Development Of Finger Contracture Prevention System For Early Post Stroke Rehabilitation

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MOHD NOR AZMI BIN AB PATAR

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Journals

[1] Mohd Nor Azmi Ab Patar, T. Komeda, C. Y. Low, and J. Mahmud, “System Integration and Control of Finger Orthosis for Post Stroke Rehabilitation,” Procedia Technology, vol. 15, pp. 756–765, 2014. **(Scopus)**

[2] M. N. A. A. Patar, T. Komeda, L. C. Yee, and J. Mahmud, “Model-based systems engineering of a hand rehabilitation device,” Jurnal Teknologi, vol. 76, no. 4, pp. 101–106, 2015. **(Scopus)**

[3] M. N. A. bin Ab Patar, T. Komeda, C. Y. Low, and J. Mahmud, “Patient-Driven Hand Exoskeleton Based Robotic with Active Control System for Early Post Stroke Rehabilitation,” Applied Mechanics and Materials, vol. 799–800, pp. 1063–1068, 2015. **(Scopus)**

Chapter in Book

[4] M. N. A. B. A. Patar, T. Komeda, J. Mahmud, and C. Y. Low, “Model Based Design of Finger Exoskeleton for Post Stroke Rehabilitation Using a Slotted Link Cam with Lead Screw Mechanism,” in Industrial Engineering, Management Science and Applications, Lecture Notes in Electrical Engineering, Springer Berlin Heidelberg, 2015, pp. 95–103.

International Conference Proceedings/Papers

[1] M. N. A. Bin Ab Patar, T. Komeda, and J. Mahmud, "Force assisted hand and finger device for rehabilitation," in ISTMET 2014 - 1st International Symposium on Technology Management and Emerging Technologies, Proceedings, 2014, pp. 133–138. **(IEEE Conf)**

[2] M. N. A. A. Patar, T. Komeda, T. Mori, T. Seki, Y. Saito, J. Mahmud, and C. Y. Low, "Hand rehabilitation device system (HRDS) for therapeutic applications," in 5th IEEE RAS/EMBS International Conference on Biomedical Robotics and Biomechatronics, 2014, pp. 381–386. **(IEEE Conf)**

[3] Mohd Nor Azmi Bin Ab. Patar, Takashi Komeda, Low Cheng Yee, Jamaluddin Mahmud, " A Robotic Hand Exoskeleton for Re-Training Hand Function after Stroke," in The 2nd International Biotechnology, Chemical Engineering and Life Science Conference (IBCELC), Hokkaido, Japan, 2015 **(Conf. Paper)**

[4] Mohd Nor Azmi Ab Patar, Takashi Komeda, Cheng Yee Low, and Jamaluddin Mahmud, "Robotic hand exoskeleton with active control system for early post stroke rehabilitation," in Intensive Workshop of 10th South East Asian Technical University Consortium Symposium (SEATUC), 22-24 February 2016

(Conf. Paper)

[5] Mohd Nor Azmi Ab Patar, Takashi Komeda, Jamaluddin Mahmud and Cheng Yee Low," Force And Angle Sensing Efficacy Of Finger Device For Early Acute Stroke Rehabilitation" in Malaysia-Japan Joint International Conference (MJJIC 2016), 6 - 7th September 2016, Kuala Lumpur, Malaysia. **(Conf. Paper)**

ABSTRACT

A finger robotic exoskeleton developed to restore and rehabilitate hand and finger functions. The robotic exoskeleton is an active actuated mechanism implemented in rehabilitation systems in which each finger attached to an instrumented lead screw mechanism that allows force and position control, according to the normal human setting. The robotic device, whose implementation based on biomechanics measurements, is able to assist the subject in flexion and extension motions. It is also compatible with various shapes and sizes of human fingers. Main features of the interface include an integration of DC servomotor and lead screw mechanisms, which allow independent motion of the five fingers with small actuators. The device is easily transportable, possess user safety precautions and offer multiple modes of training potentials. This study presented the measurements implemented in the system to determine the requirements for the finger and hand rehabilitation device, the design and characteristics of the whole system.

Keywords: Continuous Passive Motion (CPM); Active Robotic Exoskeleton; Spasticity; Motor Hand Function; Contracture Prevention

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CHAPTER 1

INTRODUCTION

In recent years, strokes have been one of the third largest causes of death in the world behind cancer and heart disease [1]. There are many stages in a stroke and the main focus is in the early acute patient care, which is to perform passive range of motion to prevent muscle contractures [2]. In many countries, finger disabilities and injuries mostly caused by strokes. A healthy finger is an important aspect in a human’s daily life. However, abnormal conditions, such as disabilities, injuries, deformation and diseases of the hand, can influence patients’ in their activities of daily living (ADL).

Post stroke rehabilitation at the acute stage usually starts with one-to-one therapies conducted by physiotherapists in acute-care clinics [3]. To reduce the total cost of the treatment, patients typically sent back to their homes when their ability to walk improves even though they have not fully recovered the function of the upper extremity, especially the distal segments such as hands and fingers. In many cases, it will take a long period to recover the function of flexion, extension, abduction and adduction of the fingers. Thus, leaving the fingers in flexed or extended positions leads to difficulties in ADL, such as feeding, dressing, grooming and personal hygiene.

One of the approaches in solving finger disabilities and injuries is undergoing finger rehabilitation [4]. The finger rehabilitation is a physiotherapy approach, which aims to recover partially or entirely the finger motor function of the patient. The physiotherapy approach based on how to manipulate the paretic limb, which supported by a physiotherapist. The approach may accomplished with daily and frequent rehabilitation of up to several months, depending on the severity of the fingers and the condition of the patient. In order to recover to a normal life, the patient requires time and must undergo consistent rehabilitation, assisted by a physiotherapist [5]. However, since the number of physiotherapists is limited, it will not be easy for the patient to do the rehabilitation that requires support from a physiotherapist at all times. Due to the limited numbers of physiotherapists, there are needs to develop a rehabilitation system where patients can conduct their own rehabilitation exercises without the aid of therapists.

Furthermore, most of the literature reviews on hand rehabilitation robotic devices focus on the recovery of motor functions, specifically the extension and flexion movements of the hand. However, there are limited established approaches or publications available on the recovery of the sensory functions of the hand. In other words, the recovery of the sensory functions of the hand has yet to be explored by researchers. Therefore, improvements in the sensory functions of the hand are just as crucial to the recovery of the motor functions of the hand.

1.1 Motivation

Many people are suffering from some kind of hand or finger disability. They require either one to one rehabilitation with a physiotherapist or using assistive devices such as orthotics and prosthetic devices. In general, rehabilitation of stroke or spinal cord injuries procedure by physiotherapist where a therapist need to guide the hand and finger, according to passive range of motion and prevent the muscle contracture in finger and hand of the patients. This is necessary to cause some positive feedback to get nervous feedback thru the spine to the brain and some recovered in brain after stroke or some recovered in the spine after spinal cord injury. However, this is very personally intensive, it is exhausting for the therapist, expensive and therefore this training is limited in time and the effect. It is much better to do longer training and training that is more intensive and could possible worth of this kind of human support.

Robotic-based rehabilitation therapy has proven their effectiveness. Robot-assisted rehabilitation can address these shortcomings and complementary to the traditional rehabilitation strategies. Robots designed to accurately control interaction forces and progressively adapt assistance/resistance to the patients' abilities can record the patient's motion and interaction forces to quantify objectively and precisely the motor performance, monitor progress, and automatically adapt therapy to the patient's state.

The motivation of this research is to improve the hand or finger rehabilitation by manipulating the robotic technology. The scope of this dissertation is to design a novel mechanism system that would support the early acute stage patients while the robotic assist in distal part of upper limb movement such as flexion and extension during static and dynamic stretching.

1.2 Research Objective

In order to counter the problem, few objectives have been determined as listed below;

i. To develop a novel and autonomous prototype system that is capable of providing repetitive finger movement of the early acute patient during the rehabilitation process especially in static and dynamic stretching conditions.

ii. To suggest a simulation model that will model the range of motion (ROM) of healthy finger movement in a dynamic environment.

iii. To deploy an active finger rehabilitation prototype with evaluation of the hardware and software integration during static and dynamic stretching conditions.

1.3 New Finding Knowledge

This research resulted in a basis mechatronic design methodology concept solution exclusively for a finger rehabilitation device that combined both hardware and software development and for assistive devices in general. The novel principle solution attained from this research will lead to a new exploration as follow;

i. The importance of a model-based system engineering (MBSE) approach as an effective medium for innovation process in multidisciplinary researchers.

ii. Development of a simple and non-invasive force finger measurement in clinical data collection.

iii. Formulation of a finger trajectory and range of motion during flexion and extension motion

1.4 Significance of Research

The proposed basis principle solution on development of mechatronic design system for hand and finger rehabilitation device will provide a complete guideline for other assistive device development process. Most of the development process typically consists of researchers mostly from multidisciplinary domain such as medical, engineering, and business experts.

The finger rehabilitation device developed for prevention contracture and spasticity of the hand or fingers. It ensures patient safety and has great potential implemented for an individualized rehabilitation session for patients who have to undergo therapy in their home. A novel rehabilitation approach for finger and hand motor functions recovery targeting early acute stroke survivors using an active exoskeleton robotic device. The device designed based on anthropometric measurement data of hand ergonomics. It is able to assist the subject in flexion and extension movements. Main specification of the device includes a differential system with a current sensing element and a lead screw mechanism, which allows independent movement of each finger using small actuators. The device is safe, easy to deploy, integrated with sensing element and offers multiple training possibilities. Furthermore, it observed to offer an objective and reliable instrumented tool to monitor patient’s progress and accurately assess their motor function.

On top of that, it leads to the improvement in the rehabilitation process, providing a new tool in robotics technology, which offers a new way to reduce the burden of the physiotherapists in a repeatable and measurable manner. Physical rehabilitation is key for recovering motor control and function for patients with neurological disorders. Conventional therapy procedures tend to be labor intensive and non-standardized, especially in the area of hand and finger rehabilitation. The positive impact in terms of improving patient safety, increasing medical reliability, reducing medical errors and decreasing health care costs is far reaching.

1.5 Scope and Limitation

i. All measurements are collected through Vernier SensorDAQ for data acquisition using LabVIEW software and all sensory manipulations is not involving invasive procedure.

ii. The mathematical modelling simulation program coded in LabVIEW language and the real experiment implemented in an open-source microcontroller platform based, ARDUINO used to integrate hardware and software.

iii. Our finger exoskeleton for the current development only limit to range of anthropometric study of the index finger conducted from a population sample of 30 people to determine ideal exoskeletal size.

iv. All measurements from healthy volunteer age between 20 – 33 years of ages with no signs of finger contracture, disease, injury, burn mark, surgery mark of finger abnormality at the area of testing.

1.6 Outline of Thesis

The research title is “DEVELOPMENT OF FINGER CONTRACTURE PREVENTION SYSTEM FOR EARLY POST STROKE REHABILITATION”. This section briefly described the content of this research thesis, so that the readers could follow the steps taken in the design process of the development.

Chapter 1: The first chapter provides a general introduction and background of the whole research including problem statement, research objective, and significance of research, scope and limitation and outline of the thesis.

Chapter 2: The second chapter explains literature review section, which describes previous study related to this research. Existing robotic devices for stroke rehabilitation presented and discussed, with a specific interest for devices dedicated to hand rehabilitation.

Chapter 3: The third chapter describes the biomechanical aspects involved in the hand and fingers joint movement, the current problems and idea to develop the new finger rehabilitation tool.

Chapter 4: The forth chapter elaborated feasibility analysis about the activity done by the authors for the preliminary study before development of a hand exoskeleton

Chapter 5: The fifth chapter focusing on prototype development. This section explained details on the hardware and software in the system.

Chapter 6: The mechanical design of the robot-based finger exoskeleton discussed in detail in this chapter. In the following sections, particular attention will focus on the design and development of the robot-based finger exoskeleton, as it is the main contribution of this thesis.

Chapter 7: The seventh chapter shows the control aspects of our system that include PWM control, position measurement using rotary encoder, and speed measurement from the frequency to voltage (F/V) converter circuit and torque control via the feedback of the current sensor.

Chapter 8: This chapter expressed some experiment results of our system in two main cases of hanging on a frame which without load and wearing the system on a healthy subject.

Chapter 9: The last chapter of this thesis give explanation on the conclusion of the entire research discovery and future recommendation for forthcoming improvement.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The mobility element is important in daily life of a healthy person to carry out basic activities of daily living (ADL). Disorders in mobility will significantly decrease a quality of life, especially the affected patients with upper limb disorders. It effected in limit the independence in mobility of the patients in daily life activity such as feeding, dressing, grooming and personal hygiene. Opportunely, there are various instruments and approaches to recovery the motor function of the upper limb, such as functional electrical stimulation (FES), orthoses and physical therapy. However, positive effect of physical therapy, especially in area of finger rehabilitation usually depends on onset, duration, intensity and task orientation in the training session [6]. Besides, the patient's health condition, motivation and effort also contribute to the positive outcome [7]. Intensive and repetitive task in coordinating motor activities establish a substantial burden for the therapists during assisting patients. Moreover, the duration of primary rehabilitation become shorter to reduce cost expensed during the rehabilitation session [8]. These problems will possibly worsen in the future as life possibility continues to growth accompanied by the frequency of both moderate and severe motor disabilities in the elderly population and subsequently increasing their need of physical assistance. Consequently, as a long-term countermeasures regarding these critical problems, fundamental researchers studies and explores a wide range of devices exactly in assisting physical rehabilitation. Robotic devices with the function of repetitive tasks on patients are amongst these technically innovative devices. In fact, robotic technology already implemented in clinical practice as well as clinical evaluation. However, since the number of devices describe in the literature, to date only a few of them have succeeded to target the subject group as the details shown in Table 1. Moreover, it look like the outcome of the previously implemented devices in clinical practice is not reveal a confident result as expected [7]. Innovative and novel solutions are need to consider. Most of the literature reviews on robotic devices for finger rehabilitation focus more on the development of the devices that already go through clinical assessment. However, there are no other publication presents a systematic review of different robotic technology counteract for finger rehabilitation, including those in the development stage. A critical review of different technical solutions would offer inventors of robotic devices for finger rehabilitation as assessment approaches already considered, and therefore others can get lesson on how to success from pioneer researchers as well as failure explorations. Later, a comparison of various robotic devices would simplify the development of novel and better devices for robotic finger rehabilitation. The motivation of this chapter is to review current technical approaches for physical therapy of the upper limb, especially on distal part such as hand and finger.

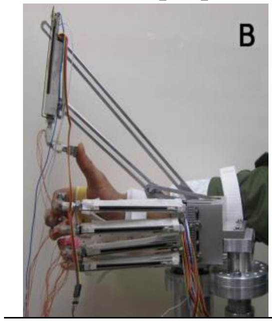
The review of robotic devices covered of advanced technology systems. As defined in this chapter, the design in advance technology systems must involve of the integration of sensors, actuators, and control units. Therefore, only mechanical-driven systems omitted from this review. Although we made an effort to categorize as many systems as possible, it is necessary to acknowledge that there are still many systems left unmentioned. However, this chapter proposed to be a valuable basis of evidence for engineers, scientists and physiotherapists who involved in the development of novel robotic devices for physical rehabilitation.

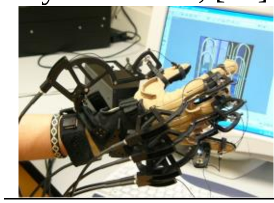
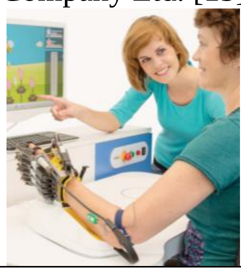
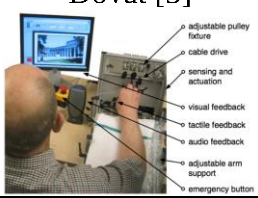
2.2 Scope of Literature Review

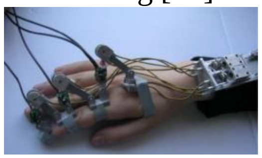
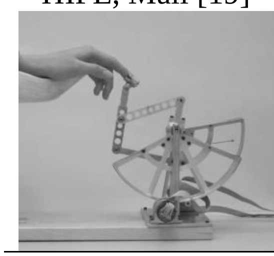
At the beginning, we identified literature related to the subject matter based on searches in PubMed, the Institute of Electrical and Electronics Engineers (IEEE), Science Direct and Google Scholar databases using different combinations of the following keywords such as hand, finger, rehabilitation, therapy, training, movement, motion, assistance, assistive, support, robot, exoskeleton, orthosis, extension, flexion, motorised, and mechatronic. In addition, related literature from the selected publications also included in the review as well. The evidence obtained from this literature compilation added to the data learned from professional caregivers, manufacturers' catalogues, websites, as well as direct communications with physician and physiotherapist, manufacturers and patients. As previously mentioned, the scope of this review is generally limited to the devices that support or retrain movement or manipulation abilities of disabled individuals. This review excludes systems developed for movement assessment, occupational purposes or improving physical abilities of healthy people. However, we considered and specialized systems, supporting finger movements, especially in the potential area of rehabilitation purposes [9]. This review also excludes devices that substitutes movements of the disabled extremity but do not replaced the movement itself like wheelchair mounted manipulators or autonomous robots. Even though these devices recover the patient's quality of life, they vary significantly from the systems defined in this review and form a separate category of devices. Some companies manufacture sensor based equipment for rehabilitation of various joints and muscles where it function like training devices found at fitness centres. Those devices application mostly to strengthen muscles, joints and provide some predefined resistance in isometric exercises or active force in continuous passive motion exercises. These devices also establish a different category from the systems incorporated in this review since their functions related to certain task. Even though difficult to classify clearly, the previously mentioned also excluded from this review.

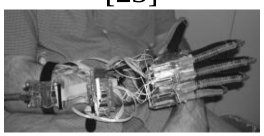
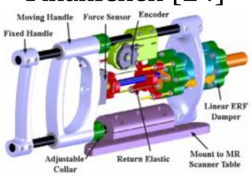
In this chapter, the terminology number of degrees of freedom (DOF) defines the summation of all independent movements such as linear motion or angular motion that available in all the joints of the device. The number of DOF stated in determining the exact position and orientation of all segments of the device. In addition, there are sections in this chapter supplementary to explain the most essential terminology for readers who are not familiar with the technical terms.

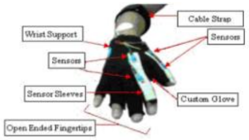
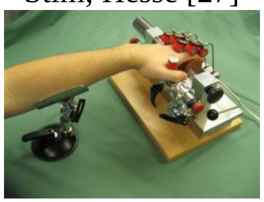
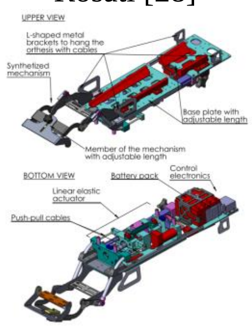
Table 1 Robotic devices for system assisting finger rehabilitation

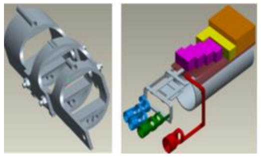
System Name, references	Degree of Freedom(DOF)	Supported movements	Main Control Inputs	Actuators	Type, Field of application	Stage of development; additional information
Amadeo, Tyromotion GmbH 	5	Fingers(each) - Flexion/Extension	End-point position and force	Electric motors	Stationary system (end-effector-based); physical therapy	Commercial system; Clinical study, C1: 7 acute stroke [10]
Chen [11] 	5	Independent linear movement of each finger	Fingers position and forces, sEMG	5 DC linear motors	Stationary system (end-effector-based); physical therapy	Clinical study, C0: 1 healthy subject
Gloreha, Idrogenet srl 	5	Independent passive movement of each finger	Fingers positions	5 Electric motors	Portable Gloreha Lite, Movable Gloreha Professional (end-effector-based, cable-driven); physical therapy	Commercial system; Clinical Study, C1: 9 stroke and 3 other diseases, 4 chronic stroke C2:10 subacute stroke

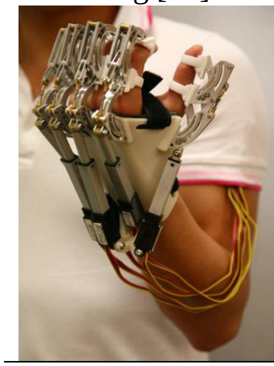
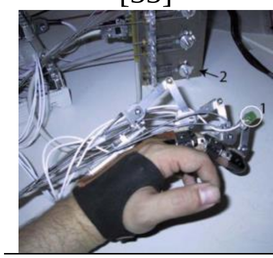
CyberGrasp, CyberGlove Systems LLC; [12] 	5	Resistive force to each finger	Joint angles	5 DC motors	Force-feedback glove; interactions with virtual environment	Commercial system for many application, used in some clinical studies [13],[14]
Hand of Hope, Rehab-Robotics Company Ltd. [15] 	5	Each finger separately-Flexion/Extension	sEMG	DC linear motors	Portable system(orthosis); physical therapy	Commercial system; Clinical Study,C1:8 chronic stroke
HandCARE, Dovat [3] 	5	Independent linear movement of each finger (1 finger at a time)	Fingers positions and forces	1 DC motor	Stationary system(end-effector based, cable-driven); physical therapy	Clinical Study,C1:5 chronic stroke and 8 healthy subjects
Ertas [16] 	1	Concurrent Flexion/Extension of 3 joints of a single finger	Joint angles	1 DC motor	Finger exoskeleton (under actuated mechanism); tendon physical therapy	Clinical Study, C0: 4 healthy subjects

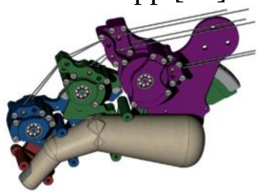
Fuxiang [17] 	4	Index finger-Flexion/Extension	Joint positions and torques	Linear stepping motors	Modular-finger exoskeleton (Continuous Passive Motion Device); Physical Therapy	Clinical Study, C0: 3 healthy subjects
HEXORR, Schabowsky [18] 	2	Thumb-Flexion/Extension, Other fingers move together-Flexion/Extension	Fingers positions and forces	1 DC motor, 1 AC motor	Stationary system (End-Effector based, cable driven); Physical Therapy	Clinical Study, C1: 5 chronic stroke and 9 healthy subjects
HIFE, Mali [19] 	2	1 Finger – Flexion/Extension	End-point position	DC motors	Haptic interface (end-effector-based); Physical Therapy	Prototype
InMotion HAND,Interactive Motion Tech., Inc.; Masia [20] 	1	All fingers together-Grasp and Release	Not mentioned	DC brushless motor	Add-on module for InMotion ARM; Physical Therapy	Commercial System
Kline [21]	1	All fingers together-extension	Joint angles, sEMG	Pneumatic	Wearable glove; grasp	Clinical Study, C1: 1 stroke

					assistance	and healthy subject(not provide specific number)
Lucas [22] 	1	Index finger - flexion (passive extension)	sEMG	2 Pneumatic	Wearable orthosis; grasp assistance	Clinical Study, C1: 1 Spinal Cord Injury (SCI)
MRAGES, Winter [23] 	5	Each Fingers – Flexion/Extension	Finger Positions and torques	5 MagnetoRheological fluid (MRF) brakes	Force-Feedback glove; Physical Therapy	Prototype
MR_CHIROD v.2, Khanicheh [24]  	1	All fingers together-Grasp and Release	Finger position and torques	electrorheological fluid (ERF) brakes	Exercising device (handle-like); Physical Therapy	Clinical Study, C0: healthy subject (not provide specific number) fMRI compatible
Mulas [25] 	2	Thumb – Flexion/Extension, Other fingers move together-Flexion/Extension	sEMG, pulleys position	2 DC servo motors	Wearable orthosis; Physical Therapy	Clinical Study, C1: 1 subacute stroke

Nathan [26] 	1	All fingers together Grasp and Release (passive release)	Hand-held trigger, index and thumb fingers joint angles	Functional Electrical Stimulation (FES)	Wearable orthosis (glove); Physical Therapy	Clinical Study, C1: 2 stroke and 1 healthy subject
PowerGrip, Broaden Horizons, Inc. 	1	Thumb, Index and middle finger together Grasp and Release	Switches or sEMG	1 DC motor	Wearable orthosis; grasp assistance	Commercial system
Reha-Digit, Reha-Stim; Hesse [27] 	1	4 fingers (except the thumb) together Flexion/Extension	None	DC motor	Portable system (rotating handle); Physical Therapy	Commercial system; Clinical Study, C2: 8 subacute stroke C1: 1 chronic stroke
Rosati [28] 	1	. 4 fingers (except the thumb) together –Flexion/Extension	Not Selected Yet	DC motor (SEA)	Wearable orthosis; Physical Therapy	Design

Rotella [29] 	4	. Index finger Flexion (Passive Extension) . Thumb-flexion, other fingers together flexion	Not specified	Electric motors	Wearable orthosis; grasp assistance	Design
Rutgers Master II-ND, Bouzit [30] 	4	. Thumb, index, middle, and ring finger – Flexion/Extension	Actuator translation and inclination	4 Pneumatic	Force Feedback glove; interactions with virtual environment	Research Device for Hand therapy
Salford Hand Exoskeleton, Sarakoglou [31] 	7	. Index, middle, and ring finger – Flexion/Extension, . Thumb – Flexion/Extension	Joint angles and end point force	DC motors	Wearable orthosis (exoskeleton); Physical Therapy	Clinical Study, C0: healthy subject (not provide specific number)

Tong [32] 	10	. Each finger – Flexion/Extension	sEMG	10 Electric linear motors	Portable system (wearable orthosis); Physical Therapy	Clinical Study, C1: 2 chronic stroke
TU Berlin Hand Exoskeleton, Wege [33] 	4	. 1 finger – Flexion/Extension, Abduction/ . Adduction	Joint Angles	4 DC Motors	Finger Exoskeleton; Physical Therapy	Clinical Study, C0: 1 healthy subject
TU Berlin Hand Exoskeleton, Fleischer [34] 	20	. Flexion/Extension and Abduction/ . Adduction of all major joints of each finger	Joint Angles, End point force, sEMG	DC motors	Wearable orthosis (exoskeleton); Physical Therapy	Prototype

Worsnopp [35] 	3	. Index Finger – Flexion/Extension	Joint angles and torque	6 DC Brushless Servo Motor	Finger Exoskeleton; Physical Therapy	Prototype
Xing	2	. Thumb-Flexion/Extension, other fingers move together-Flexion/Extension	Position, Force	2 Pneumatic (PAMs)	Wearable orthosis; Physical Therapy	Clinical Study, C0: 3 healthy subjects

2.3 Type of assistance

The most important terminology introduced in this section explained in Table 2. Devices for hand rehabilitation may provide different types of motion assistance: active, passive, haptic and coaching.

Active devices provide active motion assistance and possess at least one actuator, thus they are able to produce movement of distal part such as hand and fingers. Most of the devices discussed in this review are active (see Table 1). Such assistance of movements is required if patient is too weak to perform specific exercises. However, even with active devices, an exercise considered passive when patient’s effort is not required. For instance, devices providing continuous passive motion exercise are active, but those exercises categorized as passive because the subject remains inactive while the device actively moves the joint through a controlled range of motion. It is not necessary to apply active assistance to resist patient’s movement, to increase patient’s force or to ensure the patient is following the desired trajectory.

As an alternative, passive devices may be applied where the devices are equipped with actuators providing only resistive force for instance as brakes. Such actuators consume less energy and cheaper than the heavier actuators for active assistance. Devices using only resistive actuators include both devices for physical therapy, for instance MEM-MRB [36] and PLEMO [37], and systems for tremor suppression, for example WOTAS [38] orthosis and a system proposed by Loureiro, et al [39].

Haptic devices create another group of systems interacting with user through the sense of touch. Haptic devices similarly classified as any active or passive, depending on their type of actuator. In this review, haptic devices independently categorized because of their main function is not to cause or resist movement but rather to provide tactile sensation to the user.

Other non-actuated devices for hand rehabilitation, which do not generate any forces but provide different feedback. These systems labelled as coaching devices throughout this review. Due to coaching devices embedded with sensor, they serve as input interface for interaction with therapeutic games in virtual reality (VR) for example T-WREX [40], Armeo Spring from Hocoma AG or for tele rehabilitation, which remotely supervised therapy. Coaching systems using video-based motion recognition, for example, Microsoft Kinect would also belong to this category if it were not for their lack of any mechanical part in contact with the patient. Therefore, these systems will not discuss further in this review.

Passive and non-actuated systems are less complex, safer and cheaper than the active systems. They are usually involved with an innovative modification in the development process with more active characteristics. However, the main characteristic that identifies non-actuated or passive devices is the lack of the ability to perform movement. They may be an option for continuation of the rehabilitation process, rather than for training of people with significant movement disorders at an early stage of rehabilitation.

Table 2 Glossary of terms regarding type of assistance

Term	Description
Active device	A device capable to move limbs. Under such condition, this device requires active actuators, which may increase the weight. It may also apply to subjects which completely unable to move their limb.
Passive device	A device unable to move limbs, but may resist the movement when exerted in the wrong direction. This type of device may only be used for rehabilitation of subjects which able to move their limbs. It is usually lighter than active device since it possesses no actuators other than brakes.
Haptic device	A device that interfaces with the user through the sense of touch. Usually it provides some amount of resistive force, often also some other sensation such as vibration. It is sometimes also able to generate specific movements. However, the force generates is usually small. Haptic devices commonly used in rehabilitation settings with virtual environments.
Coaching device	A device that neither assists nor resists movement. However, it is able to track the movement and provide feedback related to the performance of the subject. As haptic devices, coaching devices also commonly used in rehabilitation settings with virtual environments.
Active exercise	An exercise in which subjects actively move their limb, although some assistance of the device may provide. Such type of the exercise may performed using any of the above listed types of devices.
Passive exercise	An exercise in which the subject remains passive, while a device moves the limb. This type of exercise requires an active device. Continuous passive motion (CPM) training is an example of passive exercise with active devices.

2.4 Mechanical design

The most important terminology introduced in this section explained in Table 3. Once comparing the mechanical structure of robotic devices for movement rehabilitation divided into two categories of devices. There are end-effector based and exoskeleton based. The difference between the two categories is how the movement is transfer from the device to the patient's distal part such as hand and fingers.

End-effector based devices contact the patient's limb only at its most distal part that attached to patient's upper limb for instance end effector. Movements of the end effector change the position of the upper limb to which it attached. However, segments of the upper limb create a mechanical chain. Thus, movements of the end effector also indirectly change the position of other segments of the patient's body as well. Compared to end effector, exoskeleton based devices have a mechanical structure that mirrors the skeletal structure of patient's limb. Therefore, movement in the particular joint of the device directly produces a movement of the specific joint of the limb.

The advantage of the **end-effector based** systems is their simpler structure and thus less complicated control algorithms. However, it is difficult to isolate specific movements of a particular joint because these systems produce complex movements. The manipulator allows up to six unique movements, which consists of three rotations and three translations. Control of the movements of the patients' index finger is possible only if the sum of possible anatomical movements of patients' finger in all assisted joints is limited to three. Increasing the number of defined movements for the same position of the end of the manipulator results in redundant configurations of the patient's index finger, thus inducing risk of injuries and complicated control algorithms.

The typical end-effector based systems include serial manipulators such as implemented in MIT Manus [41] and ACRE [42], parallel mechanism as implemented in CRAMER [43] and a system developed by Takaiwa and Noritsugu [44], and cable driven robots as in NeReBot [45]. The mechanical structure of HandCARE [3] is a series of end-effector based cable driven robots, where each induce movement of one finger. In this system, a clutch system allows independent movement of each finger using only one actuator.

Application of the **exoskeleton-based** approach allows for independent and concurrent control of particular movement of patient's finger in many joints, even if the overall number of assisted movements is higher than six degree of freedom. However, in order to avoid patient injury, it is necessary to adjust lengths of particular segments of manipulator to the lengths of the segments of the patient finger. Therefore, setting up such device for a particular patient, especially if the device has many segments, may take a significant amount of time. Furthermore, the position of the centre of rotation of many joints of human body, especially of the finger are complex [46], may change significantly during movement. Special mechanisms are necessary to ensure patient safety and comfort when an exoskeleton-based robot assists the movements of these joints [46]. For this reason, the mechanical and control algorithm complexity of such devices is usually significantly higher than the end effector based devices. The complexity increases as the number of DOF increases.

In case of systems for the rehabilitation of the whole limb the number of DOF reaches nine like implemented in ESTEC exoskeleton [47] or ten in IntelliArm [48]. Some systems for fingers or hand rehabilitation have a higher number of DOF as implemented system as proposed by Hasegawa, et al. with eleven DOF [49] and the hand exoskeleton developed at the Technical University (TU) of Berlin with twenty DOF [34]. Even though at such a high number of DOF, some of these devices remain wearable where the user able to walk within a limited area because of wire harness to power source and the connections to control unit as in ESTEC and hand exoskeleton developed at the TU Berlin. The system proposed by Hasegawa is portable system where area of the user may walk is not limited.

Apart from purely exoskeleton based or end-effector based devices, there are many **systems combines a few approaches**. In the Armeo Spring system (Hocoma AG) designed as an exoskeleton for instance focus only the distal part where it is including the elbow, forearm and wrist. Therefore, the limb posture is statically fully determined as in exoskeleton-based systems and the shoulder joint is not constrained, allowing easy individual system adaptation to different patients. A similar concept applied in Biomimetic Orthosis for the Neurorehabilitation of Elbow and Shoulder known as BONES [50]. In the case, a parallel robot consists of passive sliding rods pivoting with respect to a fixed frame provides shoulder movements. The application of sliding rods allows internal and external rotation of the arm without any circular bearing element. The distal part allowing for flexion and extension of the elbow, which resembles the exoskeleton structure. In the Mirror Image Motion Enabler (MIME)-RiceWrist rehabilitation system [51] the end-effector based MIME [52] system for shoulder and elbow rehabilitation integrated with the parallel wrist mechanism used in MAHI exoskeleton and after some modification its known as RiceWrist.

Another example is the six DOF Gentle/S [53] system allowing for relatively large reaching movements three actuated DOF of the end-effector based commercial haptic interface which is HapticMaster, made in the Netherlands [54] and arbitrary positioning of the hand which connection mechanism are three passive DOF. The Gentle/G system further supplemented with a three active DOF hand exoskeleton to allow grasp and release movements. This nine DOF system is known as GENTLE/G [55].

The Haptic Environment for Reaching and Grasping Exercise (HEnRiE) [56] is similar system based on the Gentle/S system. In addition to the three active DOF of HapticMaster, HEnRiE includes a connection mechanism with two passive DOF for positioning of the hand and grasping device where two parallelogram mechanism allowing parallel opening and closing of fingers attachments with only one active DOF.

Some systems combine **more than one robot at the same time**. This approach considered as the combination of end-effector approach, where only the most distal parts of robots attached to the upper limb of patient with the exoskeleton based approach, where movements of few segments are directly controlled at the same time. Usage of two robots in controlling the movements of the limb may allow for mimics the operations performed by therapist using two hands. Examples of systems using two-robot concept include REHAROB [57] using two manipulators with six DOF. Intelligent Pneumatic Arm Movement (iPAM) [58] and UMH [59], both having six DOF in total. Researchers at the University of Twente, in Enschede, Netherlands, attempted to use two HapticMaster systems to provide coordinated bilateral arm training, but limitations in hardware and software caused the virtual exercise to behave differently to the real life [60].

In some cases, **industrial robots** also implemented in rehabilitation domain. The REHAROB uses IRB 140 and IRB 1400H from ABB Ltd., while MIME uses PUMA 560 robot. In general, the usage of industrial robots is reduce cost, however, such robots have significantly higher impedance than the human upper limb and according to Krebs, et al. [20] , should not be in close physical contact with patients. Therefore, most of the robots used for rehabilitation of the upper limb designed with a low intrinsic impedance. Some of those devices are have **back drivable** characteristic for instance HWARD [61] and RehabExos [62]. Therefore, the patient's force is able to cause movement of those devices when they are in passive states. Back drivability increases safety of the patient because the device does not constrain patient movements. It also able implemented as an assessment tool to measure patient's range of motion.

Most of the devices presented in Table 1 allow movements in three dimensions. However, there are also **planar robots** where the systems allow movements only on a specified plane like as in MEchatronic system for MOtor recovery after Stroke (MEMOS) [63] and Quasi-3-DOF Rehabilitation System for Upper Limbs (PLEMO) [37]. Besides, the MIT Manus system also during the initial stage allowed movements only on horizontal axis [41]. Later, an anti-gravity module added possibility to perform vertical axis movements [64]. Design the device as a planar robot reduces the range of movements that exercised for particular joint. It also reduces the cost of the device. Furthermore, when the working plane well selected, the range of training motion may meet the requirements in most of therapeutic application. Some of planar devices allow changes in the working space between horizontal and vertical [65] or even almost freely selecting the working plane like as in PLEMO and Hybrid-PLEMO [66]. It further increases the range of possible exercise application while keeping the cost of the device at a minimum.

In the ARM Guide [67] and ARC-MIME [68] systems, patients practice reaching movements where the working space is limited to linear movements because of the forearm typically follows a straight line trajectory. Therefore, the orientation of the slide that assists forearm movements adjustable to reach multiple workspace regions and fit different applications.

Modularity and re-configurability are concepts that could reduce therapy cost by adopting therapeutic devices for various disabilities or stages of patient recovery. However, there are still only a few systems using these concepts. For instances, InMotion ARM robot, the commercial version of MIT Manus, previously called InMotion 2.0 from Interactive Motion Technologies, Inc., extended by InMotion WRIST robot, previously InMotion 3.0, developed at MIT as standalone system [69] and InMotion HAND add-on module, previously InMotion 5.0 for grasp and release training. Another example of modular system is MUNDUS [70], consists of various modules that included depending on the patient condition, starting from muscle weakness to lost completely of residual muscle function. Input command for residual voluntary muscular activation usually used head or eyes motion or brain signals. However, the complexity of the system might make difficult in the stage of commercialization.

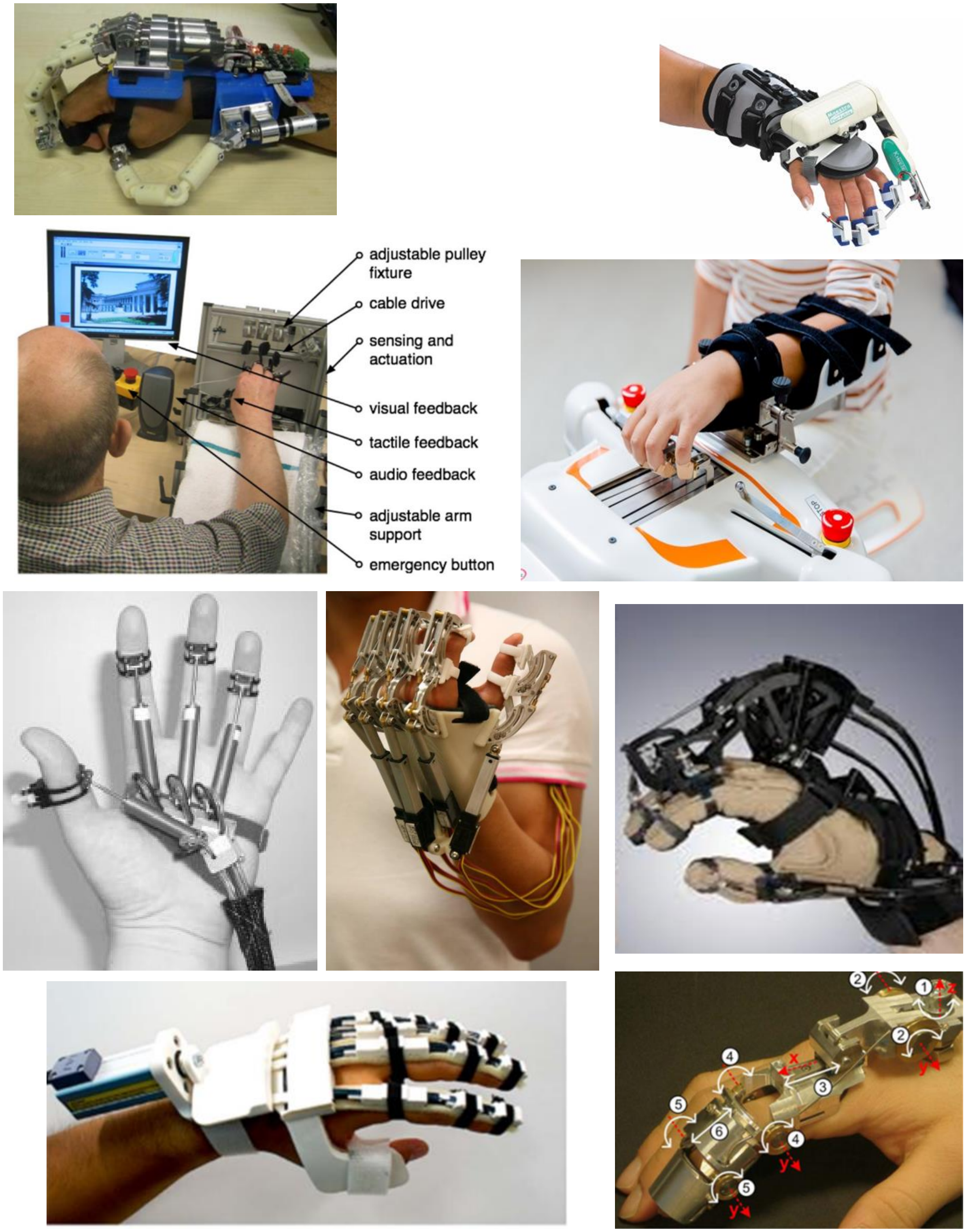


Figure 1 Examples of mechanical structures of robotic devices for finger rehabilitation

Table 3 Glossary of terms related to mechanical design of robots for finger and hand rehabilitation

Term	Description
End-effector based device	Contacts a subject's limb only at its most distal part. It simplifies the structure of the device. However, it may complicate in the control of the limb position, which related to multiple possible degrees of freedom.
Exoskeleton-based device	A device with a mechanical structure that mirrors the skeletal structure of the limb. Each segment of the limb associated with a joint movement attached to the corresponding segment of the device. This design allows independent, concurrent and precise control of movement in a few limb joints. However, it is more complex than an end-effector based device. Orthoses restricting or assisting movement in one or more joints also considered as exoskeleton-based devices.
Planar robot	A device typically end-effector-based moving in a specific plane. Design of planar robots decreases costs and the range of movements that be used in exercised. Although this device performs movements in a plane, joints of the limb still move in a three-dimensional space.
Back-drivability	A property of mechanical design shows that the patient is able to move the device, even the device is in passive state. It increases patient safety by not constrains movements limb and keeps the patient's limb in a comfortable position.
Modularity	A property of a device indicates that optional parts may adapt to a specific condition or simply perform additional exercises.
Re-Configurability	A property of a device shows that its mechanical structure can be modified without adding additional parts to adapt to the condition of the subject or to perform other form of training

2.5 Actuation and power transmission

The most important terminology in this section described in Table 4. Previously, energy supply to the actuators categorized in three forms, which are electric current, hydraulic fluid and pneumatic pressure. The selection of the energy source determines the type of actuators used in the system. Most of the devices for hand and finger rehabilitation used electric actuators but there are also other systems with pneumatic and hydraulic actuators. The electric actuators are most common because of their characteristic in easily providing and storing electrical energy besides their relatively higher power. Various types and sizes of electrical motors and servomotors are currently available commercially. Some authors like Caldwell and Tsagarakis [71] claimed that electric actuators are too heavy compared to pneumatic and its characteristics are also high impedance to implement in rehabilitation application. However, the relatively high power to weight ratio of pneumatic actuators achieved by neglecting the weight of power source. Integration of an elastic element in series with the actuators may also alleviate the high impedance of electric motors. This concept lead to the development of the Series Elastic Actuators (SEAs). This actuators mechanism decrease inertia and user interface impedance in providing an accurate and stable in force control, thus increasing the protection of the patient from injury. The drawback of this elastic element system is the lower functional bandwidth. Nevertheless, rehabilitation domain does not usually required high bandwidths. The combination of SEAs with electric motors explored in MARIONET [72] and UHD [73] systems, as well as in systems proposed by Vanderniepen, et al. in MACCEPA [74] actuators and Rosati, et al. [28].Service area of this system is limited

A few systems used pneumatic actuators. Pneumatic actuators are lighter and lower characteristic impedance than electric actuators. This actuators require pneumatic pressure, thus the system is generally either stationary like used in Pneu-WREX [75], its service area limited as in ASSIST [76] or the compressor installed on the patient's wheelchair as system proposed by Lucas, et al.[22]. Special type of pneumatic actuators called Pneumatic Artificial Muscles (PAMs), Pneumatic Muscle Actuators or McKibben type actuators frequently used in rehabilitation robotics as example in Salford Arm Rehabilitation Exoskeleton [77] or system as proposed by Kobayashi and Nozaki [78]. These types of actuators consists of an internal bladder surrounded by braided mesh shell with flexible with non-extensible threads. When pressurized the bladder, the actuator increases its diameter and shortens according to its volume, consequently providing tension at its ends [79]. Such physical configuration makes PAM's weight generally light compared to other actuators instead also have slow and non-linear dynamic response especially for large PAMs. Therefore, they are not practical for used in clinical rehabilitation scenarios [80]. Furthermore, at least two actuators are necessary permissible to provide antagonistic movements because of the unidirectional contraction mechanism. The ASSIST system has a special type of PAM with rotary pneumatic actuators that allows bending movements [76].

Hydraulic actuators, which identified in this review, are not standard and use actuators developed specifically for that purpose. The main reasons to avoid the usage of industrial hydraulic actuators take account of weight, impedance, fluid leakages and difficulties to provide fluid. Typically, these types of systems are large and noisy. Mono and bi-articular types of Hydraulic Bilateral Servo Actuators (HBSAs) as used in the wheelchairs mounted exoskeleton proposed by Umenura,et al. [81]. Miniaturized and flexible fluidic actuators (FFA) applied in the elbow orthosis proposed by Pylatiuk, et al [82]. Hydraulic SEAs used in two other systems like as the Dampace system [83], which equipped with powered hydraulic disk brakes. The Limpact system [84], developed by the same group uses an active rotational Hydro-Elastic Actuator (rHEA).

In passive systems, it is a necessary the desired to modify the amount of resistance during the exercise. This modification increases the resistance when the patient proceeds with the desired trajectory and provide haptic feedback for VR interactions. In existing systems, different solutions for providing of adjustable resistive force. Powered hydraulic brakes, for instance controlled by electro motors in a SEA used in Dampace system [83]. Magnetic particle brakes used in ARM Guide [67], in its successor ARC-MIME [68] to resist other than longitudinal movements of the forearm, and in the device for training of multi finger twist motion proposed by Scherer, et al [85]. A few groups have also investigated the application of brakes incorporating magnetorheological (MRF brakes) and electrorheological fluids (ERF brakes). These fluids change their rheological properties like viscosity depending on the applied magnetics or electric field. Those properties realized and achieved brake behaviours with high performance in rapid and repeatable brake torque [37]. MRF brakes used in MRAGES [23] and MEM-MRB [36] systems. ERF brakes used in PLEMO [37] and MR_CHIROD v.2 [24] systems. The same group, which developed PLEMO, also proposed ERF clutches to control the force provided by an electric motor in active systems. This kind of an actuation system implemented in EMUL [86], Robotherapist [87] and Hybrid-PLEMO [66] devices.

The usage of contraction ability in natural actuators, which is body muscles can fully optimized instead of external actuators. In Functional Electrical Stimulation (FES), an electrical stimulation the muscle contraction. FES significantly reduces the weight of the device. In therapeutic domain, FES allows patients to exercise muscles to improve muscle bulk and strength towards preventing muscular atrophy [88]. It has shown that FES supplemented the conversional physiotherapy and enhance the rehabilitation outcome [89]. However, FES may cause strong involuntary muscle contractions and can be painful for patients. Furthermore, it is difficult to control movements using FES because of the nonlinearity in force characteristic during contracting muscles, muscles fatigue and dependency of the achieved contraction on the quality of the contact between stimulating electrodes and the body tissue. There are two commercial systems using FES for upper limb rehabilitation which are Ness H200 (Bioness, Inc., US) and NeuroMove (Zynex Medical, Inc., US).

It is a crucial to reflect their location when selecting actuators, especially in exoskeleton based mechanical structures. The actuators be able to place distally, close to the joints on which they actuate as implemented in ArmeoPower system. This specification simplifies the power transmission by using direct drives. However, it increases the weight and inertia of the distal part of the device makes it more difficult to control the system. On the other hand, locating the actuators in proximal part of the device, usually in the part that remain constrained will reduce the weight and inertia of the distal part. However, a power transmission in mechanism will complicate the mechanical structure and lead to difficult in control due to the friction occurs during movements. For instances, the same group who developed InMotion HAND system proposed an earlier prototypes of the hand module with eight active DOF integrated with cable driven mechanism for power transmission. The friction in that mechanism and its level of complexity was too high for clinical application [20]. Nevertheless, there are systems in which power transmission using cables and gear drives successfully applied like example in CADEN-7 [9] and SUEFUL-7 [90].

Table 4 Glossary of terms related to actuation of robots for finger and hand rehabilitation

Term	Description
Electric actuators	Actuators powered by electric current. They are the most common due to their characteristic in easily provide a relatively high power and able to store energy. There are a wide range of selection of commercially available electric actuators. However, some of them are heavy and their impedance is too high for rehabilitation settings.
Hydraulic actuators	Actuators powered by hydraulic pressure usually oil. They are able to generate high forces. Their system is relatively complex in considering the maintenance of pressurized oil under pressure from leakage issues. Commercial hydraulic actuators are also heavy, therefore, only specially designed hydraulic actuators used in rehabilitation robotics.
Pneumatic actuators	Actuators powered by compressed air. They have lower impedance and weigh less than electric actuators. Special compressor or containers with compressed air required for appropriate power.
Pneumatic Artificial Muscle (PAM); McKibben type actuator	A special type of pneumatic actuator with an internal bladder surrounded by braided mesh shell with flexible but non-extensible threads. Due to their specific design, an

	actuator under pressure shortens, similarly to the muscle contraction. It is relatively light and exerts force in a single direction. It is difficult to control because of its slow and nonlinear in dynamic functions.
Series Elastic Actuator (SEA)	A generic approach for mechanism with elastic element placed in series with an actuator. This solution relatively met in the design of rehabilitation robots. It decreases the inertia and intrinsic impedance of the actuator to allow a more accurate and stable force control and increase patient safety.
Functional Electrical Stimulation (FES)	A technique uses electrical current to stimulate nerves and contract their innervated muscles. It produces the movement of the limb using natural actuators of the body. However, it is difficult to achieve precise and repeatable movement using this technique and it may be painful for the patient.

2.6 Comparison within the development device system and existing device systems

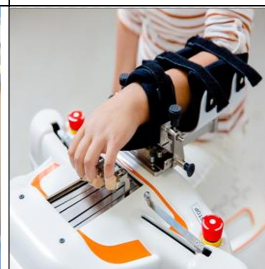
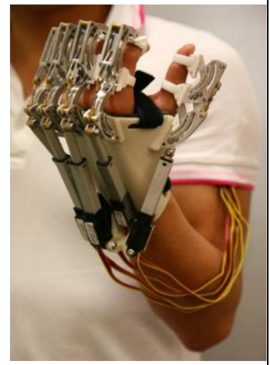
Most of the literature reviews on hand rehabilitation robotic devices focus on the recovery of motor functions, specifically the extension and flexion movements of the hand. However, there are limited established approaches or publications available on the recovery of the motor functions during static and dynamic stretching of the fingers. In other words, the recovery of the motor functions during static and dynamic stretching of the hand has yet to be explored by researchers. Therefore, improvements in the motor function of the hand during static and dynamic stretching are just as crucial as an approach in the recovery of the motor functions of the hand. Table 5 illustrates the comparison within the development device system and existing device systems.

In the table, we tried to make a comparison with the latest literatures in the field. Thus, we chose three finger rehabilitation devices as to compare what we proposed in our lab. We make a comparison based on several criteria for example, what were the target audience in the study, what kind of actuator they used etc. which we will explain later. The first column indicated our group with collaboration within SIT and Universiti Teknologi MARA.

The main difference in our study compare to others was type of actuator. All three compared study using bulky electrics motor. However, our study was using hybrid system, which is the combination of a small DC servomotor with lead screw mechanism. The sensor that were using in others study only detect position and muscle activity. However, sensor were using in our study apart from able to detect position, it also comes with benefit features of velocity and force.

Table 5 Comparison within the development device system and existing device systems

	Finger Rehabilitation Device	**Amadeo, tyromotion GmbH**	**Gloreha, ldrogenet srl**	**Robot Hand**
Research Centre	Research Organization for Advance Engineering, Shibaura Institute of Technology, Japan	Tyromotion Austria	Italian Society of Neuro rehabilitation, Italy	Department of Health Technology and informatics, The Hong Kong Polytechnic University, Hong Kong, China
Authors	Mohd Nor Azmi Ab Patar, Takashi Komeda, Jamaluddin Mahmud, Cheng Yee Low	Sale P, Lombardi V, Franceschini M	F Vanoglio, A Luisa, F Garofali, C Mora	K.Y. Tong, S.K. Ho, P.M.K. Pang, X.L. Hu, W.K. Tam, K.L. Fung, X.J. Wei, P.N. Chen, M. Chen
Last Publication	2016	2012	2013	2010
Target symptoms	Contracture	Spasticity	hemiplegic	hemiplegic
Level of Disease	Acute	all phases of finger-hand-rehabilitation	None	None
Clinical Data	Healthy Subjects	Data from 7 acute stroke patients	Data from 9 stroke patients	Data from 2 chronic stroke patients
Model Device Size	Adult	Adult	Adult	Adult
Actuator	• DC servo motor • Lead screw mechanism	• Electric motors	• Electric motors	• Electric linear motors
Sensor	Voltage Sensor, Current Sensor, Incremental Encoder	None	Position Sensor	sEMG
Finger Structure	• Flexion/Extension Movement • Stationery and	• Flexion/Extension Movement • Stationery	• Independent passive movement	• Flexion/Extension Movement • Portable

	Portable system	system • End-effector based	of each finger • Portable • End effector based • Cable driven	
Prototype				
Evaluators	Occupational therapist	Occupational therapist	Occupational therapist	Occupational therapist
Evaluation Summary	1. The research was focusing on the rehabilitation device with good haptic feedback system. 2. However, the system was not using clinical data as the reference to simulate normal finger trajectories. 3. Currently the research is still ongoing with further improvement	1. Clinical data collection 2. Clinical evaluation 3. Impairment and functional evaluations, FM, MRC, MI, AS	1. Improve functional independence of post-stroke patients in the sub-acute phase The system uses a brake torque 2. Increase grip and pinch strength on the paretic side of neurological patients in the sub-acute phase.	1. adjusted to fit for different finger length 2. Powered by the linear actuator 3. Each hand robot has five individual finger assemblies capable to drive 2 degrees of freedom (DOFs) of each finger at the same time.

Fugl-Meyer Scale(FM), Medical Research Council Scale for Muscle Strength (hand flexor and extensor muscles) (MRC), Motricity Index (MI), and modified Ashworth Scale for wrist and hand muscles (AS).

2.7 Stretching related research

Many studies have evaluated various effects of different types and durations of stretching. Outcomes of these studies categorized as either acute or training effects. Acute effects measure the immediate results of the stretching, while training effects are the results of stretching over a period of time. Stretching studies also vary by the different muscles or muscle groups that examined and the variety of populations studied, thereby making interpretation and recommendations somewhat difficult and relative. Each of these factors must therefore considered when making conclusions based on research studies. Several systematic reviews of stretching are available to provide general recommendation [91]–[93].

There are three muscle-stretching techniques frequently described in the literature, which are static, dynamic and pre contraction stretches. The traditional and most common type is static stretching where a specific position held with the muscle on tension to a point of a stretching sensation and repeated. This performed passively by a physiotherapist or actively by the patient.

There are two types of dynamic stretching which are active and ballistic stretching. Active stretching generally involves moving a limb through its full range of motion to the end ranges and repeating several times. Ballistic stretching includes rapid, alternating movements or bouncing at the end range of motion. However, due to the increased risk for injury, ballistic stretching no longer recommended [94].

The effectiveness of stretching usually described as an increase in joint passive ROM for example, in case of knee or hip ROM used to determine changes in hamstring length. Static stretching is effective at increasing ROM. The greatest change in ROM with a static stretch occurs between 15 and 30 seconds. Most authors suggest 10 to 30 seconds is sufficient for increasing flexibility [95]. In addition, no increase in muscle elongation occurs after 2 to 4 repetitions [92]–[94].

2.8 Conclusions

Stroke survivors can improve their ability to walk, use their affected limbs and carry out ADL with greater skill, by intensively practicing exercises that activate neural and muscular mechanisms. However, among the different approaches and therapies proposed, it is still not clear what is optimal for each patient. Nevertheless, some key points to improve stroke rehabilitation identified as below:

i. Rehabilitation should clearly start as early as possible after the stroke, because of high neuroplasticity for strengthening the good connections between region cells.

ii. On the other hand, rehabilitation should expenditure in the chronic phase where plasticity is lower, as further improvement is still possible. Indeed, intensive use of the impaired hand for task specific activities benefits stroke subjects, even in the chronic stage several years after the stroke, and leads to improvements in independence, speed and precision.

iii. Exercises requiring active participation of subjects should give preference, to activate neural pathways, build muscle strength, increase endurance and coordination.

A crucial point is to develop solutions to increase the intensity of therapy stroke subjects received, especially in the early acute phase, to extend the recovery process, without increasing the costs of rehabilitation. New approaches such as drug treatment and FES have produced promising results in certain types of impairments. However, this cannot generalize to all patients, and the potential benefits of these techniques still need to prove.

The overview of the different programs proposed in rehabilitation centres shows the importance of robotic devices in rehabilitation. Robots are not only used as assessment tools to measure and analyse parameters, such as gait parameters, but they now actively participate in the rehabilitation and interact with patients to exercise walking and balance. Moreover, the new developments in robot-assisted rehabilitation promised a good benefit to the patients with several devices dedicated to the training of wrist, hand and finger function.

Robotic devices may be an ideal to complement the amount of therapy provided to stroke survivors. However, robot-assisted rehabilitation is relatively new, and although the potential may be large, benefits of robots for rehabilitation after stroke still have to investigate.

Due to population changes, shortage of professional therapists, and the increasing scientific and technical potential, many research groups have proposed devices with the potential to facilitate the rehabilitation process. Many devices for finger and hand rehabilitation already been proposed. These proposed devices most technically advanced and designed for clinical setup. However, there is still a significant gaps and need to improve efficiently to reduce cost of home based devices for therapy and ADLs assistance purpose. The effectiveness of robotic approaches in rehabilitation over conventional therapy is questionable and which one is the best therapy strategy is still not clear. The situation may change rapidly, due to the competitive in development and commercialization of the robotic product related to finger and hand rehabilitation. It may inspire the next groups to propose their own solutions. Therefore, developing new devices and improving those already in the market will be easier.

CHAPTER 3

BIOMECHANICS OF HUMAN HAND

3.1 Introduction

Currently, robotic technology gradually be matured and can be adapted for physical rehabilitation in order to provide better therapy and quantitative assessments of recovery [96]. In the area of robot-assisted rehabilitation, various robotic devices for the upper limb have been developed and tested on acute and chronic stroke survivors. The impairment of hand function is reported to be one of the common problems after stroke, designing robotic devices to diagnose and assist hand movements is a challenging task due to the complexity and versatility of the human hand [97].

In previous studies, two main approaches have mainly implemented to design finger rehabilitation devices, which are end-effector [3] and exoskeleton [98]. End-effector based devices mechanically grounded for example placed on a table or fixed to a support such as a camera tripod, which simplify the development of simple design. Therefore, the size and weight are relatively unrestricted compared to exoskeleton. However, it is usually not possible to control each joint involved in the motion using end-effector based devices. An exoskeleton is generally a mechanism that can be placed around a part of the human body to mechanically guide or actuate it without impeding the joint's natural motion. In case of hand rehabilitation devices involving finger motion, the exoskeleton approach has advantage in fitting to the relatively small and complex structures of the hand. However, designing hand exoskeleton devices is a challenging task due to the characteristic of complex and flexible of the human hand. Fitting the centre of mechanically rotated part to human finger's joints is a crucial issue to be countermeasure. In addition, hand exoskeleton devices generally consist of a serially connected mechanical chain to transmit the motion to distal part. Therefore, the mechanisms inherently suffer from bigger size, weight, and number of degrees of freedom (DOF), high complexity in mechanical design, bulky and difficult to adapt to different subjects.

In previous studies, hand exoskeleton devices mainly consist of linkage mechanism, wire or cable driven and direct driven mechanism such as air cylinder or DC servomotor. Linkage mechanism have widely used since the initial stage in the exploration of this research's domain [32]. Linkage mechanism provides the robustness in power transmission, which makes linkage able to transmit bi-directional force contrasting to wire driven mechanism. However, linkage mechanism drawback from the size, weight, and backlash. Wire driven mechanisms typically deployed to avoid the complicated in mechanical setups of serial chains in hand exoskeleton [3][98]. Wire driven mechanism also provide an ideal solution in design according to the size requirement and make reasonable fitted to the hand. However, wire able transmits the force in only one directional, the mechanism become complex to transmit bi-directional movements. In addition, wire extension and wire broken or cut due to the friction while transmitting force need to take into consider for the design and control. Pneumatically driven mechanism are typically in the category of an alternative approach [30]. In this mechanism, pneumatic actuators directly integrated in a glove, thus the devices can be compact and simple in structure. However, precise guidance and assistance to the human’s finger joint centre are typically difficult due to mechanical constraints are relatively limited in direct integration using pneumatic actuators. Therefore, the pneumatic driven mechanism mainly introduced to the devices with a relatively low number of DOFs without precise joint centre actuation.

From this background, we developed a novel robotic device for finger rehabilitation based on the hybrid integration in the direct driven linkage mechanism coupled with lead screw and geared DC servomotor.

This chapter presents the biomechanical constraints for the development of robotic devices for finger rehabilitation reflect to our studies on index finger parameters for healthy and early acute post stroke subjects. The developments of the robot-based finger exoskeleton discussed in detail in this chapter. In the following sections, the biomechanics of the hand and the requirements for the exoskeleton devices will discuss and present in detail. Particular attention will focus on the design and development of the robot-based finger exoskeleton, as it is the main contribution of this thesis.

3.2 Hand anatomy and biomechanics

A mechanism of a finger exoskeleton closely coupled when attached to the finger. Developing the hand exoskeleton requires an understanding of hand anatomy and biomechanics for ensuring safe and effective operation. Specifically, considering the degree of freedom (DOF) and range of motion (ROM) of each joint is important for the design of mechanically safe structure. Figure 2 illustrates hand movements about the joints axis. Moreover, the hand movement complexity related to the intrinsic and the extrinsic muscles as well as the connective tissues.

Therefore, the systematic knowledge helps achieving proper functions for rehabilitation and assistance.

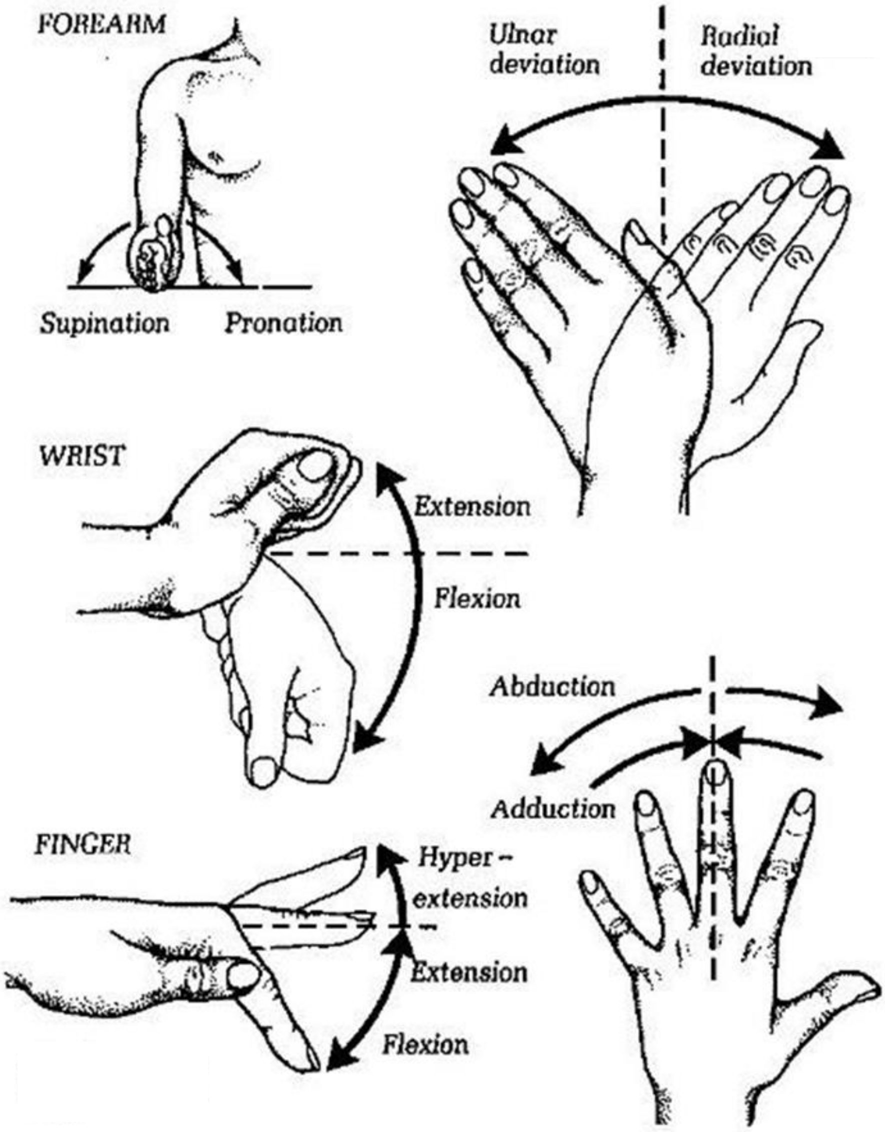


Figure 2 Hand Movements about the joints axis

3.2.1 Bones and Joints

The bones of the hand naturally grouped into the carpus, comprising the eight bones, which make up the wrist and root of the hands, and the digits, each of which is composed of its metacarpal and phalangeal segments. The five digits named as follows from the radial to the ulnar side: thumb, index finger, middle finger, ring finger, and little finger. Each finger ray composed of one metacarpal and three phalanges, except for the thumb, which has two phalanges. There are 19 bones and 14 joints distal to the carpals as shown in Figure 3.

The carpal bones arranged in two rows with those in the more proximal row articulating with the radius and ulna. Between the two is the intercarpal articulation. Each finger articulates proximally with a particular carpal bone at the carpometacarpal (CMC) joint. The CMC joint of the thumb is a sellar joint, exhibiting two degrees of freedom: flexion, extension, and abduction, adduction. The CMC joints of the fingers classified as plane joints with one degree of freedom, while the fifth CMC joint often classified as a semi-saddle joint with conjunctional rotation [99].

The next joint of each finger links the metacarpal bone to the proximal phalanx at the metacarpophalangeal (MCP) joint. MCP joints classified as ellipsoidal or condylar joints with two degrees of freedom, which again permit flexion, extension, abduction movements. In MCP joints, the metacarpal heads fit into shallow cavities at the base of proximal phalanges [100].

The proximal interphalangeal (PIP) and distal interphalangeal (DIP) joints found between the phalanges of the fingers. The thumb has only one interphalangeal (IP) joint. They are both bicondylar joints with subsequently greater congruency between the bony surfaces and have one degree of freedom.

The transverse diameters of the IP joints are greater than their anteroposterior diameters and the thick collateral ligaments are tight in all positions during flexion, contrary to those in the MCP joint. Although the IP joints frequently modelled and assumed as having single axis of rotation for simplicity, in fact they do not remain constant during flexion and extension [101].

The different shapes of the finger joints result in varying DOF at each joint. Moreover, the orientation of the thumb and the unique configuration of its CMC joint provide this digit with a large range of motion and greater flexibility. The wrist extended 20^o in neutral radial/ulna deviation at the resting posture [102]. The resting posture is a position of equilibrium without active muscle contraction. The MCP joints flexed approximately 45^o. The PIP joints flexed between 30^o and 45^o. The DIP joints flexed between 10^o and 20^o at the resting posture. Flexion of the MCP joints is approximately 90^o, and the little finger is the most flexible at about 95^o, while the index finger is the least flexible at about 70^o. The extension varies widely among individuals. For PIP and DIP joints, flexion occurs at about 90^o and 110^o. In addition, extension motion beyond the zero position depends largely on the ligamentous laxity [103].

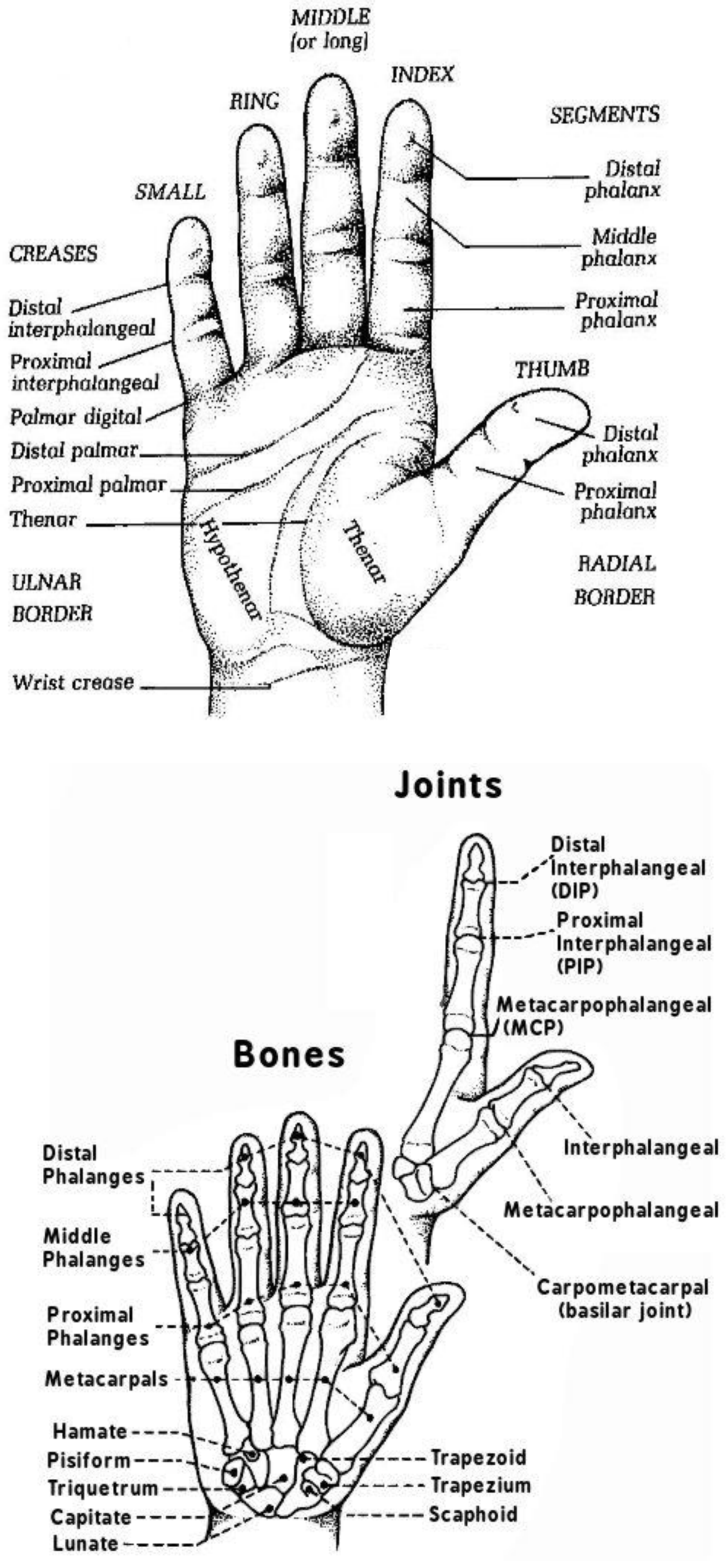


Figure 3 Bones and joints of a human hand [103]

3.2.2 Muscles

Dexterous movements of the hand accomplished because of the coordinated action of both the extrinsic and intrinsic musculature. The origin of extrinsic muscles are from the arm and forearm, and their responsible to do flexion and extension of the digits. The intrinsic muscles are located entirely within the hand, and they permit the independent action of each digit. There are nine extrinsic muscles, and three muscles among them – the flexor digitorum superficialis, the flexor digitorum profundus and the flexor pollicis longus, which contribute to finger flexion. Figure 4 demonstrates hand digits in fingers as well as thumb and their intrinsic muscles. Five extrinsic muscles contribute to the extension of the fingers while one extrinsic muscles (abductor pollicis longus) contribute to the abduction of the thumb.

The dorsal interossei (DI) and palmar interossei (PI) are groups of muscles arising between the metacarpals and attached to the base of the proximal phalanges or to the extensor assembly. The interossei flex the MCP joint, extend the PIP, and DIP joints. They are also effective abductors, adductors and produce some rotations of the MCP joint. The actions of the PIP and DIP joints functionally coupled because of this interaction between the extrinsic and intrinsic musculature.

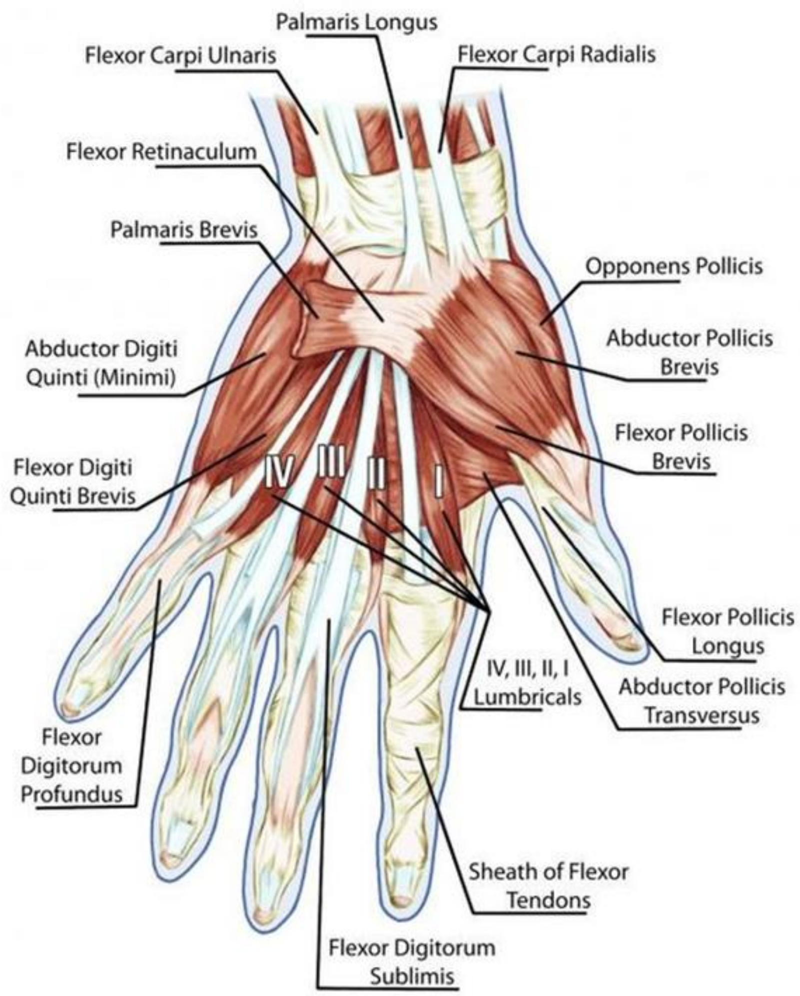


Figure 4 Hand digits (fingers and thumb) and their intrinsic muscles

3.2.3 Tendons and ligaments

During a digit moves, each tendon slides a certain distance. This excursion takes place simultaneously in the flexor and extensor tendons [104]. The relationships between the excursions of the finger tendons and the angular displacements of the MCP, PIP, and DIP joints have both linear and nonlinear [105]. The excursions are larger in the more proximal joints. Moreover, the excursion of the flexor tendons is larger than extensor tendons, and the excursion of the extrinsic muscle tendons is larger than the intrinsic tendons.

There are a number of important extracapsular and capsular ligaments, which support and stabilize the hand. The most important extracapsular ligament is the transverse inter metacarpal ligament (TIML). It attaches and runs between the volar plates at the level of the metacarpal heads across the entire width of the hand. The capsular collateral ligaments provide important joint stability to the entire finger and thumb joints. Figure 5 demonstrates the anatomy of a human finger.

The MCP joint ligaments have dual attachments, which is bony, and glenoid. The glenoid portion arises from the metacarpal head and attaches to the volar plate, while the collateral portion arises from the metacarpal head and attaches to the base of the phalanx. Besides, the PIP and DIP joint collateral ligaments attach completely to the bones. The collateral ligaments of the PIP and DIP joints are concentrically placed and in equal length. Therefore, these ligaments maximally stretched throughout their range of motion.

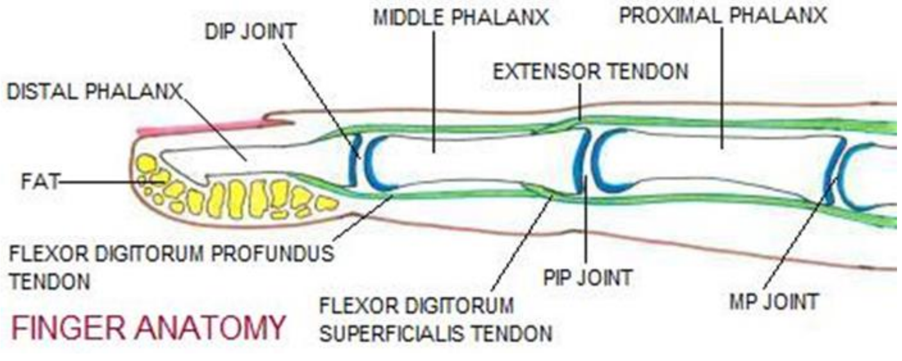


Figure 5 Anatomy of a human finger [99]

3.3 Requirements of the Hand Exoskeleton

Safety is the most important requirements of any device, which interacts with humans. Any malfunction can be seriously harmful to the user if the exoskeleton devices move under close contact with the user's fingers. Mechanical designs should consider the possibilities of unpredicted erroneous operation of the device controller when the device actively actuated. Limits to the range of motion can be set using a mechanical stopper or corresponding mechanism structural designs, which can avoid the exoskeleton from give force to the human fingers to move in an excessive range of motion.

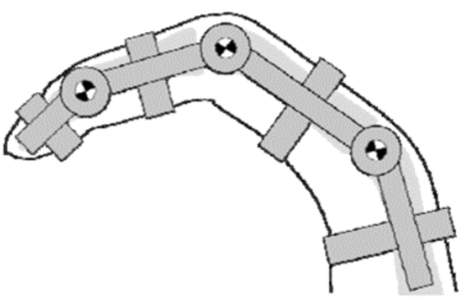
The coincidence of the centre of rotation is a primary issue in the mechanical design of hand exoskeleton. In the linkage mechanism for example, if the device with rigid linkages, the mechanism should design to have a centre of rotation that coincided with the rotational axis of the human finger joints. Otherwise, the dissimilarity in the rotational axis may cause a collision between the user's finger and the device and then may give injury to the user's hand.

The appropriate method in creating the exoskeleton's centre of rotation is to coincide the rotational axis of the user finger joints with the device joint. This method required an additional space to locate the mechanism at the side of the finger. Therefore, this approach is not suitable to implement in multi fingered structure. Otherwise, the adaptation of a remote centre of rotation will countermeasure the problem. However, if a flexible or under actuated mechanism adopted, the consideration of the coincidence of the rotational axis can be ignored.

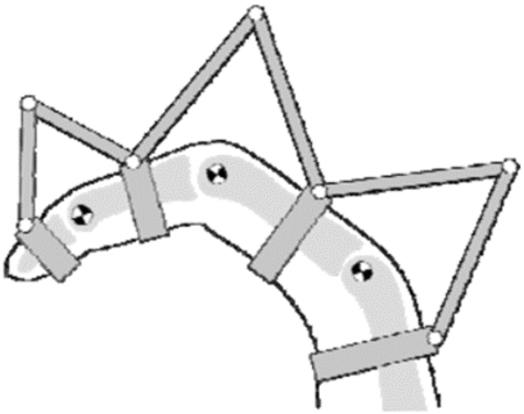
In example of a linkage mechanism with redundant DOFs, the number of DOFs of the linkage mechanism connects to the adjacent finger segments is two DOFs while the human finger IP joint is only one DOFs. The redundancy eliminated through the constraints given when attaching the device to the user's hand. A tendon-driven mechanism and soft pneumatic actuators directly attached to the joint of human fingers because the mechanism mimic the actuation of the normal human hand and provide a skeletal structure for the motion of the exoskeleton device. Furthermore, a serial linkage mechanism, which attached only to the distal segment of the finger also, does not need the alignment of joint axis. Figure 6 shows various mechanisms, which implemented for matching the centre of rotation or bypassing the issue.

Selection of a lightweight material in supporting components is a high priority consideration especially in the exoskeleton used for assistance applications. The power transmission method and actuation mechanism must also considered with the structure as main factors in the design.

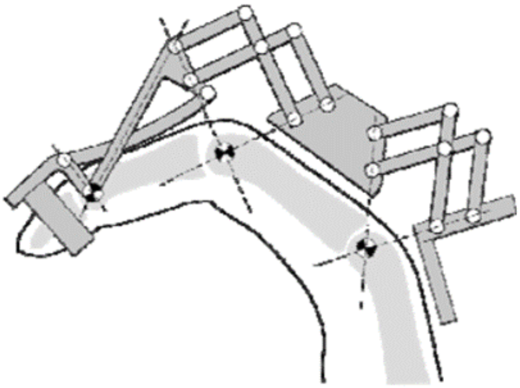
In addition, the method for sensing as according to the user has intended motion also a critical consideration. This will further discussed later in a dedicated section for intention sensing methods.



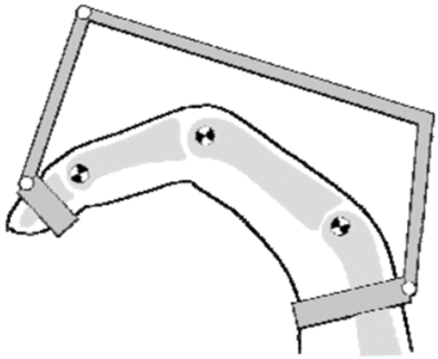
(a) Direct matching of joint centre



(b) Redundancy in DOFs of link mechanism

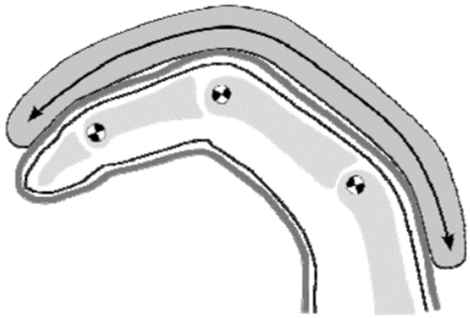


(c) Remote centre of rotation of link mechanism



(d) Serial link mechanism attached at distal segment

(e) Tendon based driven mechanism



(f) Bending actuator attached to the joint

Figure 6 Example of mechanism for matching the centre of rotation or eleminating the need for precise alignment [128]

We oriented the development of our robotic device for the treatment of early acute stroke subjects, who have at least partial motor function of the arm and shoulder because of spontaneous recovery. Design is thus oriented towards subjects capable of at least minimal movement with the hand. Because of extensor muscle weakness, the hand of stroke survivors often locked in a closed position and they are not able to control its motion well. Therefore, initial functions, which robotic devices for hand rehabilitation should train, is opening of the hand. Then, the reverse operation, which is the closing of the hand and applying suitable force to grasp objects also essential to train.

To address all of these fundamental tasks, we decided to develop robotic devices based on an exoskeleton approach where a mechanism that can be placed around a part of the human body to mechanically guide or actuate it without impeding the joint's natural motion. The advantage of using this robotic device is the simplification of design constraints, as each device dedicated to a specific activity. Later, therapy can be personalized to the subject by selecting a combination of exercises with each robot, in order to train all of the tasks, with an increased focus on those related to subject's impairment.

CHAPTER 4

FEASIBILITY ANALYSIS

4.1 Introduction

Our hands play an essential role in performing daily life activities and interacting with the surrounding world. Understanding the mechanism of our hands motion provides insight into how daily life activities performed and important elements in rehabilitation after hand injuries or stroke. Measuring the phalangeal range of motion (ROM) is an essential part in clinical practices. Medical professionals often use universal goniometers, inclinometers or electro-goniometers to measure the inclination angles of finger joints to assess the joint movement range [106]. These joints involve four main bones for each finger, which are metacarpal, proximal phalanx, middle phalanx and distal phalanx. The joint between the metacarpal and proximal phalanx named as the metacarpophalangeal joint (MCP). The joint between the proximal phalanx and the middle phalanx called as the proximal interphalangeal joint (PIP), while the joint between the middle phalanx and distal phalanx is the distal interphalangeal joint (DIP). This mechanism is not same for the thumb, where it not possesses a middle phalanx but it has MCP and interphalangeal joint (IP). The position of each joint and the angles of interest of the finger joints illustrated in Figure 7.

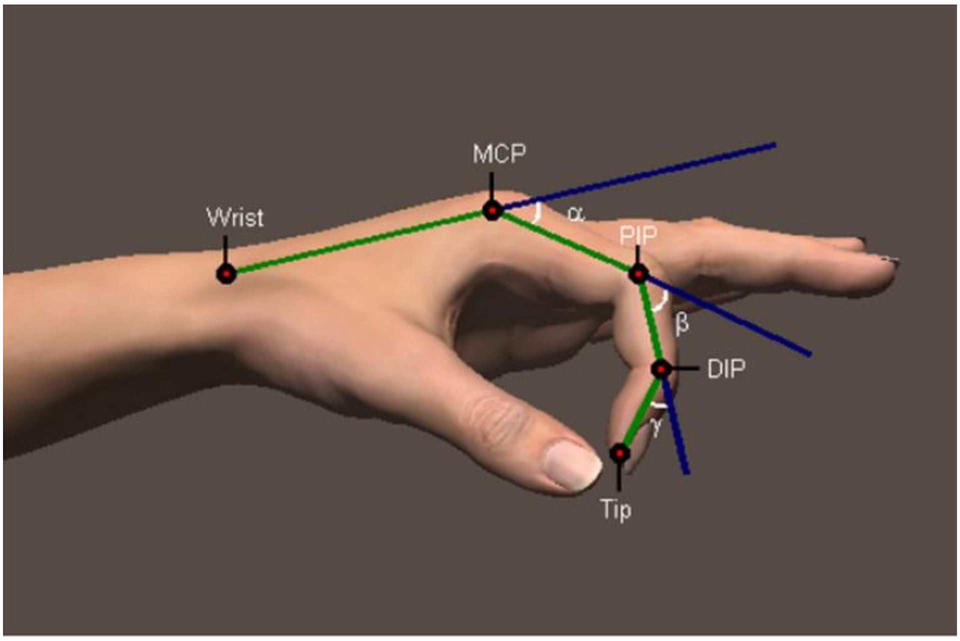


Figure 7 Position of the phalangeal joints

In previous research, subjective visual examination used to examine the range of motion (ROM), and subsequently, the declination joint angles measured with universal goniometers to evaluate ROM [107]. Nowadays with the development of technology, new goniometer models gradually introduced and improved to assist clinicians [108]. In measuring angular motions of the forearm and shoulder, Laupattarakasem et al. [109] introduced an axial rotation gravity goniometer to improve reliability. In another research works, one of the first two element optic fibre goniometers built using graded index micro lens receivers [110]. The fibre goniometer later improved in a study by Donno et al [111]. Once personal computers became popular and capable of effortlessly communicating with a variety of hardware, Barreiro et al. built a computer-based goniometer, which can directly record declination angle on a personal computer [112]. Researchers also wanted to reduce the production cost of goniometers, such as in Coburn et al. study [113], where they used remote sensors to build a goniometer. In recent research, the development of Motion Capture (MoCap) systems provided a convenient and accurate approach to evaluate ROM, such as the use of a Vicon system in Windolf et al. [114] and a Kinect based system in Pfister et al. [115]. More interestingly, smart phones with internally integrated accelerometer sensors also considered [116].

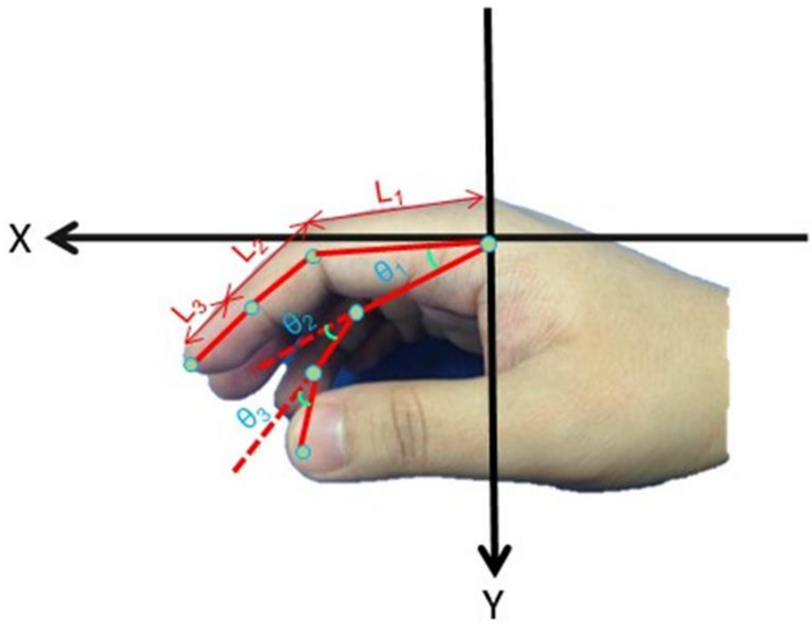
One of the challenges in the current practice is that the assessment tools, including universal goniometer, electro-goniometer, optical fibre goniometer, Vicon and accelerometer integrated smart phones, required physical contact with the finger to achieve the best accuracy. However, injuries, such as burns, wounds, lacerations or even dermatological conditions, can cause difficulties with the assessment tool, due to bandages, the risk of infection or discomfort. When clinicians align goniometers along phalangeal bones, they need to maintain a small gap with the skin or to place the tool on top of the bandage. Both techniques are inconvenient and tend to be subjective and error prone. Another significant challenge is intra and inter-rater reliability [117]. Studies into the reliability of universal goniometer report a variance of 7^o-9^o between therapists [117][118] when measuring joint angles, leading to 27^o difference over the three joints of finger. Researchers conducted on the reliability of universal goniometers and proposed devices[116][119], as reliability is an important aspect in clinical practice.

Adapting optical measurement systems or computer vision based approaches provides a non-contact type of measurement that countermeasure the current challenges. Recently, motion capture of hand movements attracted attention of many researchers all over the world, particularly with the development of a number of pervasive devices, such as the Microsoft Kinect Sensor and Leap Motion Controller, as they offer better solutions in measuring both body and finger movements [120]. Most recent implementation in this area, which used Microsoft Kinect to build a 3D skeletal hand tracking system [121][122]. Metcalf et al. recently proposed a Kinect based system to capture motion and to measure hand kinematics.

4.2 Kinematic analysis

The forward kinematics is the relationship between the lost coordinate frame and the base coordinate frame. In this section, the description of Denavit-Hartenberg (D-H) parameters method introduced to describe the link and its connections to the next or previous link. Four parameters required to describe these two coordinate frames. In fact, D-H parameters consists of four parameter, which are l_i , α_i , d_i , θ_i

The kinematic model of finger built based on D-H parameters method. According to the characteristics of the fingers, the index finger selected as an example to represent dynamics model of flexion and extension motion. Index finger has three DOFs and the model composed of three links as indicates in Figure 8.



$$(X,Y) = (L_1 \cos\theta_1 + L_2 \cos(\theta_1+\theta_2) + L_3 \cos(\theta_1+\theta_2+\theta_3), \\ L_1 \sin\theta_1 + L_2 \sin(\theta_1+\theta_2) + L_3 \sin(\theta_1+\theta_2+\theta_3))$$

Figure 8 The three link mechanism model of the index finger

Table 6 Parameter of the three link model

Joint	θ_i	d_i	l_i	α_i
MCP	θ_1	0	0	90
PIP	θ_2	0	L_1	0
DIP	θ_3	0	L_2	0
Fingertips	θ_4	0	L_3	0

Here θ_i and α_i are the rotation angle of joints and torsion angle. Whereas d_i and l_i are the distances of the offset and links. In order to design finger exoskeleton based robot, the impact of adduction and abduction motion at MCP joint are not consider in calculation. Therefore, the transformation matrix between each links as in Equation (1).

$$^{i-1}T_i = \begin{bmatrix} \cos\theta_i & -\sin\theta_i\cos\alpha_i & \sin\theta_i\sin\alpha_i & l_i\cos\theta_i \\ \sin\theta_i & \cos\theta_i\cos\alpha_i & -\cos\theta_i\sin\alpha_i & l_i\sin\theta_i \\ 0 & \sin\alpha_i & \cos\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

Therefore, the transform matrix from T1 to T4 obtained with substitute the parameters in Table 5 into Equation (1).

$$T_1 = \begin{bmatrix} \cos\theta_1 & 0 & \sin\theta_1 & 0 \\ \sin\theta_1 & 0 & -\cos\theta_1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2)$$

$$T_2 = \begin{bmatrix} \cos\theta_2 & -\sin\theta_2 & 0 & L_1\cos\theta_2 \\ \sin\theta_2 & \cos\theta_2 & 0 & L_1\sin\theta_2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3)$$

$$T_3 = \begin{bmatrix} \cos\theta_3 & -\sin\theta_3 & 0 & L_2\cos\theta_3 \\ \sin\theta_3 & \cos\theta_3 & 0 & L_2\sin\theta_3 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4)$$

$$T_4 = \begin{bmatrix} \cos\theta_4 & -\sin\theta_4 & 0 & L_3\cos\theta_4 \\ \sin\theta_4 & \cos\theta_4 & 0 & L_3\sin\theta_4 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (5)$$

Therefore, the transform matrix form of the fingertips of the index finger to the base coordinate system obtained as in Equation (6).

$$^{0}T_4 = T_1T_2T_3T_4 = \begin{bmatrix} C_1C_{234} & -C_1S_{234} & S_1 & C_1(L_1C_2 + L_2C_{23} + L_3C_{234}) \\ S_1C_{234} & -S_1S_{234} & -C_1 & S_1(L_1C_2 + L_2C_{23} + L_3C_{234}) \\ S_{234} & C_{234} & 1 & L_1S_2 + L_2S_{23} + L_3S_{234} \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (6)$$

Here S_{234} represent $\sin(\theta_2 + \theta_3 + \theta_4)$, C_{234} represent $\cos(\theta_2 + \theta_3 + \theta_4)$, S_{23} represent $\sin(\theta_2 + \theta_3)$, C_{23} represent $\cos(\theta_2 + \theta_3)$, S_1 represent $\sin\theta_1$, S_2 represent $\sin\theta_2$, C_1 represent $\cos\theta_1$, C_2 represent $\cos\theta_2$ respectively.

According to the transform matrix principle as indicate in Equation (7)

$$^{0}T_4 = \begin{bmatrix} T_R & T_p \\ 0 & 1 \end{bmatrix} \quad (7)$$

Therefore, the position of any point of the fingertip of index finger obtained as in Equation (8).

$$T_p = \begin{bmatrix} C_1(L_1C_2 + L_2C_{23} + L_3C_{234} \\ S_1(L_1C_2 + L_2C_{23} + L_3C_{234}) \\ L_1S_2 + L_2S_{23} + L_3S_{234} \\ 1 \end{bmatrix} \quad (8)$$

$$\begin{cases} P_X = C_1(L_1C_2 + L_2C_{23} + L_3C_{234} \\ P_Y = S_1(L_1C_2 + L_2C_{23} + L_3C_{234}) \\ P_Z = L_1S_2 + L_2S_{23} + L_3S_{234} \end{cases} \quad (9)$$

Through taking the partial derivatives of the rotation angles of the joint, the Jacobian matrix of the index finger as in Equation (10).

$$J(\theta_1, \theta_2, \theta_3, \theta_4) = \begin{bmatrix} \frac{\partial P_X}{\partial \theta_1} & \frac{\partial P_X}{\partial \theta_2} & \frac{\partial P_X}{\partial \theta_3} & \frac{\partial P_X}{\partial \theta_4} \\ \frac{\partial P_Y}{\partial \theta_1} & \frac{\partial P_Y}{\partial \theta_2} & \frac{\partial P_Y}{\partial \theta_3} & \frac{\partial P_Y}{\partial \theta_4} \\ \frac{\partial P_Z}{\partial \theta_1} & \frac{\partial P_Z}{\partial \theta_2} & \frac{\partial P_Z}{\partial \theta_3} & \frac{\partial P_Z}{\partial \theta_4} \end{bmatrix} = \begin{bmatrix} -S_1A & -C_1B & -C_1D & -C_1F \\ C_1A & -S_1B & -S_1D & -S_1F \\ 0 & A & E & G \end{bmatrix} \quad (10)$$

$$\begin{cases} A = L_1C_2 + L_2C_{23} + L_3C_{234} \\ B = L_1S_2 + L_2S_{23} + L_3S_{234} \\ D = L_2S_{23} + L_3S_{234} \\ E = L_2C_{23} + L_3C_{234} \\ F = L_3S_{234} \\ G = L_3C_{234} \end{cases} \quad (11)$$

Equation (12) reflects the motion position of the index finger. Then, Equation (12) divided by ∂t can derive the Equation (13) which is velocity during movement of the index finger.

$$\begin{bmatrix} dX \\ dY \\ dZ \end{bmatrix} = \begin{bmatrix} -S_1A & -C_1B & -C_1D & -C_1F \\ C_1A & -S_1B & -S_1D & -S_1F \\ 0 & A & E & G \end{bmatrix} \begin{bmatrix} d\theta_1 \\ d\theta_2 \\ d\theta_3 \end{bmatrix} \quad (12)$$

$$V = \begin{bmatrix} \frac{dX}{dt} \\ \frac{dY}{dt} \\ \frac{dZ}{dt} \end{bmatrix} = \begin{bmatrix} V_X \\ V_Y \\ V_Z \end{bmatrix} = \begin{bmatrix} -S_1A & -C_1B & -C_1D & -C_1F \\ C_1A & -S_1B & -S_1D & -S_1F \\ 0 & A & E & G \end{bmatrix} \begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \\ \dot{\theta}_3 \end{bmatrix} \tag{13}$$

Simplified Equation (13) and derived Equation (14).

$$V = J\dot{\theta} \tag{14}$$

$$\dot{\theta} = J^{-1}V \tag{15}$$

Based on the inverse of Jacobi Matrix, as long as it give the rectangular coordinates speed of fingertips of the index finger, the speed of the corresponding joint derived in Equation (15). In a similar way, the acceleration of the index finger derived as in Equation (16).

$$A = J\ddot{\theta} \tag{16}$$

4.3 Anthropometric Studies

Since there are different hand sizes according to the age, height and physique of people, a precise ergonomic design is required. As an example, the anthropometric parameters of the index finger depicted in Figure 9.

An anthropometric study of the index finger conducted from a population sample of 30 people to determine ideal exoskeletal size. This sample comprised 30 males and 30 females aged between 20-50 years old, all of whom were Asian. Figure 10 shows the anthropometric analysis results for each part of the index finger.

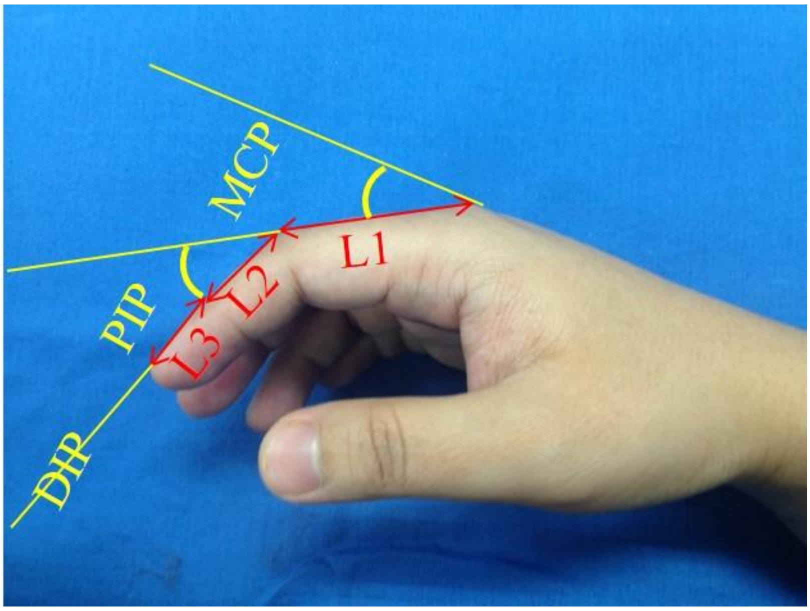


Figure 9 Index finger antropometric parameter

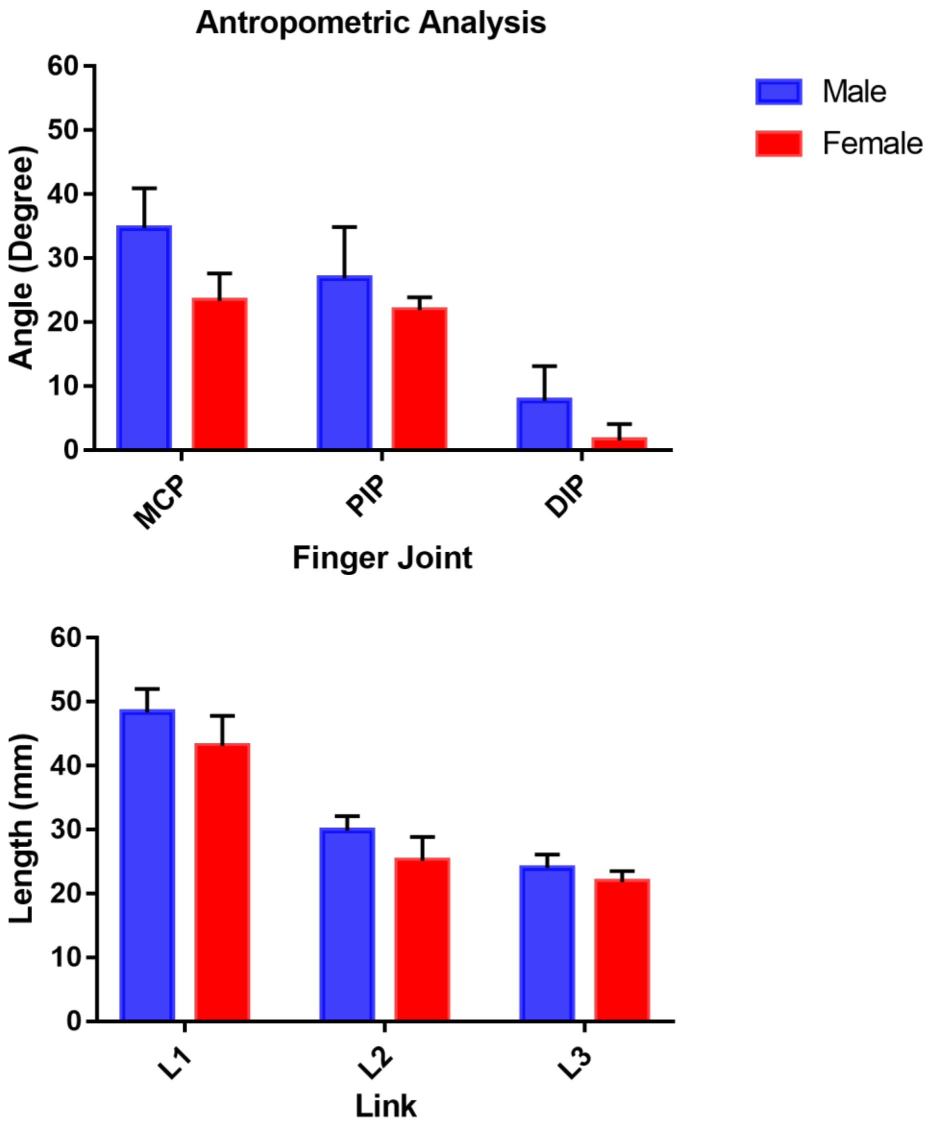


Figure 10 Anthropometric analysis results for each part of the index finger

4.4 Range of Motion (ROM) Analysis of Index Finger

Five colour markers based image processing attached to a right hand of index finger, according to the position of MCP joint, PIP joint and DIP joint of the healthy subject to measure the relationship between MCP joint angle and PIP joint angle in the extension or flexion motion. Then, the position of colour markers estimated and recorded using a monotype optical motion capture and measurement system. In the experiment, the healthy subjects need to perform the flexion and extension motion and at the same time need to grasp an object, which is a cylinder with a diameter of 50 [mm]. DIP, PIP and estimated MCP joint angle of the index finger. Figure 11 and 12 indicates the position and trajectory of the colour marker setup of the each joint accordingly.

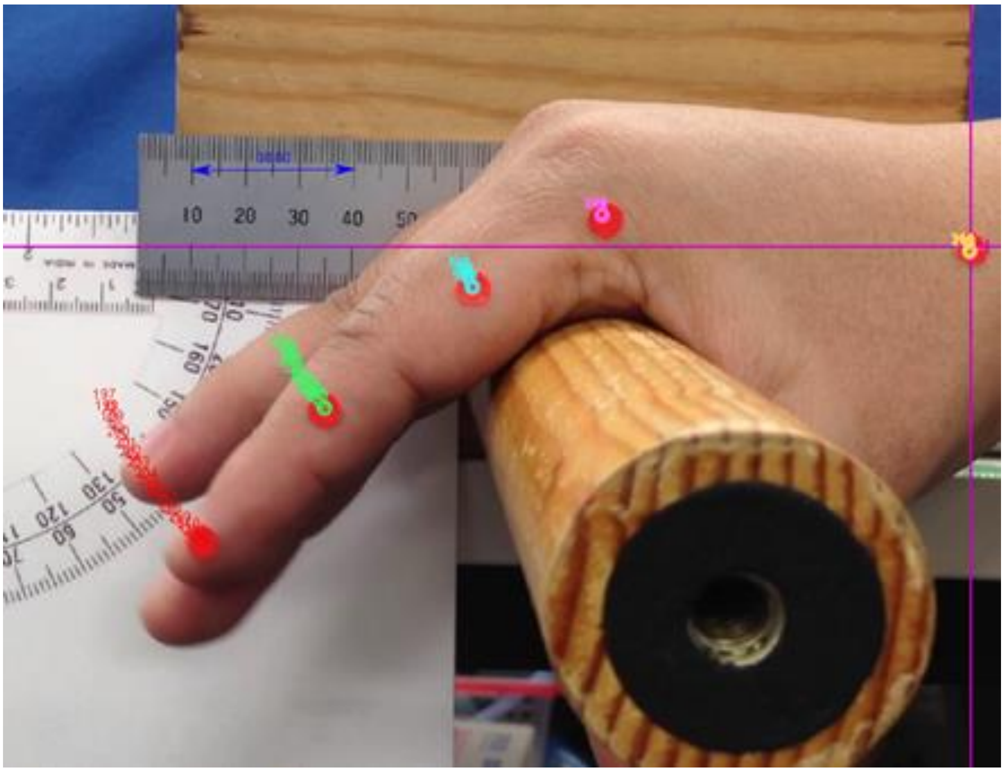


Figure 11 Color marker based image processing using calibrated monotype camera to determine range of motion joint of normal index fingers

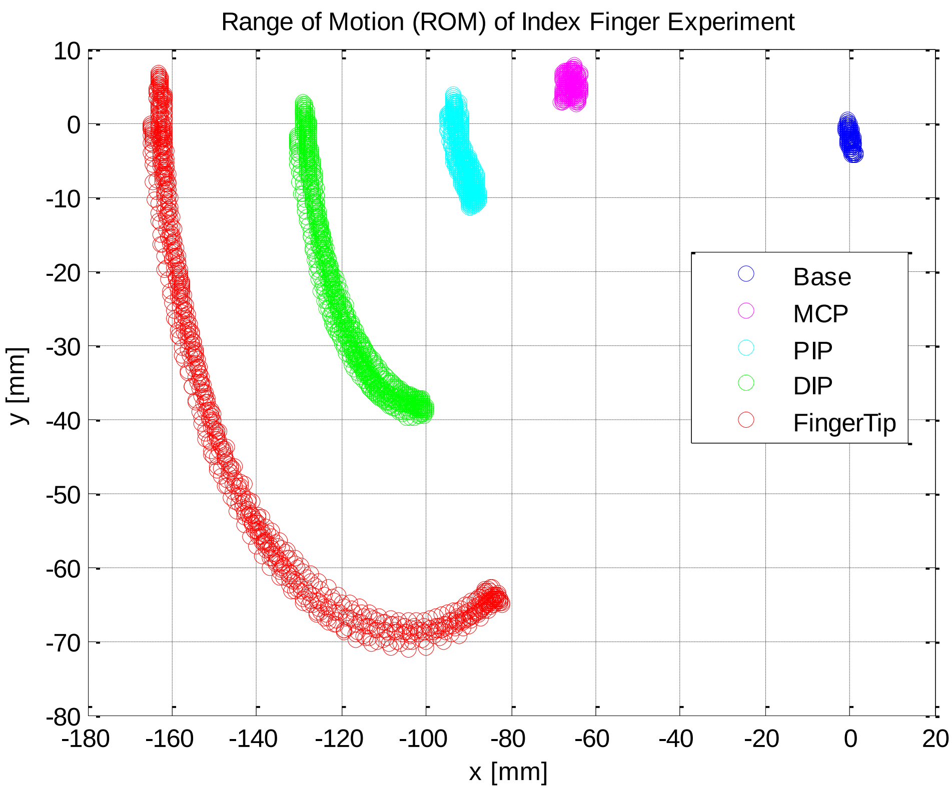


Figure 12 Range of Motion (ROM) of index finger during flexion and extension motion

4.5 Preliminary Experiment with Rehabilitation Physician

In this experiment, we focus on the measurement of force and angular displacement of extension motion of finger joints (DIP, PIP and MCP) during rehabilitation session to prevent the finger from contracture. The subject is a healthy person that does not have contracture of finger. Our objective of the development of this device is to implement on early acute stroke patients, we consider that their finger range of motion is similar to healthy person. The data from this experiment will become preliminary data of our study. Therefore, we proposed our evaluation procedure of our device according to the experimental protocol below.

4.6 Evaluation Experiment Set-up

For this study, we recruited a healthy volunteer 23 years of age with no signs of finger contracture, disease, injury, burn mark, surgery mark of finger abnormality at the area of testing. We measured two parameters, which were force and angular displacement of extension motion of finger joint on right index finger.

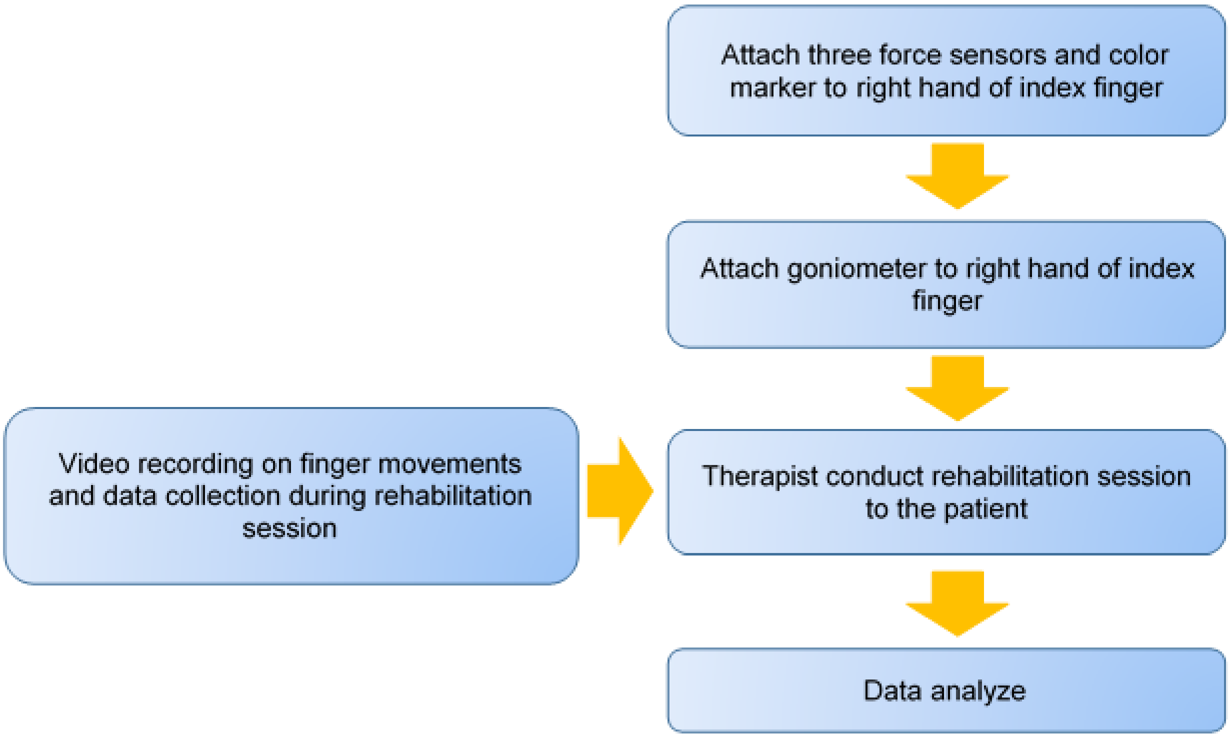
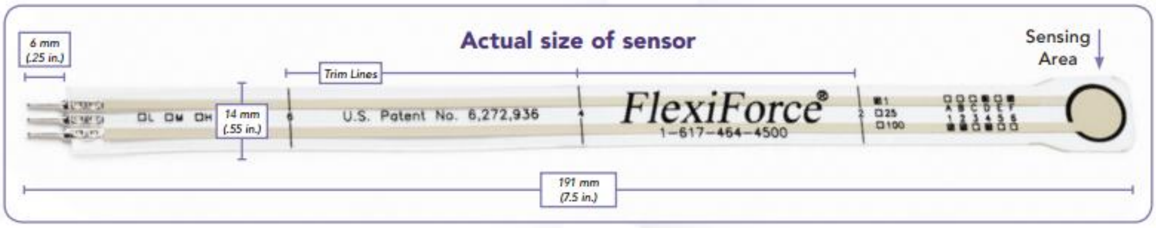


Figure 13 Flowchart of Experimental Protocol

4.6.1 Pre-Assessment Procedure: Device set up

Force measurement using flexible force sensor

Based on Figure 13, the first stage shows that the right hand of index finger of subject placed with force sensors to measure the force of finger joint during the rehabilitation session. This sensor is ultra-thin and flexible printed circuits, which can be integrated easily into force measurement applications. The sensors detect the voltage changes while the therapist applied force to the finger's subject and from the changes, we can calculate the force applied to the finger's subject during rehabilitation session. The force sensor use is a Tekscan product. The subject verified that they can move freely with the force sensor attached to the three segment of the right hand of index finger (refer to Figure 14).



	Typical Performance	Evaluation Conditions
Linearity (Error)	< ±3%	Line drawn from 0 to 50% load
Repeatability	< ±2.5% of full scale	Conditioned sensor, 80% of full force applied
Hysteresis	< 4.5 % of full scale	Conditioned sensor, 80% of full force applied
Drift	< 5% per logarithmic time scale	Constant load of 111 N (25 lb)
Response Time	< 5μsec	Impact load, output recorded on oscilloscope
Operating Temperature	-40°C - 60°C (-40°F - 140°F)	Time required for the sensor to respond to an input force

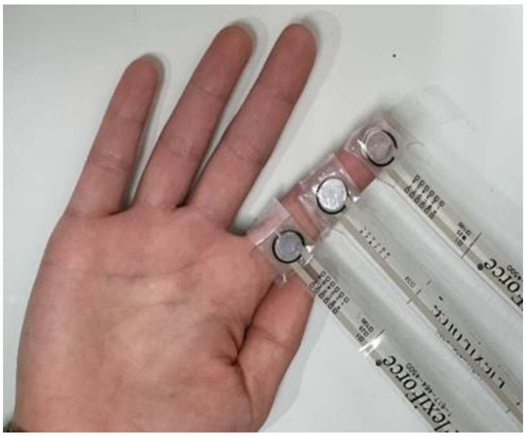


Figure 14 Placement of force sensor to right hand of index finger

Coordinate position and angular displacement measurement using colour marker

Based on Figure 13, the first stage shows that the right hand of index finger of subject also placed with colour marker diameter 8mm to measure the coordinate position and angular displacement of finger joint during the rehabilitation session. The subject verified that they can move freely with the colour marker attached to the five point of finger joints of the right hand of index finger (refer to Figure 15)

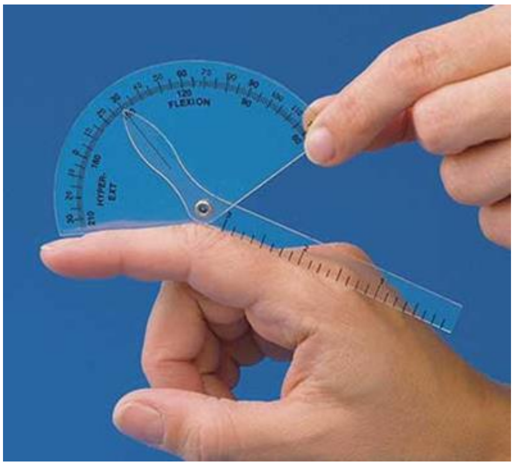


Figure 15 Placement of colour marker to right hand of index finger(Left). Example of finger joint angle measurement using goniometer (Right).

Finger angle measurement using goniometer

The flexion and extension angle of index finger joint measured by using a goniometer specialized for finger measurement during the rehabilitation session. (Refer to Figure 15)

Data collection with data logger

We connected the force sensors with data logger. Data logger records voltage data from force sensor. (Refer to Figure 16)

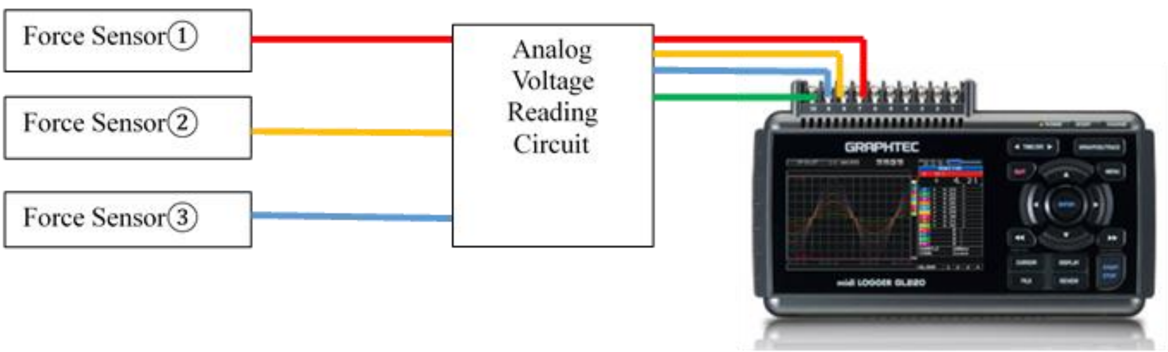


Figure 16 Data logger used in data collection

Rehabilitation session

The therapist conducted normal rehabilitation session to the subject depends on the subject's experience with the condition the subject is not attending any rehabilitation session before the day of experiment conducted. Each subject only experienced one rehabilitation session.

Video Recording and Data Collection

The rehabilitation session of the subject recorded in terms of as stated below.

a) Right hand of index finger joint angle of the subject during rehabilitation session

b) Forces given by the therapist to the subject

c) Position of the therapist and the subject during rehabilitation session

Post processing of the video analysis conducted in Motion Capture Analysis Software (Kinovia). Refer to Figure 17.

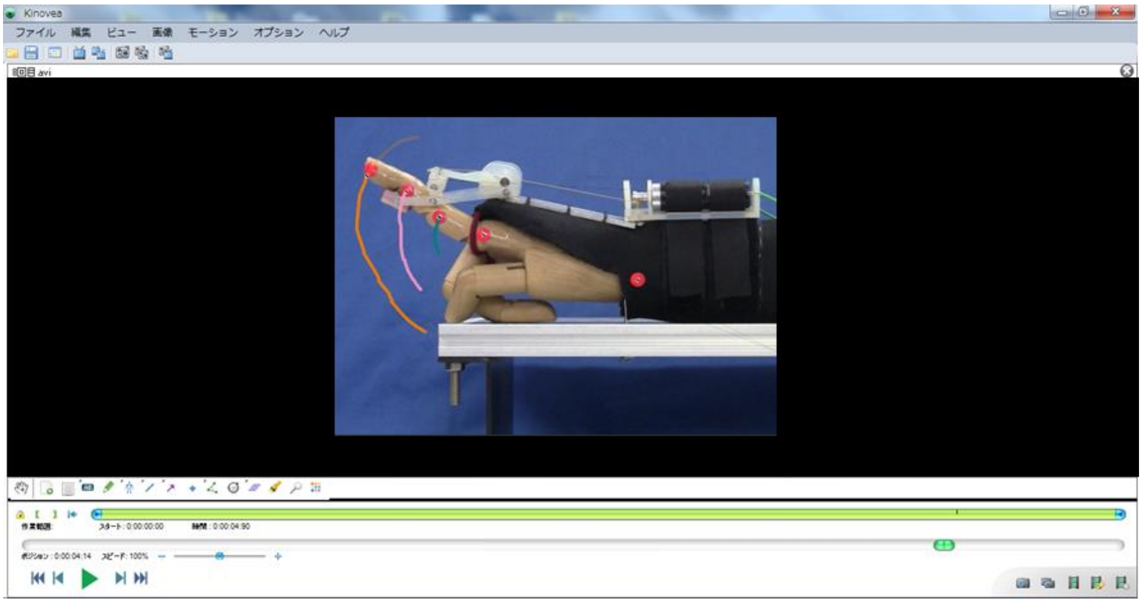


Figure 17 Motion Capture Analysis Software (Kinovia)

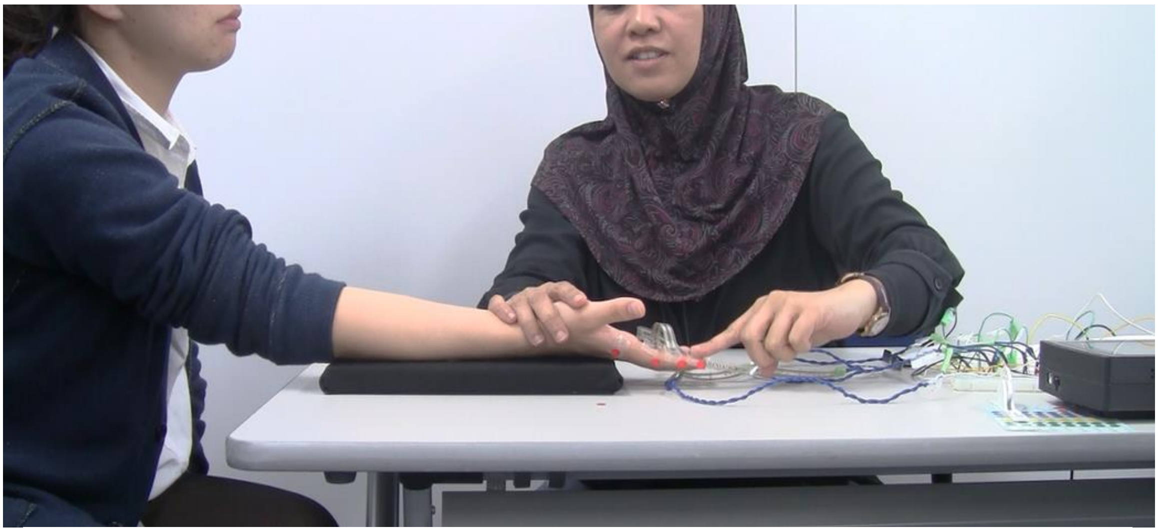


Figure 18 Position setting of therapist and subject during normal rehabilitation session

4.6.2 Pre-Assessment Procedure: Position of Therapist and Subject

We set the position of the therapist and subject according to the normal rehabilitation setting, where the video camera in the position able to record and recognize the colour markers of subject's finger. Figure 18 shows the overview of their position.

4.6.3 Post-Assessment Procedure: Data Analysis

We analysed the collected data from force sensor and video recording. We get data from goniometer in measuring angle of joints during the extension motion. We calculated the exerted force and extension angle of index finger. From these analyses, we get the preliminary data for finger rehabilitation of contracture. This data will help us to develop our safe precaution and optimized device.

4.6.4 Assessment Procedure: Parameters Measurement

The assessment procedure is non-invasive in nature and has nothing to do with blood. It is similar with the procedure of therapists during conducts a normal rehabilitation session to the patient has finger contracture in acute phase.

Parameters involved in the measurement as stated below:

1. Force given by the therapist to the subject
2. Angle of finger joint during extension motion

The assessment procedure consists of two speeds:

The therapist exerts slow and fast motion assessment to the subject's index finger as the subject could manage until the fully extension position. From two assessments, we can determine the suitable speed of rehabilitation and evaluate the differences between them.

4.7 Relationship of the finger torque, force and displacement during motion

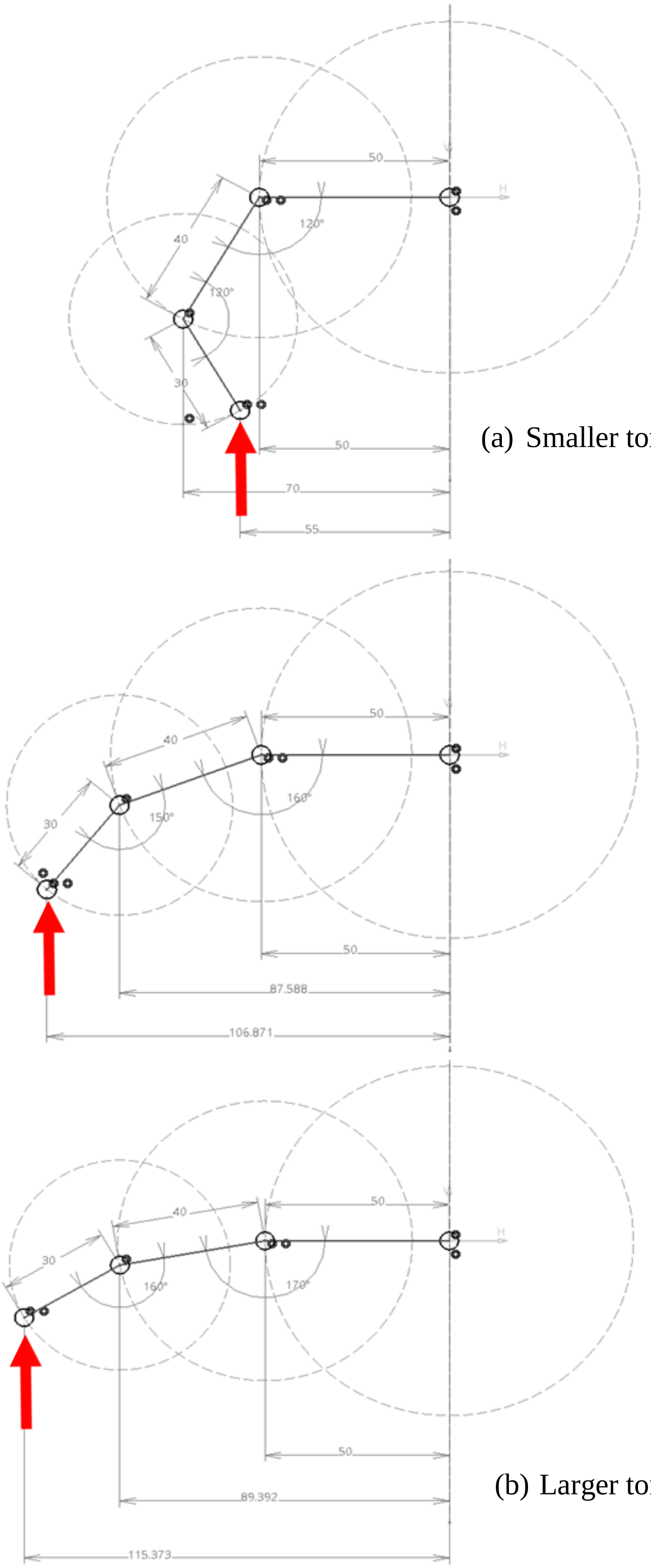
A quantity related to force, called torque, plays the role in rotation that force itself plays in translation. A torque is not separate from a force; it is impossible to exert a torque without exerting a force. Torque is a measure of how effective a given force is at twisting or turning something. For finger flexion and extension movement about a fixed axis a torque can change the rotational motion either by making it rotate faster or by slowing it down. Figure 19 demonstrates simulation of the relation of torque, force and displacement of index finger during normal rehabilitation session. It clearly indicated that the same force (red colour arrow) at different distances from the axis created the different torque.

Therefore, where physiotherapist apply the force is critical. Instinctively, they push at the outer edge, as far from the rotation axis as possible. If they pushed close to the axis, it would be difficult to open the finger.

Torque is proportional to the distance between the rotation axis and the point of application of the force (the point at which the force is applied).To satisfy the requirements of the aforementioned, we define the magnitude of the torque as the product of the distance between the rotation axis and the point of application of the force (r) with the perpendicular component of the force ($F\perp$) as in Equation (17).

$$\vec{\tau} = \vec{r} \times \vec{F}\perp \tag{17}$$

Here r is the shortest distance between the rotation axis and the point of application of the force and $F\perp$ is the perpendicular component of the force.



(a) Smaller torque

(b) Larger torque

Figure 19 Simulation of the relation of torque, force and displacement of index finger during normal rehabilitation session

CHAPTER 5

PROTOTYPE DEVELOPMENT

5.1 Introduction

From the study of anthropomorphic data and feasibility analysis, we selected optimum linkage lengths for each link of the exoskeleton mechanism module. This property not only makes the exoskeleton module simpler and lighter due to a single DC servo motor coupled lead screw mechanism drives the two links, but it also allows the finger mechanism to be self-adapting to different finger sizes. The block diagram of the electronic system design for our system as illustrated in Figure 20.

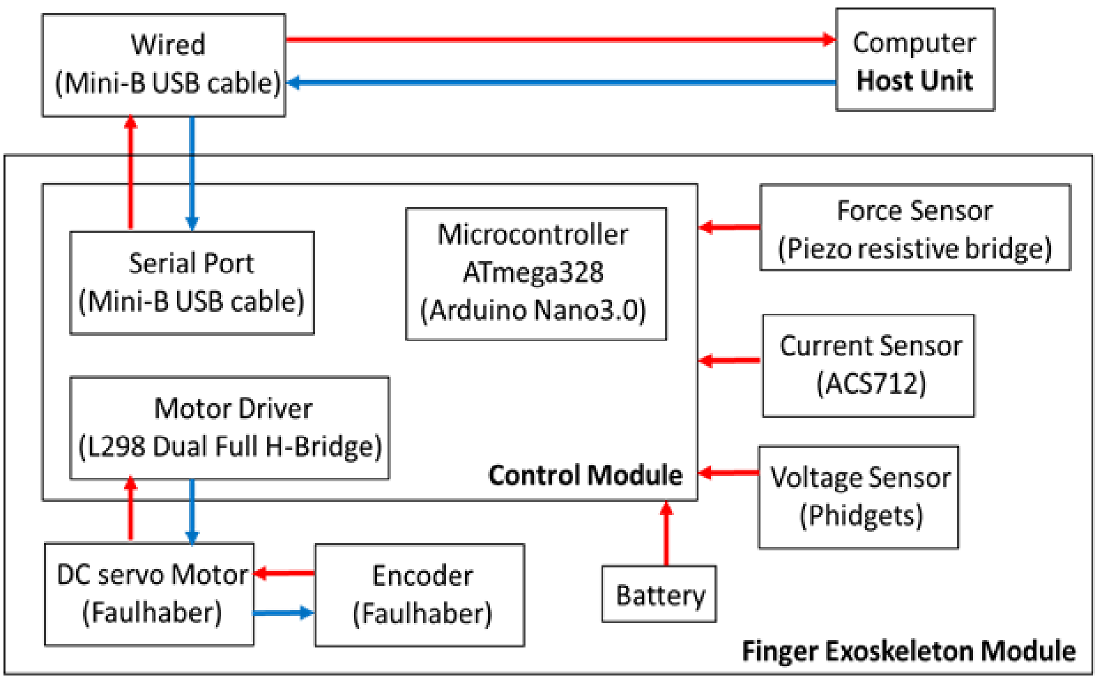


Figure 20 Electronic design diagram of the finger exoskeleton module

5.2 Hardware System

5.2.1 Microcontroller

The prototype was using Arduino Nano as shown in Figure 21, an open-source electronic platform allowing to creating interactive electronic programming as the controller system. The Arduino Nano powered via the Mini-B USB connection, 6-20V unregulated external power supply, or 5V regulated external power supply. The power source automatically selected the highest voltage source. Arduino Nano has 8 analogue inputs, each of which provide 10 bits of resolution (2^{10} = 1024 different values).

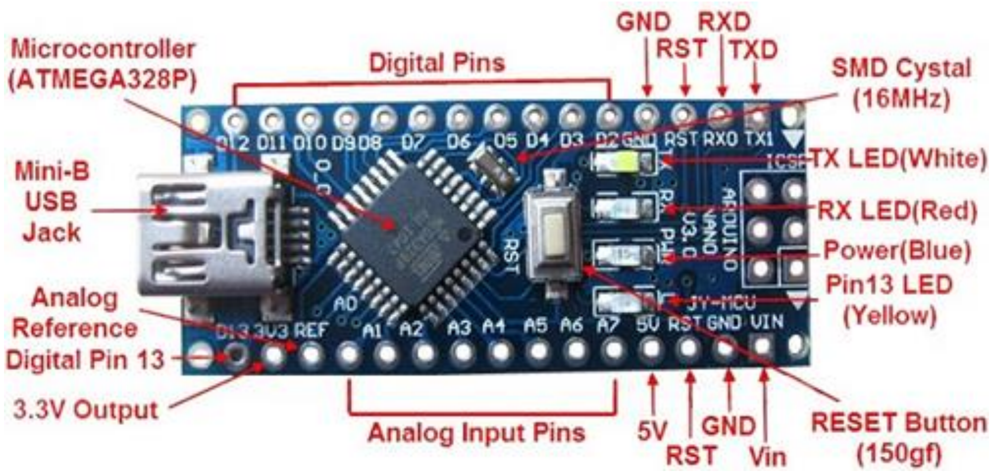


Figure 21 Overview of Arduino Nano 3.0

Table 7 Spesification of Arduino Nano 3.0

Term	Description
Microcontroller	ATmega328
Operating Voltage (logic level)	5 V
Input Voltage (recommended)	7-12 V
Input Voltage (limits)	6-20 V

Digital I/O Pins	14 (of which 6 provide PWM output)
Analog Input Pins	8
DC Current per I/O Pin	40 mA
Flash Memory	32 KB (ATmega328) of which 2 KB used by bootloader
SRAM	2 KB (ATmega328)
EEPROM	1 KB (ATmega328)
Clock Speed	16 MHz
Length	45 mm
Width	18 mm
Weight	5 g

5.2.2 Motor Driver

The system is using DC Motor Driver 2x2A module based on the L298 Dual H-Bridge driver as in Figure 22 to connect the Arduino Nano to the DC Servo Motor. It has two PWM output pins with input voltage of 7 - 12 Volt.

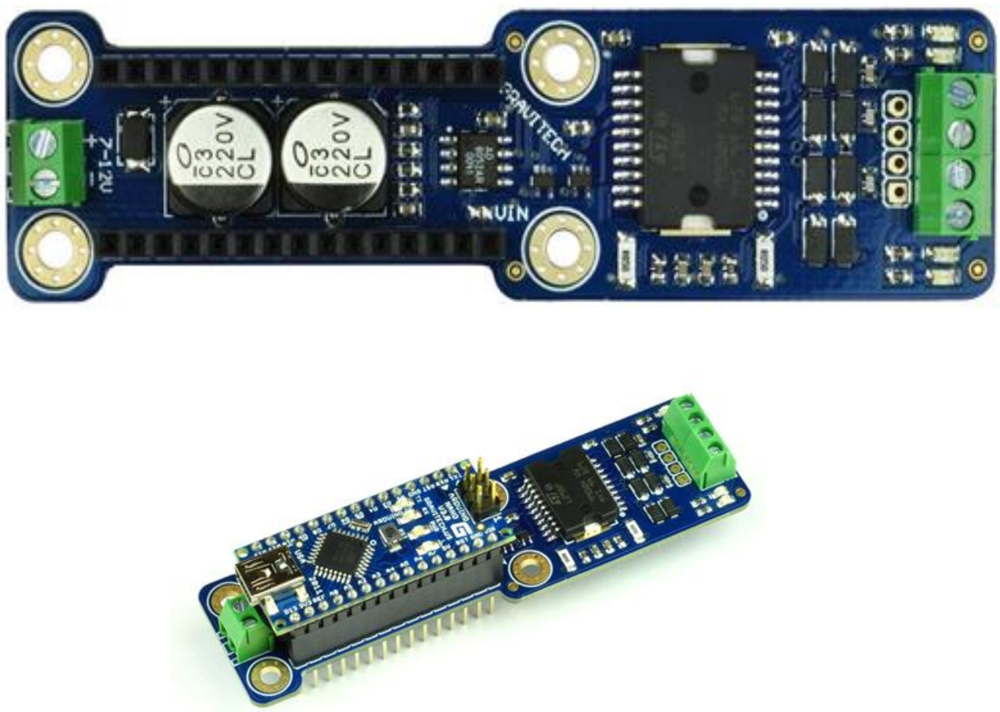


Figure 22 Motor Driver L298 with current sensing

5.2.3 DC Servo Motor

A DC servo motor acts as an actuator to drive the lead nut in lead screw mechanism in order to repetitively flexion and extension a human finger. When the actuator actuates the mechanism, lead screw will convert rotary input motion to linear output motion. The nut is constrained from rotating with the screw, thus as the screw is rotated the nut travels back and forth along the length of the shaft. Depending on the level of severity, the DC servomotor provides a reaction force against the force given by the subject’s finger.

To further realize the real training session, variations in stiffness and angular velocity is added by applying the torque control via DC servo motor to provide continuous passive motion (CPM) helping subjects reduce joint stiffness of the fingers together and individually. Figure 23 shows the DC servomotor integrated with quadrature encoder.

Figure 23 DC servomotor integrated with quadrature encoder

5.2.4 Rotary Encoder

Rotary encoder is a sensor attached to a rotating object such as a shaft or motor to measure rotation. By measuring rotation of motor shaft, we can determine any displacement, velocity, acceleration, or the angle of a rotating sensor.

There are two channels of output in quadrature referred to channels A and B. They are each a square wave, however offset from each other by 90 degrees. Whether channel A is leading or lagging channel B depends on the direction the shaft is turning, which is allows us to determine direction. For example, both channels are low and then channel A goes high, we know that we are spinning counter clockwise (CCW). If channel B had instead gone high before channel A, we would then know we are spinning clockwise (CW). Therefore, this deduced starting from any state as seen in the diagram. The output channels produced by a variety of means, usually either magnets in a disk attached to the shaft and a pair of Hall Effect sensors, or a disk with slots cut out and a pair of optical sensors looking through the slots. Figure 24 shows the principle of quadrature encoder in our application.

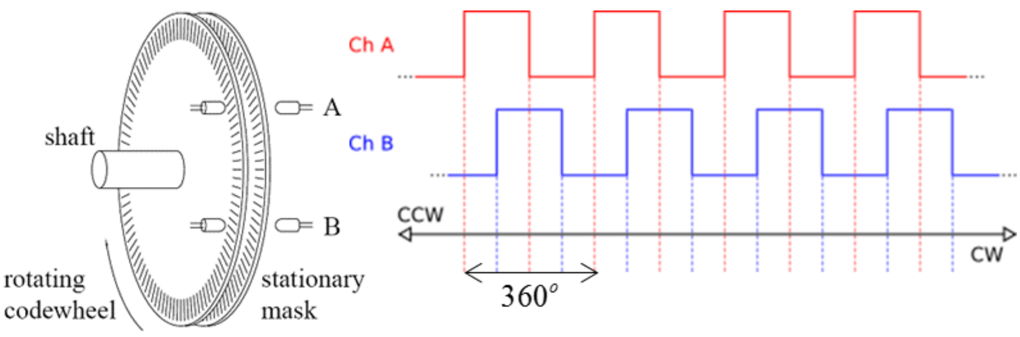


Figure 24 Rotary encoder principle

5.2.5 Voltage Sensor

The Voltage Sensor measures the differential voltage between the input terminals and outputs the difference proportionally. The maximum differential voltage that measured accurately is ±30V. Figure 25 shows the sensors for voltage and current measurement.

Figure 25 Voltage Sensor and Current Sensor

5.2.6 Current Sensor

Current sensing is a way for a robot to measure the internal state and rarely required to explore the outside world. It is useful for us to understand the power usage of the various components within a robot. Current sensing for DC motors, circuits, or servos to measure the requirements of actuator power. It will indicate the measurement of power performance in different situations. It is useful for battery monitors. Once robotic finger attached to patient finger, it will show the load detection during flexion and extension. For example, if the current use suddenly increases, that means a physical object is causing resistance.

5.2.7 Force Sensor

The force sensor using effect of piezo resistive bridge circuit formed on silicon diaphragm. Piezo resistance value changed according to the applied force to the diaphragm part. Force sensor structure and the operating principle demonstrated in Figure 26.

The force sensor has dimensions of small unit size (4.0 x 2.6 x 2.06) mm with supply voltage 1.5~3.7V for measurement range 0~10N. This sensor is a good linearity sensor, which less than 3% full-scale (FS) with high sensitivity 3.7mV/V/N. The sensor can withstand the impact force of up to 200N. However, in this experiment forces never exceeded 10N.

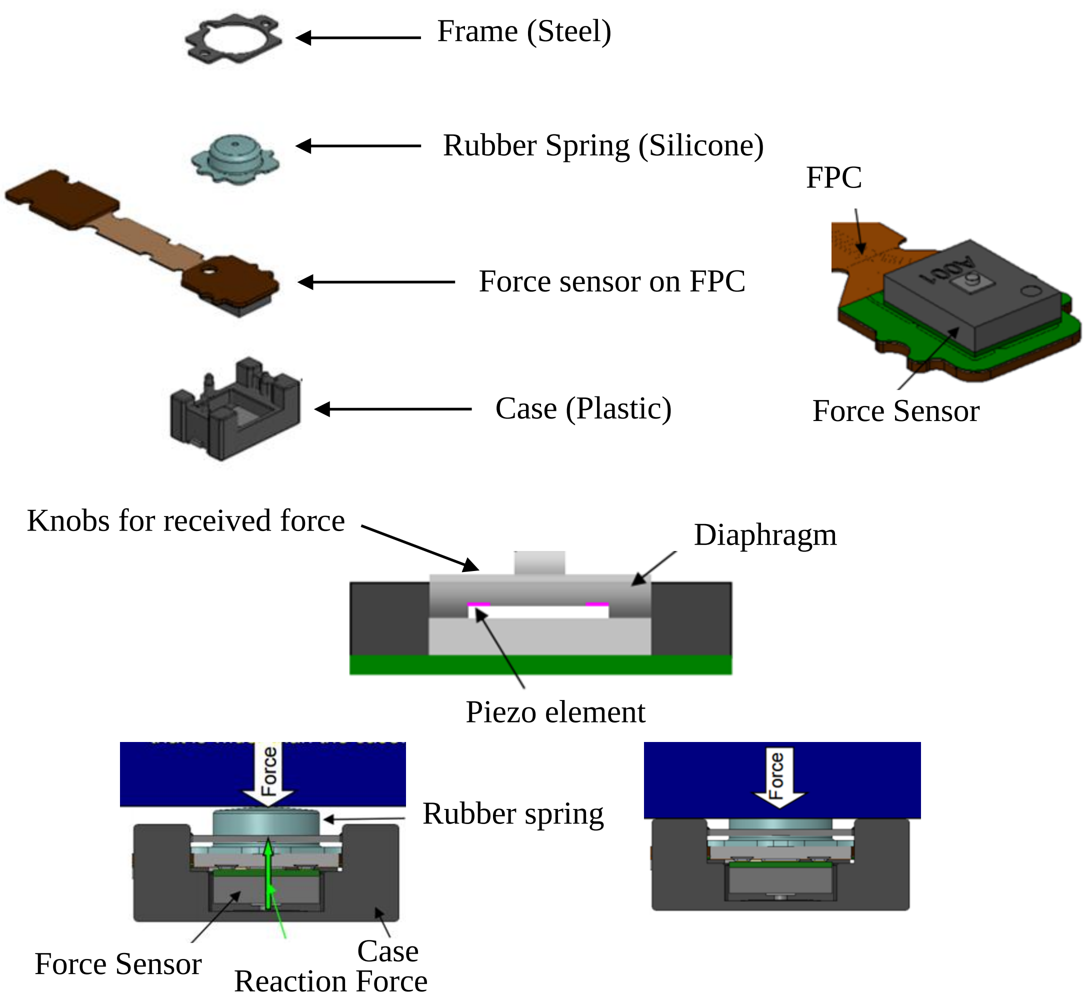


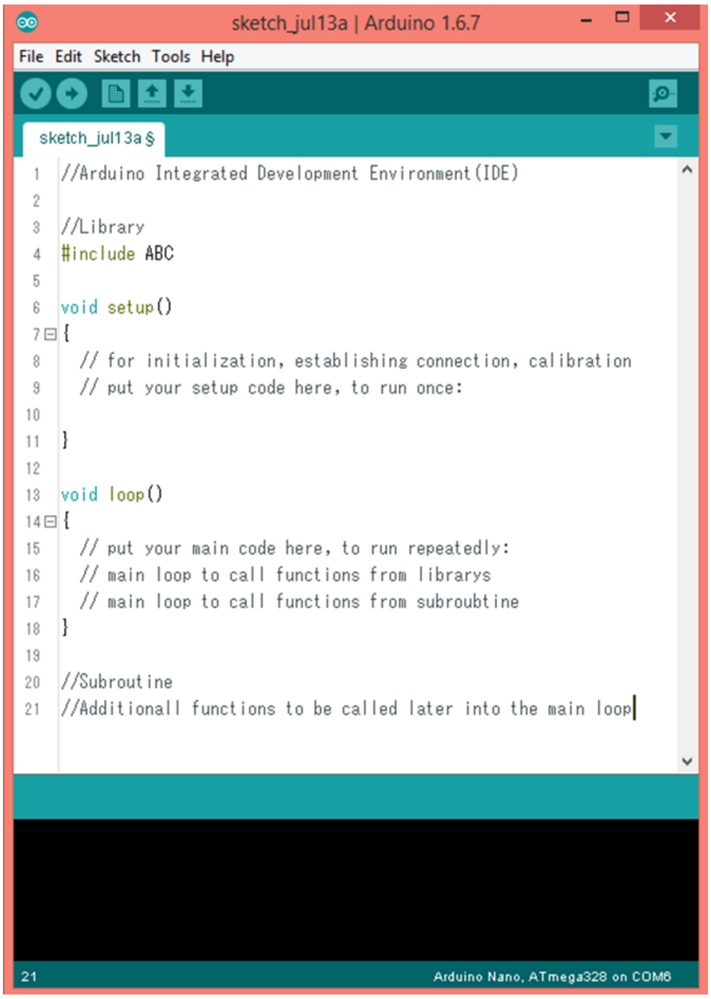
Figure 26 Force Sensor Structure and the operating principle

5.3 Software System

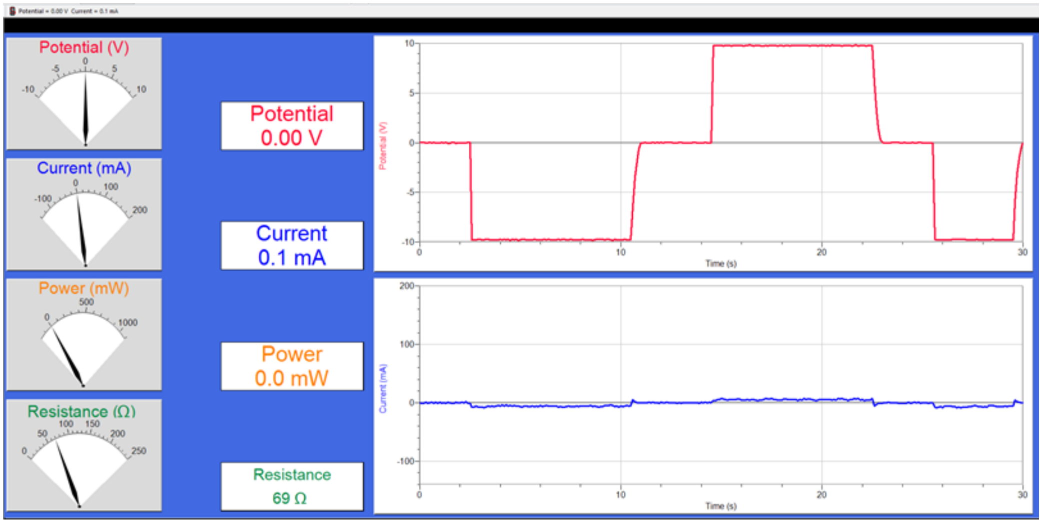
Arduino IDE ver. 1.6.7 used in computing the program system. It divided into three parts; structure, values of variables and constants and functions. Program written in Arduino IDE called as sketches. Arduino sketches consists of Library, void setup, void loop and subroutine as explained in Figure 27(a). Arduino language is a compilation of C/C++ language, which called from the code written in Arduino program.

Labview GUI software acquire data from any sensors from microcontrollers to the PC via serial port to plot graph in real-time. The GUI provides easy spreadsheet analysis of data collected and data analysis of sensors in real-time monitoring. Additional code needed in Arduino sketches to connect to the SensorDAQ tool. The GUI as shown in Figure 27(b).

The results obtain analysed using **MATLAB ver. R2015a,** a computing language tool to get enhanced data visualization. MATLAB is a programming language developed by MathWorks, which lets data manipulations, plotting of functions and interfacing programs written in other languages as well.



(a)Arduino IDE sketch structure



(b) Labview GUI for real time monitoring tool

Figure 27 Software involved in the development process

CHAPTER 6

MECHANICAL DESIGN

6.1 Introduction

In general, these rehabilitation machines are robotic exoskeleton systems worn on the patient's joints, helping them perform physiotherapy training and supervising the established routines needed to accomplish their rehabilitation. The primary causes of hand disabilities are neuro musculoskeletal diseases such as the tetraplegia, hemiplegia, tendonitis, broken bones and degenerative illnesses like arthritis, which affects the motion of fingers in the hand. In order to be treated, these illnesses require appropriate active and passive physiotherapy treatments to avoid permanent damage to the joints. Passive assisted rehabilitation requires the physiotherapist to apply lots of flexion-extension movement repetitively to the fingers of patients, whereas active rehabilitation emphases in flexibility training and specific stretching exercises for each injury. After a normal range of motion established and maintained, force training introduced to restore strength [123].

The main limitations when designing hand exoskeletons is its complex morphology. This is due to the necessity to adapt it to different human hand sizes. At present, exoskeleton robots such as the HX [124] offers adaptability to the anthropometric variability and different mechanisms of the hand, as well as self-alignment mechanisms to absorb human or robot joint axes alignment failure during implementation. It also presents an advanced mechanical design for realising this adaptability and mobility. Another robot that aims to focus on adapting to the various size of human fingers is the exoskeleton developed by the Harbin Institute of Technology [125], where a cable performs the transmission system, with actuators mounted on the forearm of the user. The Handexos [126] and the Beihang University hand robots [127] solve the issue of adapting to different finger sizes.

Furthermore, most of the literature reviews on hand rehabilitation robotic devices focus on the recovery of motor functions, specifically the extension and flexion movements of the hand. However, there are limited established approaches or publications available on the recovery of the sensory functions of the hand. In other words, the recovery of the sensory functions of the hand has yet need to explore by researchers. Therefore, improvements in the sensory functions of the hand are just as crucial to the recovery of the motor functions of the hand.

In this section, the development process of the design concept, simulation and the fabrication of the device discussed. The initial prototype of the device was also included. Since the exoskeleton only performs flexion and extension through the mechanism, the modification of the exoskeleton conducted in order to qualify as an index finger rehabilitation device. The design concept determined by these specifications described and the choice of materials, the actuation system and then the implemented control schemes detailed in this section.

6.2 System Requirement

After stroke, the survivors have different malfunctions, which contribute to the impairment of hand and finger function such as muscle weakness and muscle stiffness, which can limit the movement of agonists and antagonists muscles at multiple joints. The fingers usually locked in a flexed position and stroke patients cannot control finger motion with sufficient extension force. Therefore, it is a necessary for the robotic exoskeleton to train the extension function of the finger at an early stage of the motor function recovery program. After taking care of the extension function, finger flexion needs to train for strengthen the weak muscles. Here we consider the following four criteria for use as a rehabilitation tools:

1. Flexion and extension - Bidirectional movement ability in a simple mechanism
2. Lightweight - The device must weigh less than or equal to the normal human finger
3. Easy to attach - The device must be easily attach to the index finger less than 2 minutes
4. Safety caution – the device system has a mechanism to avoid the exoskeleton from give force to the human fingers to move in an excessive range of motion.

Although a number of finger and hand rehabilitation device proposed, none satisfy all the aforementioned criteria.

6.3 System Functionality

This section describes the specific functions of the robotic system in rehabilitating the motor function of muscle in each finger of a human hand. The key function of a hand exoskeleton device is the ability to decrease the stiffness of the contracture finger. The stiffness of the muscle in human finger need to reduce according to the normal human finger orientation, thus the robotic exoskeleton must be able to reproduce the flexion and extension of the finger movement repetitively. Besides, the device must be able to detect the angle of the flexion and extension in order to measure the trajectories for index, middle, ring and small fingers while performing the movement. As shown in Figure 28, the sub-functions of the robotic exoskeleton consist of the ability to control angular velocity and producing a normal range of motion of the finger depend on each input angle on finger joint. The point of view from the occupational physiotherapist and the feedback from the healthy subjects are important to avoid incongruity during training session with real patients.

6.4 Robotic Exoskeleton Prototype Development

This project is a pilot study to improve the finger rehabilitation. The project starts with a mechanical design of exoskeleton for an index finger. The main idea of the design is to perform an extension and flexion of the finger based on mechanisms that can transmit the force from the actuators.

In this study, we investigated a new type of a robust hand and finger rehabilitation device, which can control a human hand to do flexion and an extension motion. Our hypothesis by enforcing the correct flexion and extension motion, it can help patients with hand and finger muscle problems to close their hand and open hand correctly and improve healing. Most hand and finger devices for rehabilitation available on the market uses the passive control system. Unfortunately, the active control systems are costly and need a bigger space to install, not portable and not suitable to use at home.

Therefore, the current study for the first time attempts to produce a robust, low cost device employing an active control system with a DC motor integrated with lead screw mechanism.

An active actuation system consists of a DC servo motor integrated with lead screw mechanism has been developed to realize the functions in aforementioned criteria. The block diagram and system architecture of the control actuation system illustrated in Figure 28 and 29.

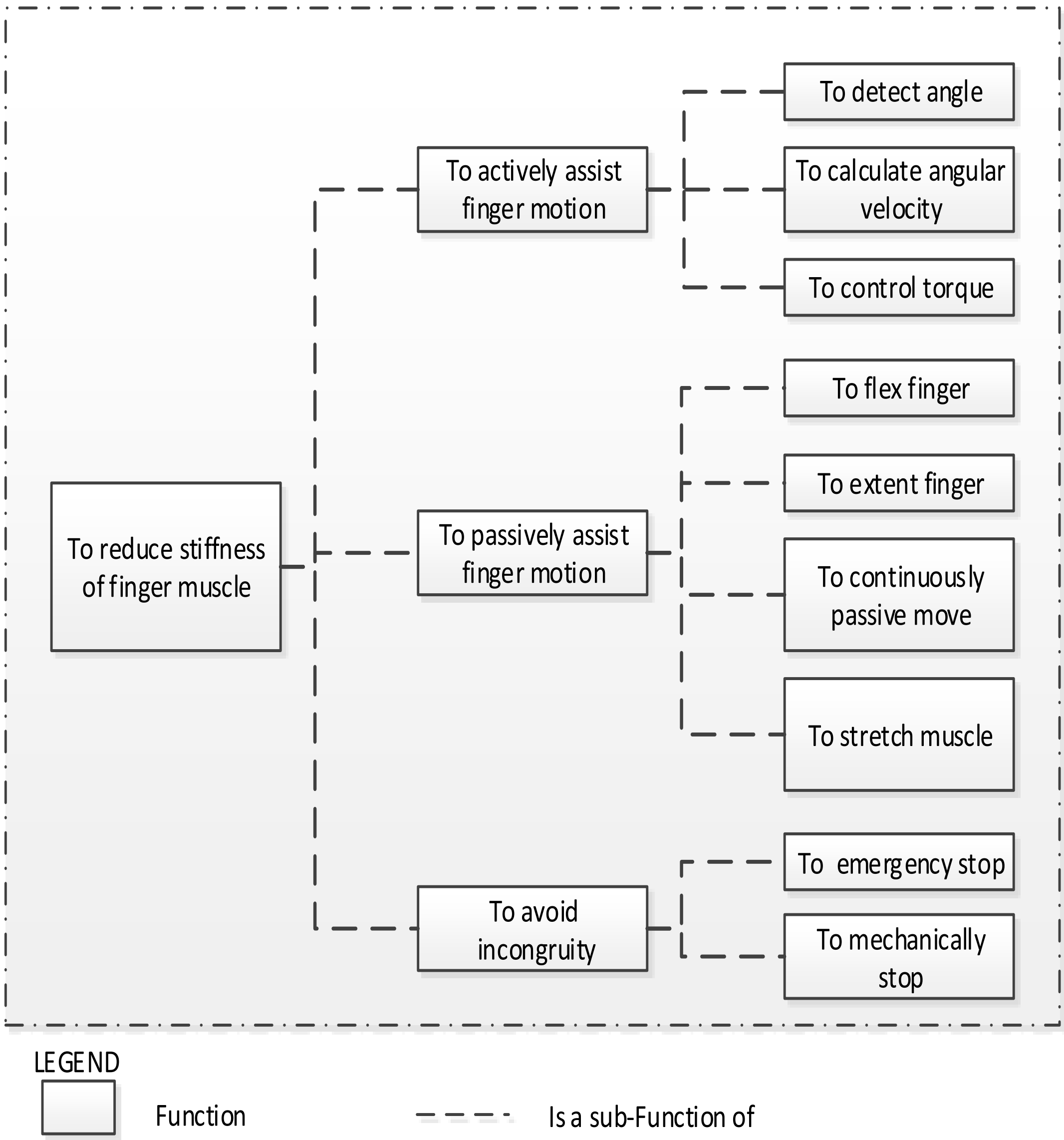
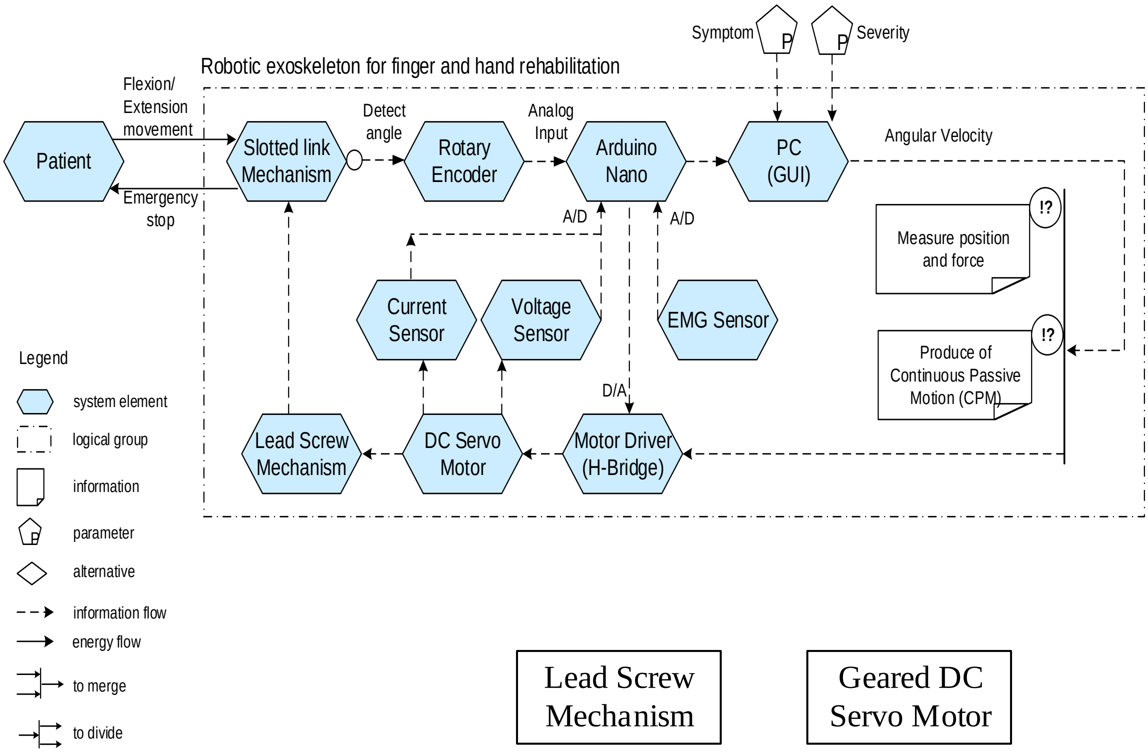


Figure 28 Functions of robotic exoskeleton for finger and hand rehabilitation



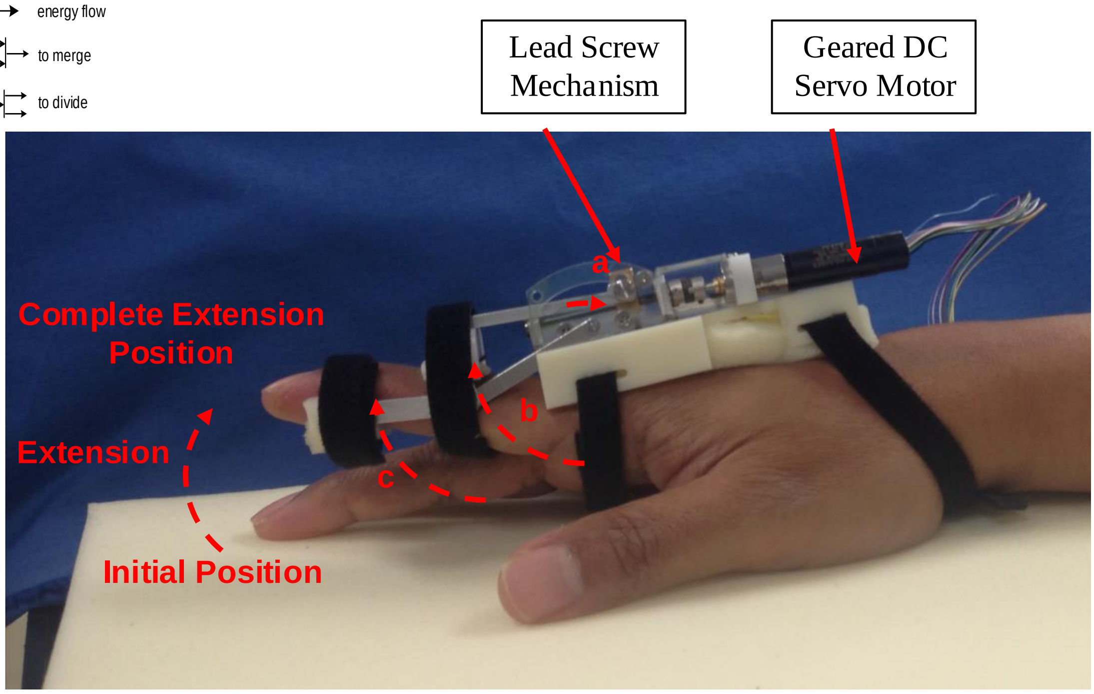


Figure 29 Block diagram and system architecture of a control system in robotic exoskeleton where DC servo motor integrated with lead screw mechanism for finger and hand rehabilitation

6.5 System Implementation

6.5.1 Lead Screw Mechanism

A lead screw typically is a linear actuator based mechanism that converts an oscillating input torque in the form of an angular displacement into a desired linear displacement. The major benefits of using a lead screw mechanism in linear actuators are inherent mechanical advantages, high stiffness, high strength, and a cost-effective package. Lead screws fall under the category of power screws and can classified into ball screw, acme/trapezoidal screw and roller screw. A ball screw mechanism consists of a ball screw and a ball nut with recirculating balls providing rolling contact between the nut and the

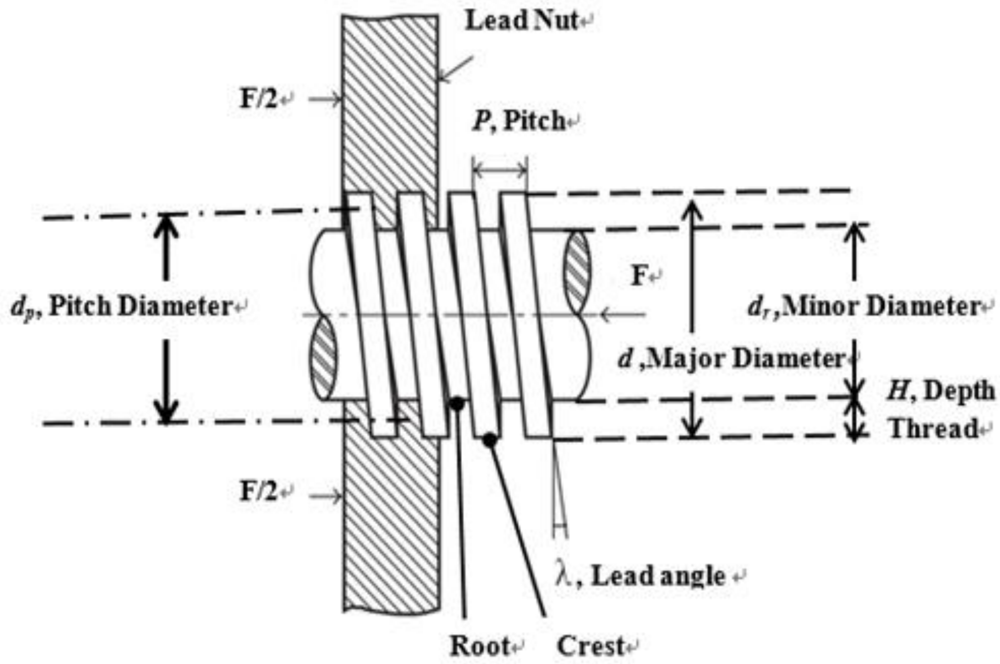


Figure 30 Trapezoidal thread profile,

Legends: d: Nominal or major diameter of screw, dr: minor diameter of screw, dp: pitch diameter, P: pitch, L: Lead, λ : Lead angle, H: depth thread of screw

screw.

An acme or trapezoidal screw, which hereafter will be addressed as lead screw, consists of a screw and a nut that are in sliding contact with each other. The screw generally made up of alloy steel with a trapezoidal thread form, and the nut is typically made of an engineering polymer or bronze. The contact between the nut and the screw is a sliding contact. Therefore, friction plays a very important role in the performance and efficiency of the mechanism. These screws offer low efficiencies due to the relatively greater coefficient of friction in sliding. Figure 30 illustrates trapezoidal thread profile of lead screw mechanism. Consider that a single thread of the screw is unrolled for exactly one turn. When determining the amount of input torque required producing an amount of output linear force, there are many factors to consider. The following equations provide a practical approach in making force and torque calculation in lead screw mechanism. Equation (6.1) used to approximate the total force involving in the system.

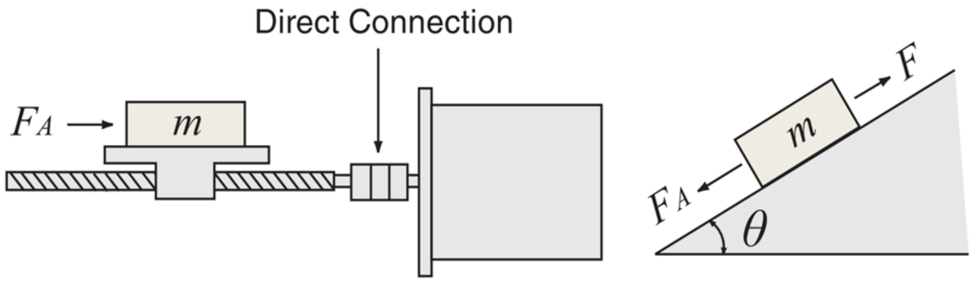


Figure 31 Free Body Diagram (FBD) of lead screw mechanism with force action reaction effect

$$F = F_A + mg(\sin\theta + \mu\cos\theta) \qquad (6.1)$$

Figure 31 illustrates free body diagram of lead screw mechanism. Here F is force of moving direction, F_A represents external force, m is the total mass of the lead screw nut and load in kilogram (kg), g is gravitational acceleration, μ is the friction coefficient of sliding surface, and θ is tilted angle in degree. External force due to clockwise (CW) and counter clockwise (CCW) motion of DC servo motor shaft direct connection with coupling in horizontal applications, which is the requirements in extension, and flexion of the finger. Friction force required overcoming all of the friction in the load bearing system with a low friction bearing system. This can be negligible. The total force must be below the compressive trust rating of the lead screw chosen. A modest factor of safety should added to the total force. Thus, unexpected dynamic loads handled safely by the lead screw mechanism.

The torque, T required moving the mechanism system approximated by Equation (6.2), where F_T is total force exerted on the finger phalanges; P represents pitch of lead screw assembly.

$$T = F_T \frac{P}{2\pi} \qquad (6.2)$$

The torque required should be well below the torque rating of the motor chosen. A modest factor of safety should added to the torque required; hence, unexpected dynamic loads handled safely by the driving system.

6.5.2 Link Cam Mechanism

As illustrated in Figure 32 and 33, the exoskeleton comprises seven parts, which are slide guide, pin, push bar, link 1, link 2, cover A and cover B. This module has two

DOF for the whole index finger. The first DOF movement is a prismatic displacement, which occurs when DC motor actuate the lead screw. Second DOF correspond to a rotational movement for flexion and extension of the proximal and distal phalanges.

The bases for distal and middle phalanges fastened respectively on the corresponding distal phalanges and middle phalange by Velcro straps as illustrated in Figure 29.

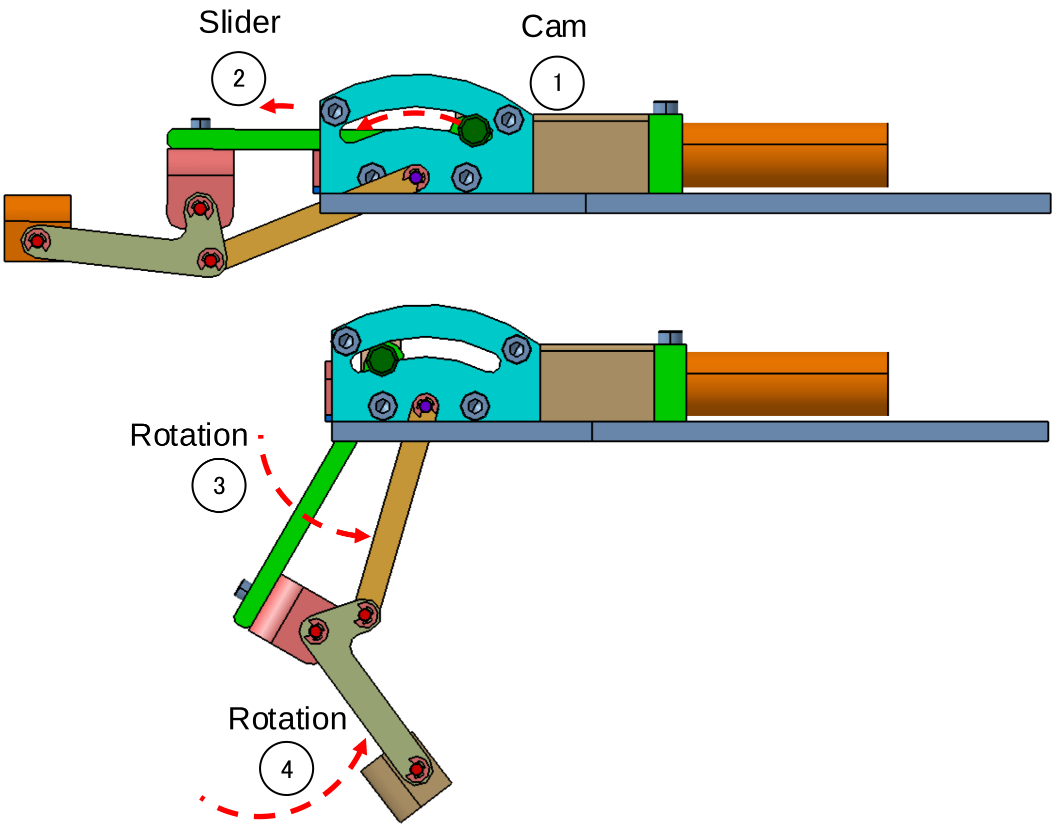


Figure 32 Link Cam mechanism in our index finger rehabilitation device

6.5.3 Safety Factor Consideration

Safety is the most important element for robotic exoskeleton, which involve in the interaction between machine and humans. Both software and hardware precaution implemented as emergency stop to prevent any injuries and damage neither to the system nor the users during the rehabilitation session. Limit switches as a mechanical stop and emergency switch triggered by subjects and a physiotherapist can stop the device motion anytime. All electronics and the drive train mechanism sealed off in an enclosed box and external parts secured for safety purpose.

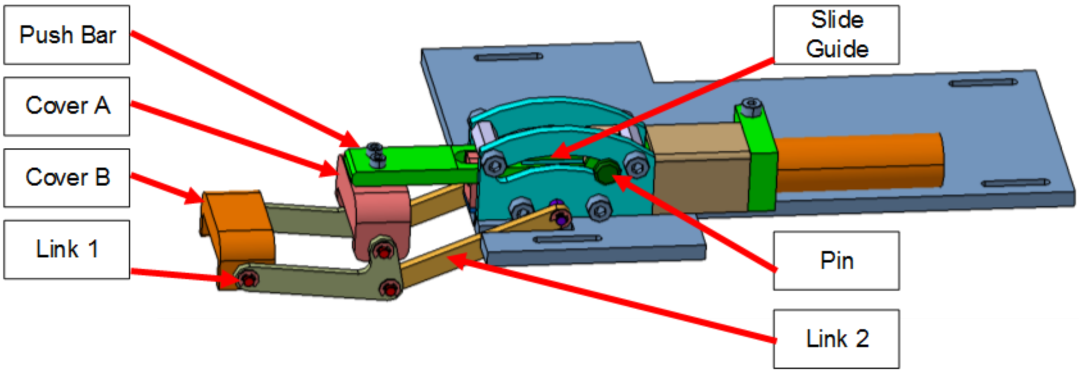


Figure 33 Fundamental mechanism of the link cam mechanism

CHAPTER 7

CONTROL ARCHITECTURE

7.1 Introduction

A lead screw nut driven by a closed loop positioning system in the robotic exoskeleton based device consists of a small geared DC servo motor with an optical encoder equipped, connected to a lead screw mechanism with flexible coupling. The lead screw has a pitch of 0.7 millimetre (mm) and is coupled to the motor shaft with three different set of gear ratio which are 16:1, 64:1 and 4096:1. We used different of gear ratio because of the different stiffness and severity of the patients. In early acute phase patients, we will use low gear ratio (16:1) because the system will actuate a high speed and less torque. Therefore, in chronic stage we will use high gear ratio (4096:1) to actuate with low speed and high torque in preventing the pain to the patients.

The geared DC servomotor actuated by a series of electrical pulse signals that transmitted from the input module. Each pulse causes the motor to rotate a fraction of one revolution, θ , the step angle in degrees, can be defined by Equation (7.1.1), where n_s is number of step angles for the motor.

$$\theta = \frac{360}{n_s} \qquad (7.1.1)$$

The DC servomotor directly connected to the lead screw with a gearbox; the angle of rotation of the lead screw derived by Equation (7.1.2).

$$A = n_p\theta \qquad (7.1.2)$$

Here A is the angle of leadscrew rotation in degrees, n_p represents the number of pulses received by the DC servomotor, and θ defined as degrees per pulse.

The movement of the nut in response to the rotation of the lead screw calculated in Equation (7.1.3).

$$S = \frac{pA}{360} \qquad (7.1.3)$$

Where, S is the distance moved or position relative to the starting position in mm, p is the pitch of the lead screw in the unit of millimetre per revolution and A per 360 is the number of revolutions of the lead screw.

From the aforementioned equations, the number of pulses, n_p required to move a predetermined position expressed in Equation (7.1.4).

$$n_p = \frac{360S}{p\theta} \qquad (7.1.4)$$

The pulses transmitted at a certain frequency, which drives the leadscrew nut at a specific velocity. The rotational speed of the lead screw, N depends on the frequency of the pulses as defined in Equation (7.1.5).

$$N = \frac{60 f_p}{n_s} \qquad (7.1.5)$$

Here, N is the rotational speed in the unit of revolution per minutes; f_p is pulse frequency in the unit of pulses per seconds.

The nut travel speed in the direction of the lead screw axis determined by the rotational speed as defined in Equation (7.1.6).

$$v_t = f_r = Np \qquad (7.1.6)$$

Where v_t is the lead screw nut travel speed in millimetre per minute, which also can be considered as feed rate, f_r and p is the pitch of the leadscrew in millimetre per revolution.

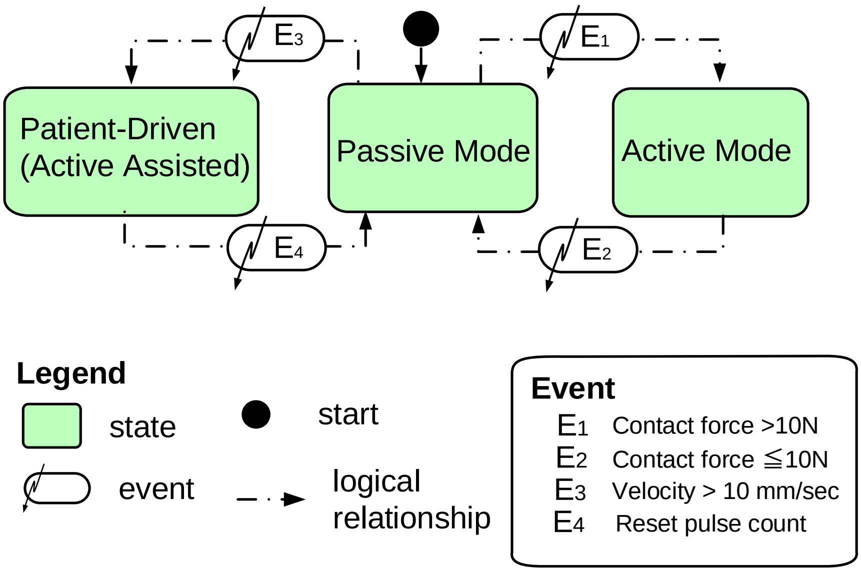


Figure 34 State diagram for a foolproof robotic exoskeleton based system

The prototype developed with three operation modes for each individual finger. Each mode has a different control system. In order to explain the active actuation strategy implemented in the system, the control system design for different levels of spasticity, which explained as illustrate in Figure 34.

Figure 34 shows the implemented lead screw mechanism allows three operation modes for every single finger. In the passive training mode, the robot exoskeleton based device will guide the extension and flexion movement for patients who do not have voluntary hand and finger motions. At the moments, the patient’s hand and finger must in the fixed position of the robotic exoskeleton based device. Therefore, a Velcro strap used for fixation purpose.

The active training mode operated when the robotic exoskeleton based device does not need to assist the patient’s movement. Stroke patients who the symptom are mild and almost recovered can train for the extension and flexion motions in this mode. When the patient attempts to move their finger or hand, the value of EMG (Electromyography) sensor increases to exceed the value of threshold. However, if the EMG sensor does not exceed the threshold value, this will be an indicator that the user could not complete the passive and active training mode.

The patient-driven (active assisted) mode can be operated using the movement intention for patients with minimal voluntary hand and finger movements. When a patient attempts to move their finger in extension or flexion motion, the device will detect the patients’ will through the EMG sensors.

7.2 PWM Control

PWM (Pulse Width Modulation) control is a common method for controlling the power across loads. This method is very easy to implement and has high efficiency. PWM signal is essentially a high frequency square wave (typically greater than 1 KHz). The duty cycle of this square wave varied in order to vary the power supplied to the load. Duty cycle usually stated in percentage and it expressed using the Equation (7.2.1).

$$\%\ Duty\ Cycle = \frac{T_{ON}}{T_{ON} + T_{OFF}} \times 100 \qquad (7.2.1)$$

Here T_{ON} is the time for which the square wave is high and T_{OFF} is the time for which the square wave is low. When duty cycle increased, the power dropped across the load increases and when duty cycle reduced, power across the load decreases. The block diagram of a typical PWM power controller scheme illustrated as Figure 35.

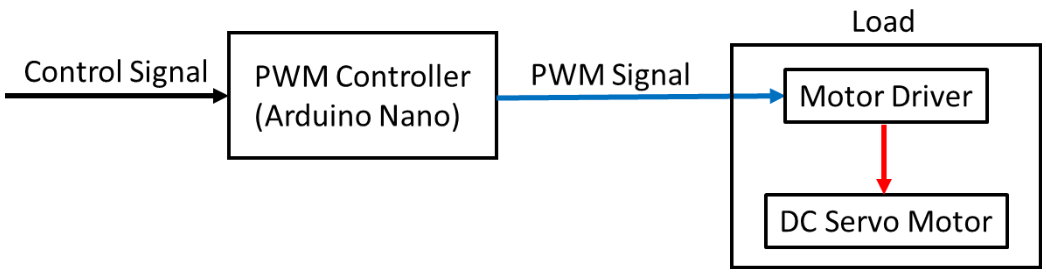


Figure 35 Block diagram of a typical PWM power controller in Open Loop Control scheme

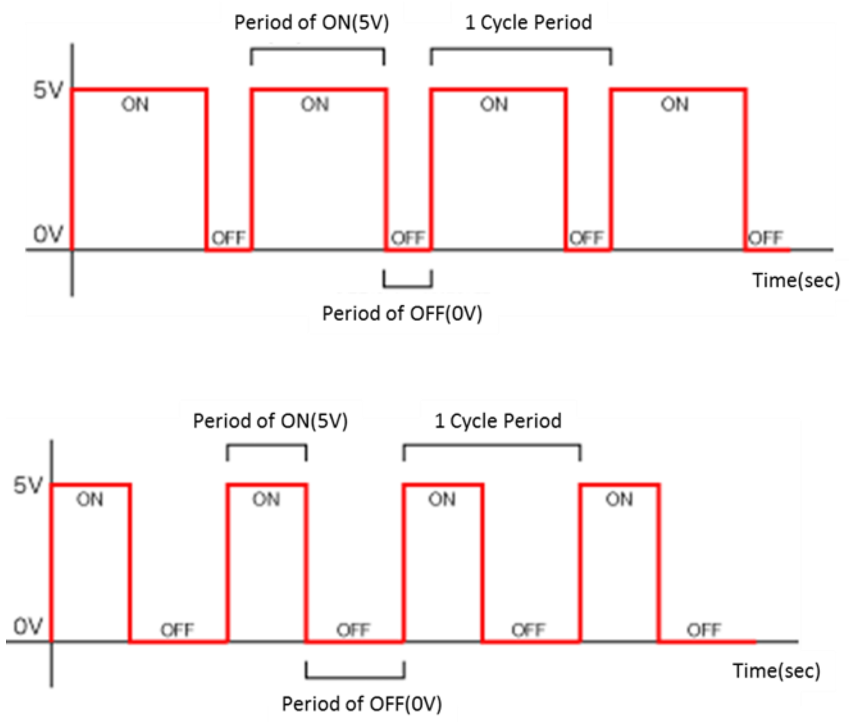


Figure 36 PWM waves with different duty cycle

Control signal is the signal transmitted to the PWM controller as the input. It might be an analogue or digital signal according to the design of the PWM controller. The control signal contains information on how much power need to apply to the load. The PWM controller accepts the control signal and adjusts the duty cycle of the PWM signal according to the requirements. PWM waves with various duty cycle shown in the Figure 36.

In the Figure 36, the frequency of the waveforms is same but ON time and OFF time are different. The applications of PWM control adapted in motor speed control using Arduino to control operation times for extension and flexion motion.

7.3 Position Measurement

Rotary encoders measure rotation of a shaft, while linear encoders' measure distance travelled. For both types of encoder, the position measurement can be either incremental or absolute. An incremental encoder measures change in position, but does not keep track of actual position. Incremental encoders lose their position reference when interrupt power, and must start over via a re-homing sequence to a reference point. Absolute encoders, on the other hand, keep track of absolute position, whether rotation of a shaft or linear travel, by assigning a unique digital value to each position. Therefore, even if power is lost, an absolute encoder will know the exact position of the shaft or the linear drive.

Incremental encoders work by producing a specific number of equally spaced pulses per revolution (PPR) or per distance (PPM—pulses per millimetre, or PPI—pulses per inch). When one set of pulses, or output channel, is used, the encoder can determine position only. But most incremental encoders use quadrature output, which consists of two channels, typically referred to as channel A and channel B, that are out of phase by 90 degrees. Quadrature output allows the encoder to also sense direction, by determining which channel is leading and which is following. Some incremental encoders also produce a third channel with a single pulse, commonly referred to as channel Z or channel I. This channel serves as the index or reference position for homing.

In quadrature output, there are three types of encoding which are X1, X2, or X4. The difference between these encoding types is simply which edges of which channel counted during movement, but their influence on encoder resolution is significant.

In X1 encoding, either the rising (leading) or the falling (following) edge of channel A is counted. If channel A leads channel B, the rising edge counted, and the movement is forward, or clockwise. Conversely, if channel B leads channel A, the falling edge counted, and the movement is backwards, or counter clockwise.

For single channel or X1, we only need to display the output of channel A, but we also want to either identify the rotation of motor in the clockwise or counter clockwise. Thus, in this case, we need to read the pulses of channel B either is lagging or leading the channel A. As show in Figure 37, in this function, we can see that if channel B is zero and the channel A also zero. The pulses will count as negative, therefore the motor is moving counter clockwise. The channel B is lagging compare to the channel A. In summary, when the channel B is leading the channel A means the motor or encoder is moving counter clockwise. When the channel A is leading the channel B means the motor or encoder is moving clockwise. Moreover, the pulses will count when channel A is trigger to one.

```
void A_CHANGE(){
  if( digitalRead(encoderB) == 0 ) {
    if ( digitalRead(encoderA) == 0 ) {
      // A fell, B is low
      pulses--; // moving reverse
    } else {
      // A rose, B is low
      pulses++; // moving forward
    }
  }
  pulsesChanged = 1;
}
```

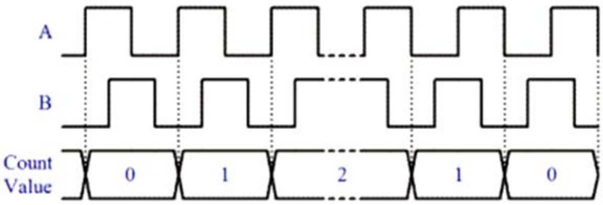


Figure 37 Timing Chart to explain the pseudocode how to read the pulses in single channel, X1

For X2, these pulses will change whether when channel A trigger either 1 or 0. Same with the X1, which read the channel B to identify the direction of the motor or encoder moving as illustrated in Figure 38. Both the rising and falling edges of channel A are counted when X2 encoding is used. This doubles the number of pulses counted for each rotation or linear distance, which in turn doubles the encoder's resolution.

```
void A_CHANGE() {
  if ( digitalRead(encoderB) == 0 ) {
    if ( digitalRead(encoderA) == 0 ) {
      // A fell, B is low
      pulses--; // Moving reverse
    } else {
      // A rose, B is high
      pulses++; // Moving forward
    }
  } else {
    if ( digitalRead(encoderA) == 0 ) {


      pulses++; // Moving forward
    } else {
      // A rose, B is low
      pulses--; // Moving reverse
    }
  }
  pulsesChanged = 1;
}
```

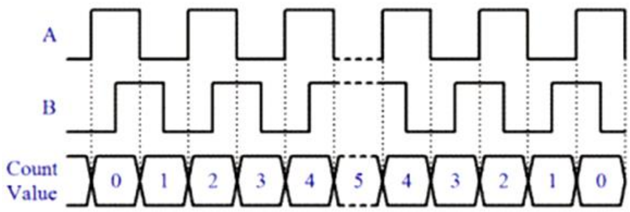


Figure 38 Timing Chart to explain the pseudocode how to read the pulses in double channel, X2

In case X4, we used a little bit different because the pulses will change either channel A or channel B trigger. Thus, we have to add an Interrupt for channel B as same as channel A as illustrated in Figure 39. X4 encoding goes one step further, to count both the rising and falling edges of both channels A and B, which quadruples the number of pulses and increases resolution by four times.

```
void A_CHANGE(){
  if( digitalRead(encoderB) == 0 ) {
    if ( digitalRead(encoderA) == 0 ) {
      // A fell, B is low
      pulses--; // moving reverse
    } else {
      // A rose, B is low
      pulses++; // moving forward
    }
  }else {
    if ( digitalRead(encoderA) == 0 ) {
      // B fell, A is high
      pulses++; // moving reverse
    } else {
      // B rose, A is high
      pulses--; // moving forward
    }
  }
  pulsesChanged = 1;
}

void B_CHANGE(){
  if ( digitalRead(encoderA) == 0 ) {
    if ( digitalRead(encoderB) == 0 ) {
      // B fell, A is low
      pulses++; // moving forward
    } else {
      // B rose, A is low
      pulses--; // moving reverse
    }
 } else {
    if ( digitalRead(encoderB) == 0 ) {
      // B fell, A is high
      pulses--; // moving reverse
    } else {
      // B rose, A is high
      pulses++; // moving forward
    }
  }
  pulsesChanged = 1;
}
```

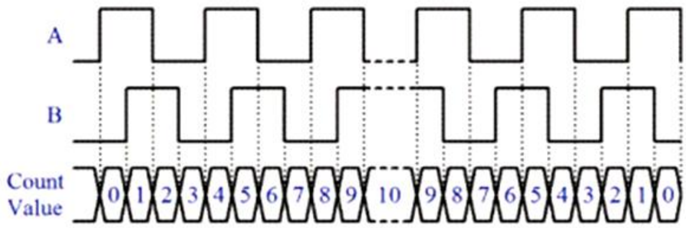


Figure 39 Timing Chart to explain the pseudocode how to read the pulses in quadrature channel, X4

For rotary encoders, position is calculated by dividing the number of edges counted by the product of the number of pulses per revolution and the encoding type described above (1, 2, or 4), and then multiplying the result by 360 in order to get degrees of motion as expressed in the Equation (7.3.1).

$$Angular\ Displacement = \frac{EdgeCount}{(xN)} \times 360^{o} \quad (7.3.1)$$

Here x is type of encoding (1, 2, or 4) and N is the number of pulses generated per shaft revolution.

In case of linear encoders, position calculated by dividing the number of edges counted by the product of the pulses per revolution and the encoding type. This result then multiplied by the inverse of the pulses per millimetre (or per inch) as expressed in the Equation (7.3.2).

$$mm = \frac{EdgeCount}{(xN)} \times \left(\frac{1}{PPM} \right) \quad (7.3.2)$$

Here x is type of encoding (1, 2, or 4) and N is the number of pulses generated per shaft revolution. *PPM* is pulses per millimetre.

7.4 Speed Measurement

In our system, the speed measurement is very important due to the requirement of our system to monitor and control the speed of DC servomotor. We used a method for measuring the rotational speed of a shaft in revolutions per minute (RPM).

A sensor is necessary to sense shaft speed. In this system, we used shaft encoder (rotary pulse generators). This device transmit speed data in the form of pulses. There are two methods for determining RPM, which are the frequency measurement method and the period measurement method. In our system, we chose the frequency measurement method because the pulses from rotary encoder will transmit to Frequency to Voltage Converter (FVC) circuit and draws correlation between converted voltage and rotational speed of the geared DC servo motor.

When using high pulse per revolution (PPR) sensors such as shaft encoder, the easiest way to determine RPM is to monitor the pulse frequency from the sensor using a digital input module and get the frequency. Then, calculate the RPM using Equation (7.4.1).

$$\text{RPM} = \frac{(\text{Pulse Frequency in pulses/sec}) \times (60\,\text{sec/ min})}{(\text{Sensor pulses/revolution})} = \frac{\text{Revolutions}}{\text{Minute}} \qquad (7.4.1)$$

Velocity feedback is need to improve accuracy of speed control as well as for compensating for system dynamics. A salient feature of optical encoders is that velocity information obtained along with position measurement. Without use of a dedicated tachometer generator, velocity measurement attained by simply processing pulse sequences generated by an optical encoder.

Figure 40 shows a pulse sequence coming from an optical encoder. Each pulse indicates a rising edge or a falling edge of phase A and B signals. Therefore, the density of this pulse train, for instance the pulse frequency is approximately proportional to angular velocity of the rotating shaft. The pulse density can be measured by counting the number of incoming pulses in every fixed period, for example T = 10 ms, as shown in the figure. This can be done with another up-down counter that counts A phase and B phase pulses. Counting continues only for the fixed sampling period, T and the result sent to a controller at the end of every sampling period. Then the counter cleared to restart counting for the next period.

As the sampling period gets shorter, the velocity measurement updated more frequently, and the delay of velocity feedback gets shorter. However, if the sampling period is too short, discretization error becomes prominent. The problem is more critical when the angular velocity is very small. Not many pulses generated, and just a few pulses counted for a very short period. As the sampling period gets longer, the discretization error becomes smaller, but the time delay may cause instability of the control system.

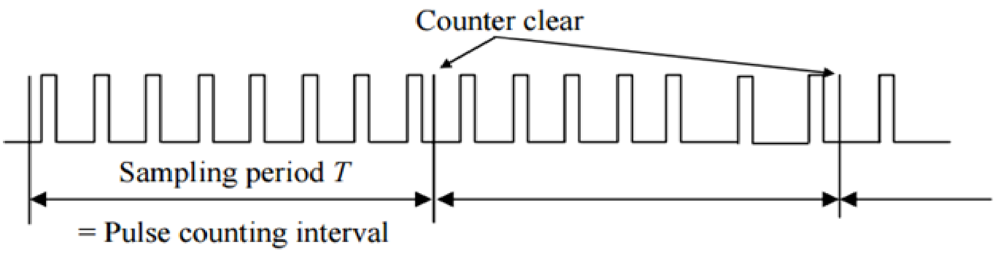


Figure 40 Velocity estimate based on pulse frequency measurement

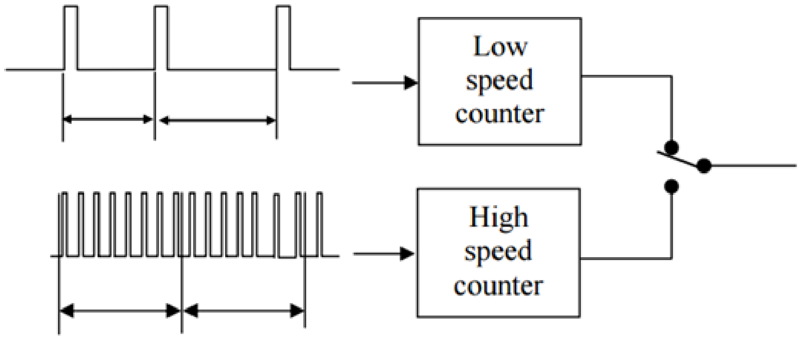


Figure 41 Velocity estimate based on pulse frequency measurement

An effective method for resolving these conflicting requirements is to use a dual mode velocity measurement. Instead of counting the number of pulses, the interval of adjacent pulses measured at low speed. The reciprocal to the pulse interval gives the angular velocity. As shown in Figure 41, the time interval measured by counting clock pulses. The resolution of this pulse interval measurement is much higher than of the encoder counting in a lower speed range. In contrast, the resolution gets worse at high speed, since the adjacent pulse interval becomes smaller. Therefore, these two methods supplement to each other. The dual mode velocity measurement uses both counters and switches them depending on the speed.

7.5 Force Measurement

From the previous literature, we found that there are mainly three approaches to measure the contact force between the human fingertip and an object.

The first approach is to attach a force sensor, for example a strain gauge to the object. This method permits precise measurement with high-resolution sensor; however, the drawback is that users have to develop different custom-made devices for different experiments. In order to measure different objects, different set of force sensors need to attach and different calibration set need to consider. As more objects added in this experiment, the method becomes gradually tedious.

The second method is to insert a thin, flexible force-sensing resistor (FSR, InterLink Electronics Inc.) between the fingertip and the object. The key merit of these sensors is their low cost, small thickness and flexibility, which allows the sensors to fit easily in an instrumented device module. This method applies to various types of experiments. The significant demerit of this method has been the user cannot feel the tactile sense of the object surface since the sensor located between the fingertips and the object. Therefore, the tactile sense of the finger deadened and the sensor may modify and influence the user's behaviour in grasping force. Besides, the non-linearity, drift, saturation and hysteresis of the FSR characteristic, difficult to adapt practically in custom fabricated solution.

Mascaro et al. proposed a method, which manipulated a camera to detect contact forces thru analysing the colour variation of a fingernail where different colour related to different contact forces. This method lets the finger to contact directly the object without blocking the natural tactile sense of the finger. However, the drawbacks of this method are clearly indicated when the result differs accordingly from person to person, and the calibration process is challenging.

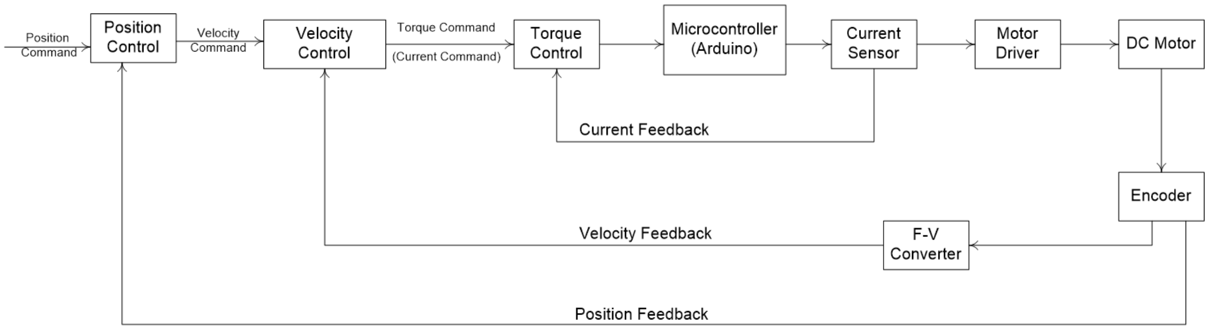


Figure 42 Overview Control Architecture of the development device system

Lately, researchers have proposed a novel technique to measure the force between the finger and the object during grasping. The idea consists of measuring the deformation of the finger pad when contacting with an object. Once the finger touches the object, normal deformation of the finger pad changes the width of the finger. The sensor on the side of the fingertip can measure this variation, thus the user can touch the object without putting any sensors between the finger and the object. Thus, Figure 42 illustrated the overview control architecture of our development device system.

CHAPTER 8

PROTOTYPE EVALUATION

8.1 Introduction

In the previous chapters, the design process during the stage of the development as well as the control architecture for the novel device system of finger contracture prevention discussed and explained. In this chapter, we explained in detail the experiment to evaluate the system. Firstly, experiment in the condition of without attached to the human finger to evaluate the behaviour of the device before attached to the load. We conducted some experiment to observe the kinematic ability of the system. The experiment on an index finger of healthy subjects conducted with slow flexion and extension speed. Finally, at the end of this chapter will discuss some of the results and the conclusion.

8.2 Kinematic experiment without load

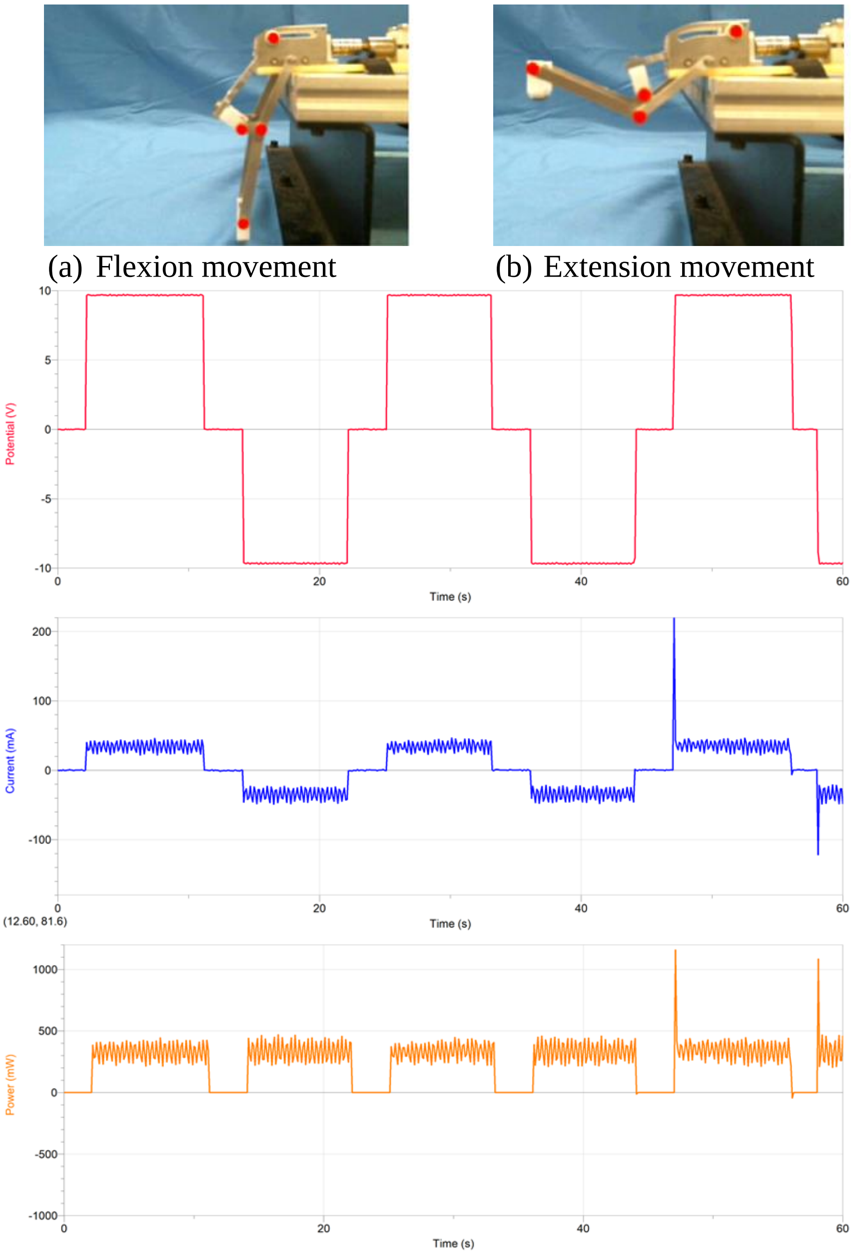
8.2.1 Experiment model

In order to evaluate the working possibility of the system including mechanics as well as the functional of the controller. The finger module of the system fit horizontally as the condition attached to normal index finger.

8.2.2 Experiment results and discussion

We conducted the kinematic experiment without load for preliminary evaluation of the developed prototype where we characterized the position output. Figure 43 and 44 illustrates electrical characteristic and kinematic analysis of robotic finger module during extension and flexion movement

Firstly, when the device started the initial movement is flexion of the finger as can be seen from graph elevation of square region until maximum flexion. Then, the device will stop for 2 sec as shown from the flat region on the graph. Lastly, the device started to extend as shown in depression of square region until maximum extension. The process repeated in 60 sec. These graphs demonstrates the electrical behaviour of the device before attached to the normal finger. Red graph shown the voltage usage during counter clock wise and clockwise behaviour of DC servomotor. The blue graph show the range of motor current of ±50mA during the rotation. The orange graph show the motor power signal of 0 to 470mW during the rotation.



(a) Flexion movement (b) Extension movement

Figure 43 Electrical characteristic of robotic finger module during extension and flexion movement

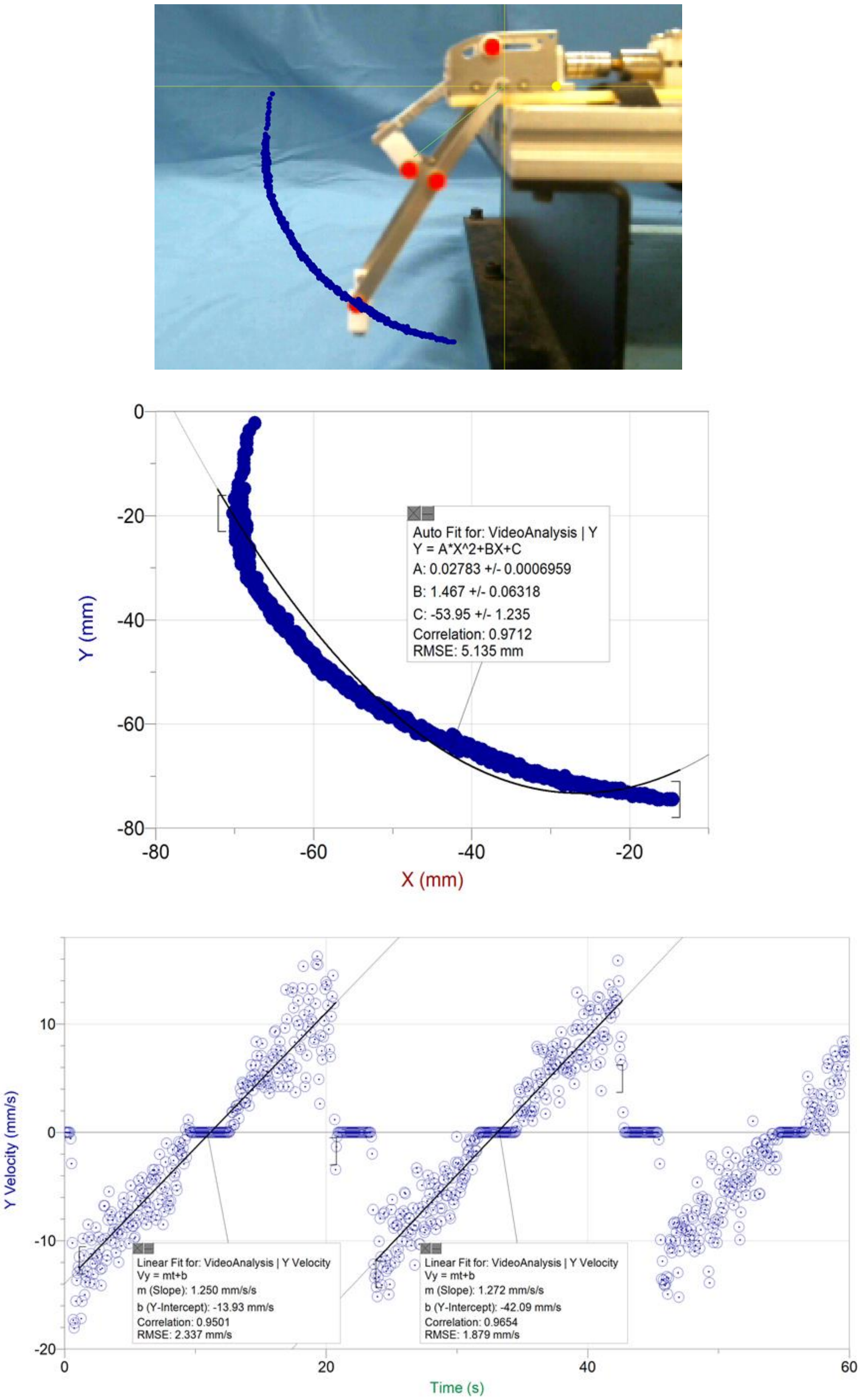


Figure 44 Kinematic analysis of robotic finger module during extension and flexion movement

8.3 Kinematic experiment when attached the system on human finger

8.3.1 Experiment model

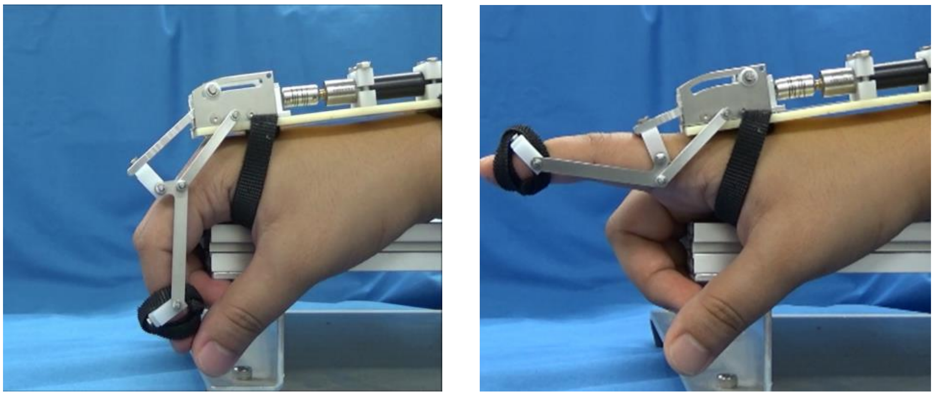
In this test, only the index finger module of the prototype worn by a healthy subject (male, 32 years old, right handed, the same subject of design parameter definition). The subject was instructed to relax the finger, and the mechanism performed the motion from the original position (the index finger and palm are straightened) to the flexed position (the index and thumb are opposed). Figure 45 and 46 illustrates electrical characteristic and the prototype motion of the index finger in a series of pictures during flexion and extension motion.

8.3.2 Experiment results and discussion

Trajectory of flexion and extension angles of DIP joint along the grasping movement cycle as shown in Figure 46. To compare with the human natural flexion motion, the flexion motion without wearing the finger mechanism and wearing the finger mechanism measured in the same experimental setup. Next step is to generate these movement patterns in playback fashion to assist a "weakened" hand to accomplish these movements. Since the user has pair of healthy hands, he was asked to passively follow the position and force trajectory from the recorded data.

In order to evaluate the possibility range of motion of the prototype, a flexion and extension motion need to perform continuously in 60 seconds. For this study, healthy volunteer recruited with no signs of finger disease, injury, burn mark, surgery mark or finger modification and abnormality at the area of testing. Volunteers gave informed consent with ethical approval from the Shibaura Institute of Technology Research

Committee. A healthy volunteer subject who is 68kg weight, 167cm height attached the prototype on right hand of index finger respectively.



(a) Flexion movement (b) Extension movement

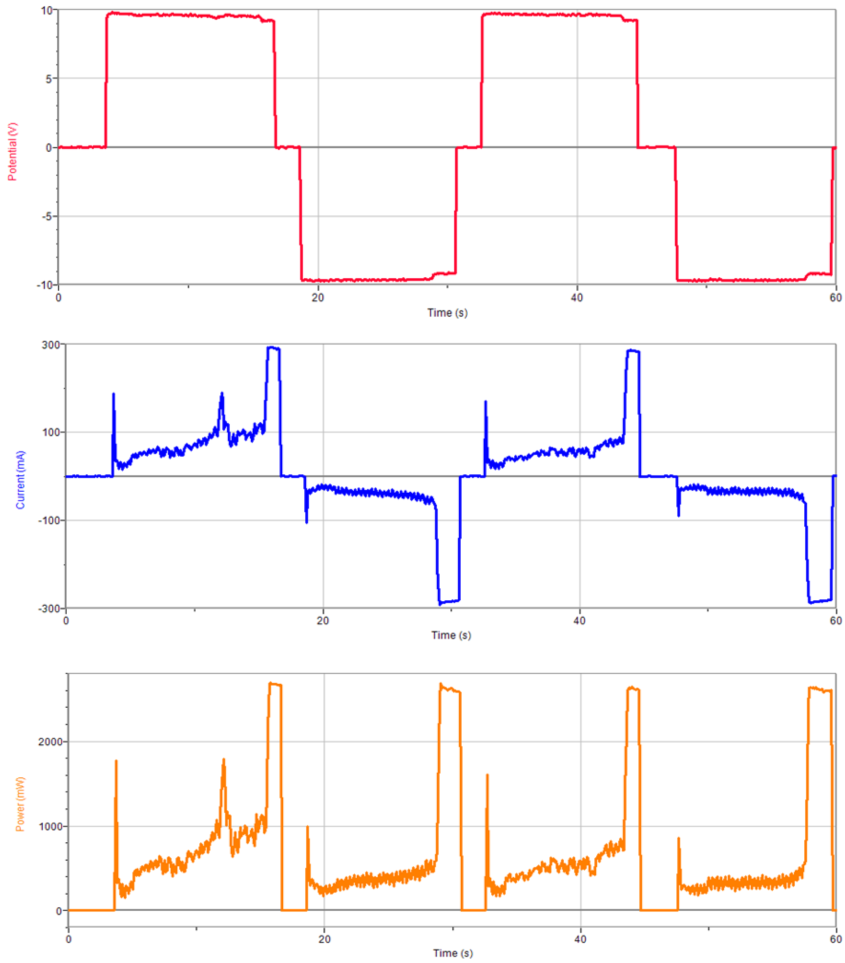


Figure 45 Electrical characteristic of robotic finger module attached to healthy subject during extension and flexion movement

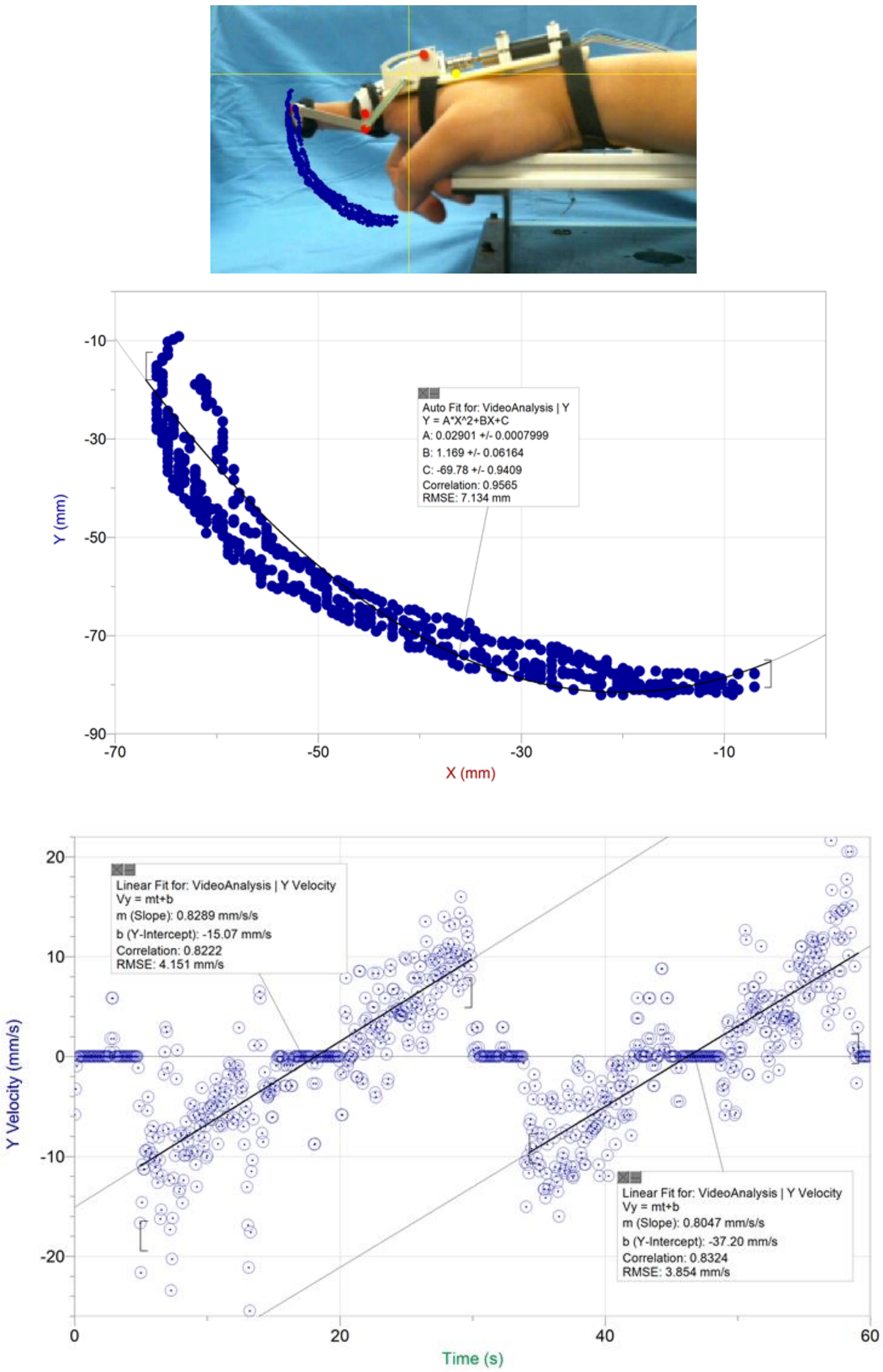


Figure 46 Kinematic analysis of robotic finger module attached to healthy subject during extension and flexion movement

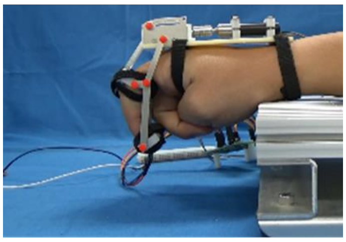
8.4 Force and current sensor calibration and measurement

8.4.1 Experiment model

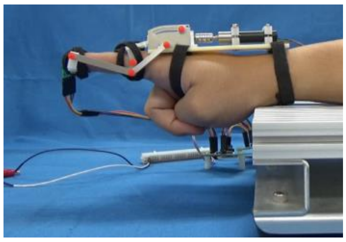
We also measured the force (in N) where we put two force sensor located at MCP and DIP joint. Initial experiments conducted with commercial force sensor (HSFPAR303A) from Alps Electric Co. Ltd., where the force sensor using effect of piezo resistive bridge circuit formed on silicon diaphragm. Force sensor structure and the operating principle illustrated in Figure 26 of Chapter 5. In this experiment, measured forces during the finger flexion and extension movement never exceeded 10N [128].Experiment setup of the force sensor and current sensor as demonstrated in Figure 47.

8.4.2 Experiment results and discussion

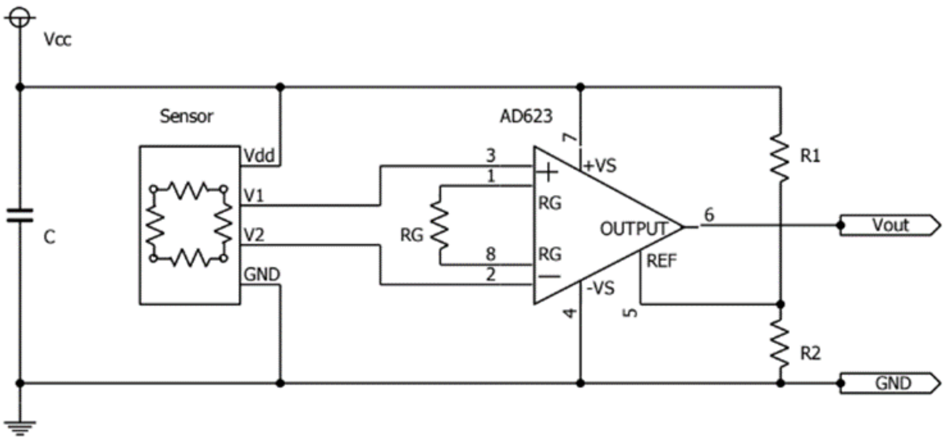
Figure 48 illustrates experiment results for force and current sensor calibration and measurement. The blue graph illustrated the force measurement of MCP joint during the device attached to the normal index finger. The force applied at MCP joint when initial flexion started is 0N until the maximum flexion 1.8N.The force applied at MCP joint when initial extension started is 0N until the maximum extension 2.2N. The red graph illustrated the force measurement of DIP joint during the device attached to the normal index finger. The force applied at DIP joint when initial flexion started is 0N until the maximum flexion 1N. The force applied at DIP joint when initial extension started is 0N until the maximum extension 0.8N.



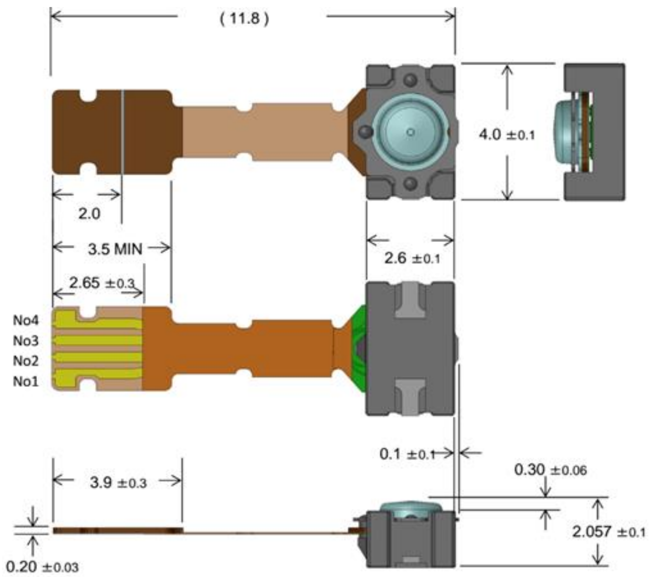
(a) Flexion movement



(b) Extension movement

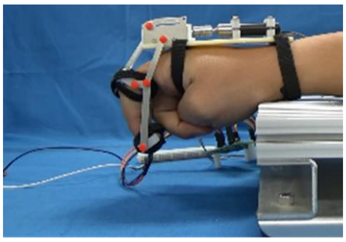


(c) Analog output circuit

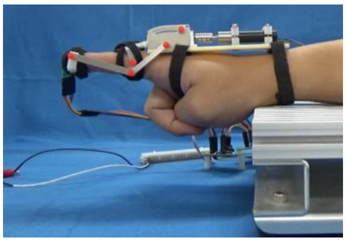


(e) Overview of the force sensor

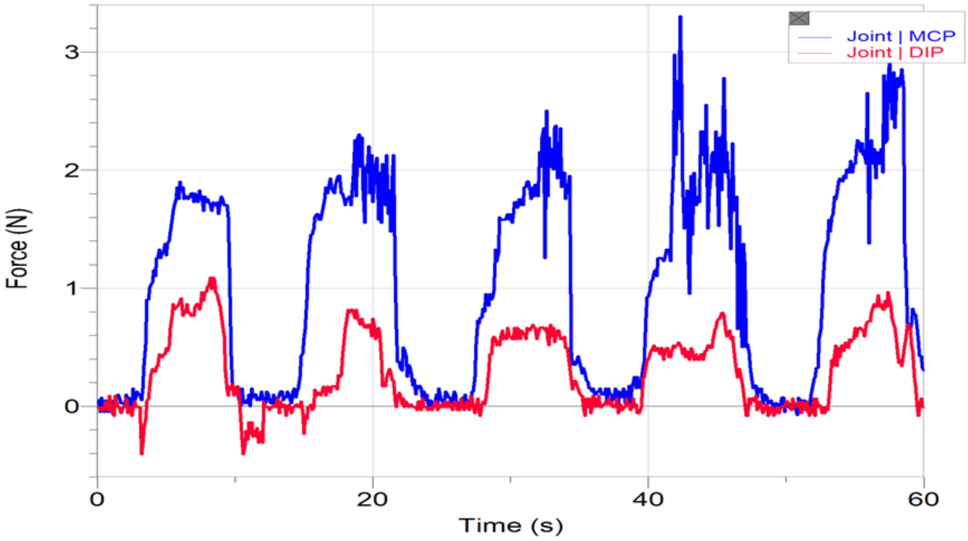
Figure 47 Experiment setup for force and current sensor calibration and measurement



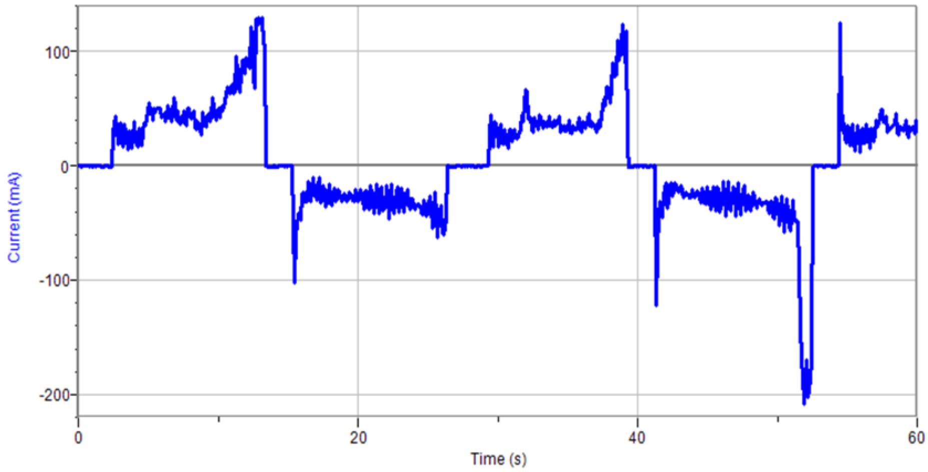
(a) Flexion movement



(b) Extension movement



(c) Force measurement of MCP and DIP joint during flexion and extension movement



(d) Calibration of current sensor during flexion an extension movement

Figure 48 Experiment results for force and current sensor calibration and measurement

8.5 Evaluation test of our system in static and dynamic stretching

8.5.1 Experiment model

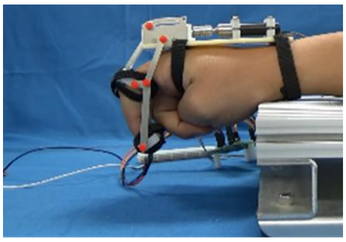
In our study, we applied both method of static and dynamic stretching. For static stretching, we started with slow speed extension within 2 to 5 seconds. Continuously extend the muscle until the duration of 30 sec. The stretching repeated with three set training.

For dynamic stretching, we started with fast speed extension at 2 seconds. Then, flexion within one second and repeated with 10 set training.

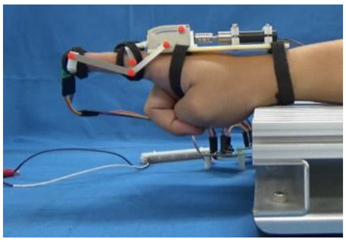
8.5.2 Experiment results and discussion

Figure 49 illustrates the electrical behaviour for the device during static stretching. Red graph shown the voltage usage during counter clock wise and clockwise behaviour of DC servomotor. The blue graph show the range of motor current of ±300mA during the rotation. The orange graph show the motor power usage of 0 to 2600mW during the rotation.

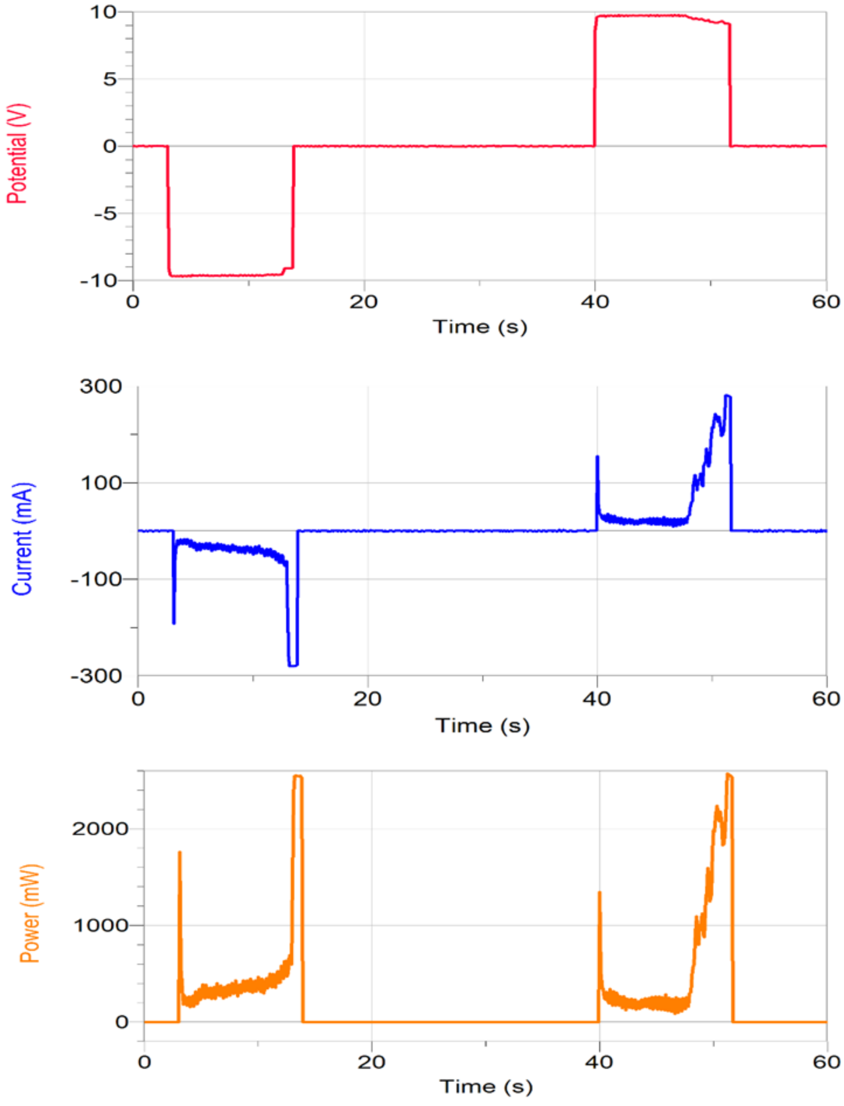
Figure 50 and 51 demonstrates the electrical behavior for the device during slow and fast of dynamic stretching. Red graph shown the voltage usage during counter clock wise and clockwise behavior of DC servomotor. The blue graph show the range of motor current of ±200mA during the rotation. The orange graph show the motor power usage of 0 to 1400mW during the rotation.



(a) Flexion movement

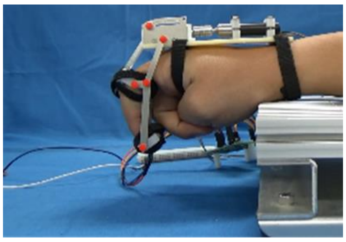


(b) Extension movement

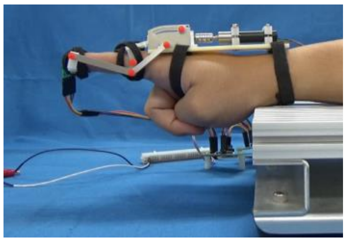


(c) Electrical characteristic of robotic finger module attached to healthy subject during static stretching

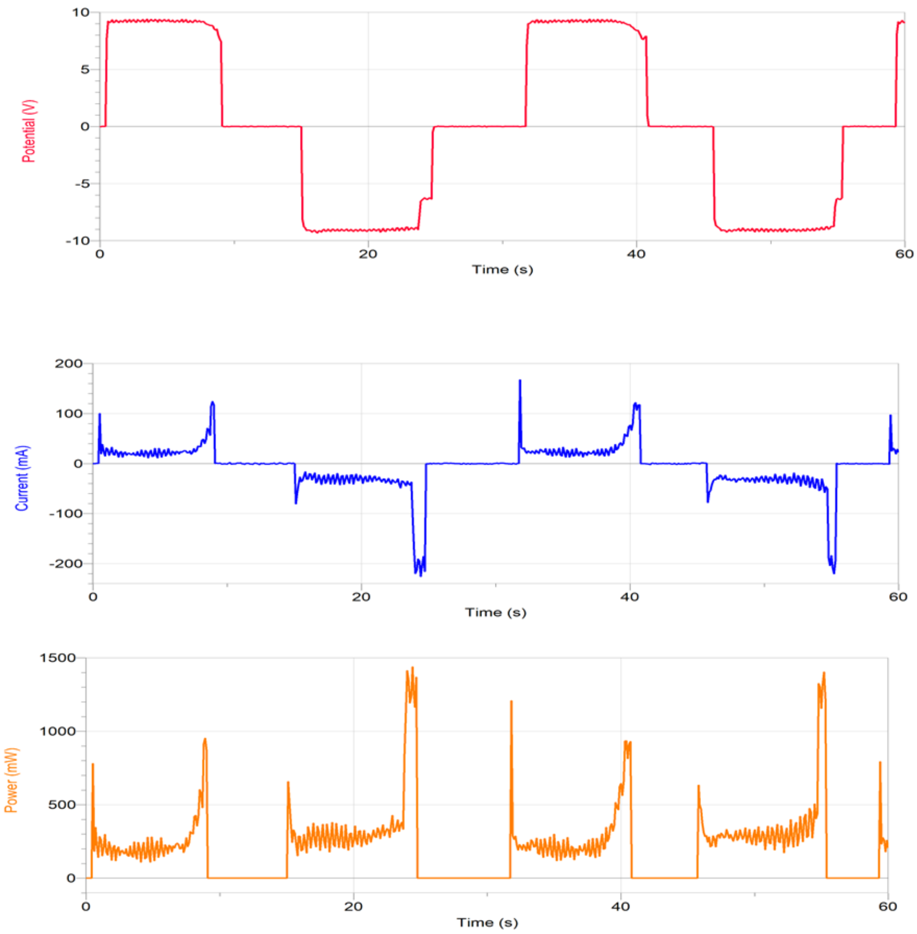
Figure 49 Experiment results for static streching



(a) Flexion movement

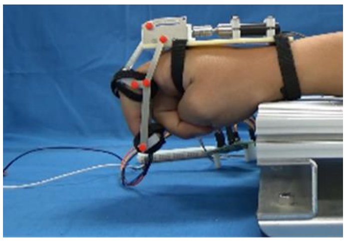


(b) Extension movement

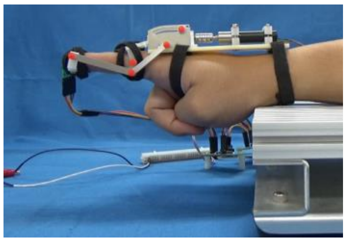


(c) Electrical characteristic of robotic finger module attached to healthy subject during slow dynamic stretching

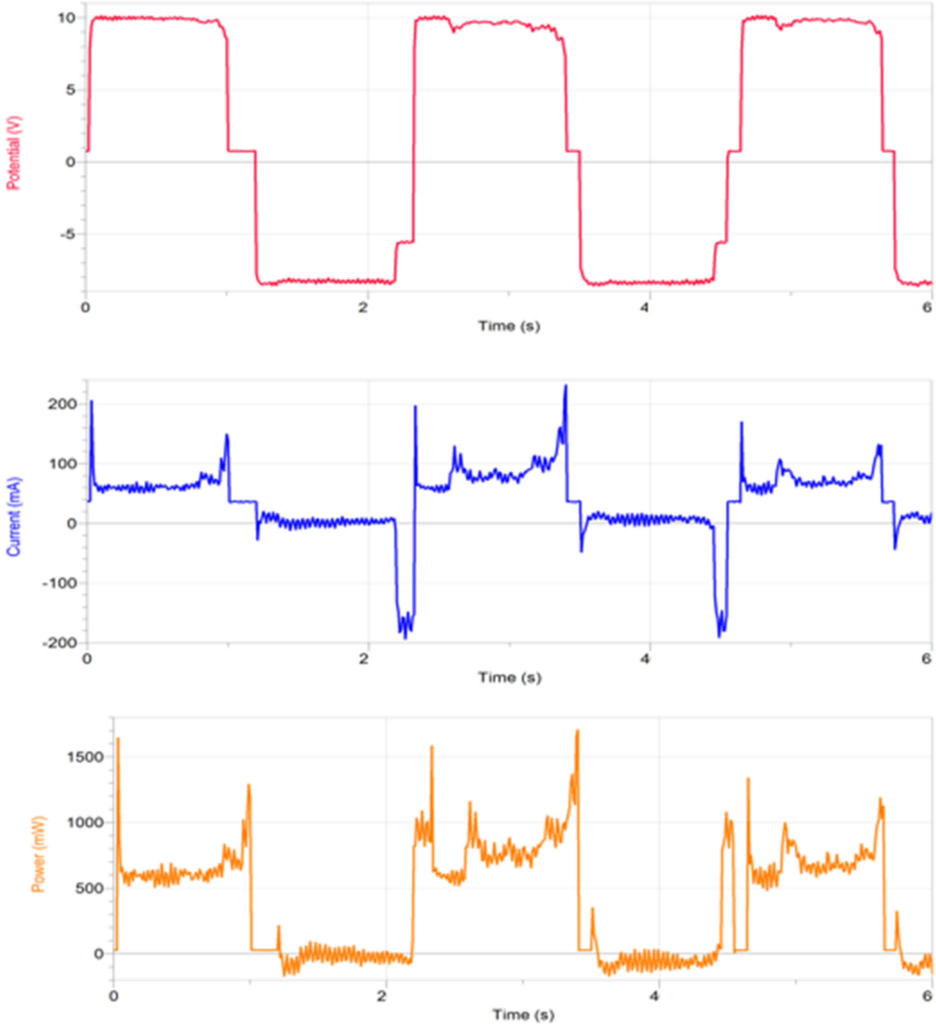
Figure 50 Experiment results for slow dynamic streching



(c) Flexion movement



(d) Extension movement



(e) Electrical characteristic of robotic finger module attached to healthy subject during fast dynamic stretching

Figure 51 Experiment results for fast dynamic streching

8.6 Conclusions

Previous study reported by Phil Page (2012) reported that by doing both of static and dynamic stretching, it improved muscle, tendon, and the flexibility of the ligaments as well as improved blood circulation in the peripheral. It also expand the joint range of motion and smooth the working of muscle motor nerve.

We have presented the novel design of an actuation system for finger rehabilitation, which is lighter weight about 60g. While our design put priority on weight reduction, it still provides sufficient output force, control capabilities, and battery life for reasonable use. Integration of the device with an existing exoskeleton demonstrated these abilities as well as the benefits of using remote actuation in reducing the weight placed on the hand and finger. Therefore, the device can reduce burden of physiotherapist with simple link cam mechanism with the benefit of leadscrew mechanism coupled with DC servomotor.

Safety is the most important requirements of our device, which when interaction with human finger. Any malfunction can be seriously harmful to the user if the exoskeleton devices move under close contact with the user's fingers. Mechanical designs already consider the possibilities of unpredicted erroneous operation of the device when the device actively actuated. Limits to the range of motion can be set using a mechanical stopper in corresponding mechanism structural designs, which can avoid the exoskeleton from give force to the human fingers to move in an excessive range of motion.

Furthermore, the system has shown itself to be capable of compensating for deficiencies in position, velocity and current control by others actuation system. The advantages effect of stretching are improve muscle, tendon, and the flexibility of the ligaments as well as improve blood circulation in the peripheral. It also expansion the joint range of motion and smooth the working of muscle motor nerve.

From current and force relationship, we can determine how much the force used during flexion and extension. Besides the capability in control, our device also clearly indicate the functionality in quantitative evaluation especially during the both static and dynamic stretching.

CHAPTER 9

CONCLUSION AND RECOMMENDATION

9.1 Summary

From the literature review chapter, previous research related to the development of finger and hand rehabilitation system has thoroughly reviewed. Even though many researchers from over the world contributed many ideas, prototypes and theory in developing finger and hand rehabilitation system, there are still gaps and spaces of improvement and exploration need to be done. All research related to finger and hand rehabilitation system were only focus on development of prototypes, which are bulky and high complexity. Therefore, it is important to continue our research and contribute innovative approaches to this field.

For patients, they should experience two rehabilitation phases to regain the motor ability, which are passive and active training phases. Nonetheless, owing to the limited number of physiotherapists, it would be difficult for patients to perform the therapy with the aid of the physiotherapist at all times. Therefore, there is a dire need for the development of a rehabilitation system that allows patients to conduct their own respective exercises with a minimum or even without the aid of therapists. As a direct consequence, robotics have been engaged to facilitate and address the shortcomings of conventional rehabilitation therapy. However, most literature on hand rehabilitation focuses on the restoration of the motor functions, in particular, the flexion and extension motion of the hand. Nevertheless, limited literature explores the recovery of the sensory roles of the hand.

It is important to note now that the improvements of the sensory functions just as crucial as the motor recovery of the hand.

9.2 Recommendation & Future Work

In future, we will upgrade the simple control to force compliant control system which more robust to external disturbance. After the performance and response of the system bounded, we will evaluate thoroughly with healthy subjects to establish the standard protocol before we test it to the targeted patients.

Furthermore, for future evaluation of the exoskeleton will inform on its ability to assist stroke survivors in performing activities of daily living. While patients suffering from muscle weakness are the primary target group for the proposed device, the force output of the current prototype might limit the applicability for stroke survivors suffering from hypertonicity of the finger muscles, which affects about 30–40% of patients. Further development of the exoskeleton will investigate the possibility of adjusting parameters of the lead screw and slotted link cam mechanism and selection of motors to increase the force output without compromising the weight of the device.

Clinical data collection

Another direction of future development of the considered hand orthosis with represented by its integration of electromyography (EMG). The system will consist of recording bioelectric signals generated by neuromuscular activity. As such, EMG signals are an electrical display of neuromuscular activations associated with contractions of skeletal muscles, regulated by the nervous system. Our intent is to carry out a clinical trial with the proposed system.

Hardware systems

In future, it will be necessary to optimize the system including arrange the wire hardness in a proper manner to facilitate the system can provide a greater variety of movements. A more detail modelling of the mechanism required for further investigation and optimization. An analysis and evaluation on the motion hysteresis is one of the issues need to consider in future work.

System Evaluation

A higher level of programming details is needed along with the real time monitor system with GUI to easily monitor the level of chronic during the physical therapy and later the system must be evaluate by a clinician before proceeding to the other level related to medical institution official evaluation. There are also an essential to develop a force compliant control method, which are fundamental task strategies for performing a class of task involving the accommodation of mechanical interactions in the face of environmental uncertainties.

9.3 Conclusions

As the conclusion, from the joint angle measurement draw the relationship between the joint angle of MCP and PIP joint. Based on the relationship, we proposed a new actuated mechanism to assist the angular motion of each fingers. The device system can mimic and replace the task of physiotherapist in static and dynamic stretching with optimized the direction, speed and sufficient force. This device system also proposed to design patient specific finger and personalized their own disability. This system will support the future of rehabilitation approaches to make the reality of personalized rehabilitation.

From the force measurement draw the relationship between the current usage by the DC servo Motor and the Force applied during flexion and extension at MCP and DIP joint. Based on the relationship, we proposed a novel quantitative evaluation device during the both stretching static and dynamic. For safety purpose, we used push button as an approach to control the device according to comfortability of the end user.

Our study has presented ongoing research activities aimed at developing a dynamic rehabilitation device system for hand or finger with electrically modulated compliance. Preliminary results suggest the feasibility and efficacy of the proposed concept based on the use of DC servo motor coupled with lead screw mechanism as actuator to translate the rotational motion to linear motion in a link cam mechanism. Rehabilitation orthosis equipped with such actuators could offer several potential advantages over alternatives based on conventional actuation technologies. The most significant benefits include lightness, flexibility, comfort, wear ability, portability and lack of noise, along with low cost. Therefore, orthotic systems endowed with DC servomotor coupled with lead screw mechanism actuation have the potential to open new paradigms in the field of wearable mechatronic systems for rehabilitation.

Future developments may focus at developing actuators with improved performances, in order to enlarge the admissible working range of the hand rehabilitation system. Moreover, implemented of EMG based controlled are envisaged as further parallel developments.

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APPENDICES