Module

In the hand rehabilitation training, each joint of the patient's hand need to be repeatedly flexed and extended independently within its allowable range [99]. These exercises involved the control of adequate forces exerted on the patient's fingers and thumb. In this session, the forces exerted by the robotics hand rehabilitation device on the patients thumb is discussed.

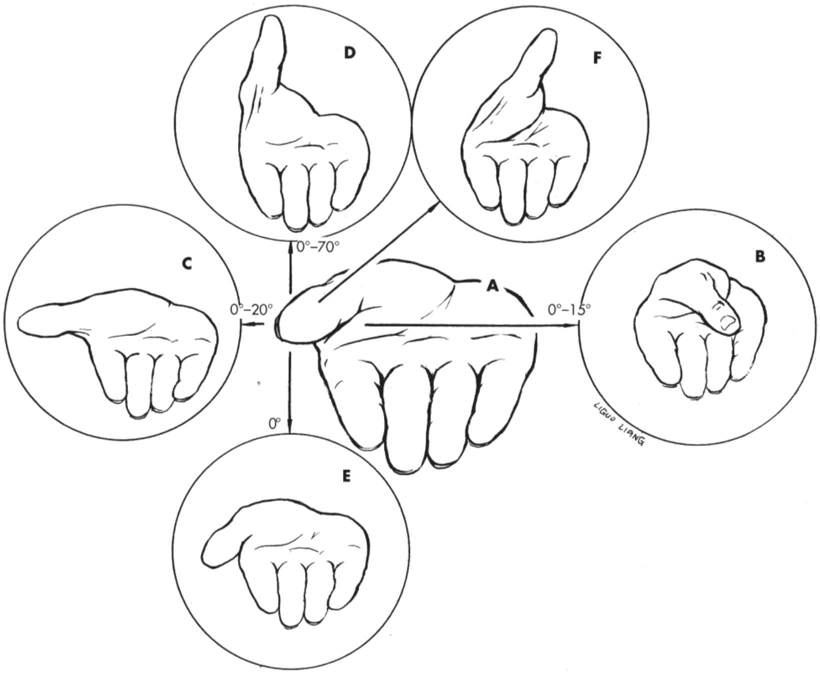


Figure 5.25: Range of Motions Performed by Thumb CMC Joint [56]

Thumb possesses 3-DOF contributed by independent movement of the CMC, MCP, and IP joints [99]. Figure 5.25 shows the range of motions performed by thumb's CMC joint, and Figure 2.7 also shows the flexion and extension of thumb. Due to human thumb CMC joint generated the adduction/abduction and opposition motions simultaneously. The design of the thumb module needed to be different from the finger modules.

To achieve rehabilitation to the thumb, the device was designed to provide training in the following exercises: (1) Flexion and extension of the MCP, and, IP joints; and (2) Abduction and adduction of the CMC joint. Thus, it was proposed to design the Thumb Module by mounting the thumb on a link. Then the link was driven to generate a circular motion which will assist the thumb CMC joint to rotate (opposition), and another driver to change the angles of the link together with the thumb CMC and MCP joints to create the circular cone motion. An angular driver would be used to assist the IP joint from flexing or extending.

Besides achieving the motions mentioned above, the device must be safe to operate in all conditions. The safety of the device involves two aspects, first is operating within the range of each joint, and second is the incident angle of the force exerting on the thumb surface under conditions that injuries should be incurred and furthermore keeping the user thumb comfortable while holding/grabbing a rigid object.

5.3.1 Workspace Analysis

As presented in Section 4.2.2, the D-H parameters (see Table 4.3) for the thumb with the generalized coordinates illustrated in Figure 4.5, and the possible workspace of the thumb fingertip is plotted by using MATLAB in Figure 4.6. The simplified thumb is modeled as 3-DOFs, the modified D-H parameters (see Table 5.4) with the generalized coordinates illustrated in Figure 5.26.

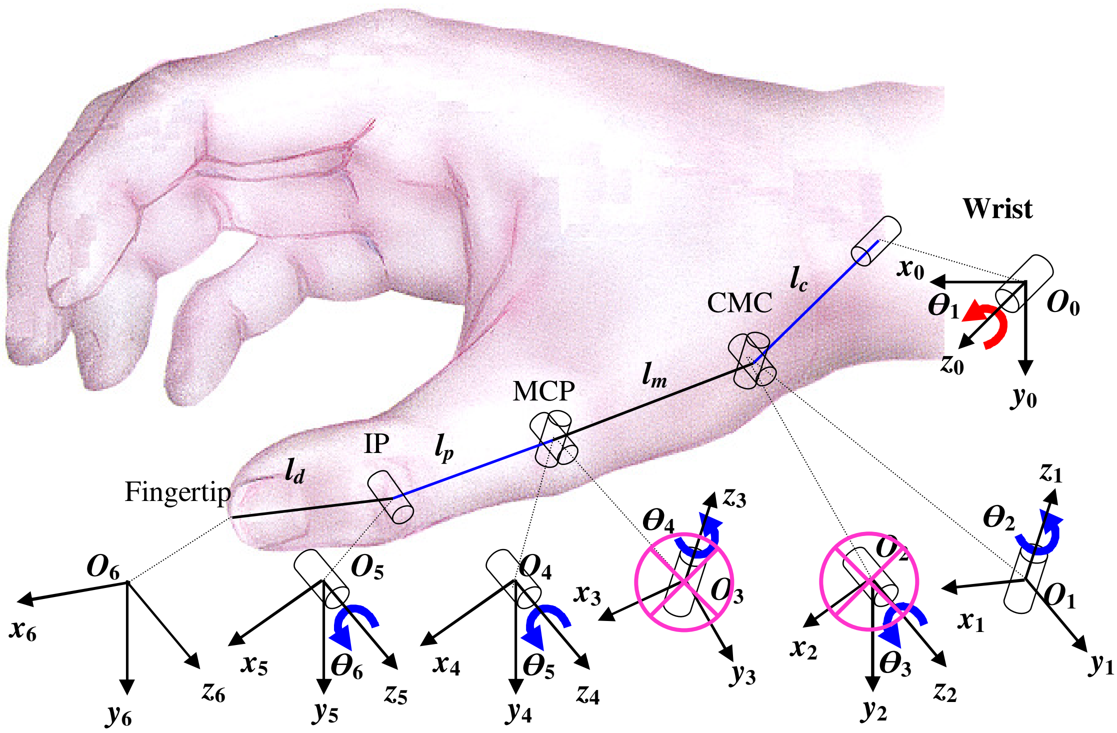


Figure 5.26: D-H Representation of Simplified Human Thumb

Table 5.4: D-H Parameters for Simplified Thumb

Joint j	**θ_j (deg)**	**α_j (deg)**	**a_j (mm)**	**d_j (mm)**	**Joint Variables**	**Range of Joint Angles [55-57]**		**Segment Lengths (Table 4.1) l_h=189 mm; b_h=87 mm**
						Max. Flexion/ Abduction	**Max. Extension/ Adduction**	
1	q_1	90°	$l_c \cos\gamma_t$	$l_c \sin\gamma_t$	θ_1	80°	-70°	l_c=22.3
2	$q_2+\beta$	-90°	0	0	θ_2	50°	-20°	-
3	q_3	90°	l_m	0	θ_3=0	0°	0°	l_m=47.4
4	q_4	-90°	0	0	θ_4=0	0°	0°	-
5	q_5	0°	l_p	0	θ_5	60°	-10°	l_p=37.0
6	q_6	0°	l_d	0	θ_6	90°	-20°	l_d=29.9

Based on the average length of human fingers for males subjects (l_h = 189 mm) and ranges of each joints as specified in Table 5.4, the possible workspace of the thumb fingertip using the simplified thumb model and the full thumb model is plotted by using MATLAB as shown in Figure 5.27. The simplified 3-DOFs of thumb model are able to cover about 75-80% of the workspace of the full DOF thumb model, and which is able to perform the five key hand functional tasks.

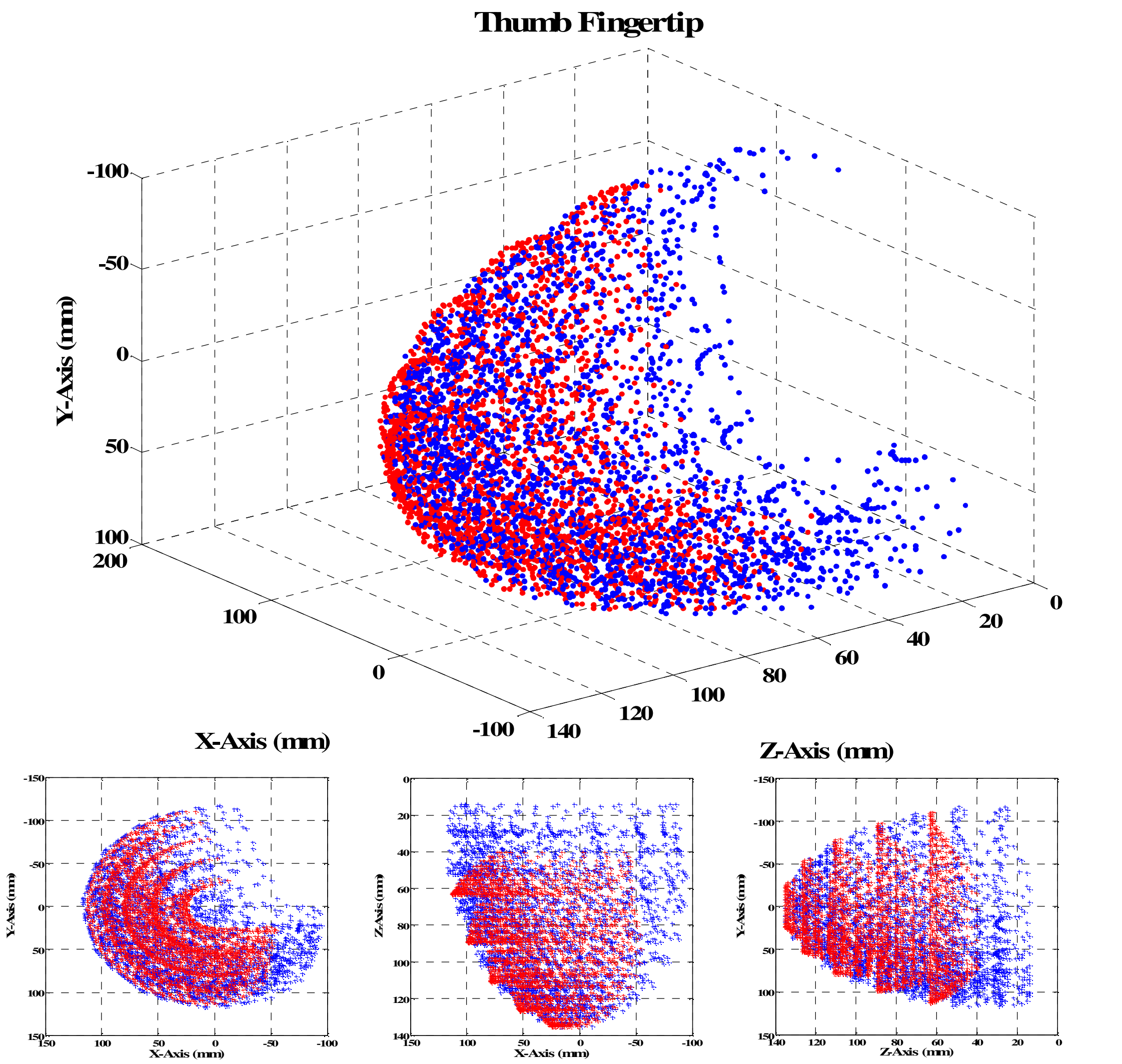


Figure 5.27: Comparison of the Workspace Between the Simplified Thumb Model (in Red Colour) and Full Thumb Fingertip (in Blue Colour) in Various Views

5.3.2 Surface Adaptive Feature

In order to develop the thumb module, an analysis was done to understand the effect of forces exerting on the surface of a human thumb. The studies analyzed the efficiency with respect to the incident angle of external forces transmitted to the thumb surfaces.

The thumb module was designed to provide assistive forces to the user's thumb through exerting force on the thumb. Arc like linkages were attached at the middle of distal phalanx, proximal phalanx, and metacarpals of the thumb respectively. Each arc linkage was then driven by the motor mounted on top it. Based on the pre-defined trajectories designed for task oriented training, each arc linkage would move to the desired angles to complete a flexion/extension and/or abduction/adduction motions.

However, the result is not satisfactory, especially in power gripping and five-pulps-pinch which required thumb abduction/adduction. The reason for this is because the structure and shape of the thumb is different than the rest of the fingers. Observed from the power-grip posture in Figure 5.28, the direction of markers T1 and T2 pointing show that the angle where the arc linkages mounted will not be perpendicular to the surface of the cylinder as of the fingers (markers I1, I2, I3 of index finger have incident angles of almost perpendicular to the cylinder surface). Hence any force that intended to drive the thumb towards the direction of securing the cylinder would be broken down in two directions, i.e. perpendicular and vertical parallel to the cylinder surface. As a result, reducing the efficiency of the force transmitted to the thumb.

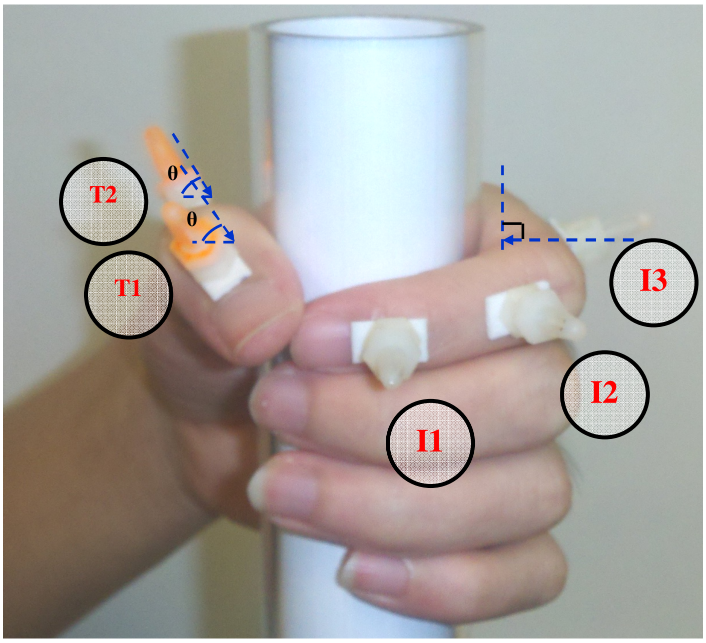


Figure 5.28: Power-grip Posture (Markers on the Hand Indicate the Area Mounted to the Robotics Device and the Incident Angles of Forces Transmission to the Thumb and Fingers)

In order to solve the issue caused by the incident angle θ as illustrated in Figure 5.29(a), the mounting of the arc linkages of thumb module is designed to be adjustable according to the surface and the desired direction. By reducing the angle of θ, the force intended to transmit would be kept at maximum level, Figure 5.29(b) illustrates the effect of the adjustable mounting.

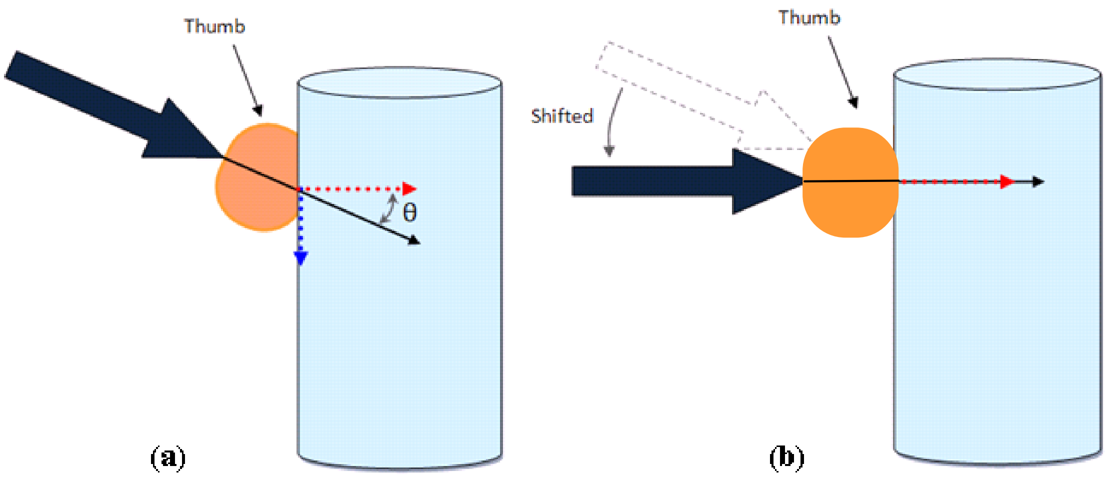


Figure 5.29: (a) Illustration of the Incident Angle of Thumb, (b) Adjustable Mounting Allow the Incident Angle to be Shifted to Position where the Exerted Force is Perpendicular to the Cylinder

The overall view of the thumb module design is shown in Figure 5.30. The mounting of the device to the thumb is located at middle of distal phalanx and proximal phalanx. While at the end of the thumb module close to the wrist is a motor driven link which will assist the thumb to perform anteposition. Motor 2 and motor 3 are to assist the user in performing flexion and extension.

The surface adaptive feature is incorporated into the design of the mounting attachment shown in Figure 5.30, where assembly between the thumb linkages and thumb surface is allowed to shift based on the desirable angle for the task oriented training. A fully design surface adaptive mounting and electromagnetic device incorporated in the attachment assembly. This electromagnetic device will be energized when adjustment of position is not required, and de-energized when to position the assembly in such a way that the force exerting on the thumb is perpendicular to the object surface.

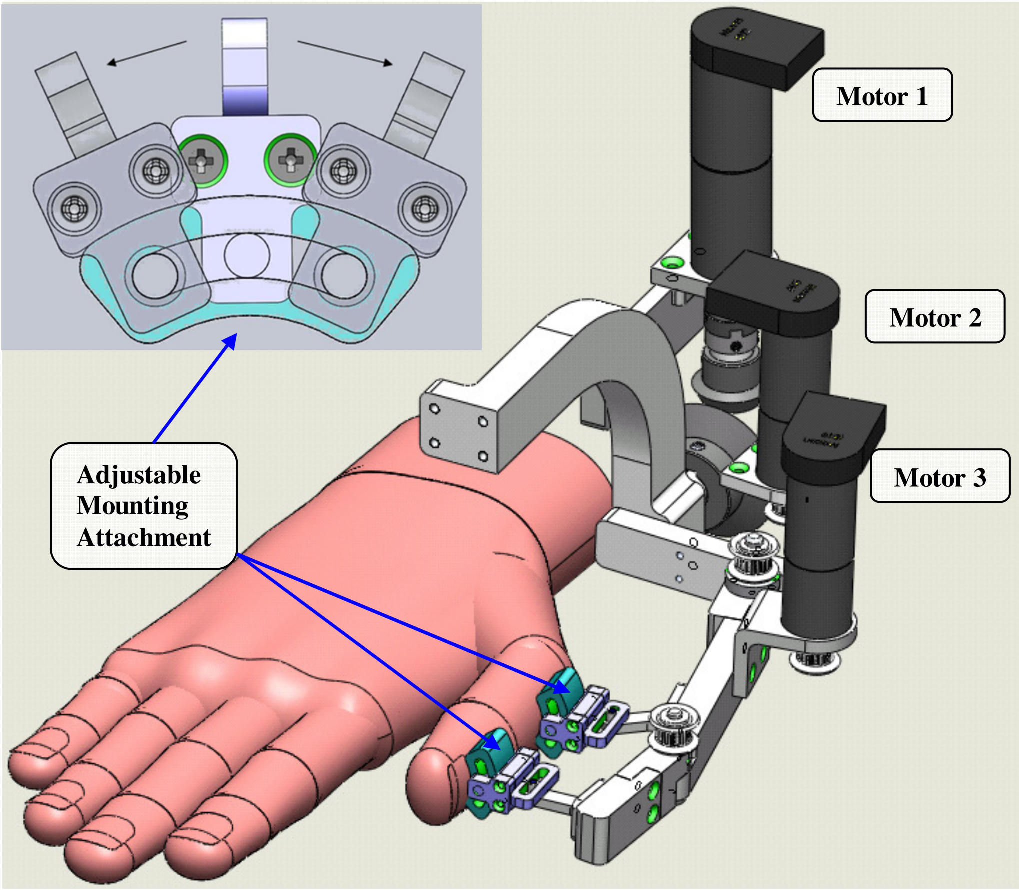


Figure 5.30: Overall View of the Thumb Module Design with Human Hand

5.4 Wrist Support Module

The main function of the wrist is to fine-tune grasp by controlling the length-tension relationship in the extrinsic muscles to the hand. Due to human ergonomics, there is slight flexion/extension at wrist during hand prehensions. Based on study in the local hospitals, some of the patients are unable to raise their palm in horizontal position during the therapeutic treatment, which is called “wrist drop”. Accordingly, the mechanism is designed for this purpose; it is used to support the wrist to perform rehabilitation activities. Strips of Velcro will be used to fix the patient’s hand in position and provide comfort and easy wearing.

The wrist module was designed to assist patient to perform flexion and extension exercises of the wrist, as well as securing all the Fingers and Thumb Modules in place. So that the patient does not need to carry the weight of the motors and mechanism, the gloves that they will be wearing are attached to the end points of the mechanisms to provide load-free exercises and training. As such, the module was designed to possess high torque in order to withstand the weight of the hand and the rest of the modules and at the same time assisting the wrist to flex or extend to the desired position.

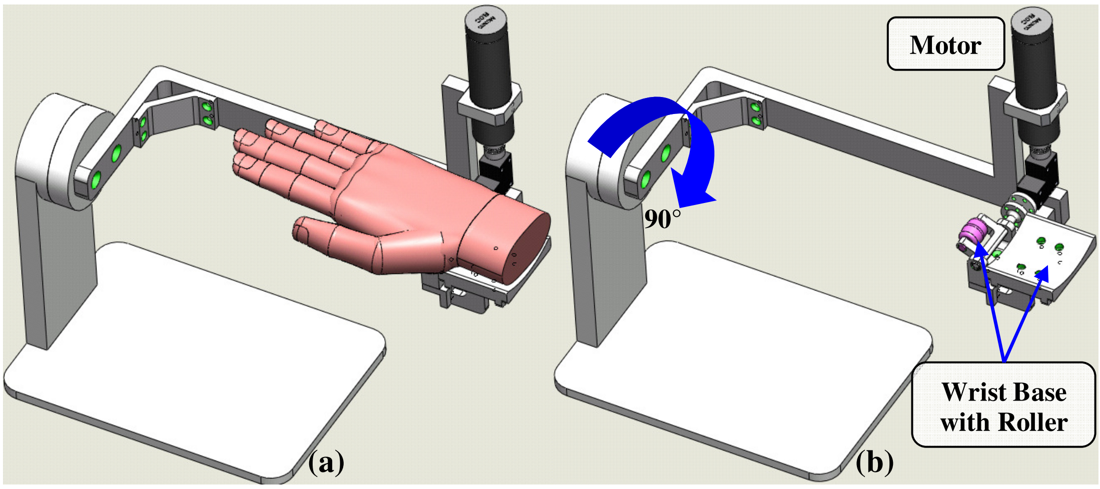


Figure 5.31: Wrist Module with Torque Motor Installed (a) with Human Hand, (b) without Human Hand (two orientations of robotic device by turning 90 degree of the rotating frame)

As shown in Figure 5.31, the Wrist Module was a simple design of lever rotational elements. All the Finger Modules and Thumb Module were mounted on horizontal bar located at the top of the level. A high torque motor was installed on the side of the device and joined to a cylinder which could transmit power to the housing where the roller was mounted. When the user put his/her hand on the device, the lower end of his/her palm would rest on the roller and the wrist was to be secured by Velcro strap. Then the high torque motor could be activated to adjust the angle of the wrist as well as all the Fingers Modules mounted on top. The roller was a passive element installed for the purpose of eliminating the shear force during operation.

In order to accomplish the five functional tasks in the activities of daily living (ADL), the supination/pronation of wrist joint is important in completing those tasks as discussed in Section 5.1.1. However, the supination/pronation of wrist joint is simplified as the dual-configuration of robotic device (by changing orientations of rotational frame manually) in our design as shown in Figure 5.31.

5.5 Assembled CAD Model of Hand Rehabilitation Device

The overall hand mechanism design is shown in Figure 5.32. The mechanism combines all the three modules to form the hand rehabilitation device: they are index & middle fingers module, the thumb module and wrist support module.

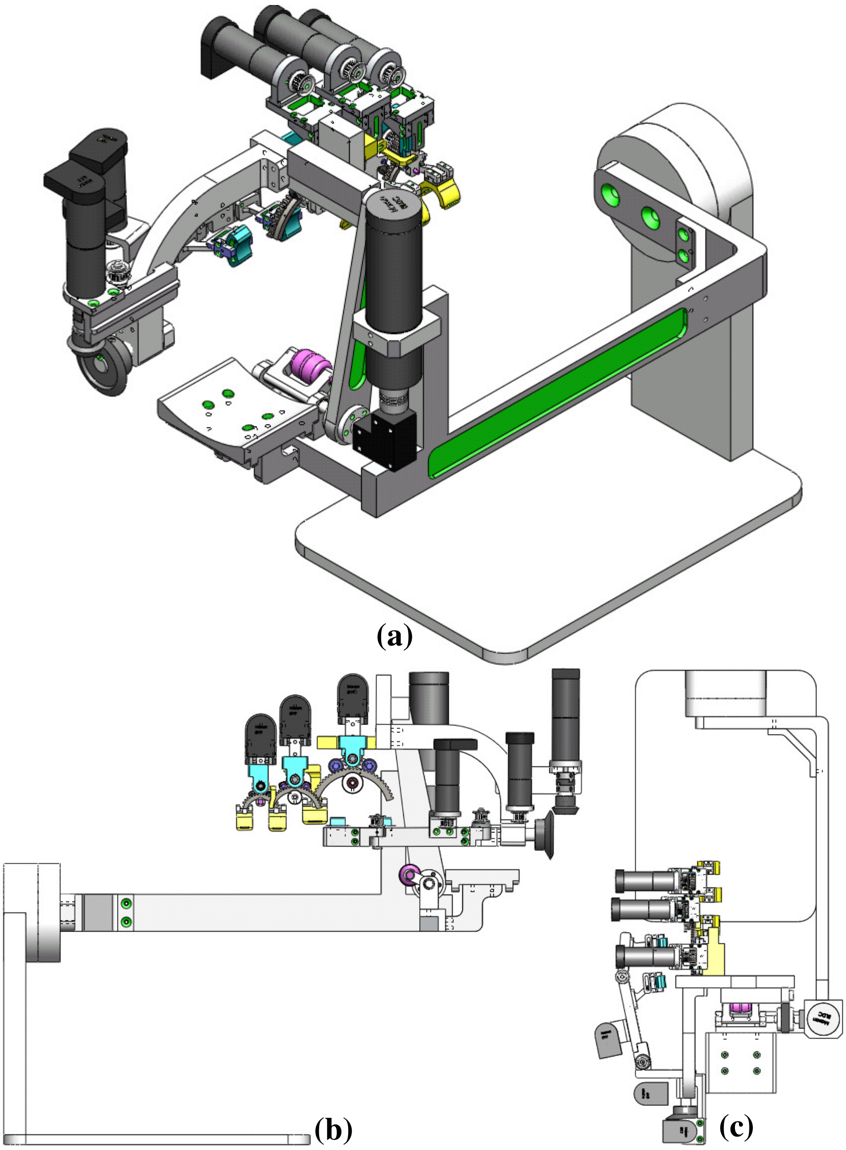


Figure 5.32: Assembled Model of Hand Rehabilitation Device (a) Isometric View (b) Front View (c) Top View

There are two orientations of the device for different Activities of daily living (ADL) and rehabilitation exercises. The vertical orientation is designed for five-pulp-pinch and lateral pinch, for example, holding a cup or a bottle, holding a card or turning a key into a lock or stirring a beverage with a teaspoon. The horizontal orientation is designed for pulp-to-pulp pinch, tripod pinch and power grip, for example, pick up small objects like coins, medicine pills or pins, handling a pen or controlling a computer mouse and holding a walking stick or door handle.

The proposed hand rehabilitation device will be attached to human hand as illustrated in Figure 5.33. The system is based on the comfortable glove with different sizes that attached at the selected MCP, PIP and DIP joints.

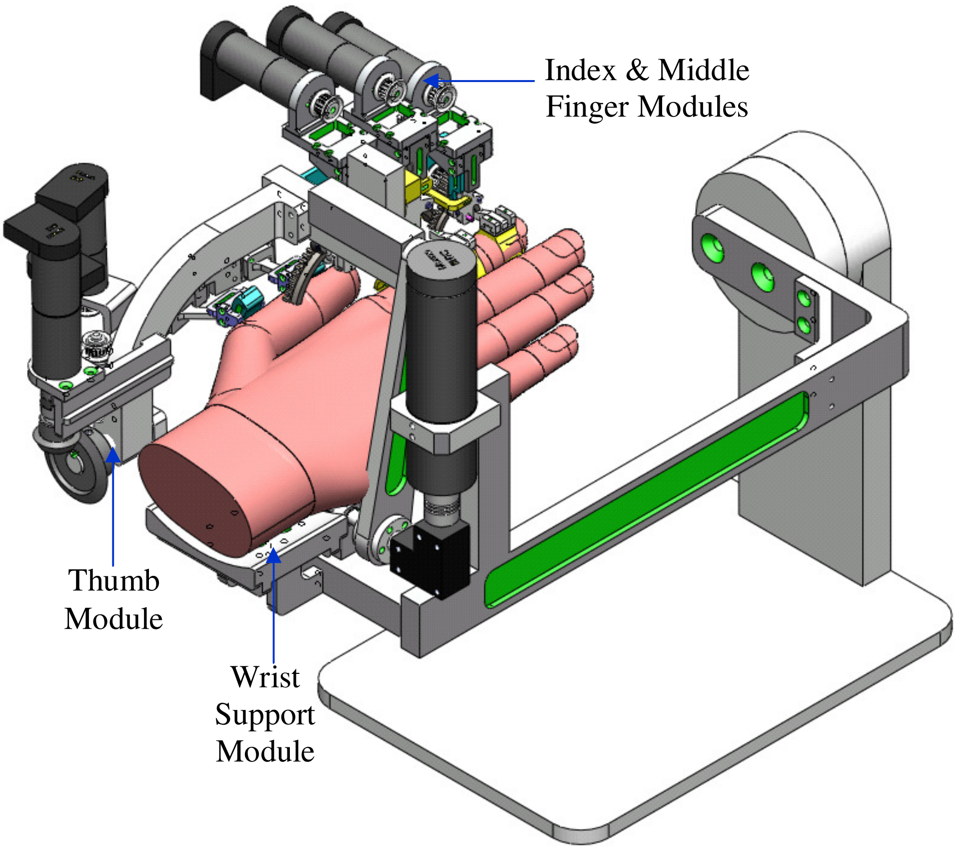


Figure 5.33: CAD Model of the Hand Rehabilitation Device (Illustration of the Device with Human Hand)

5.6 Force Analysis of Gripping Task

In order to grip an object, the required assistive force/torque by the hand rehabilitation device is studied in this section, which can be used for the control of the robotic device.

5.6.1 Force Analysis on "Load-free" Concept

For the concept of "load-free" design of the hand rehabilitation device, we aim to provide sufficient support to "hold" the fingers and minimize the load force on the fingers. The force analysis is carried out for the power/cylindrical grip with a holding object during gripping/releasing (see Figure 5.34), as it involved all the joints of the fingers.

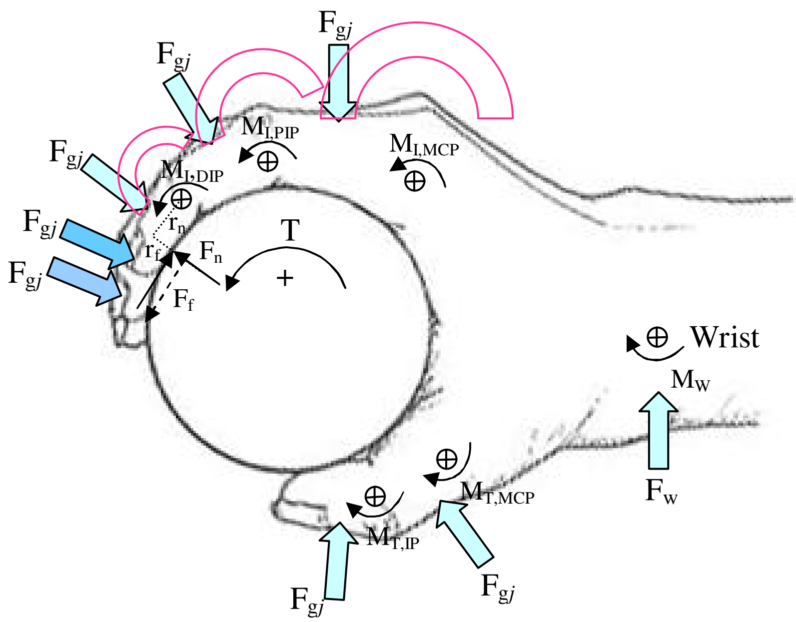


Figure 5.34: Diagram of Power/Cylindrical Grip with a Holding Object during Gripping/Releasing (Side View)

The notations in Figure 5.34 are as follows:

F_g	gripping force
F_n	normal force on the finger
F_f	friction force on the finger
M	joint moment

The modified torque model is proposed by [164], where T is the torque, n is the number of hand segments touching the object, r is the distance between the object's center of mass and the point where friction force is applied (moment arm), μ is the coefficient of friction between the hand and object, and F_n is the normal force:

$$T = \sum_{i=1}^{n} r_i \mu_i F_{ni} \tag{5.5}$$

For a cylindrical handle with a constant friction surface, the torque model can be simplified:

$$T = r\mu \sum_{i=1}^{n} F_{ni} \tag{5.6}$$

When the hand applies torque to a cylindrical object during gripping/releasing (friction force F_f acts in the opposite direction during releasing in Figure 5.34), the moment equilibrium can be applied about finger joint j:

$$M_j \pm r_{fj} F_{fj} - r_{nj} F_{nj} = 0 \tag{5.7}$$

$$\& \ F_{fj} = \mu F_{nj} \tag{5.8}$$

Where M is the joint moment, F_f is the friction force on the finger, r_f is the moment arm for the friction force vector, F_n is the normal force on the finger, and r_n is the moment arm for the normal force vector. The joint moment at DIP, PIP and MCP joints can be expressed as follows

$$M_{I,DIP} \pm r_{f,DIP} F_{f,DIP} - r_{n,DIP} F_{n,DIP} = 0 \tag{5.9}$$

$$M_{I,PIP} \pm r_{f,PIP} F_{f,PIP} - r_{n,PIP} F_{n,PIP} = 0 \tag{5.10}$$

$$M_{I,MCP} \pm r_{f,MCP} F_{f,MCP} - r_{n,MCP} F_{n,MCP} = 0 \tag{5.11}$$

The moment at the finger joint j can be expressed as

$$M_j = r_{nj} F_{nj} - r_{fj} F_{fj} = \left(r_{nj} \mp \mu r_{fj} \right) F_{nj} \tag{5.12}$$

The normal reaction force on the finger segment can be expressed as

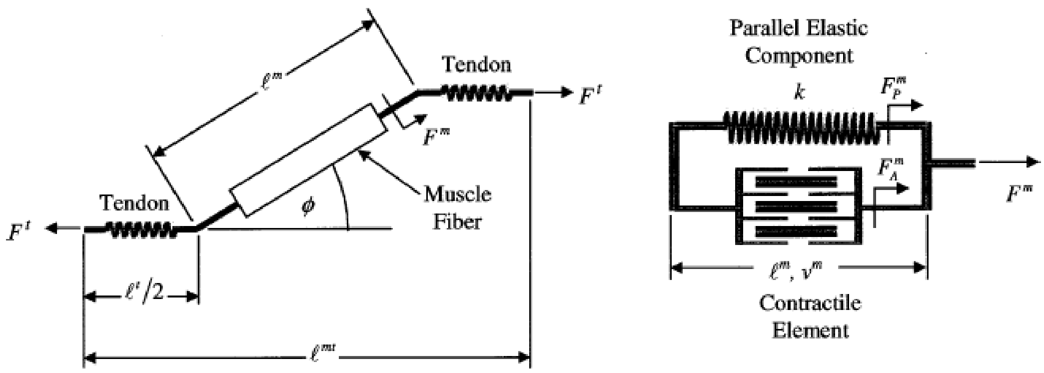
$$F_{nj} = \frac{M_j}{r_{nj} \mp \mu r_{fj}} \tag{5.13}$$

Assume that total gripping force F_G, which can be measured by the hand dynamometer, is equal to the sum of the gripping force F_g, and also equal to the sum of the normal force on the finger.

$$F_G = \sum_{j=1}^{n} F_{gj} = \sum_{i=1}^{n} F_{ni} \tag{5.14}$$

The gripping force F_g is the resulting muscle force F_m produced by a contractile element and a parallel elastic element (the simplified Hill-type muscle model is used and shown in Figure 5.35), and the assistive force F_d by the hand rehabilitation device.

$$F_g = F_m + F_d \tag{5.15}$$



(a) Schematic of muscle-tendon unit (b) Schematic of muscle fiber

Figure 5.35: Simplified Hill-type Muscle Model [165]

The contractile element produces the active muscle force during contraction of the muscle while the elastic element produces the passive force when the muscle is stretched.

$$F_m = F_{mA} + F_{mP} = f_A(l)F_0 a(u) + f_P(l)F_0 \tag{5.16}$$

where F_m is the total force produced in the muscle, F_{mA} is the active muscle force and F_{mP} is the passive muscle force, F_0 is the maximum isometric force produced by the muscle, $a(u)$ is the muscle activation and $f_A(l)$ is the active force-length function and $f_P(l)$ is the passive force-length function with $l = \frac{l_m}{l_{mo}}$, where l_m is the muscle fibre length and l_{mo} is the optimal muscle fibre length. The functions of $f_A(l)$ and $f_P(l)$ can be found in [165].

The muscle activation $a(u)$ is a function of the post-processed sEMG signal [165]. The following equation shows the conversion of sEMG signal to muscle activation.

$$a(u) = \frac{e^{AuR^{-1}} - 1}{e^{A} - 1} \tag{5.17}$$

where u is the post-processed sEMG value, R is the peak of the sEMG signal and A is the nonlinear shape factor with -3 < A < 0, with A = -3 being highly exponential and A = 0 being a linear relationship [165]. A and R requires calibration for every session for each muscle. Table 5.5 shows the values of R as obtained from the average sEMG signals of the various muscles during each hand motion.

Table 5.5: Peak sEMG Values of Each Muscle

Motion	**Muscle**	**R/uV**
Finger Flexion	Flexor Digitorum Superficialis (FDS)	17.0
Finger Extension	Extensor Digitorum (ED)	19.0
Thumb Abduction	Abductor Pollicis Longus (APL)	21.4
	Abductor Pollicis Brevis (APB)	312.7
Thumb Extension	Extensor Pollicis Longus (EPL)	27.2
Thumb Flexion (MCP and IP Joints)	Flexor Pollicis Longus (FPL)	48.8
Thumb Flexion (CMC Joint)	Flexor Pollicis Brevis (FPB)	73.3

The active force-length function is approximately equal to $a(u)$ and the passive force-length function is approximately equal to 0 when the normalized muscle length is 1. This is because the musculotendon unit originates from the forearm and inserts at the hand. In addition, the radii of rotation of the joints of the hand digits are small. With $l_m \approx l_{m0},\ l \approx 1$. The active muscle force F_{mA} is hence simplified to

$$F_{mA} = F_0 \left[a(u)\right]^2 \tag{5.18}$$

which is a function of the maximum isometric force, F_0 and the muscle activation, $a(u)$. The total force produced in the muscle is then just

$$F_m = F_{mA} = F_0\left[a(u)\right]^2 = F_0\left[\frac{e^{AuR^{-1}}-1}{e^A-1}\right]^2 \tag{5.19}$$

The maximum isometric force, F_0, of each muscle is obtained by multiplying each muscle's physiological cross-sectional area (*PCSA*) with the maximal muscle stress which is taken to be 35 N/cm^2 [165].

The total assistive force F_d, by the hand rehabilitation device can be expressed as

$$F_d = F_g - F_m = \sum_{i=1}^{n} F_{ni} - F_0\left[\frac{e^{AuR^{-1}}-1}{e^A-1}\right]^2 \tag{5.20}$$

Assume the distribution of the assistive force is the same as the muscle forces at each joint. The joint moment M_j, the torque contribution of the muscle at its joint j can be expressed as

$$M_j = \left(r_{nj} \mp \mu r_{fj}\right)F_{nj} = \left(r_{nj} \mp \mu r_{fj}\right)(F_{mj}+F_{dj}) = \left(r_{nj} \mp \mu r_{fj}\right)\left(F_0\left[\frac{e^{AuR^{-1}}-1}{e^A-1}\right]^2 + F_{dj}\right) \tag{5.21}$$

5.6.2 Estimation of Joint Torques from EMG Signals

The joint torques in the hand can be computed by multiplying the time-dependant muscle force with the average moment arm of each muscle. Recalling from Equation 5.19 that the muscle force $F_m = F_0\left[\frac{e^{AuR^{-1}}-1}{e^A-1}\right]^2$, the estimated joint torques produced by each muscle is given by

$$T = rF_m \tag{5.22}$$

Where T is the torque contribution of a muscle at its joints and r is the average approximated constant moment arm of the muscle. Table 5.6 shows the average moment arms for the muscles considered.

Table 5.6: Table of Moment Arms [166]

Muscle	**Joint**	**Moment Arm/mm**	
		Average	**At Neutral**
Flexor Digitorum Superficialis (FDS)	Fingers MCP Joints Flexion	11.9	-
	Fingers PIP Joints Flexion	6.2	-
Extensor Digitorum (ED)	Fingers MCP Joints Extension	8.6	-
	Fingers PIP Joints Extension	2.8	-
	Fingers DIP Joints Extension	2.2	-
Abductor Pollicis Longus (APL)	Thumb CMC Joint Abduction	9.41	10.5
Abductor Pollicis Brevis (APB)	Thumb CMC Joint Abduction	14.48	16.5
Extensor Pollicis Longus (EPL)	Thumb CMC Joint Extension	9.62	8.1
Flexor Pollicis Longus (FPL)	Thumb MCP Joint Flexion	9.91	13.6
	Thumb IP Joint Flexion	7.82	8.7
Flexor Pollicis Brevis (FPB)	Thumb CMC Joint Flexion	13.43	13.4

The problem hence reduces to calibration of the term A in Equation 5.19. Equation 5.22 can be expressed as

$$T = rF_m = rF_0 \left[\frac{e^{AuR^{-1}} - 1}{e^A - 1} \right]^2 \tag{5.23}$$

The parameters r and F_0 are obtained from average reference values. R is the expected maximum potential obtained from the EMG signal. For patients unable to produce much muscle force, R can be approximated by an average peak value tabulated above.

The term A, which is constrained by $-3 < A < 0$, can be calibrated by comparing the computed joint torque with the actual torque recorded at the finger and thumb joints. The torque at the finger and thumb joints can be measured using suitable torque sensors. In this project, estimations of torque joints were obtained using inverse dynamics of the forces recorded during the grasping tasks. However, this method could not allow for derivation of joint torques when no force was detected during motion of the fingers.

Comparison of Estimated and Calculated Joint Torques

Figures 5.36 &5.37 show the comparison of joint torques at the MCP and IP Joints of the thumb during the lateral pinch task. The force detected at the thumb tip by the sensors was converted to torque at the respective joints. The estimated joint torque was then obtained by using equation 5.23.

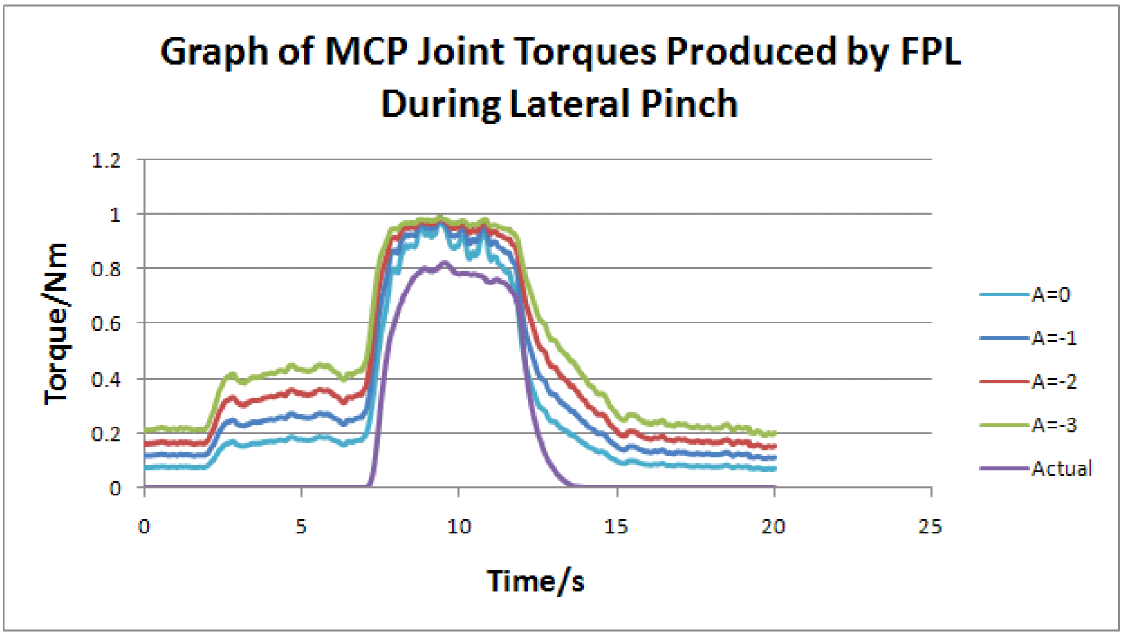


Figure 5.36: MCP Joint Torques Produced by FPL during Lateral Pinch

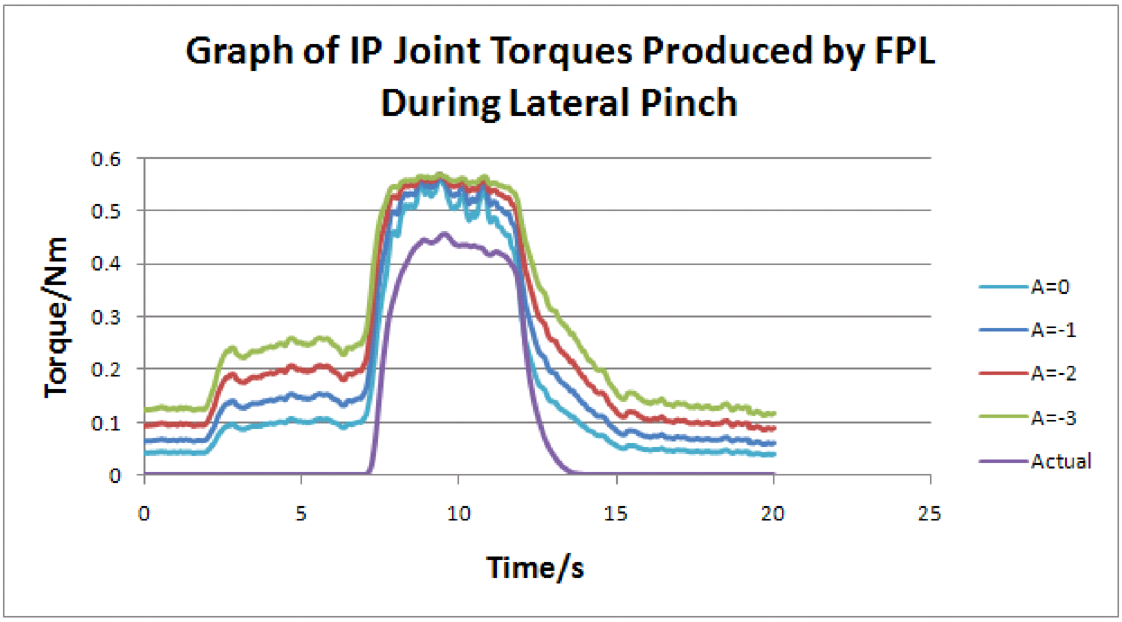


Figure 5.37: IP Joint Torques Produced by FPL during Lateral Pinch

The results show that the joint torques obtained by inverse dynamics were consistently lower than the estimated joint torques. This could be due to overestimation of the maximum isometric force, F_0, as this parameter depends on the volume of muscle mass which differs from individual to individual and assumption that the normalized muscle force is equal to a maximum of 1 when it actually varies with muscle fiber length. The moment arms may also vary between different people.

As a result, a compensation coefficient B is introduced into Equation 5.23 so that the estimated joint torque obtained from EMG signals becomes

$$T = BrF_m = BrF_0\left[\frac{e^{AuR^{-1}}-1}{e^A-1}\right]^2 \tag{5.24}$$

The coefficient B, $B > 0$, functions to reduce variability in the maximum isometric force and moment arms. The problem is then to optimize the values of A and B such that the error between the estimated and calculated torques are minimal. Since the difference between the estimated and calculated torques can be either positive or negative, the squared difference of the torques is taken and summed up over the entire period according to Equation 5.25.

$$\text{Squared Torque Errors} = \sum_{i=0}^{n}\left(T_{EMG,i} - T_{I,i}\right)^2 \tag{5.25}$$

Where T_{EMG} is the torque estimated from EMG signals with values of A and B set and T_I is the torques obtained by inverse dynamics and n is the number of samples in that period.

Figures 5.38 & 5.39 show the error values for the IP and MCP joints of the thumb during lateral pinch for varying values of A and B. The graphs also show that the FPL muscle is optimized when A = 0.01 and B = 0.8 for the IP and MCP joints of the thumb. A = 0.01 shows that the relationship between EMG detected at the sensors relate linearly to torque produced.

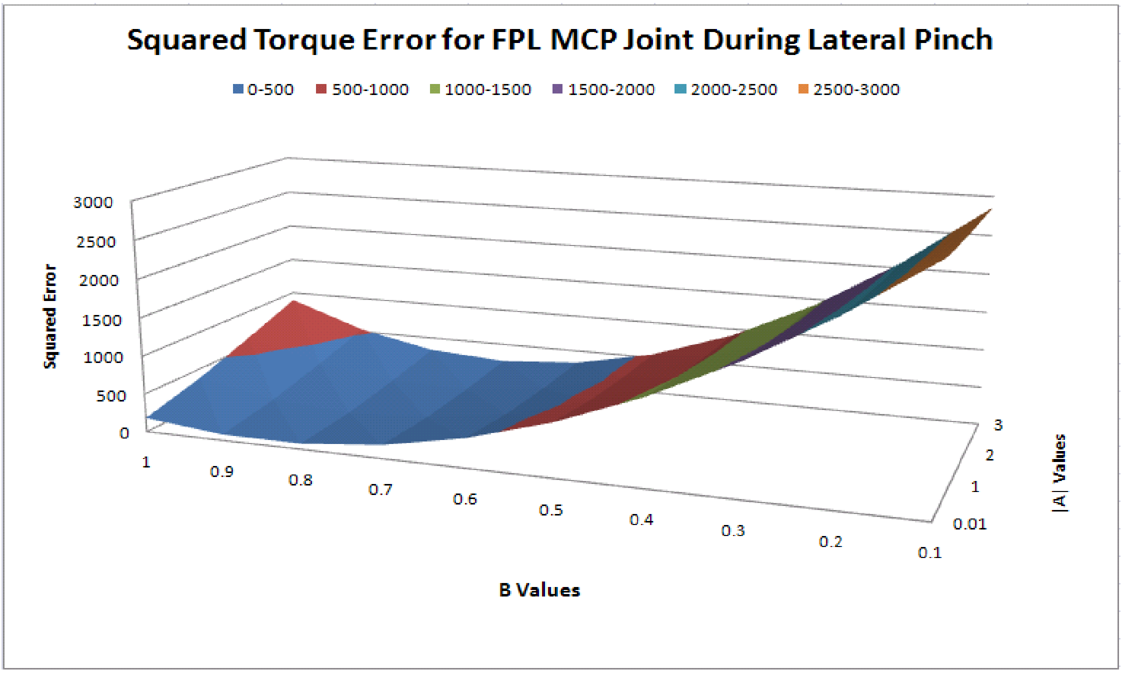


Figure 5.38: Squared Torque Error for FPL MCP Joint during Lateral Pinch

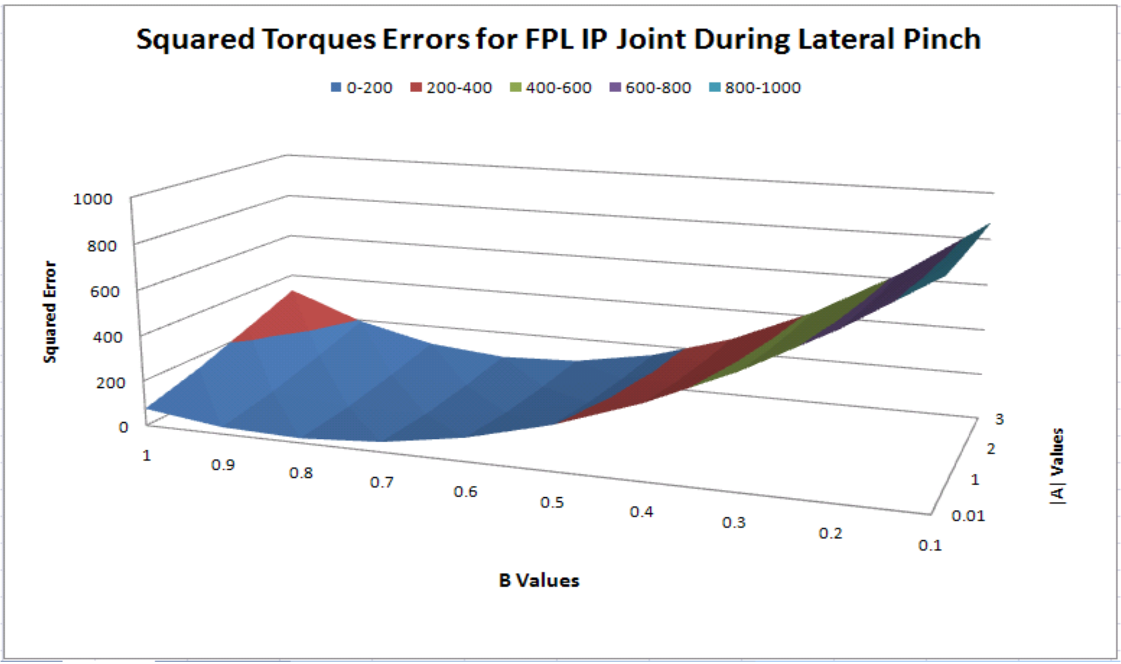


Figure 5.39: Squared Torque Error for FPL IP Joint during Lateral Pinch

The values of *A* and *B* are calibrated by minimizing the squared error between estimated torques and torques. The above procedure can be repeated easily to find the *A* and *B* values for each muscle involved in functional grasps of the hand. Figures 5.40 & 5.41 show the estimated torques plotted with the torques calculated after applying the compensation coefficient *B*.

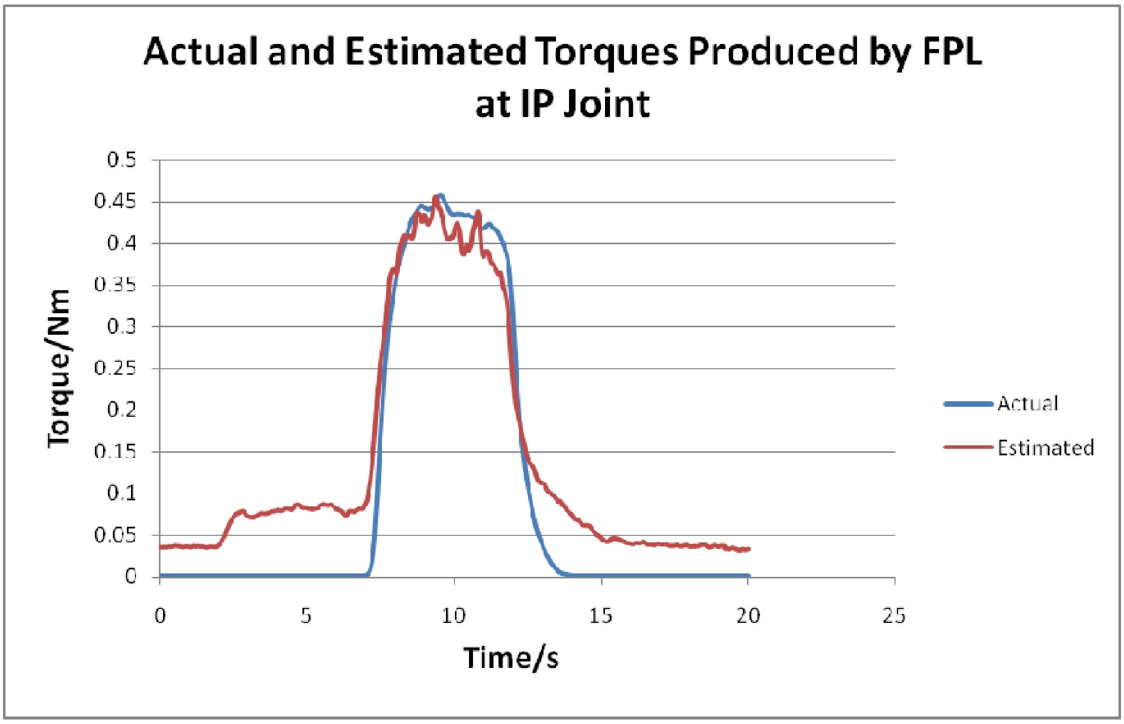


Figure 5.40: Actual and Estimated Torques Produced by FPL at IP Joint

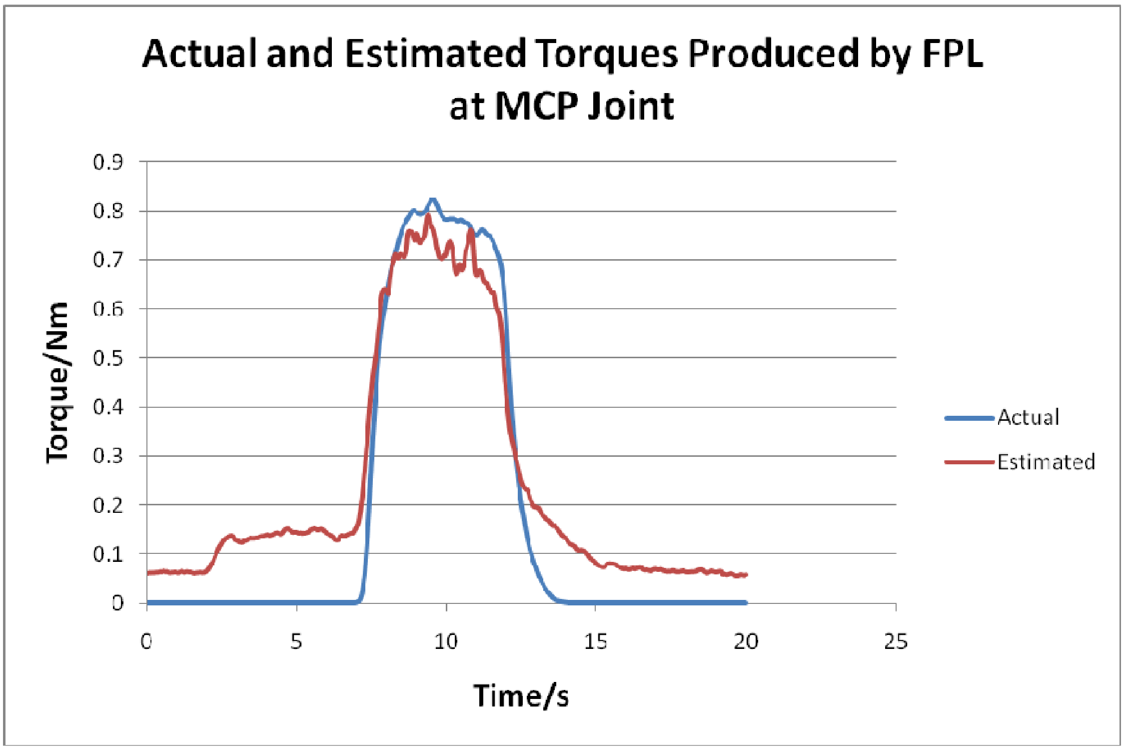


Figure 5.41:Actual and Estimated Torques Produced by FPL at MCP Joint

5.6.3 Experiment of Force Quantification for Flexion

The sub-section aims to realize the force needed to flex the fingers and thumb individually. The quantitative approach first involves the maximum force to flex different joints of the thumb and fingers. Subsequently, it is of great interest to understand if the angle of flexion affects the force required. Lastly, there is a basic study on how cup material may attribute to force exertion.

1) Maximum Force for Finger and Thumb Flexion

Taking the five-pulp grip as an example for testing, the fingers and thumb are flexed in a manner so as to hold a cup. As such, with the usage of Advance Force Gauge (AFG) [167], the fingers and thumb are guided to flex as shown in Figure 5.42. For the fingers, the AFG will be placed on the middle phalange and make a 35 degree anti-clockwise rotation about the PIP joint, and an approximately 60 degree anti-clockwise rotation about the DIP joint with the AFG positioned on the finger's distant phalange. This is conducted for all four fingers.

As for the thumb, the AFG will be placed at the proximal phalange and distant phalange to make at clockwise rotation of 70^{o} and 50^{o} about its MCP joint and IP joint respectively. Certainly, the fingers and thumb are in relax mode when the experimenter will use the AFG guided them individually to the desired position.

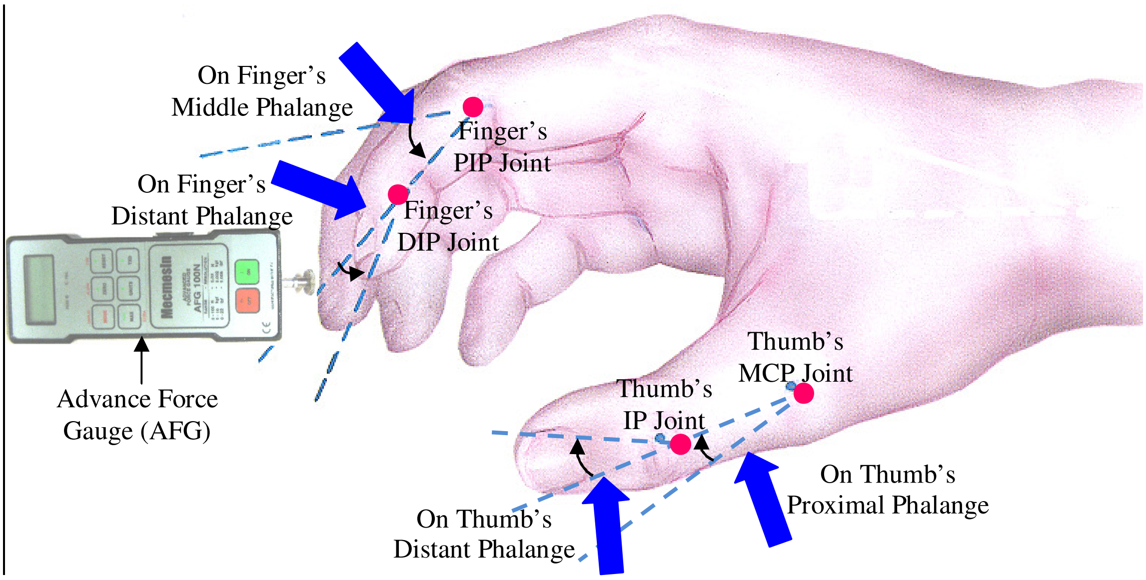


Figure 5.42: Maximum Flexion Force Measurement using Advance Force Gauge (AFG)

Figure 5.43 shows the average force results with standard deviation for eight healthy subjects. It is reflected that the forces required at the MCP (for thumb) and PIP (for individual finger) positions are much greater than those at the IP(for thumb) and DIP (for individual finger).

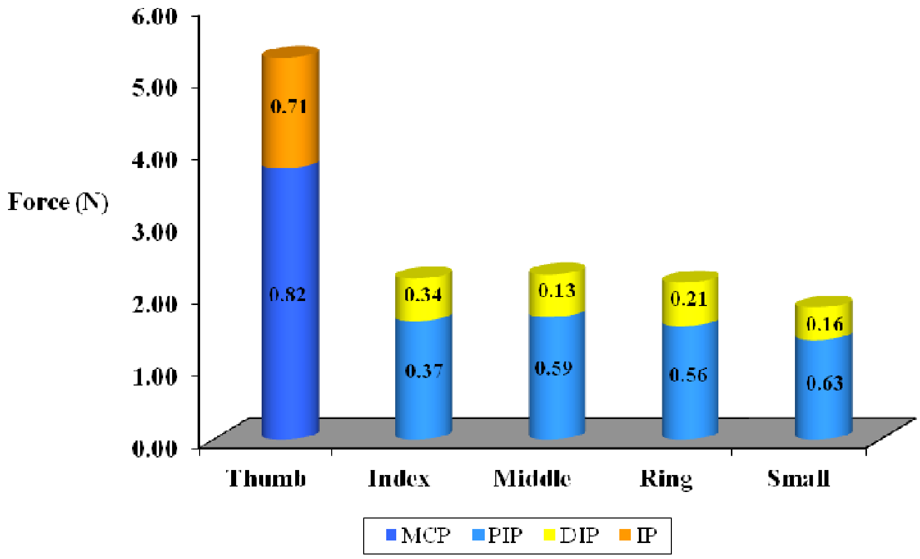


Figure 5.43: Average Maximum Force Obtained for Fingers and Thumb

This is so as the flexion of the PIP joint, the extensor digitorum (ED) will acts as a proximal stabilizer to prevent the flexor digitorum superficialis (FDS) from flexing the MCP joint and the wrist. Because of the progressively larger moment arms in the more proximal joints, the flexor torques progressively increase in a proximal direction of the joints. Therefore, it is essential to appreciate that the force exerted from the actuator has be larger when placed on the PIP joint as compared to the one placed on the distant phalange. Furthermore, it is crucial to note that post-stroke and SCI patients may in fact require more force to flex the fingers and thumb due to the spasticity of the muscles.

2) Flexion Angle for Fingers

This sub-section investigates if the angle of finger flexion affects the force required. Likewise, the fingers are in a relaxed state and that the AFG is used to measure the force. Only three fingers are taken into consideration, and that the angle of flexion is 35 and 65 degrees about MCP with AFG placed at the proximal phalange of the finger.

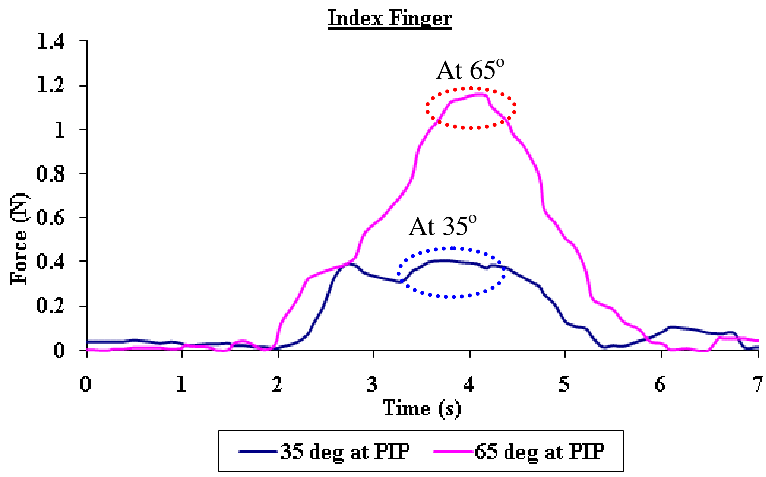


Figure 5.44: Flexion Force with AFG Placed at Proximal Phalange of Index Finger Rotating about MCP Joint at 35° and 65°

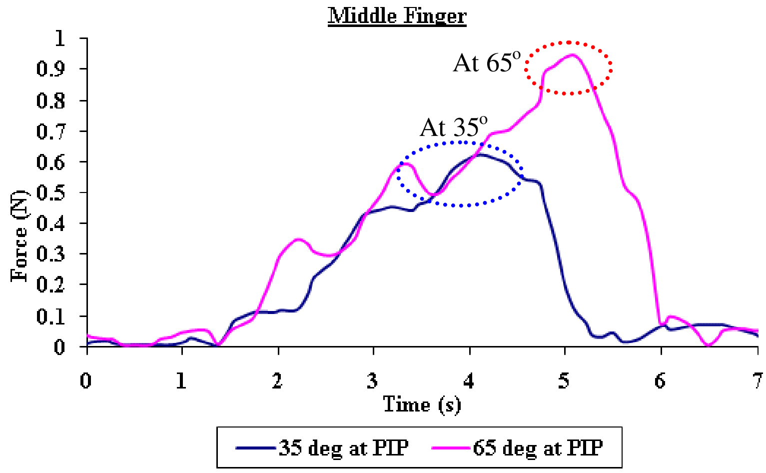


Figure 5.45: Flexion Force with AFG Placed at Proximal Phalange of Middle Finger Rotating about MCP Joint at 35° and 65°

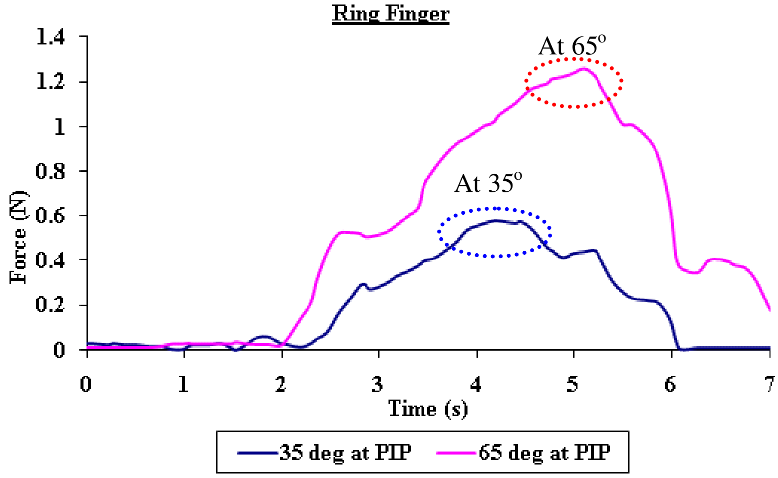


Figure 5.46: Flexion Force with AFG Placed at Proximal Phalange of Ring Finger Rotating about MCP Joint at 35° and 65°

As shown in Figures 8.34-8.36, it is not difficult to observe that for the three different fingers (index, middle and ring fingers), the force needed to flex it at 65^{o} about the MCP is greater than that at the 35^{o}. This is so as the tension in the tendon is higher at greater degree of flexion. In other words, the flexion of the finger can be viewed as a joint-pulley system [168]. Thus, the gradual change in angle across time gives rise to the force needed due to the restraining pulley system of the tendon.

3) Correlation of Object's Material and Force

This sub-section intends to find out how cup material may attribute to force exertion by the subject to crush various materials of cup in the five-pulp grip task. As such, Styrofoam, plastics and paper cups are used in the study.

Styrofoam cup is in fact made from Polystyrene which is an inexpensive and hard plastic for hot or cold drink. It is a good insulator as there is little polymer bubbles within which are also known as ‘foam cells’. It has a higher melting point and density (240^{o}C and 1050kg/m^{3}) than polypropylene

The plastics cup is usually made from polypropylene or polypropene (PP), a thermoplastic polymer. Polypropylene is reasonably economical, and can be made translucent when uncolored. Its melting point is 160^{o}C and a density of 850kg/m^{3}.

As for the paper cup, its rigidity is reinforced with single polyethylene or polyethene coating paper.

For each material testing, they each have their own critical period. For instance, Styrofoam cup’s critical period is from 16 to 18 sec (see Figure 5.47) – slightly shorter as compared than plastic cup and paper cup shown in Figure 5.48 and Figure 5.49. This is due to the brittle characteristics of the ‘foam cells’ in Styrofoam cup. That is to say, it deforms very minimal prior to fracture. In addition, due to the polystyrene’s high tensile strength, greater force (total force of 9.3N) is required comparatively.

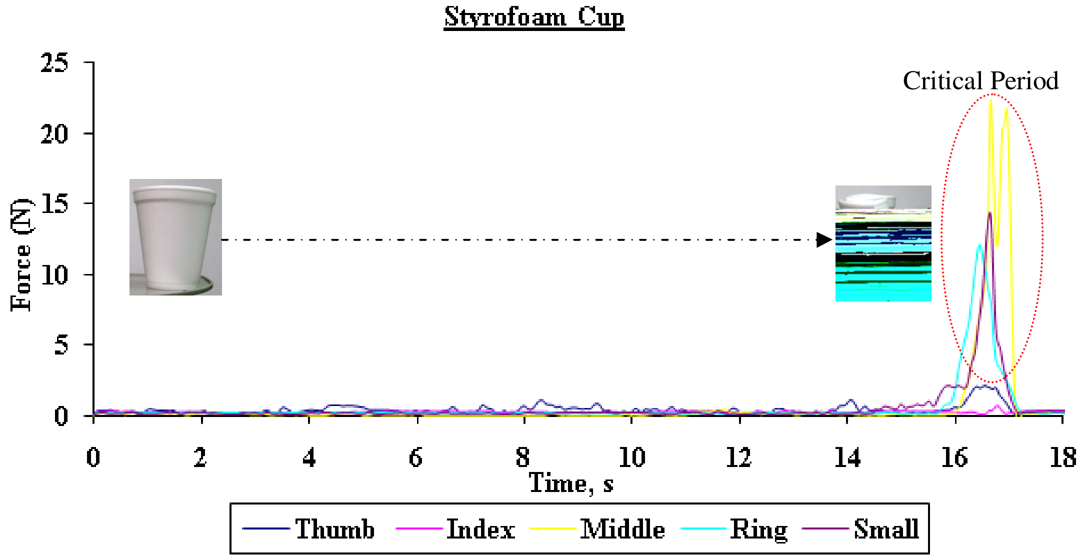


Figure 5.47: Variation in Force Exerted on Styrofoam Cup

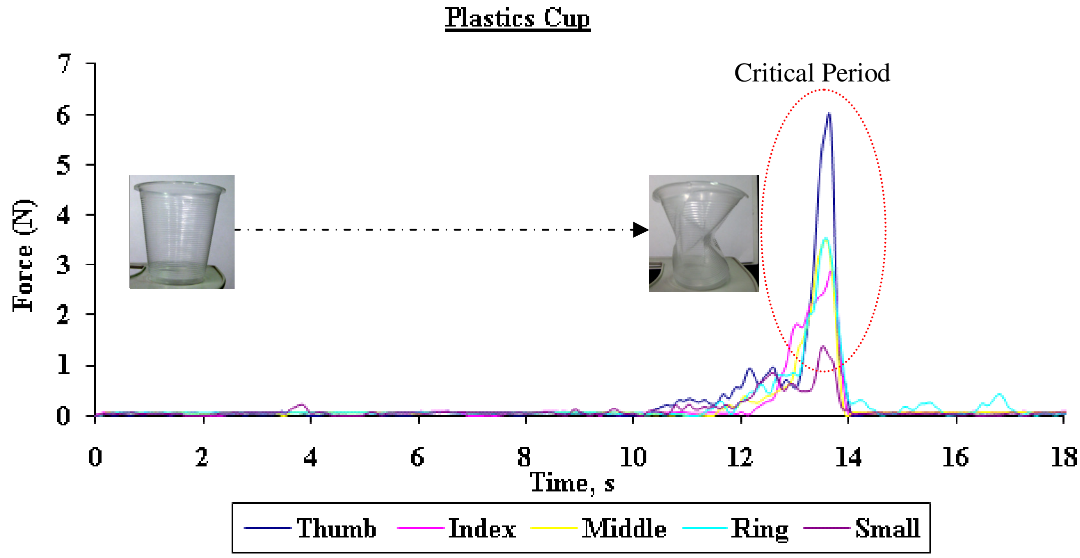


Figure 5.48: Variation in Force Exerted on Plastic Cup

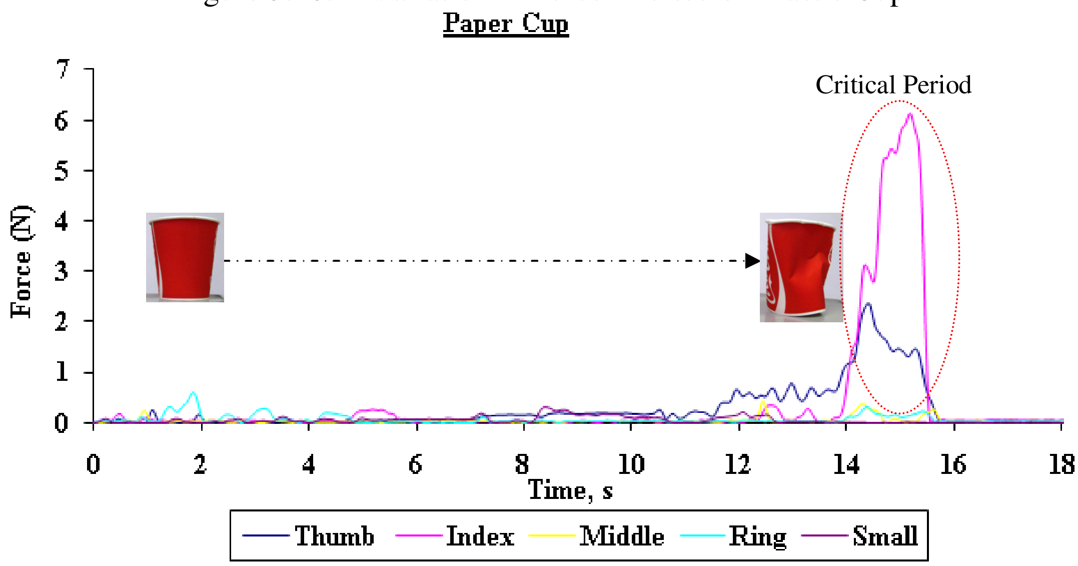


Figure 5.49: Variation in Force Exerted on Paper Cup

On the other hand, both plastics and paper cups need a roughly equivalent force to deform – 2.8N and 2N respectively. However, the percentage change is much lower for the paper cup due to its heavier weight.

While it is not exactly possible to distinguish which finger/s contribute more significantly, this sub-section has illustrated that material does led to different in force exertion. It also provides a better sensing of the force spectrum, particularly when it comes to the selection of actuator.

5.7 Summary

The task-oriented hand rehabilitation device dedicated for post-stroke or SCI patients whom suffering from hand impairment is presented in details.

The core concept used for the finger module was the concentric design of the driver in order to prevent the device from shearing the finger while driving the finger flexion and extension. The advantage of concentric design over the non-concentric design is illustrated and discussed. The concept of the finger module was abided to the human factors/ergonomics principles, so it is designed to share the same rotation centre as the joints of human hand. Hence, it eased the process of designing the rehabilitation device as many undesirable forces were avoided and the finished design processes the robustness to fit for most hand sizes. In addition, mockups and simulations were made for in depth studies of the functionalities of the device. Safety features was implemented into the device to ensure the safety of the user.

The thumb module is simplified as 3-DOF model (flexion/extension of the MCP and IP joints; and abduction/adduction of the CMC joint), covering about 75-80% of the workspace of the full thumb model. The adjustable mounting attachment of the thumb module is designed and assembled between the thumb linkages and thumb surface, which allow shifting based on the desirable angle for the task oriented training.

The wrist module was designed to assist patient's to perform flexion and extension exercises of the wrist, as well as securing all the Fingers and Thumb Modules in place. So that the patient does not need to carry the weight of the motors and mechanism, and the mechanisms are able to provide load-free exercises and training.

The force analysis for the concept of "load-free" design of the hand rehabilitation device is also presented, which aims to provide sufficient support to "hold" the fingers and minimize the load force on the fingers. The joint torque required for the robotic device is estimated from EMG signals based on the force analysis on "Load-free" concept. The assistive forces would be provided by the actuators to user during rehabilitation training.

It was shown that the force required to flex a finger of a normal person is rather minimal, approximately 1 to 2N. The concept of the pulley system in the tendon has also been verified with the experiments showing that a greater flexion angle about the joint leads to more force needed. The post-stroke and SCI patients may in fact require more force to flex the fingers and thumb due to the spasticity of the muscles. In addition, with the illustration of a five-pulp grid testing on various cup materials, it reaffirms that the texture and material characteristics do affect the force required.

Chapter 6 STUDY OF HAND STRENGTH MEASUREMENT ON ADL TASKS

The present study of hand strength aims to investigate the sEMG signals and gripping/pinch force for post-stroke and SCI patients based on the five ADL functional tasks, and also gather the necessary sEMG data to enhance the sEMG database of patient. The sEMG signal obtained from the measurement data will be used to calculate the assistive force/torque by the hand rehabilitation device for control purpose. The analysis using DOE and MVA is able to provide useful data (both statistical data and graphic information) for objective and quantitative assessment towards control applications on the hand rehabilitation device.

6.1 Overall Design and Measurement Protocol

The details of clinical study of hand strength including the protocol and procedures can be found in Appendix B.

6.1.1 Subjects and Overall Design for Measurement

This study included two population groups: a healthy group and a patient group with loss of function of the hand. As listed in Table 6.1 and Table 6.2, the healthy subject group consists of twenty-five healthy subjects, ages 17-79 years old, sixteen male subjects and nine female subjects. As for the patient group shown in Table 6.3, there are nine subjects with spinal cord injury (SCI), post-stroke or traumatic brain injury (TBI), and ages 25–69 years old, all males, participated. All subjects are given informed consent after the aim of the study and the experimental procedure had been explained to them. Prior to the research trials, all subjects are underwent an initial evaluation of their state of health including a review and evaluation of their motor power and muscle tone; along with an assessment of their blood pressure in sitting, and standing.

Entry criteria for patient group included age >18 years, Incomplete SCI patients and ASIA score as C or D with levels from C5 to L3 and at least 6 months post injury, stroke at least 6 months post injury. Exclusion criteria included inability to follow instructions, cognitively impaired; have concomitant neglect, ataxia; have severe postural hypotension; have ischemic heart disease or other medical conditions that may be aggravated by increased exertion; any other known pre-existing bone diseases that might increase the risk of bone fracture or other injury from intensive conventional therapy or robot-assisted therapy; severe spasticity limiting ambulation; with reduced joint range of motion; unable to maintain upright posture; and those who decline to participate.

Table 6.1: Summary of Subjects Information

Group	Gender	Age		
		Group mean	Range	Standard Deviation (SD)
Healthy	Male (n=16)	29.4	42.6	11.7
	Female (n=9)	44.8	56.3	21.1
Patient	Male (n=9)	53.9	43.8	13.1

Table 6.2: Basic Information of All Subjects

Subject	Group	Gender	Age	BMI	Freq of Exercise per week ≥ 3	Remarks
H1	Healthy	Male	17	19.75	Yes	Youth
H2	Healthy	Male	21	20.52	Yes	Youth
H3	Healthy	Male	24	22.23	Yes	Youth
H4	Healthy	Male	24	20.90	No	Youth
H5	Healthy	Male	25	25.56	Yes	Youth
H6	Healthy	Male	25	20.98	No	Youth
H7	Healthy	Male	25	26.51	No	Youth
H8	Healthy	Male	25	17.63	No	Youth
H9#	Healthy	Male	25	22.49	No	Youth
H10	Healthy	Male	25	22.15	No	Youth
H11	Healthy	Male	26	21.95	Yes	Youth
H12	Healthy	Male	27	24.73	Yes	Youth
H13	Healthy	Male	27	24.97	Yes	Youth
H14	Healthy	Male	46	20.05	No	Technician
H15	Healthy	Male	50	19.72	No	Taxi driver
H16	Healthy	Male	60	23.31	Yes	Gardener
H17	Healthy	Female	22	18.14	No	Youth
H18	Healthy	Female	23	19.81	Yes	Youth
H19	Healthy	Female	28	19.10	No	Youth
H20	Healthy	Female	30	26.04	No	Technician
H21	Healthy	Female	47	23.42	No	Housewife
H22	Healthy	Female	48	19.63	Yes	Technician
H23	Healthy	Female	50	22.04	Yes	Teacher
H24	Healthy	Female	75	22.83	Yes	Cleaner
H25	Healthy	Female	79	18.73	Yes	Housewife
P1	Patient	Male	50	24.74	N/A	SCI
P2	Patient	Male	52	27.68		SCI
P3	Patient	Male	69	25.39		Post-stroke
P4	Patient	Male	52	22.77		SCI
P5	Patient	Male	45	25.10		SCI
P6	Patient	Male	57	25.04		SCI
P7	Patient	Male	53	26.51		SCI
P8	Patient	Male	64	22.41		SCI
P9	Patient	Male	60	27.92		SCI
P10	Patient	Male	25	23.94		TBI

#*Note: H9 with hidrosis may affect the sEMG results.*

Table 6.3: Detailed Information of Patients Group

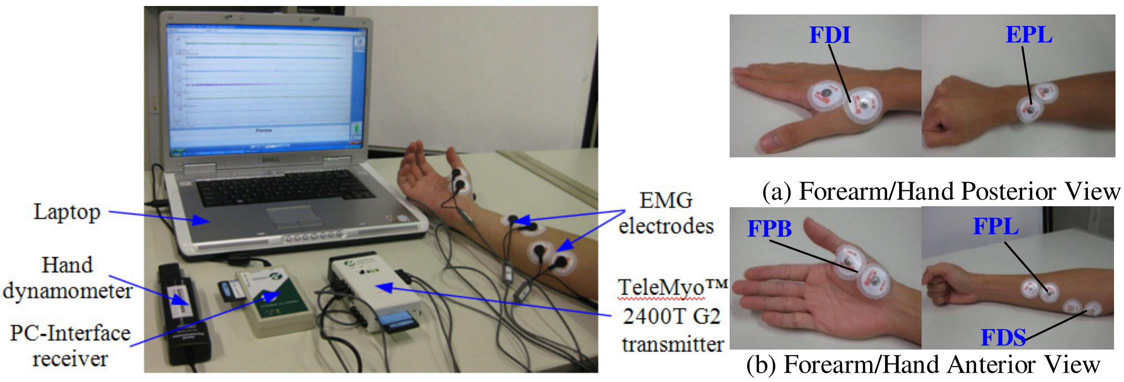
Subject Number		P1	P2*	P3	P4	P5	P6	P7	P8	P9	P10
Age		50	52	69	52	45	57	53	64	60	25
Years of injury		3	15	15	3	7	6	3	7	9	2
Impairment		SCI	SCI	Stroke (Left)	SCI	SCI	SCI	SCI	SCI	SCI	TBI
Skeletal Level Lesion		C5	C4/5	-	C3-5	C3-4	C3-4	C5	C6	C4/5	-
ASIA impairment scale		D	A	-	D	D	D	D	D	D	-
Motor scoring	**Finger flexors**	4	0	4	4	4	4	1	0	4	4
	Finger abductors	4	0	4	4	1	4	0	0	3	4
Spasticity of Wrist		1+/2	0	0	1+	1	1+	0	0	0	0
Dominant Hand		Right	Right	Right	Left	Right	Right	Right	Right	Right	Right
Testing Hand		Right	Right	Left	Left	Left	Right	Right	Right	Right	Right

**Note: P2 is excluded in this study due to his extremely weak muscle.*

6.1.2 Protocol of Measurement

1) sEMG Signal Acquisition and Processing

As shown in Figure 6.1, the sEMG data are collected at 1000 Hz with TeleMyo 2400T G2 (Noraxon, USA Inc.). Noraxon self-adhesive surface silver-silver-chloride dual snap electrodes are attached to the anatomical location for the muscles of the forearm and hand. To quantify the force exerted during the task, a hand held dynamometer is employed. The acquired raw sEMG signals are then processed using the Noraxon MyoResearch Master Edition software. The signals are full-wave-rectified to produce only positive value [169], smoothed using a 0.5 ms travelling window and then passed through a 2nd order digital low-pass Butterworth Filter with a cut-off frequency of 2 Hz.



(a) Forearm/Hand Posterior View

(b) Forearm/Hand Anterior View

Figure 6.1: Experiment Setup of the sEMG Measurement

Based on the study in Section 5.1.2, several muscles are activated during the five functional tasks. The sEMG signals of the wrist muscles (FCR, FCU, ECR and ECU) are acquired and analyzed for four different wrist motions: wrist flexion, wrist extension, radial deviation and ulnar deviation [170]. The sEMG signals of the extrinsic muscles of the hand (FDS, ED, FPL, APL and EPL) and intrinsic muscles (APB, FPB and FDI) are then acquired and analyzed for six different hand motions: finger flexion, finger extension, thumb abduction, thumb extension, thumb flexion (IP and MCP Joints) and thumb flexion (CMC Joint) [171].

The placements of the electrodes for the various muscles (FDS, FPL, FPB, FDI and EPL) are shown in Figure 6.1. The signals are acquired with the arm parallel to the body with the elbow bent at 90°.

2) Testing Procedure

The sequence of movement for each of the five tasks used in activities of daily living (ADL) are identified, noting the joints involved and moved along with patterns of muscle activation. The use of the grips in ADL is non-exhaustive and that variations of the grips exist for various functions. The execution procedure leading to the eventual actions are taken into the account in completing each of the five rehabilitation tasks. For all the tasks, the course of action is listed as follows:

a) At t = 0 s, the hand will be at neutral position. The test will start only when all muscles' sEMG signals are stable and unexcited.
b) At t = 2 s, the experimenter will prompt the subject to position his/her hand on the hand dynamometer for the respective task. No force is to be exerted at this instance.
c) At t = 5 s, the subject is requested to exert fullest strength on the force device. The exertion will last for 5 seconds.
d) At t = 10 s, the subject is to cease the exerting strength on the hand dynamometer and return to the neutral position. This portion will last for the next 4 to 5 seconds.

The sEMG signals and maximum gripping/pinch force are measured for the five functional ADL tasks based on two phases as shown in Figure 6.2: Phase I (positioning) and Phase II (action).

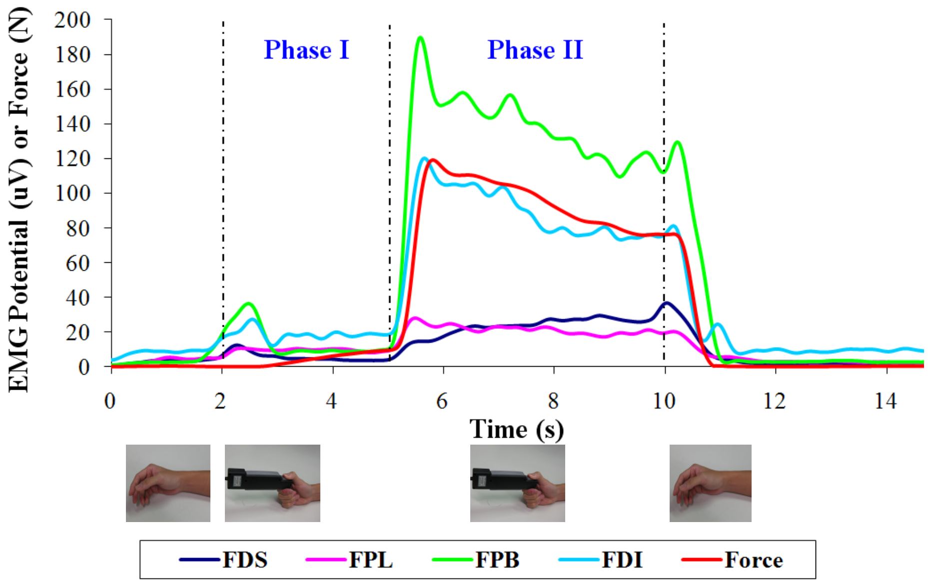


Figure 6.2: sEMG and Force Signals of the Key/Lateral Pinch

3) Muscle Groups Associated to Individual Finger Motions

The hand functions analyzed in this section can be divided into two groups: those pertaining to thumb motion and those pertaining to finger motion. For the thumb motions, sEMG signals of the muscles were acquired and analysed for thumb abduction, thumb extension, flexion of the CMC joint of the thumb and flexion of IP and MCP joints of the thumb. For finger motions, the sEMG signals acquired and analysed were for finger flexion and finger extension.

The sEMG signals of the intrinsic muscles are consistently higher than the extrinsic muscles. As the sEMG signals from the intrinsic muscles travel through less skin to reach the electrodes, there is lower resistance. Also, the electrodes for the intrinsic muscles are moved together during hand movement and this contributes to further signal noise. Furthermore, due to the high density of muscles in the forearm, there is greater crosstalk of sEMG signals, complicated further by muscle co-contraction. Hence, it is difficult to identify and isolate the corresponded sEMG signals for each muscle movement. So we decided to consider them as a group of muscles and grouping them by their combined action e.g. wrist extension, the results show patterns that are consistent with theoretical muscle-action mapping.

The intrinsic and extrinsic groups of muscles are analyzed separately and the results show that muscles that are responsible for certain hand motions produce the greatest change in sEMG signal. From the initial experiments conducted, we are able to identify wrist movement and hand function by finding the resting potential of the sEMG signals and by deriving the increase in sEMG potential during the action. For motions pertaining to the fingers and thumb, it is possible to identify motions by monitoring various muscles. The characteristics of each motion can also be identified. The flowchart of the process to identify individual hand motions is shown in Figure 6.3.

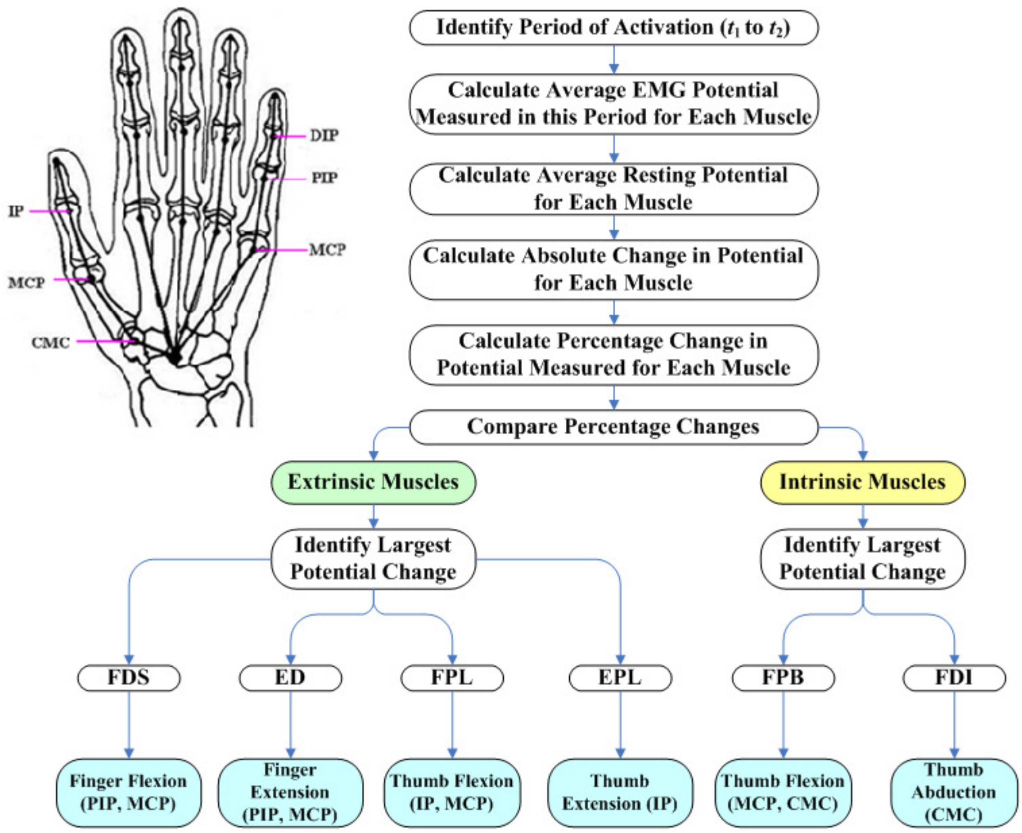


Figure 6.3: Flowchart of Individual Finger Motions Identification by sEMG signals

6.1.3 sEMG Signals for Physical Conditions

1) sEMG signals vs Passive and Active Force

In this experiment, four muscle groups, FDS, FPL, FPB and FDI are considered as the test focuses only on thumb motion. The subject's thumb is first aided by the experimenter in an up-down continuous motion from t = 5s to 10s (see Figure 6.4). Subsequently, the thumb will maintain at neutral position before the subject begins to move his thumb in the up-down motion on his own, from t = 15s to 20s. It can be observed that the active force region has a generally higher magnitude trend as compared to the sEMG signals' potential in passive region.

As such, the sEMG signals obtained during the measurement represent their own force active force of the subjects; so that the hand rehabilitation device can assist the patient's movement only as much as necessary. This will allow the patient to actively learn the spatiotemporal patterns of muscle activation associated with normal hand function.

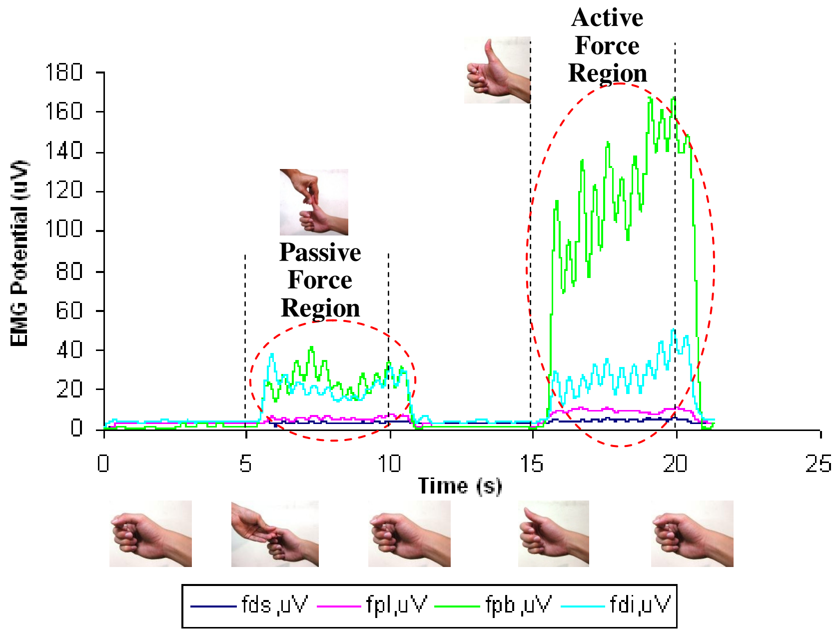


Figure 6.4: sEMG Signals Versus Passive and Active Force during Thumb Motion

2) sEMG Signals Vs Joint Angles

Figure 6.5 shows the relationship between wrist angle and sEMG signals of the wrist extensors during wrist extension. The peaks of the sEMG signals coincide with the point the wrist reaches its maximum range of motion at around t = 3.6 s. The wrist is held at this position for the next 5 seconds, which shows a decreasing sEMG potential. At t = 7.0 s, the sEMG signals of both ECR and ECU drop with the decrease in wrist extension angle until they hit the resting potentials.

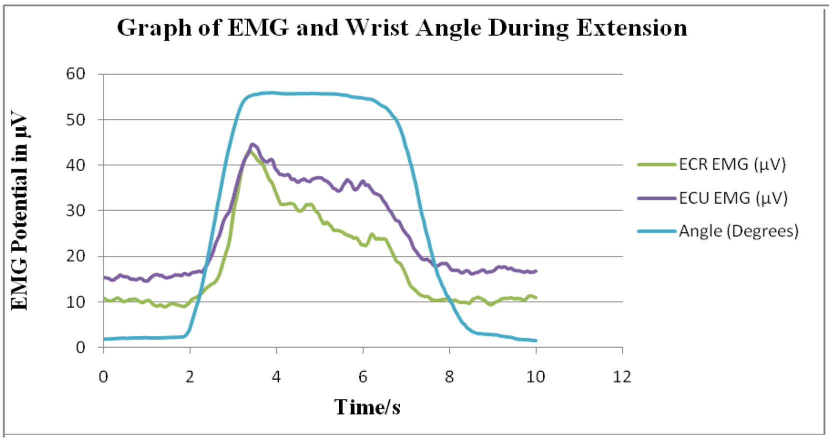


Figure 6.5: sEMG Signals and Wrist Angle during Extension

Figure 6.6 shows the relationship between wrist angle and sEMG potentials during the rise portion (t = 2.0 s to t = 3.6 s). Both ECR and ECU show an approximate logarithmic relationship between wrist angle and sEMG potentials.

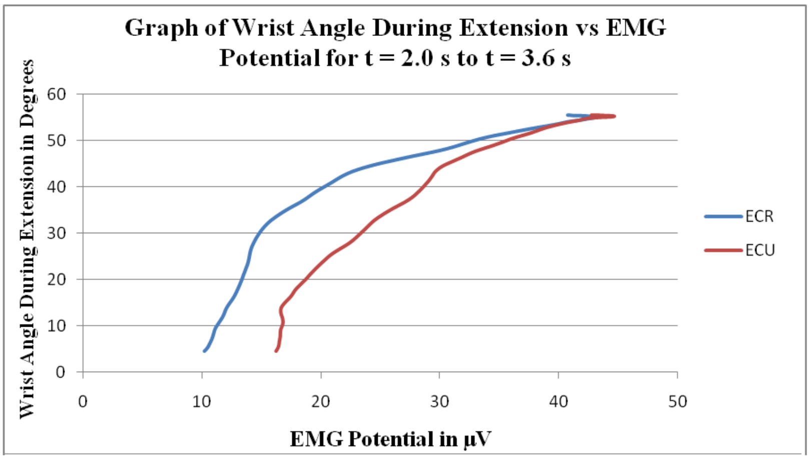


Figure 6.6: Wrist Angle during Extension versus sEMG Potential

3) sEMG Signals Vs Joint speed (Velocity)

Figure 6.7 illustrates a comparison between two different speeds of wrist extension. The slower speed is shown in red while the faster speed is shown in green. As it has been shown in the graphs, the cycle with the higher velocity gives a higher peak of 45 µV for ECR and 60 µV for ECU. However, the steady state sEMG potentials during the static holding of the wrist in its extended position seem to be relatively constant for both speeds. From these experiments, it can be seen that the greater the change of angular velocity, the higher the peak of the sEMG signal.

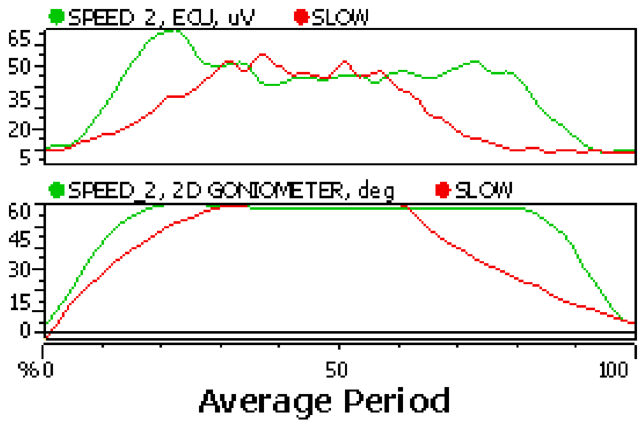


Figure 6.7: Two Velocities of Wrist Extension Versus sEMG Signals

6.2 Initial Results of Hand Strength Measurement

This section describes the initial assessment results for sEMG signals, and gripping force that are proposed to be used for subsequent objective assessment (see Figure 6.8). Figure 6.8 shows the sEMG and force measurement for the patient during key pinch.

Figure 6.8: sEMG and Force Measurement for Patient during Key Pinch

6.2.1 Comparison of sEMG Signals for Individual Task

Using the FPB signal from the five-pulp pinch as an example, four healthy subjects (two male subjects and two female subjects from different age group) and four patients (two SCI, one post-stroke and one TBI patients) are selected for the comparison. As shown in Figure 6.9, the healthy subjects have much higher sEMG signals at Phase II (maximum force exertion) compared with the two SCI patients. The FDS signal of post-stroke patient P3 (15 years recovery after stroke) and TBI patient are comparable to the healthy subjects in both measurements.

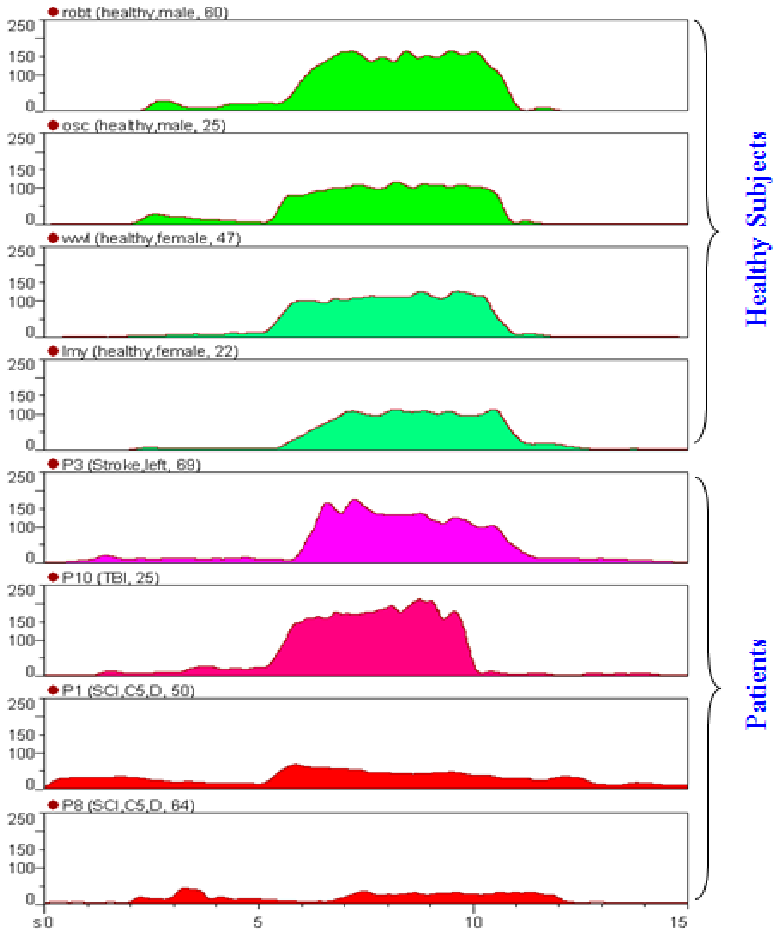


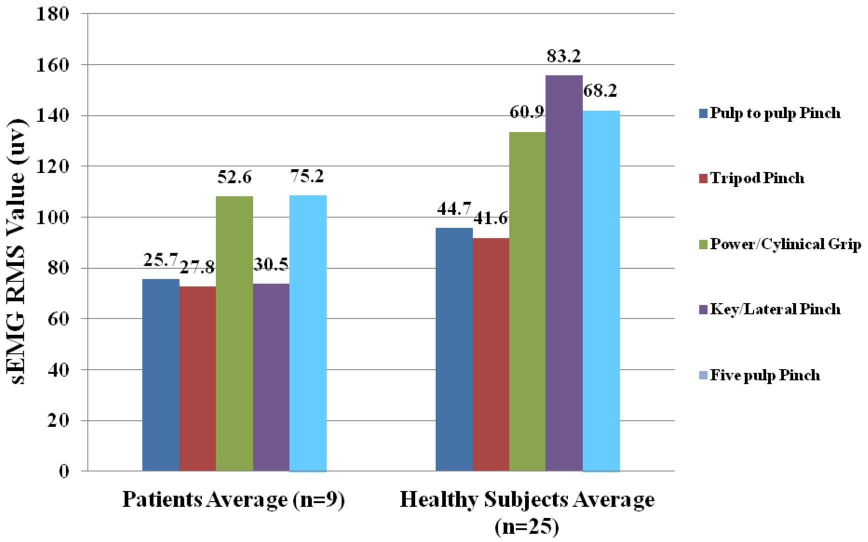
Figure 6.9: FDS Signal of Five-pulp Pinch between Patients (affected hand) and Healthy Subjects

6.2.2 Comparison of sEMG RMS and Force Strength for Different Tasks

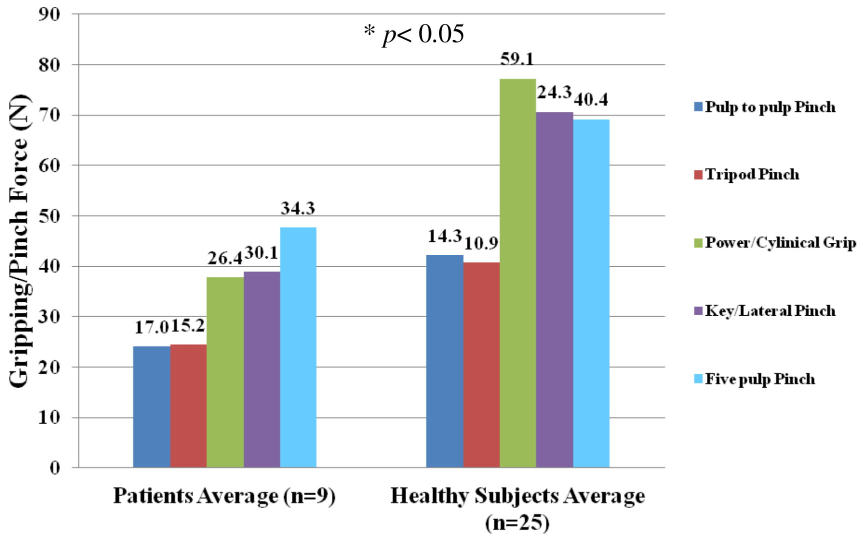
In the literature, the root-mean-square (RMS) value of the sEMG signals, which reveals its mean power in time domain, has been proposed as a reliable measure of the force contribution of the muscle groups from subjects with spinal cord injury during voluntary motor tasks [172]. The RMS potential of the sEMG signals is calculated for the individual muscle group as

$$\text{Root Mean Square (RMS)}=\sqrt{\frac{(\mathrm{EMG}_1)^2+(\mathrm{EMG}_2)^2+\cdots+(\mathrm{EMG}_n)^2}{n}} \tag{6.1}$$

The sEMG signals RMS values (Phase II) with standard deviation are calculated for each subject and the results for each task are plotted in Figure 6.10(a). As shown, the average RMS for healthy subjects is greater than the patients. As shown in Figure 6.10(b), the average gripping/pinch force (Phase II) for each rehabilitation task based on nine patients is significantly smaller than the average force of twenty-five healthy subjects (p< 0.05). Figure 6.10(b) also compares the overall gripping/pinch strength of the two groups of subjects. Figure 6.10 show the average hand strength (with standard deviation) of the patient in ascending order from pulp-to-pulp pinch, tripod pinch to power/cylindrical grip, it is because two (thumb and index finger), three (thumb, index and middle finger) and five fingers are used in the tasks respectively, assuming that the patients have higher hand strength with more fingers involved in the grasp.



(a) Average sEMG RMS Value



(b) Average Gripping/Pinch Force

Figure 6.10: Hand Strength of Five Rehabilitation Tasks

6.2.3 Subject Comparison of Gripping/Pinch Force

Figure 6.11 shows the maximum gripping/pinch force between the patients and the average force of 25 healthy subjects (age from 17 to 79). It is shown that patient P8 with an incomplete SCI (Level of Lesion C5, ASIA impairment scale D, age 64) exhibits the lowest gripping/pinch force among all the patients. The patient's motor scoring (in Table 6.3) of finger flexors and abductors are 0 (i.e. total paralysis), which is also the lowest among all the patients. The result shows that the motor scoring of SCI patients is representative of the gripping/pinch force, the lower the motor scoring, the lower the gripping/pinch force (as shown in Figure 6.11 for patients P8, P7, P5, and P9).

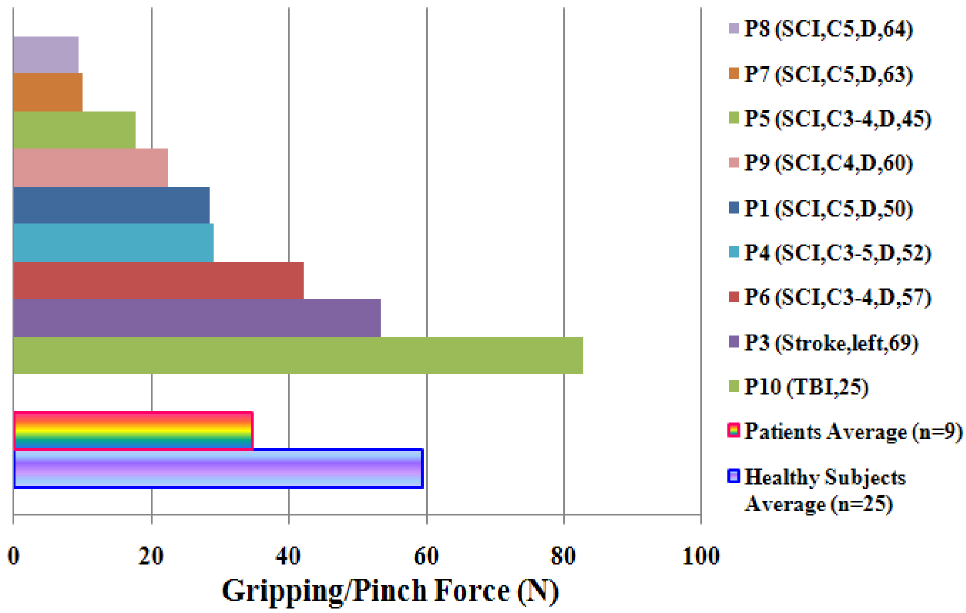


Figure 6.11: Maximum Gripping/Pinch Force between Patients and Healthy Subjects

As for the same motor scoring for patients P1, P4, and P6, the gripping/pinch force is also affected by other factors, e.g. the restricted movement of the thumb for patient P1, restricted movement of the small finger for patient P6 and the muscle pain for patient P4. The post-stroke patient P3 has better hand strength compared to the SCI patients, but the gripping/pinch force is still lower than the average value of healthy subjects. The only TBI patient (P10) is unable to control the maximum force exerted during the measurement, even though the gripping/pinch force is much higher than the average value of healthy subjects. On average, there is still room for improvement for these patients.

6.3 Interpretation of Measurement Data

From the sEMG signals of five ADL tasks presented in Section 7.2, some trends can be observed pertaining to each task. By just browsing the data, it is not possible to understand the relationships among different muscle signals. Therefore, a data analysis using the techniques of DOE and MVA [173] are suggested in the work.

6.3.1 Dominant Factors Identification using DOE

1) 2^{5-2} Fractional Experiment for Healthy Subjects

Factorial experimental designs with all possible combinations of the levels of the factors are investigated. In the proposed 2^{5-2} fractional experiment, five factors are considered: gender, age, body mass index (BMI) [174], hand ratio, and frequency of exercise per week. Each factor consists of two levels, as shown in Table 6.4. The response of the factorial experiment is griping/pinch force at Phase II. It is observed that "gender" and "age" seem to be the contributing factors to the response (gripping/pinch force) in all five rehabilitation tasks. Despite that the fact that age does not reach the significant level, the main effect of age is still much greater compared to other factors (see Table 6.5).

Table 6.4: Five Factors with Two Levels for Fractional Experiment

Factor	Low (-)	High (+)
A (Gender)	Male	Female
B (Age)	≤ 45 years old	> 45 years old
C (BMI)	≥23	< 23
D (Hand Ratio= Hand Length/Hand Breadth)	≤ 1.86	> 1.86
E (Freq. of Exercise/wk)	< 3 times	≥ 3 times

Table 6.5: Main Effect and Test Ratio in 2^{5-2} Fractional Experiment

	Pulp-to-pulp Pinch	Tripod Pinch	Power Grip	Key Pinch	Five-Pulp Pinch	Grip Strength	Pinch Strength
Main Effect							
A	**-18.99**	**-23.72**	**-65.75**	**-39.89**	**-37.83**	**-51.79**	**-170.39**
B	-8.92	**-10.10**	**-57.93**	**-29.29**	-21.23	**-39.58**	**-111.06**
C	-8.80	6.08	-37.92	-25.77	-34.85	-36.38	-48.36
D	2.75	4.45	40.00	20.44	34.68	37.34	59.01
E	**13.42**	-0.46	43.65	22.85	14.82	29.24	68.67
Test Ratio F_0							
A	**-4.82***	**-5.98***	-1.84	**-4.34***	-1.86	-1.94	**-5.39***
B	-2.27	-2.55	-1.62	-3.18	-1.04	-1.48	-3.51
C	-2.23	1.53	-1.06	-2.80	-1.71	-1.36	-1.53
D	0.70	1.12	1.12	2.22	1.70	1.40	1.87
E	3.41	-0.12	1.22	2.48	0.73	1.09	2.17

** Significant at $p \leq 0.05$ level*

2) Least Significant Difference Test on Level Means

A single factor experiment, followed by the least significant difference level (LSD) test, has been used to examine the differences between the individual level means. In the age-factor experiment, the three categories are: age less than 45 years old (Level I), age between 45 to 59 years old (Level II), and age 60 years old or older (Level III). The results of gripping/pinch force in Figure 6.12 shows that Level I, Levels II and III are insignificantly different from each other; however the result of Level 1 and Level 2 of healthy subjects are still significantly greater than the patients ($p < 0.001$ and $p < 0.007$). There is an exception for the gripping strength (average gripping force of five-pulp grip and cylindrical grip).

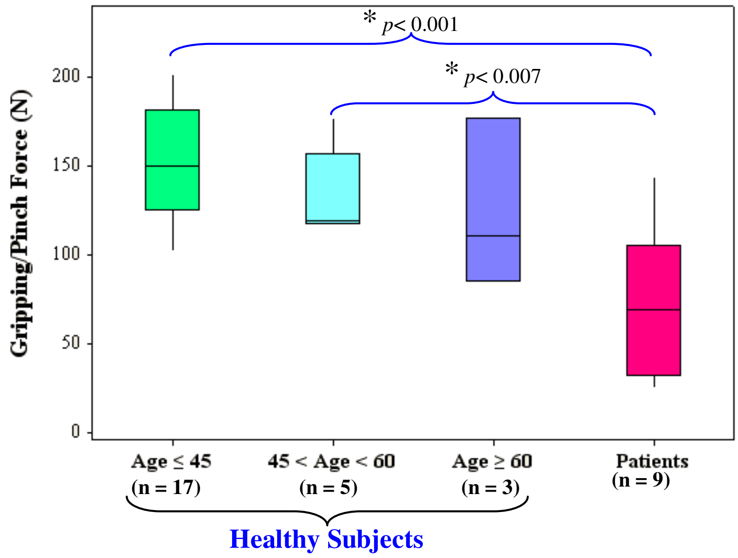


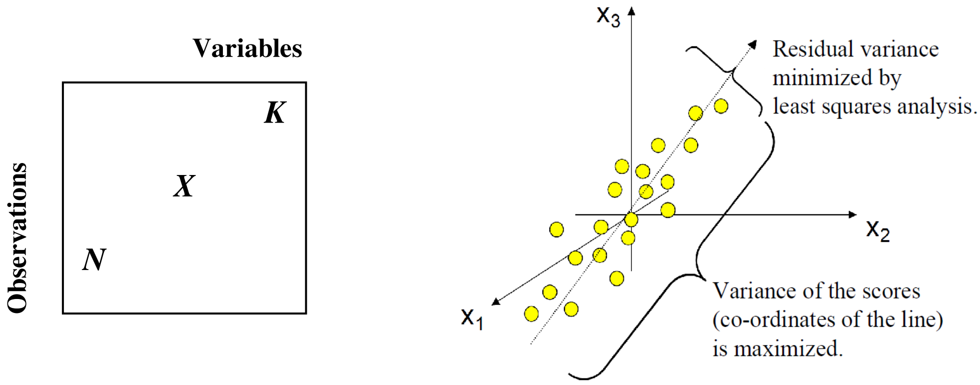
Figure 6.12: Box Plot of the Gripping Force for Healthy Subjects (in 3 Age Groups) and Patients

6.3.2 Multivariate Analysis Method

Unlike univariate approaches, multivariate methods facilitate analysis and visualization of large complex datasets and provide a holistic summary of the data. The data summary presents correlations and trends pictorially, separates systematic behavior from noise, handles missing data, detects outliers, and highlights clusters and patterns.

1) Principal Component Analysis (PCA): Data Analysis and Interpretation

Principal component analysis forms the basis for multivariate data analysis [175] and PCA was first formulated in statistics by Pearson [176, 177] . The most useful feature of PCA is indeed to represent a multivariate data table as a low-dimensional plane, usually consisting of 2 to 5 dimensions. This overview may reveal groups of observations, trends, and outliers. It also uncovers the relationships between observations and variables, and among the variables themselves.



(a) Notation used (b) PCA maximize the variance of the projection co-ordinates

Figure 6.13: PCA Notation and Co-ordinates [173]

As shown by Figure 6.13(a), the starting point for PCA is a matrix of data with N rows (observations) and K columns (variables), denoted by X. Statistically, PCA finds lines, planes and hyper-planes in the K-dimensional space that approximate the data in the least squares sense. It is obvious that a line or a plane obtained by the least squares approximation of a set of data points makes the variance of the co-ordinates on the line or plane as large as possible as shown in Figure 6.13(b). By using PCA, a data table X is modeled [176] as

$$X = 1 * \bar{x}' + T * P' + E \tag{6.2}$$

where * denotes the multiplication of two matrices.

By virtue of PCA, the X-matrix can be decomposed into the product of two matrices, the ($N * A$) score matrix T times the ($A * K$) loading matrix P', plus an ($N * K$) "noise" matrix of residuals, E. The value of A, the number of principal components, is usually determined by cross-validation. Figure 6.14 summarizes the geometric interpretation of PCA with two principal components.

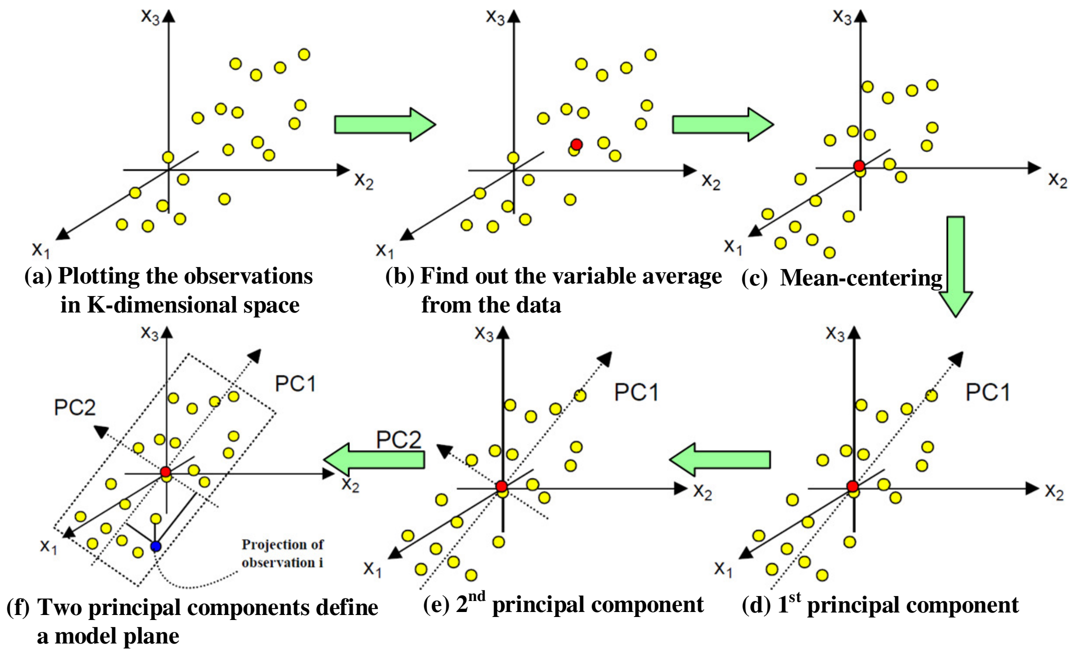


Figure 6.14: Geometric Interpretation of PCA (modified from [173])

Cross-validation (CV) is a practical and reliable way to test the significance of a PCA or a PLS model. The performance a PCA model is evaluated by simultaneously considering the explained variation R^2X (goodness of fit) and the predicted variation Q^2X (goodness of prediction). The R^2X and Q^2X parameters display entirely different behaviors as the model complexity increases (see Figure 6.15). R^2X varies between 0 and 1, where 1 means a perfectly fitting model and 0 no fit at all. R^2X is inflationary and approaches unity as model complexity increases. Q^2X is less inflationary and will not automatically come close to 1 with increasing model complexity, provided that Q^2X is correctly estimated.

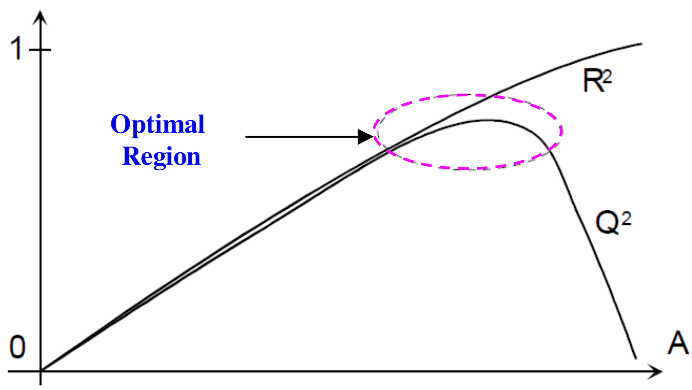


Figure 6.15: Trade-off between the Goodness of Fit R^2X, and the Goodness of Prediction Q^2X (Modified from [173])

2) Projections to Latent Structures (PLS): Data Prediction and Classification

PLS [178] (projections to latent structures) is a method for relating two data matrices, X and Y, by a linear multivariate model [173]. The method is able to analyze data with a large number, noisy, collinear, and even incomplete variables in both X and Y.

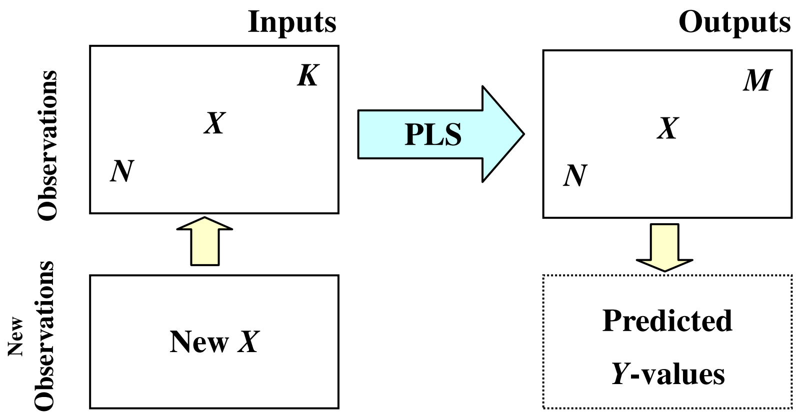


Figure 6.16: Notation used in PLS [173]

PLS is a generalization of PCA to deal with the relationship of X and Y (see Figure 6.16). PLS can be seen as a particular regression technique for modeling the association between X and Y. Figure 6.17 summarizes the geometric interpretation of PLS modeling.

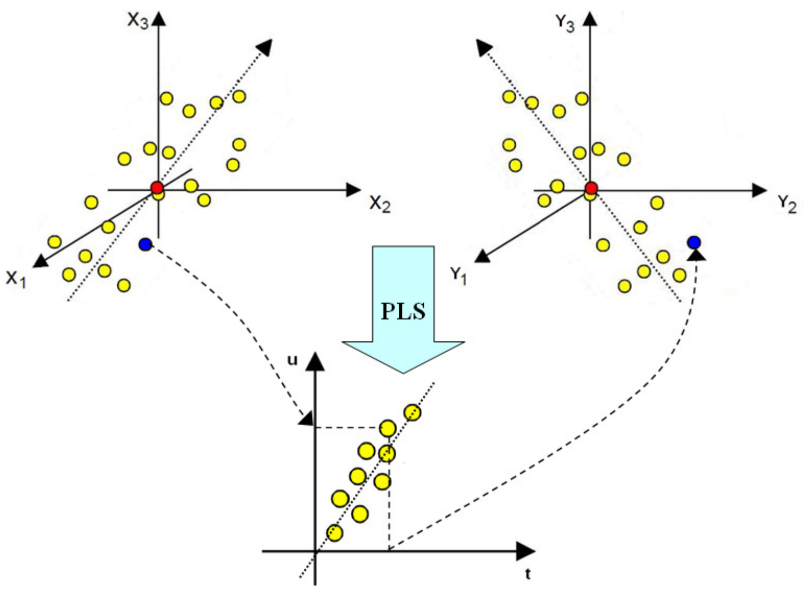


Figure 6.17: Geometric Interpretation of PLS Modeling (modified from [173])

Multivariate classification [173] is used to distinguish between the classes, to identify important or discriminatory variables, and also to interpret class differences within class variation. PLS Discriminant Analysis (PLS-DA) [178] is able to show which variables responsible for class discrimination, and suitable for tight groups. PLS-DA makes it possible to accomplish a rotation of the projection to give latent variables that focus on class separation/discrimination.

6.3.3 Graphical Interpretation using MVA

1) PCA: Data Analysis and Interpretation

The MVA analysis aims to study how the variation in muscle activation and gripping/pinch force among a number of healthy/patient subjects are related to age; gender and BMI; hence to find the similarities and dissimilarities among the subjects. The data set consists of the sEMG signals, gripping/pinch force for action phase, and the changes between the two phases (positioning/action). Figure 6.18 shows how the overall R^2X (goodness of fit) and Q^2X (goodness of prediction) statistics change as a function of increasing model complexity. Here, three components appear appropriately, as Q^2X does not increase beyond the third component based on cross-validation (CV) of the model. The model summarizes the variation in three major latent variables, describing the 81.2% of the variation $R^2X(cum)$ in the data for muscle activation and gripping/pinch force of the subjects.

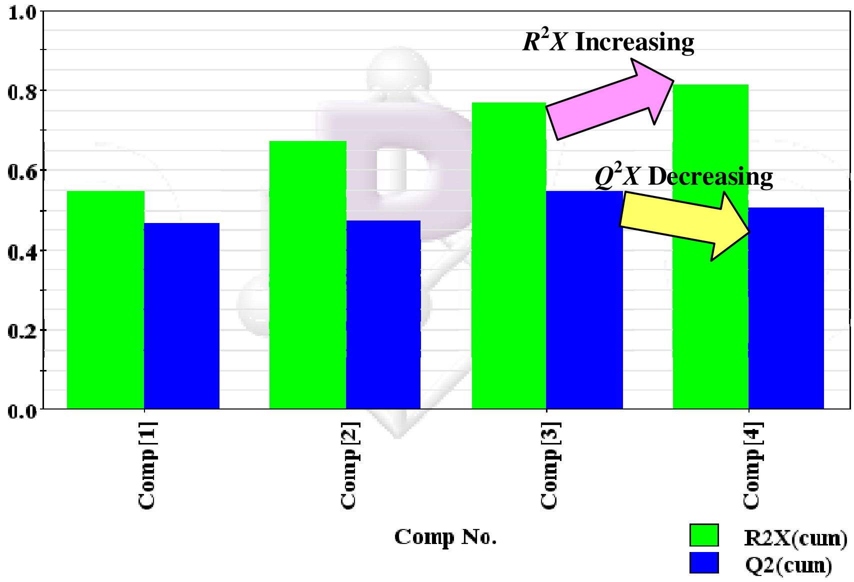


Figure 6.18: Overview of PCA Model for Five ADL Rehabilitation Task

The sEMG signals and the maximum gripping/pinch force for all the five ADL tasks are analyzed by the PCA score scatter 3D plot. As shown in Figure 6.19, the three axes, t_1, t_2, and t_3, represent the main principal components found across all of the data, which are new variables computed as linear combinations of all the original variables to provide a good summary. The ellipse is the Hotelling's T2 ellipse at 95% confidence level, which shows a possible presence of outliers and other patterns in the data. From the PCA score in 3D plot for five rehabilitation tasks as illustrated in Figure 6.19, one strong outlier, "P10", is found in the score plot, which confirms the overall correlation structure of the data. However, it might have an extreme character that is outside the ellipse and far away from the most of the data: "P10" with TBI affects the sEMG signals. The PCA score scatter plot can also be used for single ADL rehabilitation task.

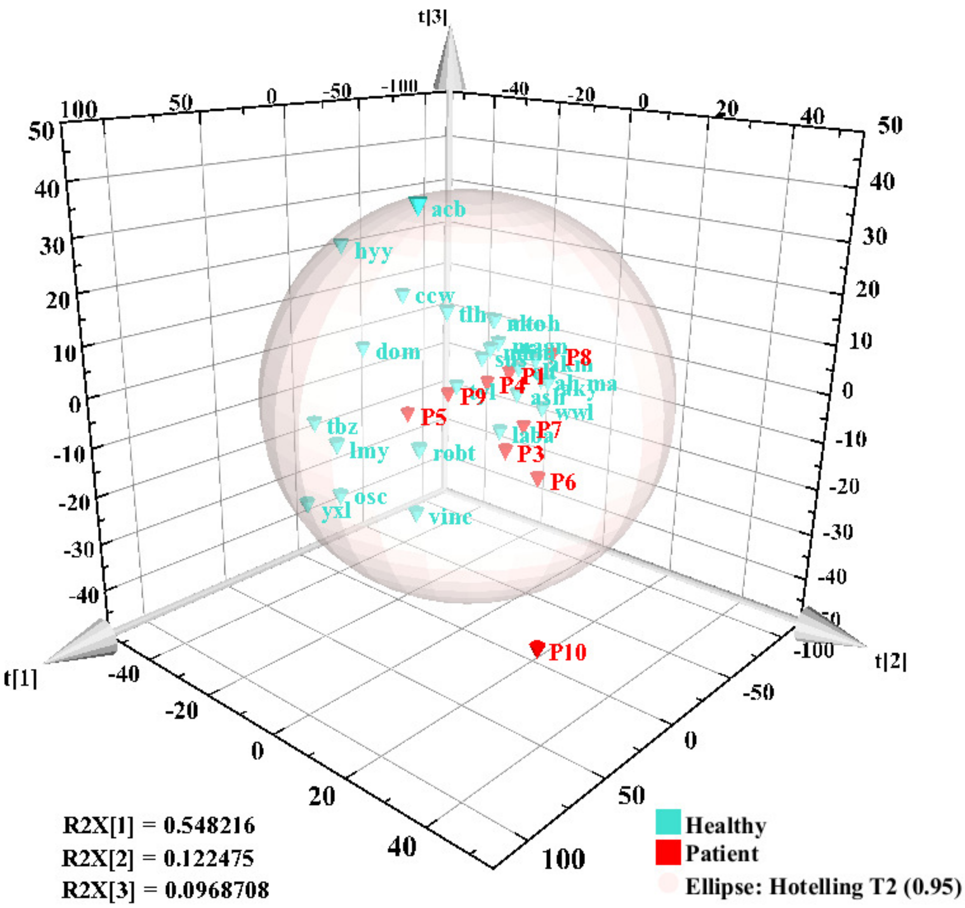


Figure 6.19: PCA Score Scatter 3D Plot for Five ADL Rehabilitation

The PCA score scatter plot can also be used for single ADL rehabilitation task. For example, the score plot provides a good summary the five-pulp pinch based on the age group (see Figure 6.20). Although there are overlaps between the young and old subjects, the trends for the old subjects can be diagnosed from the same figure. The results in Figure 6.20 also demonstrate that the "age" is a dominant factor compared to other factors.

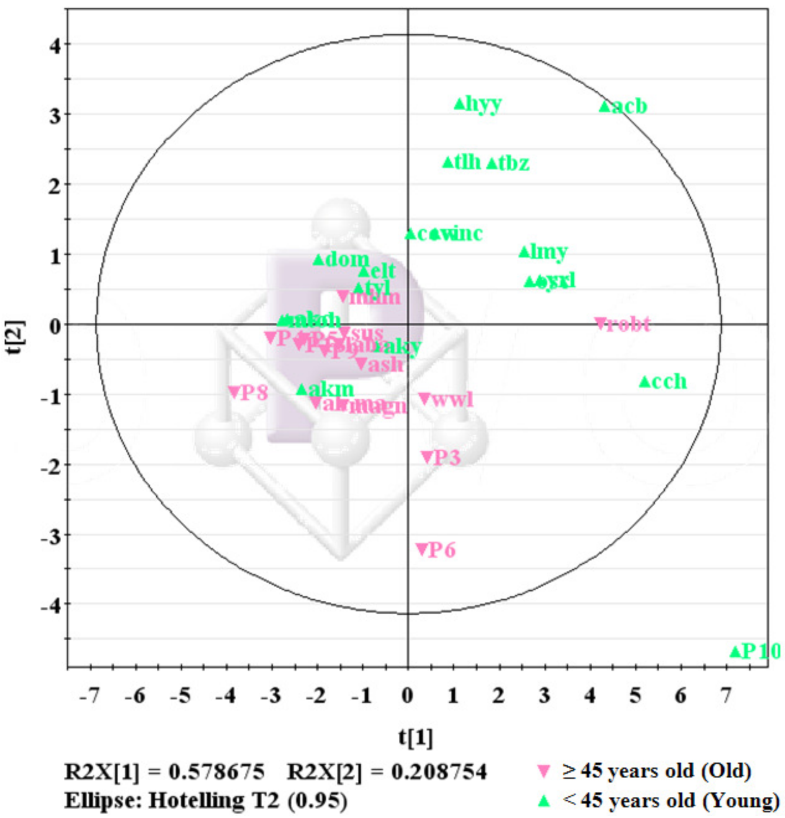


Figure 6.20: PCA Score Scatter Plot for Five-pulp Pinch

2) PLS: Data Prediction and Classification of Each Associated Task

Another objective of this MVA study is to develop a predictive model, relating the gripping/pinch force X 's to the sEMG measurements Y (RMS potential). Note that the RMS potential is calculated for the individual muscle group, as the sEMG signals are very small for SCI patients; and the interference from noise is large for post-stroke patients, due to the spasticity. Moreover, the hand dynamometer is specifically designed to measure gripping/pinch force. It has a large surface area to detect the applied force. Therefore, it is easy to measure the gripping/pinch force compared with the sEMG signals. PLS Discriminant Analysis (PLS-DA) is able to show which variables responsible for class discrimination, and suitable for tight groups.

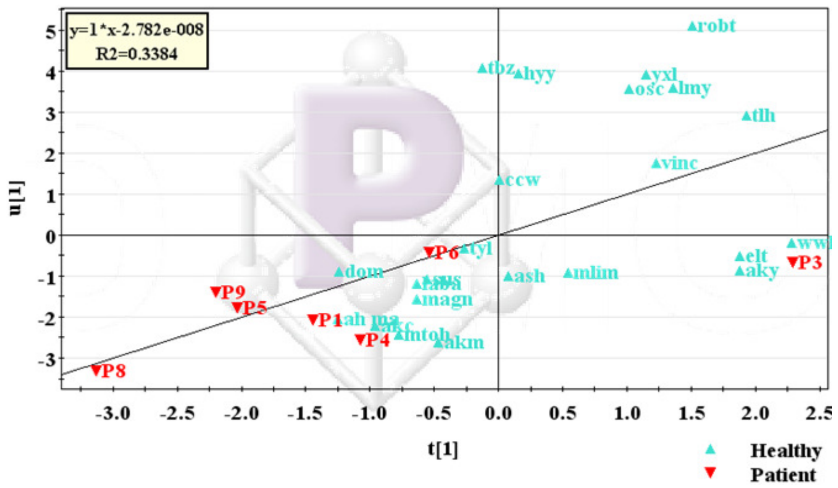


Figure 6.21: PLS Score Scatter Plot for Five Pulp Pinch

We take five pulp pinch as an example of ADL rehabilitation tasks to illustrate the application of PLS modeling. The present PLS model (see Figure 6.21) covers both the healthy subjects (in blue) and the patients (in red) with SCI or post-stroke for five pulp pinch. We have a relatively good relationship between the first summary of the X 's (t_1) and the first summary of the Y 's (u_1), with some spreading in the data. A regression line is fitted to the observations. The PLS model can be used to predict the outcome of the sEMG results for the subjects with difficulties in sEMG measurement. An improved PLS model for patient group could be obtained with an increased number of data from the patient group.

In PLS-DA, the score plot can be useful as one might wish to overview the class discriminating ability of a developed model. Figure 6.22 shows that the two groups of healthy subjects (in blue) and patients (in red) are clearly separated by the PLS-DA score plot. More quantitative estimate of the discriminatory power can be obtained by means of the PLS-DA Variable Importance Plot (VIP). Figure 6.23 shows that the FDS muscle (corresponding to flexion the MCP and PIP joints of fingers during the five pulp pinch) displays the strongest discriminatory power. It is also shown that the RMS value with second strongest discriminatory power is well presented for all the sEMG signals.

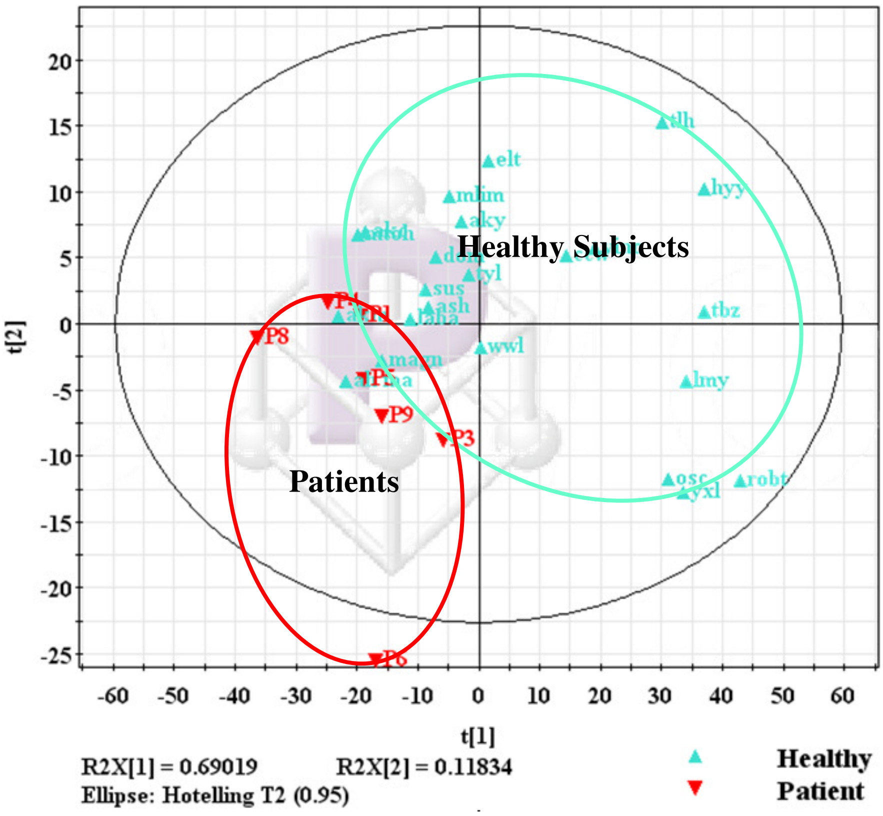


Figure 6.22: PLS-DA Score Scatter Plot for Five Pulp Pinch

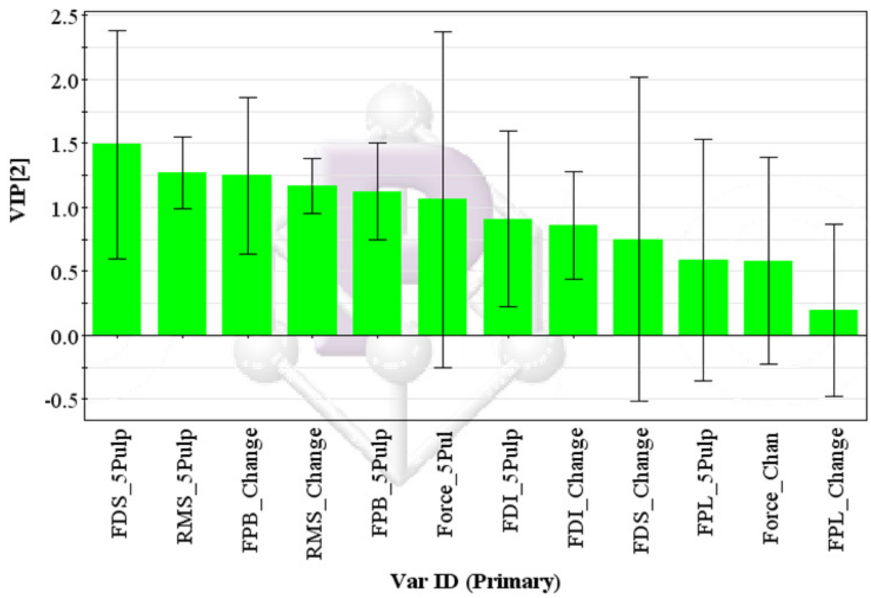


Figure 6.23: PLS-DA Variable Importance Plot for Five Pulp Pinch

6.4 Summary

Initial sEMG measurement and gripping/pinch strength associated with the specified tasks have been carried out for healthy subjects and designated patients. The individual sEMG signal at Phase II, which measures the force contribution of that particular muscle group shows a great difference between the healthy subjects and patients. Every stroke is different. It affects patients in different ways. Therefore, the performance, problems and difficulties have to be assessed for each affected person. The motor scoring of SCI patients represents the gripping/pinch force. The lower the motor scoring implies the lower the gripping/pinch force. The hand strength is also affected by other factors, such as the cause of injury of the patient and their hand condition (e.g. the restricted movement of the thumb or finger).

The clinical data have also been processed and streamlined for better interpretation and characterization by virtue of well-established data analysis models: DOE and MVA. In this study, the conducted fractional experiments suggest that “gender” and “age” are the dominant factors contributing to the difference in gripping/pinch force. The least-significant–difference-level test has further shown that there are significant differences between various levels of the “gender” and “age” groups. The sEMG signals and gripping/pinch force results were also analyzed by PCA, which demonstrates the main variation of muscle activation and gripping/pinch force for all selected rehabilitation tasks in the recruited healthy subjects and patients. PLS model is also used to establish relationships between gripping/pinch force and sEMG RMS value to predict the outcome of the sEMG results for the subjects with difficulties in sEMG measurement. Two classes of subjects with different subject’s groups are separated by the PLS-DA. The discriminatory variables are also identified.

Chapter 7 CONCLUSION AND FUTURE WORK

The aim of this chapter is to conclude the finding of works done, the summary of contributions and future direction of this research. The list of publication is provided in Appendix D.

7.1 Conclusion

The work presented in this thesis focuses on the biomechanical model of human hand, the study & analysis of tasks-oriented hand rehabilitation for the key hand movements that are essential for hand functioning in activities of daily living (ADL), and the task-oriented assessment methodology for robotic therapy. The proposed robotic device with load-free concept of mechanism design is only one of the solutions for hand-fingers rehabilitation in order to achieve our goal. However, the biomechanical model, analysis of task-specific hand rehabilitation and the task-oriented assessment methodology are applicable to other robotics devices for hand rehabilitation as well.

The research work aims to bridge the gap between the engineers and the clinical groups, by applying clinical aspects to robotics rehabilitation. By adopt an objective approach, the proposed rehabilitation methodology for robotic hand rehabilitation should enhance the programme planning and assessment of hand functionality for effective hand rehabilitation through clinical trials.

The major contributions of the research work are summarized as follows:

1) A biomechanical model of the human hand is developed for specified rehabilitation tasks, which consists of kinematics model, workspace analysis and virtual model.

The kinematics modeling of the fingers (Index, Middle, Ring and Small Fingers) and the thumb using D-H method and throughout its workspace is developed for different hand sizes. It can be used for the patients with limited ROM compared to healthy subjects. The muscles of human hand for different hand movements and its corresponding range of motion (ROM) are also studied and presented.

In order to securely hold an object for a specified task, the required kinematics joints angles are required for control purposes. The kinematics and workspace analysis of ADL tasks (five pulp pinch, lateral/key pinch and pulp-to-pulp pinch) are also studied and discussed.

The 23-DOF virtual model was established according to the skeletal anatomy of a realistic human hand for performing simulations of the specified functional tasks. It is constituted from 22 articulated rigid bodies, representing palm, forearm, all phalanges and metacarpals of fingers, connected by rotational joints with one or two degrees of freedom.

2) A new load-free concept of mechanism design of hand-fingers rehabilitation device is proposed, the concentric design of finger module, simplified thumb module, wrist support module, force analysis and reduced DOF of the hand device are also studied and analyzed.

The core concept used for the finger module was the concentric design of the driver in order to prevent the device from shearing the finger while driving the finger flexion and extension. The concept of the finger module was abided to the human factors/ergonomics principles, so it is designed to share the same rotation centre as the joints of human hand. Hence, it eased the process of designing the rehabilitation device as many undesirable forces were avoided and the finished design processes the robustness to fit for most hand sizes.

The thumb module is simplified as 3-DOF model (flexion/extension of the MCP and IP joints; and abduction/adduction of the CMC joint), covering about 75-80% of the workspace of the full thumb model. The adjustable mounting attachment of the thumb module is designed and assembled between the thumb linkages and thumb surface, which allow shifting based on the desirable angle for the task oriented training.

The wrist module was designed to assist patient to perform flexion and extension exercises of the wrist, as well as securing all the Fingers and Thumb Modules in place. So that the patient does not need to carry the weight of the motors and mechanism, and the mechanisms are able to provide load-free exercises and training. The supination/pronation of wrist joint is simplified as passive motion by dual-configuration of robotic device (by changing orientations of rotational frame of the wrist support module manually) in our design.

The force analysis for the concept of “load-free” design of the hand rehabilitation device is also presented, which aims to provide sufficient support to “hold” the fingers and minimize the load force on the fingers. The joint torque required for the robotic device is estimated from EMG signals based on sEMG measurement. The assistive torque/forces would be provided by the actuators to user during rehabilitation training.

3) The study of hand strength measurement is carried out to investigate the sEMG signals and gripping/pinch force for SCI and post-stroke patients based on the five ADL functional tasks, and also gather the necessary sEMG data to enhance the sEMG database of patient. The analysis using Design of Experiment (DOE) and Multivariate Analysis (MVA) is introduced to provide useful data (both statistical data and graphic information) for objective and quantitative assessment towards control applications on a hand rehabilitation device being developed.

sEMG measurement and gripping/pinch strength associated with the specified tasks have been carried out for healthy subjects and designated patients. From the sEMG signals of five ADL tasks studied, some trends can be observed pertaining to each task. By just browsing the data, it is not possible to understand the relationships among different muscle signals. Therefore, the clinical data have also been processed and streamlined for better interpretation and characterization by virtue of well-established data analysis models of DOE and MVA.

Unlike univariate approaches, multivariate analysis facilitates the visualization of large complex datasets and provides a holistic summary of the data. The summarized data presents correlations and trends pictorially, separates systematic behavior from noise, handles missing data, detects outliers, and highlights clusters and patterns. The two MVA methods are Principal Components Analysis (PCA) for data analysis and interpretation, while Projections to Latent Structures (PLS) for data prediction and classification.

4) The proposed rehabilitation methodology for robotic hand rehabilitation device using the modified QFD template applicable to hand rehabilitation is discussed and presented.

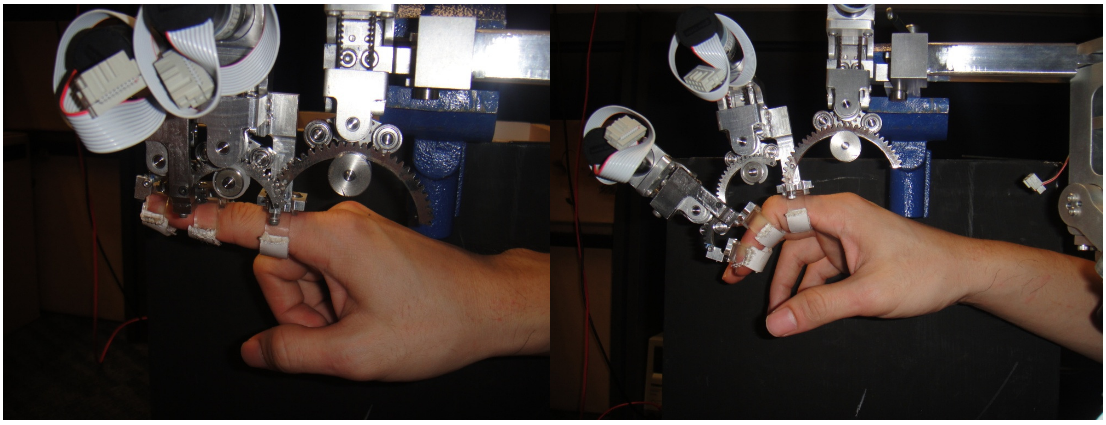
   By adopting an objective approach; the template should enhance the programme planning and assessment of hand functionality for effective hand rehabilitation through clinical trials. This method complements the multidisciplinary team approach to hand rehabilitation. It provides a structure that all involved disciplines contributed effectively towards a common goal for the patients. Both clinical and robotics engineering can benefit from these techniques. It provides a medium to communicate clinical and engineering information to the patients, clinicians, engineers, and researchers. The proposed scheme with several key components is applicable to other robotic device for task-oriented hand rehabilitation. The proposed QFD template can easily extended to other rehabilitation training programmes, like gait rehabilitation, by considering respective requirements and factors.

7.2 Future Work

7.2.1 Realization of Robotic Hand Rehabilitation System

The prototype of the rehabilitation device (see Figures 7.1 and 7.2) will be modified and fine-tuned to optimize their function before its use for subject testing, so that the full features of the hand rehabilitation system will be realized. The force analysis equations derived in Section 5.6.1 is based on some assumptions, it needs to be verified by experiments. The prototype will be evaluated by applying usability criteria for rehabilitation technologies, and pilot studies within the rehabilitation community.

The feasibility and benefits of the proposed rehabilitation methodology for robotic hand rehabilitation with the modified QFD needs to be verified in experiments and clinical studies. It provides a medium to communicate clinical and engineering information to the patients, clinicians, engineers, and researchers. And both clinical and robotics engineering can benefit from this approach.



(a) Index Module at Neutral Position (b) All Three Joints Rotated

Figure 7.1: Prototype of Index Finger Module

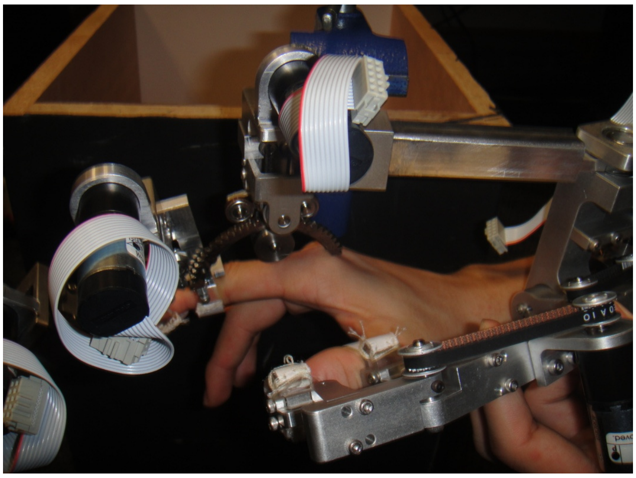


Figure 7.2: Prototype of Thumb Module

Proposed Scheme for Robotic Hand Rehabilitation Methodology

Pre-measurement (study of hand strength for ADL tasks) is carried out to obtain information as the reference for outcome measure of robotic assisted hand rehabilitation. First of all, the initial clinical evaluation will be carried out by the doctor or therapist, the ASIA score, FIM, and FMA are the most commonly used outcome to measure the SCI and post-stroke patients. Secondly, the study of hand strength measurement (details can be found in Chapter 6) will be carried out by the engineer, while there will be at least one doctor or therapist attending in the section. The data interpretation using DOE and MVA is able to provide useful data (both statistical data and graphic information) for diagnosis and evaluation of the progress of therapy.

The linkage length of the robotic device will be adjusted according to the hand dimension measurement for individual patient (based on the calculation in Table 4.1). Based on ROM measurement results and kinematics of ADL tasks (e.g. five pulp pinch, lateral/key pinch and pulp-to-pulp pinch) as presented in Section 4.3, the task parameters (e.g. object radius or thickness) are selected and then the desired joint angles are calculated for the robotic hand rehabilitation training. The sEMG signals obtained off-line are analyzed based on hand motion for specified tasks and different gripping conditions. The sEMG measurement and recordings of muscle actions for each respective movement are useful for analyzing which muscles and at what times they are active. The sEMG signal obtained from the measurement data will be used in equation 5.17 (Section 5.6.1 *Force Analysis on "Load-free" Concept*) to calculate the assistive force/torque by the hand rehabilitation device for control purpose.

In the modified QFD as presented in Appendix C, the *patient-oriented goals* of the rehabilitation service will be determined based on the pre-measurement results and feedback from patient and therapist. The *Clinical-Engineering Response* section contains both engineering measurement and clinical assessment will be filled up based on the pre-measurement results. In the *Programme Planning* section, a set of engineering and clinical target values to be met by the next rehabilitation programme will be decided based on the pre-measurement results. The current performance of the responses provides a strong baseline for improvement of the rehabilitation program. It can be served as a report card for therapists by means of diagnosis and evaluation of the progress of therapy for the patient, and also the feedback information for the engineer or researcher for the control purposes. In the *Progressive Outcome* section, the patient's performance with current rehabilitation program based on their needs and patient-oriented goals will be determined.

Having discussed with several therapists at several local hospitals, it is noted that for the post-stroke patients, the progress of therapy and its recovery is usually slow in regaining functional use of their impaired arm and hand. Therefore, it is possible to develop a scheme that uses the clinical data from the therapists as the input to the robotics system, together with the measurement results based on assessment and evaluation of hand function in each progress stage.

The details of proposed rehabilitation methodology for robotic hand rehabilitation is illustrated in Figure 7.3.

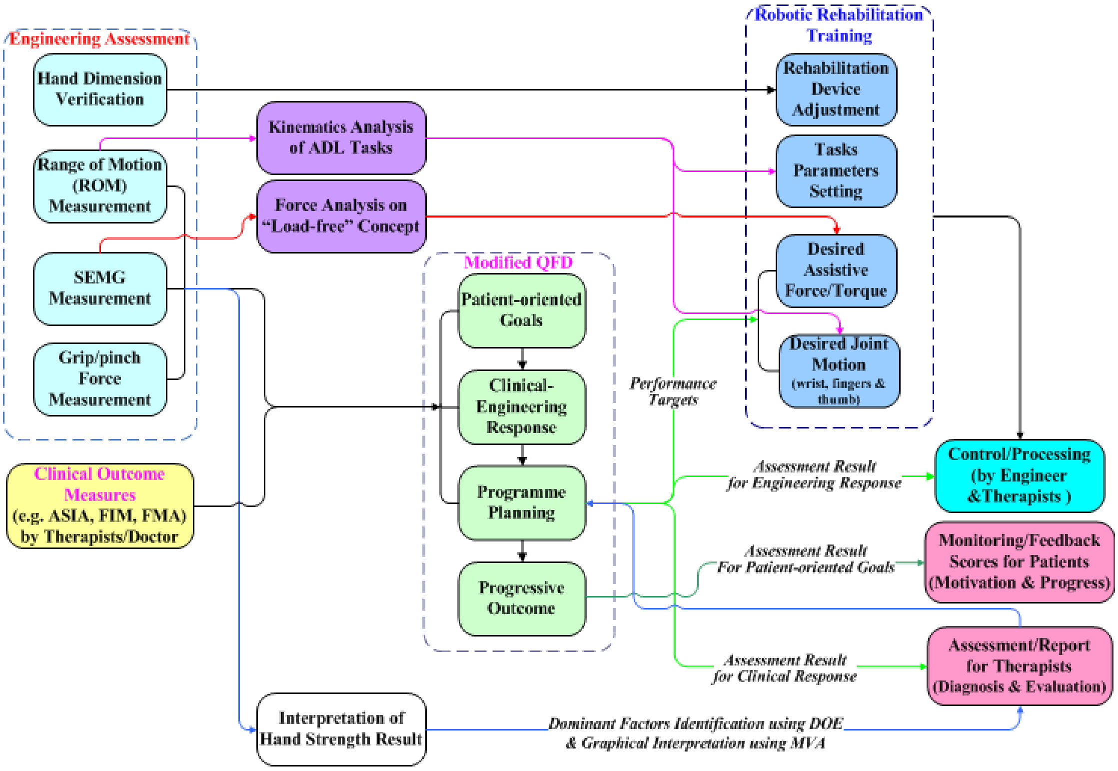


Figure 7.3: Proposed Rehabilitation Methodology for Robotic Hand Rehabilitation

With the data collected from the therapists can serve as inputs to the robotics system for re-adjustment of the rehabilitation training program regularly and consistently based on feedback, together with the quantified parameters (sEMG, grip/pinch force, joint angle, etc.) based on assessment and evaluation of hand function at each progress interval, through an interactive control, the system is able to assist the patient to perform activities of daily living (ADL) rehabilitation on the impaired hand.

7.2.2 Development and Implementation of Control Schemes

The best control strategy will do the same procedure as a qualified human therapist; it will assist the patient's movement only as much as necessary. This will allow the patient to actively learn the spatiotemporal patterns of muscle activation associated with normal arm/hand function. It will stimulate patient's active participation, and increases the motivation of the patient (through the assessment feedback scores and the interaction with real objects), because changes in muscle activation will be reflected in the grasping patterns, consistently creating a feeling of success.

The control schemes are required to be integrated with the developed hardware and respective modules. The control schemes are in hybrid manner, which integrates position and force control. There are four types of assistance based on the stage of recovery and hand condition of the patient: (i) passive (manual muscle test score is 0 or 1), (ii) active-assist (manual muscle test score is 2 or 3), (iii) active-unassisted (manual muscle test score is 4 or 5), and (iv) active-constrained (manual muscle test score is 5). These can be provided by the hand rehabilitation device based on carefully designed control schemes and algorithms. In passive assisted rehabilitation scheme, the patients targeted are those without hand control at all. All the necessary movement of each joint of hand will be driven by the robotics device to complete the task. Following this specification, the control scheme can be implemented using position control strategy. Velocity and acceleration will not be part of the control parameters since the motion is slow and for safety reason. In this case, suitable rehabilitation activities are required as a reference for hand rehabilitation.

The stretching exercises by the robotics device will be performed to reduce the spasticity of the patients before the task-oriented training. While performing the manipulation tasks of the rehabilitation, it is often useful to allow different control strategies for different stages of the process: motion control in free space (unconstrained space) and interaction control in constrained space. Before the fingers are in contact with the environment (e.g. the object), they are controlled by position control. The force control will be activated when fingers are in contact with the object. The implementation of control scheme involves the conversion of different kinematics parameters into control parameters. Apart from the conversion, the synchronization among the control schemes is a highly complex network of controllers and between the controllers is an important issue. Also, the hand device is crucial to ensure the rehabilitation system operates in a reliable and safely manner.

The overall architecture of the control system for the hand rehabilitation device is shown in Figure 7.4.

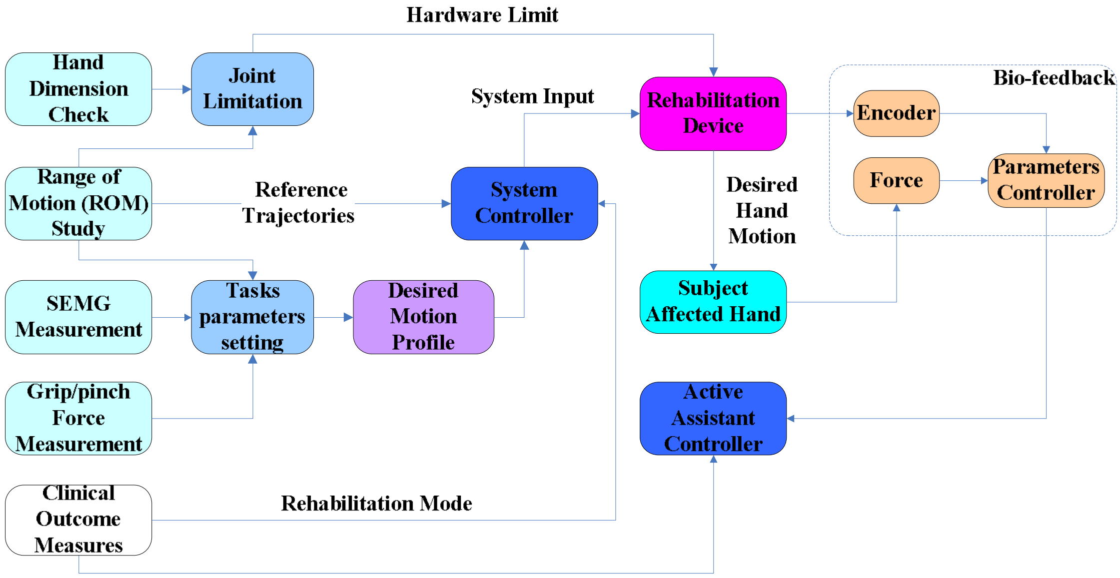


Figure 7.4: Control System Architecture of the Hand Rehabilitation System

7.2.3 Clinical Trials and ADL Rehabilitation Training

The mechatronics capability developed should facilitate patient's understanding and therapist's assessment of the rehabilitation process. A series of feasibility test will be carried out in a local hospital for the patients with different hand conditions.

To ensure that the developed rehabilitation system is clinically compatible, two stages of clinical trials will be conducted in a local hospital with SCI and post-stroke patients. The first phase of clinical trial will be carried out at two milestones of the prototyping phase: (1) Completion of position control scheme and (2) Completion of force/torque control scheme. The second phase of the clinical trial will be carried out to fully test the integrated hand rehabilitation system. The complete system will be validated through the second phase of clinical trials to ensure that the research outcomes comply with the SCI and post-stroke patient hand rehabilitation requirements.

After that the hand rehabilitation device is ready to provide training based on the five functional tasks that we have proposed. However, more ADL exercises or tasks are needed in order to fully re-gain the hand functions in everyday life as shown in Figure 7.5.

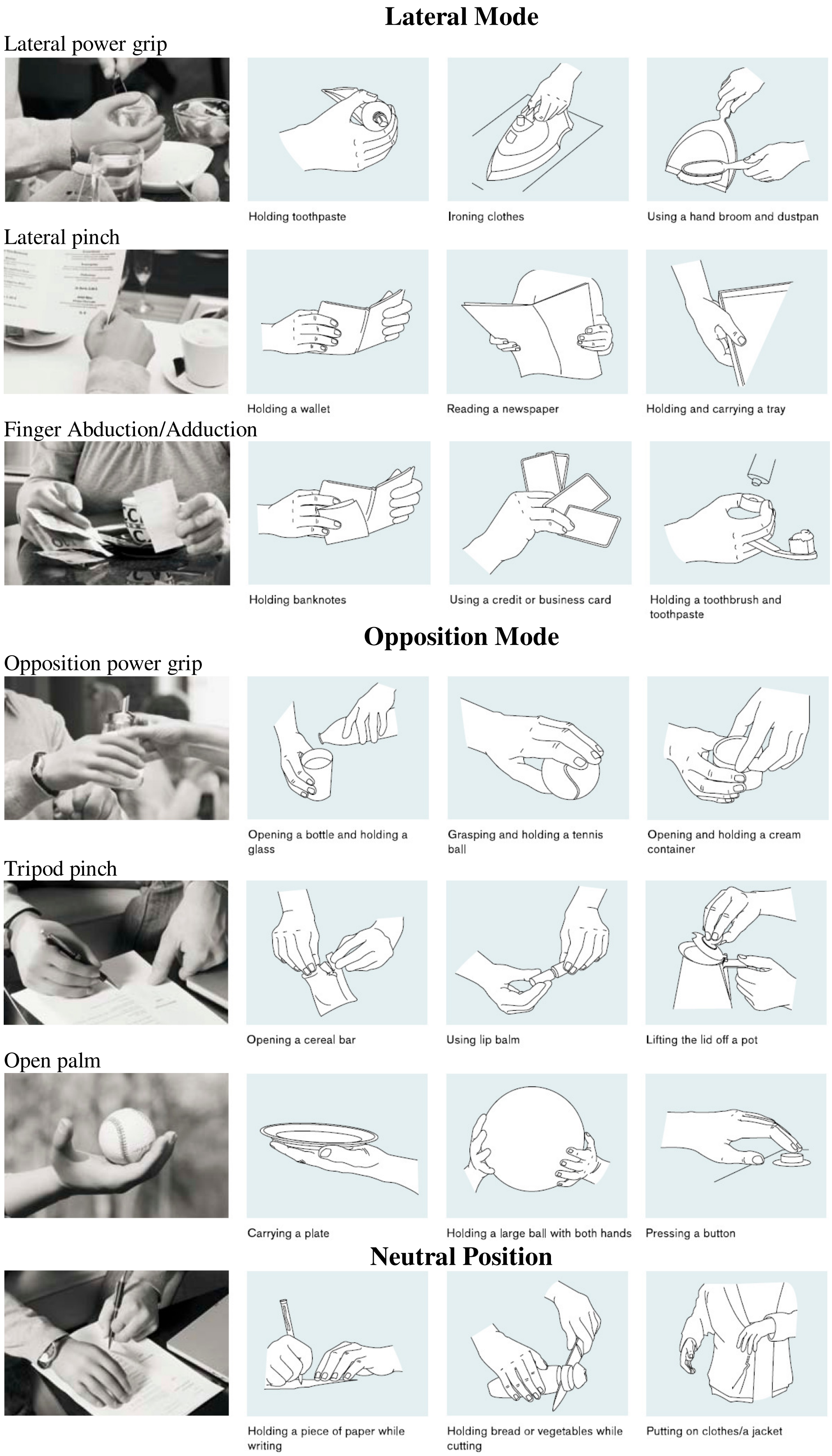


Figure 7.5: ADL Training of Michelangelo Hand [179]

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Appendix A: SUPPLEMENTARY DESIGN INFORMATIONS

Power Transmission Method

In the design process of the MCP angular driver, the student has used two types of the power transmission methods: (1) Timing belt and pulley, (2) Bevel gear box. Initially, timing belt and pulley were used because of their efficiency in power transmission but alignment problem between the pinion housing and the driver base was introduced. For bevel gear box the consideration was more on solving the alignment issue and for clean and easy assembly, but it took larger space in the assembly which caused interference between assemblies. Both methods have it own positive and negative contribution to the design.

To decide which method to use in the final design, considerations must be made on three things, the size, alignment, and power transmission because they determine the potential interference, stability, and torque of the assembly respectively.

Table A1 shows how the student justified the better transmission method.

Table A1: Comparison of Transmission Method

Consideration Method	Size	Alignment	Power Transmission
Timing belt & pulley	Occupy smaller space as miniature timing belt and pulley used	Additional assembly of shaft and bearings were needed for securing the pulley and pinion	The gear ratio can be fine tune through changing of pulley sizes
Bevel gear box	Gear box casing size is fixed, the bigger the gear ratio the bigger the casing	Pinion can be mounted directly on the gear box shaft. No additional housing assemblies needed	Limited option of gear ratio, value fixed at 1 and 2.

Limited by size of human hand, the size of the angular driver was required to kept as small as possible because each fingers (index and middle) would be mounted with three angular drivers, so six angular drivers would be working together simultaneously in the therapy. Hence, collisions among the driver assemblies would be big concerns for the device. Priority was first given to size reduction.

To ensure the torques apply on each finger phalanxes were sufficient for safe and comfortable operation; the torque transmitted from the motor to the pinion must be correct and precise, and at the meantime maintaining the motor at its optimum performance. To fulfill what was mentioned above, flexibility in gear ratio (GR) was required in the driver.

Whereas for the alignment concern, tighter tolerance in fabrication could be introduced to minimize the problem, striker precaution was to be taken during assembly of the driver to further minimize the issue. Hence, with all the concerns addressed, the timing belt and pulley power transmission method was chosen for the final design.

Sizing of DC Motor

The sizing of motor was identified as another crucial step in the design as it was not just affecting the efficiency in the actuation aspect but the aspect in safety as well. In hand rehabilitation therapy, the patient's impaired hand was assisted by slow and steady external forces to achieve various flexion and extension motions. To achieve the same smooth and fine motions through utilization of DC motor, the type of encoder used in the DC motor was especially important. The reason was because the DC motor relied on the feedback from the encoder to determine the angular position/ angle and output speed, the finer the feedback, the more precise of the control output.

To satisfy the slow, precision feedback and fine control of the motor, optical encoder was chosen as the sensory feedback for the DC motor based on the recommendation from the motor supplier, Maxon. In the subsequent step, the apply forces at each finger phalanx segments were to be calculated before determining the torque of the motors. According to therapists' estimation torques listed in Table A2 [28], all apply forces were obtained by dividing the maximum acceptable torque at MCP, PIP, and DIP joints with respective half-gear radii.

Table A2: Acceptable Torque for Fingers as Estimated by Therapists' Experiments [28]

Joints		Thumb [Ncm]	Index [Ncm]
CM	Extension	29.3	
	Flexion	29.0	
	Abduction	32.8	
MP	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

Subsequently, the gear ratio between the half-gear and pinion, between driven pulley and driver pulley were taken into account to accurately estimate the torque required at each motor. The apply force and gear ratios were illustrated in Figure A1.

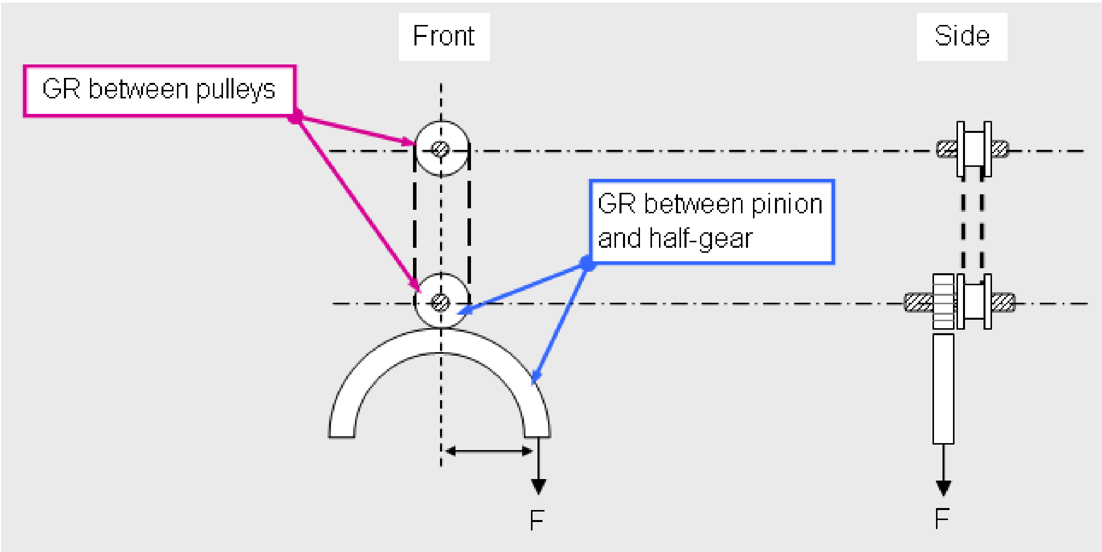

Figure A1: Apply Force and Gear Ratios (GR)

Finally the DC motors which fulfill all the torque required were selected (see Table A3). Listed in the following was the motors coupled with gear box:

Table A3: Selected Maxon A-max Motor Details

Joint	Motor				Gear Box	
DIP	**A-max 110090**	**Ø19mm**	**1.5W**		**149043**	
	Nominal Voltage	1.2	V		Gear Ratio	29
	Nominal Torque	1.34	mNm			
	Stall Torque	6.50	mNm			
	Nominal Speed	5030	RPM			
PIP	**A-max 110091**	**Ø19mm**	**1.5W**		**149042**	
	Nominal Voltage	2.4	V		Gear Ratio	24
	Nominal Torque	2.49	mNm			
	Stall Torque	6.53	mNm			
	Nominal Speed	4380	RPM			
MCP	**A-max 110090**	**Ø19mm**	**1.5W**		**149043**	
	Nominal Voltage	1.2	V		Gear Ratio	29
	Nominal Torque	1.34	mNm			
	Stall Torque	6.50	mNm			
	Nominal Speed	5030	RPM			

After selected all the motors, there was one more point to take noted of before moving on to the next session. Due to the compact design and various transmissions stages of the gears, the efficiency of the gear box was often reduced and the drop of efficiency would directly affect the torque output of the motor. Hence, to ensure motors were able to retain and drive the device stable and efficiently, the gear box efficiency need to be mitigated.

According to the Maxon planetary gear box datasheet, the efficiency of the gear boxes selected earlier were all rated at 81% (maximum). To solve the problem, proposal was made on changing the timing belt pulleys ratio to compensate the lost efficiency, so that the torque could be restored back to values required.

Appendix B: CLINICAL STUDY OF HAND STRENGTH –PROTOCOLS AND PROCEDURES

Clinical Study Safety Precaution

The clinical study is carried out in Tan Tock Seng Hospital (Rehabilitation Center). There will be at least one doctor or therapist attending in every session of the clinical study. The doctor or therapist will be briefed for the clinical study process prior before carry out the study.

The subjects will be examined by the doctor or therapist to ensure their physical condition is fit for the clinical study prior before the study start.

All the method and procedure proposed in this clinical study are non-invasive.

Purpose of the Hand Strength Study

This study aims to investigate the sEMG signals and gripping force for post-stroke and spinal cord injury patients based on the five ADL (activities of daily life) functional tasks. The results will be analyzed and compared with normal/health people to provide useful information for the researchers and the therapists.

In this study, it is an attempt to extrapolate the analysis on sEMG signals from selected muscles groups for research on hand rehabilitation. The systematic procedures for the accurate and objectively methodology of hand function evaluation will then be developed for functional activities of daily living (ADL) tasks and rehabilitation exercises by introducing those quantitative parameters (sEMG, ROM, grip/pinch force and clinical outcome measures). Particularly, the keen significance is in developing the pre-clinical grading system based on the engineering parameters and the clinical outcome measures.

Electrodes Placement on Hand and Forearm

The electrodes will be putted on his/her hand and upper arms- for acquiring of sEMG signals. The signals are acquired with the arm parallel to the body with the elbow bent at 90°.

Testing Procedures

The following steps illustrate the conduct of the experimental testing:

1. The experimenter will first explain to the patient/subject the purpose of the test.
2. A run through of the equipments - electrodes, hand dynamometer, transmitter and receiver - used in the testing. This is to ensure the participant that no invasive items are used. Wireless sEMG system will be used for sEMG signal acquisition.
3. Briefly explain the five rehabilitation tasks to the patient/subject.
   i) The five-pulp grip is used mostly to wrap around cylindrical objects. Holding a cup or a bottle utilizes this type of grip.
   ii) The key grip is used when holding a card or turning a key into a lock or stirring a beverage with a teaspoon. It is also used during eating, where one has to grip utensils.
   iii) The pulp-to-pulp pinch grip is used in many activities where a small object needs to be picked up or manipulated. For example, one would use a pulp-to-pulp pinch grip to pick up small objects like coins, medicine pills or pins.
   iv) The tripod grip is used when both stability and holding are needed. For example, this grip is used in preparation for throwing an object such as a baseball. This grip is also used when one is controlling a computer mouse.
   v) The cylindrical power grip is a commonly used grip in activities where relatively large forced needs to be applied to an object. The daily activities include gripping a door handle to turn it and hold a walking stick.
4. Place two surface electrodes on the each muscle - for obtaining of sEMG signals.
5. Connect wires from transmitter to the electrodes.
6. Demonstration of task one, five-pulp-pinch. In which, the phases are to be clearly explain to the patient/subject

   For all the rehabilitation tasks, the course of action is primarily classified into two phases, Phase I and Phase II.
   i) At time, t = 0 second, the hand will be at neutral position. The test will start only when all muscles' sEMG signals are stable and unexcited.
   ii) From t = 2 s to 5 s, Phase I (positioning), the subject would position his/her hand on the hand dynamometer for the respective task. No force is to be exerted during this time.

iii) Next, in Phase II (action), t = 5 s to 10 s, the subject exerts his fullest strength on the hand dynamometer. This exertion will last for about 5 seconds.

iv) After t = 10 s, the subject is to cease exerting strength on the hand dynamometer and return to the neutral position. This procedure will last till t = 15 s. For each task, three runs were conducted to obtain the average readings.

7. Study attempt by the subject
8. Ensure that the subject is comfortable prior to performing the task.
9. For each task, three set of readings are to be collected.
10. Repeat steps 6 to 9 for the other four tasks.

    The entire study will take about 45 minutes.

Data Collection Form

Subject number: ___________________________

Age/ Date of birth: ___________________________

Date of injury: ___________________________

Date of evaluation: ___________________________

Impairment: Stroke/ Spinal Cord Injury#

Patient Inclusion and Exclusion Criteria

The inclusion and exclusion criteria for the patient recruited are as follows:

Inclusion Criteria

1. Patients with Incomplete spinal cord injury and American Spinal Injury Association Impairment Scale (ASIA) as C or D with levels from C5 to L3 and at least 6 months post injury
2. Patients with Stroke at least 6 months post injury
3. Age 18 years and older with written informed consent

Exclusion Criteira

1. Patients who are not able to follow instructions, cognitively impaired
2. Patients who have concomitant neglect, ataxia

3. Patients who have severe postural hypotension (symptomatic blood presure drop on standing)
4. Patients who have ischemic heart disease or other medical conditions that may be aggravated by increased exertion
5. Any other known pre-existing bone diseases that might increase the risk of bone fracture or other injury from intensive conventional therapy or robot-assisted therapy
6. Severe spasticity limiting overground ambulation
7. Patients with reduced joint range of motion
8. Patients who are unable to maintain upright posture
9. Those who refuse to participate

Initial Evaluation for spinal cord injury/stroke (Upper limb session):

General assessment: ________________________________

Blood pressure:

Sitting : ____________

Standing : ___________

Spinal cord injury

I. Skeletal Level Lesion: ____________________

II. ASIA impairment scale: A / B / C / D#

III. Caused of injury: trauma / medical#

If stroke:

I. Type of stroke: Ischemic Stroke / Hemorrhagic Stroke#

II. Site of stroke: ___________________

III. Side of stroke: Left / Right#

Motor scoring: (all)

Motor Scoring of upper limbs:

	Right	Left
Biceps		

Wrist extensors

Elbow extensors

Finger flexors

Finger abductors

Joint range of motion restrictions: Yes/ No#

If yes, degree of restriction

1. Elbow ____________
2. Wrist, fingers ____________

Spasticity of limbs: Yes / No#

(Modified Ashworth scale) 0/1/1+/2/3/4/

Elbow: 0/1/1+/2/3/4/

Wrist: 0/1/1+/2/3/4/

Skeletal parameters

1. Hand length ____________
2. Hand breadth ____________
3. Height ____________
4. Weight ____________

sEMG measurement parameters

Upper limb

sEMG database filename: ____________________

Comments: ____________________

Other parameter and comment

Appendix C: APPLICATION OF QFD ON HAND REHABILITATION

The following section introduces the quality function deployment (QFD) and demonstrates how the modified QFD based on rehabilitation outcomes is used to enhance the programme planning and assessment/evaluation of hand functionality for effective hand rehabilitation.

Background

QFD (quality function deployment) [180] is a method for structured product planning and development that enables a development team to specify clearly the customer's wants and needs, and then to evaluate each proposed product or service capability systematically in terms of its impact on meeting those needs. The techniques can be applied to develop new products or modify existing products. As QFD itself evolved, it could be used to support service development as well.

Today, QFD has been extended to apply to many planning process where a team has decided systematically to prioritize their possible responses to given objectives [181]. QFD is also related to and can thus be applied to rehabilitation engineering [182]. However, the application was still limited to the design of the prosthetic device. For our study, we would like to take the advantages of QFD and extend its application to the clinical and engineering areas applicable to hand rehabilitation, which can be served as a template of programme planning for the clinical assessment and robotics system for effective hand rehabilitation during clinical trials.

Modified QFD Applicable to Hand Rehabilitation

As the QFD was initially developed for design application [181] and in order to apply it to the hand rehabilitation programme, we have modified the QFD with six regions A to F, as shown in Figure C1. The feature and application of the six regions are described in detail next.

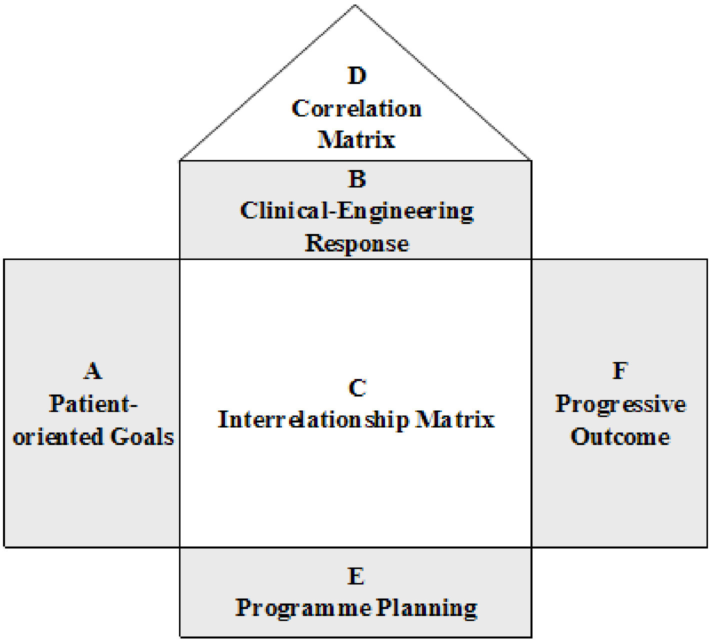

Figure C1: Improved QFD Applicable to the Evaluation and Implementation of Hand Rehabilitation Process with Robotics System (Modified from [180])

1) Patient-oriented Goals

Region A in Figure C1 (*Patient-oriented Goals*) contains a structured list of the patient-oriented goals of the rehabilitation service. For most of the patients, the choice of rehabilitation exercise would probably be determined and guided by the physical therapists (PT) or occupational therapists (OT) involved in the training. The therapists help to facilitate the treatment, the work should focus on the interests and the requirements of the patients. Furthermore, a programme that satisfies the requirements and needs of the therapists will indirectly satisfy those of the patients in terms of the quality of therapy they receive. However, the actual customer could have been asked for their input. This would identify any discrepancies between clinician impressions and the actual consumer input. In order to have a success of the rehabilitation program, the patients and their family, therapists, all need to be satisfied that this training program is best suited to the patient. The information can be gathered through conversations with the patients in which they are encouraged to describe their goals and problems.

This study identified therapists as important sources of information since they have direct contact with a large number of patients as well as their families. Although input from a large number of patients would provide more representative data from a user perspective, it is felt that polling of clinicians would expedite the collection of data for the purpose of this study. The therapists must also rate the importance of each of these patient-oriented goals to obtain a better understanding of these requirements. The rating scales are set up such that the total of all importance ratings for each age group is to be 100. This required the clinicians to interrelate the importance of each patient-oriented goal as shown in Figure C2.

Row #	Relative Weight	Weight / Importance	Patient-oriented Goals
1	6.1	6.0	Minimal muscle spasticity/rigidity of movements
2	6.1	6.0	Objects can be hold in different orientation
3	8.2	8.0	Able to grasp cylindrical objects (Five-Pulp-Pinch)
4	8.2	8.0	Able to grasp flat objects (Key/Lateral Pinch)
5	7.1	7.0	Able to grasp small objects (Pulp-to-Pulp Pinch)
6	6.1	6.0	Able to grasp spherical objects (Tripod Pinch)
7	5.1	5.0	Able to grasp cylindrical objects with strength
8	8.2	8.0	Secure and stable grasp
9	8.2	8.0	Grasp appears natural
10	7.1	7.0	Minimal compensatory movements
11	7.1	7.0	Good hand-eye coordination
12	7.1	7.0	Good control of gripping/pinch force
13	8.2	8.0	Good repeatability of movements
14	7.1	7.0	Good fine motor control
Total	100.0		

Figure C2: The Patient-oriented Goals (Region A in Figure C1) and Relative Weight Importance of Hand Rehabilitation for Patients (Filled up by clinician)

2) Clinical-Engineering Response

Region B in Figure C1 (*Clinical-Engineering Response*) contains engineering and clinical responses, a high-level description of the rehabilitation service they plan to develop. Normally this description is generated from the patient-oriented goals in Region A. With all the information accumulated from the clinicians, the next phase of the investigation involved building a more specific understanding of how specific responses affect the patient-oriented goals. The responses are grouped into two general categories (see Figure C3): the engineering measurement and clinical assessment. An additional row is included in this region to illustrate the direction of improvement in each of these variables: Minimize (▼), Maximize (▲), or Target (x) symbol to indicate, which is considered to result in an improvement in the overall performance.

Column #	1	2	3	4	5	6	7	8	9	10	11	12	13
Categories	Engineering Measurement								Clinical Assessment				
Direction of Improvement: Minimize (▼), Maximize (▲), or Target (x)	▲	▲	▲	x	▲	▼	▲	x	▲	▼	▲	▲	▼
Clinical-Engineering Response	PROM and AROM	Gripping force	Pinch force	EMG RMS value	Force/EMG RMS value	Torque provided by the actuator	Actuator speed	Force feedback	Motor scoring	ASIA score	FIM (Functional Independence Measure)	FMA (Fugl-Meyer Assessment)	Modified Ashworth scale

Figure C3: The Clinical-Engineering Response (Region B in Figure C1) of Hand Rehabilitation for Patients (Filled up by clinician/engineer)

3) Interrelationship Matrix

Region C in Figure C1 (*Interrelationship Matrix*) contains the QFD team's judgments of the strength of the relationship between each element of their response and each patient-oriented goal. It forms the main body of the QFD matrix. Its purpose is to translate the requirements as expressed by the consumer into the engineering and clinical responses. Its structure is that of a standard two dimensional matrix with cells that relate to combinations of individual patient-oriented goal and engineering and clinical responses. It is the task of the QFD team to identify where these interrelationships are significant.

Once this list of responses is completed, interrelationships between each patient-oriented goal and engineering and clinical responses are considered. By group consensus, the power of the relationship is categorized as either having: strong relationship, moderate relationship, weak relationship and none, and a symbol representing this level if interrelationship is entered into the matrix cell. This shows how changing any engineering and clinical responses will affect the patient-oriented goals. Each level of interrelationship is assigned a score which the team should understand and agree to before completing this matrix (see Figure C4), strong relationship (Θ) – 9, moderate relationship (O) – 3, weak relationship (▲) – 1, and none – 0.

			Column #	1	2	3	4	5	6	7	8	9	10	11	12	13
			Categories	Engineering Measurement								Clinical Assessment				
			Direction of Improvement: Minimize (▼), Maximize (▲), or Target (x)	▲	▲	▲	x	▲	▼	▲	x	▲	▼	▲	▲	▼
Row #	Relative Weight	Weight / Importance	Patient-oriented Goals / Clinical-Engineering Response	PROM and AROM	Gripping force	Pinch force	EMG RMS value	Force/EMG RMS value	Torque provided by the actuator	Actuator speed	Force feedback	Motor scoring	ASIA score	FIM (Functional Independence Measure)	FMA (Fugl-Meyer Assessment)	Modified Ashworth scale
1	6.1	6.0	Minimal muscle spasticity/rigidity of movements		▲	▲	O		O	▲	▲	▲				
2	6.1	6.0	Objects can be hold in different orientation	▲												
3	8.2	8.0	Able to grasp cylindrical objects (Five-Pulp-Pinch)	▲	O		O		▲		▲			O	O	▲
4	8.2	8.0	Able to grasp flat objects (Key/Lateral Pinch)	▲		O	O		▲		▲			O	O	▲
5	7.1	7.0	Able to grasp small objects (Pulp-to-Pulp Pinch)	▲		O	O		▲		▲			O	O	▲
6	6.1	6.0	Able to grasp spherical objects (Tripod Pinch)	▲		O	O		▲		▲			O	O	▲
7	5.1	5.0	Able to grasp cylindrical objects with strength	▲	Θ		O		▲		▲			O	O	▲
8	8.2	8.0	Secure and stable grasp	O	Θ	Θ	O	▲	O		O			O	O	O
9	8.2	8.0	Grasp appears natural				▲									
10	7.1	7.0	Minimal compensatory movements				O									
11	7.1	7.0	Good hand-eye coordination							▲						
12	7.1	7.0	Good control of gripping/pinch force		O	O					O					
13	8.2	8.0	Good repeatability of movements		▲	▲	▲									
14	7.1	7.0	Good fine motor control			O					O			▲	▲	
Total	100.0															

Figure C4: Interrelationship Matrix (Region C in Figure C1) between Patient-oriented Goals and Clinical-Engineering Response (Filled up by clinician/engineer)

4) Correlation Matrix

Region D in Figure C1 (*Correlation Matrix*) is half of a square matrix, split along its diagonal and rotated 45°. It contains the QFD team's assessments of the implementation interrelationships between elements of the engineering and clinical response. Since few engineering and clinical responses can be changed independent of the others, considerations are made to identify and record this influence. This information is presented in the triangular matrix above the responses as shown in Figure C5: Strong Positive Correlation (++), Positive Correlation (+), Negative Correlation (–) and Strong Negative Correlation (▼). The triangular interrelationship matrix will show how changing any one response will affect any of the others. Direction of influence between the responses of the interrelationship matrix is an important factor. The information recorded in this matrix is useful to the engineering and clinical team in several ways. It highlights where a focused rehabilitation improvement could lead to a range of benefits to the patient.

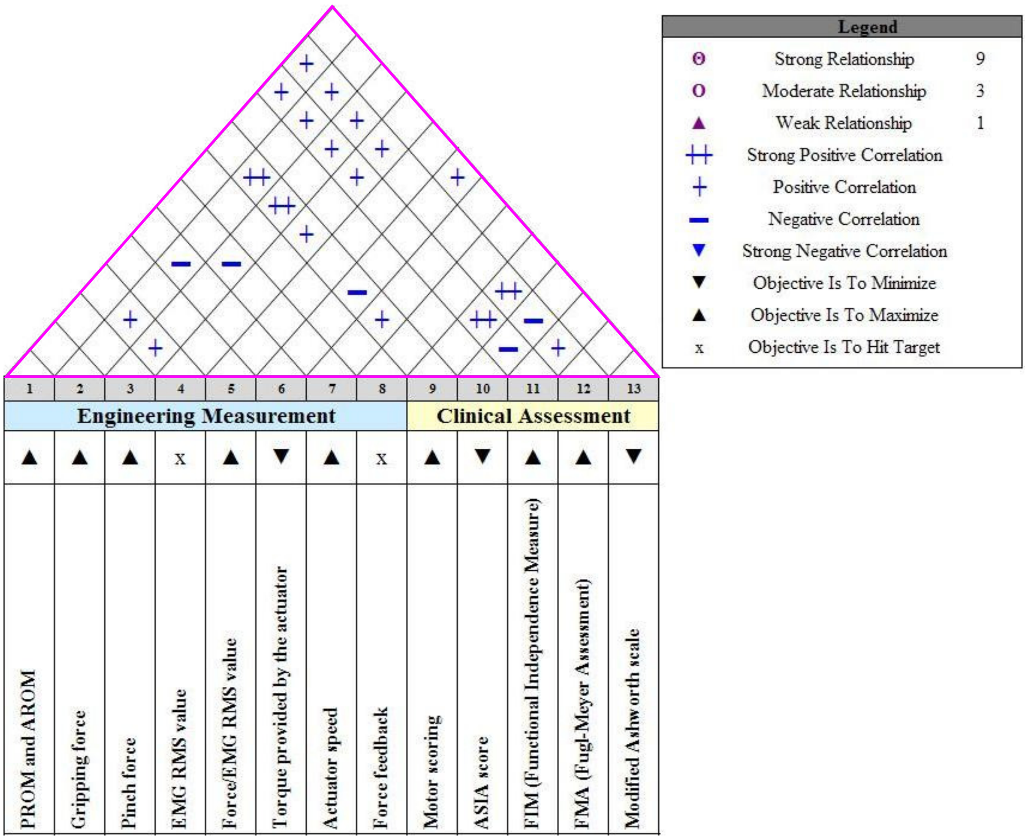

Figure C5: Correlation Matrix (Region D in Figure C1) of Clinical-Engineering Response and the Legend (Filled up by clinician/engineer)

5) Programme Planning

Region E in Figure C1 (*Programme Planning*) of the QFD summarizes the conclusions drawn from the data contained in the entire matrix and the team's discussion. It contains four types of information (see Figure C6):

Patient-oriented Goals \ Clinical-Engineering Response	PROM and AROM	Gripping force	Pinch force	EMG RMS value	Force/EMG RMS value	Torque provided by the actuator	Actuator speed	Force feedback	Motor scoring	ASIA score	FIM (Functional Independence Measure)	FMA (Fugl-Meyer Assessment)	Modified Ashworth scale
Minimal muscle spasticity/rigidity of movements		▲	▲	O		O	▲	▲	▲				
Objects can be hold in different orientation	▲												
Able to grasp cylindrical objects (Five-Pulp-Pinch)	▲	O		O		▲		▲			O	O	▲
Able to grasp flat objects (Key/Lateral Pinch)	▲		O	O		▲		▲			O	O	▲
Able to grasp small objects (Pulp-to-Pulp Pinch)	▲		O	O		▲		▲			O	O	▲
Able to grasp spherical objects (Tripod Pinch)	▲		O	O		▲		▲			O	O	▲
Able to grasp cylindrical objects with strength	▲	Θ		O		▲		▲			O	O	▲
Secure and stable grasp	O	Θ	Θ	O	▲	O		O			O	O	O
Grasp appears natural				▲									
Minimal compensatory movements				O									
Good hand-eye coordination							▲						
Good control of gripping/pinch force		O	O					O					
Good repeatability of movements		▲	▲	▲									
Good fine motor control			O					O			▲	▲	
Assessment 1													
Assessment 2			To be filled up by Rehabilitation Team during Clinical Trial										
Assessment 3													
Assessment 4													
Assessment 5													
Assessment 6													
Target or Limit Value													
Difficulty (0=Easy to Accomplish, 10=Extremely Difficult)													
Weight / Importance	182.5	209.6	222.8	158.8	7.0	66.7	19.3	111.4	84.2	126.3	158.8	143.0	50.9
Relative Weight	11.8	13.6	14.5	10.3	0.5	4.3	1.3	7.2	5.5	8.2	10.3	9.3	3.3

Figure C6: Programme Planning (Region E in Figure C1) for Hand Rehabilitation (Filled up by clinician/engineer)

a) *Responses priorities*: the relative importance of the engineering and clinical responses in meeting the consumer's specified patient-oriented goals can be simply calculated from the weightings contained in the Regions A and C. Each interrelationship weighting is multiplied by the relative weight from the importance ratings of the patient-oriented goals. These values are then summed down the columns to give a priority score for each response. The overall importance of each of the response can be determined by summing the weighted interrelation values for all the patient-oriented goals.

b) *Performance targets*: a set of engineering and clinical target values to be met by the next rehabilitation programme. The process of building this matrix enables these targets to be set and prioritized based on an understanding of both the patient and the therapist, the past and current performance of their rehabilitation training. The QFD team needs to draw on all this information when deciding on these values.

c) *Difficulty to improve*: the engineering and clinical teams categorized the technical difficulty to improve a specific engineering and clinical response into scores (0 = Easy to Accomplish, 10 = Extremely Difficult). It is useful in setting strategic goals and better understanding the relationship between the responses, patient-oriented goals and performance satisfaction.

d) *Assessment*: the rehabilitation performance of the patient is assessed by the engineering and clinical team. The current performance of the responses provides a strong baseline for improvement of the rehabilitation program. It can be served as a report card for therapists by means of diagnosis and evaluation of the progress of therapy for the patient, and also the feedback information for the engineer or researcher for the control purposes.

6) Progressive Outcome

Region F in Figure C1 (*Progressive Outcome*) is restructured from the planning matrix in the traditional QFD as the previous session is no longer valid in our application. This modified session provides a measure of the patient's performance with current rehabilitation program based on their needs and patient-oriented goals from Region A. It is the task of the clinical team to determine the scores between 0 to 5 (0 = worst, 5 = best).

				Progressive Outcomes (0=Worst, 5=Best)					
Row #	Relative Weight	Weight / Importance	**Functional Goals**	Assessment 1	Assessment 2	Assessment 3	Assessment 4	Assessment 5	Assessment 6
1	6.1	6.0	Minimal muscle spasticity/rigidity of movements						
2	6.1	6.0	Objects can be hold in different orientation		To be filled up by Rehabilitation Team during Clinical Trial				
3	8.2	8.0	Able to grasp cylindrical objects (Five-Pulp-Pinch)						
4	8.2	8.0	Able to grasp flat objects (Key/Lateral Pinch)						
5	7.1	7.0	Able to grasp small objects (Pulp-to-Pulp Pinch)						
6	6.1	6.0	Able to grasp spherical objects (Tripod Pinch)						
7	5.1	5.0	Able to grasp cylindrical objects with strength						
8	8.2	8.0	Secure and stable grasp						
9	8.2	8.0	Grasp appears natural						
10	7.1	7.0	Minimal compensatory movements						
11	7.1	7.0	Good hand-eye coordination						
12	7.1	7.0	Good control of gripping/pinch force						
13	8.2	8.0	Good repeatability of movements						
14	7.1	7.0	Good fine motor control						
Total	100.0								

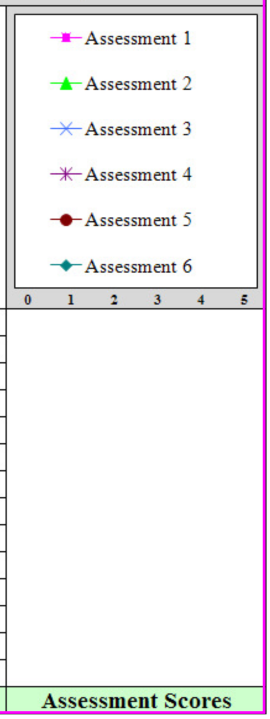

Figure C7: Progressive Outcome (Region F in Figure C1) based on Patient's Performance (Filled up by clinician)

An overall rating can then be calculated by summing down the columns to give a final score for each assessment (see Figure C7). It can be served as feedback scores for patients by means of motivating and monitoring patient progress. The chart at the right of the session compares the past and current assignment scores.

Once the matrices are completed, the template shown in Figure C8 is able to assemble and combine information so that decisions can be made. QFD is a method to prioritize these responses to address the patient-oriented goals of the patients. Therefore, the improved QFD can serve as a medium to communicate clinical and engineering information to the patients, therapists, engineers, and researchers. It is a flexible tool that can be improved to suit the requirements of application.

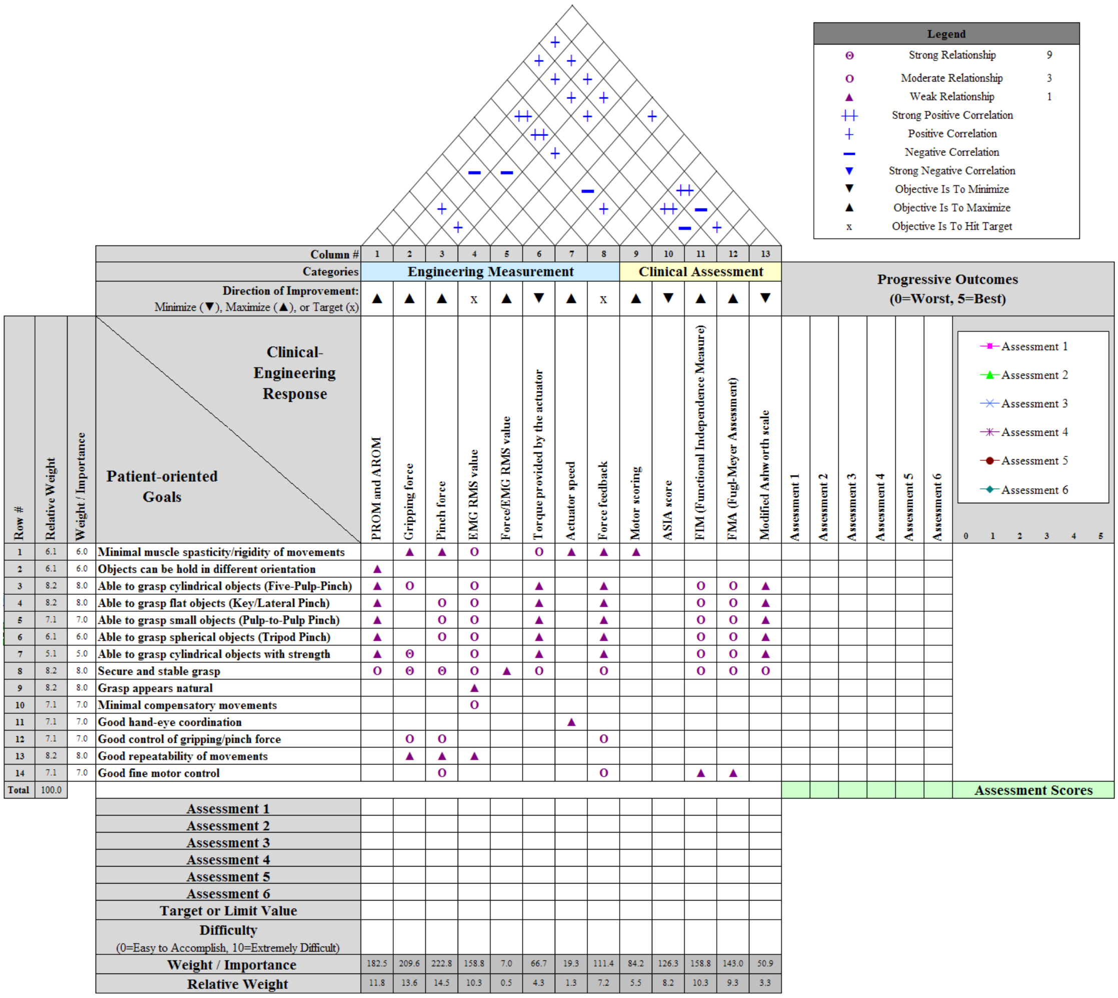

Figure C8: Sample Results of the Proposed QFD for Hand Rehabilitation (for details refer to Figures C2-C7)

Appendix D: LIST OF AUTHOR'S PUBLICATIONS

1. Y. Y. Huang, K. H. Low, and A. H. McGregor, Modeling and Design of a Task-Oriented Hand-Fingers Rehabilitation Device for Robotics Therapy", IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2013) (Submitted for Review), 2013.
2. Y. Y. Huang, A. H. McGregor, K. H. Kong, and K. H. Low, "Analysis and Design of a Task-Oriented Hand-Fingers Rehabilitation Device for Robotics Therapy", *Robotica* (require revisions by journal), 2012.
3. Y. Y. Huang, A. H. McGregor, K. H. Kong, and K. H. Low, "Clinical-based Engineering Assessment of Hand Strength and Results Interpretation for Tasks-oriented Robotic Rehabilitation," *Advanced Robotics, Special issue on Rehabilitation Robotics on Mobility & Manipulation*, vol. 25, pp. 1991-2018(28), 2011.
4. Y. Y. Huang and K. H. Low, "Comprehensive Planning of Robotic Therapy and Assessment of Task-Oriented Functions Via Improved QFD Applicable to Hand Rehabilitation," *Proceedings of the 6th annual IEEE Conference on Automation Science and Engineering (CASE)*, Toronto, Ontario, Canada, pp. 252-257, 2010. ***(Awarded 2010 Society for Laboratory Automation and Screening (SLAS) Young Scientist Award Finalist)***
5. Y. Y. Huang and K. H. Low, "A multi-disciplinary approach for effective hand rehabilitation with clinical-based assessment outcomes," *Proceedings of the 2009 IEEE International Conference on Automation Science and Engineering (CASE 2009)*, Bangalore, India, pp. 597-603, 2009.
6. Y. Y. Huang and K. H. Low, "Comprehensive Signal Interpretation of Functional Hand Strength for Activities of Daily Living (ADL) Rehabilitation via Multivariate Data Analysis (MVA)," *Proceedings of the 2009 IEEE International Conference on Mechatronics and Automation*, Changchun, Jilin, China pp. 937-942, 2009.
7. Y. Y. Huang, K. H. Low, and H. B. Lim, "Initial analysis of EMG signals of hand functions associated to rehabilitation tasks," *Proceedings of the IEEE International Conference on Robotics and Biomimetics (ROBIO 2008)*, Bangkok, Thailand, pp. 530-535, 2009.

8. Y. Y. Huang, K. H. Low, and H. B. Lim, "Objective and quantitative assessment methodology of hand functions for rehabilitation," *Proceedings of the IEEE International Conference on Robotics and Biomimetics (ROBIO 2008)*, Bangkok, Thailand, pp. 846-851, 2009.
9. Y. Y. Huang and K. H. Low, "Initial analysis and design of an assistive rehabilitation hand device with free loading and fingers motion visible to subjects," *Proceedings of the IEEE International Conference on Systems, Man and Cybernetics (SMC 2008)*, Singapore, pp. 2584-2590, 2008.
10. K. Y. Ang, Y. Y. Huang, and K. H. Low, "Electromyography analysis for pre-clinical trials of hand rehabilitation tasks using design of experiments," *Proceedings of the 2009 IEEE International Conference on Mechatronics and Automation*, Changchun, Jilin, China pp. 915-920, 2009.