Quantifying the force exerted by a therapist for the calibration of rehabilitation devices

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Declaration

I, George Johan Dyason hereby declare that the dissertation entitled "Quantifying the force exerted by a therapist for the calibration of rehabilitation devices" is my own original work and has not already been submitted to any other university or institution for examination.

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Signed on the 24th day of November 2019 at Potchefstroom.

Abstract

Robotic-assisted rehabilitation devices show promising results regarding increasing the recovery rate for stroke patients experiencing hemiparesis. A significant amount of research and development has been focused on robotic-assisted rehabilitation devices in recent years. These rehabilitation devices are intended to help patients regain functionality of their limbs after an event such as a stroke. This dissertation is focused on the development of a device aimed at hand rehabilitation.

A hand rehabilitation device in the form of an exoskeleton was designed, and a prototype was constructed. The rehabilitation device is capable of moving each finger of a patient's hand, including the thumb. The device is capable of measuring the forces applied to the patient as well as the amount of force applied by the device for each finger. The force measuring capability of the device can be used to measure external forces acting on the wearer's hand; this was used to measure the amount of force therapists apply to a patient in different positions.

The results showed that it is possible to quantify the forces applied by a therapist during rehabilitation exercises; however, due to the large fluctuations in the forces applied by different therapists, a therapist making use of robotic rehabilitation devices needs to be characterised and the device configured accordingly.

Keywords: *rehabilitation, exoskeleton, stroke, force, hand*

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List of Acronyms

ABS acrylonitrile butadiene styrene

ADC analogue to digital converter

ANOVA Analysis of Variance

CIMT Constraint-Induced Movement Therapy

DC direct current

DMA Direct Memory Access

DOF Degrees Of Freedom

EMG Electromyography

ENOB Effective Number of Bits

FCC Federal Communications Commission

fMRI Functional Magnetic Resonance Imaging

HAL Hardware Abstraction Layer

HSD Honest Significant Difference

MCP Metacarpophalangeal

MCU Micro Controller Unit

PCB Printed Circuit Board

PCTPE Plasticised Copolyamide Thermoplastic Elastomer

PWM Pulse Width Modulation

sEMG Surface Electromyography

TIA Technology Innovation Agency

USART Universal Synchronous/Asynchronous Receiver/Transmitter

USB Universal Serial Bus

VR Virtual Reality

WMSD work-related musculoskeletal disorders

Chapter 1

Introduction

This chapter provides background of hand rehabilitation and devices used to improve the rate of recovery. The research is motivated and justified. The goal of the research is discussed and outlined, followed by the methodology.

1.1 Background

Globally strokes are ranked as the fifth leading cause of death when considered separately from other cerebrovascular diseases [2]. The majority of strokes are ischemic, meaning they are caused by a narrowing of the arteries in the brain or caused by a thrombus (blood clot). Both of which results in oxygen starvation in parts of the brain. The oxygen-starved brain cells start dying within a few minutes. This often results in hemiparesis, which is a weakness of one side of the body. Hemiplegia is an extreme form of hemiparesis which results in complete paralysis of an entire half of the body [3].

The location of the stroke determines which side of the body is affected; if the stroke occurred in the left side of the brain the right side of the body will be weakened and vice versa.

Hemiparesis is treatable, to some extent, with treatment results typically depending on the severity of the injury and the intensity of the treatment. Various treatment options have been developed, and patients typically require physiotherapists or occupational therapist to find the best course of treatment.

The need for rehabilitation can arise from physical injury, a neurological event such as a stroke or other medical complications. After a stroke, the patient's limbs are in the same condition physically as they were before the stroke and it is only the controlling signals from the brain that is the cause of disability. Rehabilitation after an injury can be a lengthy process with diminishing returns over the course of treatment. This has led to the development of rehabilitation devices aimed at decreasing recovery times and increasing the efficacy of the rehabilitation process [4].

Recovery after a stroke has been proven to be more effective if the rehabilitation process is started as soon after the stroke as possible [5]. The use of rehabilitation devices can allow patients to receive therapy soon after the injury has occurred. Some of the existing devices are as simple as adjustable rubber bands or special playdough aimed at strengthening the patient's fingers [6]; others are complex pneumatic devices that aid the weakened limbs. The majority of rehabilitation programs in use still heavily rely on physical therapy, and trained professionals to rehabilitate the patients [7]. This can limit the amount of therapy a patient can receive per day and results in slower and, possibly less effective recovery. Physical therapy is also primarily focused on the larger limbs and gross motor skills while often neglecting fine motor skills. The reason for the latter can be attributed to the primary objective of patient mobility.

Robotic-assisted rehabilitation has been proven to be an effective method of regaining the fine motor skills that are often overlooked. These are primarily focused on the upper extremities such as the arm and hand [8].

1.2 Motivation and Justification

The rehabilitation devices currently on the market are not aimed at early stage recovery and mainly focus on retraining the hand specific tasks such as holding a pen and writing [9]. The majority of these devices, therefore, can generally not apply significant force and also do not measure the forces applied to the patient or by the patient.

Conventional therapy that is dependent on therapists relies on the skill and experience of a therapist to perform the rehabilitation effectively. For patients suffering from spastic hands, rehabilitation involves the therapist applying force to the hand to retrain the patient's brain to relax the muscles of the hand. This is accomplished through repetition which means patients have to spend a considerable amount of time in therapy. The amount of force applied by the therapist should be enough to be useful but not too much as to harm the patient. The latter is a key element in the training of therapists. The muscles of a patient with a spastic hand are contracted, applying too much force at once can cause harm to the tendons and the muscles of the hand. The goal of therapy is to get the brain to form new connections to control the muscles once again and not to exercise the muscles themselves.

For a robotic rehabilitation device to be widely applicable and safe, the force limits need to mimic those as applied by qualified therapists. By establishing a baseline of how much force is applied during the treatment of a spastic hand, the rehabilitation device can be made to replicate these exercises.

1.3 Problem Statement

Robotic-assisted rehabilitation devices currently available or in development are mainly focused on patients with weakened hands, and the devices use actuation methods such as servo motors, pneumatics or linear actuators. The devices typically apply very little force to the patient since the patient's hand offers little resistance against the movement of the device.

Patients who are left with a spastic hand after an injury will require different rehabilitation therapies to regain function in their hands. The fingers of a spastic hand will resist the movement of a therapist and a robotic-assisted rehabilitation device. During rehabilitation a therapist will apply some force to the patient's hand to slowly extend the patients range of motion.

The force applied by a therapist to a patient with a spastic hand is unknown and needs to be measured and characterised before a robot-assisted rehabilitation device can be used for patients with spastic hands. This will allow for robot-assisted rehabilitation devices to be used on patients with spastic hands and not only on patients with weakened hands.

1.4 Proposed Research

The research is focused on characterising the amount of force applied to a patient's hand during physical therapy. The results of the research can be used to calibrate a robotic rehabilitation device which would allow for increased recovery rates of patients.

Force characterisation can also be used to compare different therapists and determine if there is any correlation between the amount of force applied by different types of therapists and their experience levels. This research question aims to answer whether the force exerted by a therapist can be quantified and used for the calibration of mechanical rehabilitation devices?

1.5 Research Methodology

The research presented in this dissertation follows a methodology similar to the scientific method. The scientific method involves formulating a question after an observation has been made, from this a hypothesis is formulated. A prediction is made based on the hypothesis before the hypothesis is tested to generate results. The results can either support the predictions made or the predictions can be proven wrong. The test can be altered or a new hypothesis can be formulated after the results have been studied.

A project was started with the aim of developing a robotic hand rehabilitation device primarily for stroke patients. This led to an investigation into robot assisted rehabilitation devices and the capabilities of devices currently available and in development. An in-depth literature study was performed on the field of strokes and rehabilitation after strokes.

The conceptual design phase of the project focused on the movement and control of the device. As part of the conceptual design phase the limitations of the existing devices were investigated.

The literature study and conceptual design was used to formulate the hypothesis that therapists should theoretically apply similar amounts of force to the same patient. Robotic assisted rehabilitation devices can be improved if the forces therapists apply to patients during rehabilitation can be quantified.

The rehabilitation device that forms the foundation of this study required minor modifications to allow for the recording of force data. The verification for this dissertation is to confirm that the force measurement capability of the rehabilitation device was functioning correctly and was reliable.

1.6 Project Overview

The project started as a final year project in 2014 where a student developed a hand rehabilitation device. The project was followed up by the NeuHand project with financial support from the Technology Innovation Agency. The NeuHand project aimed to develop a cost effective robotic assisted rehabilitation device that focused on the hand. The requirements of the project is discussed in more detail in Chapter three.

1.7 Dissertation Overview

The structure of the remainder of the dissertation will be as follows. A detailed literature study, Chapter two, is followed by Chapter three giving an overview of the existing rehabilitation device and the modifications made to allow for the data to be captured.

Chapter four focuses on the calibration process of the force sensors used and the verification of the calibration. Results and statistical analysis of the captured data are discussed in Chapter five. The dissertation is concluded in Chapter six.

Chapter 2

Literature Study

This chapter reviews the existing literature related to the research field of this study. The biological aspects related to rehabilitation and the potential benefits of robot assisted rehabilitation devices are reviewed. Finally the existing rehabilitation devices currently available and under development is studied and compared.

2.1 The Human Hand

The human hand is a complex and intricate appendage and is comprised of three main sections when referring to the bones. These sections are the phalanges, the metacarpals and the carpal bones. The phalanges are the bones that make up the fingers, each finger consists of three phalanges. The tip or end of the finger is known as the distal phalanx, next is the middle phalanx and then the proximal phalanx that reaches the metacarpal [1]. The metacarpal make up the dorsal part of the hand, and the carpal bones join the metacarpals to the rest of the arm.

The thumb is generally considered a digit rather than a finger since it has only one interphalangeal joint and two phalanges, namely a distal phalanx and a proximal phalanx. A basic diagram of the human hand is shown in figure 2.1.

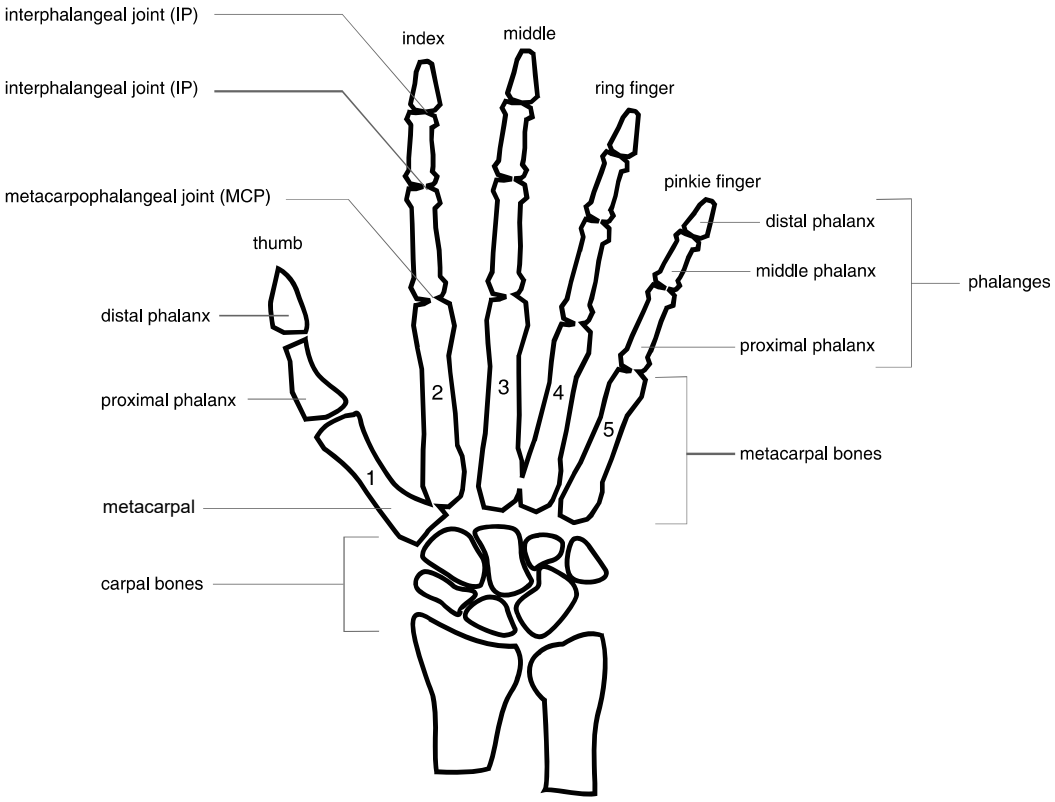


Figure 2.1: Bones of the hand

The muscles that control the flexion and extension of the fingers are located in the forearm and connected to the fingers via a series of longitudinal fibres(tendons), the actuation of the thumb is accomplished similarly through a different set of longitudinal fibres [1]. The muscles in the forearm narrows into tendons, these tendons connects the fingers through a series of sheaths and ligaments along the arm and wrist that guides the tendons to make flexion and extension possible; an illustration of this is shown in figure 2.2.

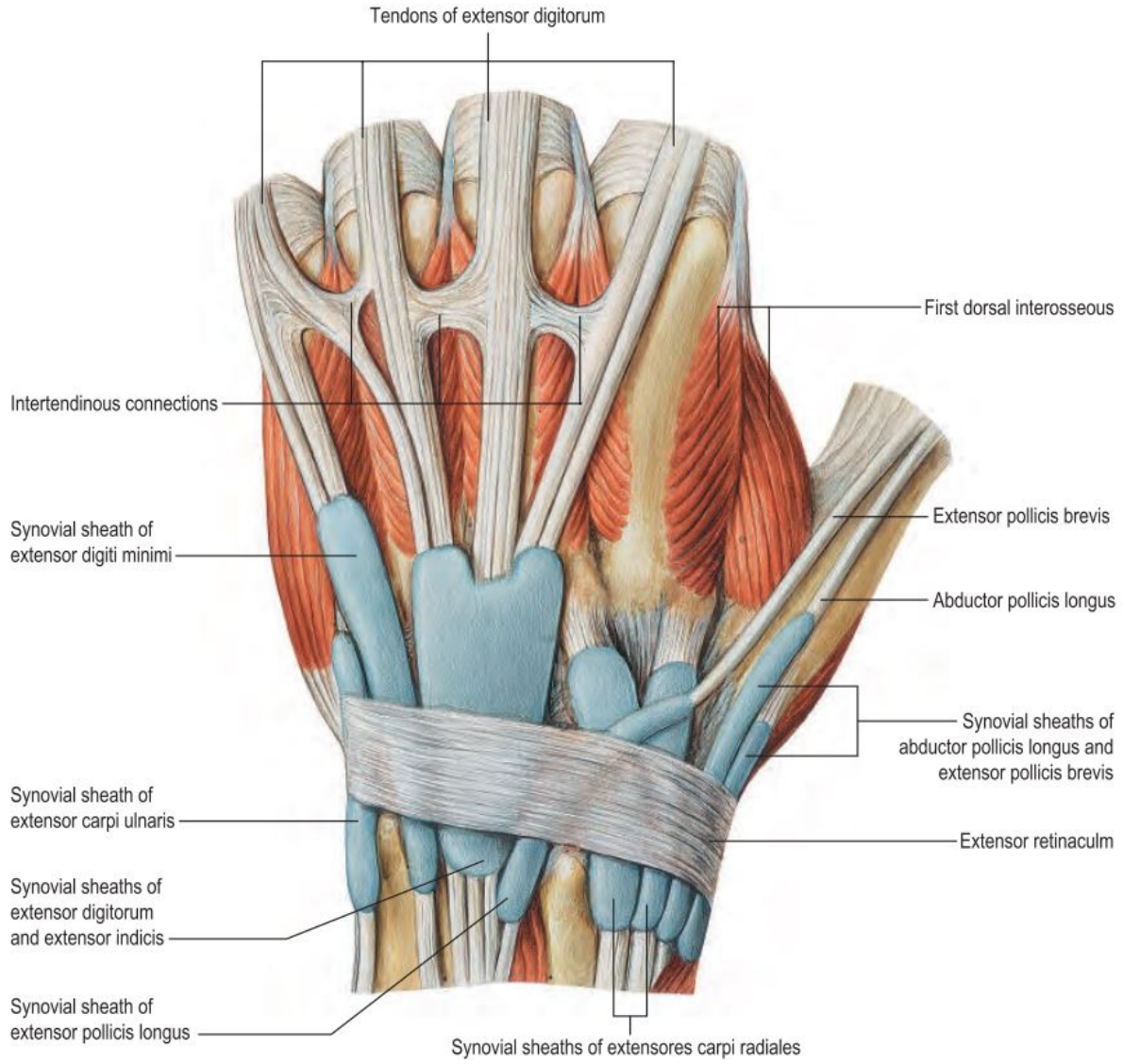


Figure 2.2: Shieths and tendons of the wrist and hand. Adapted from Gray's Anatomy. The Anatomical basis of clinical practice. p.864 [1]

Flexors, the muscles responsible for closing the hand into a fist, is partially attached to the humerus(the upper forearm) and to the radius and the ulna [1]. These muscles also form part of the muscles responsible for rotating(supinating) the hand. The extensors of the wrist and fingers are attached to the humerus at the lateral epicondyle and the ulna. The lateral epicondile is a small raised portion of the humerus that forms the anchor point for muscles. The tendons connected to the extensors pass down the dorsal side of the forearm to the wrist.

The thumb shares some muscles with the other digits. The abductor muscles of the thumb are the muscles located in the hand and are responsible for moving the thumb towards and perpendicular to the the palm.

2.2 Muscle Control

The central motor system is responsible for all muscle activity, which includes voluntary and involuntary activities, and is tasked with controlling both movements and forces. The primary motor cortex generally referred to as M1, is one of the main parts of the central motor system and is responsible for motor control. The role of the motor cortex is to generate neural impulses responsible for movements.

Muscle control is contra-lateral in regards to the motor cortex; resulting in the right hemisphere controlling the left side of the body and vice versa. Each body part or muscle group of the body has a separate area in the motor cortex and the size allocated to each group differs [10]. This size difference is related to the complexity of the movements of that part; for instance, the human hand has quite complex movements compared to the foot and thus has a higher allocation.

Muscle movement is also partially controlled by other regions of the brain of which the premotor cortex and the supplementary motor area is the most important after M1. Another area of motor control is the posterior parietal cortex which is mainly responsible for converting visual inputs into movements. The posterior parietal cortex is not directly responsible for motor movements but merely provide information to the premotor cortex as do the other supplementary motor areas of the brain. The posterior parietal cortex provides M1 with information such as the hand's proximity to an object and assists in picking up objects.

The primary motor cortex (M1) and supplementary areas are connected to the corticospinal tract which is directly connected to the spine. The signals from the motor cortex travel down the spinal white matter to synapse on neurons in the spinal cords ventral horn. The neurons of the ventral horn send axons out of the ventral roots to individual muscle fibres. An axon is the nerve fibres carrying the electrical impulses used to control muscles. The combination of the muscle fibres, axon and ventral horn neuron is called a motor unit.

Smaller motor units typically control smaller muscle fibres. A single motor neuron of a motor unit can be connected to multiple muscle fibres, but each muscle fibre can only be connected to a single neuron. This means that a group of muscle fibres contracts when a single motor neuron fires [1], [11].

Each motor neuron can belong to one of two classes, the alpha-motor neuron and gamma-motor neuron. The alpha-motor neuron provides direct control of muscle fibres and is responsible for regulating force. The gamma-motor neuron provides feedback to the brain about the length of the muscle. A simplified version is shown in figure 2.3.

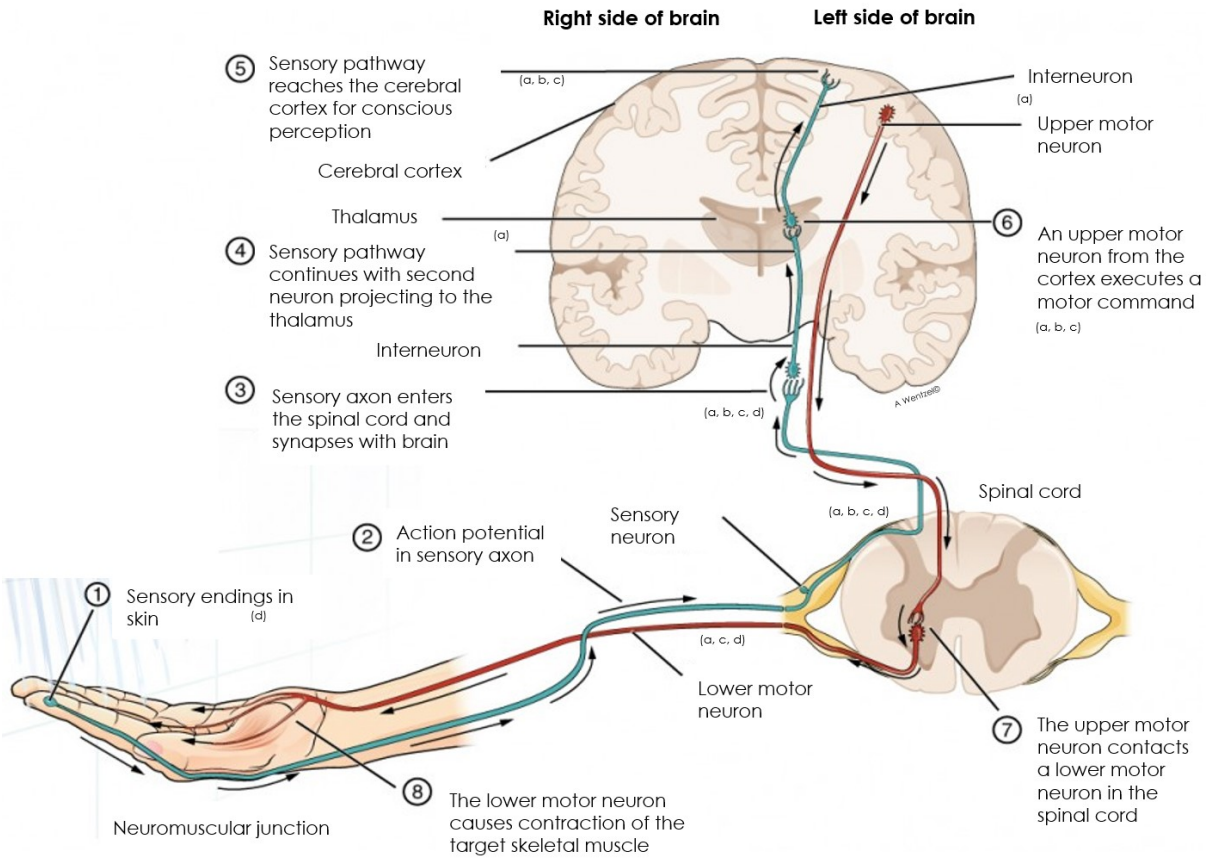


Figure 2.3: Figure showing how the motor cortex is connected to the hand. Compiled as described in (a)Kumru et al, 2016; (b)Montagna et al, 2005; (c) Rodriguez et al, 2005; (d) Schieber M.H. (2009) Motor Cortex – Hand Movements and Plasticity.

When a stroke or similar event occurs that damages the central motor system, it can disrupt the impulses sent to the muscles. The limbs are physically unaffected but the disrupted signals as a result of the stroke often causes disabilities. During rehabilitation the brain has to reorganise itself and find a way to restore functionality to the affected area, this is known as cortical reorganisation and is discussed in the next section.

2.2.1 Cortical Reorganization

The rehabilitation process after a stroke is based on the known cortical reorganisation capabilities of the human brain. The field of cortical reorganisation has been studied extensively [12], [13]. Studies involving monkeys and rats [5] have given researchers insights into the brain's ability to compensate for damage. These studies have shown that starting the rehabilitation process as soon as possible after a stroke or other damaging event, increases the efficacy of cortical reorganisation.

A study that focused on cortical reorganisation after stroke [14] confirmed the research from [5] and other researchers [12], which found that for a short while after the stroke there is an increase in neural activity based on fMRI scans. It was observed that the increase in activity does not start immediately after the stroke but rather starts to increase a few days after the event and only lasts a few weeks. During this time of increased activity, the patients were shown to have a better chance of functional recovery which correlated with the studies done on monkeys [5].

Using fMRI to determine brain activity [14] showed that the neural activity of a stroke patient two days after the stroke is slightly less than compared to a healthy subject. The activity increases steadily, and after five days the neural activity of the patient (while trying to move the affected hand) is slightly elevated. The increased neural activity suggests that the brain is actively reorganising itself to regain control of the affected hand. Neural activity was seen to be nominal for the unaffected hand throughout the study period. Ten days after the stroke neural activity was increased drastically and the side of the brain associated with the unaffected hand also showed increased activity.

2.2.2 Electromyography

Electromyography or better known by the acronym EMG is the study of the electrical signals controlling the muscles. EMG signals can be used to study muscle activity in real time and can be used to extrapolate muscle forces [11]. The relationship between the EMG signals and muscle forces has led the development of different biomechanical models [15].

The challenge with EMG signals is isolating signals sent to a specific muscle since most muscle groups work together to actuate the human body and an individual can not consciously actuate only one specific muscle. This becomes especially troublesome when studying the muscles controlling the fingers. Fingers are actuated by the contraction of muscles in the forearm, these muscles are in close vicinity to each other and lie deep within in the forearm. A study [16] aimed at the classification of finger movements using electromyography used pattern recognition as a method of recognising different hand movements through myoelectric pattern recognition [17]. Identifying different hand movements have been the topic of many studies in recent years [18], the results can be used to develop artificial limbs for amputees. Artificial limb advancements led to the development of many other classification methods, but these methods tend to ignore force extrapolation.

Surface EMG electrodes are typically used in an array when the aim is to detect finger movements. This allows for noise to be filtered out while still collecting enough information to determine finger movements. Different methods of gesture classification may require the sensors to be placed in specific locations and require a specific amount of electrodes. Typically when more electrodes were used, more movement patterns could be identified. One study used four EMG electrodes to determine six finger movements [18].

EMG is not a suitable solution for both movement detection, and force measurements for the rehabilitation device of this study since the EMG signals of stroke patients tend to be weaker and therefore harder to classify than that of a healthy subject.

2.3 Hand Grip-Strength

The grip strength of a hand has been the focus of previous studies [19], primarily to determine the effect of tools commonly associated with work-related musculoskeletal disorders (WMSD). The national institute of Occupational Safety and Health of America developed a glove for measuring the pressures exerted by the wearer on different hand tools. The quantified grip strength was used to assess the risk of WMSD.

Hand grip-strength can be used as a measure of muscle weakness of stroke patients. Measuring the grip strength of the hand can provide insight into the strength of the upper extremities of a patient. Studies [20], [21] focused on the correlation between handgrip strength and the strength of the rest of the upper extremities. Results showed that there is a strong correlation between the grip strength and the arm strength. This means that grip strength can be used as a means of inferring the strength of the upper extremities and without resorting to, expensive dynamometers typically used for measuring the arm strength. Furthermore, grip-strength can also be used as a progress indicator of sorts for rehabilitation schemes.

2.4 Stroke

When a section of the brain is starved of oxygen due to a lack of, or severe reduction of, blood flow to a part of the brain, it is referred to as an ischemic stroke. A stroke can also be caused by excessive bleeding in the brain due to a brain aneurysm bursting or an artery leaking. The blood around the brain creates swelling and pressure which damages brain cells [7].

Brain damage results in over 80% of stroke patients experiencing some weakness in one side of their body. This weakness is known as hemiparesis. Hemiplegia is the most severe form of hemiparesis and is the term used for patients who are completely paralysed in one side of their body.

Hemiparesis can also be caused by a traumatic brain injury or other medical conditions such as brain tumours, multiple sclerosis, autoimmune conditions, brain infections and conditions such as cerebral palsy [3].

Post-stroke hemiparesis often results in patients struggling to accomplish tasks such as moving the arms and legs of the affected side. Balance is also affected, typically resulting in the patient not being able to walk. Tasks that require smaller and more precise hand movements are made difficult and often impossible due to the hemiparesis. The severity of the loss of limb control varies and is dependant on the location in the brain where the stroke occurred and the extent of the damage. This means some patients recover faster and to a better extent than others.

According to the National Stroke Association [3], the patient's behaviour can also be affected by a stroke. Left-sided hemiparesis, as a result of the stroke happening in the right side of the brain, may result in patients struggling to communicate non-verbally. Damage in the right side of the brain may also result in memory problems and patients talking more than before. In the case of a stroke in the left side of the brain, resulting in right-sided hemiparesis, the patients tend to have trouble communicating verbally and may have trouble understanding other people.

In some cases, the brain stem, the lower part of the brain, is damaged resulting in both sides of the body being affected. In extreme cases, this may lead to the patient not being able to move below the neck and being unable to speak. Resulting in the patient being in a medical condition known as locked-in syndrome [3].

For patients struggling with post-stroke or similarly induced hemiparesis, rehabilitation is often recommended to regain some of the lost functionality [22]. The rehabilitation is not to strengthen the affected limbs themselves but rather to help the brain to reorganise itself and create new control pathways to compensate for the damaged areas.

The American National Stroke Association recommends treatment and rehabilitation as soon as possible after the stroke. A therapist is usually required to help restore functionality and attempt to prevent permanent disability as a result of the stroke [3]. Post-stroke patients often need to relearn skills used in day-to-day activities and regain fine motor skills. These fine motor skills are predominantly located in the upper limbs and hands and are what allows us to perform intricate tasks. Additionally, depending on the side of the brain the stroke occurred in, patients may also require speech and language therapy.

2.5 Stroke Rehabilitation Techniques

Physical rehabilitation typically comprises of range of motion training, strengthening exercises and practising fine motor skills. The activities are all aimed at regaining control over the limbs, although the limbs are not the cause of the disability. Several techniques to help the brain recover have been developed with one such an experimental technique called mental practice or motor imagery [10]. During this exercise, the patient imagines moving the affected limbs, and this helps the brain practice the movement as if the limbs were moving.

It should be noted that in the majority of cases the limbs and hands of the patients were functioning normally before the stroke, the goal of rehabilitation is to retrain the brain, not the muscles. The muscles might be in a relaxed or contracted state. The patient can be injured if the limbs or fingers are forced in the desired direction. For example, if a patient has a closed spastic hand as a result of the stroke and the hand is forced open, it may result in a sprain. The muscles will be forcing the hand closed while the external force is working against them, this can result in the ligaments and tendons stretching and tearing with enough force. This should be avoided since it will induce unwanted injuries.

Patients who have some movement in the weaker limb may benefit from Constraint-Induced Movement Therapy (CIMT) [3]. This involves forcing the patient to use the weaker limb over the stronger one and is typically used to strengthen the arms of post-stroke patients. A study by Liepert [14] showed that constraint-induced movement therapy can benefit stroke patients. It is important to remember that this rehabilitation technique can only be applied to patients who have a moderate amount of control over the weaker limb and therefore can perform most tasks with the stroke-affected limb. Liepert required that all participants in the study had at least six months of recovery after the stroke.

Lower limb exercises can be performed with the help of special treadmills that support some of the patient's body weight to help them with walking and allowing the affected limb to be rehabilitated and possibly give patients the ability to walk again [23].

More modern and experimental rehabilitation techniques involve technology such as Virtual Reality (VR) systems which immerse patients into environments to encourage them to move and use their weaker limbs. A study [24] concluded that the VR system was not statistically more effective than typical treatments. The VR system was shown to be useful for the patients in regaining some upper limb functionality, especially in terms of performing daily activities. There are a variety of different VR or augmented reality systems available for rehabilitation [25]. The types of exercises and VR technology is still being developed and is currently a novel tool that may assist in conventional rehabilitation.

The goal of most of the physical rehabilitation techniques is to re-establish the appropriate pathways of the brain to regain control over the limbs. This can either be done with repetitive exercises or by tricking the brain.

One way of tricking the brain is with a mirror, this experimental technique involves hiding the weak limb behind a mirror and placing the unaffected limb in front of the mirror, this gives the illusion that the weaker hand is moving [26]. This has been shown to increase excitability of the primary motor cortex of the brain. This technique works because the motor cortex is excitable by both ipsilateral limb movement or observation of the movement of contralateral limb movement [27].

Robotic therapies have, in recent years, become a common research topic [28], [29], [8], [9]. Robotic rehabilitation therapy has many forms and is applicable to almost all affected limbs. These experimental devices typically aid the patient's movement, either for exercise or to assist the patient in everyday activities. A common form of robotic rehabilitation is in the form of exoskeletons, either for full upper limb rehabilitation, focusing on the arm and shoulder muscle recovery, or a smaller device mainly focused on the hand [30]. The hand exoskeletons focus mainly on re-learning the fine motor skills required for normal hand activities.

2.5.1 Conventional Hand Rehabilitation Instruments and Aids

The rehabilitation device used depends on the stage of recovery, the severity of the impairment and the type of impairment. Some patients requires devices for rehabilitation only, this can be for strength or dexterity training. Other patients may require devices to assist them with activities of daily living. This section will discuss devices and techniques that a patient can use to aid rehabilitation on their own.

Conventional rehabilitation devices can include very simple devices such as balls or putties for patients to press against or more modern methods such as computer games with external instruments. Rehabilitation devices can also be passive devices that simply hold the patient's hand in a desired position to slowly relax the muscles.

Choosing a device will depend on the stage of recovery of a patient and the severity and category of injury. For example a patient that is capable of moving his or her fingers but is lacking in strength will benefit from devices and methods that resists their movement. Resistive devices can either be as simple as balls or putties or devices using springs or rubber bands to provide resistance for the patient to work against. The SaeboGlove Kit is a good example of such a device [31].

Saebo rehabilitation techniques for strengthening the impaired hand requires the patient to simply repeat making a fist and extending the hand with the fingers spread out. As stated in the section about cortical reorganisation, repetition is an important part of rehabilitation.

Patients who has lost dexterity in their hands might also benefit from the putties but rather than pressing against the putty, the patient can hold the putty with their fingers in different positions and manipulate the putty [32]. Other exercises for dexterity rehabilitation is to pickup and manipulate small objects such as coins or a pen. One such excise with a pen is to place the pen on a flat surface and using the tips of the fingers to rotate the pen. As with all rehabilitation exercises repetition is key to the efficacy of the exercise.

Dexterity training can also be done without an aid by starting with an open hand and moving each finger to the thumb so the tip of the finger touches the tip of the thumb and repeating this for each finger [33].

2.5.2 Robotic Assisted Therapy

The standard rehabilitation process typically consists of the patient having short therapy sessions once a day. Studies have shown that therapy can be made more effective if the sessions can be extended. An increase in therapy sessions and repetitive movement exercises has shown to be more effective at increasing the rate at which the brain forms new pathways [34], [5].

In a study aimed at determining the efficacy of robot-assisted rehabilitation, it was found that when robot-assisted rehabilitation techniques were used, patients showed some improvements [8], [35]. The study also found that when robotic-assisted therapy was used in conjunction with conventional therapy, patients showed an extended period of improvement. The study was conducted with 56 participants with sub-acute stroke, and although the study focused on the upper limb recovery, the recovery process is similar to other extremities.

A more extensive study comprising of 127 chronic stroke participants [8], also reported that patients who received robot-assisted rehabilitation showed an increase in motor recovery versus conventional rehabilitation. The benefit of robot-assisted therapy was, however, not observed until after 36 weeks of therapy.

The main benefit of robot-assisted therapy is the amount of therapy a patient is capable of receiving since (ideally) the patient no longer needs a therapist present to perform certain exercises. This increase in frequency and intensity of therapy is, in many cases, the most significant contributor to an increased recovery rate [8], [36], [28]. These studies also agree that repetition is a key part of rehabilitation.

Robotic-assisted therapy can, in most cases, be performed without formal assistance and therefore allow the patient to effectively exercise more than conventional methods [37], [38].

2.6 Existing Robotic Hand Rehabilitation Devices

The rehabilitation device is intended to help patients regain functionality of their hands after an event such as a stroke or other event resulting in similar injuries. Hand and upper limb paralysis or weakness due to hemiparesis is a common challenge faced by more than 80% of stroke patients.

Patients generally recover strength and motor skills after the stroke, with the chance and rate of recovery their highest within the first three months after the stroke [34]. Rehabilitation devices increase the recovery rate by increasing the amount of therapy available to the patient.

A short review of some of the existing robotic rehabilitation devices for the hand follows. Only devices that focus on the hand exclusively will be included. There are two distinct groups of devices, soft robotic devices, meaning devices with little to no rigid components in contact with the patient. The other is in the form of an exoskeleton; these are devices which has a rigid series of linkages and a mechanical structure.

This section will first discuss a review study done regarding the soft robotic devices and then consider some of the exoskeleton and other rigid type devices. For this study, only devices that focus on the hand exclusively will be included. It should be mentioned that there are a number of other exoskeleton type rehabilitation devices that focus more on upper limb rehabilitation than the hand itself.

Spring operated devices such as the handSOME [6] device will not be investigated. Hand exoskeleton devices not focused on rehabilitation applications will also be excluded.

2.6.1 Soft Robotic Devices Review

Robotic-assisted rehabilitation has become a popular research and development topic, a study reviewing some of the recent developments in the field of soft robots for rehabilitation provides a narrative review [39]. The authors defined soft robot as follows: ”no rigid components on the robot-human interface or minimal rigid components that will not impose physical restraints in joint motions”. From the 44 unique devices that were reviewed, most of the devices used pneumatics for movements.

As part of the study, the safety measures present in the devices were reviewed, and it was found that of the 44 devices only 12 had hardware safety mechanisms in place that was not purely limited to software-based approaches. A possible explanation for the lack of safety precautions in these devices are that many of these devices are still prototypes [39].

When considering feedback from these devices, it was found that less than 30% of the devices provided some form of feedback. The ability of a device to measure parameters of the patient and respond to them is a major advantage. Chu et al. [39] state that a possible reason for the lack of feedback is that for purely assistive devices feedback is not strictly required. The devices using surface EMG signals as feedback would be more suitable for patients who have injuries or disabilities that are not related to neurological damage and for devices not aimed at finger movements. The sEMG feedback mechanism was, however, the most popular choice with 42% of devices with feedback using this method.

The Degrees Of Freedom (DOF) of the devices were also compared, and the majority of devices is capable of 15 degrees of freedom. This means each finger and the thumb is actuated. Each actuated finger contributed three degrees of freedom. The thumb also contributes three DOF.

Devices with the primary focus on gripping and grasping objects where only the necessary digits were actuated, typically had 9 DOF and was the second most popular configuration. Another option is to have the fingers actuated but without actuating the thumb. The thumb plays an important part in daily activities, and this is possibly why the 15 DOF configuration is more popular even though it is significantly more complex.

The degrees of freedom of the devices only considers the movement of the fingers and the thumb; this means that if the device uses one actuator to move all digits, the device still counts as a 15 DOF device. Only six of the 19 devices with 15 DOF or more is capable of independent finger movements.

2.6.2 Exoskeleton Rehabilitation Devices

There is a wide variety of exoskeleton configurations. However, this study focused on active rehabilitation devices capable of assisting the patient during opening and closing of their hands.

The actuation method used for active hand exoskeleton devices can range from simple servos to more complex pneumatic systems. One system utilised Bowden cables to actuate each finger joint, this allows for bi-directional finger movement of the fingers and relocates the bulk of the mechanical parts away from the patient [40]. This exoskeleton also uses hall effect sensors to measure the angle of each joint.

A different approach to Bowden style actuation is to place the actuators on the patient, this results in a heavier and bulkier device but does make it more portable since there is no external actuator assembly. The integrated approach could allow each finger to be flexed and extended completely and independantly [41]. The device developed by the University of Technology in Sydney uses the unimpaired hand to help with the rehabilitation of the impaired hand, this is known as bilateral therapy. The exoskeleton assists the impaired hand to mimic the movement of the healthy hand. The movement of the unimpaired hand is tracked by a glove onto which flex sensors are added that relays the state of the finger to a controller.

As with the soft robotic rehabilitation devices, the degrees of freedom of a device will ultimately determine the type of exercises that can be performed. Some devices are intended for repetitive training programs wherein the patient performs a single task repeatedly to regain functionality, and this has proven to increase the recovery rate of stroke patients [42]. For simple repetitive tasks, a device with fewer degrees of freedom might be more suitable.

Some rehabilitation devices have a very focused area of application; one such device is the reScribe device developed by the University of Cape Town [9]. The device is focused on rehabilitation of the fine motor skills through handwriting exercises.

2.7 Force Measurement Techniques

This dissertation focuses on forces applied to patients. The following is a brief investigation into force measurement techniques and their relevant applications.

The methods used for force measurement is dependant on the application and actuation method used. For example, with a pneumatic operated device, a pressure sensor can be utilised as a force sensor since the pressure in the system is relative to the amount of force applied.

When using electrically actuated devices, a similar method can be used since the amount of power drawn by the motor is related to the force applied by the actuator. The drawback of this method of force measurement is that it is not a direct measurement, the force measurement is inferred from the current drawn and supplied voltage. This also requires two values to be measured, inducing more uncertainties into the system. If the mechanical structure allows for it, a better solution would be to use a dedicated force sensor such as a strain gauge.

A strain gauge is a thin metallic strip of which the resistance changes when the strip is stretched or compressed. Strain gauges are typically bonded to a bar or shaft onto which a force is applied, the force causes the bar or shaft to flex which results in the strain gauge to also deform. The change in resistance due to the deformation of the strip is very small and therefore hard to measure accurately [43], [44]. The most common type of strain gauge is called a bonded metallic strain gauge which typically consists of a fine wire or metallic foil that is arranged into a grid pattern. When stress is applied, the the change in resistance of all the strips in parallel will add up and result in a larger change which is easier to measure.

The change in resistance of a stain gauge is typically measured with the help of a Wheatstone bridge. A Wheatstone bridge is a circuit consisting of four resistors with two resistors in series, and this pair of resistors are in parallel with a similar pair [44]. The Wheatstone bridge is excited at one of the points where the two pairs meet and grounded at the other junction. Figure 2.4 is a simple representation of a Wheatstone bridge.

With a Wheatstone bridge it is possible to measure the resistance of an unknown resistor if the resistance of the other three resistors are known. The output of a Wheatstone bridge is the voltage between the two pairs, this is indicated as V_m in Figure 3.3. The voltage measurement will be zero if all the resistors are equal. If a resistor is replaced by a variable resistance, the measurement of V_m will change accordingly and the resistance of the unknown resistor can be calculated.

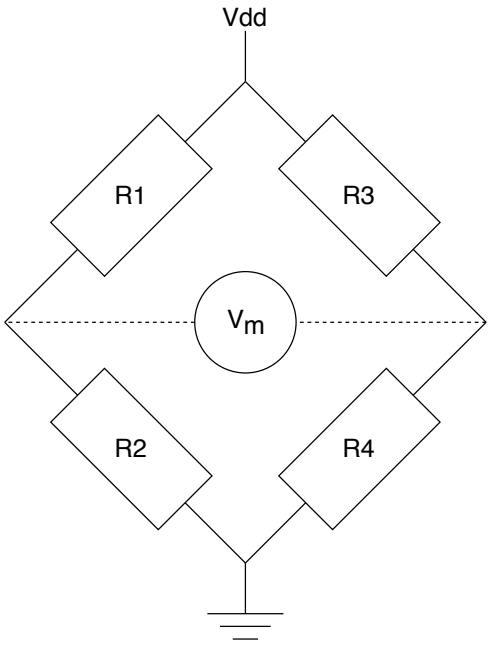


Figure 2.4: Typical Wheatstone Bridge

Two of the resistors of a Wheatstone bridge can be replaced with two stain gauges, the two strain gauges should have the same resistance when not deformed and the two fixed resistors should have the same resistance as the nominal resistance of the strain gauges for the Wheatstone bridge to be balanced. If the strain gauges is deformed, their resistance will change which will result in the Wheatstone bridge being unbalanced and V_m will no longer be zero. The voltage can be measured using an analogue to digital converter. The measured voltage is still very small and a high resolution analogue to digital converter is required

Typically when strain gauges are used with a Wheatstone bridge four strain gauges make up the entire Wheatstone bridge, this is known as a full bridge configuration and delivers the best results. This configuration is capable of self-compensating for changes in temperature. A full bridge configuration should be used whenever the mechanical structure allows for it.

When two strain gauges are used to form a half bridge configuration, two fixed value resistors are used to make up the rest of the bridge. A half bridge configuration is also capable of self-compensating for temperature changes to a degree although the fixed value resistors might not react in the same manner as the strain gauges to changes in temperature. For this application a half bridge Wheatstone configuration was used with R3 and R4 from figure 2.4 representing the strain gauges.

2.8 Conclusion

The contents of this chapter gives a short overview of the human hand and discusses the biological aspects of stroke recovery. The neurological aspects of stroke recovery and rehabilitation are discussed and explains why robotic-assisted rehabilitation devices can be an effective tool to help increase the recovery rate of stroke patients. This chapter also discusses the robotic rehabilitation devices currently available and under development.

Based on the literature study and the existing rehabilitation devices reviewed, the robotic hand rehabilitation device required to answer the research problem of this dissertation needs to be able to measure the forces applied to the patient and need to measure the forces the patient applies to the device. The device has to be able to move each finger independently and should, therefore, have at least 15 degrees of freedom.

A hard exoskeleton type device will be better capable of measuring and applying forces to patients with a limited range motion than a soft robotic device. An exoskeleton device is easier to configure for different hands and can be divided into smaller sections; making equipping the device easier for patients and therapists. The design aspects of the exoskeleton type hand rehabilitation device are discussed in Chapter three.

Chapter 3

Device Overview

Studies have shown the potential benefits robotic rehabilitation devices can have for patients who have suffered a stroke or a cerebral vascular injury by increasing the recovery rate when combined with conventional therapy. This chapter provides a detailed overview of a device that has been developed for this study and the technologies used in it. The device is an exoskeleton type rehabilitation device focused on increasing the range of motion and strength of a patient's hand as well as allowing a patient to repeatedly perform training exercises.

3.1 Problem Statement

This study aims to characterise the force applied to patients during rehabilitation therapy. The force measurement capability of the device is intended to add functionality in terms of exercises and to act as a safety measure. For this study, the device will be used to measure the force applied to the device by a therapist.

3.2 Motivation

The goal of existing robot-assisted rehabilitation devices is to assist a therapist with the slow process of rehabilitation. The majority of these devices tend to focus on fine motor skills and regaining grip strength with patients who have weakened hands but with the full range of motion. Existing rehabilitation devices typically have a form of position feedback and in some cases force measurements. The force measurement is either a safety mechanism or a method to determine if the patient is regaining strength.

Most devices are not intended for patients with a limited range of motion or spastic hands. The therapy of a patient who has a limited range of motion of their hands differs from the conventional therapy since in the majority of cases force need to be applied to the patient. The amount of force typically used in these types of exercises is currently unknown and is thus the focus of this study.

Therapists apply force to a patient according to what they consider to be enough force to aid in the rehabilitation process. One essential aspect to consider is that the force applied to the patient should not harm the patient.

3.3 Design Requirements

After reviewing the existing hand exoskeletons the goal and specifications for the rehabilitation device were defined. A device was developed for a Technology Innovation Agency (TIA) project as a follow-up of a previous prototype. The initial device was a simple device capable of opening and closing the hand. It was constructed out of metal and was not adjustable for different hand sizes.

The primary goal for the new device is to allow for all the fingers and the thumb to move independently while still keeping the cost of the device down. The device should be adjustable for different size hands, ranging from small female hands to large male hands.

The device is intended for personal use with the assistance of a professional. A patient should, therefore, be able to equip and operate the device themselves after a consultation with a trained therapist. The device should be portable and lightweight.

The material requirements for the device were considered along with the environmental requirements and, as such, the device is made of hypo-allergenic materials that are strong enough for the application, is easy to manufacture, cost-effective, and corrosion resistant.

The key requirements are listed below:

- The device should be able to aid patients with different disabilities; primarily spastic or weak hands.
- The patient should be able to equip and operate the device with one hand.
- The device needs to be compact and portable as to not be restricted to usage in medical or care facilities.
- A patient should be able to operate the device themselves after a consultation with a therapist and limited training.

- Safety features should be implemented to prevent injury to a patient.
- The device should be configurable to fit different hand sizes, ranging from small female hands to large male hands.
- The device should be able to function in both medical facilities and in residential environments.
- The control board should be as small as possible and preferably wearable.
- The material used for the device should be hypo-allergenic and corrosion resistant.
- TIA required that the device be cost effective to manufacture.

Additional requirements for the study includes:

- A serial port should be made available for data capture.
- The components of the structure of the device should be optimised for 3D printing with a conventional filament deposition modelling (FDM) printer.
- The design should use as many off the shelf components as possible.

3.4 Detailed design

This section provides a brief summary of the major components of the control electronics. Components such as power regulation and other passive components will not be discussed. The schematics for the control board is provided in Appendix F. The architecture of the control board is shown in figure 3.1.

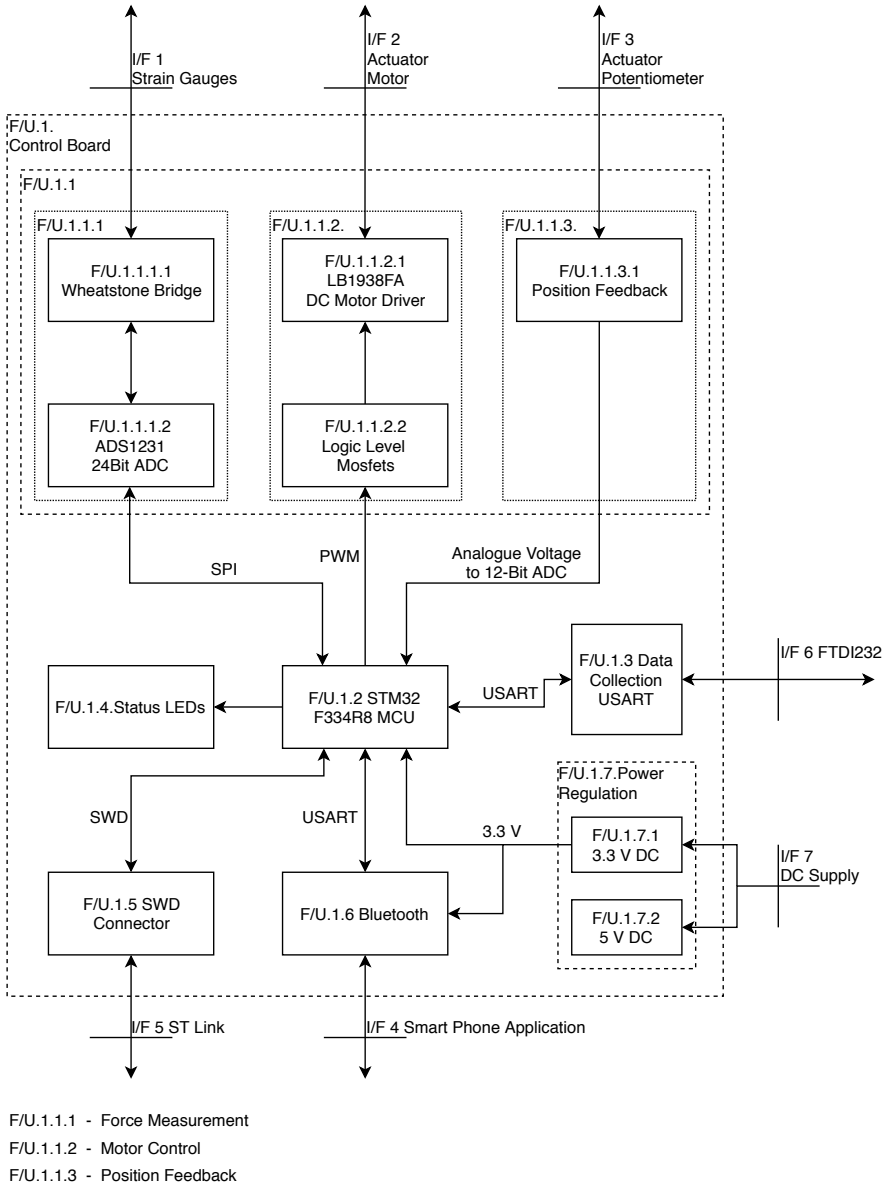


Figure 3.1: Control Board Architecture Diagram

Figure 3.1 shows the design of the functional architecture of the control board of the rehabilitation device. The control board is designed to control all five fingers of the device, F/U.1.1 is therefore repeated five times and is only shown once to simplify the diagram. F/U.1.3 is an additional USART Connection only used for data collection purposes through an FTDI232 serial to USB module (I/F 6).

3.4.1 Micro Controller

The microcontroller was selected based on the following criteria:

- Five or more analogue to digital converters with a resolution of 8-bits or higher.
- Two or more UARTs, for bluetooth and data capture.
- Capable of ten or more PWM outputs for motor control.
- The microcontroller should be available in a package that can be soldered by hand.
- A microcontroller from ST Microelectronics or Microchip(Atmel) was preferred since the designer was familiar with these environments.
- Availability and cost of programmers. Microcontrollers requires specialized programmers; the designer had access to a STlink and a PICkit 3.

Two microcontrollers were considered. The ATSAM4LC2B from Microchip(Atmel) and the STM32F334-R8 from ST Microelectronics were the main candidates. When the requirements are considered, these microcontrollers are equally well suited to the requirements. The STM32 microcontroller was selected due to the developer being more familiar with the STM32 environment and this would accelerate the development process.

The microcontroller used for the control of the device is the STM32F334-R8 from ST Microelectronics [45]. This micro-controller is classified as a mixed signals Micro Controller Unit (MCU) consisting of an ARM Cortex-M4 core CPU in a 64-pin package (PQFP64). The microcontroller is capable of being clocked at 72 MHz with 64 kilobytes of flash memory. The microcontroller has a total of three USARTs, one of which is used for Bluetooth communication and another is used for data capture from the device.

The microcontroller has two configurable analogue to digital converter (ADC) with a resolution of 12 bits that is capable of measuring up to 21 individual channels. The position feedback from the actuators is measured by five separate channels all controlled by the internal Direct Memory Access (DMA) controller of the microcontroller. The microcontroller is capable of supplying 22 Pulse Width Modulation (PWM) signals that can be used for motor control. The device requires two PWM channels per finger for bi-directional control of the actuators.

3.4.2 Firmware

The firmware for the rehabilitation device was created using a combination of the STM32Cube package and MDK Version 5 (Keil). These packages are recommended by the manufacturer of the microcontroller used in the device. The STM32Cube includes the STMCubeMX package that has a graphical configuration tool that simplifies the configuration of the STM32 series microcontrollers and includes STM32Cube HAL. STMCube HAL is a library that is used to control the peripherals of the STM32 microcontroller. MDK Version 5 Keil is a C or C++ compiler that is compatible with the STM32Cube package. The firmware is loaded onto the device via an ST Link single wire debug interface.

The graphical configuration of the STM32CubeMX tool is shown in figure 3.2 for the firmware of the rehabilitation device.

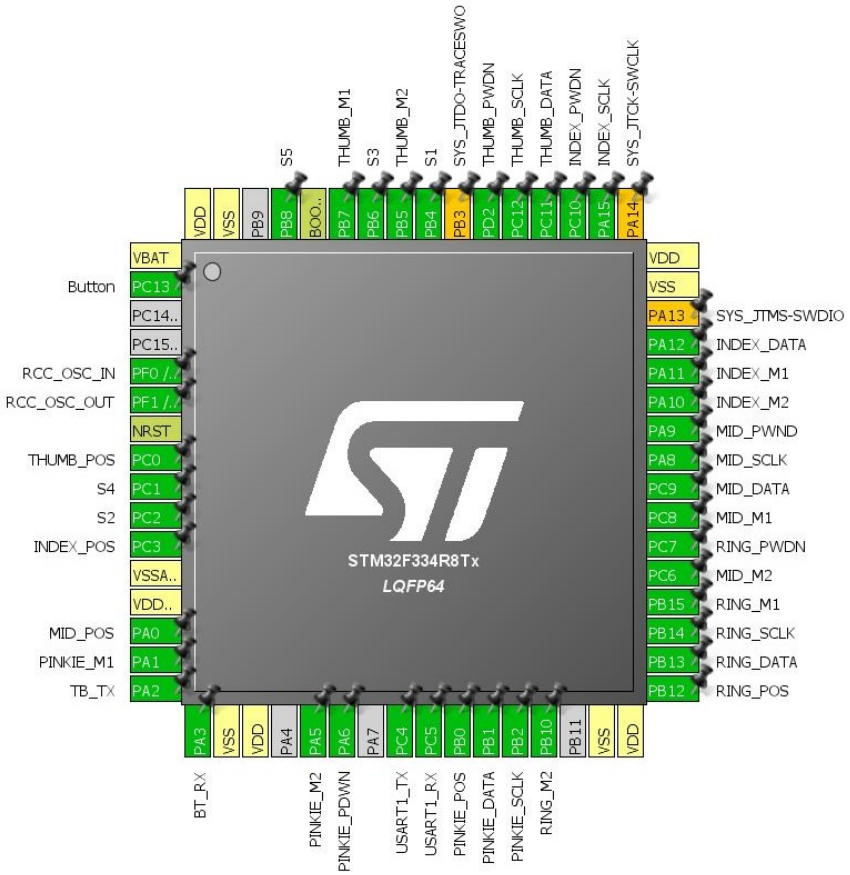


Figure 3.2: STM32CubeMX Graphical Software Configuration Tool

3.4.3 Actuation

The device needs to be portable and light weight as per the requirements. Methods considered for actuation was pneumatic cylinders, electromagnetic actuators and electric actuators.

The pneumatic cylinders require air pressure to move, this requires an air compressor to supply the system with air. Pneumatics also require valves and airlines to control the cylinders as well as an air tank to store air pressure. All the required hardware to make a pneumatic system work makes it too heavy and cumbersome for the application.

Electromagnetic actuation has the advantage that when the system is not energised, the actuators are capable of moving freely. This can be useful when a patient is attaching the device to their hand. Electromagnetic actuators capable of incremental movement is not readily available, this form of actuation is typically used as solenoids in application that require an on off type of movement. This is not suitable for a rehabilitation device.

Electric linear actuators typically consist of an electric motor that turns a lead screw to create linear motion. These actuators can be made in different sizes to suite a range of applications. The electric motor can be connected through a gearbox to the lead screw; the gearbox can increase the torque to the lead screw, creating an actuator with a high force output. Electric linear actuators that use DC motors are easy to control and can be made into a small form factor; this makes them a good choice for the rehabilitation device.

The actuators used for the rehabilitation device is the Actuonix PQ12-P, which is a small electric linear actuator with position feedback made by Actuonix Motion Devices. The model used has an internal gearbox with a 100:1 reduction ratio and requires a maximum of 6 V_{dc} to operate [46]. This variant was selected since speed was not a key requirement. The gear ratio allows the actuator to apply a significant amount of force for this application. According to the manufacturer the actuator is capable of providing a maximum force of 50 Newton.

Electric actuators were selected due to their compact size, light weight and ease of operation. The actuators with built-in position feedback also simplify the mechanical and electronic design. Electric actuators also have the advantage of being self-contained and do not need any additional input other than electrical power; unlike pneumatic systems. This allows the device to be compact and either be battery powered or powered from a direct current (DC) power supply.

3.4.4 Actuator Control

The actuators are controlled via a PWM signal from the microcontroller. The actuators have a maximum stall current of 550mA, and therefore a motor driver is required.

The motor drivers used is the LB1938FA from ON-Semiconductor. The motor drives are suitable for a maximum current draw of 800mA and come in a very small package, making them a good fit for this application. The motor drivers are connected to the microcontroller through logic level MOSFETs. This is to translate the 3.3V from the microcontroller to 5V for the motor driver as well as a safety measure to protect the microcontroller.

3.4.5 Position Feedback

The PQ12-P actuators have position feedback that enables the controller to move the patient's fingers into the desired position. The actuators contain an internal potentiometer that provides an analogue voltage that can be read by the microcontroller.

3.4.6 Force Measurement

The force measurement capability of the device is achieved via two strain gauges mounted on the arm that attaches the actuator to the rest of the finger. This allows for the force exerted by the patient to be measured, should the actuator be stationary; as well as the force exerted by the actuator to be measured.

Strain gauges are used to measure force since they offer a physically small and cost-effective solution. The mechanical structure was designed to allow room for two strain gauges between the actuator and the finger assembly. The strain gauges are 9mm long and 3.5mm wide and are bonded to the mounting location using epoxy as recommended in the datasheet.

The strain gauges are mounted in opposite directions, meaning one is rotated 180 degrees with reference to the other. When forces are applied to the arms, the arms will deform slightly. The strain guages will also deform and their resistance will change accordingly. The strain gauges are capable of measuring the forces acting upon the arm in both directions. A simulation done in Solid Works shows that the strain gauges are mounted in the correct location, this is shown in Figure 3.3. Areas of higher strain are coloured in green, yellow and red. Blue indicates areas of little to no strain.

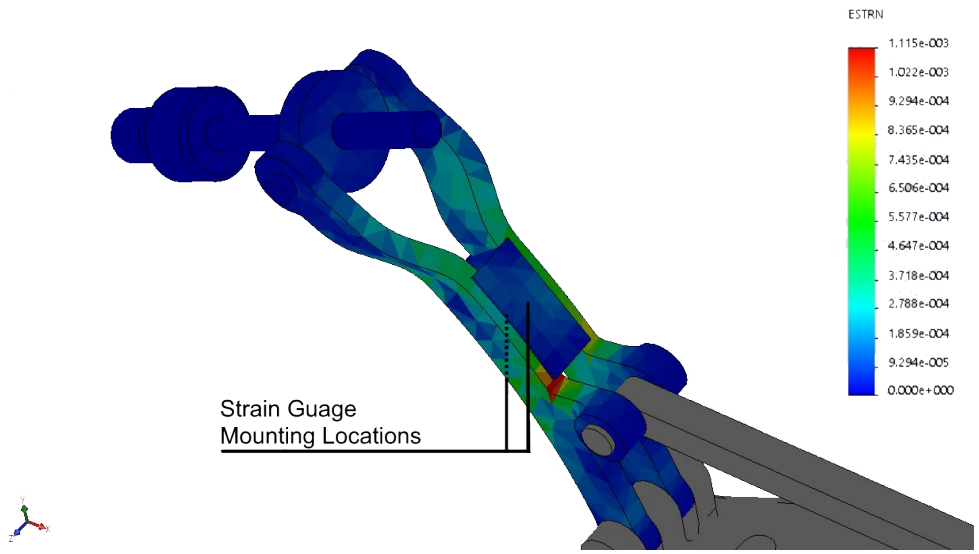


Figure 3.3: Strain in the actuator arm and strain gauge mount

3.4.7 External ADC

The force is measured as a change in voltage from a Weatstone bridge, the resulting change in voltage can be measured with and analogue to digital converter. Since the change in voltage is relatively small, the ADC needs to have a high resolution.

An alternative to a higher resolution ADC is to use a instrumental amplifier and use the ADC of the microcontroller. An instrumental amplifier is a differential amplifier, meaning it amplifies the difference between two input voltages, with an added input buffer stage. The two outputs from the Weatstone bridge was fed into the amplifier and the output of the amplifier was fed into the ADC of the microcontroller. The microcontroller has a built in ADC with a resolution of 12 bits.

This configuration was tested but did not provide satisfactory results. The measurement accuracy was improved by changing the reference voltage of the ADC to 1.023V. This alternative to an external high resolution ADC was initially investigated in an attempt to reduce cost, complexity and power consumption of the device.

The external analogue to digital converters used for measuring the change in voltage from the strain gauge circuit is the ADS1231 from Texas Instruments. This is a 24-bit ADC commonly used with Wheatstone bridge circuits. This ADC has an internal amplifier with a gain of 128. The Effective Number of Bits (ENOB) usable with an ADC is often less than the number of bits provided by the ADC; this is due to noise from the environment and introduced by other circuit components. The current circuit configuration allows for a resolution of 16 bits. The calibration process of the strain gauges and the ADC is discussed in chapter four.

The data from the ADC is sent to the microcontroller via a two-wire serial interface, appendix D contains a snippet of the code responsible for reading the data from the ADC. The device can be disabled to reduce power consumption, this also has the benefit of disabling the Weatstone bridge and strain gauges which greatly limits the amount of self heating that can occur in strain gauges.

3.4.8 Bluetooth

The control board communicates with a smart-phone or similar device via a Bluetooth connection. Bluetooth was selected since the majority of smart-phones have Bluetooth functionality. The distance between the device and the user's smart-phone will be within the capable range of Bluetooth. The Bluetooth module used is a class 1 device which typically has a range of 100m, this is sufficient for this application. The connection is used for simple instructions between the device and the smart phone and does not require a large bandwidth.

The control board has space for a Bluetooth module that communicates serially via a USART with the MCU. The module used is the SPBT3.0DP1 from ST Microelectronics. The module was tested by the manufacturer and is Federal Communications Commission (FCC) compliant.

3.5 Printed Circuit Board

The Printed Circuit Board (PCB) for the device was designed in Altium Designer. Two Unique PCBs was designed during the development of the device; the first was a smaller simpler board intended only to control one finger. The first iteration used a different approach for measuring the change in resistance of the strain gauges and used a different motor driver for actuator control. After the first iteration, PCB was tested, the second and final version was designed. The Altium Designer Board layout is shown in figure 3.4.

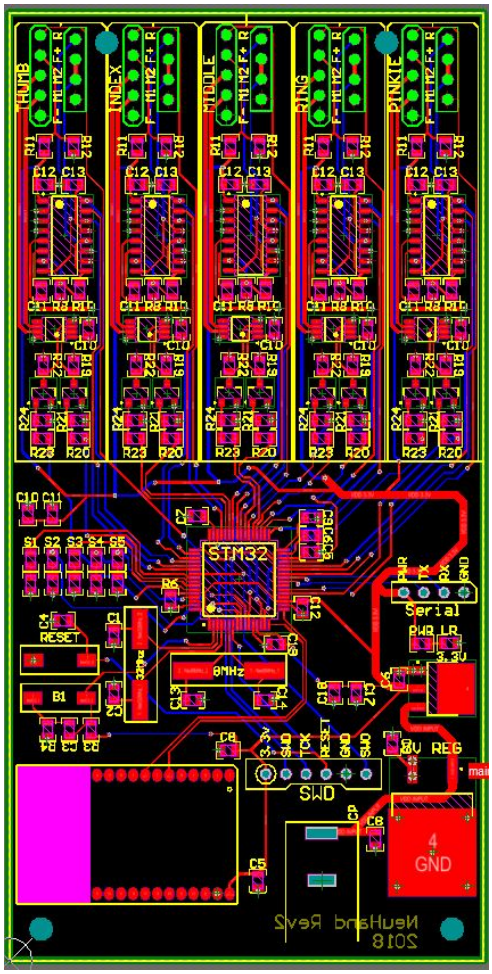


Figure 3.4: Altuim Designer Board Layout

The final PCB is intended to be powered by a 12V DC power supply but can accept a voltage range from 7.8V to 16V. The board is powered through a 2.5 mm centre positive DC jack. The actuators and strain gauges are made to connect to the PCB via male header pins at the end of the PCB. The actuator wires and the wires coming from the strain gauges come together in a specially designed connector that, in conjunction with the placement of the header pins on the board, can only connect in one orientation.

The PCB was designed to be a long narrow rectangle, that is 120 mm long and 60 mm wide as to be able to fit on the fore arm of the patient. A photo of the populated PCB is shown in figure 3.5. The PCB is housed in a box with openings for the actuators and strain gauges to connect and is secured to the forearm of the hand that is undergoing therapy. The box and PCB is secured to the patient using adjustable hook and loop fastening straps.

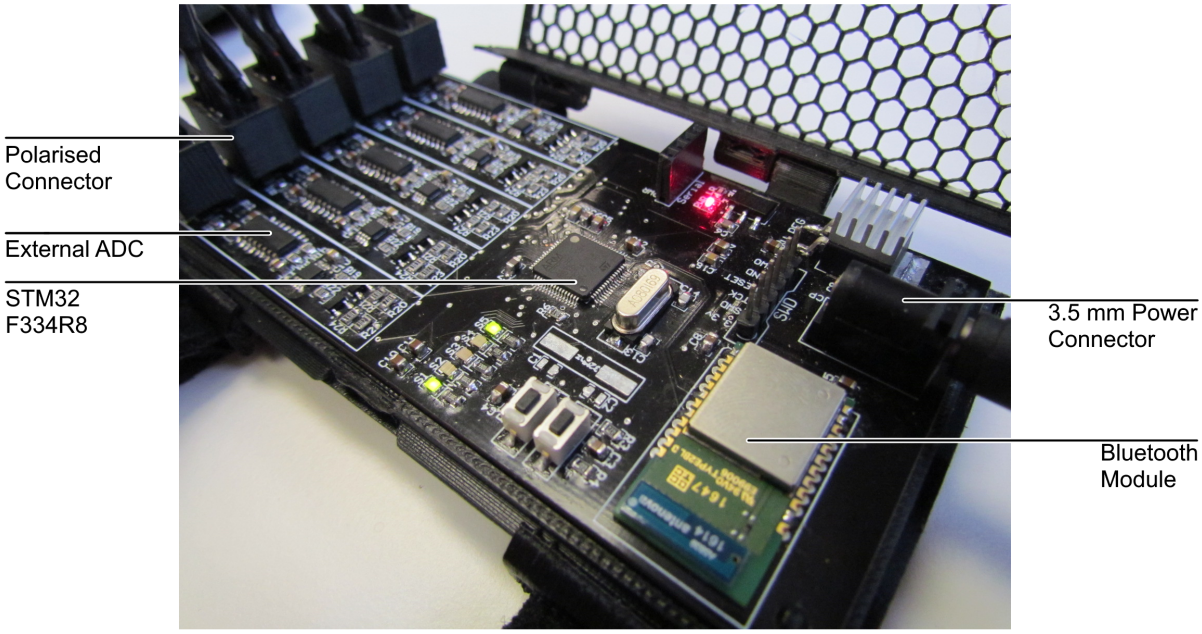


Figure 3.5: Completed Device

3.5.1 Control Board Overview

Figure 3.6 provides a summary of the rehabilitation device.

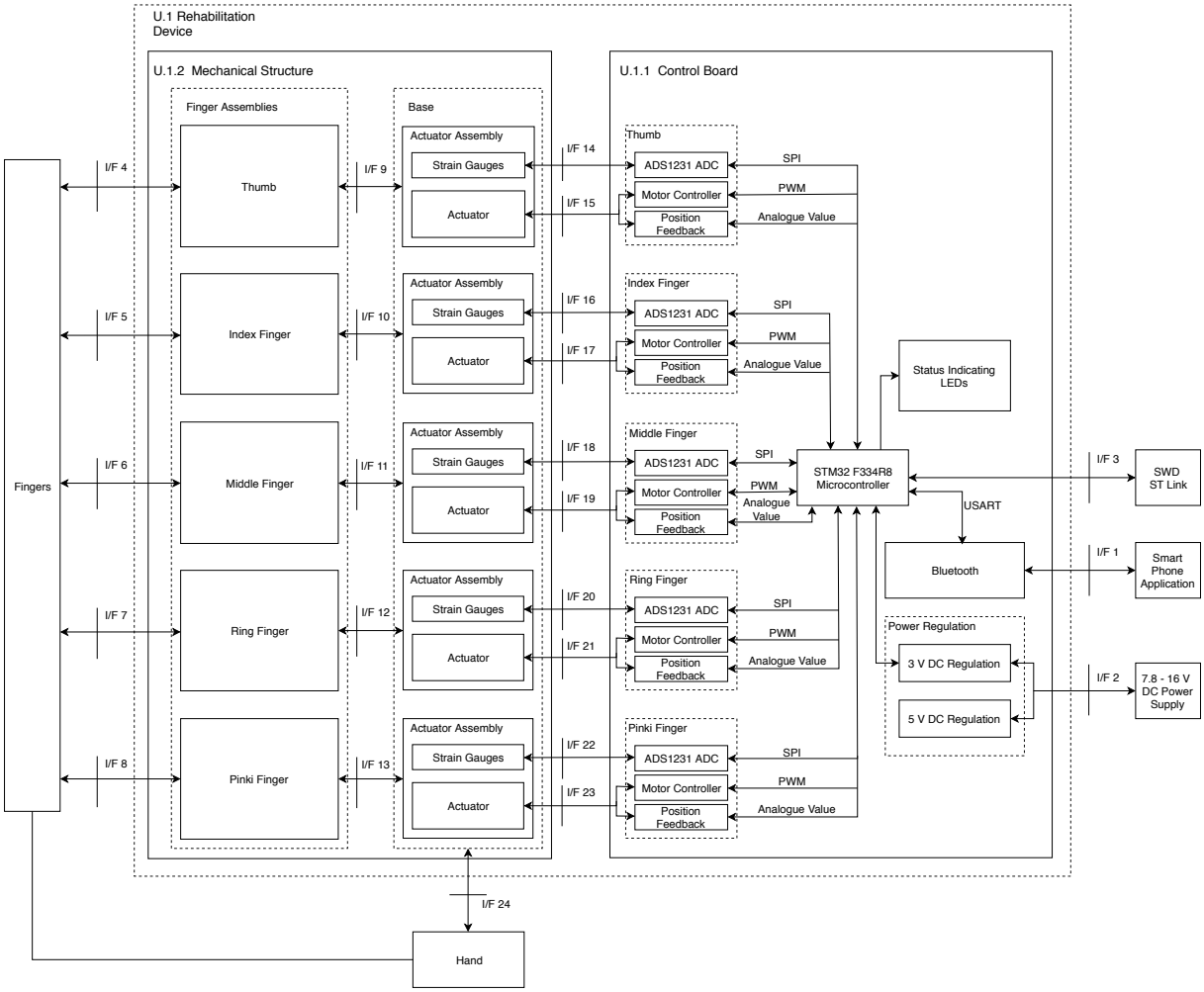


Figure 3.6: PCB Overview

In figure 3.6 the control board (U.1.1) interfaces (I/F 1) over a wireless connection to a smart phone application. Programming of the device is done via a ST Link programmer using SWD (I/F 3). The device is powered by a DC power source via a 2.5 mm DC jack (I/F 2). The incoming DC voltage is regulated down to 3.3 V for the microcontroller and 5 V for the actuators, strain gauges and external ADCs. The actuators and strain gauges are connected to the control board (U.1.1) via I/F 14 -I/F 23. Quick release mechanisms are used to connect the mechanical structures of the fingers, to the actuator assemblies (I/F 9 - I/F 13).

3.6 Functionality and Ease of Use

The rehabilitation device is capable of moving each finger individually or all of them simultaneously. The device allows for the fingers to be extended entirely and bend to a point where the fingertip is aligned with the metacarpophalangeal joint(knuckle) of the finger with a gap between the tip and the palm. This is sufficient range of motion for rehabilitation of most patients. The exact range of motion will vary for different hand sizes and finger lenghts since the actuator stroke is fixed.

The intended use for the device is for a patient to be able to equip the device themselves and perform exercises with the help of the device. The actions of the device are controlled via a control board attached to forearm of the hand that is being exercised.

The exercises are controlled via a smartphone application. The application communicates via Bluetooth with the device. The rehabilitation device is capable of performing four basic exercise. For each exercise, three basic parameters need to be set, namely starting position, end goal and force parameter. The starting position is the position of the actuators where the male part of the quick release mechanism meets up with the female part attached to the finger. This is to allow the patient to start in a comfortable starting position for each finger. The goal is the desired ending position of the exercise for each finger. The device will either extend or flex the fingers, depending on the exercise, starting position and the goal.

The force parameter is either the amount of force the patient needs to apply to the device for strength training or the maximum amount of force the device is allowed to apply to the patient for range of motion training. A secondary use for the force sensors is as a safety mechanism. If the device is moving the fingers towards the goal set by the patient and the device is applying force to the patient, the device will stop and move back to the starting position if the amount of force applied to the patient reaches the maximum set limit. This is to prevent injury.

The starting position, goal and force parameters are set before the start of the exercise. The application stores the last position of each parameter; this allows a patient to continue an exercise with the same settings as before.

Exercise one resembles the patient closing their hand with a stress ball inside. The application requires the patient to set the desired starting position, for this exercise the starting position should be as close to completely open or extended as the patient's hand will allow. The force requirement allows the patient to effectively start with a softball that is easy to compress and gradually increase the force required as their hand regains strength. The device measures the amount of force that the patient is applying while holding the fingers stationary, if the patient is exerting enough force, the actuators will extend, closing the hand as if compressing the stress ball. If the patient stops applying force, the actuators will retract to the starting position.

Exercise two is the reverse of exercise one. The patient should again set the starting position. Since the goal of this exercise is for the patient to extend their hand, the starting position should be set to the point where the hand is as close to a fist as possible. This exercise resembles an elastic band around the patient's fingers. The patient can set the strength of the band and increase it as they progress.

Exercise three resembles the patient opening and closing their hand. This is a repetitive training exercise intended to stimulate cortical reorganisation. This exercise can also be used as a range of motion training exercise. As with the other exercises, the starting position needs to be set along with the maximum amount of force that the device can apply to the patient. For the range of motion training, the patient can adjust the goal during the exercise until they reach the end of their range of motion. Once the goal is set just outside the range of motion, the force the device is allowed to apply can be increased slowly. The device can therefore slowly increase the range of motion of the patient through repetition. The goal can be adjusted further once progress has been made.

Exercise four is a dexterity training exercise, the device assists the patient in moving each finger in a sequence. The sequence resembles a patient touching each finger to the thumb individually. When the ring finger is moving, the pinki finger is also flexed slightly since these fingers tend to move together naturally. The same happens to the ring finger when the pinki finger is moving.

Screenshots of the mobile application is shown in figure 3.7. The application gives a moving visual representation of each exercise before the patient selects the exercise; this is shown on the right side of figure 3.7.

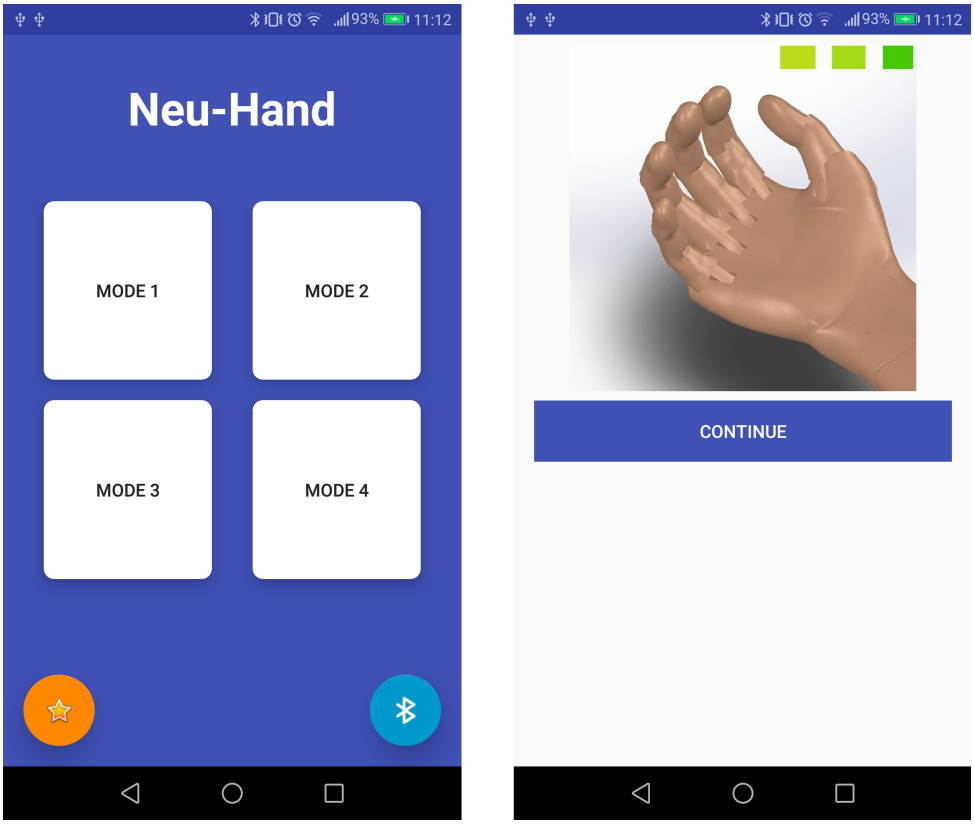


Figure 3.7: Screen Shots of the Mobile Application

3.6.1 Mechanical Structure

A hard exoskeleton style device was chosen over a soft robotic device because it allows more flexibility with regards to hand sizes and is considered easier to equip for a patient since each finger can be added individually.

The mechanical structure consists of an exoskeleton that covers the dorsal side of the hand and attaches to each finger and the thumb. The mechanical structure can be separated into three sections, the fingers, the actuator assembly and the base.

The fingers were designed to be highly customisable; the fingers consist of three main sections, one piece that covers the distal phalanx, one that is secured to the middle phalanx and a smaller piece attached to the proximal phalanx. The middle and proximal pieces are secured to the patient using hook and loop straps around the finger.

The piece covering the distal phalanx is meant to be a press fit piece that covers the tip of the finger and is mainly held in place by friction. If needed provisions have been made for small hinges that connect the distal and middle phalanx pieces and should be aligned with the interphalangeal joint.

The three sections that make up a finger can all be scaled to fit a particular patient. The intention is for a therapist to have a selection of differently sized parts for each section of the finger and hand and then assemble the finger structure from the parts that fit the patient the best. To accomplish this a sample set of different size parts was designed. Each finger of a patient has its own set of components, both regarding the three main components mentioned, as well as the linkages that connect the sections. The linkage lengths are chosen based on the length of the fingers of the patient.

In addition to the component sizes and linkage lengths, the linkage that connects the finger assembly to the actuator can also be adjusted for finer adjustments. This adjustment is achieved via a piece of threaded rod that moves the male part of the quick release mechanism; this allows for the last connector to be made longer or shorter, depending on the dimensions of the specific finger.

The fingers constructed for the prototype is shown in Figure 3.8, the middle finger and the index finger required the same components, the ring finger only required a different tip. The pinki finger required a different set of components with only the proximal and quick release components being shared with the other fingers. The thumb has a different tip, the rest of the components are the same as the components used for the index and middle finger.

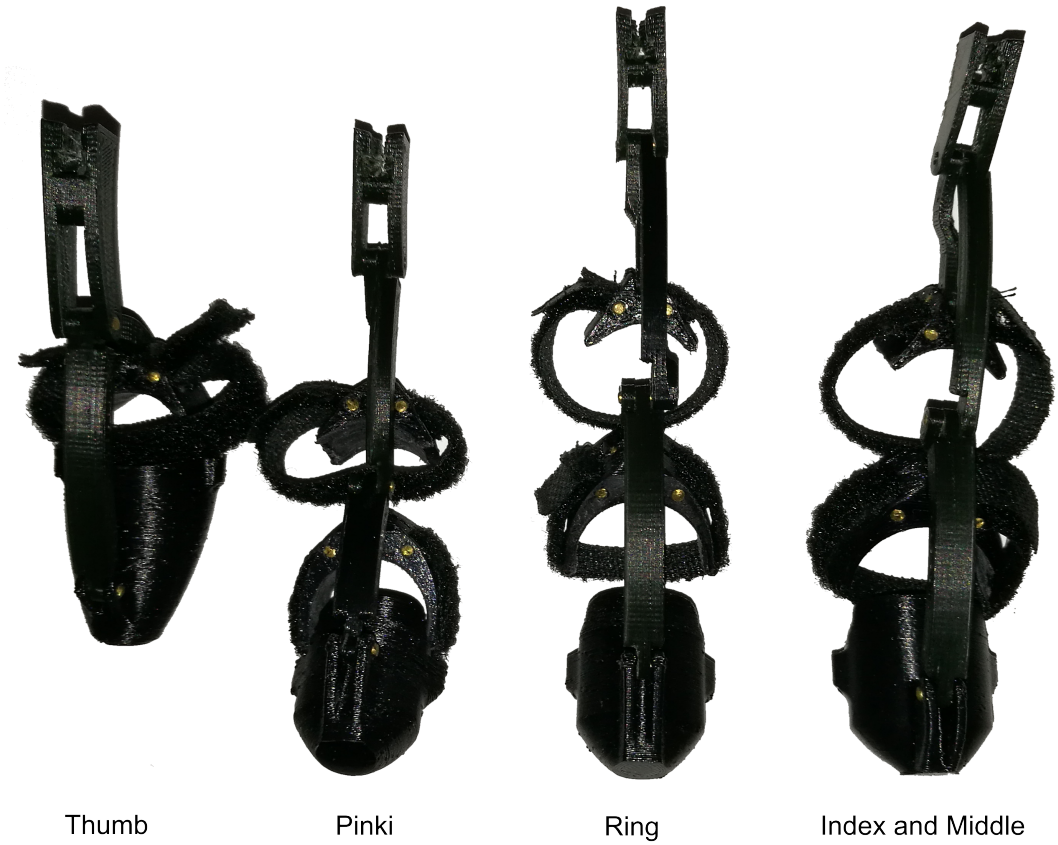


Figure 3.8: Different Finger Assemblies for Prototype

Each finger is made up of eight pieces in total, excluding the pins and hinges. A diagram of the finger is shown in Figure 3.9. Finger flexion and extension is achieved by the linear actuator moving the linkages forward and backward; these linkages are attached to the middle and proximal phalangeal pieces with smaller guide pieces. The result is the exoskeleton guiding the fingers and allowing the mechanical structure to apply force to the finger to both open and close the hand.

The quick release mechanism consists of a male and a female part; the male part is made from aluminium for the prototype. This part was initially manufactured by an additive manufacturing process, but due to the shape and size of the part coupled with the directional strength properties of additive manufacturing, it was not capable of handling any significant load and had a tendency to break after a few uses. The female part of the quick release mechanism is attached to the rest of the finger assembly. The female part forms a cup that holds the male part in place while still allowing the finger assembly to rotate at this joint. The two parts clip together.

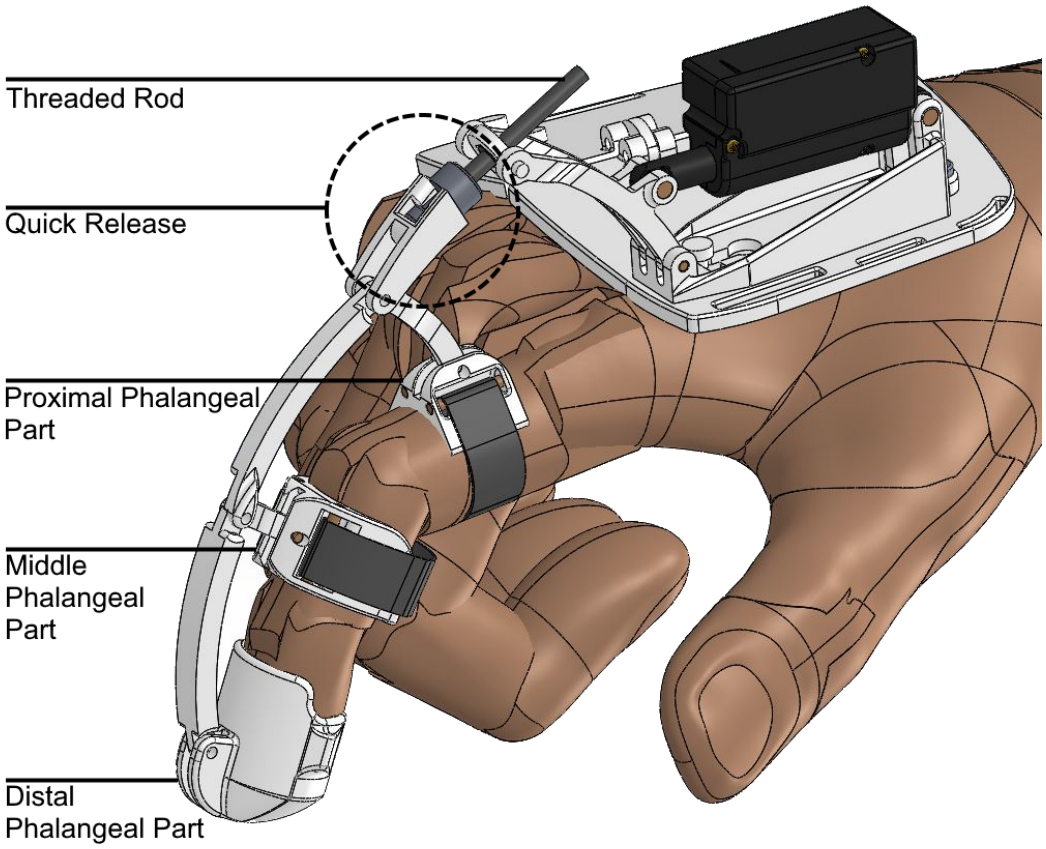


Figure 3.9: Mechanical structure of a finger and the actuator

The operation of the thumb is similar to that of the other fingers, the main difference being the location of the actuator assembly. The actuator for the thumb is located on the smaller base plate that covers the first metacarpal of the thumb. The thumb consists of a distal phalanx and a proximal phalanx and fewer linkages. The working principle of the thumb is the same as that of the other fingers.

The second major sub-system is the actuator assembly. The actuator assembly is made up of three distinct parts; this includes the actuator, the actuator cradle and the actuator arms. The actuators have a fixed stroke length of 20 mm and were chosen for their compact size. The reach of the actuators is increased by the mechanical design of the actuator cradle and arms. The design of the actuator assembly was developed through a spiral development methodology to experiment with as many variations in as short a period as possible.

The final design of the actuator assembly was selected since it extends the reach of the actuator while still maintaining a small form factor. The smaller form factor is critical for patients with smaller hands. This design also allows for the arms to be actuated closer to the bottom hinge; this creates the needed space for the strain gauges to be mounted. The strain gauges need to be mounted between the top of the actuator arms and the point of actuation since any forces from the patient or the actuator will result in temporary deformation of this area. The actuator is held in the actuator cradle by two 3 mm brass pins.

The actuator is connected to the control board via a flat flexible five way cable, two connections are for the motor control of the actuator and three used for position feedback.

The actuator assembly is designed to be removable from the rest of the device, as it is fixed to the base by two pins; one pin is part of the base, and is located near the front. It has a narrow base with a larger diameter top. The head of the pin is made to pass through a hole in the bottom of the actuator cradle, the actuator assembly then slides backwards until the pin reaches the front of the slot. The end of the slot is another circular slot that forms a T-shape with the other; this can be seen in Figure 3.10 that shows the bottom of the actuator housing.

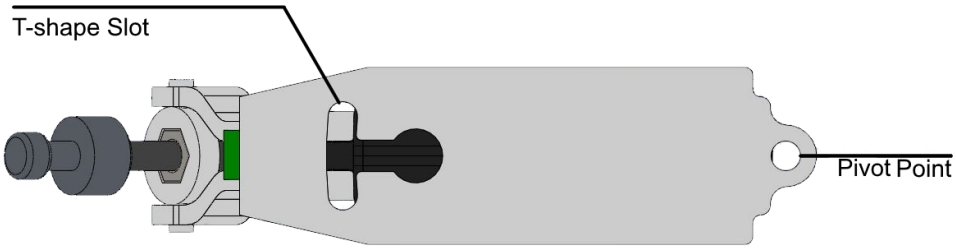


Figure 3.10: Bottom view of actuator cradle, showing connection mechanism to base

The goal of this slot is to allow for some movement of the actuator assembly to make the device capable of compensating for variations in hand sizes. At the back of the actuator assembly is another hole that lines up with a hole in the base once the first pin is in the T-slot. These holes are for an M3 by 6 mm machine screw to secure the actuator assembly to the base and to act as the pivot point for the actuator assembly. The actuator assembly with the male part of the quick release mechanism is shown in Figure 3.11.

The actuator assemblies are expensive parts of the device. By making the actuator assemblies easily removable, the cost to the patient can be decreased since the actuator assemblies can be removed from the device when rehabilitation is completed and re-used.

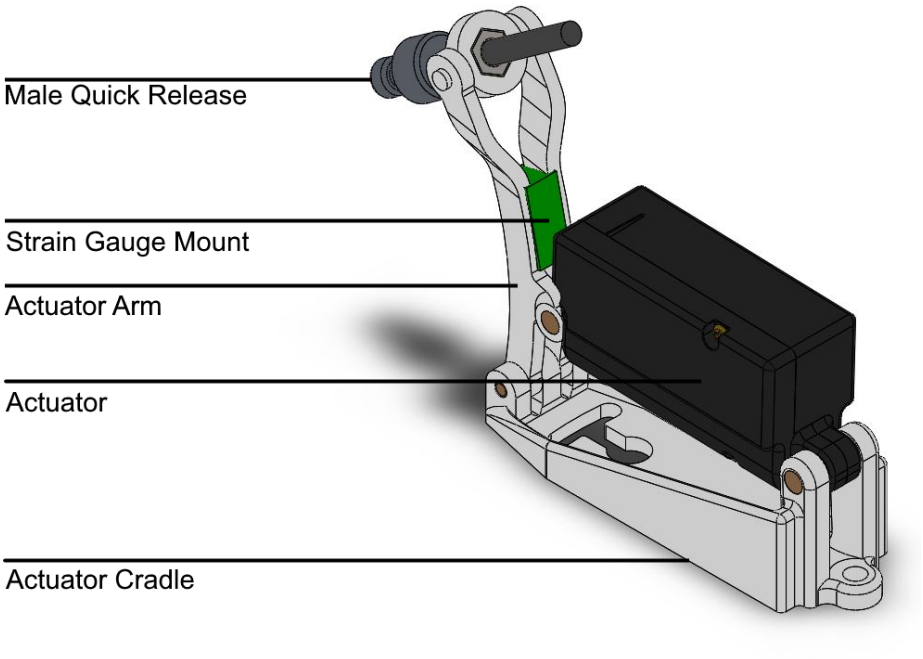


Figure 3.11: Actuator Assembly

The most substantial part of the device is the base. This is a large flat section that attaches to the dorsal aspect (back) of the hand and is also secured with hook and loop straps. The base is made up of three separate parts, two covers the dorsal aspect and one smaller part covers the metacarpal of the thumb. The two parts that cover the dorsal aspect is joined with two hinges that allow for a more comfortable fit. Figure 3.12 shows the base of the device; this figure also shows the smaller part for the thumb and an actuator cradle with the actuator removed to show the connection mechanism of the two assemblies.

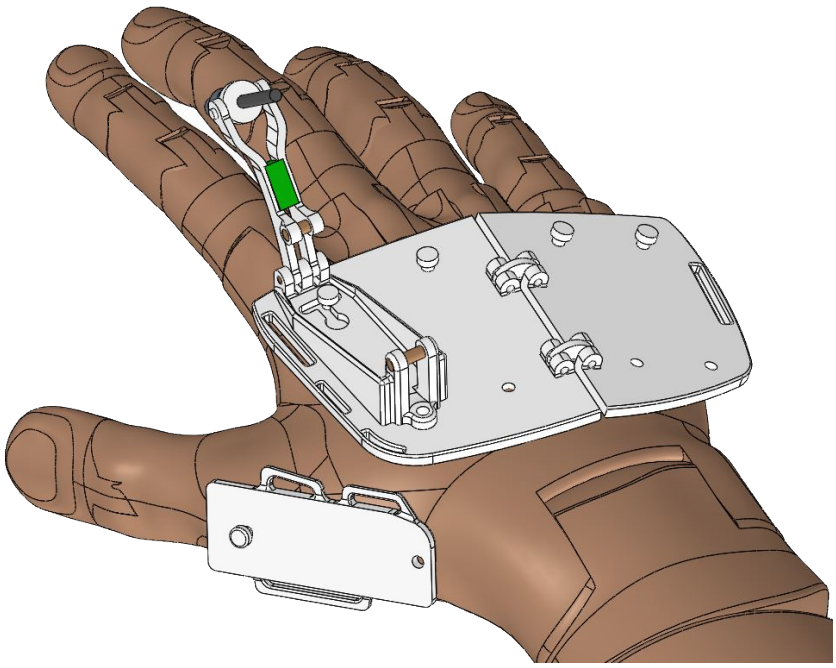


Figure 3.12: Base and Thumb Assembly

After the final design was completed, a functional prototype was constructed. The prototype was constructed using additive manufacturing techniques since the parts were designed with this manufacturing method in mind. The majority of components and linkages are made of acrylonitrile butadiene styrene (ABS). This material is relatively easy to use thermoformable plastic and is a cost-effective prototyping material with suitable mechanical properties. The parts of the fingers that make direct contact with the patient is manufactured from a plasticised copolyamide thermoplastic elastomer, better known as PCTPE, manufactured by Taulman3D. This material is recommended for wearable devices by the manufacturer since it results in a smooth surface finish and is more flexible than ABS.

The pins that connect the finger linkages are made from brass; this was selected for being corrosion resistant and easy to work with while still being strong enough for the application. Brass is available in rods with diameters of 2 mm and 3 mm, which can easily be cut and used for pins. The majority of pins are made from 2 mm brass rods. Only the pins used for securing the actuator to the cradle are made from 3 mm pins.

The completed device and control board is shown in Figure 3.13.



Figure 3.13: Complete Rehabilitation Device and Control Board

A complete, functional prototype was manufactured for a test subject's hand. Figure 3.14 shows a photo of the prototype attached to a test subject.

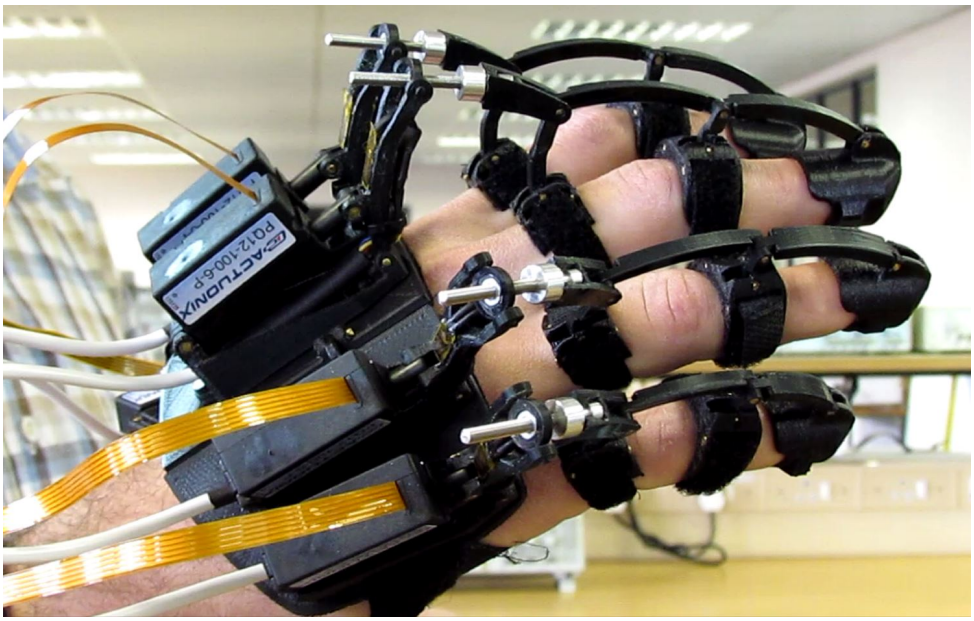


Figure 3.14: Complete Rehabilitation Device Fitted to Test Subject

3.7 Conclusion

An exoskeleton rehabilitation device was designed to assist therapists and patients during the rehabilitation process after a stroke or similar event resulting in neurological damage. The device is capable of moving each finger and the thumb individually and is designed to fit almost any size hand due to the modular and adjustable design. The mechanical structure was designed to be easy to manufacture using additive manufacturing techniques and to be easily customisable for each patient.

The device uses compact electric linear actuators for movement, and strain gauges are implemented as a force measurement mechanism. A specially designed electronic controller controls the device and the user interacts with the device via a smartphone application connected to the device via Bluetooth.

The device is a functional prototype and can therefore not be tested on patients due to ethical constraints.

The device has not been tested as a rehabilitation device on human patients.

Chapter 4

Test-bed and Experimental Setup

This chapter provides a overview of the force measurement techniques used in the device. The calibration processes and testing of components of the device is explained and discussed in this chapter.

4.1 Calibration and Characterisation

The strain gauges of the device must be calibrated for the output to be in a known force unit. The measurement unit that used throughout this study is gram; this can be converted to Newton if needed.

The calibration of the strain gauges requires mounting the complete actuator assembly containing the actuator, actuator cradle and the arm containing the strain gauges to a specially designed block that houses a calibrated load cell. The block keeps the actuator assembly secure while also allowing the actuator arm to press and pull against the load cell by means of a piece of M3 threaded rod. The threaded rod replaces the adjustable quick release mechanism used for the rehabilitation device. This means that the rod

can be turned to force the actuator arms in either direction. The hardware setup for the calibration process is shown in figure 4.1. The calibration process is set up to recreate the way forces will be applied to the actuator arms when the device is attached to a patient. The forces acting on a finger will be transmitted through the threaded rod of the quick release mechanism to the arms during rehabilitation.

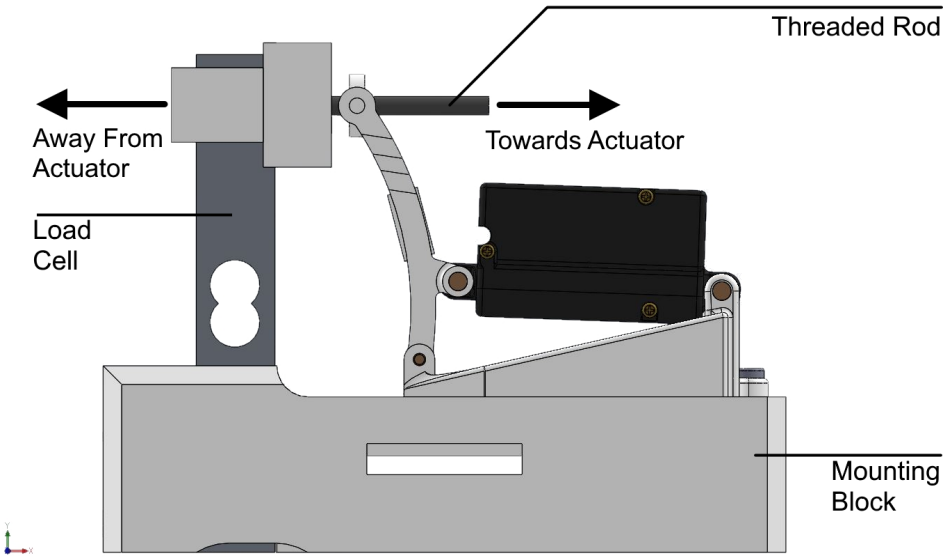


Figure 4.1: Load cell and actuator calibration setup

The load cell used for calibration is rated for 10 kg and has an uncertainty of measurement of 0.05% of full-scale output. Since only a small part of the range is used for most measurements, this has to be approximated for the used range. For calibration the used range is less than 1 kg of the full-scale range, this means the uncertainty is closer to 0.5% which is still acceptable.

The load cell is calibrated in grams since it is typically used to measure the mass of an object pushing down onto it, by rotating the load cell 90 degrees, gravity no longer affects the load cell in the direction of measurement. The values in grams can be converted to Newton by multiplying with the conversion factor of 0.00981 m/s^2.

The characterisation process consists of a series of measurements. A load is applied via the machine screw in increments of 50 grams starting at 100 grams, going up to 450 grams, the load is then decreased incrementally, using the same increments as before. The strain gauge output values are sent to a computer via a serial interface and logged using Matlab. For each increment, a sample size of around 200-300 samples is recorded once the desired load is applied to the system. The samples are recorded at 150 millisecond intervals.

Once the force on the load cell has reached zero again, the force was increased in the opposite direction and back down to zero. The resulting data set resembles a set of stairs firstly ascending and then descending again to the no-load value. An example of this is shown in Figure 4.2. The data plotted is the raw reading from the ADC.

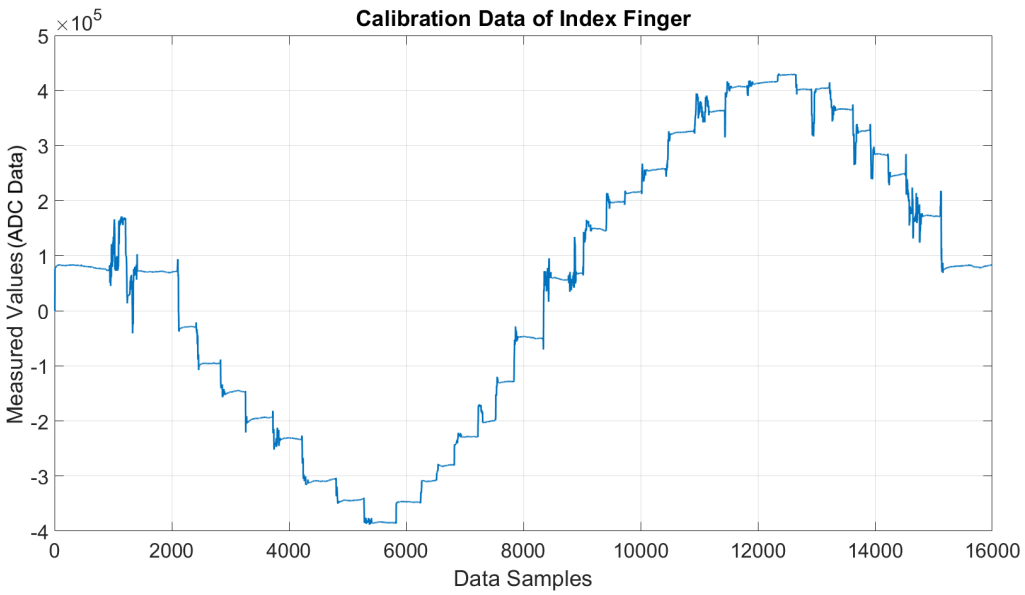


Figure 4.2: Data Captured for Calibration

The first set of measurements resembles the actuator extending and pressing against the load cell, the force applied to the force sensors are in the direction towards the actuator (samples 2000 to 9000). The second part of the data set (samples 9200 to 15900) resembles the actuator pulling against the load cell; forces applied in the direction away from the actuator. This resulted in a calibrated range of 900 grams. This process was performed twice for each actuator arm and compared. The resulting best fit line is shown in figure 4.3. The figure shows the best fit line for the index finger and shows a linear relation.

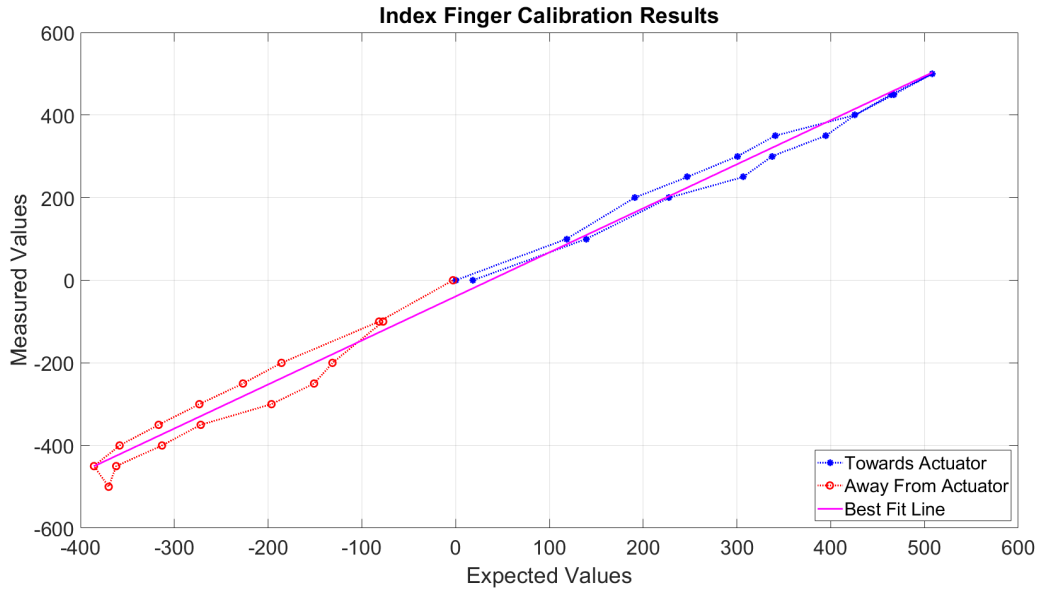


Figure 4.3: Best Fit Line from Calibration

It is important to remember that the raw data values of the strain gauges do not start at zero but is dependant on the strain gauge pair and how they are mounted. The starting value gets subtracted from the measured values in the same way a scale is set to zero before use. The resting value of the strain gauges can be measured by merely measuring the value of each strain gauge with no forces applied.

4.1.1 Calibration Results

The average value of the obtained samples at each increment was calculated; this was necessary since the samples at each force increment are not always constant. This is due to the plastic actuator arms which are slightly deformable. The drift due to deformation is negligible since it is highly unlikely that a therapist would apply a constant force to the device for an extended period of time. The averages taken from the datasets were then plotted and clearly resembled a straight line.

The accuracy of each assembly will be different due to human error in the assembly process of each unit. The assemblies are therefore treated entirely separate from each other. The results of the calibration process are shown in Table 4.1 for the forces towards the actuator and in Table 4.2 for forces away from the actuator. The confidence interval for 95% accuracy was calculated using a paired-t interval statistical method to calculate the confidence interval from paired data [47]. The paired data sets consists of the load cell measurement and the measurement from the strain gauges. A t-distribution was used since the sample size is limited and the degrees of freedom is smaller than 30.

The accuracy of the force sensing offers an acceptable degree of accuracy and repeatability. The calibration process exacerbated the problem of temporary deformation in the plastic structures. The calibration process applies force for far longer than the data collection process; this represents a worst case scenario with regards to the temporary deformation characteristic of the plastic.

Table 4.1: Calibration Results Towards Actuator

Finger	Accuracy (gram)	Confidence
Index	$\pm$ 12	95 %
Middle	$\pm$ 25	95 %
Ring	$\pm$ 26	95 %
Pinki	$\pm$ 21	95 %

Table 4.2: Calibration Results Away from Actuator

Finger	Accuracy (gram)	Confidence
Index	$\pm$ 25	95 %
Middle	$\pm$ 39	95 %
Ring	$\pm$ 28	95 %
Pinki	$\pm$ 18	95 %

4.2 Experimental Protocol

The hypothesis of the study is that therapists should apply a similar amount of force to the same patient. If the force applied to a patient can be quantified and characterised, it can be used to calibrate robotic rehabilitation devices to perform the same exercises. The experiment aims to test the hypothesis by measuring the amount of force exerted by different therapists on the same patient under the same conditions. The data collected from the experiment will be analysed to determine if the force applied by therapists can be characterised.

4.2.1 Therapist Selection

The subject of the experiment will be therapists with experience in hand rehabilitation. The therapists should preferably have two years of experience with hand rehabilitation after neurological trauma. Additional data can be gathered for less experienced therapists to compare against the more experienced therapists.

4.2.2 Data Collection

Data will be collected in distinct hand positions; all of which will resemble a spastic hand or a hand with a limited range of motion. The rehabilitation device will only be able to exert measurable force if the patient's fingers are not moving freely. Patients who have a limited range of motion in their fingers resembles a spastic hand at the end of their range of motion.

The device allows for the fingers of the test subject to be positioned and held in place in several positions. This allows for the experiment to be performed at repeatable hand positions. The position of the fingers is in relation to the distance the actuators of the exoskeleton can move. This means that 0% refers to the actuator being fully retracted, and the fingers being fully extended; therefore the angle between the phalanges and the metacarpals at the Metacarpophalangeal (MCP) joint is also zero or close to zero but not overextended. When referring to 100% closed, the actuator is fully extended, and the fingers should be closed as far as the device allows, the exact angle of the interphalangeal joints will depend on the length of the finger. The exoskeleton does not allow for the patient to close their hand into a tight fist; the 100% closed position is to where the mechanical constraints of the device will allow the hand to close.

The data will only be focused on the fingers, data regarding the thumb will not be gathered. The thumb will be excluded since it has a different range of motion to the fingers and if rehabilitated using different techniques. The device can only move the fingers of the hand and the thumb, this means that the therapist should focus from the MCP to the fingertips and that the rest of the hand should be held as still as possible.

Data collected will comprise of two positions, the force will be measured in both directions for each position. The measurement should be performed multiple times per therapist to ensure reliable data.

The primary variable of the experiment is the force measurements. The constant factor is the position of the fingers. The sensors used to measure the force is slightly temperature sensitive which can be considered as an uncontrollable variable. The experiments should, therefore, all be conducted at a similar temperature, a room temperature of 25 degrees is preferred. The sensors heat up slightly when first turned on but stabilises quickly to a constant value when no force is applied; the sensors reach a stable point within 5 to 10 seconds after the first activation.

4.2.3 Experimental Patient

The position of the patient should be consistent for all tests. The patient setup for the experiments resembles a patient sitting on a chair with the arm of the hand being tested resting on the arm of a chair or a similar surface at a height that allows the therapist to perform their exercises comfortably.

Exercises is performed on an articulated hand that has the same number of degrees of freedom as a human hand. The joints of the hand are capable of moving freely and the hand is manufactured by an additive manufacturing process. The exoskeleton parts used in the experiment is chosen to fit the hand. An articulated hand is used instead of a human hand due to ethical considerations. A photo of the hand is shown in Figure 4.4 and a photo showing how the hand is secured is shown in Figure 4.5.

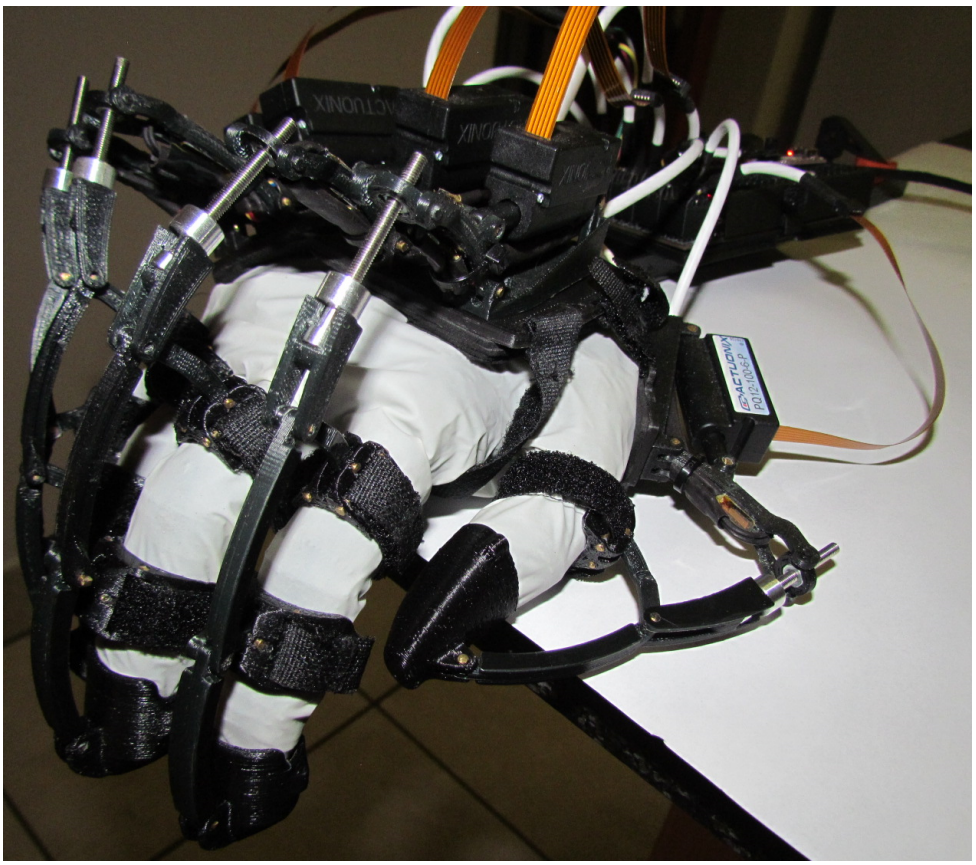


Figure 4.4: Articulated hand wearing rehabilitation device

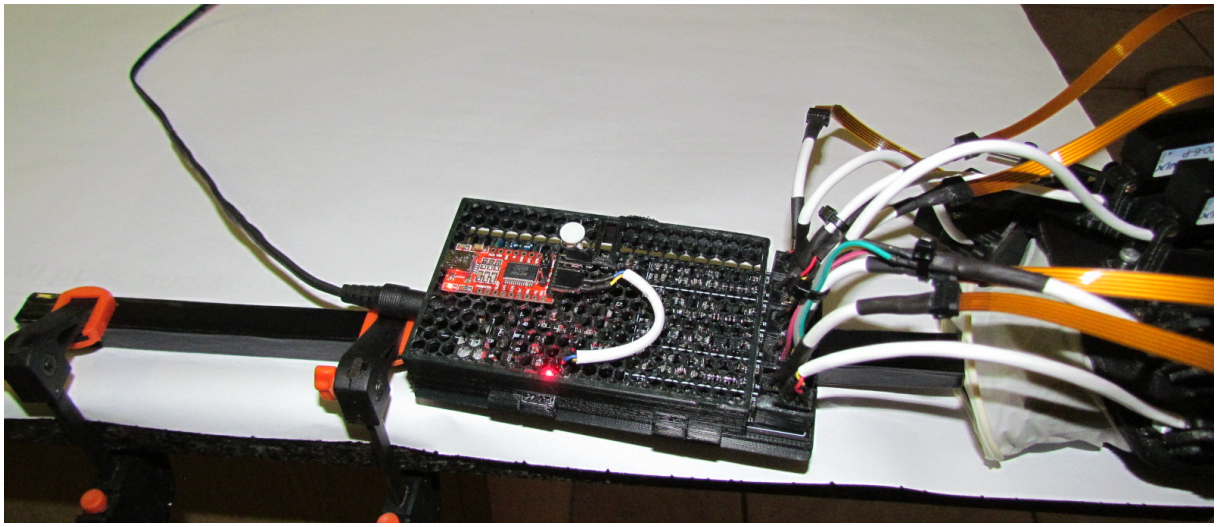


Figure 4.5: Photo showing how the articulated hand is secured

4.2.4 Experimental procedure

The exoskeleton requires pressure to be applied at the fingers to register force and only allows the whole finger to be moved at once. This means that the exercises should focus on extending and bending the fingers along all joints up to the MCP joint. The results of the experiment is the maximum force applied during each exercise.

The four exercises used in the experiment is discussed below and was used as brief instructions to the therapists. These exercises were created after a consultation with a therapist. The exercises are meant to resemble situations where therapists and the rehabilitation device will need to apply force to the patient. All the exercises represent a scenario where the patient is at the end of their range of motion and their fingers can not move freely.

The articulated hand is held in position by the rehabilitation device for each exercise and therefore resembles a spastic hand. The actuator length was adjusted accordingly to change the position of the hand. The rehabilitation scenario is discussed with the therapists prior to starting the exercises.

Exercise One

The patient can only close their hand to 30%; the goal is to close the hand further. Attempt to close the hand as with a normal patient, stop when the pressure you are applying feels enough to make progress but will not harm the patient.

Exercise Two

The patient's hand is spastic and closed at 30%. The goal is to open the hand to allow the patient a wider range of motion. Attempt to open the hand and stop when you feel the pressure applied is enough but will not harm the patient.

Exercise Three

The patient's hand is spastic and closed at 55%. The goal is to open the hand to allow the patient a wider range of motion. Attempt to open the hand and stop when you feel the pressure applied is enough but will not harm the patient.

Exercise Four

The patient can only close their hand to 55%; the goal is to close the hand further. Attempt to close the hand as with a normal patient, stop when the pressure you are applying feels enough to make progress but will not harm the patient.

4.3 Conclusion

The results of the calibration process show that the deformation of the plastic parts does affect the accuracy of the measurements but the current strain gauge configuration does yield a reliable force reading for the application. The calibration process can be considered as a worst case scenario regarding deformation of the plastic parts since the forces were applied for extended periods of time. When the device is used for its intended purpose and during the data gathering process for this study, forces will be applied for short periods which will result in negligible deformation.

The results of the experiment and the verification of the calibration process is discussed in Chapter five.

Chapter 5

Results and Validation

This chapter provides details on how the calibration of the force sensors was verified. A summary of the data gathered is provided along with the results that can be generated using this data. The statistical methods and results are discussed to validate the results generated. An additional research question is also discussed and analysed.

5.1 Introduction

This chapter describes how the calibration of the force sensors was verified. The results of the experiment are analysed and discussed before statistical analysis was performed to support the results. An additional research question was investigated, and another statistical analysis was performed. The effect of the mechanical structure of the device was investigated. Finally, the results of the chapter are discussed and concluded.

5.2 Calibration Verification

The calibration process was repeated for all four measured fingers after all the data has been recorded. This is to verify that the calibration ratios from the best fit line are still applicable and accurate. This ensures that the conversion from raw data to force values are accurate and trustworthy. The initial calibration has a range of 450 grams in both directions. The data rage was unknown prior to the experiment and therefore the data exceeded the calibration range. Therefore, the validation of the calibration had to be done over a greater range to ensure the conversion from raw data to a known unit is applicable for the larger data range.

The verification process is done in the same manner as the original calibration with only two changes made to improve accuracy. The first change was to record both the data from the strain gauges and the data from the load cell, this allows for smaller increments that closely resembles the conditions under which the data was recorded. The change to record smaller increments at set intervals was made to curb the amount of temporary deformation there was in the first calibration process. The deformation results in a small deviation to the measured values due to the plastic actuator arms yielding when a force is applied for an extended period of time. In the initial calibration around 200 samples were recorded at each increment. The data from the experiments show that the forces applied is only applied for a short amount of time.

The range of calibration was increased to 1200 grams in both directions; this is as far as the test rig can allow but is still a substantial increase over the initial range. The increase in the range is enough to establish whether or not the initial calibration results are accurate across the data range.

The verification results for forces towards the actuator show that the initial calibration is valid and correct over the entire range for all four fingers with the accuracy well within the parameters established by the initial calibration. The results of the validation data, in grams, is shown in Table 5.1.

Table 5.1: Calibration Validation: Towards Actuator Results

Finger	**Average Accuracy**	**Standard Deviation**	**Accuracy**	**Confidence**
Index	4	13	$\pm$ 8	95%
Middle	9	18	$\pm$ 11	95%
Ring	1	8	$\pm$ 8	95%
Pinki	15	26	$\pm$ 18	95%

The validation results for forces acting in the opposite direction, meaning away from the actuator as force would be applied when a patient is attempting to close the hand against the device, showed that the initial calibration was not valid for forces higher than 500 grams.

The original calibration parameters are valid and within the defined specification for forces up to 450 grams but when applying more force, the measured values start to deviate from the expected values. A second order best fit line was calculated to correctly interpret the raw analogue values and correctly convert them into a value in grams. The results for the ring finger is shown in Figure 5.1 as an example of the corrected calibration. The results of the calibration verification is presented in Appendix A.2.

Figure 5.1 shows the expected value of the data, the original calibration and the corrected calibration. It should be mentioned that the calibration data was not measured at specific calibration points as they were before since both the device data and the load cell data was recorded. The two recorded values should be equivalent when the raw analogue data is converted to grams; therefore the margin for error with regard to the calibration points can be relaxed in favour of a faster calibration process that minimises the temporary deformation of the plastic. A sample of the data captured during the verification of the ring finger is presented in Figure 5.2.

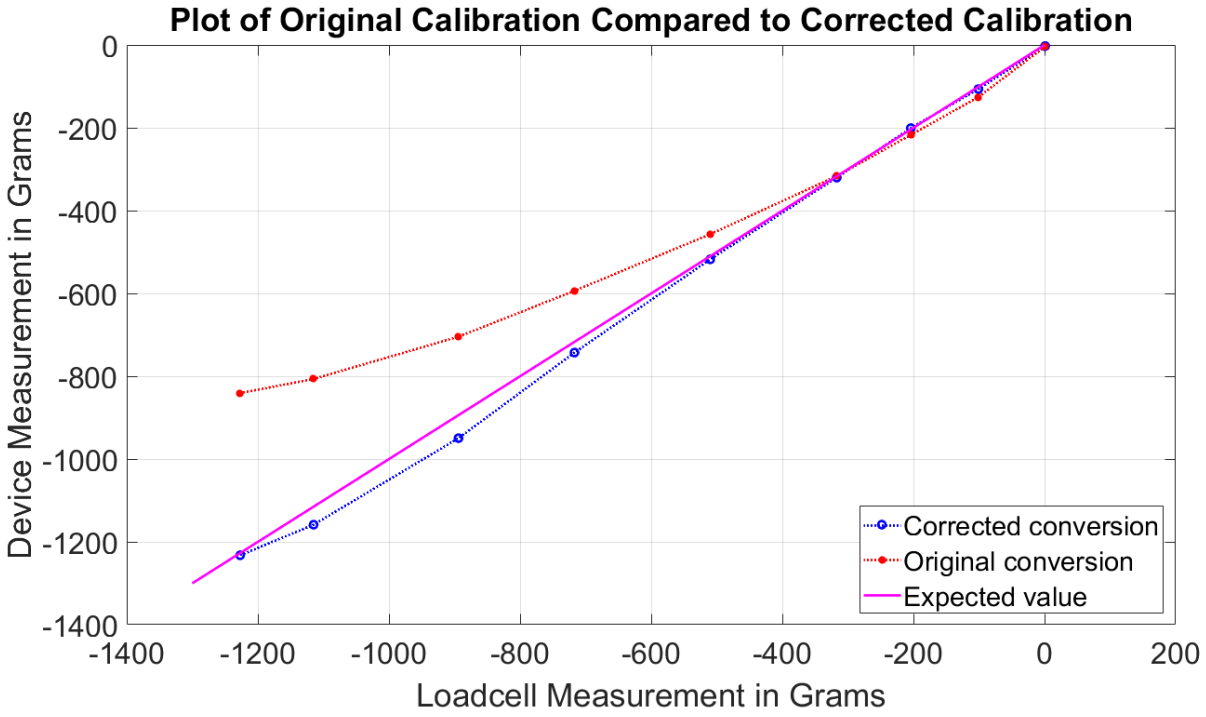


Figure 5.1: Comparison between the original calibration and the corrected calibration of the ring finger

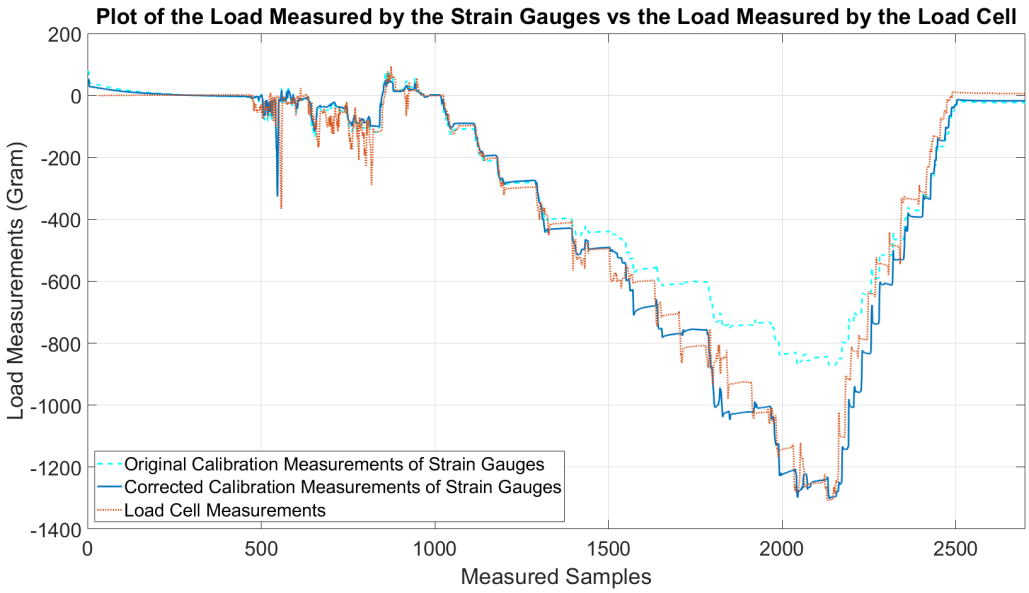


Figure 5.2: Comparison between the original calibration and the corrected calibration of the ring finger

The certainty of the measurement of the corrected calibration is shown in Table 5.2. The paired-t interval statistical method for paired data was used to determine the confidence interval. The paired data is the data from the load cell and the data from the strain gauges. The t-distribution was used since the sample set for the calibration was smaller than 30 with most calibration experiments consisting of 12 values which results in 11 degrees of freedom to establish the critical t-value for a two-sided confidence interval. This was performed multiple times for each set, the additional data is available in Appendix A.2.

Table 5.2: Corrected Calibration Results

Finger	**Accuracy**	**Standard Deviation**	**Accuracy**	**Confidence**
Index	23	47	$\pm$ 32	95 %
Middle	21	29	$\pm$ 18	95 %
Ring	18	26	$\pm$ 17	95 %
Pinki	19	49	$\pm$ 35	95 %

5.3 Results

This section gives a detailed overview of the data gathered from the experimental setup described in chapter four. Tables 5.4 to 5.11 show the key aspects of the data gathered from each subject. A visual representation of the data is then provided in scatter plots before a summary of the data is provided in Table 5.12 along with a summary and brief discussion of the data.

The data was gathered from eight subjects, four of which was occupational therapists, and four was physiotherapists. More information about the therapists are provided in Table 5.3. The majority of therapists used for data collection were females, with only subjects 5 and 6 being male. Subjects 1 to 6 were employed at a state hospital where they primarily treat stroke patients and patients with neurological disorders. Subjects 7 and 8 are both in private practice.

Table 5.3: Subject Information

Subject	Occupation	Age	Experience (years)
1	Occupational Therapist	28	5
2	Occupational Therapist	25	2
3	Occupational Therapist	25	1
4	Physiotherapist	24	1
5	Physiotherapist	23	1
6	Physiotherapist	52	18
7	Occupational Therapist	36	14
8	Physiotherapist	39	15

5.3.1 Subject Datasets

The data of each subject is summarised in the tables below; the tables show the maximum amount of force applied per finger and per exercise. The tables also show the average force applied along with the standard deviation of each dataset.

The subjects were allowed to perform the exercises using the technique they prefer and use with normal patients, some performed the test by moving all the fingers at once while others chose to perform the exercises on a per finger basis. For some of the exercises the pinki finger recorded little to no applied force due to how the exercises were performed. These data points were excluded as to not skew the results towards a lower force value.

Table 5.4: Subject One Results

Subject One - Occupational Therapist

	Finger	Maximum	Average	Standard Deviation
Exercise 1	Index	2066	1487	550
	Middle	1492	1902	406
	Ring	1405	1914	650
	Pinki	1703	-878	716
Exercise 2	Index	714	621	132
	Middle	702	645	80
	Ring	591	560	44
	Pinki	470	441	41
Exercise 3	Index	810	743	94
	Middle	172	172	-
	Ring	885	779	150
	Pinki	713	550	230
Exercise 4	Index	1832	1795	52
	Middle	3933	3218	1010
	Ring	975	858	165
	Pinki	571	511	84

Table 5.5: Subject Two Results

Subject Two - Occupational Therapist

	Finger	Maximum	Average	Standard Deviation
Exercise 1	Index	2453	1226	1735
	Middle	2241	2075	234
	Ring	1586	1554	46
	Pinki	1639	1259	537
Exercise 2	Index	844	817	36
	Middle	1016	1006	13
	Ring	761	662	139
	Pinki	1043	921	172
Exercise 3	Index	1161	1025	197
	Middle	1182	866	348
	Ring	1351	998	349
	Pinki	1280	848	553
Exercise 4	Index	2417	2003	584
	Middle	1770	1664	149
	Ring	1157	1106	71
	Pinki	1467	1402	91

Table 5.6: Subject Three Results

Subject Three - Occupational Therapist				
	Finger	**Maximum**	**Average**	**Standard Deviation**
Exercise 1	Index	2696	2445	354
	Middle	2044	1935	153
	Ring	850	762	124
	Pinki	-	-	-
Exercise 2	Index	488	426	88
	Middle	698	600	139
	Ring	255	204	73
	Pinki	-	-	-
Exercise 3	Index	1257	1021	334
	Middle	621	582	54
	Ring	426	423	4
	Pinki	-	-	-
Exercise 4	Index	1695	1479	306
	Middle	1157	920	335
	Ring	508	421	124
	Pinki	-	-	-

Table 5.7: Subject Four Results

Subject Four - Physiotherapist				
	Finger	**Maximum**	**Average**	**Standard Deviation**
Exercise 1	Index	1043	886	150
	Middle	2781	1234	1347
	Ring	500	382	141
	Pinki	622	421	225
Exercise 2	Index	347	301	44
	Middle	288	215	64
	Ring	266	214	51
	Pinki	332	332	-
Exercise 3	Index	604	604	-
	Middle	456	456	-
	Ring	234	234	-
	Pinki	334	334	-
Exercise 4	Index	905	985	113
	Middle	731	859	181
	Ring	295	314	26
	Pinki	-	-	-

Table 5.8: Subject Five Results

Subject Five - Physiotherapist

	Finger	Maximum	Average	Standard Deviation
Exercise 1	Index	2421	2279	199
	Middle	3876	3335	764
	Ring	1631	1346	403
	Pinki	-	-	-
Exercise 2	Index	1262	1232	42
	Middle	243	121	172
	Ring	329	255	105
	Pinki	369	351	26
Exercise 3	Index	1457	1345	157
	Middle	607	417	268
	Ring	450	376	104
	Pinki	851	663	265
Exercise 4	Index	2381	2381	-
	Middle	1934	1934	-
	Ring	-	-	-
	Pinki	-	-	-

Table 5.9: Subject Six Results

Subject Six - Physiotherapist

	Finger	Maximum	Average	Standard Deviation
Exercise 1	Index	1533	1329	288
	Middle	2198	1505	979
	Ring	898	743	218
	Pinki	635	446	266
Exercise 2	Index	417	305	157
	Middle	166	149	24
	Ring	262	234	38
	Pinki	312	303	12
Exercise 3	Index	432	289	202
	Middle	195	179	23
	Ring	146	87	83
	Pinki	353	256	141
Exercise 4	Index	2985	1995	1400
	Middle	1908	1552	502
	Ring	307	280	38
	Pinki	-	-	-

Table 5.10: Subject Seven Results

Subject Seven - Occupational Therapist				
	Finger	**Maximum**	**Average**	**Standard Deviation**
Exercise 1	Index	2880	2268	499
	Middle	2397	1420	807
	Ring	1285	866	373
	Pinki	1270	849	417
Exercise 2	Index	852	764	99
	Middle	711	446	220
	Ring	401	247	111
	Pinki	367	260	101
Exercise 3	Index	711	487	216
	Middle	577	372	181
	Ring	339	288	61
	Pinki	591	385	161
Exercise 4	Index	2923	2578	488
	Middle	1973	1558	587
	Ring	1889	1712	250
	Pinki	1382	1085	419

Table 5.11: Subject Eight Results

Subject Eight - Physiotherapist				
	Finger	**Maximum**	**Average**	**Standard Deviation**
Exercise 1	Index	1258	1195	61
	Middle	1244	1159	86
	Ring	763	483	420
	Pinki	251	251	-
Exercise 2	Index	619	522	79
	Middle	628	448	173
	Ring	382	205	126
	Pinki	531	425	125
Exercise 3	Index	727	687	60
	Middle	396	323	65
	Ring	207	156	57
	Pinki	651	557	103
Exercise 4	Index	1750	1608	184
	Middle	1164	1072	96
	Ring	1074	842	202
	Pinki	364	269	88

5.3.2 Data Scatter Plots

The data of each subject for each exercise is plotted in a scatter plot to give a visual representation of the data and allows for an easy comparison between subjects. The force measurements for exercise one and four are shown as negative values in the plots since forces applied in these exercises are in the direction away from the actuator, as shown in Figure 4.1.

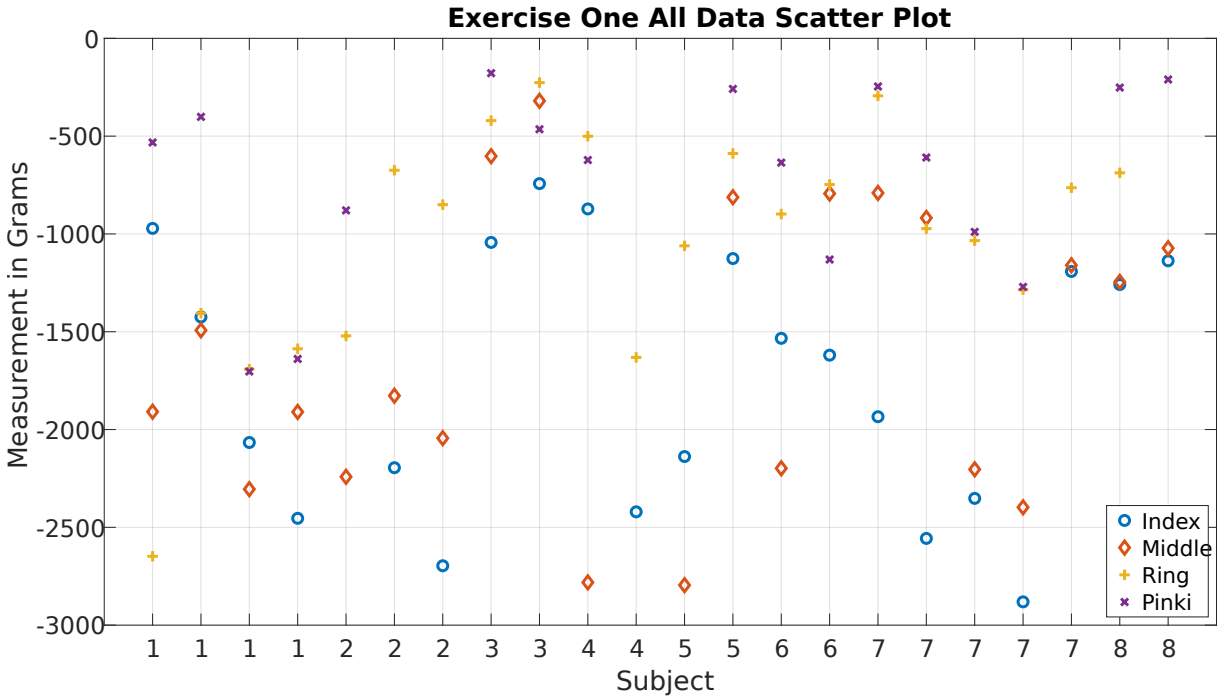


Figure 5.3: Scatter Plot of All Subjects for Exercise One

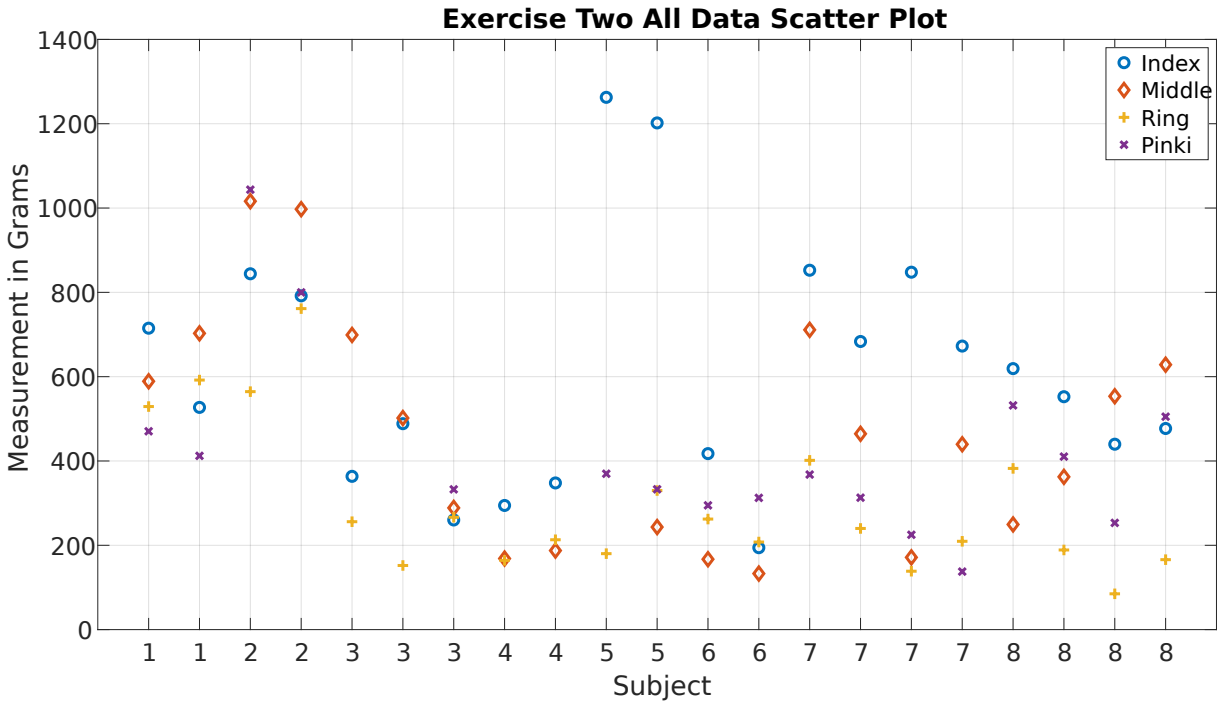


Figure 5.4: Scatter Plot of All Subjects for Exercise Two

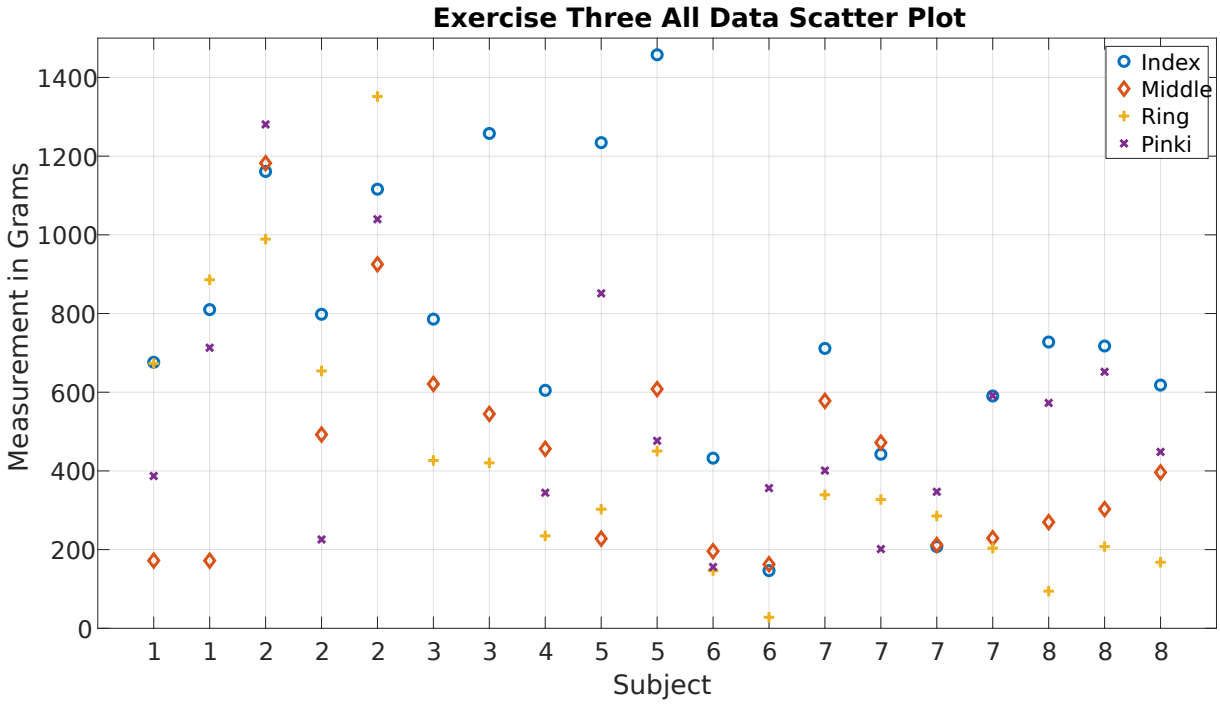


Figure 5.5: Scatter Plot of All Subjects for Exercise Three

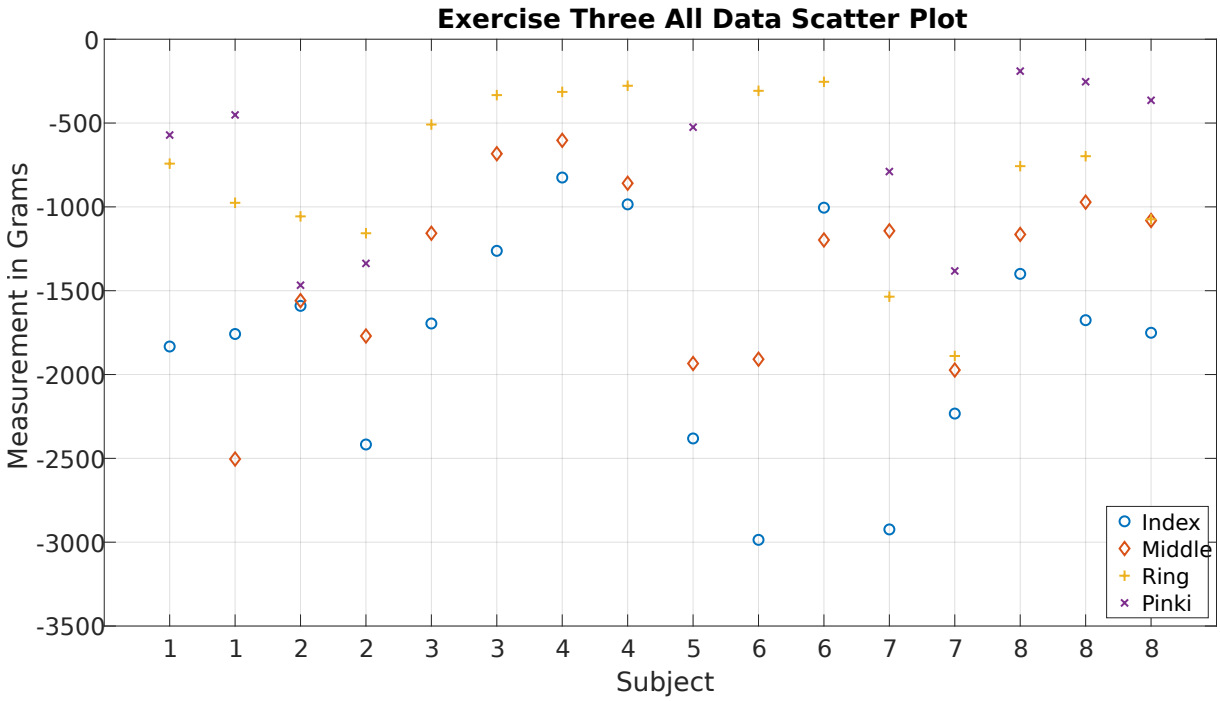


Figure 5.6: Scatter Plot of All Subjects for Exercise Four

5.3.3 Data Summary

The main goal of this study is to determine if the force that therapists apply to patients during rehabilitation can be characterised in order to use this data to configure a rehabilitation device capable of performing similar exercises. A summary of the data is shown in Table 5.12.

Table 5.12: Data Summary

	Finger	**Maximum**	**Average**	**Standard Deviation**
Exercise 1	Index	2880	1743	670
	Middle	3876	1713	874
	Ring	2648	1023	576
	Pinki	1703	707	488
Exercise 2	Index	1262	612	285
	Middle	1016	463	271
	Ring	761	299	177
	Pinki	1043	418	218
Exercise 3	Index	1457	762	351
	Middle	1182	432	274
	Ring	1351	431	341
	Pinki	1280	532	302
Exercise 4	Index	2985	1795	650
	Middle	3933	1527	792
	Ring	1889	792	492
	Pinki	1467	733	487

The first observation that can be made when reviewing the data from Table 5.12 is that the highest force measurement recorded for each finger is in most cases considerably greater than the average force for the related finger and exercise and there is a large difference between measurements. This is supported by the large standard deviation values.

The second observation that can be made is that the forces applied to the fingers tend to be higher for the larger fingers; in most cases more force was applied to the index and middle fingers than to the ring and pinki fingers.

For exercise one, the hand was only 30% closed when referring to the actuator positions. Exercise four was performed on a hand which is 55% closed. The goal of the exercises were for the therapists to attempt to close the hand further by applying force.

The data from exercise one and four can be compared since during these exercises the forces are applied in the same direction with the only difference being the position of the hand. A boxplot is shown in Figure 5.7 to provide a visual representation of the data of the two exercises. The box plots also show the mean value of each dataset, indicated by the '+' symbol. The force values of exercises one and four are once again represented as negative values since the forces are in the direction away from the actuator as per Figure 4.1.

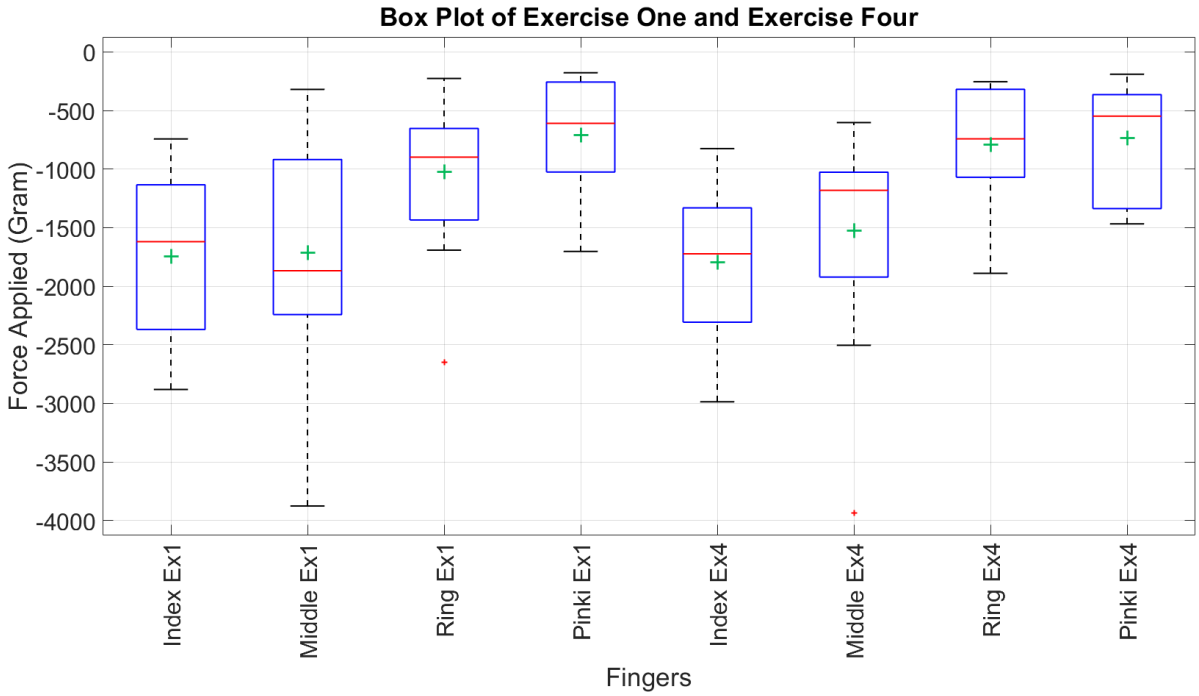


Figure 5.7: Bar Graph Comparing Exercise One and Four

Exercise two and three are both focused on opening the patient's hand from two different starting positions. Exercise two starts with the hand 30% closed when referring to the actuator stroke while exercise three was performed on a hand that is 55% closed. A box plot comparison of the two exercises are shown in figure 5.8.

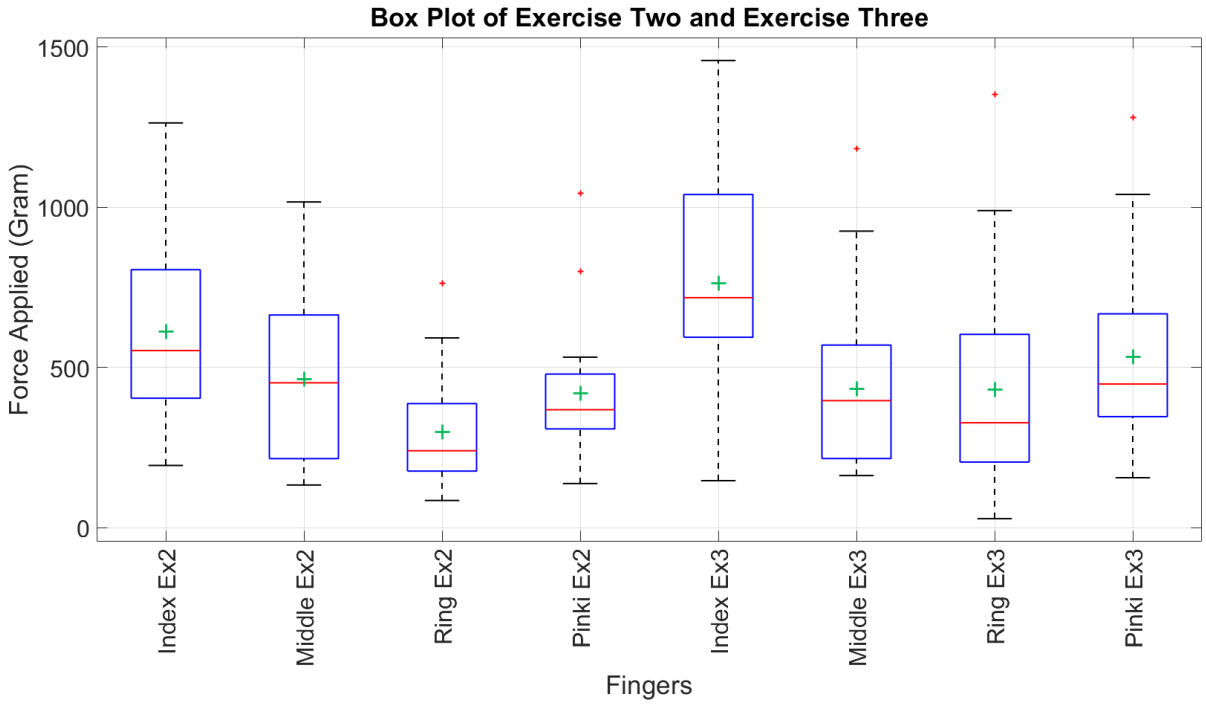


Figure 5.8: Bar Graph Comparing Exercise Two and Three

5.4 Discussion

The data shows that the forces applied by the therapists are spread over a large range, this is clear when reviewing the scatter plots of each exercise; Figures 5.3 to 5.6. The organised representation of the data in the boxplots show that although the forces applied varies greatly, there is a consensus between the forces applied for each finger. The boxplots of Figures 5.7 and 5.8 can be rearranged to allow for a better comparison of the forces applied during each exercise on the respective fingers. The reorganised boxplots are shown in Figure 5.9 and Figure 5.10.

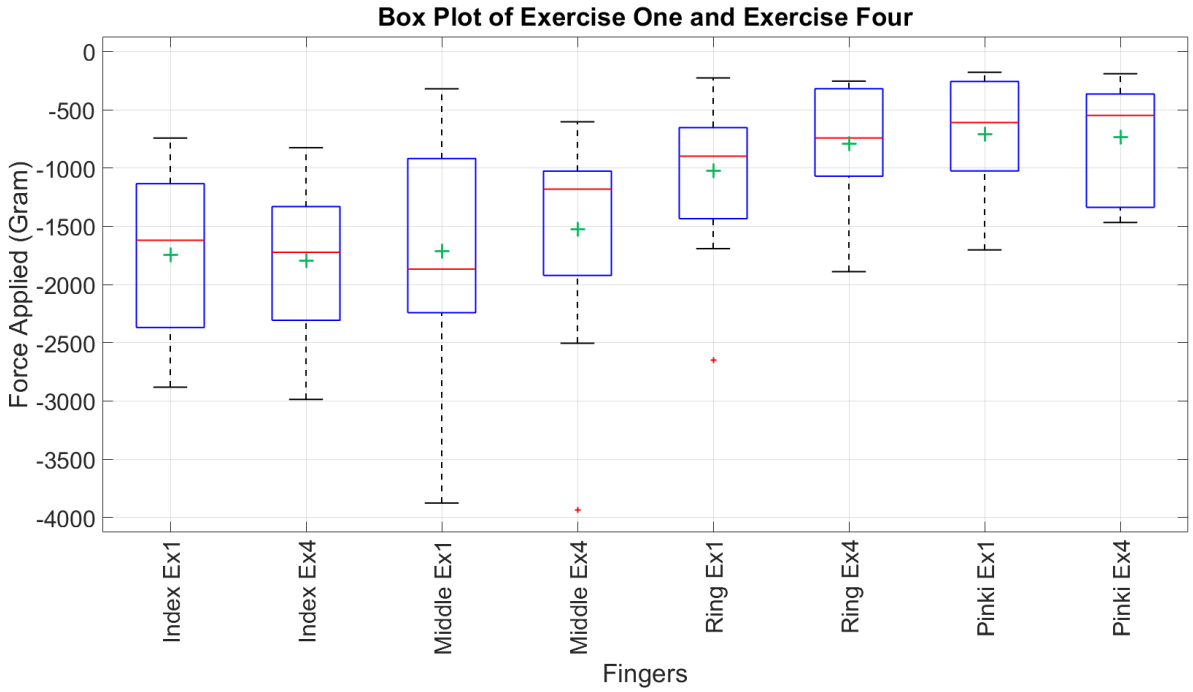


Figure 5.9: Reorganised Boxplot Comparing Exercise Two and Three

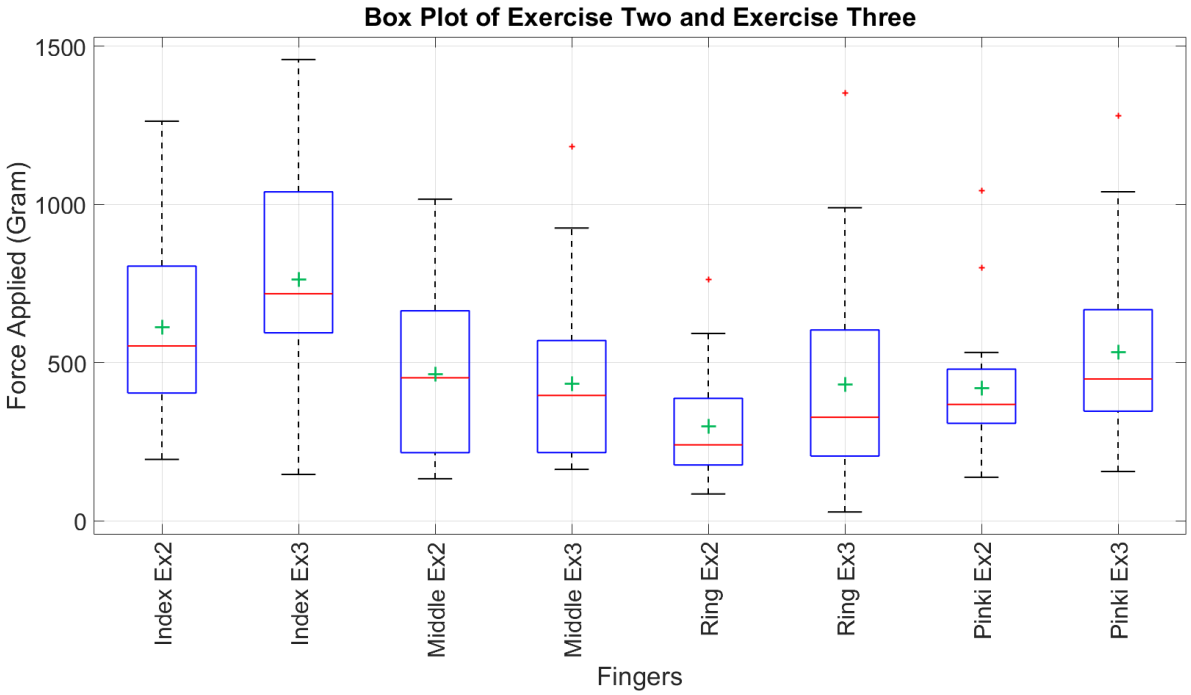


Figure 5.10: Reorganised Boxplot Comparing Exercise Two and Three

When comparing the forces applied to each finger, a correlation between the forces applied for similar exercises can be observed. From the boxplots in Figure 5.9 and Figure 5.10 the observation can be made that the force applied to a finger will be similar for different finger positions.

The reorganised boxplot of exercise two and three, Figure 5.10, show that, similar to exercise one and four, the force applied to each finger is closely related between exercises. The results of exercise two and three indicate a higher correlation in the amount of force applied between all the fingers, with the index finger being the notable exception; especially for exercise three.

The results indicate that the forces applied during rehabilitation exercises can be, to some extent, characterised on a per finger basis based on the 25^{th} and 75^{th} percentiles of the box plots, as well as the averages indicated by the '+' symbol in the boxplots. Additionally the scatter-plots comparing the subjects used indicate that the subjects do not apply the same amount of force in the same scenario; this is investigated in more detail in section 5.6.

5.5 Validation of Results

The results showed that it is possible to characterise the forces applied to a specific patient on a per finger basis. In order to confirm that there is a correlation between the forces applied between the related exercises, an Analysis of Variance (ANOVA) test was performed to test the validity of this observation. The ANOVA test performed is known as a one-way analysis of variance test; Matlab 2018a was used to perform the test using the 'anova1' function. This statistical analysis method is typically used to compare two or more groups of data sets. The test shows whether or not there is a statistically significant difference between the groups.

The test was performed on the data of each finger for the comparable exercises. The results of the test is in terms of the *P*-value; this value is an indicator of statistical significance. When comparing data groups, if the *P*-value is larger than a selected significance indicator then the null hypothesis can not be rejected [47].

The null hypothesis is that the forces applied to each respective finger in one exercise is closely related to the forces applied to that finger during the comparable exercise. For example, the forces applied to the middle finger in exercise two is closely related to the forces applied to the middle finger in exercise three. If the *P*-value is larger than the significance indicator of 0.05 then there is no statistically significant difference between the two groups of data.

Table 5.13: ANOVA Results of Exercise One and Four

Finger	**F-Value**	**P-Value**
Index	0.06	0.8159
Middle	0.44	0.5136
Ring	1.59	0.2171
Pinki	0.2	0.8947

The results for the test comparing the force of each respective finger of exercise one and four show that there is no statistically significant evidence that the null hypothesis needs to be rejected. This means that the forces applied to the respective fingers are closely related between the two exercises. This supports the assumptions that, at least per finger, a baseline for force can be established.

Table 5.14: ANOVA Results of Exercise Two and Three

Finger	**F-Value**	**P-Value**
Index	2.24	0.1431
Middle	0.13	0.7241
Ring	2.4	0.1294
Pinki	1.58	0.2180

Table 5.14 shows the ANOVA results of the force comparisons between exercise two and three. The *P*-value for all fingers are greater than the 0.05 significance level and it can therefore be concluded that there is a statistical significant correlation between the force applied to each finger in similar exercises when considering each finger individually.

To confirm the results of the ANOVA test, a post hoc test is performed on the same data sets. There are various post hoc test that can be performed, one such test is the Tukey test also known as the Tukey HSD, a variant of this test is the Tukey-Kramer procedure which is designed for situations where the sample sizes are not equal. The Tukey-Kramer procedure will be used to confirm the results of the ANOVA test.

The results of the Tukey-Kramer procedure is shown in Tables 5.15 and 5.16. The results of these tests support the results of the ANOVA test; this was expected since the ANOVA tests showed a strong significance level. The 'multcompare' function of Matlab 2018a was configured to perform the Tukey-Kramer test.

Table 5.15: Tukey-Kramer Results for Exercise One and Four Comparison

Finger	**Lower Limit**	**Difference in Group Means**	**Upper Limit**	***P*-value**
Index	-394	51	497	0.82
Middle	-756	-185	-385	0.51
Ring	-604	-231	142	0.22
Pinki	-374	26	426	0.89

Table 5.16: Tukey-Kramer Results for Exercise Two and Three Comparison

Finger	**Lower Limit**	**Difference in Group Means**	**Upper Limit**	**P-value**
Index	-355	-150	53.39	0.14
Middle	-145	31	208	0.72
Ring	-303	-131	40	0.13
Pinki	-297	-113	70	0.22

The Difference in Group Means column in Table 5.15 shows the difference between the estimated group means, the columns named upper and lower limit shows the limits for a 95% confidence interval of the true mean difference. The *P*-value is for a hypothesis test that the mean differences are equal to zero. The *P*-values are higher than 0.05, indicating that there is no significant difference between the means.

5.6 Additional Results

The primary goal of this study is to determine if a baseline for force can be established. An additional research question is if all therapists apply a similar amount of force in the same situation. Since all therapists receive similar training and is expected to be able to perform the same tasks, it is reasonable to form the hypothesis that all therapists should apply the same amount of force when faced with the same patient. To test this hypothesis, the data gathered for each finger during each exercise is compared between subjects, the data is represented visually in boxplots in Appendix B.1. As an example the boxplots of the index finger for exercise one is shown in figure 5.11.

The boxplots of figure 5.11 provides an organised representation of the data. The figure shows that the forces applied by the subjects are significantly different, the box plots also show that the majority of therapists are consistent in the amount of force they apply between repetitions of an exercise. An ANOVA test was performed to confirm the conclusion of the observations form the box plots. Each exercise and finger was treated separately.

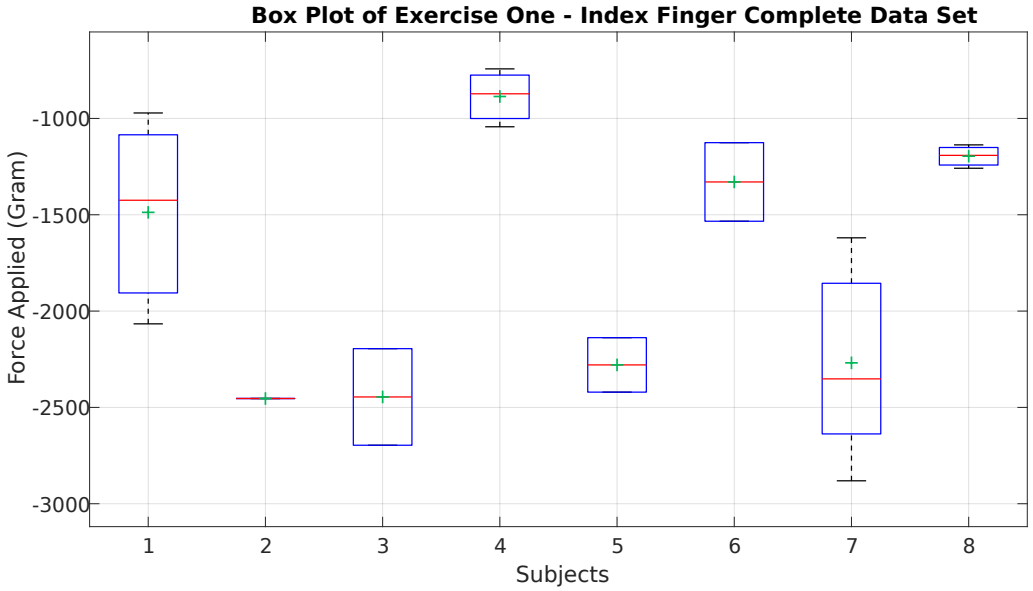


Figure 5.11: Boxplot of Force Applied for Exercise One - Index Finger

The null hypothesis for this test is that all therapists should exert a similar amount of force on the same patient under the same circumstances. The results of the ANOVA test for all subjects is shown in Table 5.17.

ANOVA Results

The complete data set was compared using an ANOVA test. The alpha value for determining significance is chosen at 0.05. If the *P*-value is less than the significance level, the hypothesis can be rejected for the available data.

Table 5.17: ANOVA Results of Complete Data Set

	Finger	**Total DF**	**F-value**	**P-value**
Exercise 1	Index	20	6.91	0.0015
	Middle	21	1.91	0.1425
	Ring	20	5.52	0.0040
	Pinki	16	1.64	0.2289
Exercise 2	Index	20	26.67	0.0000
	Middle	19	7.11	0.0017
	Ring	20	7.16	0.0012
	Pinki	16	9.81	0.0011
Exercise 3	Index	20	6.91	0.0026
	Middle	20	3.42	0.0340
	Ring	20	9.35	0.0007
	Pinki	18	1.19	0.3824
Exercise 4	Index	15	1.52	0.2833
	Middle	15	5.42	0.0149
	Ring	14	21.94	0.0001
	Pinki	9	11.66	0.0095

The results of the ANOVA test for all the subjects show that there is a statistically significant difference between most subjects and that the observations made from the boxplots in appendix B.1 is correct.

The data can however be separated into two sections since the therapists were allowed to chose how they performed the exercises as stated in section 5.3.1. Some subjects chose to attempt to move each finger separately while others chose to move the all the fingers at once. These two groups were separated and an ANOVA test was performed on both to determine if this could explain the large fluctuations in forces applied between subjects. The results of these tests are shown in Table 5.18 and Table 5.19. A *P*-value of more than 0.05 is used to indicate agreement between subjects.

ANOVA for Data With All Fingers Moving

Table 5.18: ANOVA for Data With All Fingers Moving

	Finger	**Total DF**	**F-value**	**P-value**
Exercise 1	Index	12	8.77	0.0063
	Middle	12	3.4	0.0708
	Ring	11	1.18	0.4166
	Pinki	7	1.25	0.4038
Exercise 2	Index	13	30.57	0.0000
	Middle	12	1.92	0.1998
	Ring	13	0.14	0.9648
	Pinki	11	1.92	0.2050
Exercise 3	Index	12	9.56	0.0039
	Middle	12	1.91	0.2023
	Ring	12	9.8	0.0036
	Pinki	10	2.68	0.1281
Exercise 4	Index	9	0.94	0.5121
	Middle	9	1.89	0.2502
	Ring	8	25.76	0.0018
	Pinki	5	6.31	0.0842

The results for ANOVA test of the filtered data showing only the data of therapists who chose to move all fingers at once is shown in Table 5.18. This shows an increase in agreement between the therapists. For exercise one and two the index finger data is the only one that rejects the hypothesis when alpha is 0.05. The data of the fingers that do support the hypothesis, shows relatively high levels of homogeneity; this is supported by the respective boxplots in Appendix B.3.

When considering exercise three, the data of the index finger and ring finger both rejects the hypothesis while the other two fingers do support the hypothesis. Exercise four has the ring finger showing an extremely small *P*-value, suggesting that the forces applied varies significantly.

ANOVA for Individual Finger Sets

Table 5.19: ANOVA for Individual Finger Movement

	Finger	**Total DF**	**F-value**	**P-value**
Exercise 1	Index	5	3.87	0.2122
	Middle	6	0.67	0.6266
	Ring	6	29.66	0.0099
	Pinki	6	2.47	0.2386
Exercise 2	Index	8	18.81	0.0037
	Middle	8	28.34	0.0015
	Ring	8	12.76	0.0089
	Pinki	5	8.02	0.1129
Exercise 3	Index	7	6.63	0.0146
	Middle	7	6.27	0.0434
	Ring	7	10.81	0.0153
	Pinki	7	2.36	0.1900
Exercise 4	Index	5	18.84	0.0008
	Middle	5	8.8	0.0556
	Ring	5	31.36	0.0098
	Pinki	3	101.37	0.0097

With the data sets where each finger is moved separately, the majority of data sets would suggest that the hypothesis should be rejected for the data tested and that the force applied by the subjects are statistically different. For exercise one, only the ring finger rejects the hypothesis. The other exercises all tend to have only one finger in support of the hypothesis.

The degrees of freedom for this data set is smaller than for the data set where all the fingers are exercised at once, this has to be kept in consideration when reviewing statistical data, especially during validation analysis of the results since most statistical analysis methods tend to produce type two errors with small sample sizes. A type two error is when a hypothesis that is false is not rejected [47]. No test procedure can provide complete protection against statistical errors.

5.7 Validation

5.7.1 Validation of Additional Results

The results from the three ANOVA tests all reject the hypothesis that all therapists should apply a similar amount of force under the same circumstances. Normally it is recommended to perform only one post hoc test for ANOVA results, since post hoc tests tend to deliver differing results depending on the strengths and weaknesses. One aspect of the data that needs to be considered is that the sample sizes are small and even smaller when the data is separated according to technique. This has an influence on almost all commonly used post hoc tests.

The Tukey HSD test can be used to compare all subjects with each other to validate the results of the anova test. A variant on this test is the Tukey-Kramer Method, this method is intended for data with unequal sample sizes. This test was used in section 5.5 as well.

An alternative to Tukey's test or the Tukey-Kramer test, is the Games-Howell test. This test is also intended for data with unequal sample sizes and uses elements of Tukey's test. The Games-Howell test is known to be too liberal when used with data with small sample sizes and will therefore commonly result in a type two error.

It should also be noted that there has been many reviews of statistical analysis methods suggesting that methods that rely on a *P*-value system is largely unreliable [48] [49] [50]. These methods is still widely used for analysis. In this study these methods are used as a indicator of statistical significance of the data gathered. The results of all the tests and their statistical and practical significance is discussed later in this chapter.

5.7.2 Tukey-Kramer

The results of the Tukey-Kramer test that was performed to support the results of the ANOVA test is shown in Table 5.20. The rest of the results are available in Appendix C.

Table 5.20: Tukey-Kramer

Exercise One - Index Finger

Subject 1	Subject 2	Lower Limit	Difference of Group Means	Upper Limit	P-value	Significance
1	2	-611.59	966.26	2544.1	0.416	1
1	3	-289.21	958.19	2205.6	0.193	1
1	4	-1717.2	-601.49	514.22	0.559	1
1	5	-455.56	791.84	2039.2	0.377	1
1	6	-1405.2	-157.84	1089.6	1.000	1
1	7	-216.76	781.16	1779.1	0.178	1
1	8	-1407.4	-291.66	824.05	0.977	1
2	3	-1681.6	-8.066	1665.5	1.000	1
2	4	-3145.6	-1567.7	10.105	0.052	1
2	5	-1848	-174.42	1499.1	1.000	1
2	6	-2797.7	-1124.1	549.46	0.317	1
2	7	-1682	-185.09	1311.8	1.000	1
2	8	-2835.8	-1257.9	319.93	0.164	1
3	4	-2807.1	-1559.7	-312.28	0.011	0
3	5	-1532.8	-166.35	1200.1	1.000	1
3	6	-2482.5	-1116	250.43	0.147	1
3	7	-1320.3	-177.03	966.23	0.999	1
3	8	-2497.2	-1249.8	-2.449	0.049	0
4	5	145.92	1393.3	2640.7	0.024	0
4	6	-803.75	443.65	1691	0.895	1
4	7	384.73	1382.7	2380.6	0.005	0
4	8	-805.88	309.83	1425.5	0.968	1
5	6	-2316.1	-949.68	416.78	0.282	1
5	7	-1153.9	-10.674	1132.6	1.000	1
5	8	-2330.9	-1083.5	163.91	0.109	1
6	7	-204.26	939	2082.3	0.144	1
6	8	-1381.2	-133.82	1113.6	1.000	1
7	8	-2070.7	-1072.8	-74.901	0.032	0

The results of the Tukey-Kramer test for the index finger of exercise one is presented as an example. The Tukey-kramer test indicates that there is no significant difference for most of the data sets compared of the index finger in exercise one. The significance column shows a value of '1' if the test shows a correlation between compared data and a '0' when the P-value is less than 0.05. The results of the test for the other fingers show similar results. It is clear that this test has resulted in a type two error resulting in the null hypothesis not being rejected. This is due to the small sample sizes and is known to occur with small sample sizes.

5.8 Additional Results Discussion

The data from the ANOVA tests and the box plots show that there is little to no agreement in the amount of force the subjects applied during the exercises.

The results also show that if the subjects are divided according to how they chose to perform the exercises, that there is a noticeable increase in agreement compared to the complete data set. This increase in agreement is, however, too small to suggest that there is consensus between subjects on how much force should be applied.

The results suggest that the subjects can be characterised individually to configure a rehabilitation device according to each subject.

The post hoc test to confirm the results of the anova test resulted in a type two error since it suggested that there is no significant difference between most of the measurements. The Games-Howel post hoc test was also performed on the data; this also resulted in a type two error with the test showing no significant difference between data samples and the test was abandoned since it produced worse results than the Tukey-Kramer test. The calculated results are shown in appendix C.2. Post hoc tests can not be used as a validation technique for the data being compared.

5.9 Effect of the Mechanical Structure of the Finger

The forces applied during the exercises were applied to the fingers. When the device applies force to the patient or the patient applies force to the device, the forces are also applied to the fingers and measured along the same path. The forces measured during the data gathering exercises can therefore be used to calibrate the device for use with a patient.

The mechanical structure of the finger is expected have an effect on the force measured by the strain gauges. The effect of the mechanical structure will depend on the components used to construct the finger, meaning it will differ for different size fingers. The level of flexion and extension of the finger will also influence the measurements. The effect the of mechanical structure on the force measurements can be ignored since the device should not be calibrated according to the amount of force applied to the finger but according to the force measured by the strain gauges as a result of force being applied to the finger.

To investigate the effect of the mechanical structure of the finger has on the force measurements a test jig was constructed. The test jig allows for a force to be applied and measured to the tip of the finger while allowing the finger to be held in different positions; as with the data gathering exercises. Figure 5.12 shows a picture of the test jig. The jig allows for the finger and actuator assembly to be moved up or down depending in the position of the finger. The load cell slides on two stainless steel rails and is held in position by four linear bearings. A threaded rod is used to slowly move the load cell along the rails. The load cell pushes against the tip of the finger and the reading of the load cell and the strain gauges are recorded.

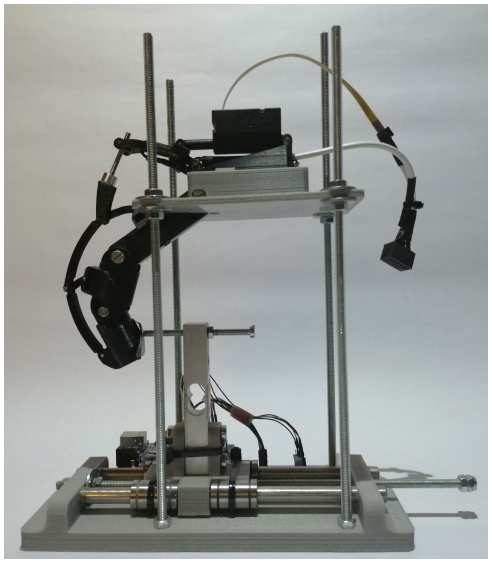


Figure 5.12: Finger Test Jig

The results of this experiment confirmed that the forces measured by the strain gauges are different from those applied at the tip of the finger. The forces measured by the strain gauges were typically higher than the forces measured at the finger tip. This means that the linkages in the finger, along with the finger itself is acting as a lever towards the strain gauges. The data gathered from the experiments are shown in Appendix E.

The results of this experiment was expected and does not influence the data gathered from the therapists and does not influence the results. The device will have to be calibrated according to the needs of each patient and according to the amount of force the therapist deems necessary for rehabilitation.

5.10 Conclusion

The calibration of the rehabilitation device was verified and adjusted accordingly. The accuracy of the measurements are sufficient to draw accurate conclusions from the data gathered to compare the forces applied to each finger as well as compare the forces applied by each subject. The calibration process simulates the manner in which forces will be applied when the device is warn by a patient. The calibration process does not take the mechanical structure of the finger components into account.

This chapter also provides a detailed overview of the data gathered from the experiment performed. The experiment required therapists to apply force to a hand wearing an exoskeleton, the hand resembled a patient which has limited range of motion and can be considered spastic. The therapists were asked to apply force to the hand as they would normally in an attempt to open or close the hand. The main goal was to determine if this data can be used to characterise the forces used during rehabilitation exercises in order to allow a robotic exoskeleton to apply a similar amount of force to a patient without harming the patient.

The results show that although there were generally a large variance in forces applied to the patient, the average values, 25^{th} and 75^{th} percentiles of the data tend to be in agreement when the forces of related exercises are compared.

The data was also used to compare the forces from different subjects. The results of this comparison suggested that therapists do not apply the same amount of force when faced with the same patient. There are some instances that show agreement between subjects; however, the majority of data sets show that there are significant variances in the amount of force applied. The majority of the data sets suggests that therapists tend to be consistent in the amount of force they apply. Therefore, it can be concluded that therapists in general can not characterised, each therapist can be measured and characterized as an individual and this can potentially be used to calibrate rehabilitation devices.

The effect of the mechanical structure was investigated. The mechanical structure of the finger does influence the measurements; however the effect of the mechanical structure does not influence the results since the therapists all performed the experiment on the same patient with the fingers in the same positions. The experiment aims to determine if the forces exerted can be quantified and additionally if therapists all apply the same amount of force to the same patient. Since all the results were gathered with the same hand and the experiments were all performed with a specified hand position, the effect of the mechanical structure can be ignored when comparing therapists.

Chapter 6

Conclusion

This chapter summarises the work presented in this dissertation. The research problem and the results are discussed followed by recommendations for future work.

6.1 Research Summary

The research of this dissertation aimed to quantify the force exerted by a therapist for the calibration of rehabilitation devices. In Chapter one a problem was identified by applying the scientific method. A detailed literature study regarding the human hand, stroke and similar neurological traumas was conducted followed by an overview of existing rehabilitation devices in Chapter two.

Chapter three provides an overview of the rehabilitation device developed as a TIA project. A prototype of the rehabilitation device was constructed. The calibration and experimental setup used for data collection are presented in Chapter four. In Chapter five the calibration of the strain gauges are verified before the data gathered from the experiments analysed, compared and discussed.

6.2 Research Problem Discussion

The research problem presented in this dissertation is stated in Section 1.3. The problem is that the forces that robotic-assisted rehabilitation devices can apply, can exceed that which is safe for humans. The forces applied by therapists during rehabilitation is unknown and needs to be characterised. The characterisation of forces can be used as a baseline to allow robot-assisted rehabilitation devices to perform rehabilitation exercises in an unsupervised manner with patients who have spastic hands or limited range of motions.

Results were gathered from four exercises performed by eight experienced therapists. The results indicate that a different amount of force is applied to each finger during rehabilitation of a spastic hand. The results do show that the forces applied to each finger is consistent between similar exercises and therefore the forces applied during rehabilitation can be characterised on a per finger basis.

The hypothesis formulated in Chapter one can be modified and accepted on a per finger basis only. The original hypothesis stated that therapists should apply similar amounts of force to the same patient; this is only acceptable when considering the forces applied to each finger.

The amount of force each subject applied to each finger for every exercise was also compared. This led to the observation that there are large fluctuations in the amount of force applied by the subjects. The original hypothesis can therefore be rejected since the data gathered from the therapists suggest that they do not apply similar amounts of force on the same patient.

The variance in the forces applied by each subject for a specific scenario is minimal, suggesting that the forces applied by each subject tend to be consistent. The data suggested that the forces applied by each subject could be characterised.

The force a therapist applies during rehabilitation can be characterised; however, the data suggests that each therapist needs to be measured and characterised and the data from these measurements can be used to configure a robotic rehabilitation device. This allows the device to perform similar exercises to what a patient would have received with a therapist.

6.3 Recommendations for Future Work

This section discusses some recommendations for future work on hand rehabilitation devices.

6.3.1 Larger Sample Sizes

The study only consists of eight subjects; although this was enough to form a conclusion, the comparison between subjects can be improved by including more subjects. Finding suitable participants that are willing to take part in the study can be difficult.

6.3.2 Mechanical Structure Characterisation

The results of this study ignores the effect of the mechanical structure. The aim was to measure the forces applied by therapists and use the results to improve the functionality and capabilities of the rehabilitation device. All the therapists performed the exercises on the same patient with the hand in specific positions; this means that data from different therapists can be compared and the effect of the mechanical structure of the finger can be ignored. The forces measured as a result of the therapists applying forces to the fingers are comparable to the device applying force to the fingers. Therefore the data gathered from the therapists can be used to calibrate the rehabilitation device.

The experiment performed to investigate the effect of the mechanical structure of the finger shows that the mechanical structure of the finger acts as a lever, the forces measured at the tip of the finger is smaller than those measured by the strain gauges on the actuator arms. Future studies could characterise the structure of the finger and develop a model for calculating the force for different finger lengths and positions.

6.3.3 Accuracy of Force Measurements

The accuracy of the force measurements can be improved by replacing the plastic actuator arms with metal arms, preferably aluminium as to not add too much weight. The aluminium should offer a more rigid solution than the plastic arms, resulting in less deflection of the strain gauges which should result in higher accuracy measurements. The aluminium arms will however be considerably more expensive to manufacture which is in contrast with the original design requirements. A mechanical redesign of the actuator arms can be attempted to allow space for four strain gauges per actuator assembly, this may also yield a more accurate calibration result.

6.3.4 Printed Circuit Board Improvements

The printed circuit board can be made smaller with the help of smaller footprint components. The PCB in the prototype uses components large enough to be soldered by hand. The connection between the control board and the actuator modules can also be improved by using standardised connectors.

6.3.5 Testing on Human Patients

The experiments were performed on a articulated hand, this was due to ethical constraints. The experiments can only be performed on human patients if the study is done as part of a registered clinical trial. A clinical trial was not possible due time and budgetary constraints of a masters degree. The TIA project is still ongoing and a clinical trial is planned. Using stroke patients would also introduce more variables such as different hand sizes and different levels of disability and recovery.

6.4 Concluding Remarks

Robotic-assisted rehabilitation devices show promising results regarding increasing the recovery rate for stroke patients experiencing hemiparesis. The majority of existing rehabilitation devices are aimed at patients with weak hands. The rehabilitation device developed in this study is capable of applying forces to a patient with a spastic hand or a patient with a limited range of motion. The amount of force that the device should be allowed to apply for effective rehabilitation was unknown.

The results showed that it is possible to quantify the forces a therapist applies during rehabilitation exercises, and this data can be used to calibrate a rehabilitation device to perform similar exercises and apply force as the therapist would have done.

The results indicate that each therapist that makes use of a rehabilitation device capable of applying force to a patient needs to be characterised and the device calibrated accordingly. Comparing the results to other studies proved to be difficult, primarily because most devices focus on weakened hands rather than spastic hands. Comparing the results to studies measuring grip strength would not result in any meaningful conclusions since there studies focus on the amount of force the patient can exert rather than the amount of force the therapists exert.

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pdf

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Appendix A

Calibration

For all the graphs included in Appendix A, the x-axis indicates the expected values and the y-axis shows the measured values.

A.1 Initial Calibration

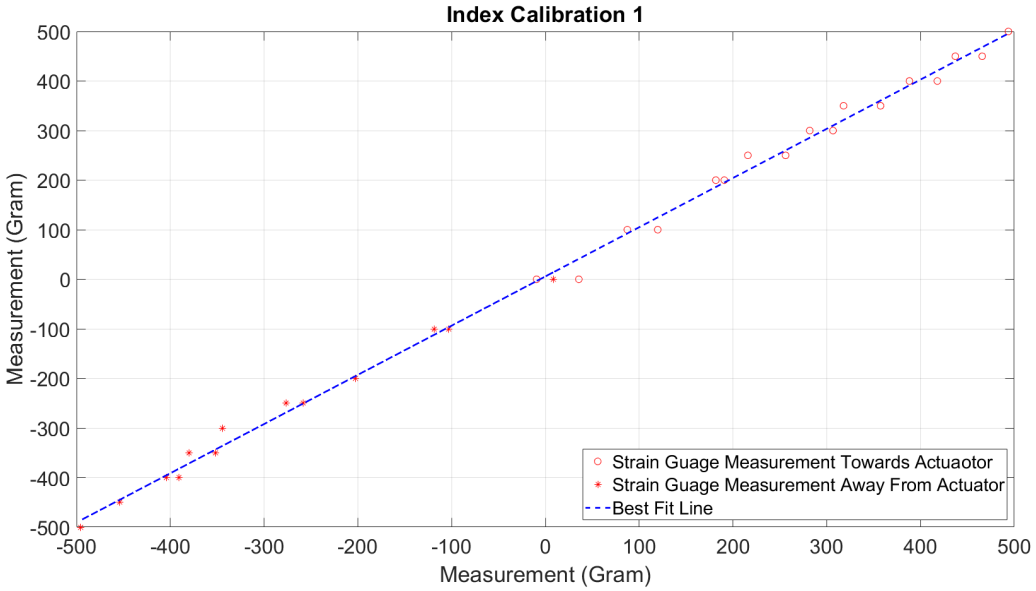


Figure A.1: Calibration - Index Finger 1

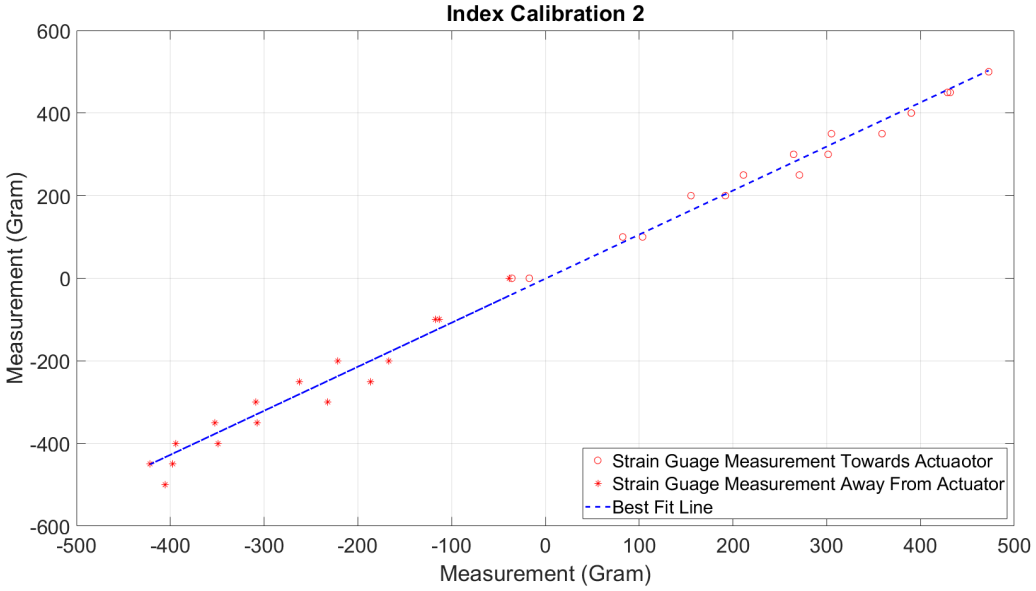


Figure A.2: Calibration - Index Finger 2

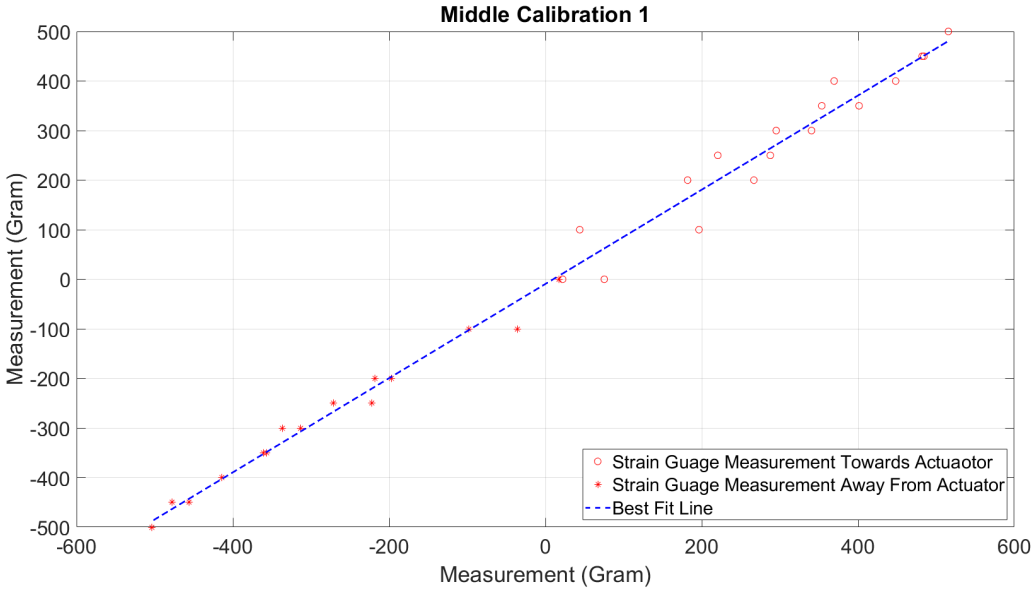


Figure A.3: Calibration - Middle Finger 1

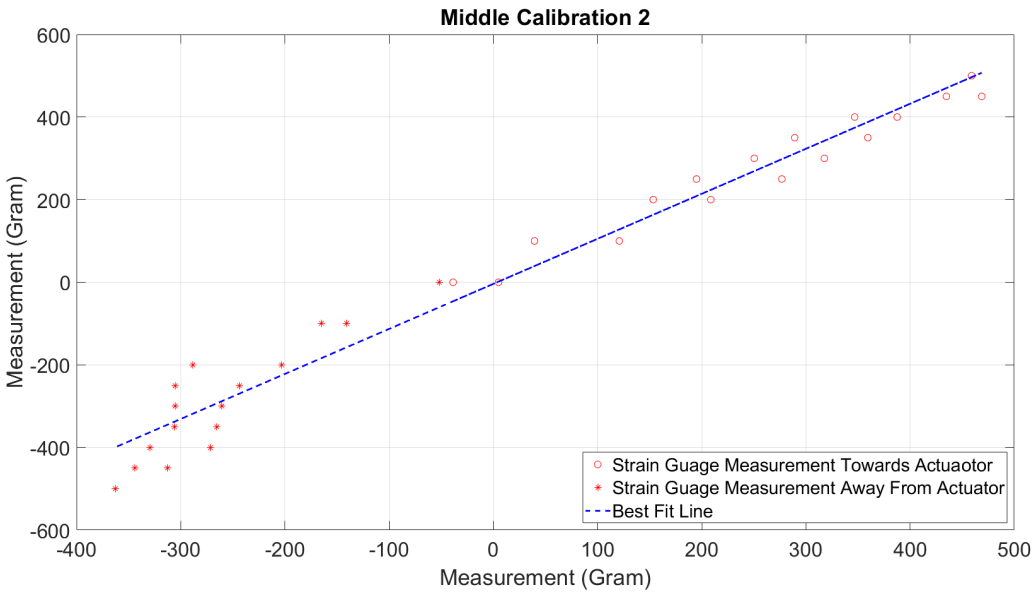


Figure A.4: Calibration - Middle Finger 2

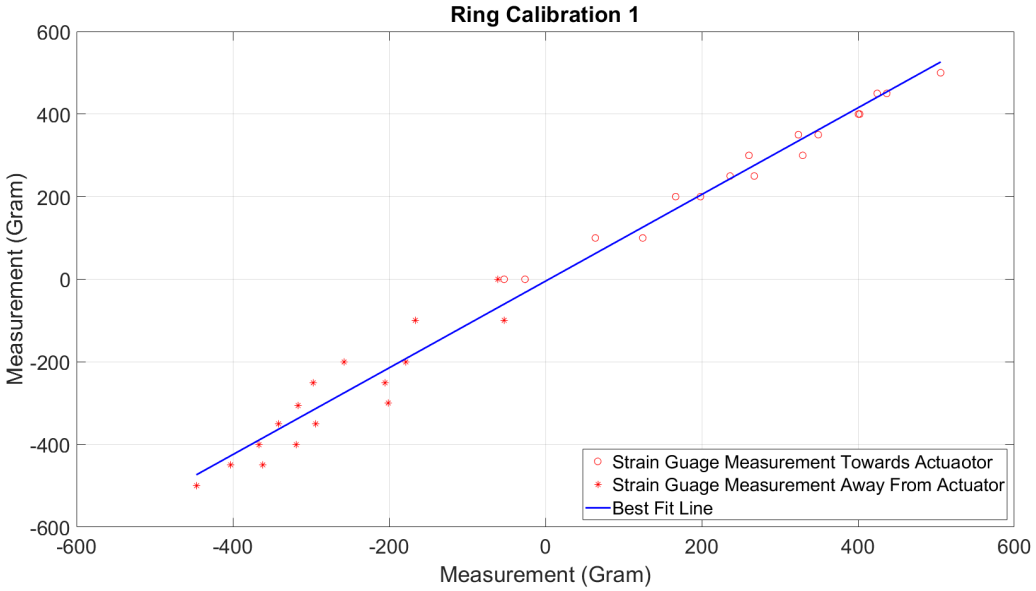


Figure A.5: Calibration - Ring Finger 1

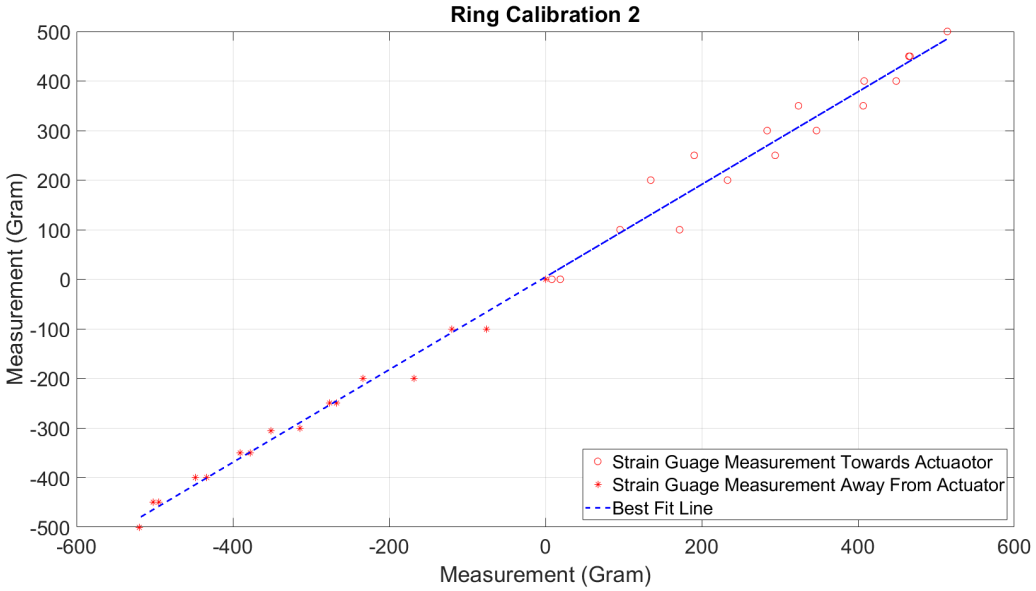


Figure A.6: Calibration - Ring Finger 2

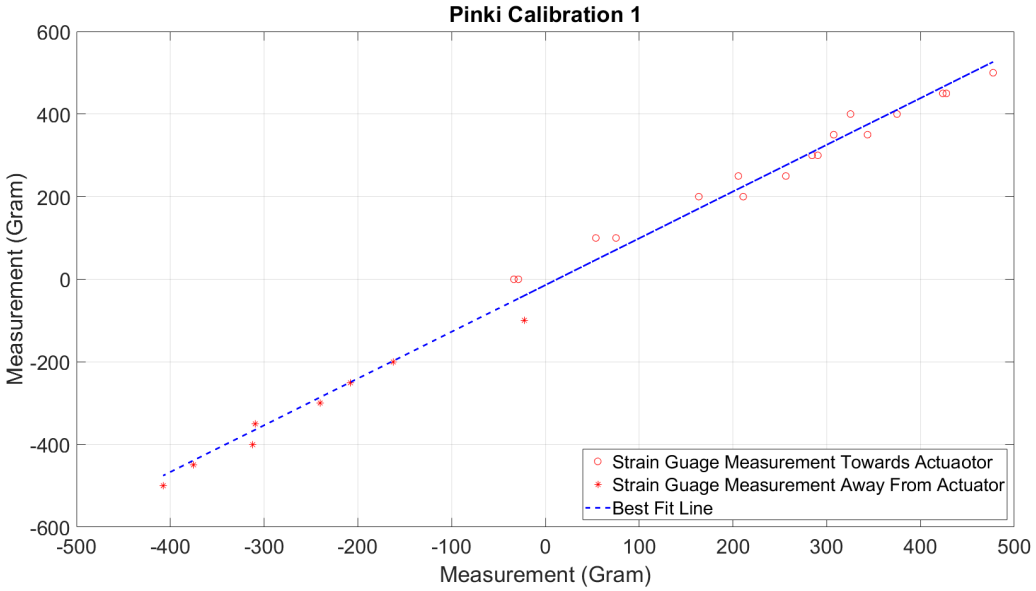


Figure A.7: Calibration - Pinki Finger 1

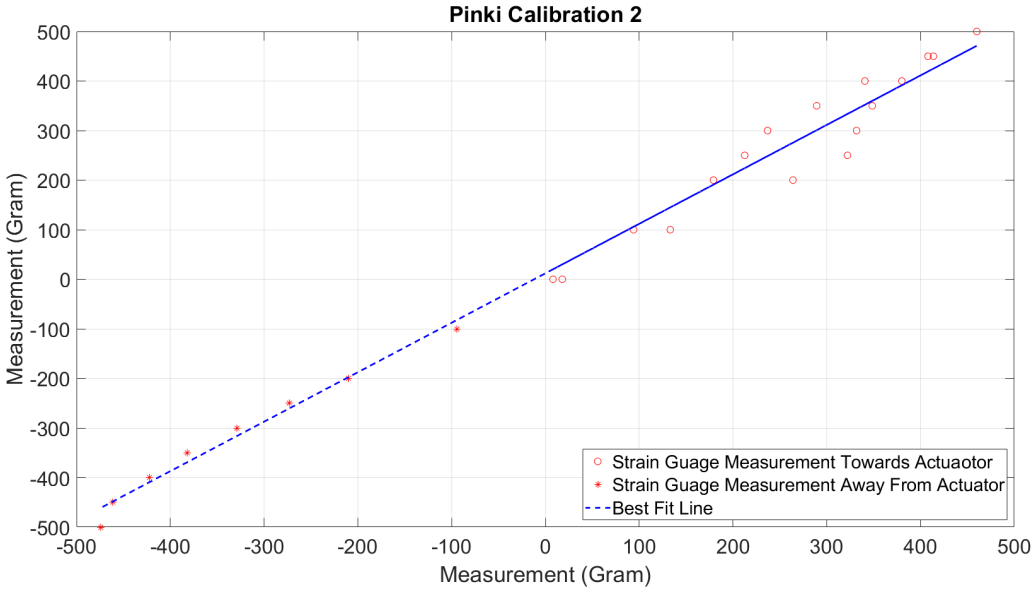


Figure A.8: Calibration - Pinki Finger 2

A.2 Calibration Verification

A.2.1 Calibration Verification Towards Actuator

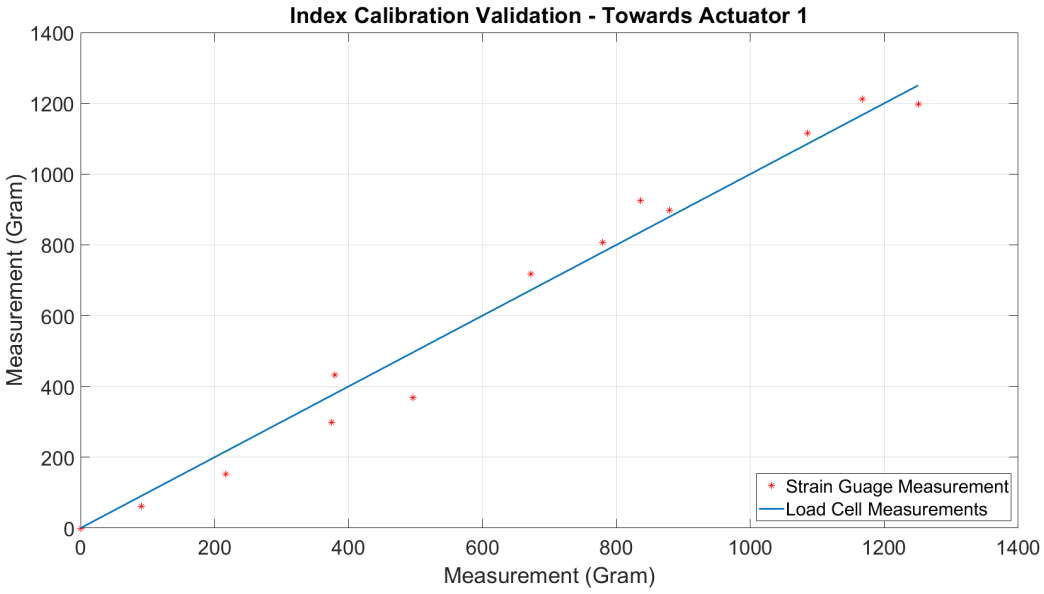


Figure A.9: Calibration Verification - Index Finger 1

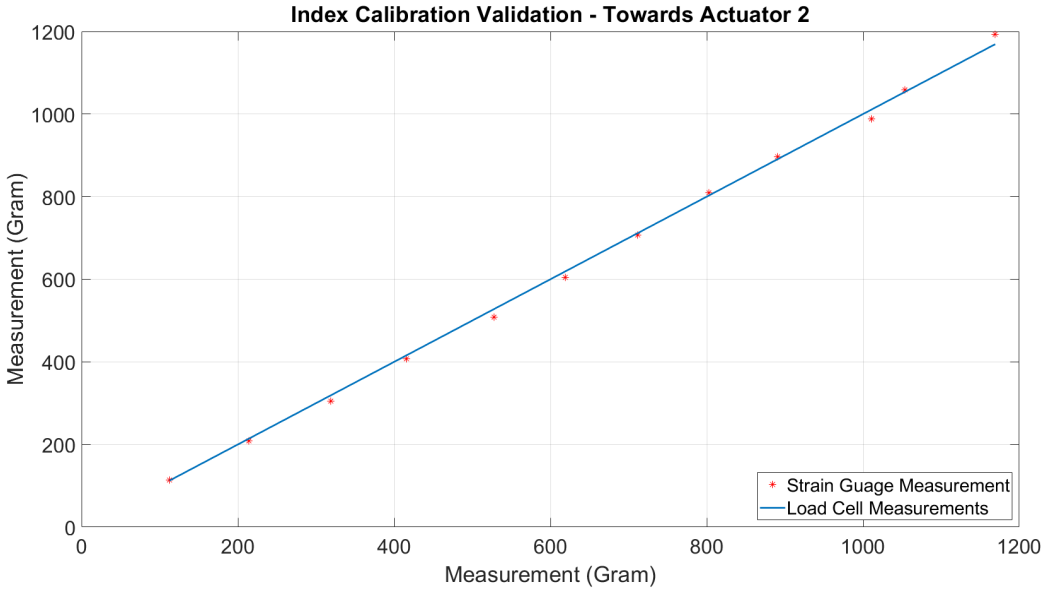


Figure A.10: Calibration Verification - Index Finger 2

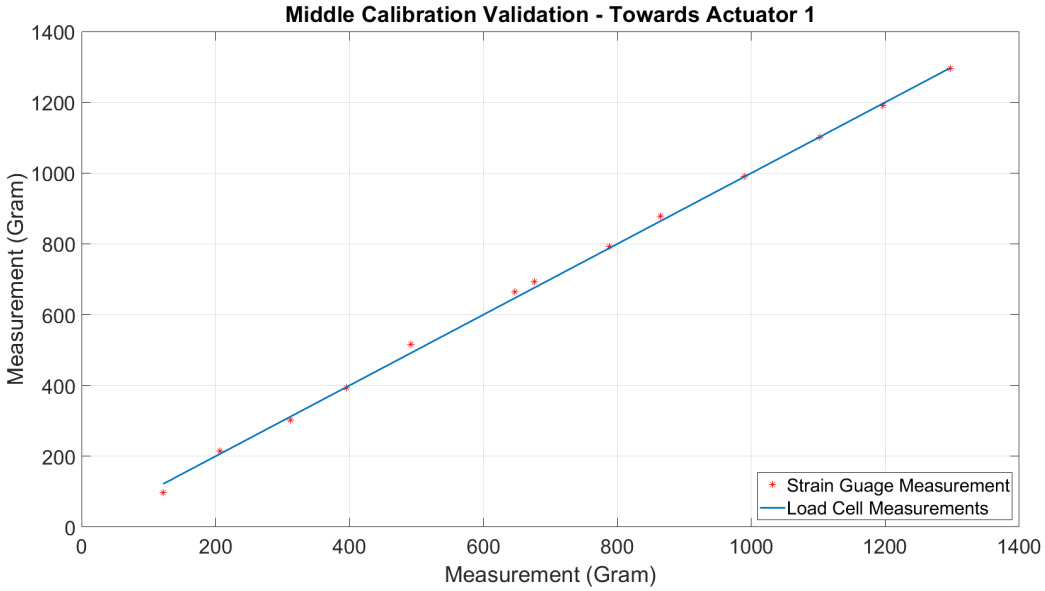


Figure A.11: Calibration Verification - Middle Finger 1

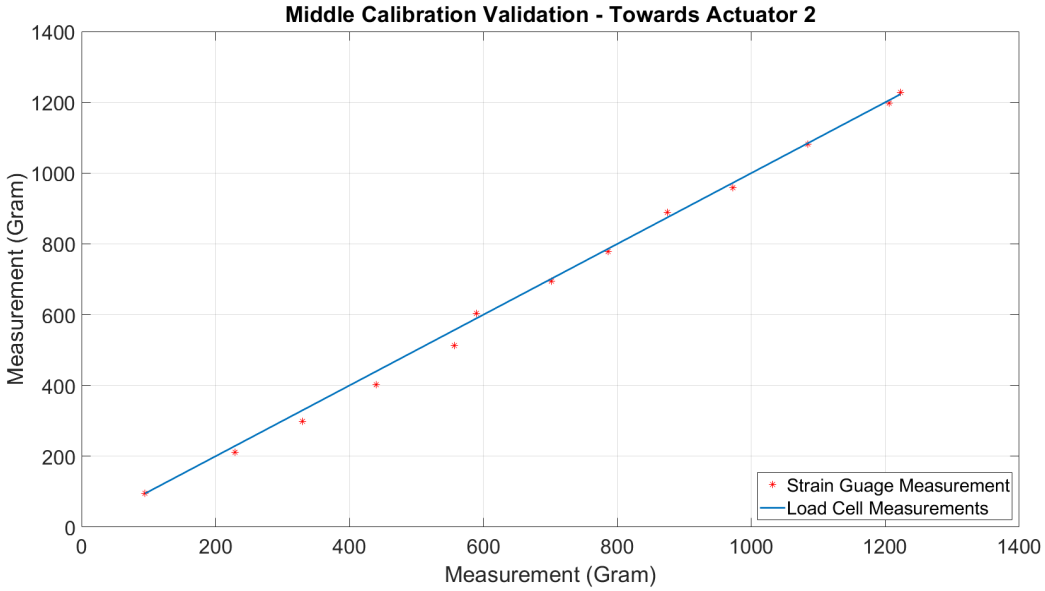


Figure A.12: Calibration Verification - Middle Finger 2

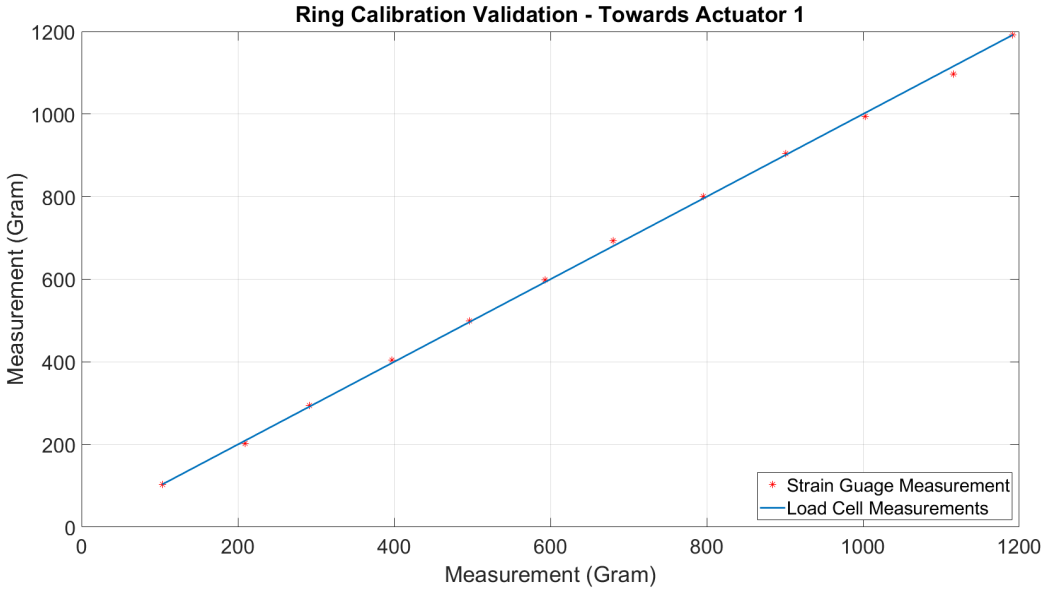


Figure A.13: Calibration Verification - Ring Finger 1

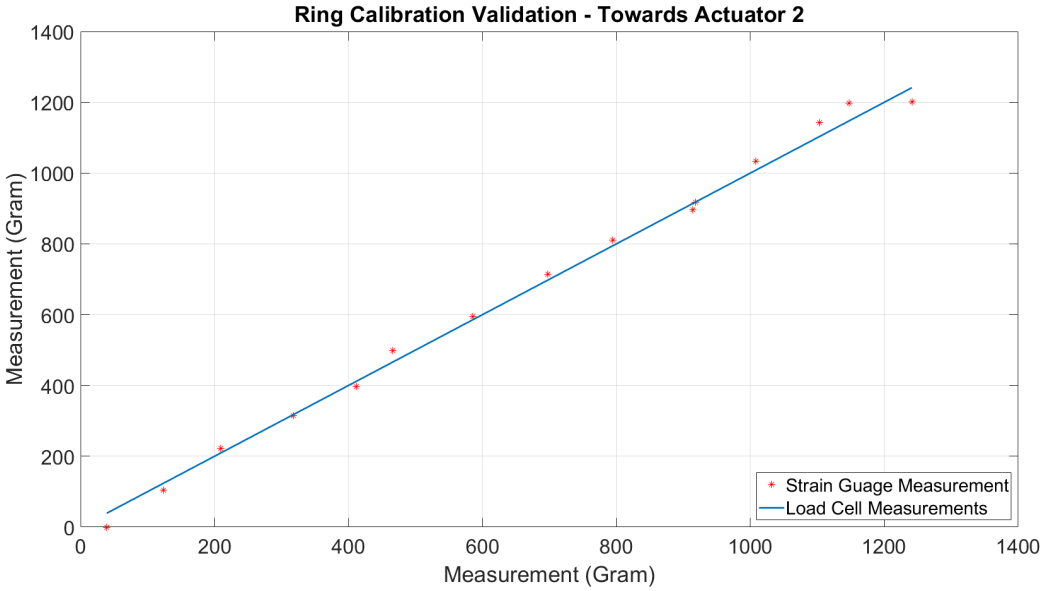


Figure A.14: Calibration Verification - Ring Finger 2

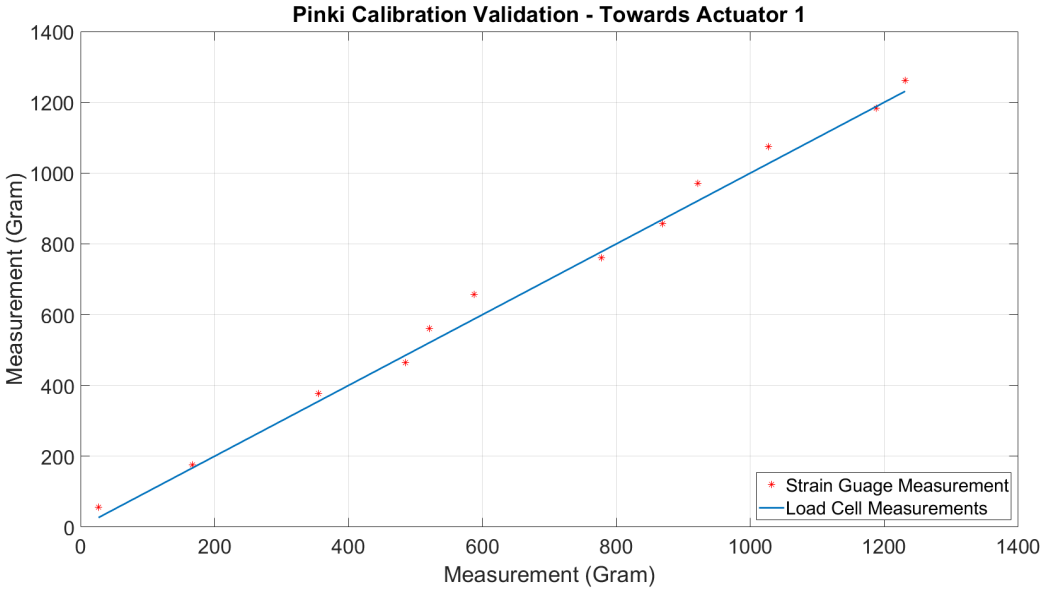


Figure A.15: Calibration Verification - Pinki Finger 1

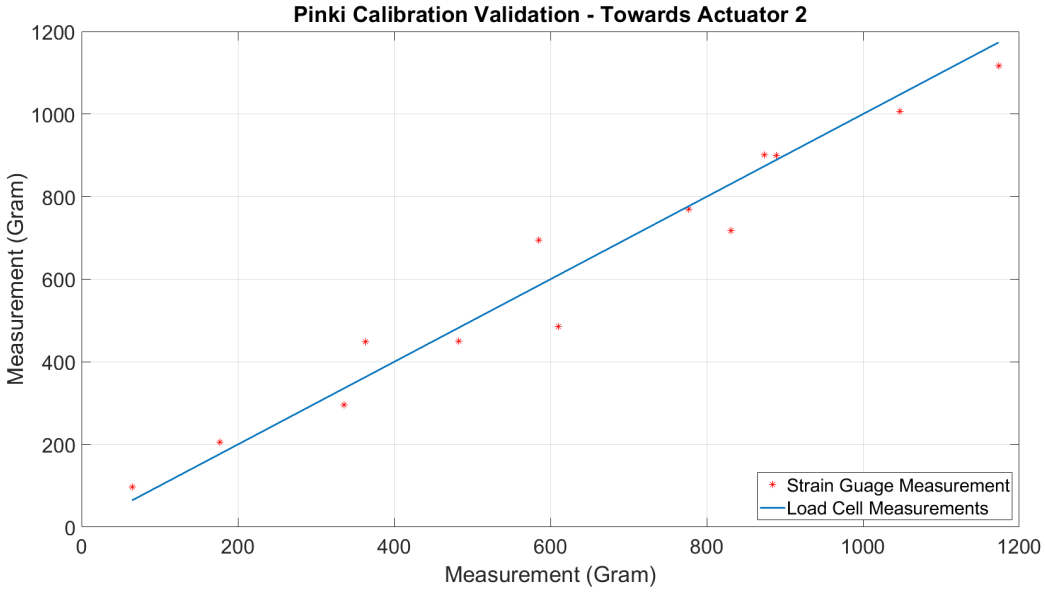


Figure A.16: Calibration Verification - Pinki Finger 2

A.2.2 Calibration Verification Away From Actuator

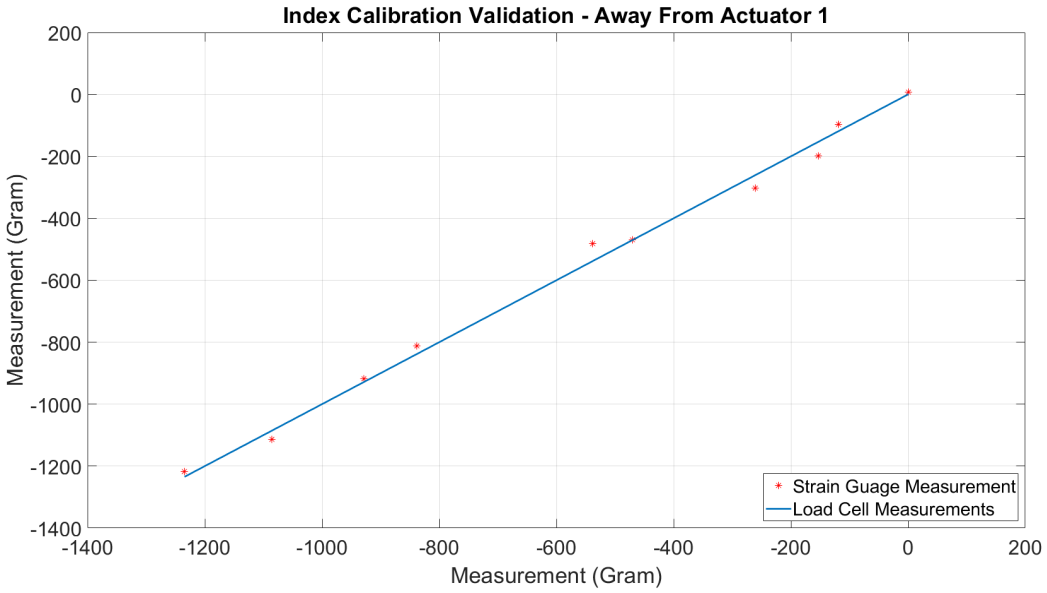


Figure A.17: Calibration Verification - Index Finger 1

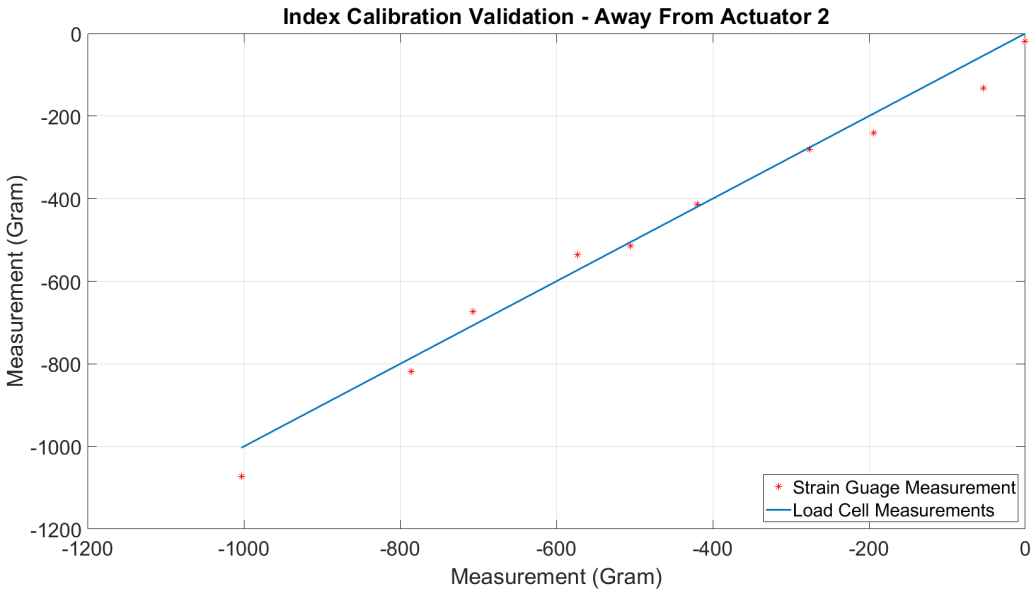


Figure A.18: Calibration Verification - Index Finger 2

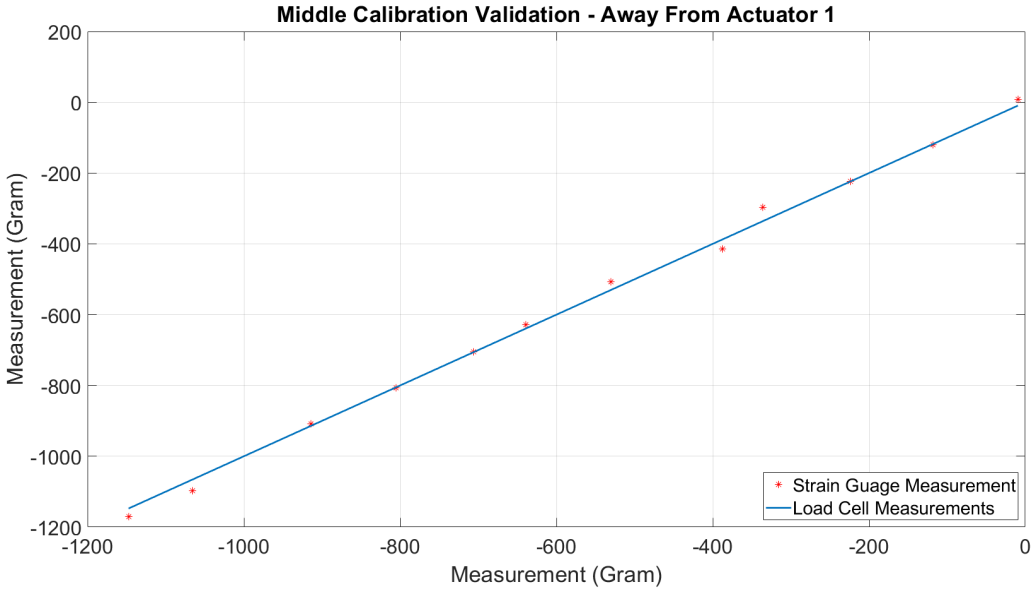


Figure A.19: Calibration Verification - Middle Finger 1

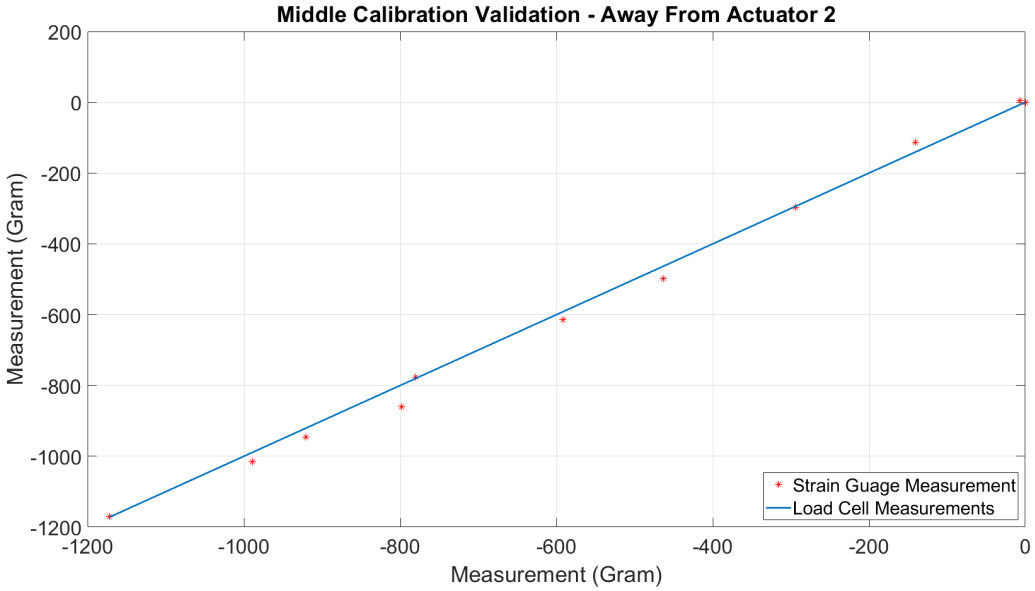


Figure A.20: Calibration Verification - Middle Finger 2

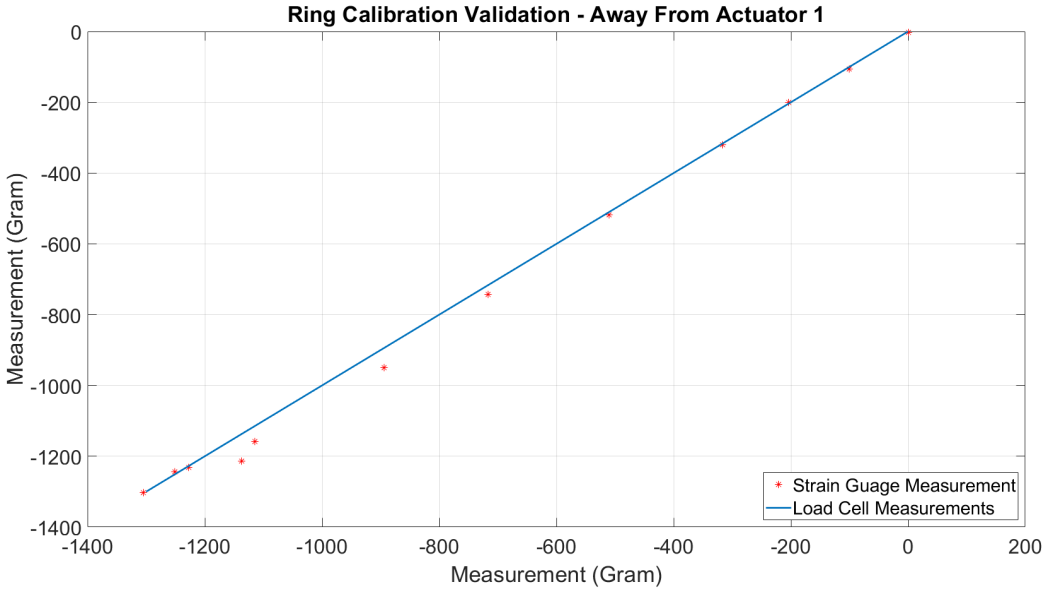


Figure A.21: Calibration Verification - Ring Finger 1

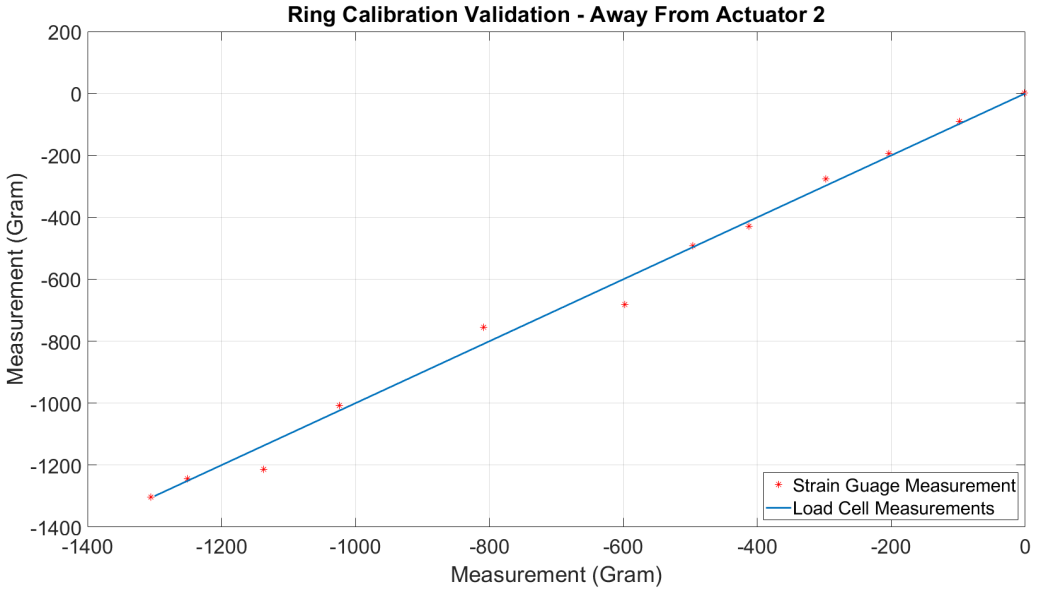


Figure A.22: Calibration Verification - Ring Finger 2

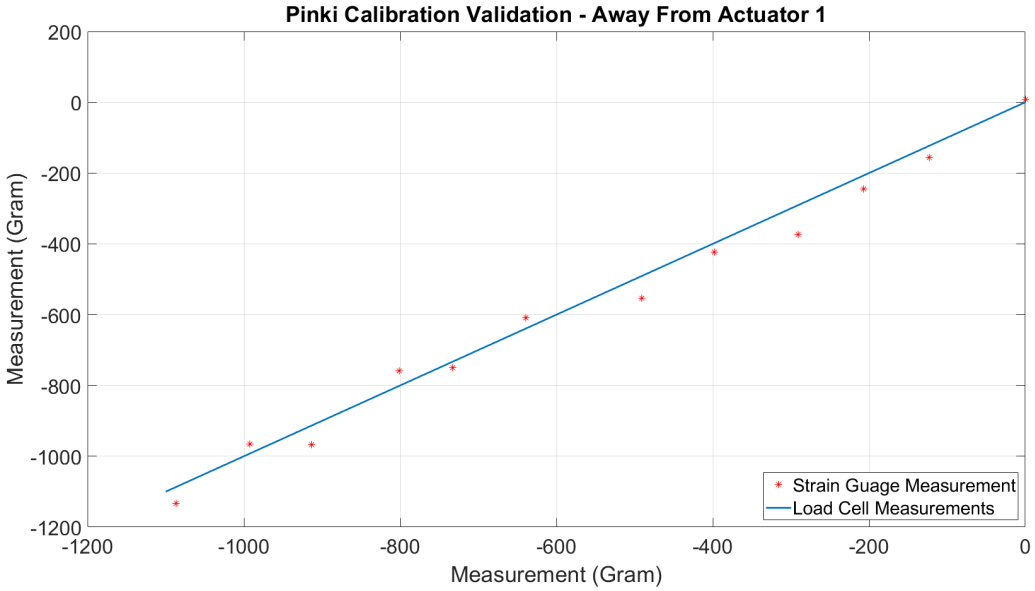


Figure A.23: Calibration Verification - Pinki Finger 1

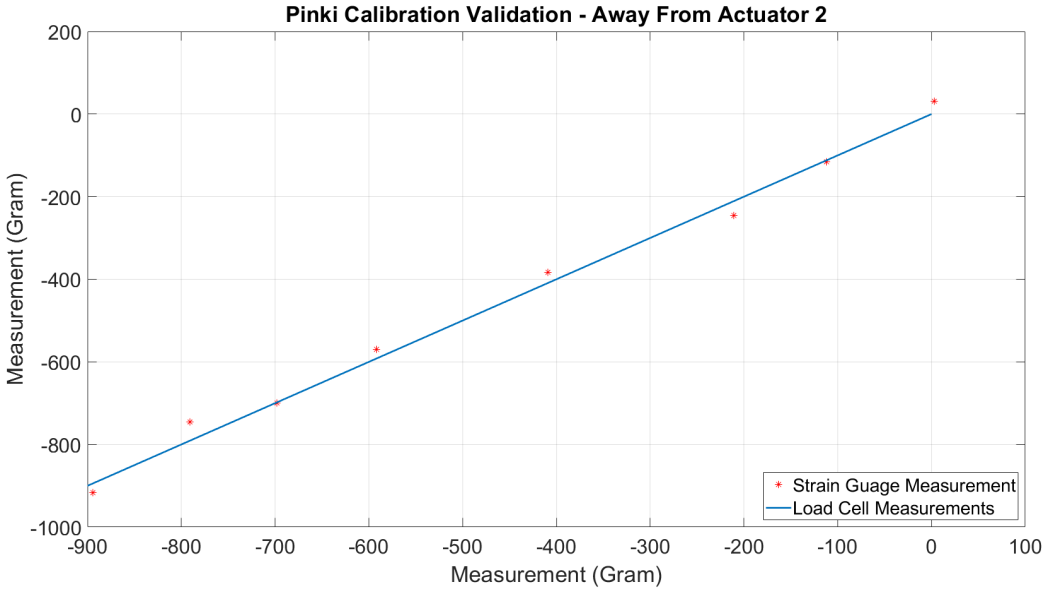


Figure A.24: Calibration Verification - Pinki Finger 2

Appendix B

Additional Results

B.1 Box Plots of Exercise One - All Data Sets

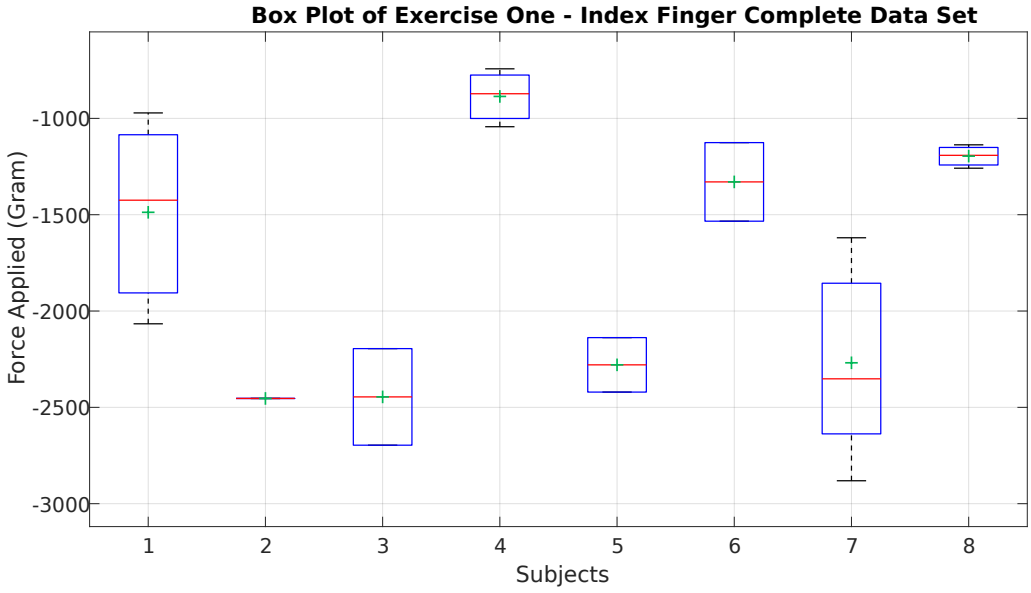


Figure B.1: Boxplot of Force Applied for Exercise One - Index Finger

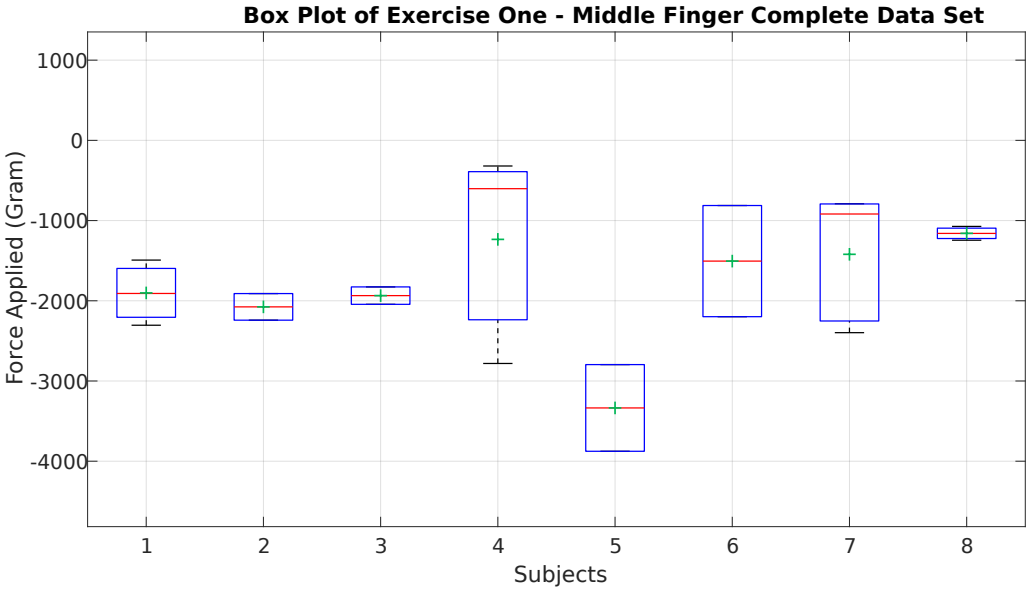


Figure B.2: Boxplot of Force Applied for Exercise One - Middle Finger

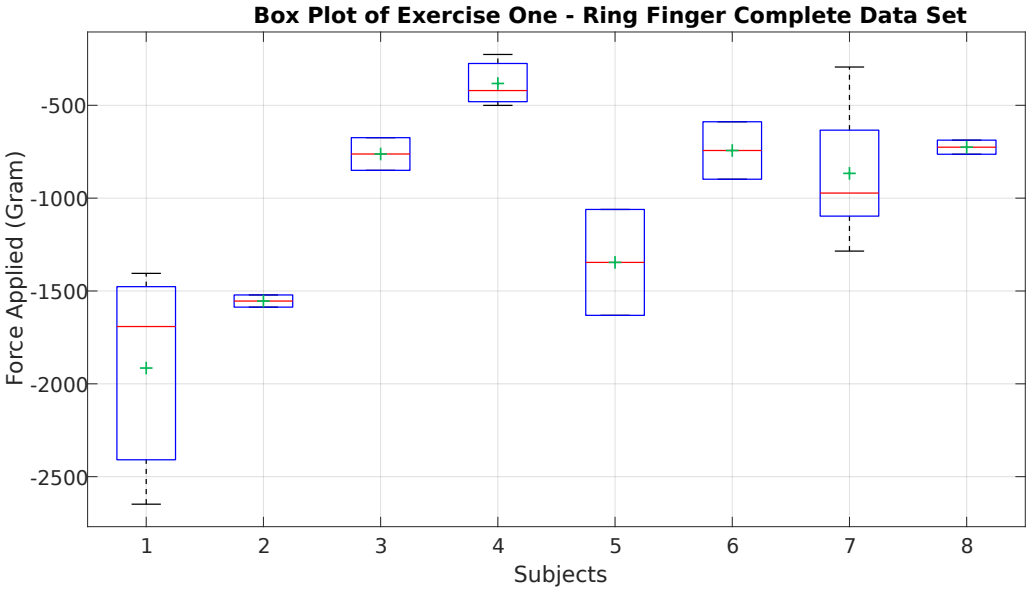


Figure B.3: Boxplot of Force Applied for Exercise One - Ring Finger

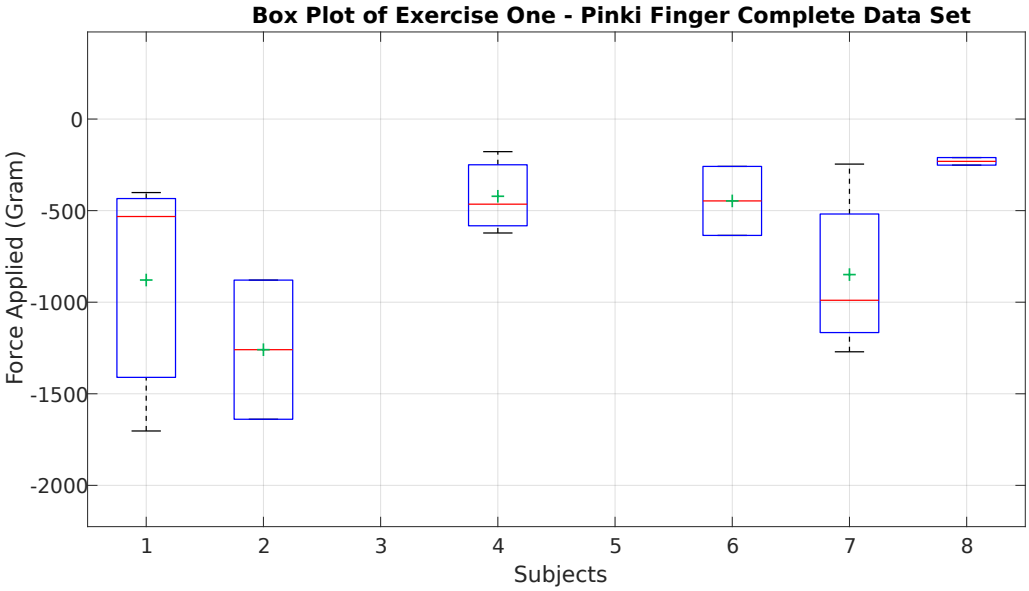


Figure B.4: Boxplot of Force Applied for Exercise One - Pinki Finger

B.2 Box Plots of Exercise Two - All Data Sets

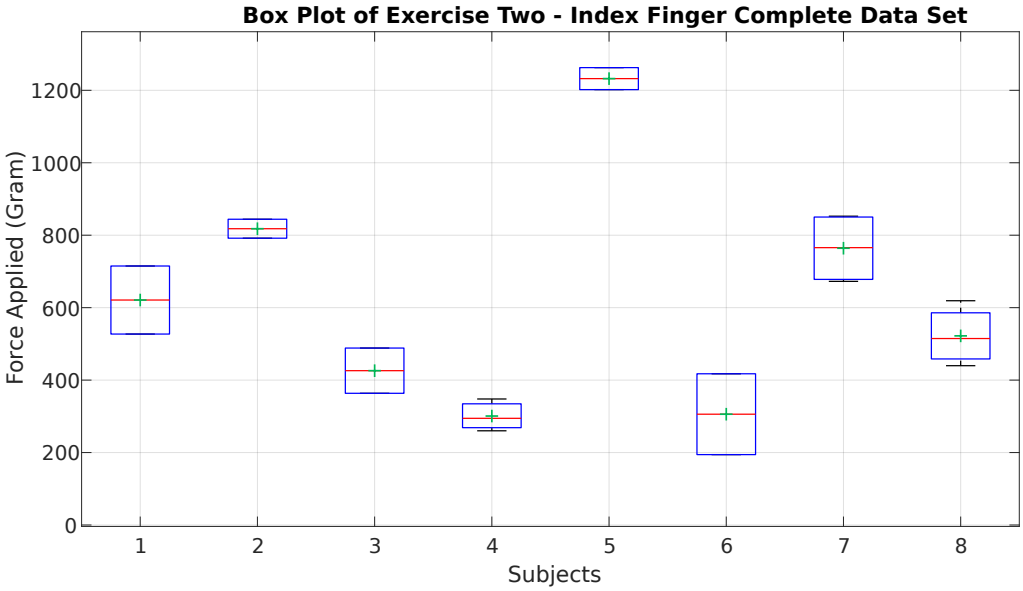


Figure B.5: Boxplot of Force Applied for Exercise Two - Index Finger

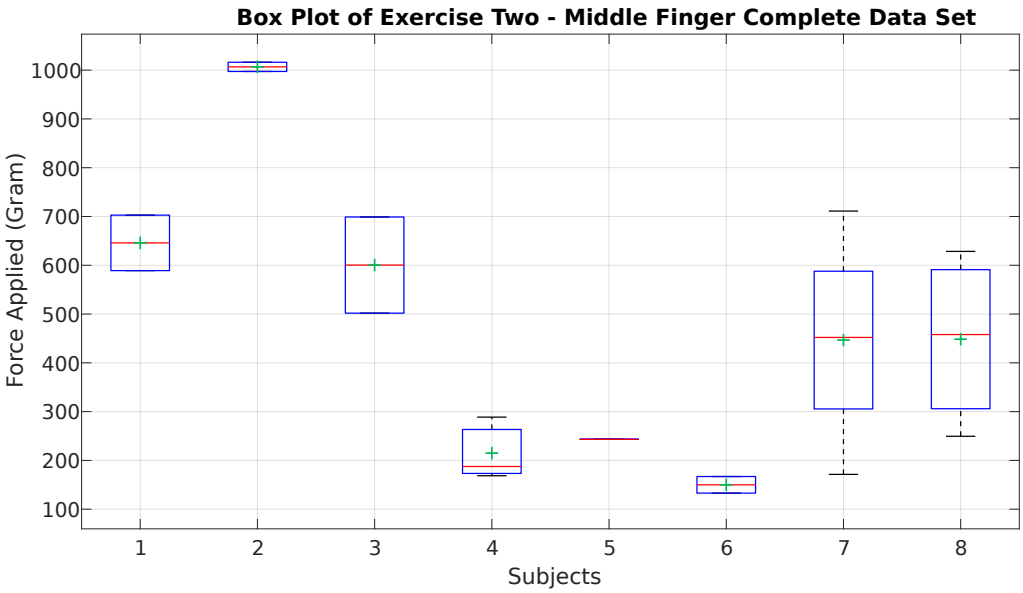


Figure B.6: Boxplot of Force Applied for Exercise Two - Middle Finger

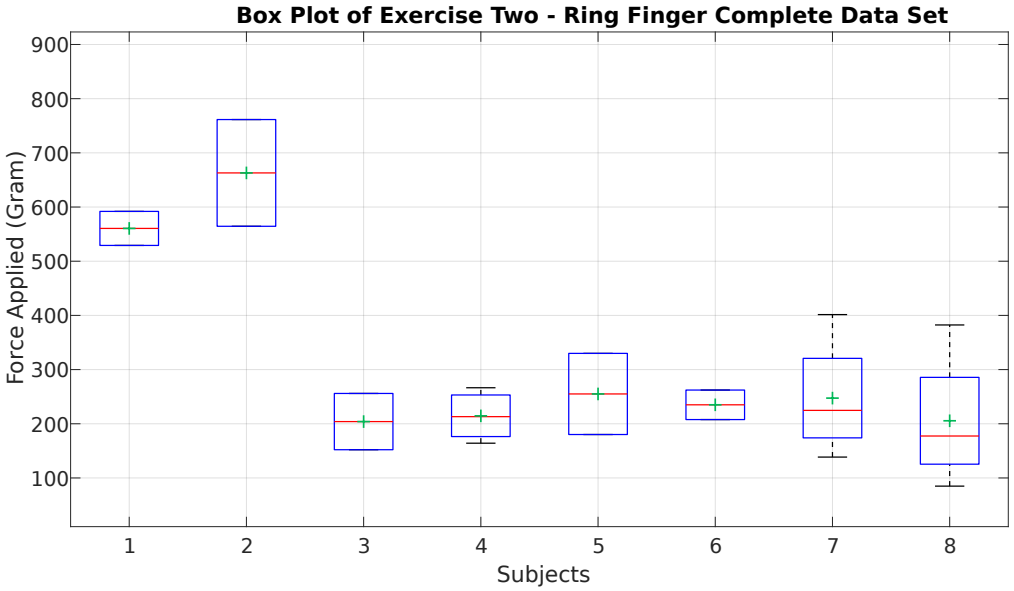


Figure B.7: Boxplot of Force Applied for Exercise Two - Ring Finger

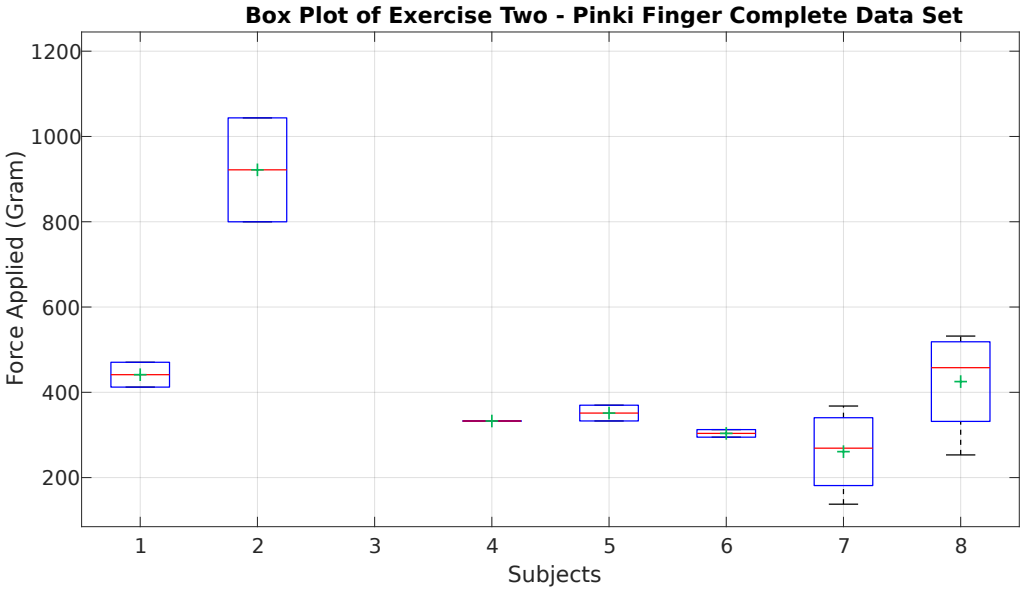


Figure B.8: Boxplot of Force Applied for Exercise Two - Pinki Finger

B.2.1 Box Plots of Exercise Three - All Data Sets

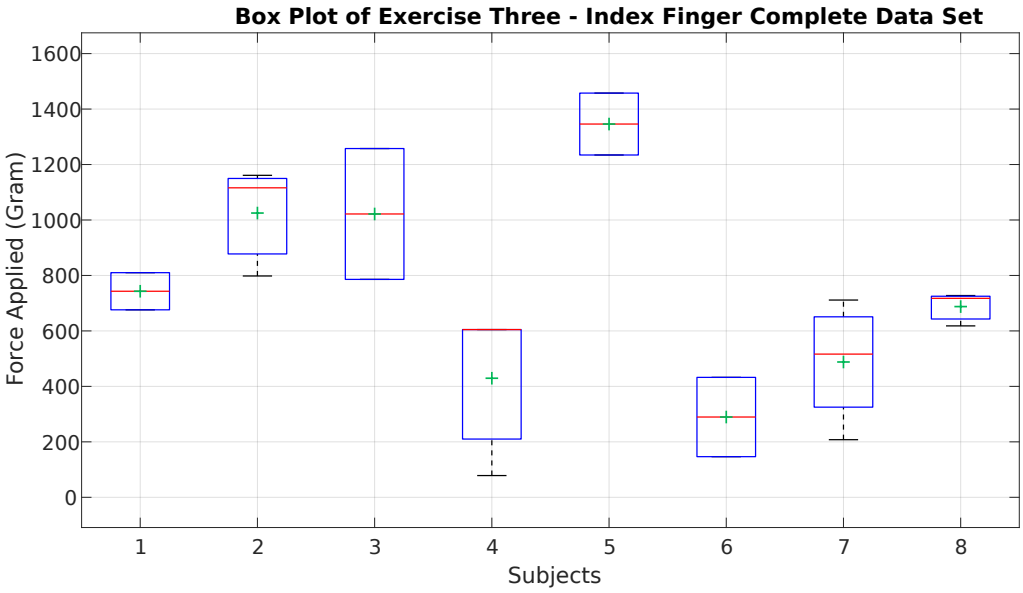


Figure B.9: Boxplot of Force Applied for Exercise Three - Index Finger

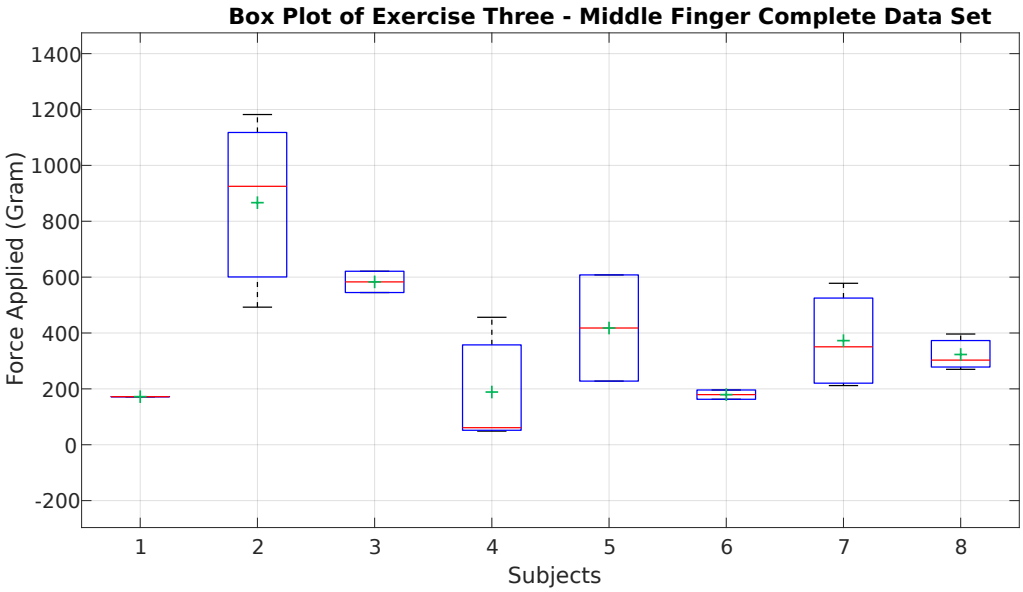


Figure B.10: Boxplot of Force Applied for Exercise Three - Middle Finger

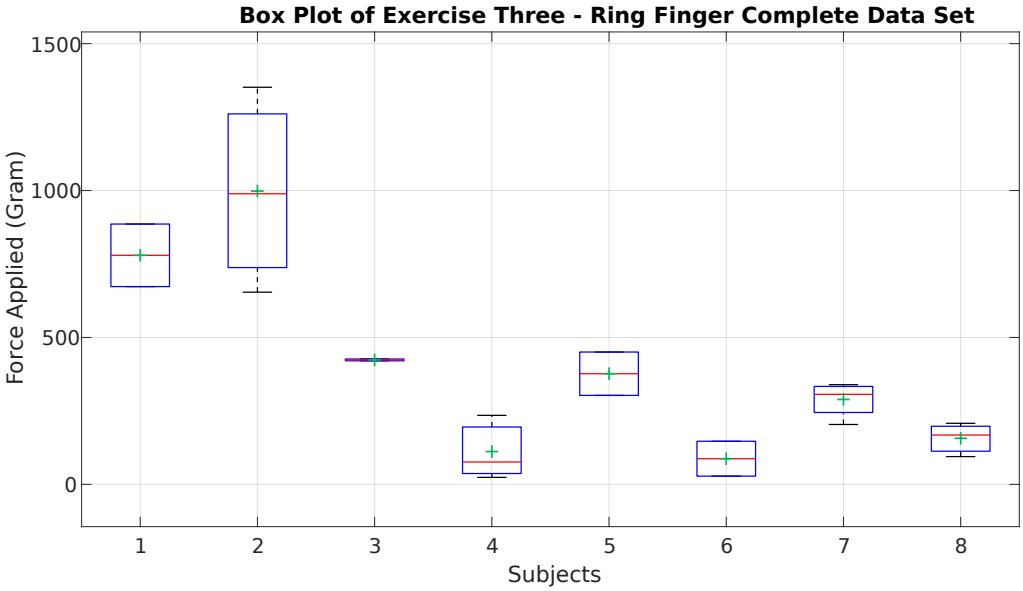


Figure B.11: Boxplot of Force Applied for Exercise Three - Ring Finger

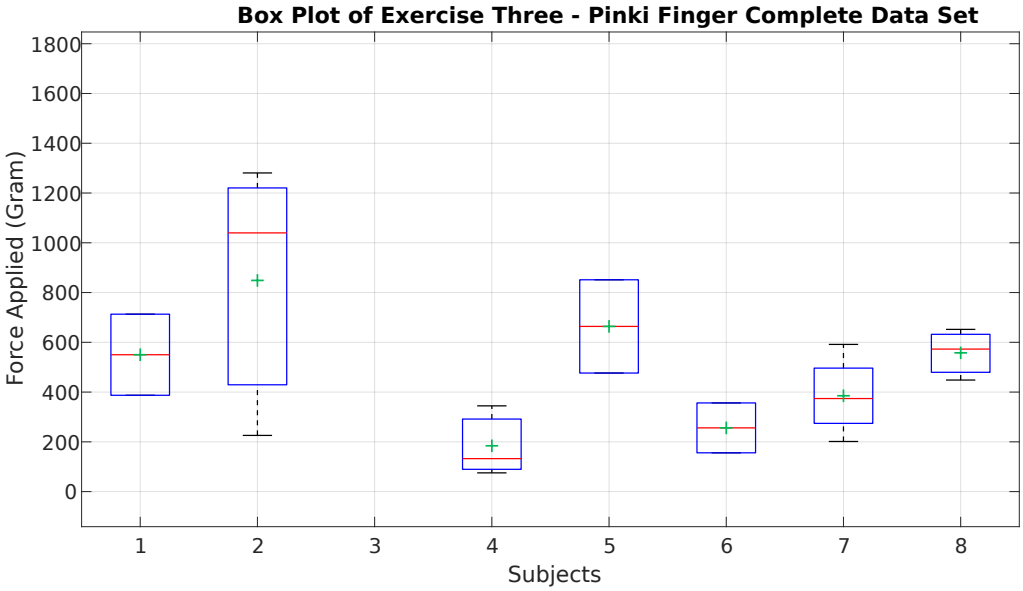


Figure B.12: Boxplot of Force Applied for Exercise Three - Pinki Finger

B.2.2 Box Plots of Exercise Four - All Data Sets

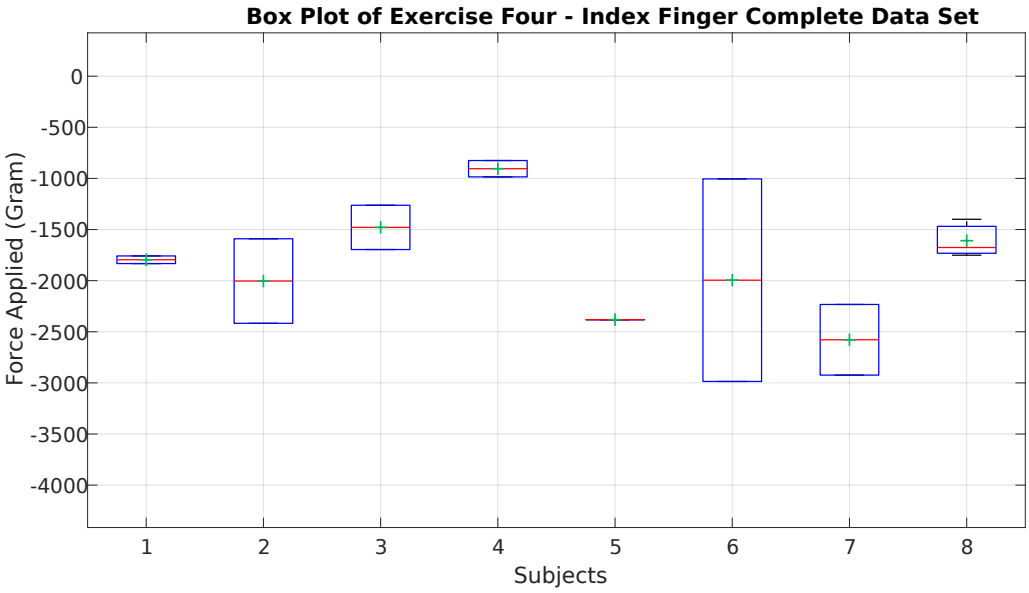


Figure B.13: Boxplot of Force Applied for Exercise Four - Index Finger

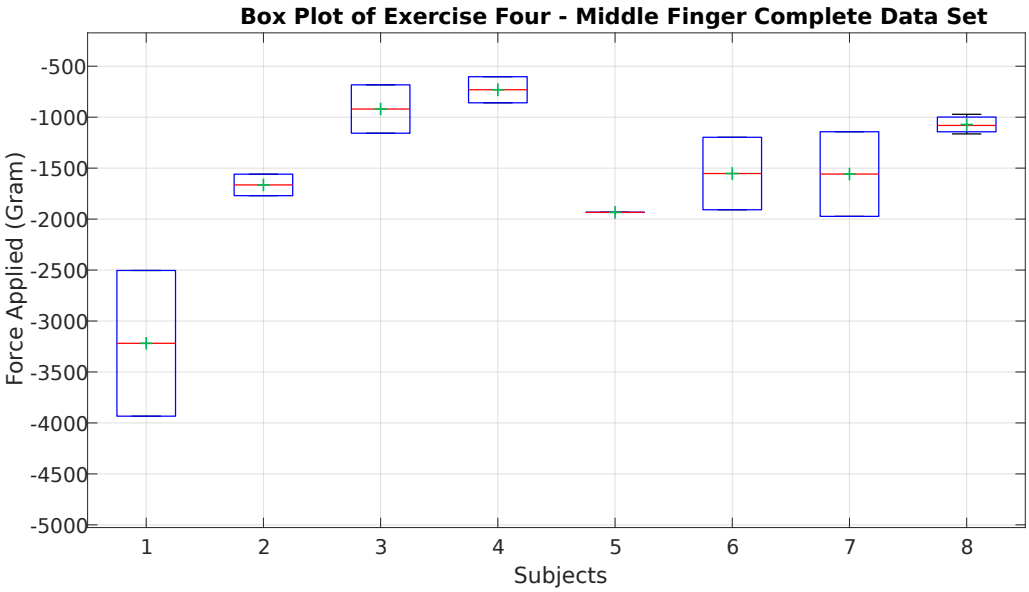


Figure B.14: Boxplot of Force Applied for Exercise Four - Middle Finger

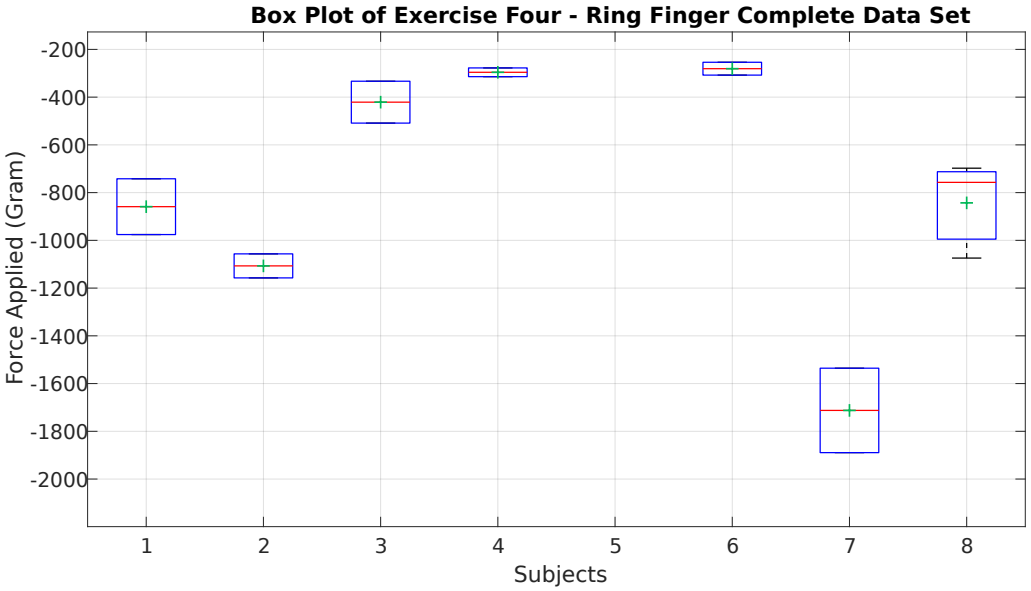


Figure B.15: Boxplot of Force Applied for Exercise Four - Ring Finger

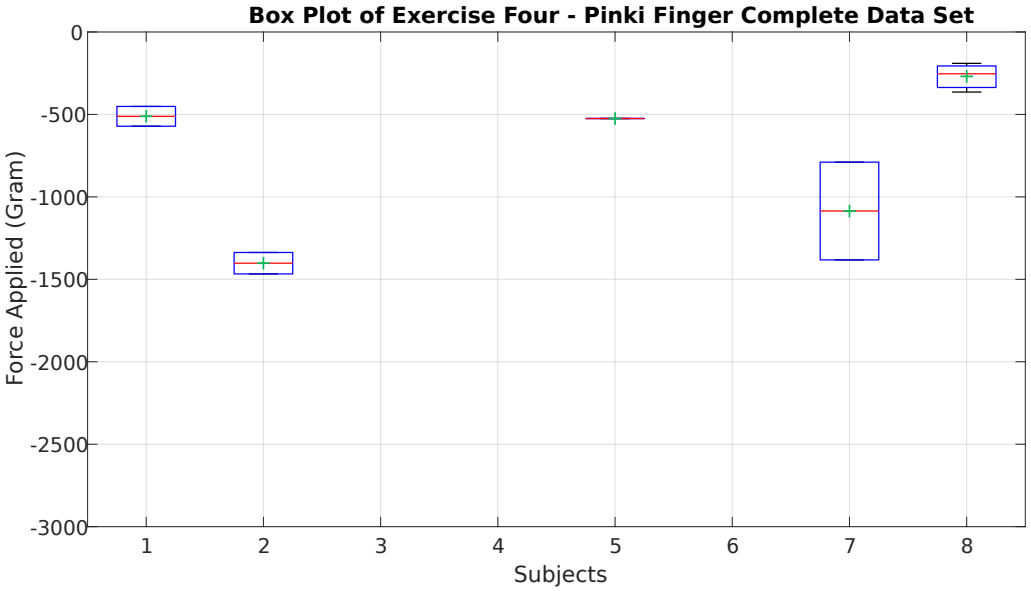


Figure B.16: Boxplot of Force Applied for Exercise Four - Pinki Finger

B.3 Box Plots Comparing Subjects Using Moving All Fingers at Once

B.3.1 Box Plots of Exercise One - All Fingers Moving

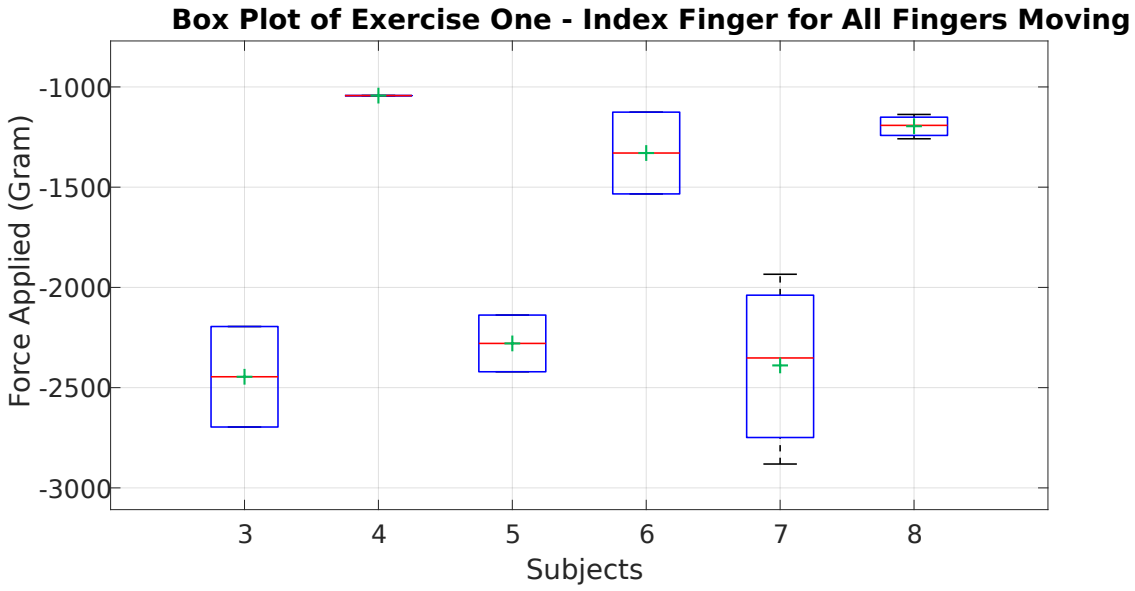


Figure B.17: Boxplot of Force Applied for Exercise One For All Fingers Moving - Index Finger

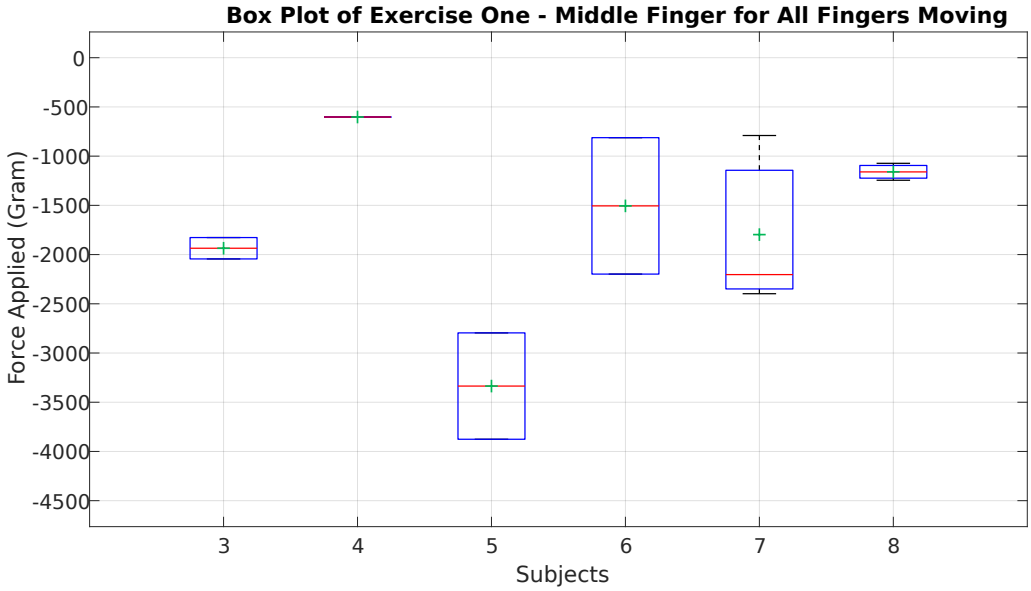


Figure B.18: Boxplot of Force Applied for Exercise One For All Fingers Moving - Middle Finger

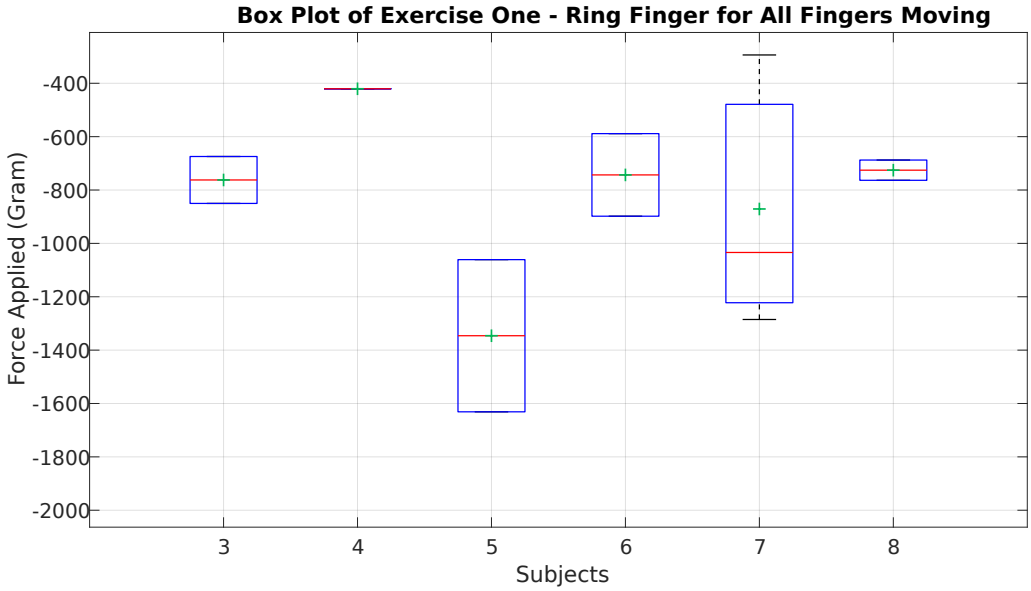


Figure B.19: Boxplot of Force Applied for Exercise One For All Fingers Moving - Ring Finger

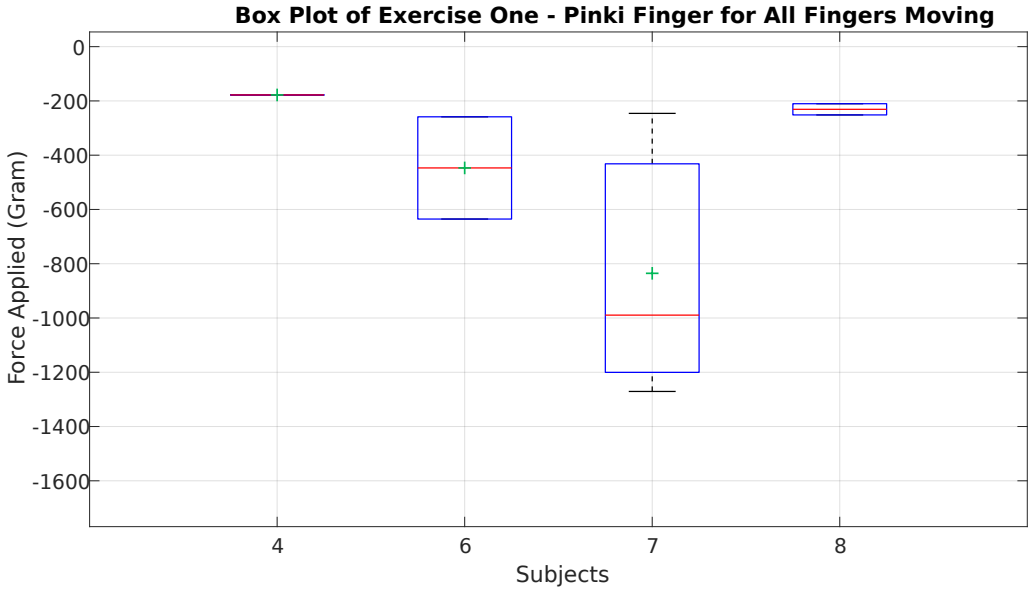


Figure B.20: Boxplot of Force Applied for Exercise One For All Fingers Moving - Pinki Finger

B.3.2 Box Plots of Exercise Two - All Fingers Moving

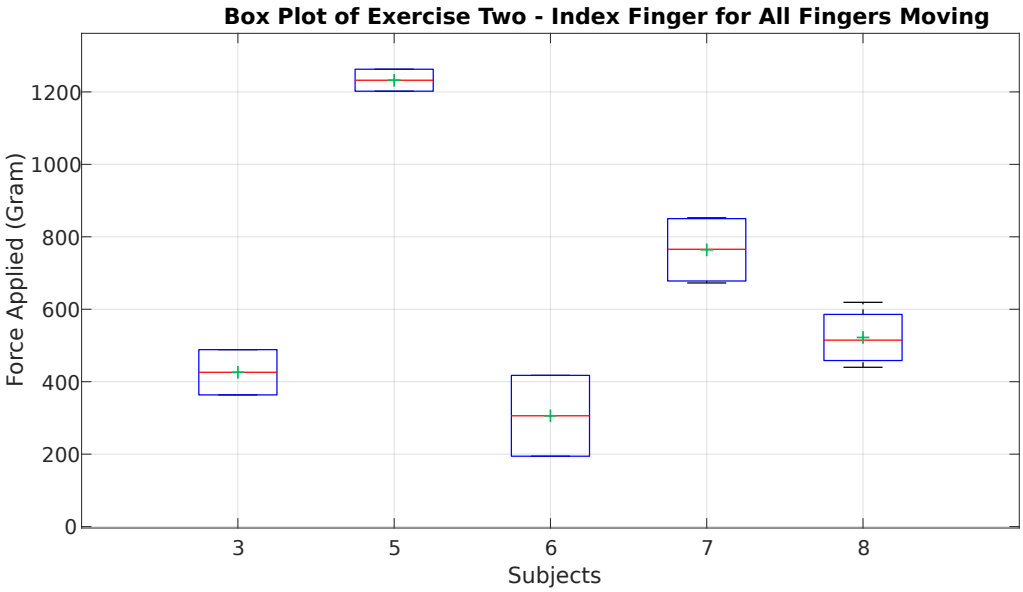


Figure B.21: Boxplot of Force Applied for Exercise Two For All Fingers Moving - Index Finger

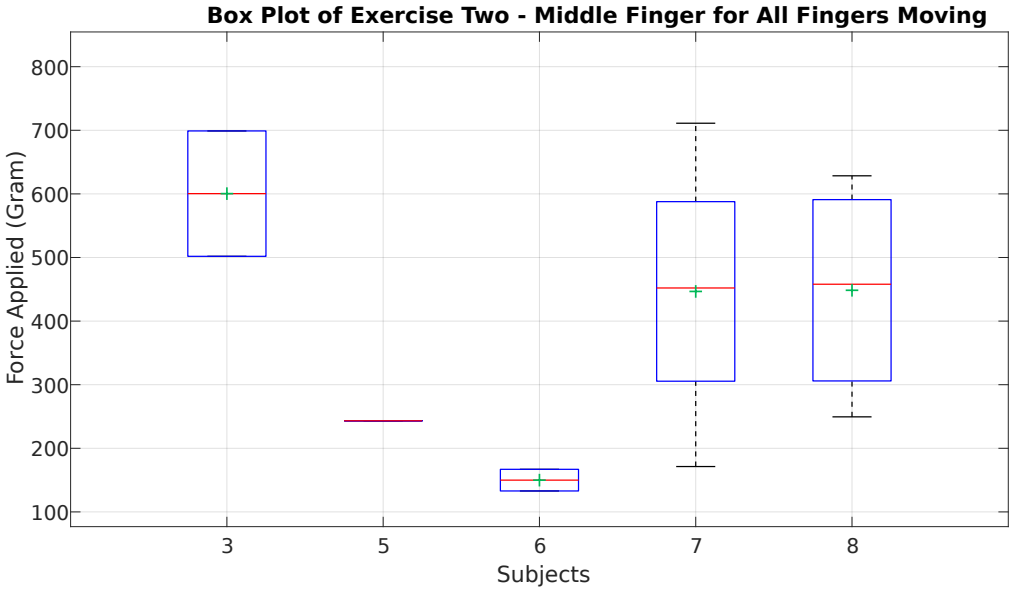


Figure B.22: Boxplot of Force Applied for Exercise Two For All Fingers Moving - Middle Finger

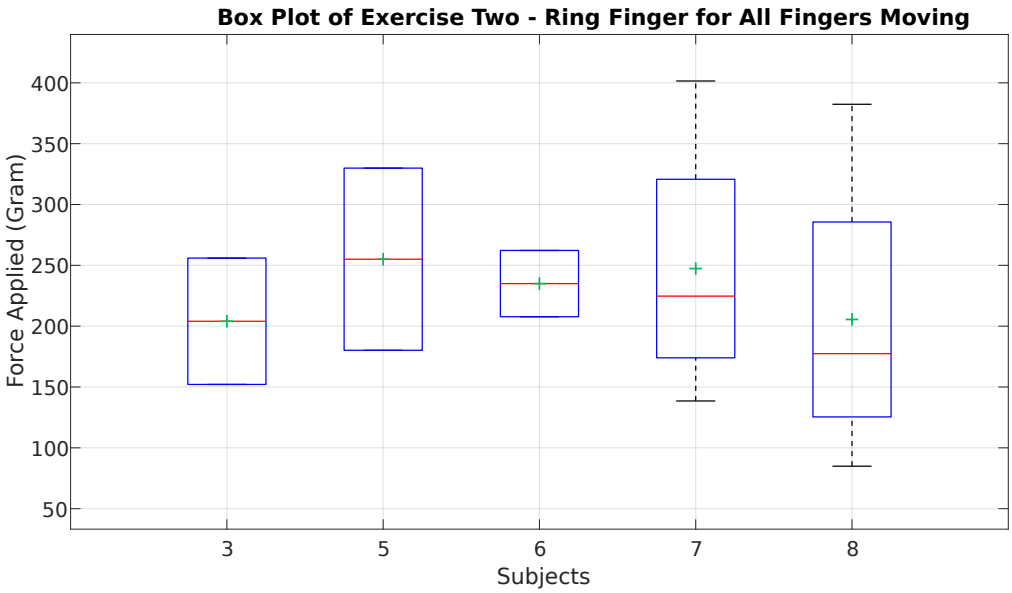


Figure B.23: Boxplot of Force Applied for Exercise Two For All Fingers Moving - Ring Finger

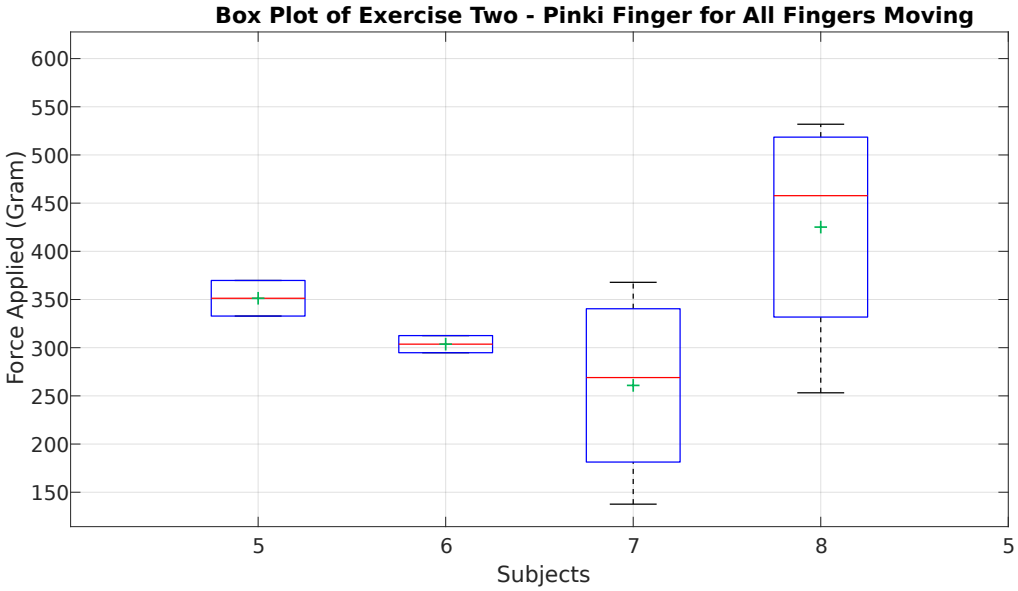


Figure B.24: Boxplot of Force Applied for Exercise Two For All Fingers Moving - Pinki Finger

B.3.3 Box Plots of Exercise Three - All Fingers Moving

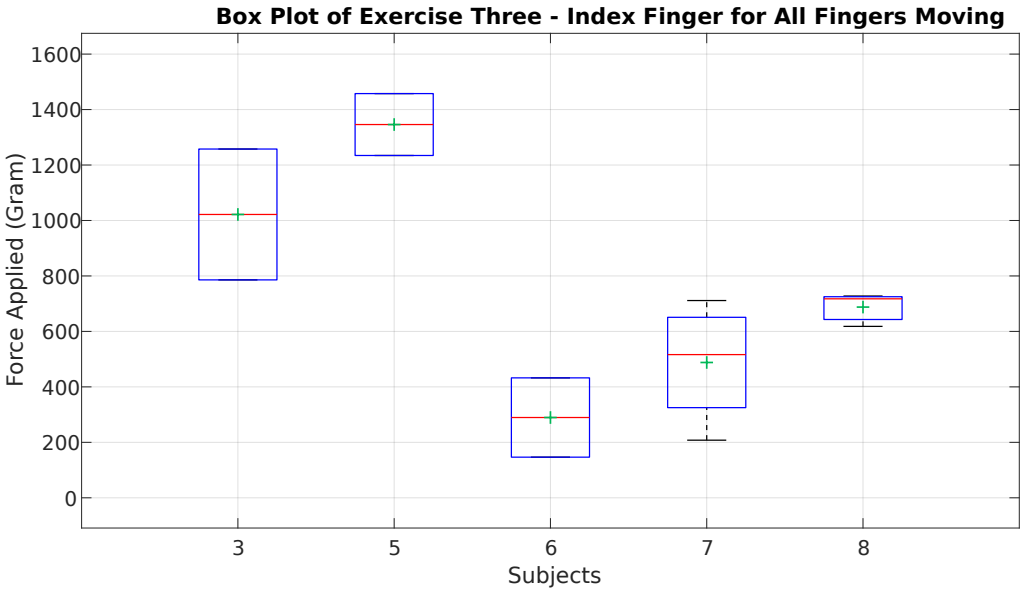


Figure B.25: Boxplot of Force Applied for Exercise Three For All Fingers Moving - Index Finger

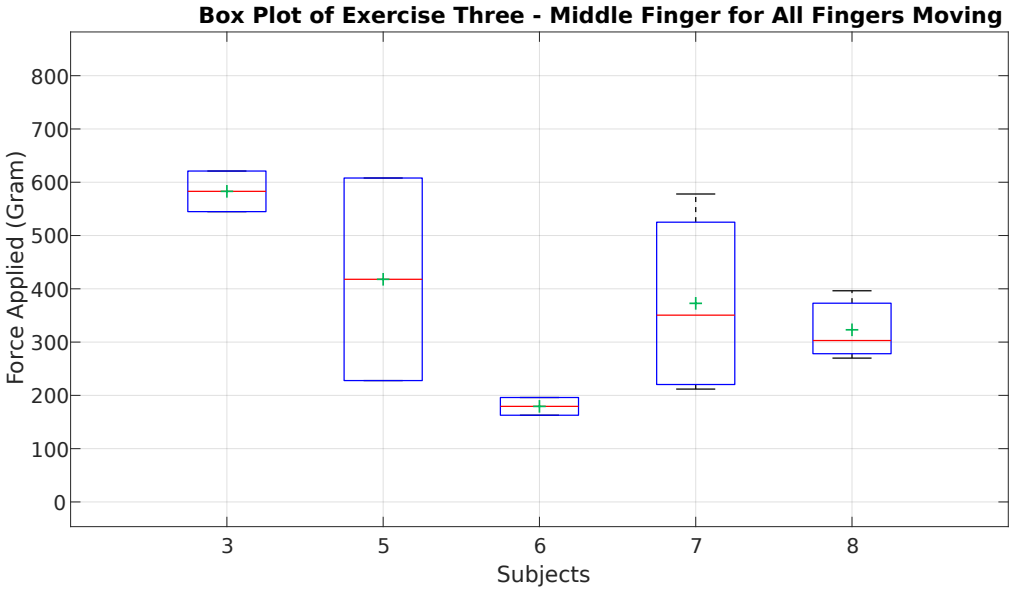


Figure B.26: Boxplot of Force Applied for Exercise Three For All Fingers Moving - Middle Finger

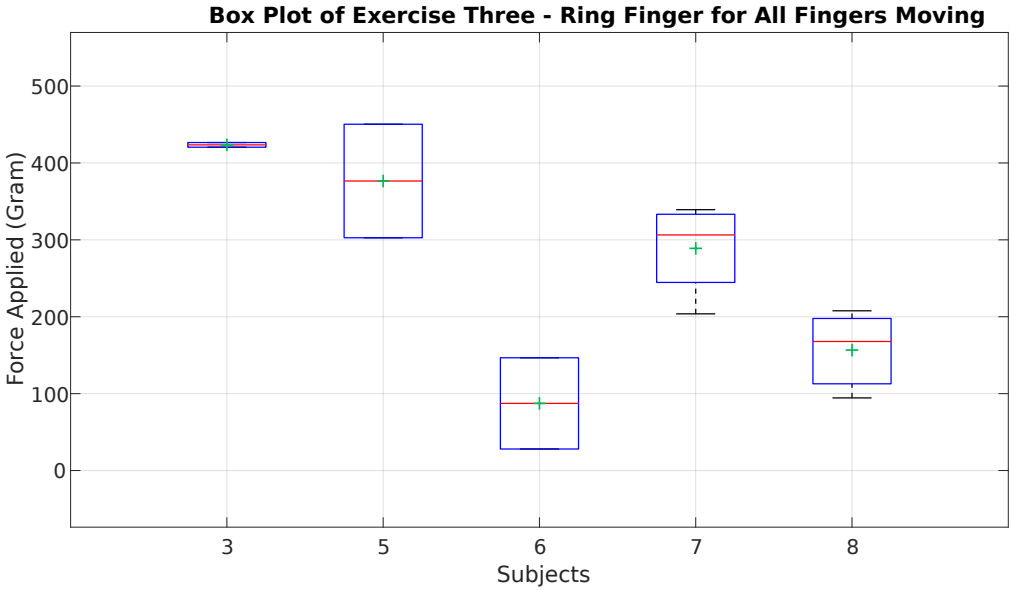


Figure B.27: Boxplot of Force Applied for Exercise Three For All Fingers Moving - Ring Finger

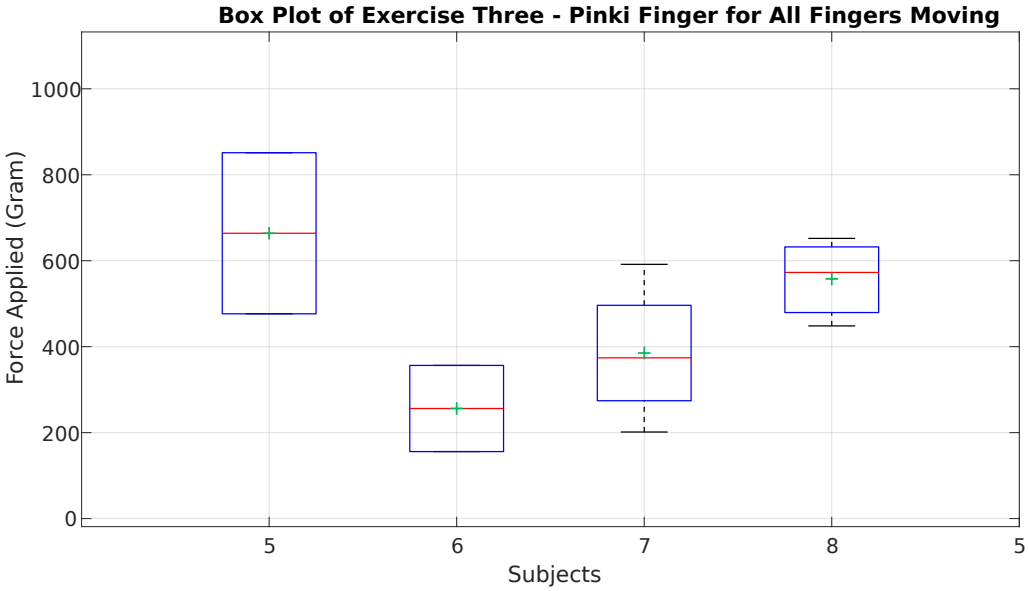


Figure B.28: Boxplot of Force Applied for Exercise Three For All Fingers Moving - Pinki Finger

B.3.4 Box Plots of Exercise Four - All Fingers Moving

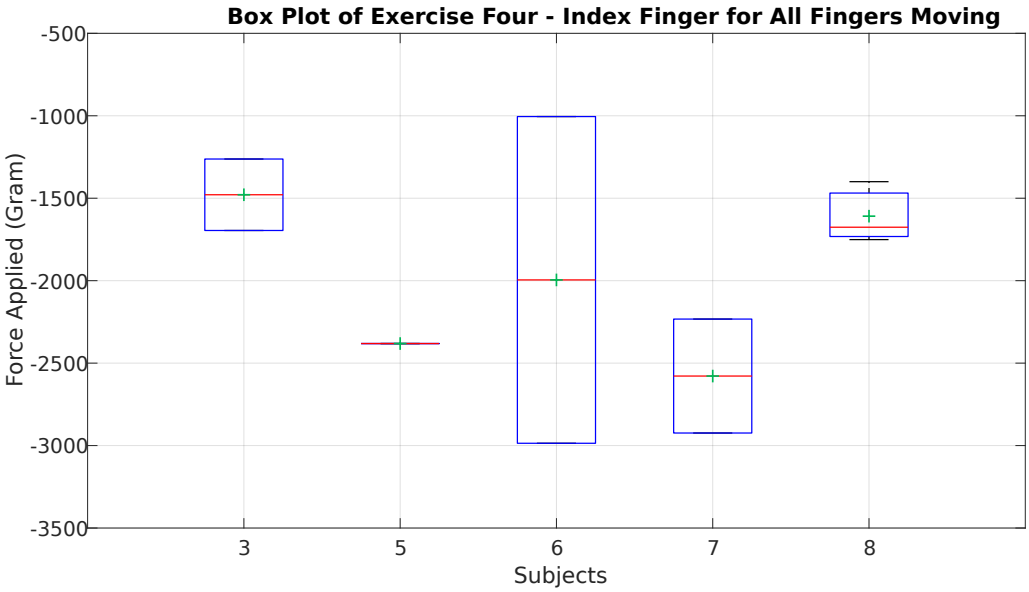


Figure B.29: Boxplot of Force Applied for Exercise Four For All Fingers Moving - Index Finger

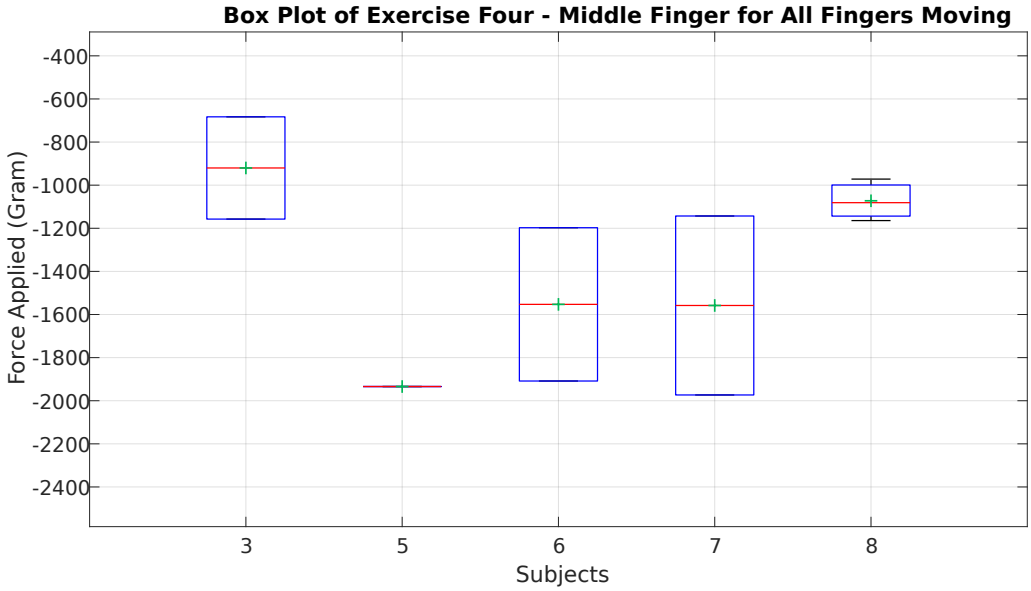


Figure B.30: Boxplot of Force Applied for Exercise Four For All Fingers Moving - Middle Finger

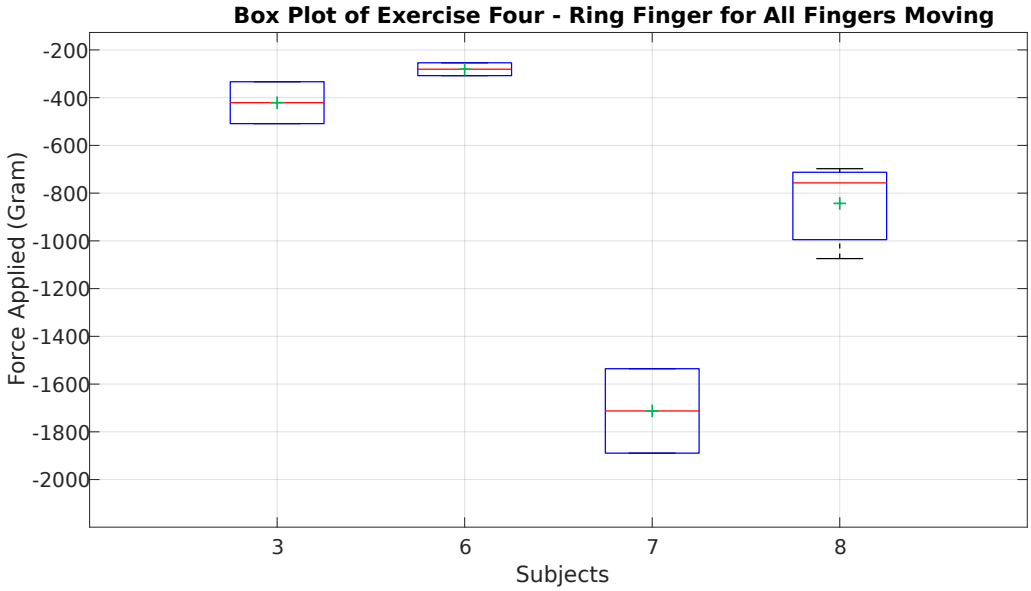


Figure B.31: Boxplot of Force Applied for Exercise Four For All Fingers Moving - Ring Finger

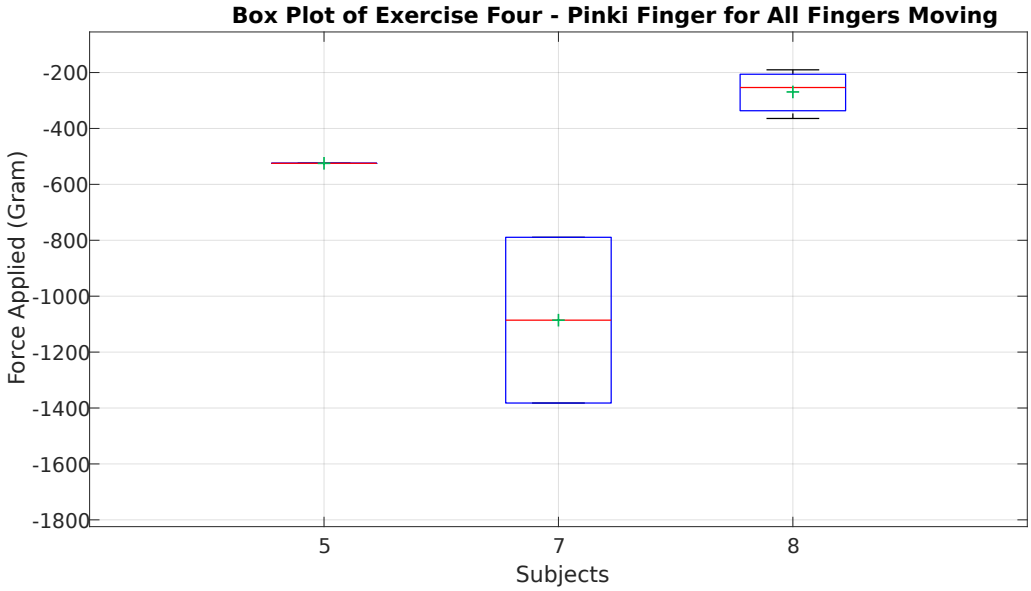


Figure B.32: Boxplot of Force Applied for Exercise Four For All Fingers Moving - Pinki Finger

B.4 Box Plots Comparing Subjects Using Individual Finger Movement

B.4.1 Box Plots of Exercise One - Individual Finger Movement

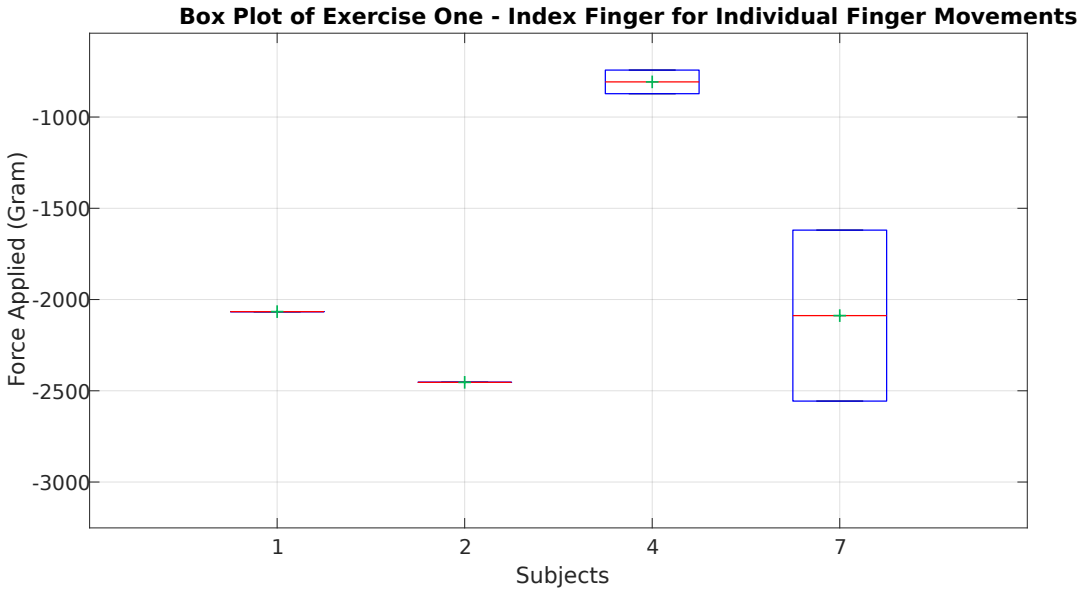


Figure B.33: Boxplot of Force Applied for Exercise One For Individual Finger Movement - Index Finger

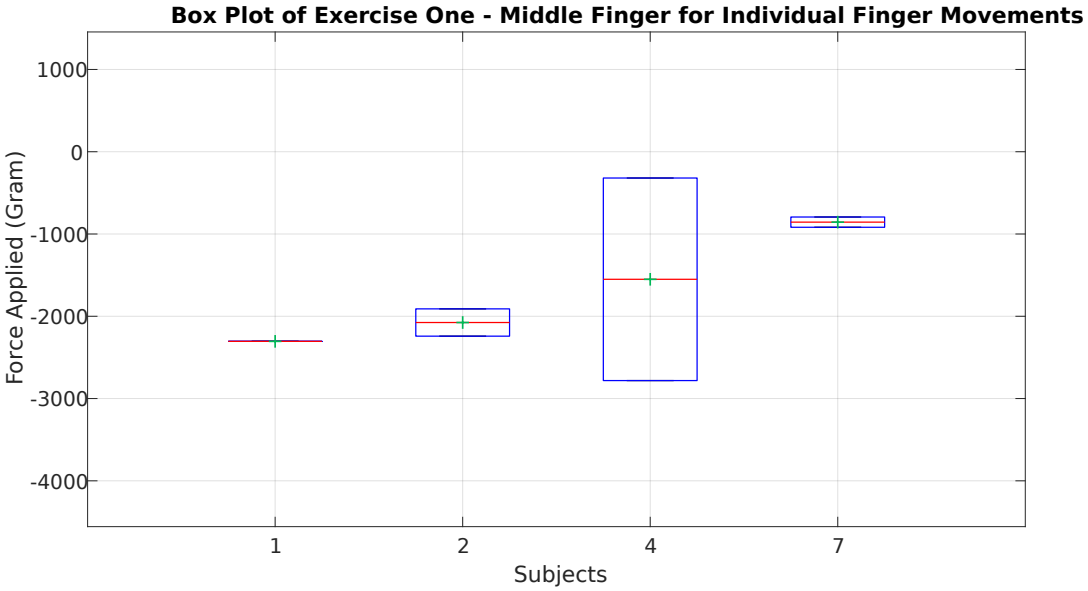


Figure B.34: Boxplot of Force Applied for Exercise One For Individual Finger Movement - Middle Finger

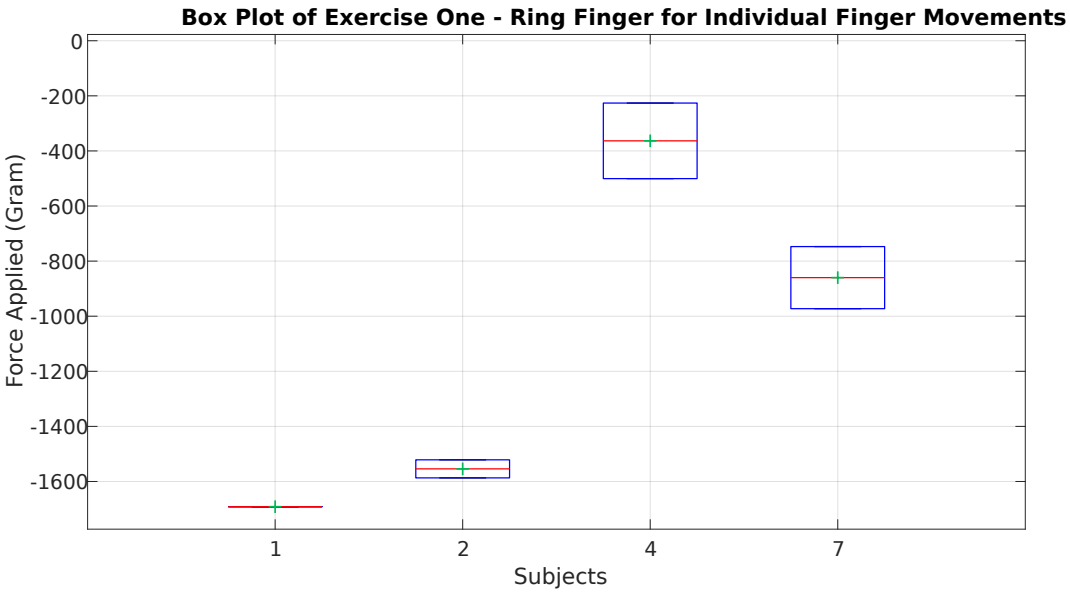


Figure B.35: Boxplot of Force Applied for Exercise One For Individual Finger Movement - Ring Finger

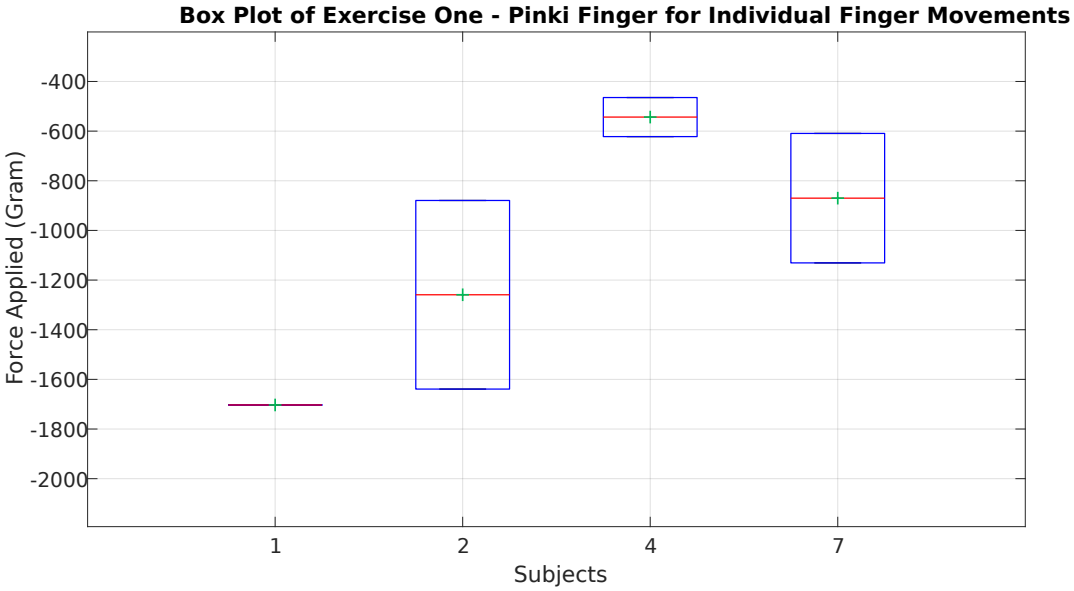


Figure B.36: Boxplot of Force Applied for Exercise One For Individual Finger Movement - Pinki Finger

B.4.2 Box Plots of Exercise Two - Individual Finger Movement

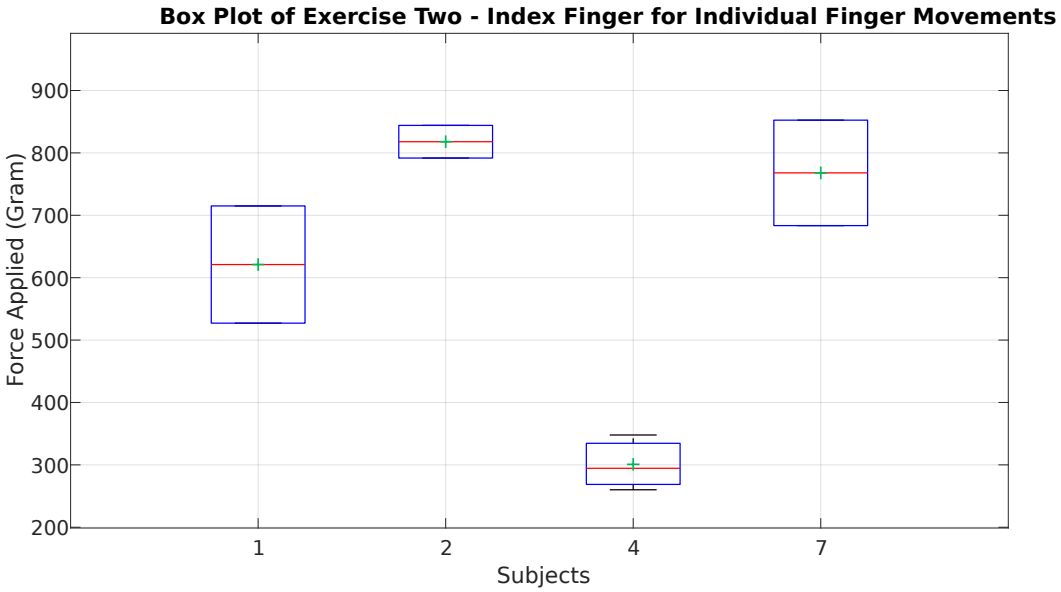


Figure B.37: Boxplot of Force Applied for Exercise Two For Individual Finger Movement - Index Finger

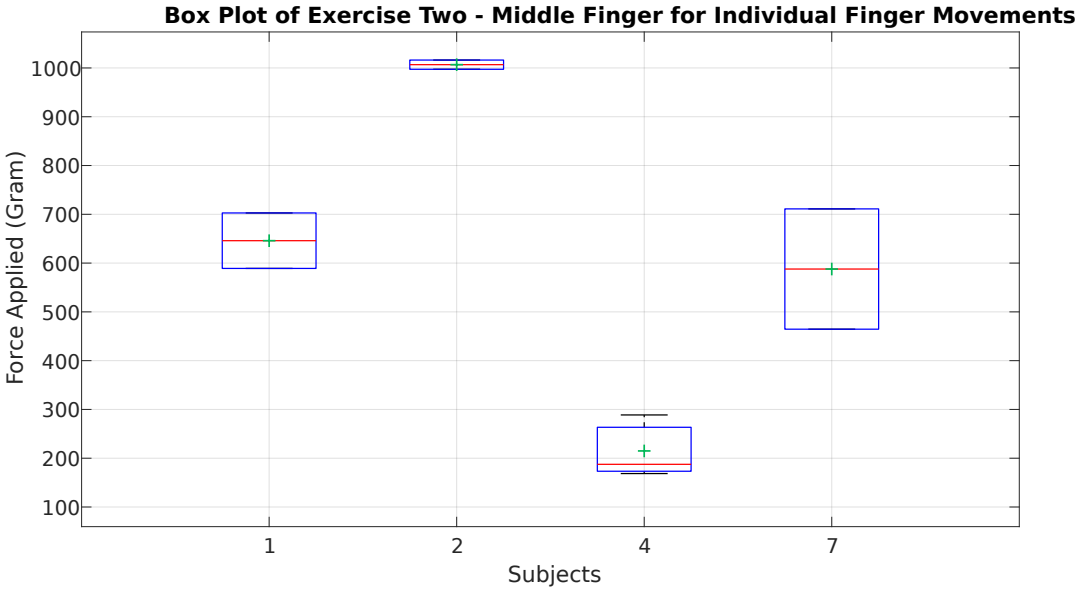


Figure B.38: Boxplot of Force Applied for Exercise Two For Individual Finger Movement - Middle Finger

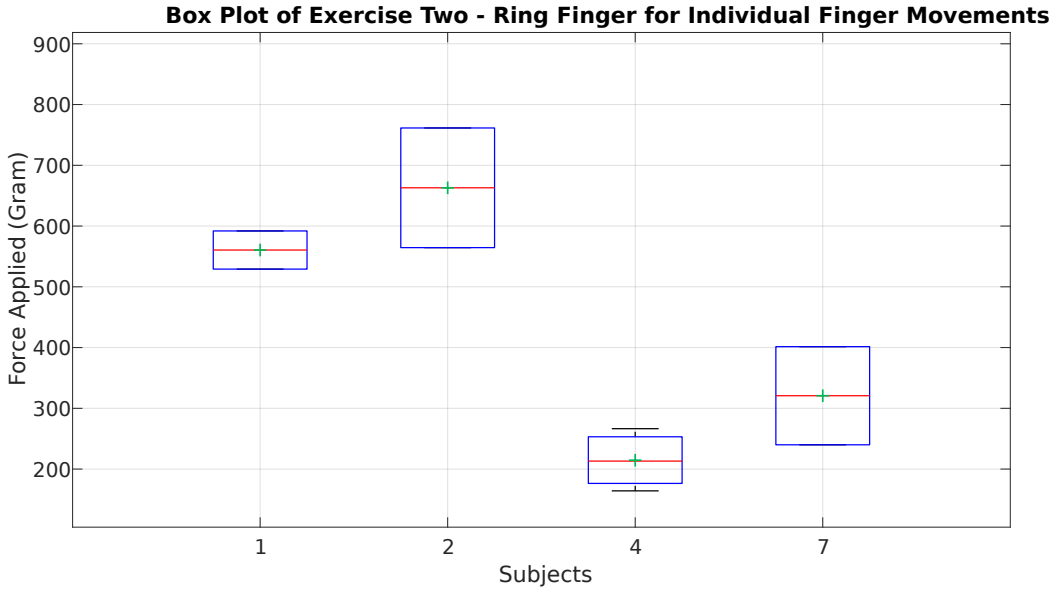


Figure B.39: Boxplot of Force Applied for Exercise Two For Individual Finger Movement - Ring Finger

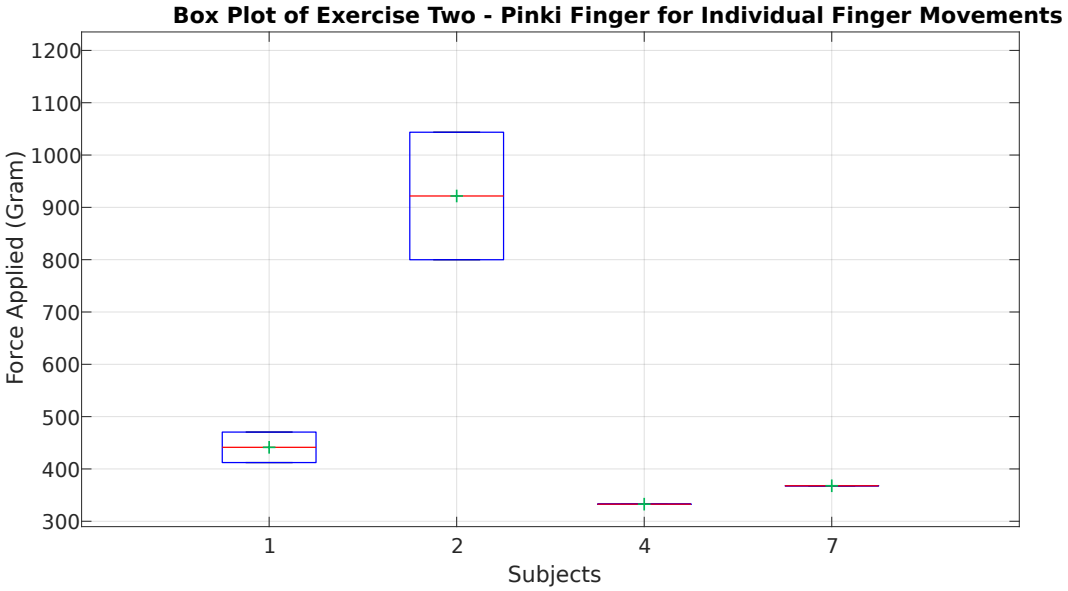


Figure B.40: Boxplot of Force Applied for Exercise Two For Individual Finger Movement - Pinki Finger

B.4.3 Box Plots of Exercise Three - Individual Finger Movement

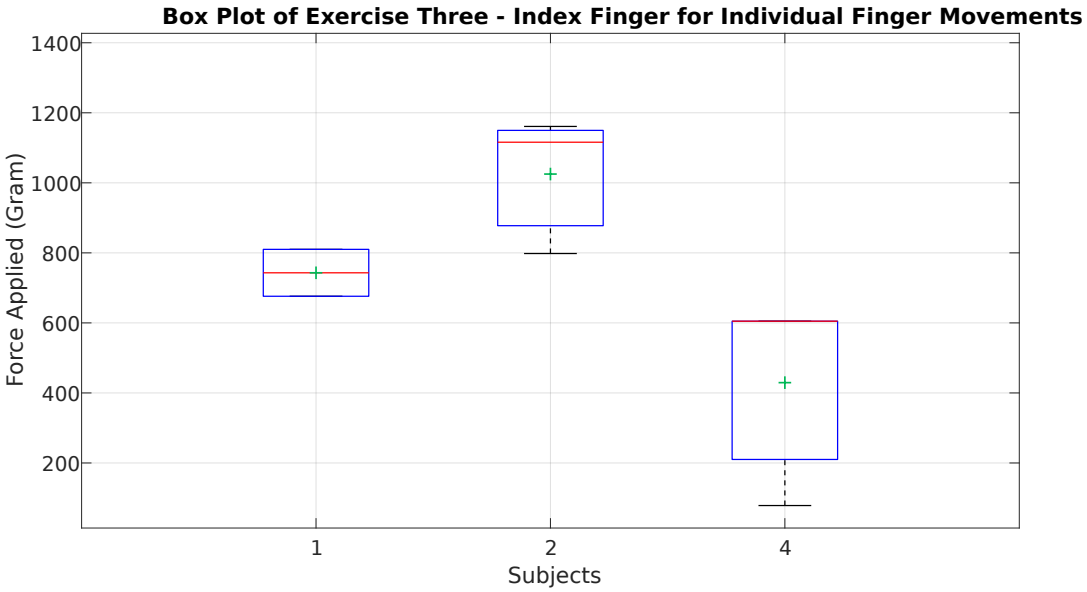


Figure B.41: Boxplot of Force Applied for Exercise Three For Individual Finger Movement - Index Finger

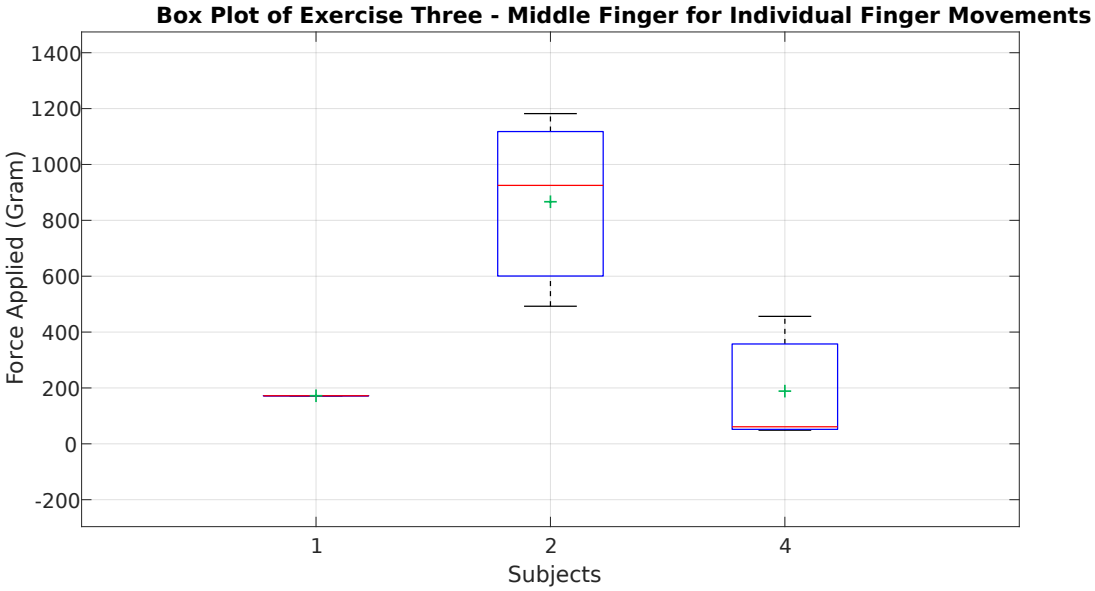


Figure B.42: Boxplot of Force Applied for Exercise Three For Individual Finger Movement - Middle Finger

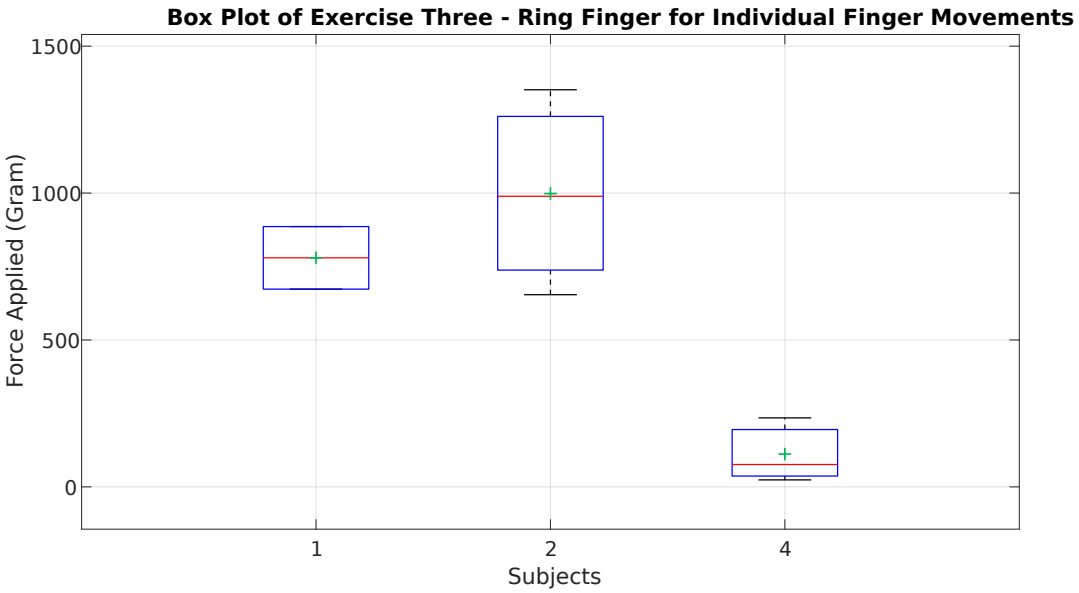


Figure B.43: Boxplot of Force Applied for Exercise Three For Individual Finger Movement - Ring Finger

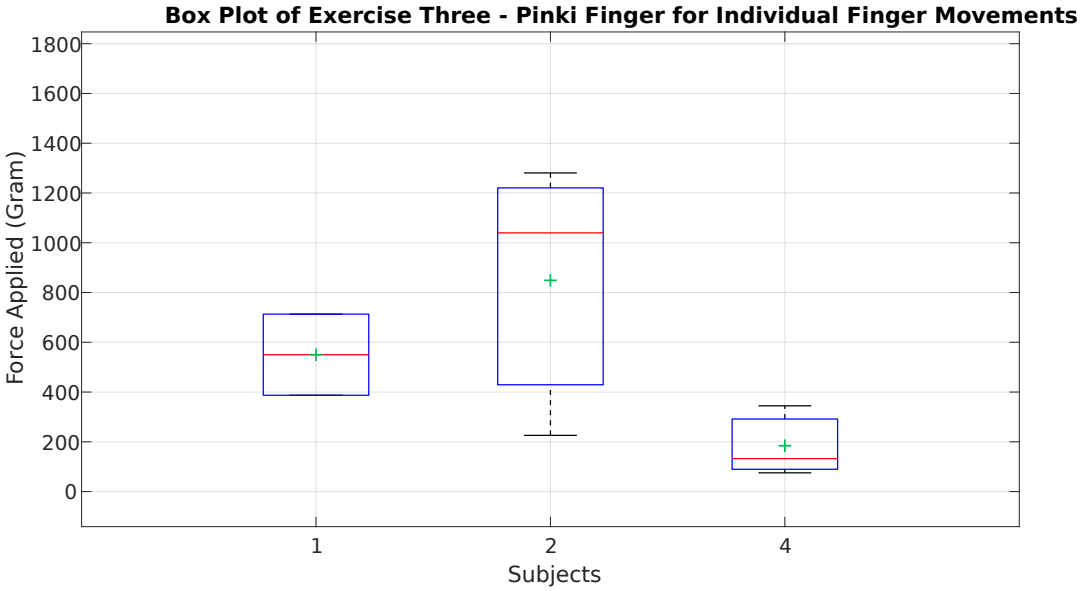


Figure B.44: Boxplot of Force Applied for Exercise Three For Individual Finger Movement - Pinki Finger

B.4.4 Box Plots of Exercise Four - Individual Finger Movement

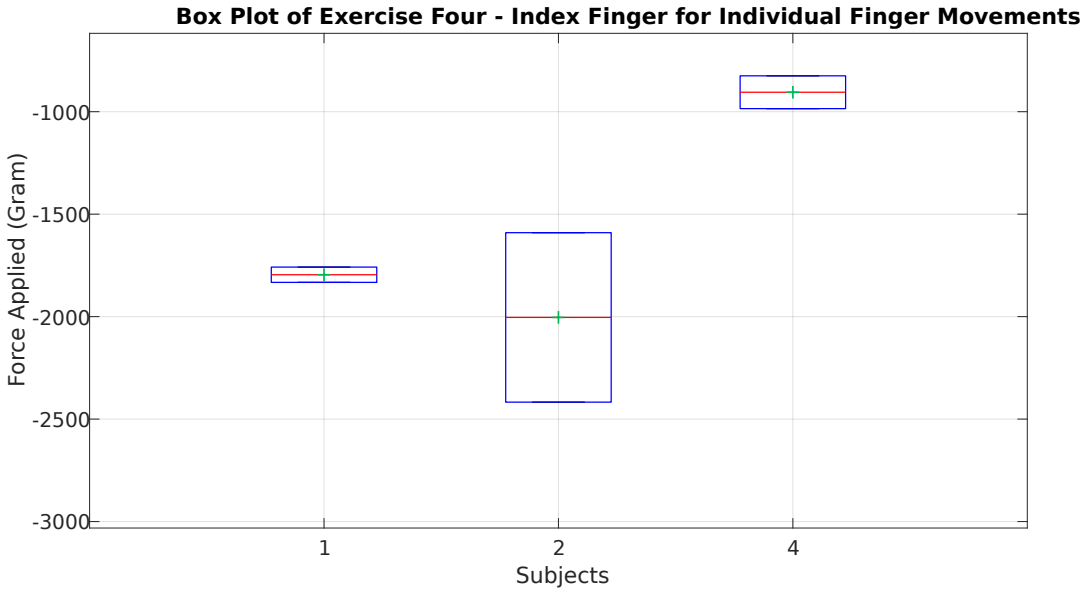


Figure B.45: Boxplot of Force Applied for Exercise Four For Individual Finger Movement - Index Finger

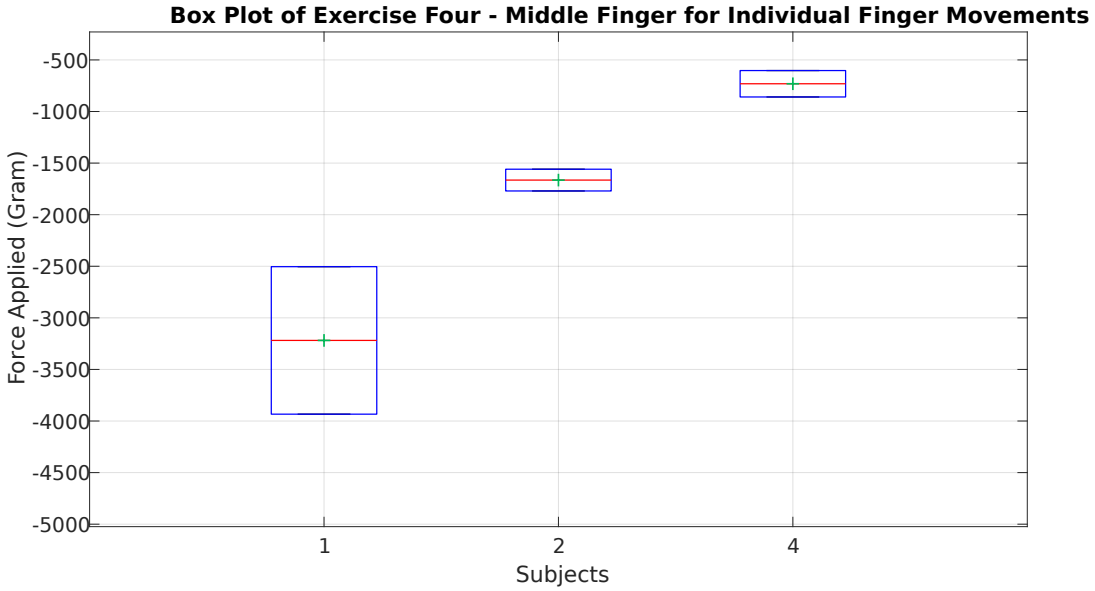


Figure B.46: Boxplot of Force Applied for Exercise Four For Individual Finger Movement - Middle Finger

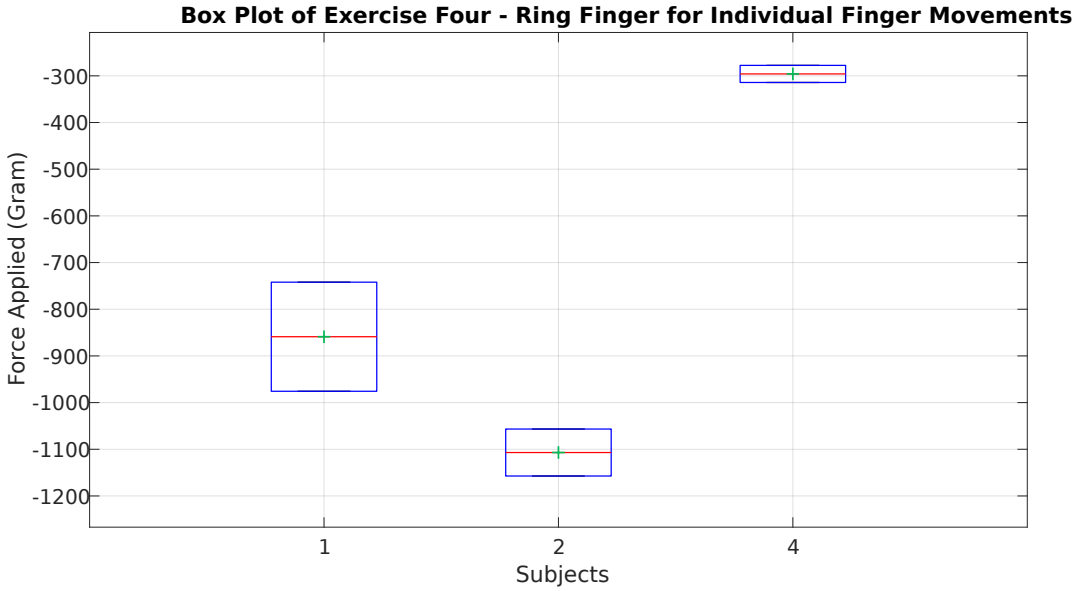


Figure B.47: Boxplot of Force Applied for Exercise Four For Individual Finger Movement - Ring Finger

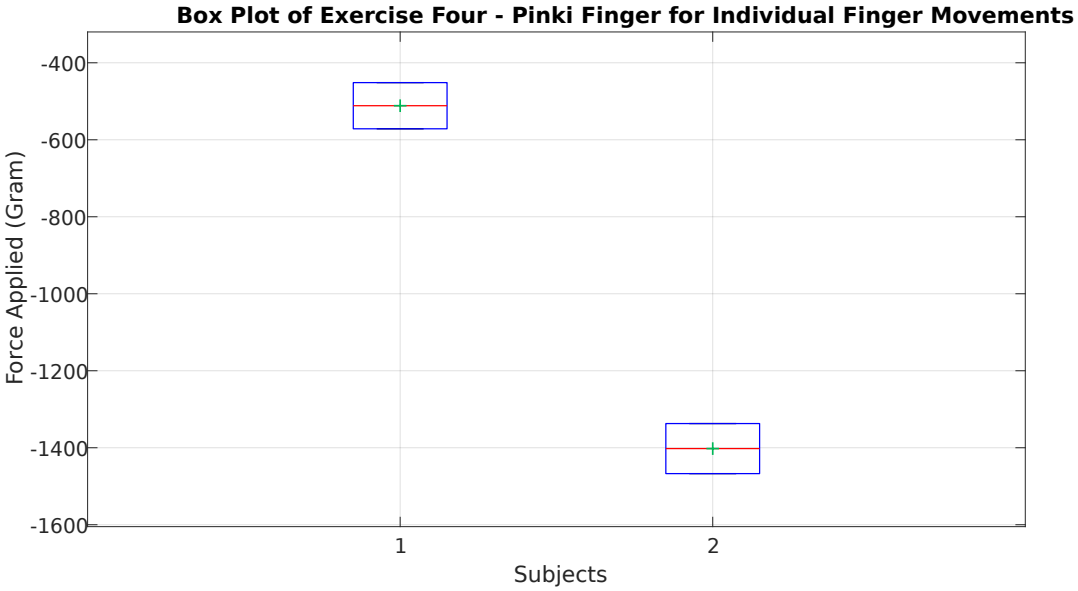


Figure B.48: Boxplot of Force Applied for Exercise Four For Individual Finger Movement - Pinki Finger

Appendix C

Post Hoc Results

C.1 Tukey-Kramer Additional Results

Table C.1: Tukey-Kramer Result for Exercise One - Middle Finger

Exercise One - Middle Finger						
Subject 1	**Subject 2**	**Lower Limit**	**Difference of Group Means**	**Upper Limit**	**P-value**	**Significance**
1	2	-2292.5	173.81	2640.2	1	1
1	3	-2432.8	33.544	2499.9	1	1
1	4	-2873.5	-667.57	1538.4	0.954	1
1	5	-1032.6	1433.8	3900.1	0.485	1
1	6	-2863.1	-396.78	2069.6	0.999	1
1	7	-2454.6	-481.49	1491.6	0.985	1
1	8	-2948.8	-742.8	1463.2	0.923	1
2	3	-2842	-140.26	2561.5	1	1
2	4	-3307.7	-841.37	1625	0.918	1
2	5	-1441.8	1260	3961.7	0.718	1
2	6	-3272.3	-570.58	2131.2	0.994	1
2	7	-2915.7	-655.29	1605.2	0.963	1
2	8	-3383	-916.6	1549.7	0.88	1
3	4	-3167.5	-701.11	1765.2	0.966	1
3	5	-1301.5	1400.2	4102	0.613	1
3	6	-3132.1	-430.32	2271.4	0.999	1
3	7	-2775.5	-515.03	1745.4	0.99	1
3	8	-3242.7	-776.34	1690	0.944	1
4	5	-365.03	2101.3	4567.7	0.123	1
4	6	-2195.6	270.79	2737.1	1	1
4	7	-1787	186.08	2159.2	1	1
4	8	-2281.2	-75.232	2130.7	1	1
5	6	-4532.3	-1830.5	871.22	0.315	1
5	7	-4175.7	-1915.2	345.2	0.126	1
5	8	-4642.9	-2176.6	289.79	0.102	1
6	7	-2345.2	-84.712	2175.7	1	1
6	8	-2812.4	-346.02	2120.3	0.999	1
7	8	-2234.4	-261.31	1711.8	1	1

Table C.2: Tukey-Kramer Result for Exercise One - Ring Finger

Exercise One - Ring Finger						
Subject 1	**Subject 2**	**Lower Limit**	**Difference of Group Means**	**Upper Limit**	**P-value**	**Significance**
1	2	-1530.7	-360.79	809.15	0.945	1
1	3	-2322.6	-1152.6	17.317	0.055	1
1	4	-2578.9	-1532.5	-486.06	0.003	0
1	5	-1738.8	-568.9	601.05	0.667	1
1	6	-2341.5	-1171.6	-1.613	0.05	0
1	7	-1984.3	-1048.4	-112.4	0.024	0
1	8	-2359.3	-1189.3	-19.372	0.045	0
2	3	-2073.4	-791.84	489.78	0.406	1
2	4	-2341.6	-1171.7	-1.756	0.0490	0
2	5	-1489.7	-208.1	1073.5	0.999	1
2	6	-2092.4	-810.77	470.85	0.38	1
2	7	-1759.8	-687.56	384.71	0.366	1
2	8	-2110.1	-828.52	453.09	0.357	1
3	4	-1549.8	-379.87	790.08	0.93	1
3	5	-697.88	583.73	1865.3	0.729	1
3	6	-1300.5	-18.931	1262.7	1	1
3	7	-968	104.28	1176.5	1	1
3	8	-1318.3	-36.689	1244.9	1	1
4	5	-206.35	963.6	2133.5	0.142	1
4	6	-809.01	360.94	1530.9	0.945	1
4	7	-451.81	484.14	1420.1	0.604	1
4	8	-826.77	343.18	1513.1	0.957	1
5	6	-1884.3	-602.66	678.95	0.7	1
5	7	-1551.7	-479.45	592.82	0.745	1
5	8	-1902	-620.42	661.19	0.672	1
6	7	-949.07	123.21	1195.5	1	1
6	8	-1299.4	-17.759	1263.9	1	1
7	8	-1213.2	-140.97	931.31	1	1

Table C.3: Tukey-Kramer Result for Exercise One - Pinki Finger

Exercise One - Pinki Finger						
Subject 1	**Subject 2**	**Lower Limit**	**Difference of Group Means**	**Upper Limit**	**P-value**	**Significance**
1	2	-1008	380.36	1768.7	0.929	1
1	3	-1699	-457.26	784.49	0.802	1
1	4	-1820.2	-431.9	956.41	0.887	1
1	5	-1140.3	-29.635	1081	1	1
1	6	-2036.2	-647.92	740.39	0.619	1
2	3	-2225.9	-837.61	550.7	0.372	1
2	4	-2333.1	-812.26	708.56	0.491	1
2	5	-1682.4	-409.99	862.42	0.872	1
2	6	-2549.1	-1028.3	492.54	0.269	1
3	4	-1363	25.358	1413.7	1	1
3	5	-683.03	427.62	1538.3	0.773	1
3	6	-1579	-190.66	1197.6	0.996	1
4	5	-870.14	402.26	1674.7	0.88	1
4	6	-1736.8	-216.02	1304.8	0.996	1
5	6	-1890.7	-618.29	654.12	0.582	1

Table C.4: Tukey-Kramer Result for Exercise Two - Index Finger

Exercise Two - Index Finger						
Subject 1	**Subject 2**	**Lower Limit**	**Difference of Group Means**	**Upper Limit**	**P-value**	**Significance**
1	2	-519.7	-196.86	125.99	0.421	1
1	3	-127.83	195.02	517.86	0.431	1
1	4	25.513	320.23	614.94	0.029	0
1	5	-934.06	-611.22	-288.37	0	0
1	6	-7.682	315.16	638.01	0.058	1
1	7	-422.63	-143.04	136.56	0.615	1
1	8	-180.65	98.939	378.53	0.897	1
2	3	69.031	391.88	714.72	0.013	0
2	4	222.37	517.09	811.8	0.001	0
2	5	-737.2	-414.36	-91.513	0.009	0
2	6	189.18	512.02	834.87	0.001	0
2	7	-225.77	53.822	333.41	0.996	1
2	8	16.206	295.8	575.39	0.035	0
3	4	-169.5	125.21	419.93	0.787	1
3	5	-1129.1	-806.23	-483.39	0	0
3	6	-202.7	120.15	442.99	0.872	1
3	7	-617.64	-338.05	-58.462	0.014	0
3	8	-375.67	-96.078	183.51	0.91	1
4	5	-1226.2	-931.44	-636.73	0	0
4	6	-299.78	-5.065	289.65	1	1
4	7	-709.84	-463.26	-216.69	0	0
4	8	-467.87	-221.29	25.287	0.092	1
5	6	603.53	926.38	1249.2	0	0
5	7	188.59	468.18	747.77	0.001	0
5	8	430.56	710.15	989.75	0	0
6	7	-737.79	-458.2	-178.61	0.001	0
6	8	-495.81	-216.22	63.368	0.187	1
7	8	13.69	241.98	470.26	0.035	0

Table C.5: Tukey-Kramer Result for Exercise Two - Middle Finger

Exercise Two - Middle Finger						
Subject 1	**Subject 2**	**Lower Limit**	**Difference of Group Means**	**Upper Limit**	**P-value**	**Significance**
1	2	-905.3	-360.83	183.64	0.321	1
1	3	-498.96	45.506	589.97	1	1
1	4	-66.043	430.99	928.02	0.108	1
1	5	-264.16	402.67	1069.5	0.42	1
1	6	-48.501	495.97	1040.4	0.084	1
1	7	-272.26	199.27	670.79	0.779	1
1	8	-274.07	197.46	668.98	0.787	1
2	3	-138.13	406.34	950.8	0.211	1
2	4	294.79	791.82	1288.8	0.002	0
2	5	96.667	763.5	1430.3	0.021	0
2	6	312.33	856.8	1401.3	0.002	0
2	7	88.574	560.1	1031.6	0.016	0
2	8	86.765	558.29	1029.8	0.017	0
3	4	-111.55	385.48	882.51	0.18	1
3	5	-309.67	357.17	1024	0.553	1
3	6	-94.006	450.46	994.93	0.136	1
3	7	-317.76	153.76	625.29	0.923	1
3	8	-319.57	151.95	623.48	0.927	1
4	5	-657.01	-28.314	600.38	1	1
4	6	-432.05	64.982	562.01	1	1
4	7	-647.56	-231.72	184.13	0.509	1
4	8	-649.37	-233.53	182.32	0.501	1
5	6	-573.54	93.296	760.13	0.999	1
5	7	-812.14	-203.4	405.33	0.914	1
5	8	-813.95	-205.21	403.52	0.911	1
6	7	-768.22	-296.7	174.82	0.376	1
6	8	-770.03	-298.51	173.01	0.369	1
7	8	-386.81	-1.81	383.19	1	1

Table C.6: Tukey-Kramer Result for Exercise Two - Ring Finger

Exercise Two - Ring Finger						
Subject 1	**Subject 2**	**Lower Limit**	**Difference of Group Means**	**Upper Limit**	**P-value**	**Significance**
1	2	-458.71	-102.43	253.85	0.962	1
1	3	0.22	356.5	712.78	0.05	0
1	4	20.712	345.95	671.19	0.034	0
1	5	-50.783	305.5	661.78	0.117	1
1	6	-30.738	325.54	681.82	0.084	1
1	7	4.63	313.18	621.73	0.046	0
1	8	46.46	355.01	663.56	0.02	0
2	3	102.65	458.93	815.21	0.009	0
2	4	123.14	448.38	773.62	0.005	0
2	5	51.645	407.93	764.21	0.021	0
2	6	71.69	427.97	784.25	0.015	0
2	7	107.06	415.61	724.15	0.006	0
2	8	148.89	457.44	765.98	0.003	0
3	4	-335.79	-10.551	314.69	1	1
3	5	-407.28	-51.003	305.28	0.999	1
3	6	-387.24	-30.958	325.32	1	1
3	7	-351.87	-43.323	265.23	0.999	1
3	8	-310.04	-1.493	307.06	1	1
4	5	-365.69	-40.452	284.79	1	1
4	6	-345.64	-20.407	304.83	1	1
4	7	-304.89	-32.772	239.34	1	1
4	8	-263.06	9.058	281.17	1	1
5	6	-336.24	20.045	376.32	1	1
5	7	-300.87	7.68	316.23	1	1
5	8	-259.04	49.511	358.06	0.999	1
6	7	-320.91	-12.365	296.18	1	1
6	8	-279.08	29.466	338.01	1	1
7	8	-210.1	41.831	293.76	0.998	1

Table C.7: Tukey-Kramer Result for Exercise Two - Pinki Finger

Exercise Two - Pinki Finger						
Subject 1	**Subject 2**	**Lower Limit**	**Difference of Group Means**	**Upper Limit**	**P-value**	**Significance**
1	2	-861.2	-480.42	-99.632	0.012	0
1	3	-357.72	108.64	575	0.974	1
1	4	-290.75	90.036	470.82	0.972	1
1	5	-243.12	137.66	518.45	0.833	1
1	6	-149.3	180.47	510.24	0.477	1
1	7	-313.58	16.187	345.95	1	1
2	3	122.69	589.06	1055.4	0.012	0
2	4	189.67	570.45	951.24	0.004	0
2	5	237.3	618.08	998.86	0.002	0
2	6	331.12	660.88	990.65	0	0
2	7	166.84	496.6	826.37	0.004	0
3	4	-484.97	-18.605	447.76	1	1
3	5	-437.34	29.023	495.38	1	1
3	6	-353.9	71.829	497.56	0.995	1
3	7	-518.18	-92.454	333.27	0.981	1
4	5	-333.15	47.628	428.41	0.999	1
4	6	-239.33	90.434	420.2	0.944	1
4	7	-403.62	-73.849	255.92	0.978	1
5	6	-286.96	42.806	372.57	0.999	1
5	7	-451.25	-121.48	208.29	0.822	1
6	7	-433.54	-164.28	104.97	0.367	1

Table C.8: Tukey-Kramer Result for Exercise Three - Index Finger

Exercise Three - Index Finger						
Subject 1	**Subject 2**	**Lower Limit**	**Difference of Group Means**	**Upper Limit**	**P-value**	**Significance**
1	2	-932.36	-282.01	368.35	0.745	1
1	3	-991.09	-278.66	433.77	0.823	1
1	4	-734.37	138.18	1010.7	0.998	1
1	5	-1315.4	-602.93	109.5	0.119	1
1	6	-258.9	453.54	1166	0.351	1
1	7	-361.9	255.08	872.07	0.783	1
1	8	-595.06	55.299	705.66	1	1
2	3	-647.01	3.347	653.71	1	1
2	4	-402.46	420.18	1242.8	0.588	1
2	5	-971.28	-320.93	329.43	0.624	1
2	6	85.183	735.54	1385.9	0.024	0
2	7	-7.039	537.09	1081.2	0.054	1
2	8	-244.39	337.31	919	0.451	1
3	4	-455.71	416.84	1289.4	0.656	1
3	5	-1036.7	-324.27	388.16	0.702	1
3	6	19.763	732.19	1444.6	0.043	0
3	7	-83.241	533.74	1150.7	0.107	1
3	8	-316.4	333.96	984.32	0.583	1
4	5	-1613.7	-741.11	131.44	0.117	1
4	6	-557.19	315.36	1187.9	0.87	1
4	7	-679.62	116.91	913.43	0.999	1
4	8	-905.52	-82.878	739.77	1	1
5	6	344.04	1056.5	1768.9	0.003	0
5	7	241.03	858.01	1475	0.005	0
5	8	7.872	658.23	1308.6	0.047	0
6	7	-815.44	-198.45	418.53	0.921	1
6	8	-1048.6	-398.24	252.12	0.392	1
7	8	-743.91	-199.78	344.34	0.861	1

Table C.9: Tukey-Kramer Result for Exercise Three - Middle Finger

Exercise Three - Middle Finger						
Subject 1	**Subject 2**	**Lower Limit**	**Difference of Group Means**	**Upper Limit**	**P-value**	**Significance**
1	2	-1355	-694.43	-33.819	0.037	0
1	3	-1134.5	-410.83	312.84	0.474	1
1	4	-1170.4	-284.13	602.18	0.922	1
1	5	-969.42	-245.75	477.92	0.9	1
1	6	-730.93	-7.258	716.41	1	1
1	7	-827.32	-200.61	426.11	0.923	1
1	8	-811.58	-150.96	509.65	0.986	1
2	3	-377.01	283.6	944.22	0.753	1
2	4	-425.31	410.31	1245.9	0.629	1
2	5	-211.93	448.68	1109.3	0.287	1
2	6	26.561	687.18	1347.8	0.04	0
2	7	-58.885	493.83	1046.5	0.092	1
2	8	-47.4	543.47	1134.3	0.079	1
3	4	-759.6	126.71	1013	0.999	1
3	5	-558.59	165.08	888.75	0.986	1
3	6	-320.09	403.57	1127.2	0.494	1
3	7	-416.49	210.22	836.94	0.905	1
3	8	-400.75	259.87	920.49	0.819	1
4	5	-847.94	38.372	924.68	1	1
4	6	-609.44	276.87	1163.2	0.931	1
4	7	-725.57	83.516	892.6	1	1
4	8	-702.46	133.16	968.78	0.998	1
5	6	-485.17	238.5	962.16	0.912	1
5	7	-581.57	45.144	671.86	1	1
5	8	-565.82	94.791	755.41	0.999	1
6	7	-820.07	-193.35	433.36	0.935	1
6	8	-804.32	-143.7	516.91	0.989	1
7	8	-503.06	49.647	602.36	1	1

Table C.10: Tukey-Kramer Result for Exercise Three - Ring Finger

Exercise Three - Ring Finger						
Subject 1	**Subject 2**	**Lower Limit**	**Difference of Group Means**	**Upper Limit**	**P-value**	**Significance**
1	2	-775	-218.74	337.53	0.819	1
1	3	-253.36	356	965.36	0.443	1
1	4	-201.65	544.66	1291	0.223	1
1	5	-206.38	402.99	1012.3	0.313	1
1	6	82.852	692.21	1301.6	0.023	0
1	7	-37.138	490.58	1018.3	0.075	1
1	8	66.595	622.86	1179.1	0.025	0
2	3	18.47	574.74	1131	0.041	0
2	4	59.77	763.4	1467	0.031	0
2	5	65.452	621.72	1178	0.025	0
2	6	354.68	910.95	1467.2	0.001	0
2	7	243.91	709.32	1174.7	0.003	0
2	8	344.06	841.6	1339.1	0.001	0
3	4	-557.65	188.66	934.97	0.976	1
3	5	-562.38	46.981	656.34	1	1
3	6	-273.15	336.21	945.57	0.505	1
3	7	-393.14	134.58	662.3	0.975	1
3	8	-289.41	266.86	823.13	0.652	1
4	5	-887.99	-141.68	604.63	0.995	1
4	6	-598.76	147.55	893.86	0.994	1
4	7	-735.37	-54.081	627.21	1	1
4	8	-625.43	78.198	781.83	1	1
5	6	-320.13	289.23	898.59	0.663	1
5	7	-440.12	87.599	615.32	0.998	1
5	8	-336.39	219.88	776.15	0.816	1
6	7	-729.35	-201.63	326.09	0.838	1
6	8	-625.62	-69.35	486.92	1	1
7	8	-333.13	132.28	597.69	0.956	1

Table C.11: Tukey-Kramer Result for Exercise Three - Pinki Finger

Exercise Three - Pinki Finger						
Subject 1	**Subject 2**	**Lower Limit**	**Difference of Group Means**	**Upper Limit**	**P-value**	**Significance**
1	2	-1265	-298.63	667.77	0.908	1
1	3	-1091.1	205.5	1502.1	0.996	1
1	4	-1172.4	-113.79	944.85	1	1
1	5	-764.7	293.94	1352.6	0.941	1
1	6	-751.96	164.85	1081.7	0.993	1
1	7	-973.99	-7.583	958.82	1	1
2	3	-718.28	504.13	1726.5	0.743	1
2	4	-781.57	184.84	1151.2	0.99	1
2	5	-373.82	592.58	1559	0.362	1
2	6	-345.07	463.48	1272	0.43	1
2	7	-573.33	291.05	1155.4	0.871	1
3	4	-1615.9	-319.29	977.27	0.966	1
3	5	-1208.1	88.446	1385	1	1
3	6	-1224.2	-40.65	1142.9	1	1
3	7	-1435.5	-213.08	1009.3	0.994	1
4	5	-650.9	407.74	1466.4	0.793	1
4	6	-638.17	278.64	1195.5	0.914	1
4	7	-860.19	106.21	1072.6	1	1
5	6	-1045.9	-129.1	787.72	0.998	1
5	7	-1267.9	-301.53	664.88	0.904	1
6	7	-980.98	-172.43	636.12	0.983	1

Table C.12: Tukey-Kramer Result for Exercise Four - Index Finger

Exercise Exercise Four - Index Finger						
Subject 1	**Subject 2**	**Lower Limit**	**Difference of Group Means**	**Upper Limit**	**P-value**	**Significance**
1	2	-2099.6	208.29	2516.2	1	1
1	3	-2624.5	-316.6	1991.3	0.999	1
1	4	-3198.4	-890.53	1417.3	0.777	1
1	5	-2240.8	585.71	3412.3	0.986	1
1	6	-2108	199.83	2507.7	1	1
1	7	-1525	782.82	3090.7	0.86	1
1	8	-2293.5	-186.76	1920	1	1
2	3	-2832.8	-524.89	1783	0.978	1
2	4	-3406.7	-1098.8	1209	0.592	1
2	5	-2449.1	377.42	3204	0.999	1
2	6	-2316.3	-8.458	2299.4	1	1
2	7	-1733.3	574.52	2882.4	0.964	1
2	8	-2501.8	-395.05	1711.7	0.992	1
3	4	-2881.8	-573.92	1733.9	0.965	1
3	5	-1924.2	902.31	3728.9	0.89	1
3	6	-1791.4	516.44	2824.3	0.979	1
3	7	-1208.4	1099.4	3407.3	0.592	1
3	8	-1976.9	129.85	2236.6	1	1
4	5	-1350.3	1476.2	4302.8	0.499	1
4	6	-1217.5	1090.4	3398.2	0.6	1
4	7	-634.52	1673.3	3981.2	0.2	1
4	8	-1403	703.77	2810.6	0.868	1
5	6	-3212.4	-385.88	2440.7	0.999	1
5	7	-2629.4	197.1	3023.7	1	1
5	8	-3437.4	-772.47	1892.4	0.927	1
6	7	-1724.9	582.98	2890.8	0.962	1
6	8	-2493.4	-386.59	1720.2	0.993	1
7	8	-3076.4	-969.57	1137.2	0.625	1

Table C.13: Tukey-Kramer Result for Exercise Four - Middle Finger

Exercise Four - Middle Finger						
Subject 1	**Subject 2**	**Lower Limit**	**Difference of Group Means**	**Upper Limit**	**P-value**	**Significance**
1	2	-3434	-1554.1	325.81	0.12	1
1	3	-4178.5	-2298.6	-418.75	0.017	0
1	4	-4367.6	-2487.7	-607.85	0.011	0
1	5	-3587.1	-1284.7	1017.7	0.432	1
1	6	-3545.7	-1665.9	214.04	0.089	1
1	7	-3540.6	-1660.7	219.2	0.09	1
1	8	-3862.5	-2146.4	-430.29	0.015	0
2	3	-2624.4	-744.56	1135.3	0.757	1
2	4	-2813.5	-933.65	946.24	0.55	1
2	5	-2033	269.37	2571.8	1	1
2	6	-1991.7	-111.77	1768.1	1	1
2	7	-1986.5	-106.61	1773.3	1	1
2	8	-2308.4	-592.31	1123.8	0.85	1
3	4	-2069	-189.09	1690.8	1	1
3	5	-1288.4	1013.9	3316.3	0.667	1
3	6	-1247.1	632.79	2512.7	0.864	1
3	7	-1241.9	637.95	2517.8	0.86	1
3	8	-1563.8	152.25	1868.3	1	1
4	5	-1099.4	1203	3505.4	0.498	1
4	6	-1058	821.88	2701.8	0.674	1
4	7	-1052.8	827.04	2706.9	0.668	1
4	8	-1374.8	341.35	2057.4	0.989	1
5	6	-2683.5	-381.14	1921.2	0.996	1
5	7	-2678.4	-375.98	1926.4	0.997	1
5	8	-3032.4	-861.68	1309	0.756	1
6	7	-1874.7	5.162	1885	1	1
6	8	-2196.6	-480.54	1235.6	0.938	1
7	8	-2201.8	-485.7	1230.4	0.935	1

Table C.14: Tukey-Kramer Result for Exercise Four - Ring Finger

Exercise Four - Ring Finger						
Subject 1	**Subject 2**	**Lower Limit**	**Difference of Group Means**	**Upper Limit**	**P-value**	**Significance**
1	2	-347.11	248.08	843.27	0.692	1
1	3	-1033	-437.83	157.36	0.185	1
1	4	-1158.2	-562.96	32.228	0.065	1
1	5	-1173.3	-578.06	17.13	0.058	1
1	6	258.39	853.58	1448.8	0.007	0
1	7	-559.22	-15.891	527.44	1	1
2	3	-1281.1	-685.9	-90.714	0.024	0
2	4	-1406.2	-811.04	-215.85	0.009	0
2	5	-1421.3	-826.14	-230.95	0.008	0
2	6	10.315	605.51	1200.7	0.046	0
2	7	-807.3	-263.97	279.36	0.552	1
3	4	-720.33	-125.14	470.05	0.978	1
3	5	-735.42	-140.23	454.96	0.963	1
3	6	696.22	1291.4	1886.6	0	0
3	7	-121.4	421.94	965.27	0.152	1
4	5	-610.29	-15.097	580.09	1	1
4	6	821.36	1416.5	2011.7	0	0
4	7	3.74	547.07	1090.4	0.048	0
5	6	836.45	1431.6	2026.8	0	0
5	7	18.837	562.17	1105.5	0.042	0
6	7	-1412.8	-869.48	-326.14	0.003	0

Table C.15: Tukey-Kramer Result for Exercise Four - Pinki Finger

Exercise Four - Pinki Finger						
Subject 1	**Subject 2**	**Lower Limit**	**Difference of Group Means**	**Upper Limit**	**P-value**	**Significance**
1	2	74.64	890.68	1706.7	0.036	0
1	3	-986.24	13.202	1012.6	1	1
1	4	-241.79	574.25	1390.3	0.163	1
1	5	-987.08	-242.14	502.8	0.702	1
2	3	-1876.9	-877.48	121.96	0.08	1
2	4	-1132.5	-316.43	499.61	0.575	1
2	5	-1877.8	-1132.8	-387.88	0.009	0
3	4	-438.39	561.05	1560.5	0.294	1
3	5	-1197.6	-255.34	686.94	0.807	1
4	5	-1561.3	-816.39	-71.453	0.035	0

C.2 Games-Howell

The results shown in this section is intended as a example that the Games-Howell post hoc test was performed, the results are considered erroneous and no conclusion can be reached from teh result.

The number of samples are: 7

Table of the difference between each pair of means in terms of the Tukey's statistic and then comparing them with its critical value.

Comparison	D	q	df'	Conclusion
7 6	869.4756	4.1009	1	NS
7 5	562.1694	4.6869	2	NS
7 4	547.0723	4.6239	2	NS
7 3	421.9354	2.8869	2	NS
7 2	263.9697	2.0743	2	NS
7 1	15.8911	0.0961	2	NS
6 5	1431.6450	8.0016	1	NS
6 4	1416.5479	7.9657	1	NS
6 3	1291.4110	6.5404	1	NS
6 2	605.5058	3.2925	1	NS
6 1	853.5845	4.0264	1	NS
5 4	15.0971	0.4640	1	NS
5 3	140.2339	1.5281	1	NS
5 2	826.1391	14.4793	1	NS
5 1	578.0605	4.8210	1	NS
4 3	125.1368	1.3962	1	NS
4 2	811.0420	15.1468	1	NS
4 1	562.9634	4.7598	1	NS
3 2	685.9052	6.7816	1	NS
3 1	437.8266	2.9963	1	NS
2 1	248.0786	1.9500	1	NS

With a given significance level of: 0.0500
The results are significant (S) and/or not significant (NS).

Figure C.1: Games-Howell Post Hoc Test For Index Finger for Exercise One

The number of samples are: 7

Table of the difference between each pair of means in terms of the Tukey's statistic and then comparing them with its critical value.

Comparison	D	q	df'	Conclusion
7 6	869.4756	4.1009	1	NS
7 5	562.1694	4.6869	2	NS
7 4	547.0723	4.6239	2	NS
7 3	421.9354	2.8869	2	NS
7 2	263.9697	2.0743	2	NS
7 1	15.8911	0.0961	2	NS
6 5	1431.6450	8.0016	1	NS
6 4	1416.5479	7.9657	1	NS
6 3	1291.4110	6.5404	1	NS
6 2	605.5058	3.2925	1	NS
6 1	853.5845	4.0264	1	NS
5 4	15.0971	0.4640	1	NS
5 3	140.2339	1.5281	1	NS
5 2	826.1391	14.4793	1	NS
5 1	578.0605	4.8210	1	NS
4 3	125.1368	1.3962	1	NS
4 2	811.0420	15.1468	1	NS
4 1	562.9634	4.7598	1	NS
3 2	685.9052	6.7816	1	NS
3 1	437.8266	2.9963	1	NS
2 1	248.0786	1.9500	1	NS

With a given significance level of: 0.0500
The results are significant (S) and/or not significant (NS).

Figure C.2: Games-Howell Post Hoc Test For Middle Finger for Exercise One

The number of samples are: 8

Table of the difference between each pair of means in terms of the Tukey's statistic and then comparing them with its critical value.

Comparison	D	q	df'	Conclusion
8 7	117.3640	0.9550	2	NS
8 6	986.8395	5.4548	1	NS
8 5	444.8054	9.5615	1	NS
8 4	429.7083	10.1970	1	NS
8 3	304.5715	3.1860	1	NS
8 2	381.3337	6.0503	1	NS
8 1	133.2551	1.0846	1	NS
7 6	869.4756	4.1009	1	NS
7 5	562.1694	4.6869	2	NS
7 4	547.0723	4.6239	2	NS
7 3	421.9354	2.8869	2	NS
7 2	263.9697	2.0743	2	NS
7 1	15.8911	0.0961	2	NS
6 5	1431.6450	8.0016	1	NS
6 4	1416.5479	7.9657	1	NS
6 3	1291.4110	6.5404	1	NS
6 2	605.5058	3.2925	1	NS
6 1	853.5845	4.0264	1	NS
5 4	15.0971	0.4640	1	NS
5 3	140.2339	1.5281	1	NS
5 2	826.1391	14.4793	1	NS
5 1	578.0605	4.8210	1	NS
4 3	125.1368	1.3962	1	NS
4 2	811.0420	15.1468	1	NS
4 1	562.9634	4.7598	1	NS
3 2	685.9052	6.7816	1	NS
3 1	437.8266	2.9963	1	NS
2 1	248.0786	1.9500	1	NS

With a given significance level of: 0.0500
The results are significant (S) and/or not significant (NS).

Figure C.3: Games-Howell Post Hoc Test For Ring Finger for Exercise One

The number of samples are: 7

Table of the difference between each pair of means in terms of the Tukey's statistic and then comparing them with its critical value.

Comparison	D	q	df'	Conclusion
7 6	869.4756	4.1009	1	NS
7 5	562.1694	4.6869	2	NS
7 4	547.0723	4.6239	2	NS
7 3	421.9354	2.8869	2	NS
7 2	263.9697	2.0743	2	NS
7 1	15.8911	0.0961	2	NS
6 5	1431.6450	8.0016	1	NS
6 4	1416.5479	7.9657	1	NS
6 3	1291.4110	6.5404	1	NS
6 2	605.5058	3.2925	1	NS
6 1	853.5845	4.0264	1	NS
5 4	15.0971	0.4640	1	NS
5 3	140.2339	1.5281	1	NS
5 2	826.1391	14.4793	1	NS
5 1	578.0605	4.8210	1	NS
4 3	125.1368	1.3962	1	NS
4 2	811.0420	15.1468	1	NS
4 1	562.9634	4.7598	1	NS
3 2	685.9052	6.7816	1	NS
3 1	437.8266	2.9963	1	NS
2 1	248.0786	1.9500	1	NS

With a given significance level of: 0.0500
The results are significant (S) and/or not significant (NS).

Figure C.4: Games-Howell Post Hoc Test For Index Finger for Exercise Two

Appendix D

External ADC Data Sampling

The change in resistance of the strain gauges, results in a change in voltage of the Weatsone bridge; this change in voltage is measured by the external ADC. Figure D.1 shows the section of the firmware of the device responsible of reading the data from the external ADC via a two-wire serial digital interface. The example is for the force measurements of the index finger. The function is called when the ADC signals that data is ready.

```
void Iadcread(void)
{
      int32_t IsensorValue =0;
      for(int t=0;t<24;t++)
      {
        HAL_GPIO_WritePin(INDEX_SCLK_GPIO_Port,INDEX_SCLK_Pin,GPIO_PIN_SET);
        IsensorValue = (IsensorValue<<1) + HAL_GPIO_ReadPin(INDEX_DATA_GPIO_Port,INDEX_DATA_Pin);
        HAL_GPIO_WritePin(INDEX_SCLK_GPIO_Port,INDEX_SCLK_Pin,GPIO_PIN_RESET);
      }
      IsensorValue = IsensorValue << 8;
      IsensorValue = (IsensorValue/1000.00);
      forceRead[1] = IsensorValue;
      HAL_GPIO_WritePin(INDEX_SCLK_GPIO_Port,INDEX_SCLK_Pin,GPIO_PIN_SET);
      HAL_GPIO_WritePin(INDEX_SCLK_GPIO_Port,INDEX_SCLK_Pin,GPIO_PIN_RESET);
}
```

Figure D.1: External ADC firmware example

Appendix E

Effect of the Mechanical Structure

The results of the experiment to investigate the effect of the mechanical structure on the force readings. The experiment was performed with the finger in three different positions and with the force applied to the finger tip in both directions.

Figure E.1 shows the data from the experiment with the actuator extended 20% and the loadcell pushing against the tip, opening the hand.

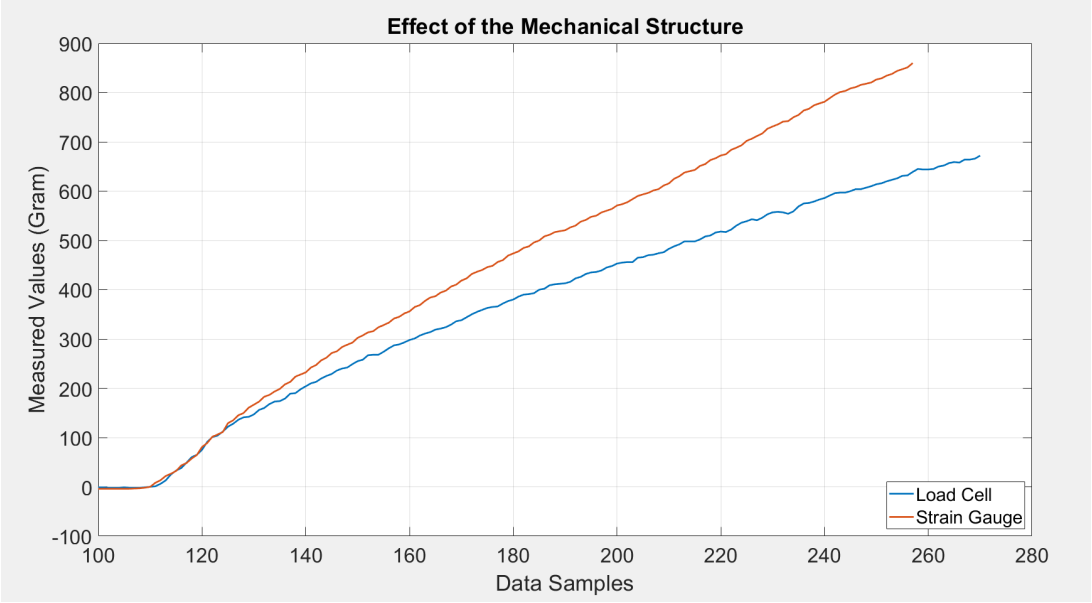


Figure E.1: Comparison between the loadcell measurement and the strain gauge measurement

Figure E.2 shows the data from the experiment with the actuator extended 20% and the loadcell pulling the tip, closing the hand.

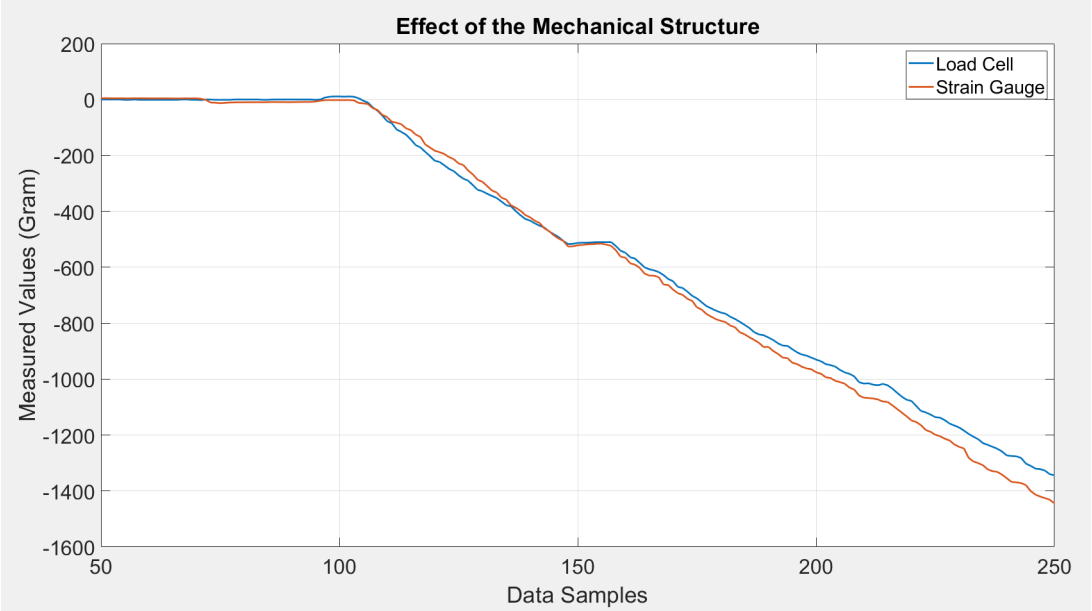


Figure E.2: Comparison between the loadcell measurement and the strain gauge measurement

Figure E.3 shows the data from the experiment with the actuator extended 40% and the loadcell pushing against the tip, opening the hand.

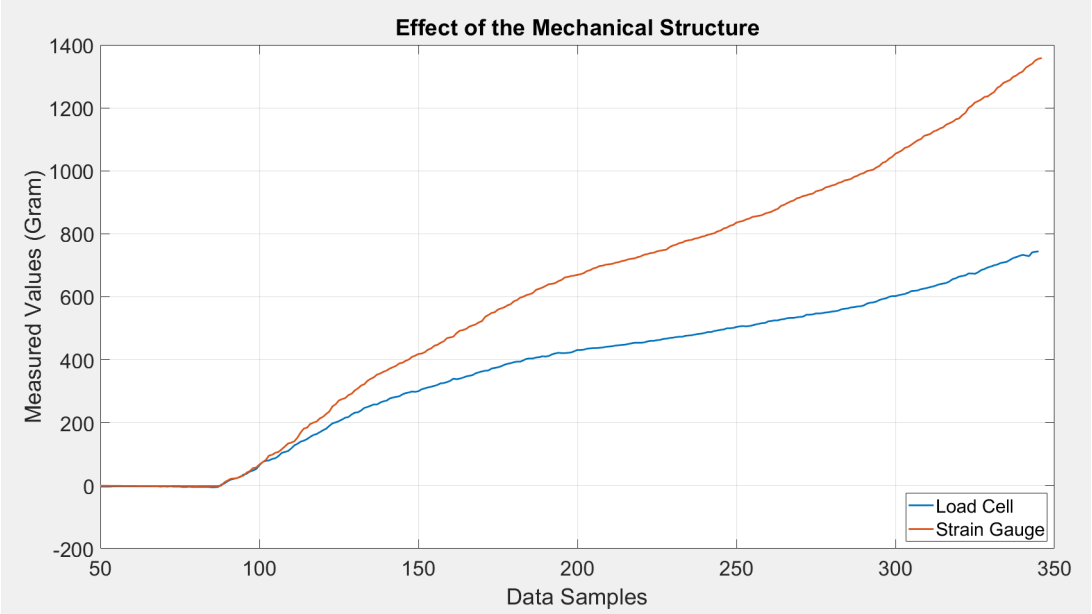


Figure E.3: Comparison between the loadcell measurement and the strain gauge measurement

Figure E.4 shows the data from the experiment with the actuator extended 40% and the loadcell pulling the tip, closing the hand.

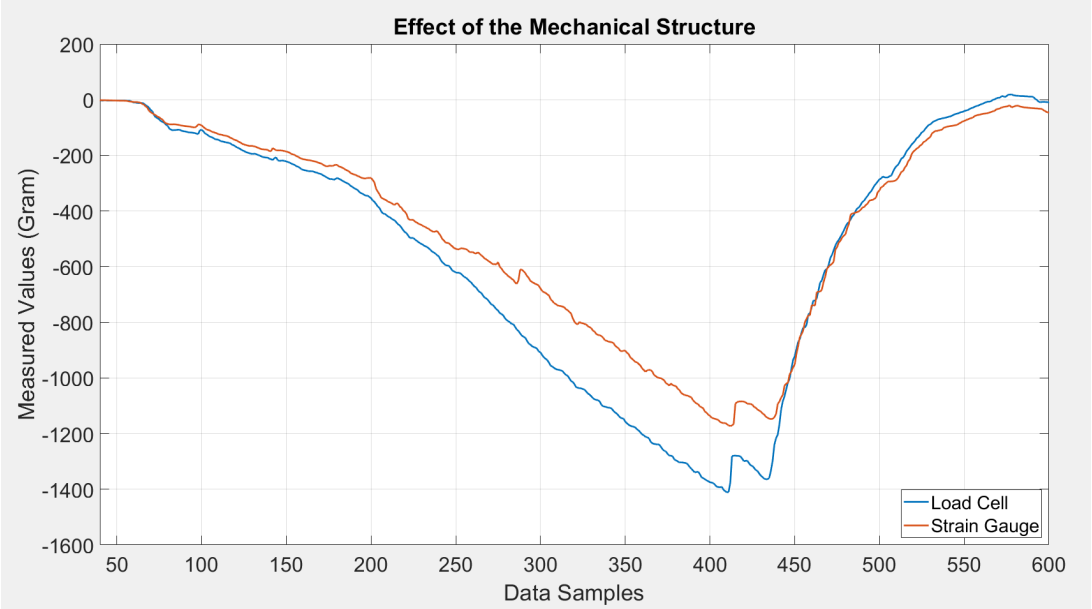


Figure E.4: Comparison between the loadcell measurement and the strain gauge measurement

Figure E.5 shows the data from the experiment with the actuator extended 80% and the loadcell pushing against the tip, opening the hand.

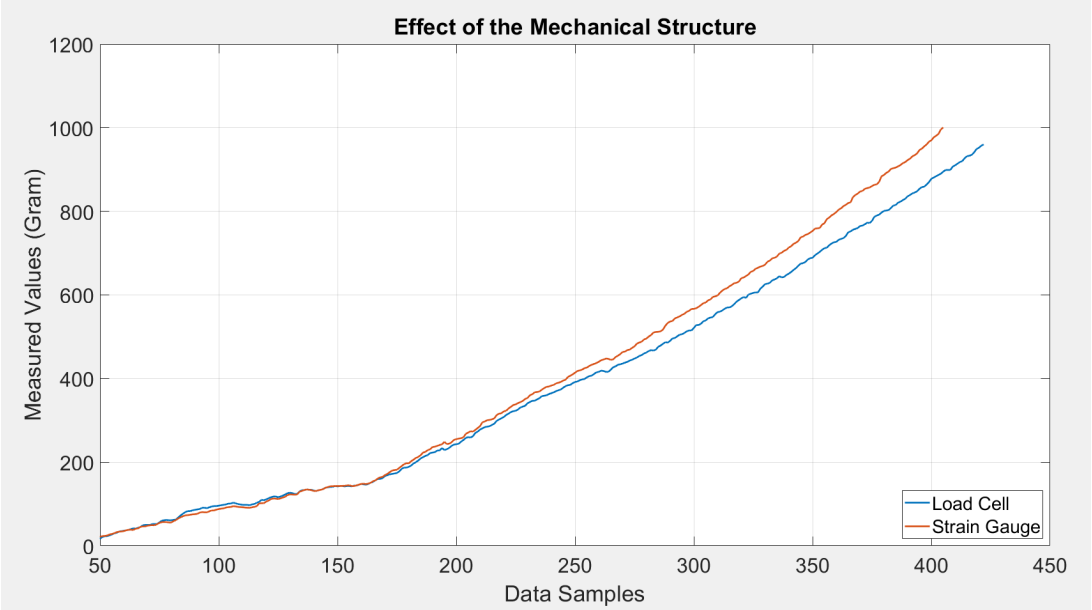


Figure E.5: Comparison between the loadcell measurement and the strain gauge measurement

Figure E.6 shows the data from the experiment with the actuator extended 80% and the loadcell pulling the tip, closing the hand.

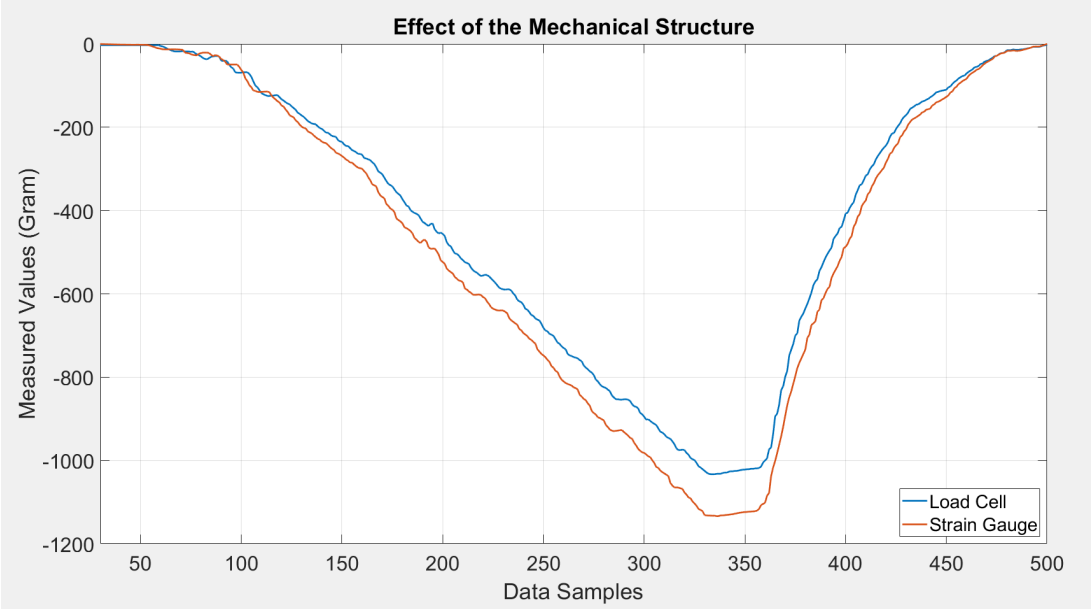
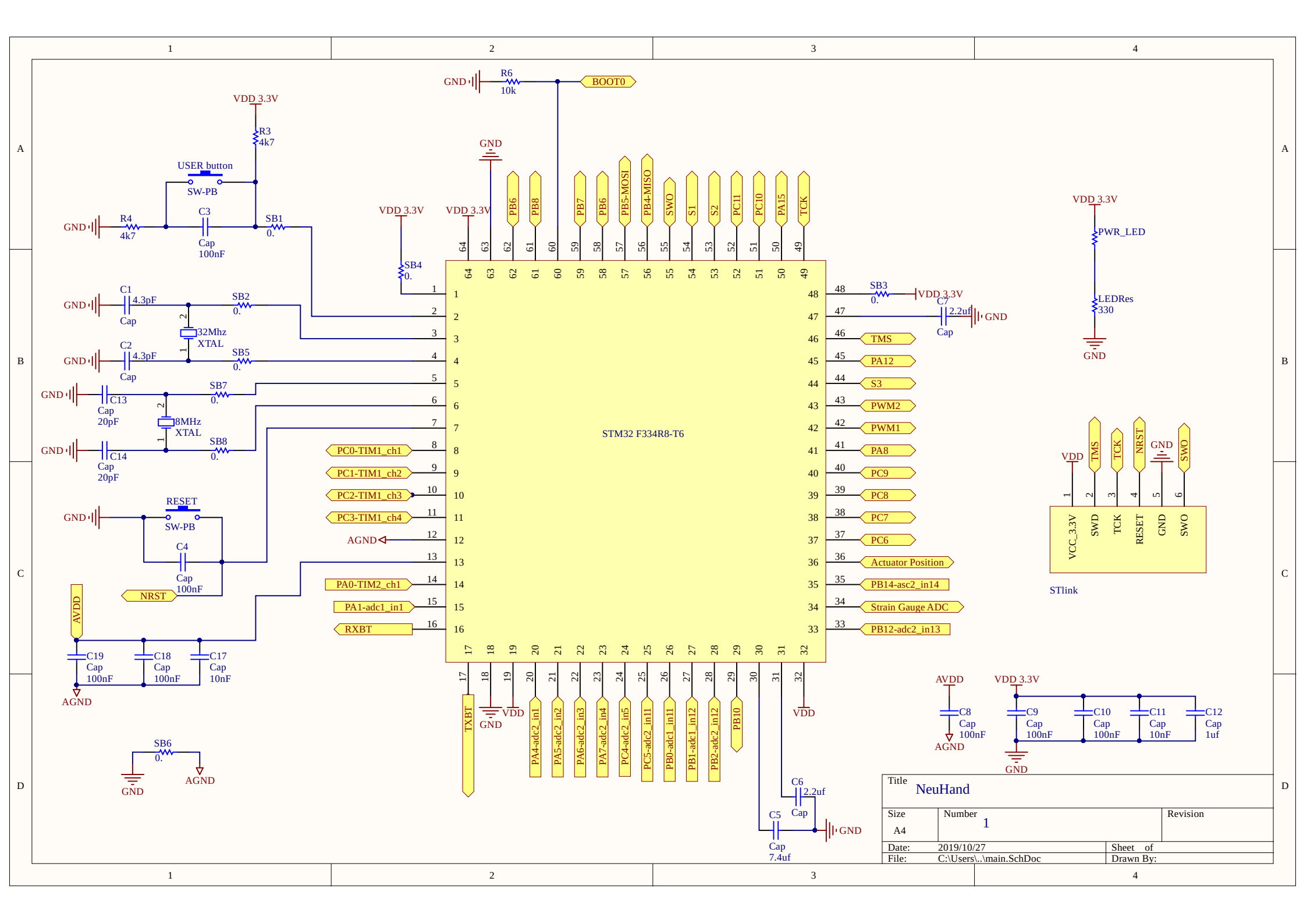
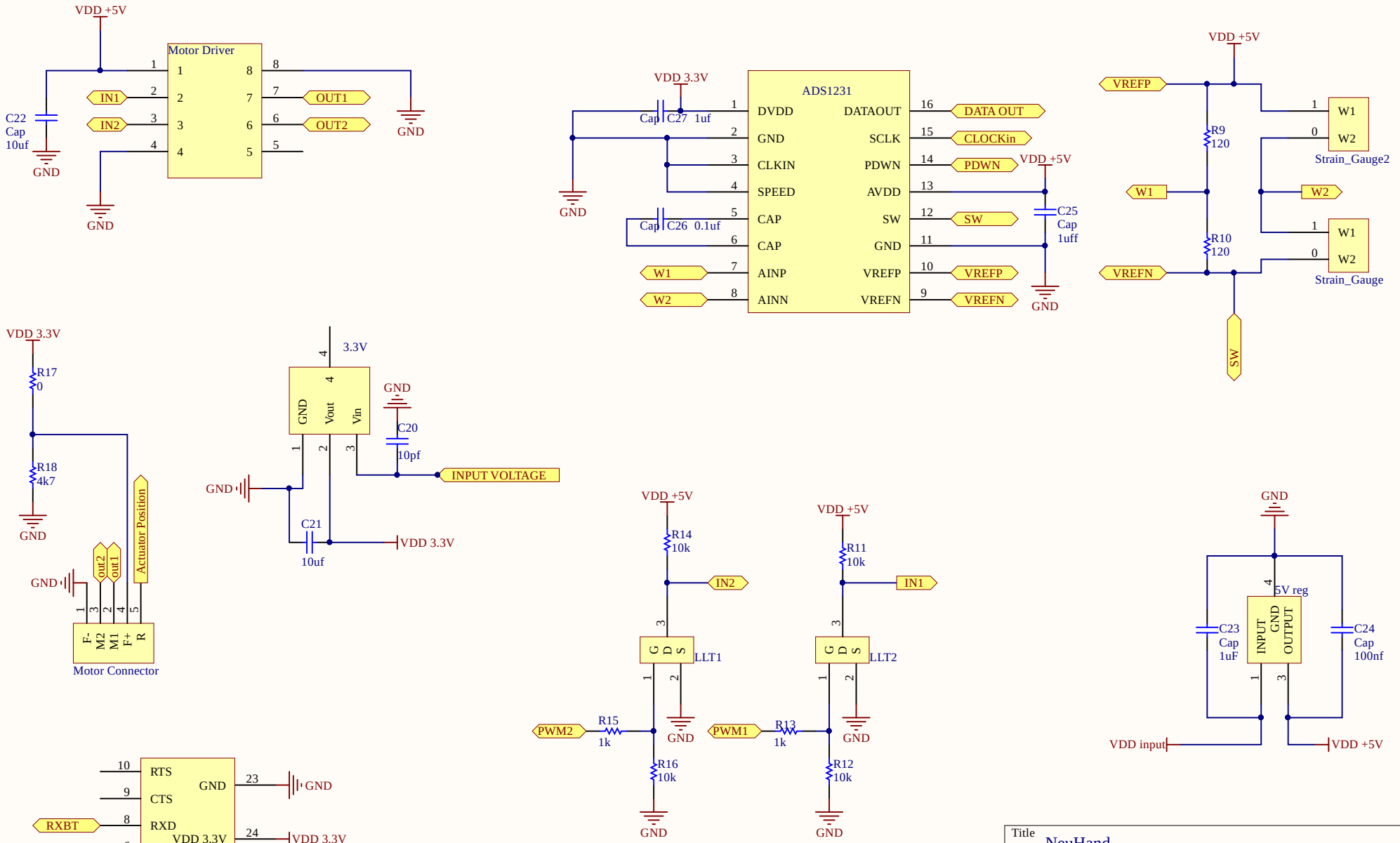


Figure E.6: Comparison between the loadcell measurement and the strain gauge measurement

Appendix F

Schematics of Control Board


STM32 F334R8-T6
R6
10k
BOOT0
R3
4k7
USER button
SW-PB
R4
4k7
C3
Cap
100nF
SB1
0.
SB4
0.
C1
4.3pF
Cap
SB2
0.
32Mhz
XTAL
C2
4.3pF
Cap
SB5
0.
C13
Cap
20pF
SB7
0.
8MHz
XTAL
C14
Cap
20pF
SB8
0.
RESET
SW-PB
C4
Cap
100nF
NRST
AVDD
C19
Cap
100nF
C18
Cap
100nF
C17
Cap
10nF
AGND
SB6
0.
SB3
0.
C7
2.2uf
Cap
PWR_LED
LEDRes
330
VDD
TMS
TCK
NRST
GND
SWO
VCC_3.3V
SWD
STlink
C8
Cap
100nF
C9
Cap
100nF
C10
Cap
100nF
C11
Cap
10nF
C12
Cap
1uf
C6
2.2uf
Cap
C5
Cap
7.4uf
PB6
PB8
PB7
PB6
PB5-MOSI
PB4-MISO
SWO
S1
S2
PC11
PC10
PA15
TCK
PC0-TIM1_ch1
PC1-TIM1_ch2
PC2-TIM1_ch3
PC3-TIM1_ch4
PA0-TIM2_ch1
PA1-adc1_in1
RXBT
TMS
PA12
S3
PWM2
PWM1
PA8
PC9
PC8
PC7
PC6
Actuator Position
PB14-asc2_in14
Strain Gauge ADC
PB12-adc2_in13
TXBT
PA4-adc2_in1
PA5-adc2_in2
PA6-adc2_in3
PA7-adc2_in4
PC4-adc2_in5
PC5-adc2_in11
PB0-adc1_in11
PB1-adc1_in12
PB2-adc2_in12
PB10
Title
NeuHand
Size
A4
Number
1
Revision
Date:
2019/10/27
Sheet of
File:
C:\Users\..\main.SchDoc
Drawn By:



Title	NeuHand	
Size: A4	Number: 2	Revision:
Date: 2019/10/27	Sheet of	
File: C:\Users\..\main2_rev2.SchDoc	Drawn By:	

Appendix G

Research Ethics Committee Letter

Research Ethics Committee Letter of Decision

Private Bag X1290, Potchefstroom
South Africa 2520

North-West University Engineering Research Ethics Committee (NWU-ENG-REC)

Tel: 018 299-2645
Email: ENG-REC@nwu.ac.za

9/6/2019

RESEARCH ETHICS COMMITTEE LETTER OF DECISION: NO RISK

Based on the review by the North-West University Engineering Research Ethics Committee (NWU-ENG-REC) on 8/23/2019, the NWU-ENG-REC hereby clears your study as a No risk study. This implies that the NWU-ENG-REC grants its permission that, provided the general conditions specified below are met, the study may be initiated, using the ethics number below.

Study title:
Quantifying the force exerted by a therapist for the calibration of rehabilitation devices
Principal Investigator/Study Supervisor/Researcher: MJ Grobler
Student: George Johan Dyason (georgejohandyason@gmail.com)

Ethics number: **NWU-00321-19-A1**
Institution Study Number Year Status
Status: S = Submission; R = Re-Submission; P = Provisional Authorisation; A = Authorisation

Application Type: Single
Commencement date: **8/23/2019**

Risk: **No**

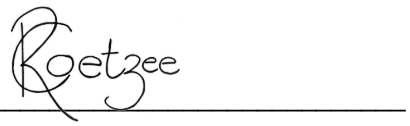
General conditions:

The following general terms and conditions will apply:

- *The commencement date indicates the first date that the study may be started.*
- *In the interest of ethical responsibility, the NWU-ENG-REC reserves the right to:*
  - *request access to any information or data at any time during the course or after completion of the study;*
  - *to ask further questions, seek additional information, require further modification or monitor the conduct of your research;*
  - *withdraw or postpone clearance if:*
    - *any unethical principles or practices of the study are revealed or suspected;*
    - *it becomes apparent that any relevant information was withheld from the NWU-ENG-REC or that information has been false or misrepresented;*
    - *submission of the required amendments, or reporting of adverse events or incidents was not done in a timely manner and accurately; and/or*
    - *new institutional rules, national legislation or international conventions deem it necessary.*
- *NWU-ENG-REC can be contacted for further information via ENG-REC@nwu.ac.za or 018 299 2645*

The NWU-ENG-REC would like to remain at your service and wishes you well with your study. Please do not hesitate to contact the NWU-ENG-REC for any further enquiries or requests for assistance.

Yours sincerely,



Dr Rojanette Coetzee
Chairperson NWU-ENG-REC

Current details:(25767984) \NWUNextCloud\ENG-REC\Letters sent\[Date]\9.1.5.4.3_NWU-ENG-REC_REC_LOD_NR_[student surname_name]

File Reference: 9.1.5.4.3

Appendix H

Improvement Report

Improvement Report

Dissertation of GJ Dyason

1. Scope of document

This document outlines the improvements made to the original dissertation submitted for the degree of master of engineering in computer and electronic engineering. The document summarises the changes that were made to the original document to address the main concerns identified.

2. Main concerns identified

2.1 Research methodology

The original document stated that the scientific method was used with minor modifications. The improved dissertation defines the research methodology in more detail and explains why and how the scientific method was altered to suit the study.

2.2 Device specification

A robotic rehabilitation device was constructed as part of the study. A specification document for the device was drawn up before designing the prototype. Concern was raised that the device was developed without proper specifications. This was addressed by adding a section outlining the key specifications of the device.

2.3 Editing

The spelling and grammar mistakes from the original document were corrected.

3. Detailed change log

A detailed change log is included in Table 1. The table contains the comments made by the examiners as well as a short description of the changes that were implemented along with the location of the changes in the updated document.

Table 1 Changes made to the original dissertation

Comment			Changes Implemented	Location
E1				
1	A	"The forces that Robotic-assisted rehabilitation devices can apply easily exceeds that which is safe for human beings." This statement is contradicted in the "Motivation and Justification" section and is not referenced. It is therefore not clear if this is a pertinent problem, especially if these devices have built-in safety features.	Revised the problem statement. Added a section to Motivation and Justification to explain the rehabilitation procedure for spastic hands.	P. 3
	B	It is unclear exactly which types of injuries the research will target. The symptoms of these targeted injuries should also be listed (stiff or free moving hands etc.).	The research is targeted at devices capable of assisting patient with spastic hands. Added in the revised problem statement that once the forces are characterised then the devices can be used on patients with spastic hands and will not be limited to weakened hands.	P. 4

2	A	The manner in which a rehabilitation device can injure or impair the recovery of a patient should be discussed in detail.	Explained that the hand of the patient was functional and healthy before and after a stroke. Forcing the hand open or closed is like spraining a hand or over extending a muscle.	P. 17
	B	A section that details the exercises that are typically employed by therapists is required in the literature study.	Add a section on conventional therapy methods, instruments and aids.	P. 19-20
3	A	The specifications of the device where not provided as quantitative values. These should be presented in the form of a table.	Added section 3.3 that outlines the design requirements of the device.	P. 31 - 32
	B	The required specifications should at least be clearly compared to the specifications of the pre-existing device.	The existing device was a simple proof of concept device. The existing device was made out of metal and cannot be adjusted for different hands. This is stated in section 3.3.	P. 31
	C	The device was not designed to minimise the effect that it would have on the technique employed by the therapist. The exoskeleton will impact the exercises that the therapist performs.	Forces measured by the device from external forces is measured in the same manner as the forces the device applies to the patient. All the therapists performed the same exercise under the same conditions. The effect of the mechanical structure on the force measurements was investigated and an experiment designed, this can be found in section 5.9	P. 97
	H	An interesting (and somewhat pedantic) improvement might be to add a low resistance relay (or MOSFET) to disconnect the measurement circuitry when samples aren't being taken in order to minimize temperature drift. A temperature measurement integrated circuit can also be added to measure the board	This is implemented in firmware through the ADC, the ADC is disabled when not in use and therefore the Weatstone bridge is also not powered. This is described in section 3.4.7	P. 40
4	A	The experiments should ideally have been performed on actual patients. In their current form they measure the force upon the exoskeleton and not the force upon a hand.	The experiments cannot be performed on actual patients since this would require a clinical trial (http://www.sanctr.gov.za/). Due to budgetary and time constraints it was decided to not perform the experiments on human hands.	P. 65
5	A	The rehabilitation device measures the force upon itself and not an actual hand. The exoskeleton also affects the exercises performed as part of the experiments. This adversely affects the verification.	Performed an experiment to investigate the effect of the mechanical structure and explained why the results are still valid. Added section 5.9	P. 97
6	A	The results were not compared to other datasets or theoretical values.	Comparable datasets are not available since the existing rehabilitation	

			devices are not suitable for spastic hands.	
	B	The results should have been compared to the force ratings of existing devices in order to determine how suitable they are for their purpose. This would also serve as an additional form of validation.	Not available since the majority of devices are not for spastic hands and are not meant to apply any significant amount of force. The forces applied buy these devices are also not available.	
E2				
7	A	The candidate identified the research problem but the objectives can be formulated more clearly.	Refer to comments 1-A and 1-B	P. 3-4
	B	Various methods are available to measure force but did not discuss them	Added section 2.7 to give more information on force measurement methods.	P. 25-28
	C	A more in-depth review of existing rehabilitation devices is also necessary. This will create the context of what is available commercially.	Added section 2.5.1 on conventional rehabilitation instruments. Refer to comment 2-B	P. 19-20
8	A	The candidate did not define and apply a suitable research methodology	Revised the research methodology to explain the research methodology that was implemented. Refer to section 2.1 of this document.	P. 5
	B	No proper requirements analysis for device.	Refer to comment 3-A	P. 31-32
	C	The selection of many items was not supported by a proper trade-off study to motivate the design decisions	Added trade-off studies for the key components of the device.	P. 34-41
	D	The influence of the exoskeleton on the measurements was not evaluated and discussed.	Performed an experiment to investigate the effect of the mechanical structure and explained why the results are still valid. Added section 5.9	P. 97

Appendix I

Solemn Declaration and Permission to Submit

NORTH-WEST UNIVERSITY
NOORDWES-UNIVERSITEIT
YUNIBESITI YA BOKONE-BOPHIRIMA

Higher Degrees Administration

SOLEMN DECLARATION AND PERMISSION TO SUBMIT

Solemn declaration by student

I, **G.J. Dyason**

declare herewith that the thesis/dissertation/mini-dissertation/article entitled (**exactly as registered/approved title**),

Quantifying the force exerted by a therapist for the calibration of rehabilitation devices

which I herewith submit to the North-West University is in compliance/partial compliance with the requirements set for the degree:

Master of engineering in computer and electronic engineering

is my own work, has been text-edited in accordance with the requirements and has not already been submitted to any other university.

LATE SUBMISSION: If a thesis/dissertation/mini-dissertation/article of a student is submitted after the deadline for submission, the period available for examination is limited. No guarantee can therefore be given that (should the examiner reports be positive) the degree will be conferred at the next applicable graduation ceremony. It may also imply that the student would have to re-register for the following academic year.

Ethics number: NWU-00321-19-A1

ORCiD: 0000-0001-5690-8497

Signature of Student: George J. Dyason — Digitally signed by George J. Dyason Date: 2019.11.21 20:12:21 +02'00'

University Number: 23369043

Signed on this 21 day of November of 2019

Permission to submit and solemn declaration by supervisor/promoter

The undersigned declares that the thesis/dissertation/mini-dissertation complies with the specifications set out by the NWU:

- with regards to A-rules (PhD students shoud have at least one paper on aspects of the thesis submitted for review in an accredited scientific journal) Yes ○ No ● Not applicable (n/a) ◉
- with regards to faculty rules on submission or acceptance by an accredited scientific journal: Yes ○ No ◉ n/a ○ The student will prepare and submit an appropriate paper before end Jan 2020
- with regards to faculty rules on peer reviewed conference proceedings: Yes ○ No ○ n/a ○
- the student is hereby granted permission to submit his/her mini-dissertation/ dissertation/thesis: Yes ◉ No ○
- that the student's work has been checked by me for plagiarism (by making use of TurnItIn software for example) and a satisfactory report has been obtained: Yes ◉ No ○

and that the work was language edited before submission for examination.

Signature of Supervisor/Promoter

Digitally signed by Dr MJ Grobler
Date: 2019.11.22 15:59:00 +02'00'

Date: 22/11/2019