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MODELING THE HUMAN HAND: A GUIDE FOR PRELIMINARY EXOGLOVE DEVELOPMENT

A thesis submitted in partial satisfaction of the
requirements for the degree of

MASTERS OF SCIENCE

in

COMPUTER ENGINEERING
with an emphasis in ROBOTICS AND CONTROL

by

John M. Kolar

March 2018

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Abstract

Modeling The Human Hand: A Guide For Preliminary ExoGlove Development

by

John M. Kolar

People who suffer from paralysis or weakened muscles caused by injuries and diseases such as spinal cord injury, stroke, cerebral palsy, and other conditions experience great difficulty in doing everyday tasks. The development of soft robotic exoskeletons is making it easier for these patients to perform everyday tasks they would otherwise not be able to do. The use of one's hands and fingers are an essential physical function for interacting with tools and objects in our surroundings. This paper provides a framework of the fundamental steps in designing an exoglove. An understanding of the precise movements of the fingers and muscular activity are essential in designing such systems. An extensive literature review, experiments that obtain motion capture and EMG data, and analysis of this data may provide a basis for others to apply these techniques to their own exoglove or exoskeletons in general.

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Chapter 1

Introduction

There are about 39.6 millions patients in the U.S. who have any type of physical functioning difficulty according to a 2016 survey conducted by National Center for Health Statistics [8], with many different diseases and conditions causing these physical impairments of varying degrees. These physical impairments can range from simple weakness of the muscles to debilitating shaking from Parkinson's Disease or near crippling effects of surviving a stroke. Alleviating or curing these physical impairments has always seemed like a hopeful impossibility until recently where modern technology is making it seem like a possibility.

Curing or fixing these types of conditions still seems like a hopeful impossibility, with the bioengineering field still solving fundamental problems regarding such a feat. This is why there is such a focus on alleviating these symptoms with the help of computer and electrical systems. The field of powered robotic exoskeletons has gained much interest in the past decade due to advances in numerous fields of technology that have now made it a possibility to realize feasible systems. While all classes of exoskeletons ranging from upper-extremity to lower-body types present numerous challenges, developing one for the hand is an especially interesting challenge because of the fine motor control and dexterity

that healthy hands perform in activities of daily living (or ADLs, an acronym that will be used throughout the paper). There are several different approaches to designing such robotic gloves depending on what the specific goals are.

An extensive literature review of existing exogloves that have had papers published was done. This includes nearly 60 papers which all cover a different design. A thorough table was created based on the properties of each design such as actuators used, sensors, intended use, etc. This table can be found in the appendix for reference in the following sections. The paper numbers on the table make reference to the numbered bibliography. With the knowledge gained from this, experiments were done to gather preliminary data that would eventually lead to building an exoglove. The experiments included collecting motion tracking data and EMG data simultaneously. These datasets were imported into MATLAB so that various simulations and analyses can be performed. The results show a correlation in the data that may be helpful when considering a controls system. The results also provide a basis for more advanced simulations including dynamic modeling.

1.1 Intended Uses

There are several different intended uses for powered exogloves depending on the establishment that's researching them ranging from military power armor to industrial heavy lifting suits. The medical community is interested in this technology to improve the lives of patients who suffer from muscular impairments through rehabilitative and assistive techniques. Virtual Reality and haptic devices are also incorporating exogloves in research for their potential in rehabilitation therapy and video games.

1.2 History



Figure 1.1: G.E. Hardiman (1965-1971) [57]

The history of powered exoskeletons spans several decades with early prototypes emerging in the 1960's and mainly focusing on large limbs such as lower body and upper body exoskeletons. The Hardiman pictured in figure 1.1 was developed by General Electric and it's goal was to be a full body exoskeleton that would allow the user to carry large loads. It wasn't very successful however, with the technology at the time holding it back by being too bulky, heavy, and power hungry. Two simple grasping mechanisms can also be seen at the arm extremities, which can be considered a very early hand exoskeleton.

Exogloves weren't researched nearly as much as other body parts until the last decade or two. This is mainly due to the complexity and intricate nature of

the hand and fingers which makes it more difficult to design a feasible system. Actuators and other components have traditionally been too large and heavy to easily incorporate around the hand.

1.2.1 Rehabilitative

Depending on the conditions, some patients are able to recover through rehabilitation methods but this traditionally involves a therapist which can be expensive and inconvenient for many patients. The rehabilitation process can be made more accessible with exogloves which is one of the major intended uses for them in the medical community.

1.2.2 Assistive

The other intended use for medical patients is assistive technology which is meant to take the strain off the user as they perform ADLs. This allows patients to live a more normal life in cases where rehabilitation is slow or not effective.

1.2.3 Virtual Reality and Haptic Gloves

Various types of exogloves are being developed to interface with virtual reality systems. The intentions for these can range from rehabilitative to entertainment purposes such as VR gaming. Exogloves can be used as a means for input, allowing users to actually use their hands and fingers to interact with virtual worlds. Haptic gloves which give the user feedback or resistance for a high level of interactivity and immersion are also being developed.

1.3 Anatomy of the Hand

The anatomy of the hand is unique in that it is probably the most intricate combination of bones, joints, muscles and tendons in the human body. The hands are our main method of interacting with physical objects and allow us to do very complex and dexterous movements which are required for many tools and items. Recreating these dexterous movements in an exoglove is a very challenging task and something that has yet to be accomplished.

1.3.1 Bones and Joints

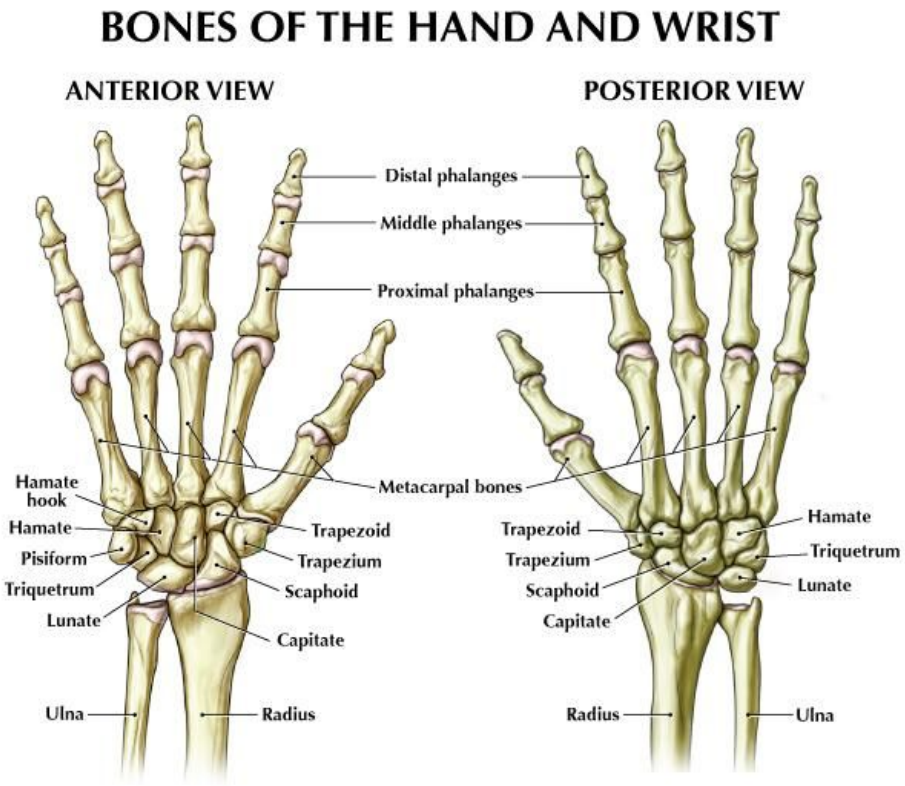


Figure 1.2: The bones of the hand [23]

At the core of every limb are a series of bones connected together at joints. The bones in the palm of the hand are called the metacarpals and are numbered I-V starting from the thumb. The thumb contains two bone segments called phalanges while the fingers contain three of them. Starting from the knuckle they are named the proximal phalanx, intermediate phalanx, and distal phalanx. The joints between these bones starting with the knuckle joint are named the metacarpophalangeal joint (MCP), proximal interphalangeal (PIP), and distal interphalangeal joint (DIP) [12].

1.3.2 Muscles and Tendons

To the surprise of many people, fingers don't actually contain any muscles. The muscles that control the fingers are located in the palm and forearm which are connected to tendons in the fingers. The three types of muscles in the palm are named the volar interosseous, dorsal interosseous, and lumbricals. The interousseous muscles are responsible for the adduction and abduction movements in the fingers while the lumbricals help move the metacarpals which aid in gripping [12]. The lumbricals are a unique muscle because they aren't connected to bone, but rather are connected to tendons in a complex net [38].

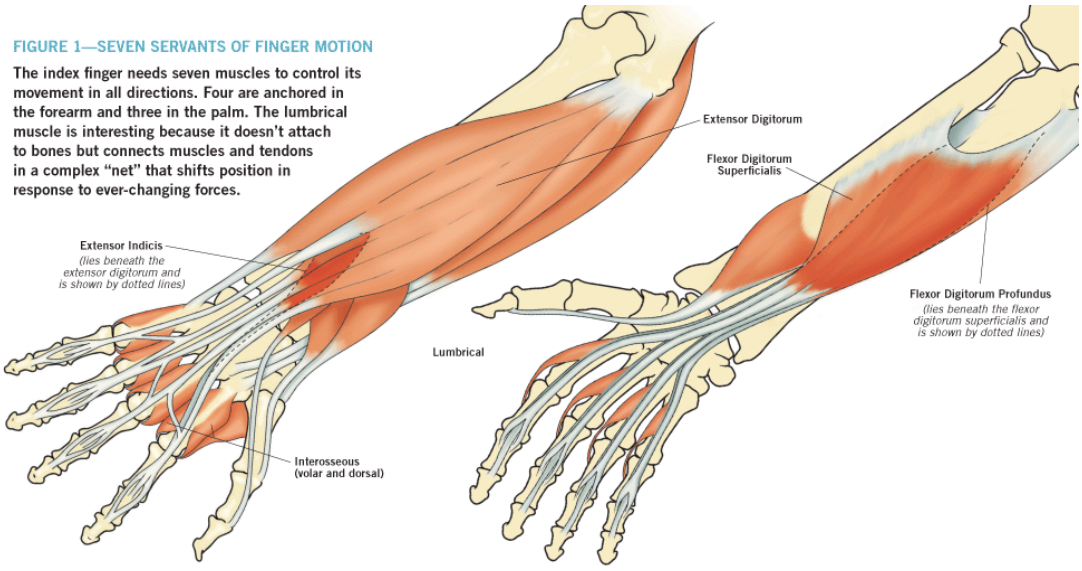


Figure 1.3: The muscles of the hand [74]

The four muscles located in the forearm are named the extensor indicis, extensor digitorum, flexor digitorum superficialis, and flexor digitorum profundus. As their name implies, they are used to control the flexor and extensor motions of the fingers. These are connected to tendons near the knuckle and these tendons are connected on the other end to bone in the fingers. There is a direct relationship between the flexor and extensor tendons and the joint angles of the finger which were found in the Landsmeer models [12].

1.3.3 Special Considerations in Exoglove Mechanics Design

There are a large number of complications to consider when designing a dexterous exoglove that will perform similar to a healthy hand. This is because the mechanics of the human hand are incredibly complex and there are many factors that come into play that aren't obvious. Becoming familiar with these can lead to better insight in designing an exoglove and gives the reader an appreciation for

how robust and versatile our hands really are.

When looking at the mechanics of the hand at the whole, it can be seen that the fingers aren't completely independent, but are actually restricted due to coupling with other fingers. For example, the ring and pinky finger have a coupling that places some restrictions on their individual movements, but work well together in accomplishing certain tasks [37]. The dexterity of each finger is important for people such as musicians who would prefer to not have these restrictions. Research into force optimization techniques with pianists and the restrictions of each finger with guitarists have been done to give insight on how these mechanics problems might be solved.

Biologically inspired mechanics in robotics systems have had an increase in research because nature has already created optimized mechanics in our bodies. However, it becomes increasingly difficult to model these natural systems as we learn more about them. For example, tendon excursions are when the tendons take different paths to accomplish the same movement. This results in non-linear behavior which makes the system very difficult to model [3]. There's also a distinction between intrinsic and extrinsic muscles and both are equally important for such things as balancing a force on the finger tip, which certainly would be a difficult controls problem in a dexterous exoglove [69].

Another important aspect to consider is what the skin material is made of and how it interacts with grasped objects. For example, the elasticity of the human flesh and skin gives certain qualities when grabbing various objects that would need to replicated for the exoglove to feel natural. This means that the deformation of the finger would need to be replicated as well [68]. Also the friction of such material would also need to be similar to human skin for true dexterity [36].

1.4 Soft Exoskeletons

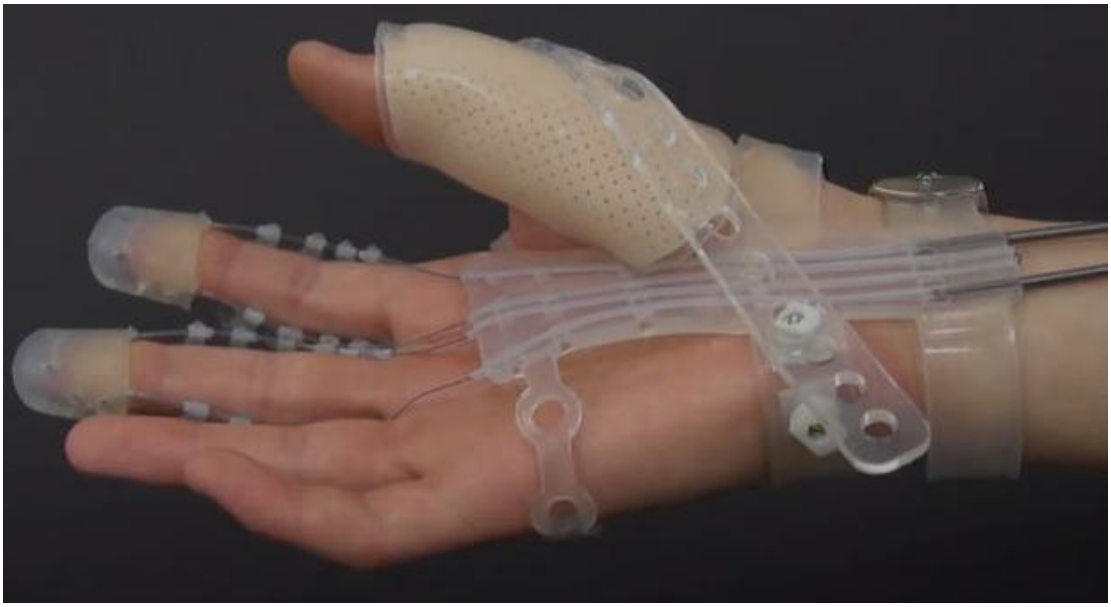


Figure 1.4: Example of a soft exoglove [1]

Soft-tendon driven robotic gloves are one of the most commonly developed types of hand exoskeletons because of their simplicity, adaptability, and similarity to how real muscles and tendons function [55], [29]. These characteristics make them a well suited choice for both rehabilitation purposes and assistive devices where the intention isn't to amplify the user's strength beyond what is required to perform ADLs. Artificial tendons can be made from a variety of different types of cables depending on their specific function and can be used in soft glove type exoskeletons or rigid ones such as hybrid designs with bar link mechanisms [13, 40, 25, 20, 11].

A common feature found in many of the soft glove type exoskeletons is an external actuating unit where Bowden cables extend from and connect to the actuating tendons on the hand. These units typically contain linear actuators or rotary motors and can vary in size depending how many degrees of freedom

(DOF) the exoskeleton can actuate. These external actuating units typically are placed on a table in a lab setting but more recently they are commonly made as backpacks or belt clips to allow for portability [29, 83, 55].

1.5 Rigid Exoskeletons

Hand exoskeletons that are primarily rigid in their structure or use a rigid actuation delivery method are typically considered rigid exoskeletons. The benefits of going this route over soft technologies are sparse. The most compelling reason to choose rigid structures is the massive increase in force that can be exerted in such a system. For example, such a system would allow for powerful pneumatics actuators to be used, giving unrivaled force output. The amount of force exerted from these would be more likely to cause injury to a patient in a soft system when compared to a rigid system.

The high force output also makes these rigid systems ideal for assistive technologies, but because of their large size and weight, many of them are confined to an indoor setting and as a result can be found in rehabilitative technologies as well. Overall, there has been a large shift in interest away from rigid system and more towards soft technologies because of their numerous benefits.

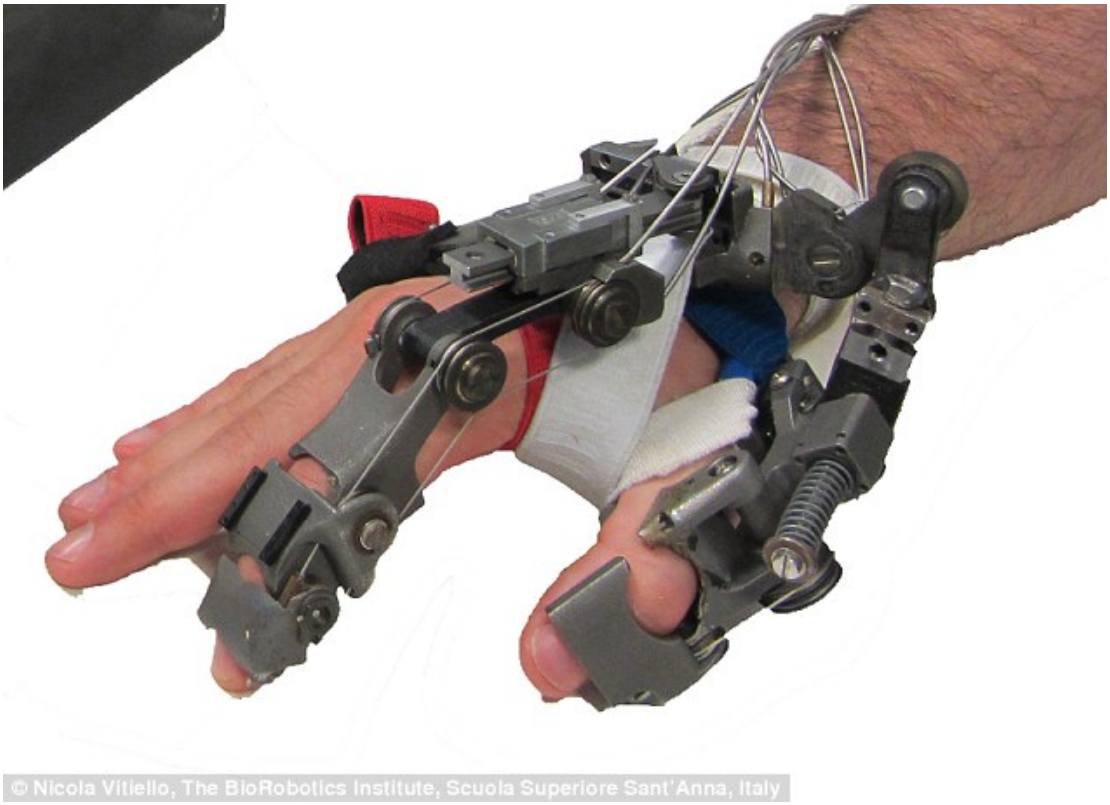


Figure 1.5: Example of a rigid exoglove [49]

1.6 Types of Actuators

Actuators are what generate the force in powered exogloves and create movement. The common types of actuators found in exogloves are rotary, linear, pneumatic, and passive designs. The decision of which type of actuator to use is based on system goals and personal preference. Different types of actuators can vary greatly in how they function, size, weight, and other distinct qualities.

1.6.1 Rotary Actuators

Rotary actuators are a very common type and come in different varieties such as DC and stepper motors. Rotary actuators are typically only found in con-

junction with artificial tendon based system. They allow for large range without requiring extra space and can be extremely fast depending on gear ratios, however, exoglove systems require varying degrees of slack and has led to research in novel solutions to compensate this [28].

1.6.2 Linear Actuators

Linear actuators are also a very popular choice for exogloves. They're found in both external actuation units or directly mounted on the hand itself. Linear actuators allow for a simple actuation system that directly connects to the actuation structure but are limited in range by their stroke length. They're also typically electrically powered like rotary motors for these applications.

1.6.3 Pneumatic Actuators

Pneumatics are a type of actuation that relies on air pressure create the exerted force. Pneumatics aren't seen as commonly in exogloves as other types such as upper body and lower body exoskeletons. The main reason for this is because pneumatics are typically very large and heavy and would be counterintuitive to place on a limb extremity. However, pneumatics can exert an extreme amount of force which makes them better suited for leg assisted exoskeletons where a larger force is desired to support the weight of a person.

1.6.4 Other

There are a few other actuation technologies that have had minimal research in conjunction with an exoglove. One example is shape memory alloys and polymers. These materials are typically activated with a voltage, heat, or some other method of excitation. When this excitation occurs, the material will exert a force and will

return to it's former state when the excitation ends. Although some promising applications for this technology are being developed, there are some challenges that still need to be addressed. These limitations include relatively small usable strain, low actuation frequency, low controllability, low accuracy and low energy efficiency.

1.7 Types of Force Delivery Methods

The method of how a force is delivered from the actuator to the system is also of great importance when considering different designs of exoskeletons. Some methods of force delivery can be implied by the type of actuator used, such as linear actuators in conjunction with cables or bar links. Soft exoskeletons tend to use cable driven actuation while rigid exoskeletons typically incorporate link mechanisms, gears, or direct actuation. It's also somewhat common to see a combination of actuation delivery methods working together in a single system.

1.7.1 Cables

Cables are a common method of delivering actuation force to the system. Because of the considerable weight of actuators and batteries to power them, there has been a shifted focus to using an external actuation box that may be worn as a backpack. Cables are routed from the backpack to the intended point of actuation, in this case, the hand. This presents many difficulties because of the long distance the cables must take when routed down the arm. The alternative to this is to place the actuators on the forearm while cables are lined along the fingers to produce flexor and extensor motions. While this is a fairly simple and effective method, the added weight from the actuators on the forearm presents

obvious problems.

1.7.2 Link Mechanisms

Bar linkage mechanisms are another fairly common choice as an actuation delivery method [39, 30, 76, 52]. Unlike soft glove types, exoskeletons based on links are inherently rigid which is a desirable quality in devices that deliver a large amount of force. Drawbacks to link based designs include weight, bulkiness, and complexity, however some link designs have alleviated these qualities through clever mechanics. Link based exoskeletons may also vary vastly in design and actuation units powering it, with most systems containing either a rotary motors, electric linear actuators, or pneumatic actuators.

1.7.3 Gears

Gears aren't seen very commonly in exoglove designs because of several limitations. Most of the designs that include gears in the actuation delivery structure are hybrid designs that also contain artificial tendons and/or bar link mechanisms. This should not be confused with systems that use gears in their actuation units to adjust torque before delivering the force to the structure. Rather, in this context, the gears are used in the actuation structure itself, for example in a joint. Gears typically make designs much bulkier and in general have been abandoned except in novel cases that have a hybrid design [85].

1.7.4 Direct

Direct actuation methods are extremely limited when it comes to feasible systems for assistive and rehabilitative purposes. The designs that use direct actuation are meant for collecting data or for VR purposes.

1.8 Sensors

Sensors are a crucial aspect in exogloves because of their various roles in a system. They may act as direct inputs or feedback sensors in a controls system to actuate the exoglove or measure various parameters to give quantitative data for analysis. The most common types of sensors found in exogloves are EMG, force, position, angle, and others in special cases. The selection of which sensors to use depends on what the specific application is.

1.8.1 EMG

Electromyography (EMG) sensors can be found in a moderate amount of exogloves as a primary input in controlling the actuation of the system [51, 34, 77, 26, 43, 55, 39, 5, 70]. EMG sensors measure and amplify the electrical activity in skeletal muscles where higher voltages correspond to increased muscular activity. The direct measurement of muscle activity is an extremely useful tool when trying to control a powered exoglove but unfortunately there are many problems associated with EMGs. In order to get the most accurate readings, invasive techniques need to be used which are too extreme in most cases for this application.

More typically, electrodes are placed on the skin over the muscles that need to be measured. Because of the flesh in-between the electrode and the muscle, EMG signals are typically noisy and need to be filtered to get usable data. In addition to this, muscles are composed of many smaller strands of muscle fibers, each of which can have different levels of electrical activity. As a result, the exact placement of the electrodes is crucial and needs to be reproduced exactly in sequential trials to get comparable results. However, there is still promising research that EMG signals can be used reliably for certain aspects in a control system.

1.8.2 Force

Force sensors or strain gauges are a very common source of input for exogloves. These sensor have a resistance that varies with applied force. They convert force, pressure, tension, weight, etc into varying electrical resistance which can then be measured. These types of sensors may be used as a means to detect if the user is intending to move a certain direction. Another common use for them is to detect if a mechanical system has reached its mechanical limits of motion. Force sensors are usually seen in conjunction with other sensors for a complete array of inputs for the system.

1.8.3 Position and Angle

Two other types of sensors that are commonly found in exogloves are positions sensors and angle sensors. There are many different methods to measure these values and other data including force, such as calculating the current in the actuator or by taking advantage of the Hall effect. However, more direct methods to measure these values are preferred for precision such as infrared sensors to determine distance. This is just one example of different types of sensors to acquire the same types of data. Angles and distance may also be calculated indirectly from the kinematic model if enough variables are known.

1.8.4 Implementation in an Exoglove

The most common uses of sensors in exoglove type systems are as direct inputs or feedback inputs to a controls system. They may also be used to collect performance data for analysis. An example is if a patient is using a rehabilitative exoglove that has limited actuation force, the use of strain gauges may provide useful data of rehabilitative progress and muscle growth. Similarly, EMG sen-

sors may be give useful data of the patient's muscle activity for analysis of their performance.

If the goal is to create a robust controls system then a combination of different sensors working in conjunction with each other is typically necessary to operate an exoglove. This allows for more precise and responsive controls which are especially important when dealing with fingers because of their highly dexterous nature. However, because there is limited space on the hand and complexity, some exogloves neglect advanced sensors and controls in favor of focusing on researching new and novel mechanical designs first.

A few things must be taken into consideration when designing such a controls system. The primary input to the controls is typically the wearer of the exoglove. Sensors may act as a bridge from the user to the system, allowing the user to directly influence the actuation of the system. An example is using EMG sensors to detect the intention to begin a movement from the muscles directly. Another example is to use force sensors placed inside the glove that will trigger if the users finger presses against it. It's possible to use both as detection methods for more accurate results.

These sensors are typically read as a voltage into a microcontroller where a feedback loop may be implemented. The described sensors are meant to sense the user and would typically be the input to the feedback loop. The exoglove itself is the system that the feedback loop regulates. Other types of sensors to sense aspects of the system itself may be used as well. These proprioceptive sensors may include angle, current sensors, or others and these could be used for such things as to detect if a mechanical limit has been reached or to simply detect velocity. These feedback sensors not only can ensure smooth functionality of the exoglove but may also provide safety measures against joints being hyperflexed and other

injuries.

Exteroceptive sensors are also typically a requirement if the goal is a fully functional exoglove. These feedback sensors allow the system to detect events with the outside world. An example with an exoglove might be pressure senors on the finger of the glove that detect when the user has successfully grabbed a ball. These types of sensors are also important because they allow the system to automatically correct itself if unforeseen outside stimuli occur.

The basic steps an exoglvoe controls system might take could be described as follows. First the user starts moving all their fingers in a grasping motion. The EMG signals detect muscle activity in the forearm and force sensors along the inside lining of the glove's fingertips detect the fingers pressing down. This leads to the input to the controller to change and the system begins to actuate to compensate for this change. This continues to happen until the system settles which entirely depends on the specific implementation and action being performed. Sensors such as angle or current sensors could be placed along the feedback loop whose job are to self regulate the system. Finally a pressure sensor may also be placed on the feedback loop whose job is to detect when the ball has been fully grasped. The user will sense this with their own nervous system and stop grasping while the system will also determine this as well thanks to the exteroceptive sensor.

Chapter 2

Motivations

The extensive literature review that was done for this paper has also provided better insight into the design choices of those existing exogloves. The knowledge gained from these papers helped guide the experiments performed for this paper. One of the observations made is that many of the papers explained the creation and performance of an exoglove, but failed to give preliminary experimental data to motivate the design choices of the exogloves. Although engineering is an art in many ways, design choices should also be rooted in sound mathematical and scientific reasoning.

2.1 Fundamentals of Exoskeleton Design

The end result of this paper gives a mathematical and scientific basis of the beginning stages of designing an exoglove. The strategies presented here may also be applied to the design of any type of exoskeleton, such as lower body or upper extremity exoskeletons. Some of the more successful papers in the literature review contained sections explaining their design choices. These helped motivate some of the experiments presented here while other experiments are original ideas

of this paper.

The successful design of anything in engineering requires the system to be built from the ground up. If any individual piece isn't working properly then the entire system as a whole won't function correctly. This is why basic data collection is a requirement before starting a successful design. This paper explains the process of collecting and analysis of some of these basic sets of data.

2.2 Kinematics

One of the fundamental aspects of the function of an exoglove is that it should replicate the natural motion of the human hand. A solid understanding of the kinematics of an individual finger is the first step in designing an exoglove. Understanding the motions of a healthy human hand doing ADLs may begin with understanding the ubiquitous curling motion of the index finger. The purpose of these experiments with the OptiTrack is to collect motion tracking data of the hand so that a model of the hand can be created and the kinematics can be analyzed. Simulations running the recorded actions are also desired from this data. Once this is done, it may be extended to the other fingers. This also allows for the next natural step in understanding the motions of the hand, the dynamics of the hand.

2.3 EMG

The purpose of incorporating EMG sensors into the experiment is to gain a better understanding of the neural and muscle activity during the sessions with the OptiTrack motion capturing system. Although EMGs are limited in what we can ascertain from them, they may still be helpful. Because of noise and other

factors, it's nearly impossible to determine the magnitude of the muscle activity accurately. However, if the gain is increased to saturate the signal, it still may be useful to determine the activation of muscles or frequency of motion. By finding a correlation between the muscle activity data and the kinematics data that result from them, it's possible to use this as a basis for a controls system.

2.4 ExoGlove

The ultimate goal of this paper is to influence the design of an Exoglove specifically, however, any type of exoskeleton may find the techniques in this paper useful. The extensive literature review of the field has made it evident that research on a true dexterous exoglove is nearly nonexistent and certainly not developed enough to begin clinical studies. Such a device as a dexterous exoglove would certainly need a strong scientific foundation to be successful. This paper aims to provide the fundamental steps in accomplishing a dexterous exoglove.

Chapter 3

Experimental Setup

The first step in accomplishing such an endeavor is to understand the motions of a healthy human hand doing ADLs. The most basic gesture found in many ADLs is curling the finger. To understand the motions better, they were recorded using an OptiTrack motion capture system. EMG sensors were also incorporated in these experiments to gain a better understanding of how these movements are controlled. Both of these dataset types were then imported to MATLAB where various simulations and analysis were performed.

3.1 OptiTrack Motion Capture

The data was recorded inside our lab's CAVE virtual reality environment room where OptiTrack Prime 13W motion capture cameras are mounted. There is an array of eight of these cameras arranged in square shape and mounted near the ceiling. The software used for recording the optical motion tracking data is OptiTrack's Motive software.

A simple curling motion of the index finger was chosen as a starting point because of how ubiquitous it is in hand gestures. Succeeding experiments include

abduction and adduction motions in order to study dexterous movements of the index finger. The types of motions and gestures that are being researched are intended to be applied to a hand exoskeleton. These motions consist of everyday movements to assist in ADL and therefore don't contain extremely fast motions. The OptiTrack has a sampling rate of 120 Hz which is more than adequate enough for these basic hand gestures.

An iterative design process was chosen in order to simplify the process at first. This means that only a single finger was captured first before moving on to a complete hand model. With this in mind, different designs to record motion tracking data of a single finger were considered. The final design of the experiment is displayed in figure 3.1.

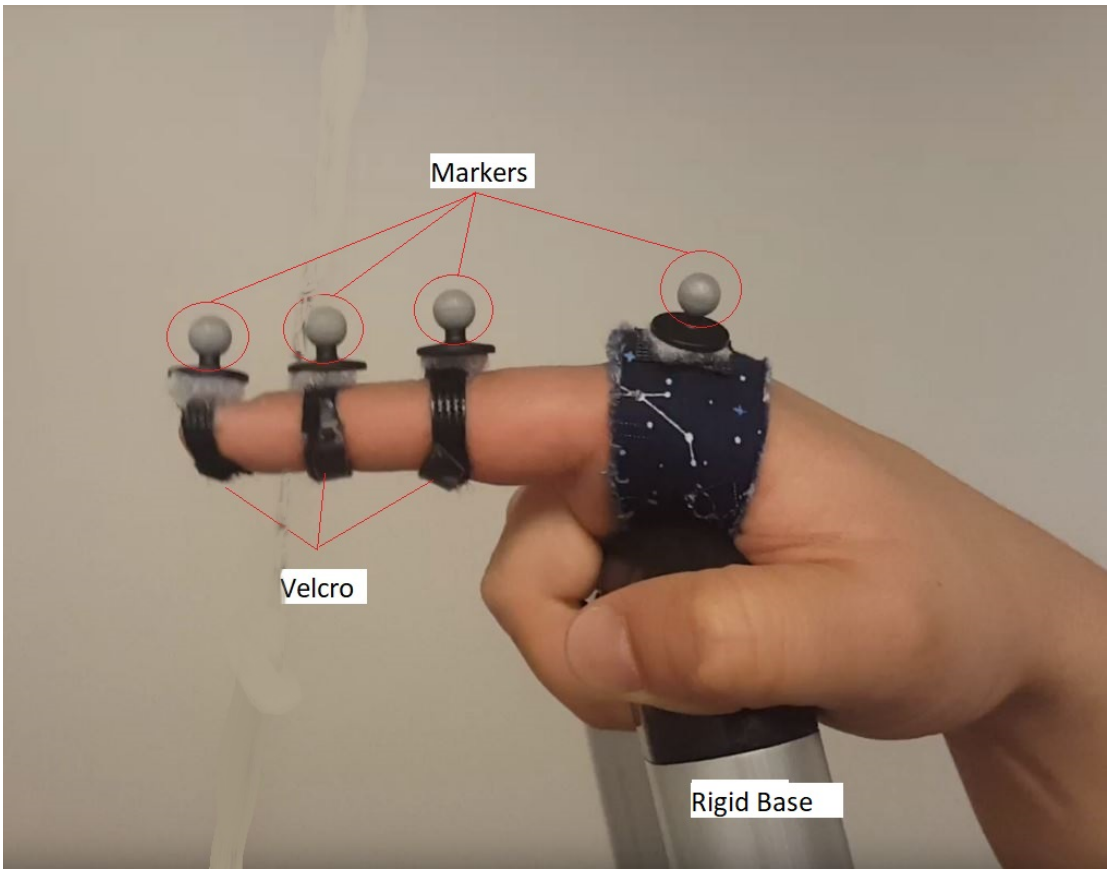


Figure 3.1: Photo of experiment setup

Because of the limited space available on the finger and the size of each motion tracking marker, it was decided that the best solution is to record with the minimum number of required markers. The OptiTrack system records the XYZ coordinate position of each marker, so in order to get the angles at each joint of the finger, one marker per joint is required at minimum. The average error of the combined cameras is less than 0.100 of a millimeter.

To attach the markers to the finger, thin strips of velcro were cut so that they can be wrapped near each knuckle of the finger and one for the tip of the finger. Velcro is also useful for testing on multiple people where the snugness can easily be adjusted for different sized fingers. The MCP joint marker was attached with a combination of fabric and velcro.

A ladder was placed near the origin of the coordinates of the ground plane of the OptiTrack system. The experiment was conducted with the hand being placed on the ladder. The rest of the fingers that weren't being motion captured gripped this ladder firmly to ensure the base marker (MCP) gave a consistent origin. The MCP joint marker is treated as the reference point for the other markers, so it is essential that the hand is resting on a stable structure where movement of the entire system won't occur so that accurate results can be obtained. Another reason why a ladder was chosen is because the cameras are mounted at the top of the walls, roughly 8 feet above the ground. This causes a tendency for markers to be lost if they're too low to the ground or being covered by another part of the body.

Several runs were recorded and analyzed during this first session. Successive sessions added more complexity to the experiment. The motions of the finger became more dynamic and included adduction and abduction movements and EMG sensors were also incorporated during following sessions.

3.2 EMG Sensors

EMG sensors are used to obtain muscle activity that is measured as a voltage. The sensor comprises of electrodes that are placed onto the skin and a circuit that amplifies and filters the signal. Various trials were undertaken where EMG signals were measured in multiple parts of the arm while simultaneously recording motions of the index finger with the OptiTrack cameras.

3.2.1 Circuit

A schematic of the EMG sensor used can be seen in figure 3.2. The circuit contains amplifiers and filters of typical values found in EMG sensors. A low pass filter with a corner frequency of 48 Hz is used to filter out interference. We also don't expect high frequency activity from the muscles themselves since the motion captured is relatively slow. The gain was adjusted so that the output was just barely clipped by 0.1 - 0.2 volts. This was done to obtain a better signal to noise ratio (SNR) since noise is one of the most common problems with EMG sensing [7].

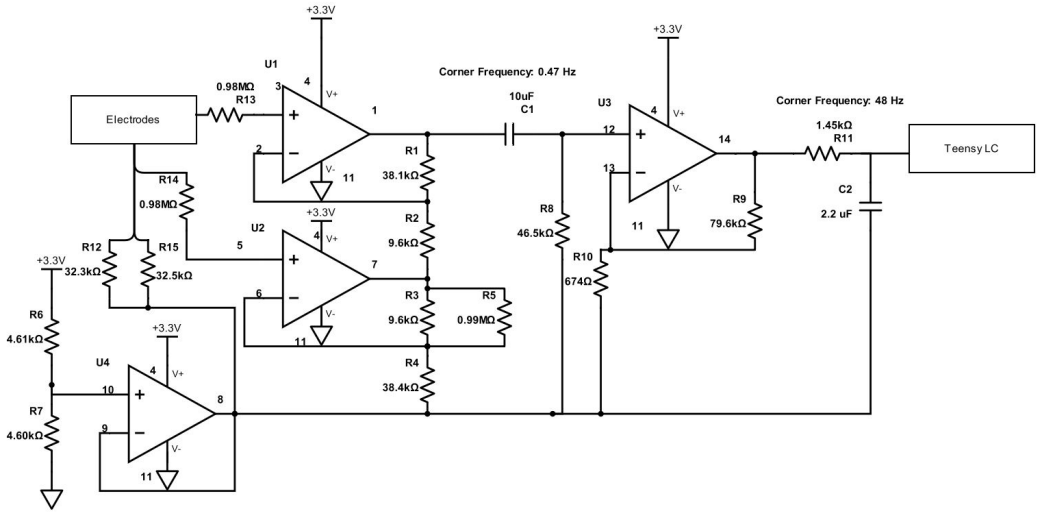


Figure 3.2: Schematic of the EMG sensor circuit used to obtain results

Two of these circuits were built on a breadboard in order to obtain results from multiple locations simultaneously. The output of these circuits were connected to a TeensyLC micro-controller in order to obtain the data. The micro-controller was connected to a laptop via a serial connection over USB to record and save these results.

3.2.2 Electrodes

The electrodes chosen for the experiment were of the disposable variety and their dimensions were 2" x 2.25". These were determined to be too large for the muscles that we are interested in monitoring. These muscles include the extensor indicis, extensor digitorum, flexor digitorum superficialis, and flexor digitorum profundus. The disposable electrodes were cut down to a smaller size for precision and were attached to the EMG circuit by alligator clips and wire. The location of were the electrodes were to be placed were determined by studying the anatomy of the hand and forearm. It was decided that monitoring these muscles in both

the forearm and hand simultaneously would give more complete results.

3.2.3 Trials

The first two runs with the EMG sensors had both of the electrodes placed on the top of the hand and forearm which can be seen in figure 3.3. After studying the anatomy of the hand and arm, tactile tests were done to determine the best place for the electrode. This was done by moving the index finger while using the other hand to determine where there was the most muscle activity. EMG probe 1 was placed specifically to detect the extensor digitorum muscle. EMG probe 2 was positioned based on two reasons. The first reason is because the tendon connecting the muscles to the finger runs in the place. The second reason is because that vicinity is also near the muscles that control adduction and abduction movements.

The last run with the EMG sensors had a slightly different arrangement which can be seen in figure 3.4. EMG probe 1 was changed from the top of the forearm to the bottom, where the flexor digitorum superficialis and flexor digitorum profundus muscles are located which are responsible for the finger flexor actions. EMG probe 2 was left in the same place to continue to monitor potential adduction and abduction signals.

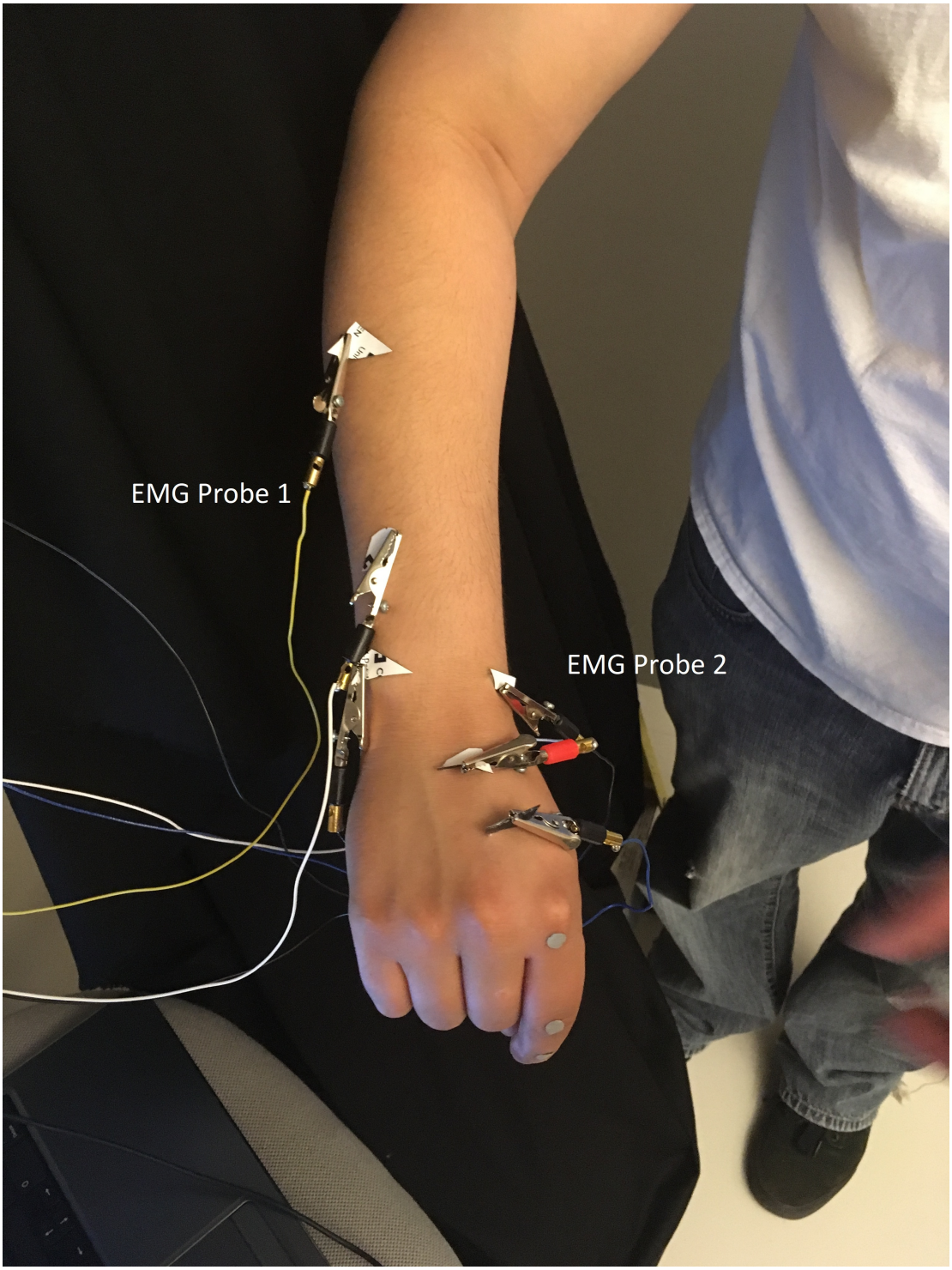


Figure 3.3: Photo of EMG sensor experiment with probes on top of the forearm

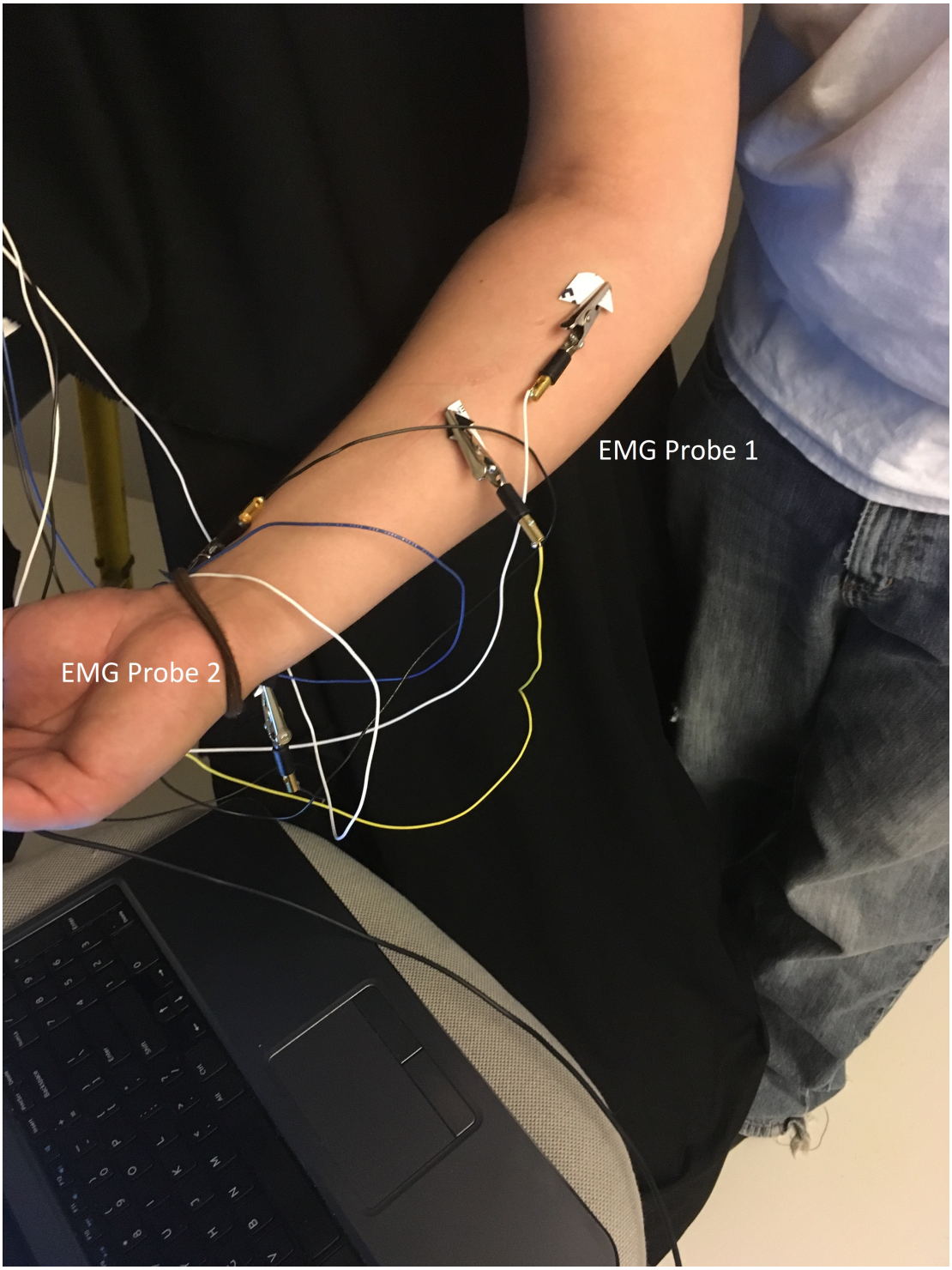


Figure 3.4: Photo of EMG sensor experiment with the forearm probe placed on the bottom of the forearm

The markers which were used for the motion capturing aspect of the EMG experiments were changed from previous trials. The previous markers were obtrusive and potentially caused slight positional errors because they were raised above the finger by a few centimeters as can be seen in figure 3.1. The solution to this was to use reflective tape specifically designed for motion capture applications. This approach remedied the mentioned problems but also worsened another aspect of the experiment.

The cameras had a harder time keeping track of the new markers because they're flat and lack volume. This wouldn't normally be an issue, but it arose in this situation because of how the OptiTrack cameras were mounted. The cameras were placed in a square orientation about 8 feet above the floor and were angled down to observe the staged area. When the finger performs a flexor motion, the cameras had a tendency to lose track of the markers on the extremity of the finger because the rest of the hand covered the marker. The issue was also present when using the spherical markers but was worse when using the flat markers.

This is why a ladder was used in trials where no EMG sensors were used; performing the experiment at a taller position allowed the cameras to always see the markers. However, because of the constraints of having electrodes attached to the skin which were then connected to a breadboard circuit and finally to a laptop, it wasn't feasible to use a ladder. When a camera loses position of a marker, the Motive software automatically creates a new marker when it comes back into view. After reviewing the results, it was found that the data from the new markers created could be formatted back into the original markers, essentially making this issue irrelevant. However, extra time was required in order to format the data correctly.

3.3 Kinematics Equations

The first step in designing a simulation to analyze this data is creating a free body diagram along with the corresponding kinematic equations. The majority of the motion capture experiments involved only the index finger so the free body diagram was created to express this. Figure 3.5 shows the free body diagram followed by equations of motion of the link system with rotation and translation matrices. This is the basis of the equations that were programmed into MATLAB for the simulation.

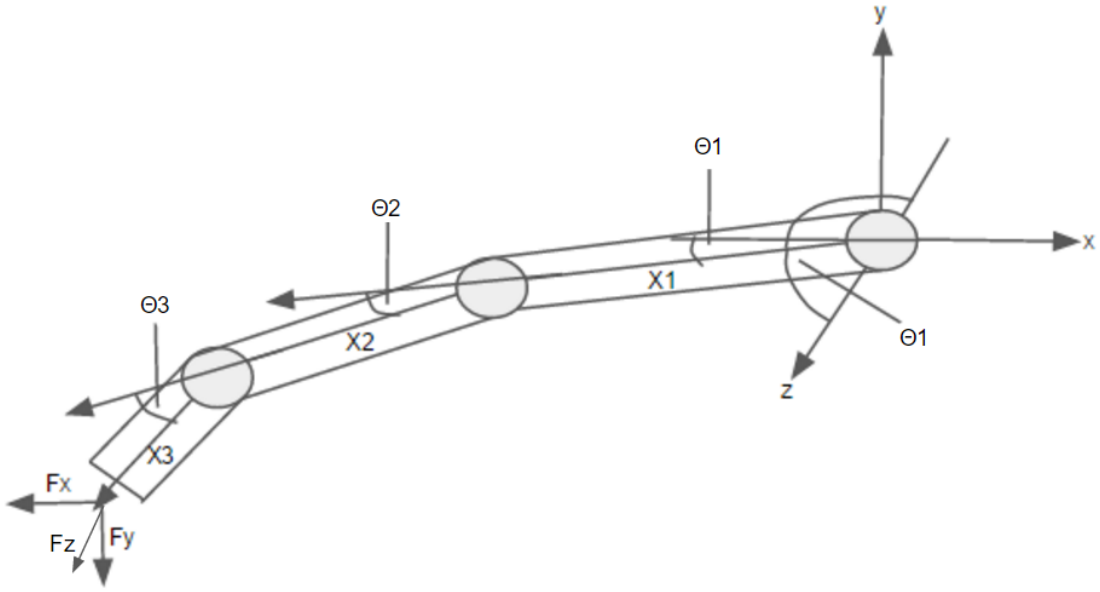


Figure 3.5: Free Body Diagram of Index Finger

$$ {}^{0}_{4}T = {}^{0}_{1}T\,{}^{1}_{2}T\,{}^{2}_{3}T\,{}^{3}_{4}T $$

${}^{0}_{1}T$: MCP Lateral Rotation Matrix ($\theta 1$)

${}^{1}_{2}T$: MCP Rotation/Translation Matrix ($\theta 1$/X1)

${}^{2}_{3}T$: PIP Rotation/Translation Matrix ($\theta 2$/X2)

${}^{3}_{4}T$: DIP Rotation/Translation Matrix ($\theta 3$/X3)

The joint angles are expressed by the following equation:

$$\cos\theta = \frac{\vec{u} \bullet \vec{v}}{\|\mathbf{u}\| \bullet \|\mathbf{v}\|}$$

3.4 MATLAB

3.4.1 Robotics Toolbox

With these tools at hand, a MATLAB simulation can be created using the Robotics Toolbox created by Peter Corke. Before integrating motion capture and EMG data, the simulation was hard coded with various gestures to gain a good understanding of how the toolbox functions. The basis of this toolbox lies within the two objects **Link** and **SerialLink**. A Link object holds all information related to a robot link such as kinematics parameters, rigid-body inertial parameters, motor and transmission parameters, some of these features which may be implemented in future work.

SerialLink is a concrete class that represents a serial-link arm-type robot. The mechanism is described using Denavit-Hartenberg parameters, one set per joint. A screen shot of setting up the initial index finger in the toolbox is pictured

in figure 3.6 where the first joint gives the lateral angle and the remaining are the curling knuckle joints with the specified length of each joint. The angles were then hard coded and updated in a for loop to produce an animation along with a real-time graph that shows each joint angle.

```
% create the finger links based on DH parameters
%         theta   d     a     alpha
J1 = Link([0      0     0     pi/2 ], 'standard');
J2 = Link([0      0     L1     0   ], 'standard');
J3 = Link([0      0     L2     0   ], 'standard');
J4 = Link([0      0     L3     0   ], 'standard');

% create finger
f = SerialLink([J1 J2 J3 J4], 'name', 'Index Finger');
```

Figure 3.6: Construction of the index finger in the Robotics Toolbox

3.4.2 Simulation

MATLAB supports importing .CSV files which allowed the data to be transfered to arrays. The most efficient way to animate the simulation is to update it with angles for each joint. To get angles from the data, each joint was projected with the calculated length with an angle of zero from the previous joint. This is the reference vector. Then the actual vectors were calculated of each joint from the motion capture data, and used the formula of angle between two vectors to computer the angle to be sent to each joint in the toolbox.

This ran in a continuous for loop that constantly updates the animation and also moves the timer line across the graph. In addition to position coordinates, the .CSV file also had useful columns of data for frame number and time, which made it possible to have a moving graph showing accurate time during the animation.

After the preliminary simulations without EMG were run, incorporating the

EMG data was more straight forward. The goal of analyzing the EMG data in conjunction with the kinematics data is to find patterns between the two which may be used for a controls algorithm incorporating feedback theory and even stochastic theory. To accomplish this it's necessary to first represent the data in the frequency domain. Doing this in MATLAB is as simple as using an FFT function. However, visualizing the data in an appropriate way to obtain meaningful results requires more than a simple FFT. After applying digital filters and narrowing down the peak frequencies between the EMG data set and kinematics data set, meaningful relationships were found between the two.

Chapter 4

Results

The human hand is a very intricate system in many ways, but especially from a biomechanical point of view. Because of this extreme complexity of many different possible motions and gestures, it's important to have a complete theoretical understanding of how it works before the designing phase of an exoskeleton can begin. The purpose of the experiments were to gather data from the most fundamental aspects of the movements and control signals of these hand gestures. With the recorded kinematics and EMG data, analysis of this many lead to better insight into how a controls system may be derived to control human-like fingers. This should lead to better experimental setups in further research that focuses on analysis of the dynamical forces of the human hand.

4.1 Simulation of Single Finger

The first sessions of recording motion began with just a single finger and no EMG sensors. Results were analyzed in levels starting within the OptiTrack Motive software and eventually MATLAB.

4.1.1 OptiTrack

A simple curling motion of the index finger was recorded and analyzed. The complete curling motion begins with the finger fully extended and contains both the flexion and extension motions until the finger comes back to it's original fully extended position. Figure 4.1 shows the results of the motion capture data from the OptiTrack system in snapshots. Each snapshot was taken at 1 second intervals and took about 4 seconds for the full gesture to complete. The first three snapshots show the flexion motion which was done somewhat slowly in comparison to the final snapshot at t=4 which shows the extension motion. The actual recording was longer but the beginning and end were cut out to focus on the actual gesture movement of the finger.

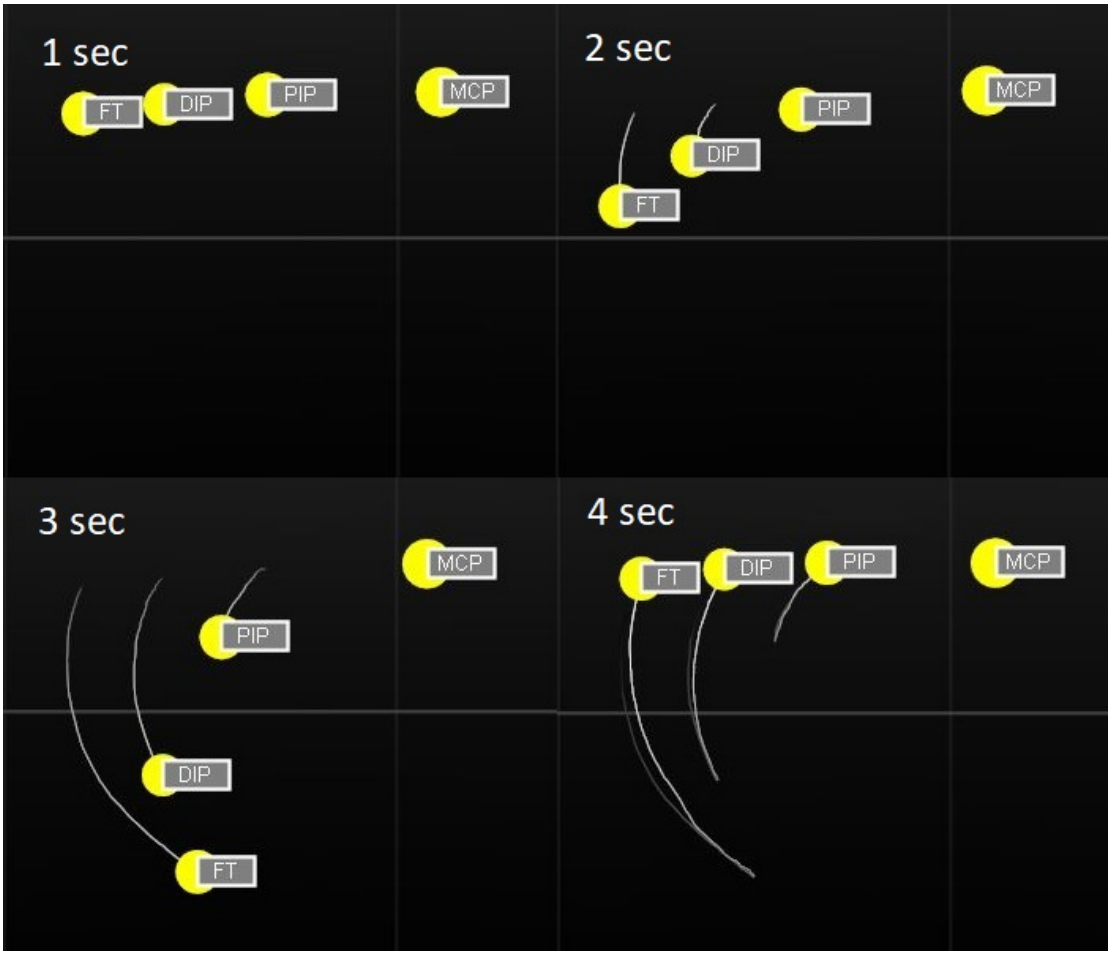


Figure 4.1: Screenshots of finger curl motion recorded in OptiTrack

Each joint of the finger is represented by a marker that is placed as closely as possible to its respective joint. There's an additional non-joint marker that was placed at the finger tip. These joint markers are labeled in figure 4.1 as follows: metacarpophalangeal joint (MCP), proximal interphalangeal joint (PIP), distal interphalangeal joint (DIP), and the finger tip (FT). The white lines are traces of each marker so that the reader may better visualize the motions that are happening in between each snapshot.

4.1.2 MATLAB

The following results in figure 4.2 were produced using MATLAB and the Robotics Toolbox credited to Peter Corke [16]. The snapshots on the left are from video taken from one of the trials during motion capture. The snapshots on the right were taken from the simulation animation from the MATLAB Robotics Toolbox script that was specifically written to give a visual representation of the data. It is based on the free body diagram and equations covered in the previous section. The snapshots of both sides were taken at the same time interval and show that the data is being processed correctly in the simulation.

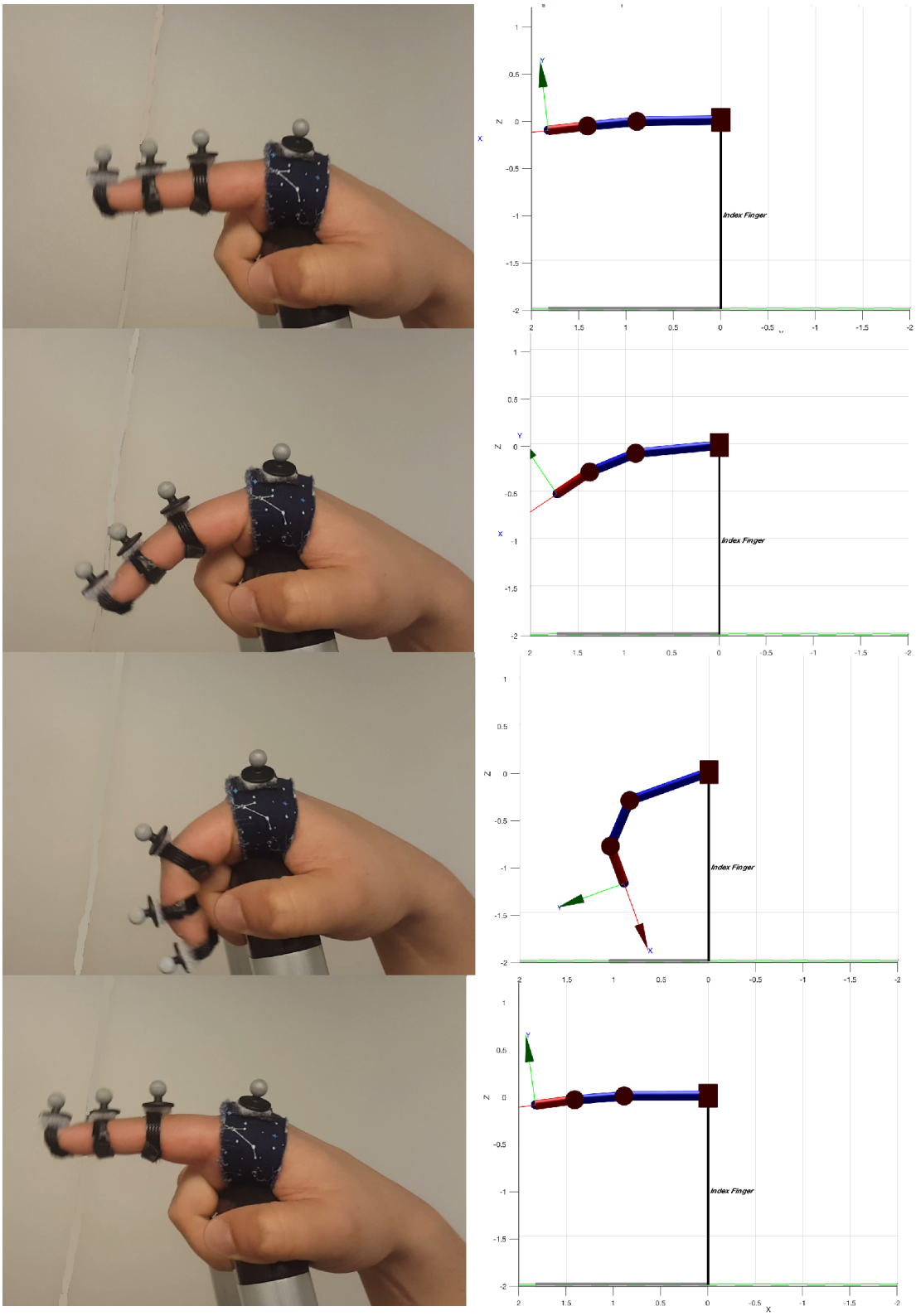


Figure 4.2: Left: Slices from video sequence. Right: MATLAB screenshots and corresponding time in simulation animation

Another reason this was done is so that we can use the power of MATLAB to mathematically manipulate the data to show more useful details of the kinematics. An animation of the index finger displaying the recorded movements along with an animated plot showing the angles of each knuckle of the finger are shown in figure 4.3. The angles are with respect to the parent body in this example rather than with respect to the horizontal. A vertical line sweeps across the knuckle angle plot in real time based on the animations movements so the user may gain better intuition in what angles of the system correspond to a certain movements or position. The recorded trial in this instance highlights the adduction and abduction movements of the index finger followed by the full curling of the finger demonstrating the flexor and extensor motions of the finger.

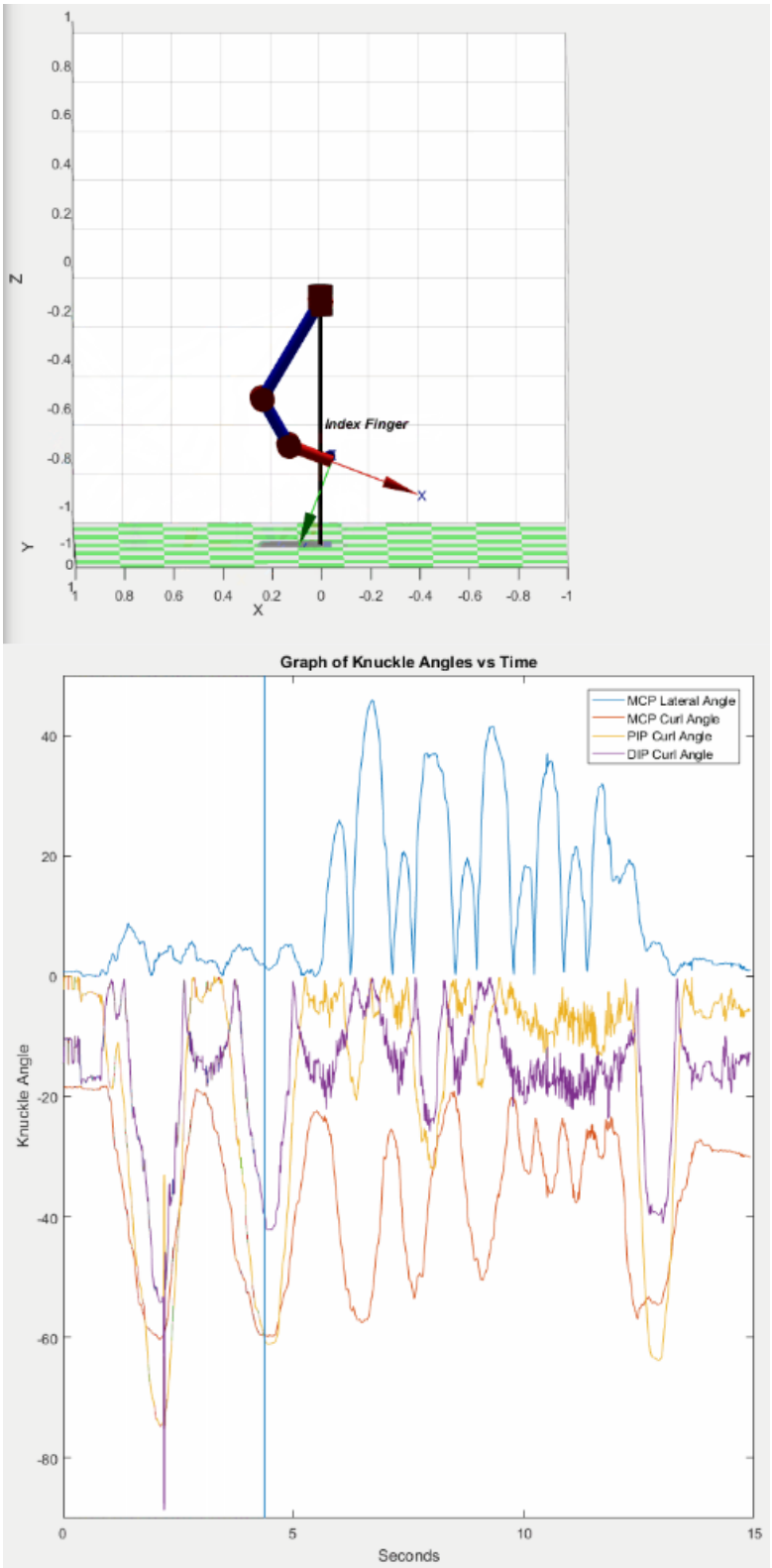


Figure 4.3: Snapshot of simulation corresponding to video snapshot

The blue line of the graph represents the lateral angle of the MCP knuckle from adduction and abductions movements. The orange line represents the curling angle of the MCP knuckle. The yellow and purple lines represent the curling motions of the PIP and DIP knuckle angles respectively. The complete motion of the 15 second recording may be inferred by studying the angles of the plot. The first 5 seconds consist of two curling motions. The following 7 seconds represent the finger doing a circular motion as if drawing a circle with the fingertip repeatedly. The last few seconds represent a final curling motion.

Depending on what the data is being analyzed for or being applied to, it may be necessary to represent the angles in a different fashion. The previous simulation displayed the knuckle angles with respect to the parent body which may be useful for such applications that don't involve an external body to the system. Figure 4.4 demonstrates another trial run with the motion tracking system of just one simple curling motion that is much slower than the previous example. The top graph represents the knuckle angles with respect to the parent body while the bottom graph represents the knuckle angles with respect to the horizontal. We can see large differences in the angles and the shape of the combined graphs.

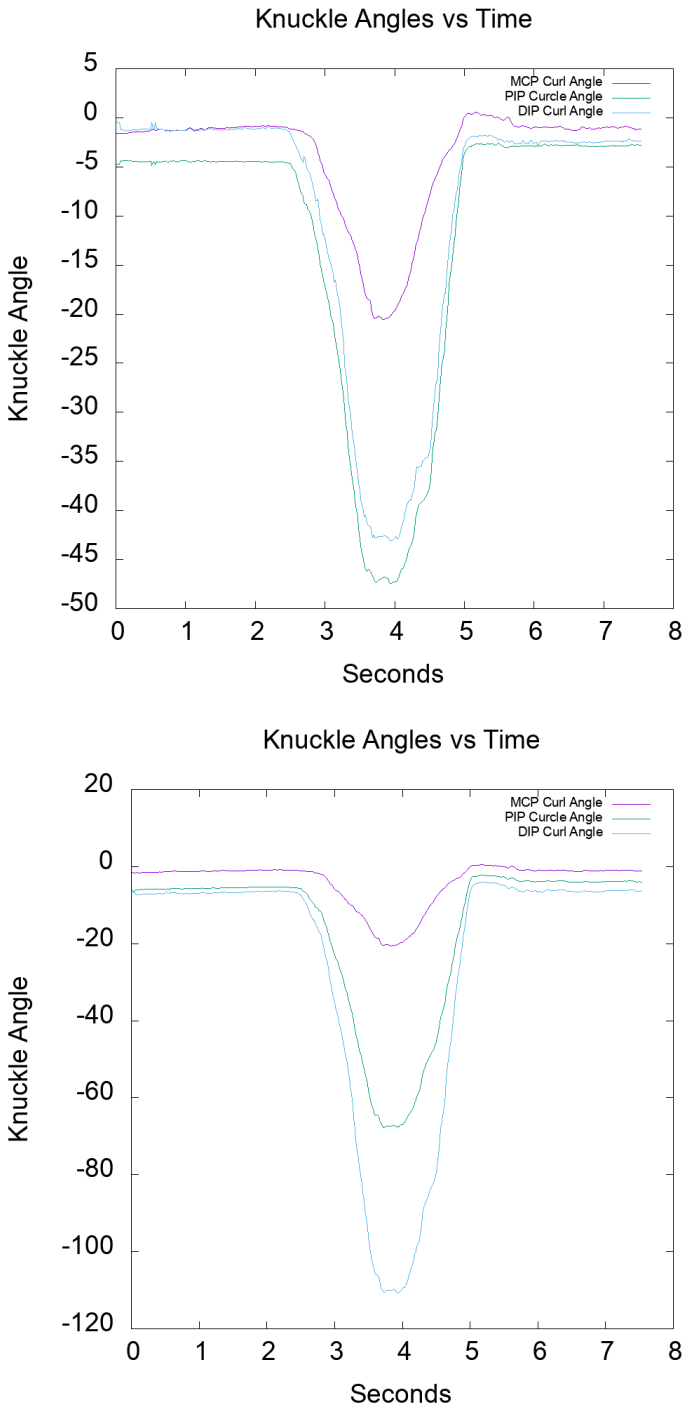


Figure 4.4: Top Graph: Knuckle angles with respect to parent body. Bottom Graph: Knuckle angles with respect to the horizontal

4.2 Simulation of Hand

The natural next step after successfully implementing a simulation of a single finger is to extend the simulation to the entire hand. This can be extremely useful to simulating actual hand gestures that are used in the real world to interact with objects.

4.2.1 MATLAB

The MATLAB simulation of the index finger was extended to include four fingers. The process of doing this was relatively straight forward. All of the fingers are their own SerialLink which are essentially copies of the index finger. No kinematics data of the entire hand was recorded for this simulation which may be considered future work. The motions of this simulation were hard coded to demonstrate the potential usefulness of simulating motions without any motion tracking data. By hard coding certain gestures we can still extract valuable data such knuckle angles and forces of the finger bodies in future work.

Figure 4.5 demonstrates an open hand with all four fingers slightly curled. This was done by hard coding the gesture. The following figures 4.6 and 4.7 display just a single finger curled starting with the index finger, middle finger, ring finger, and finally pink. Each of these simulations used the kinematics data from the runs of the single index finger, so each finger produced the same motion in their own simulations. This was done to show that it could be quite simple to integrate the motion tracking data of all four fingers recorded at once.

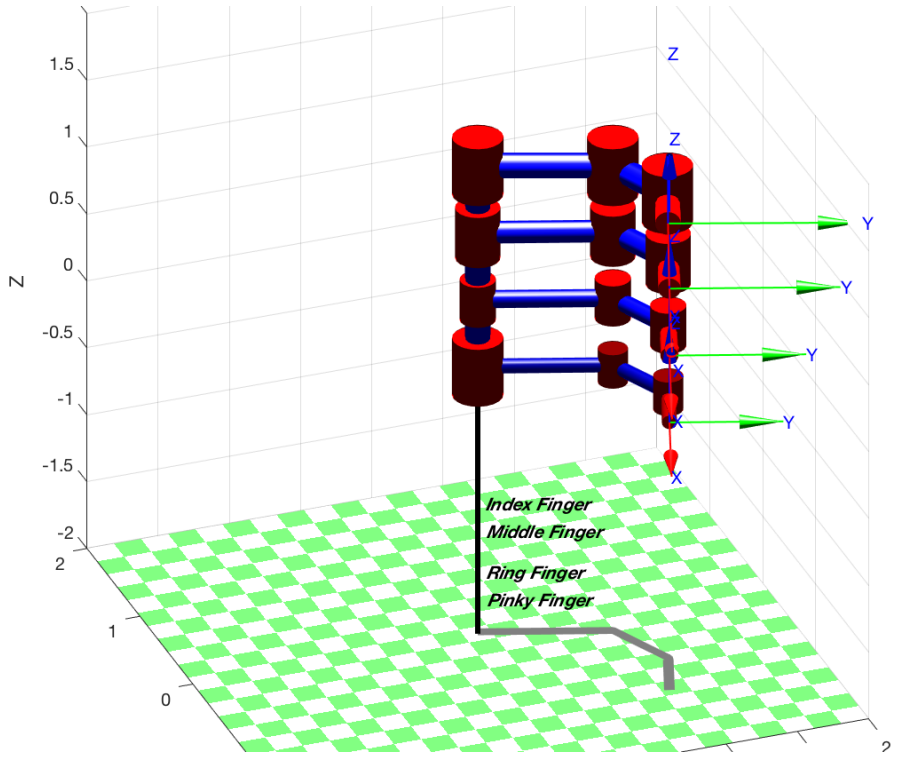


Figure 4.5: MATLAB simulation of hand with four fingers

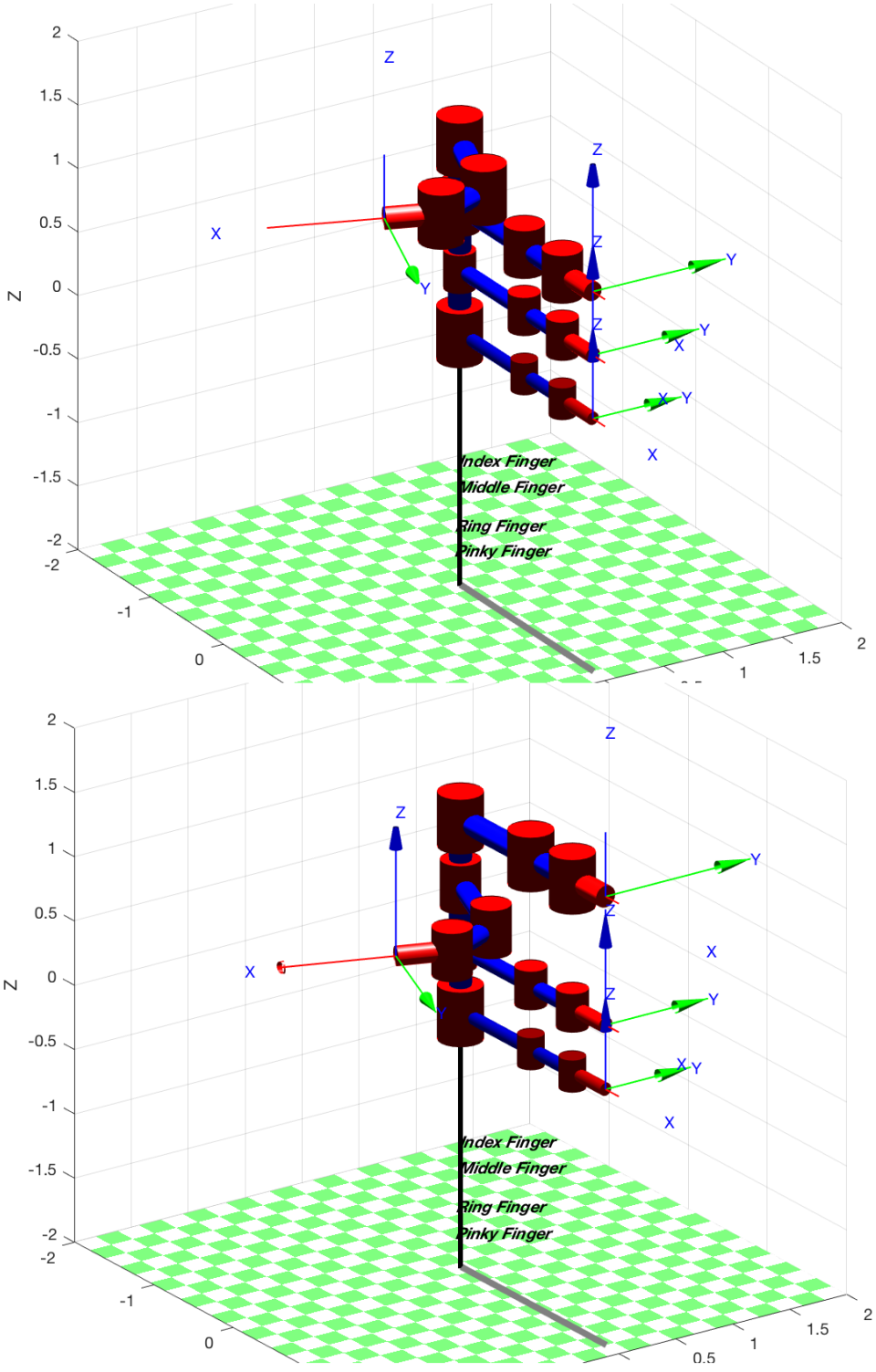


Figure 4.6: MATLAB simulation of hand. Top: Index finger curl. Bottom: Middle finger curl.

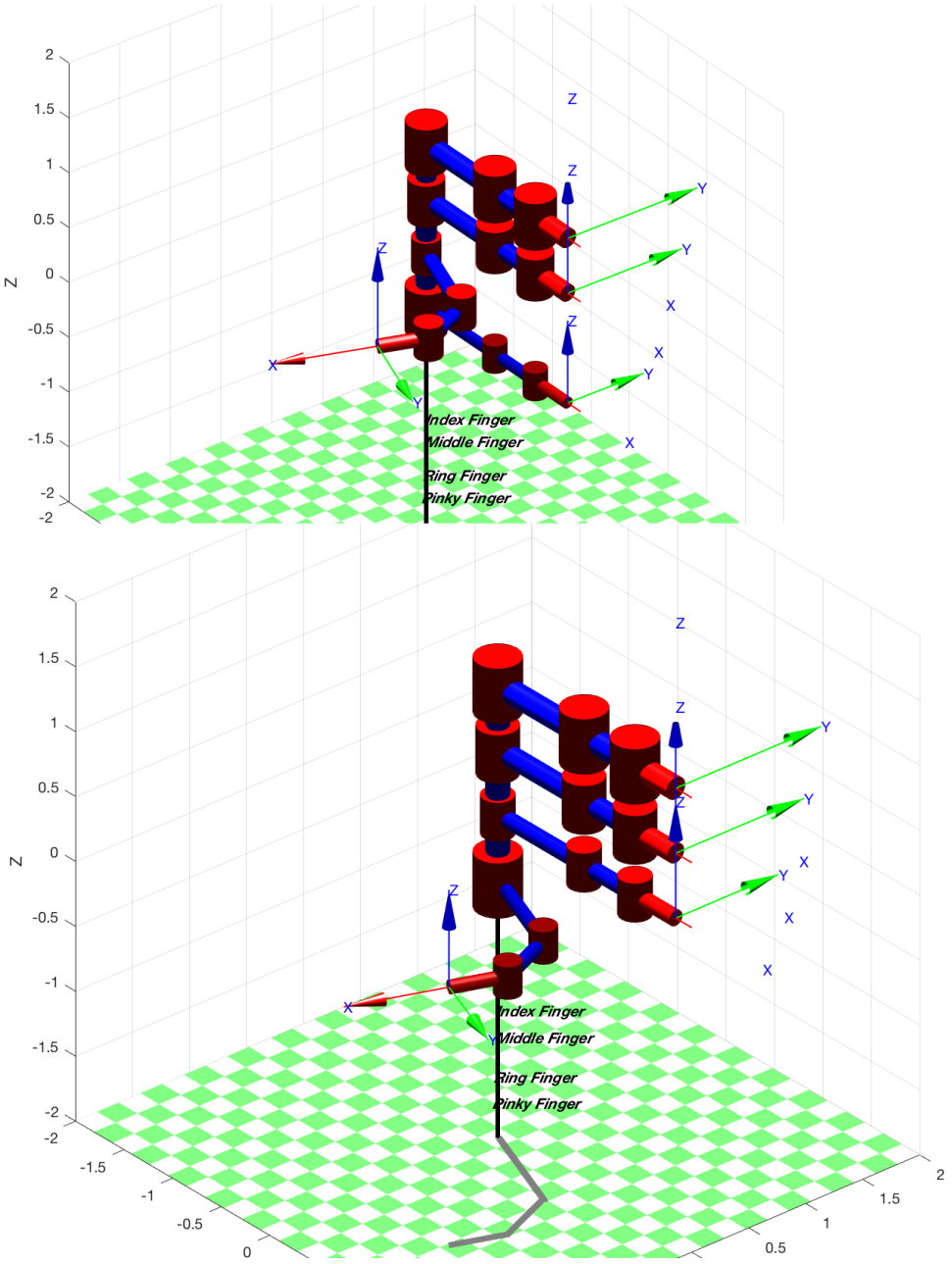


Figure 4.7: MATLAB simulation of hand. Top: Ring finger curl. Bottom: Pinky finger curl.

4.3 EMG and Kinematics Data Analysis

EMG signals from the muscles that control the fingers may give incredible insight into what type of signals are related to certain types of motions or gestures. This may be even more true when they're analyzed in conjunction with the kinematics data with OptiTrack. With this combination, we can see exactly what signals occurred on the muscles and the resulting motions from these muscles.

4.3.1 EMG

The data from the EMG sensors was imported into MATLAB for analysis. Figures 4.8, 4.9, and 4.10 display the EMG results of trial runs 1, 2, and 3 respectively. The raw signals can be seen on the left side of the figures. The signals were slightly clipped in the gain stage of the circuit before being processed through the ADC in the micro-controller. This is evident by the flat lines at the top of the wave form. The right side of the figures shows the results of performing an FFT on the signals.

It appears that EMG Probe 1 was able to pick up good data in both cases of sensing the flexor digitorum profundus and extensor digitorum muscles. EMG Probe 2 however appears to not have taken the best results. The intention of EMG Probe 2 was to detect signals from the lumbrical muscles which are responsible for the adduction and abduction motions of the fingers. The lumbricals are a complex net of muscles and tendons which may be the cause of poor EMG data. Another possibility was to detect if the tendons connecting the muscles to the fingers may give useful data. It appears that the EMG Probe 2 data may still be useful for analysis, however, these signals don't conform to what a typical EMG signal would look like and had a tendency to saturate the ADC.

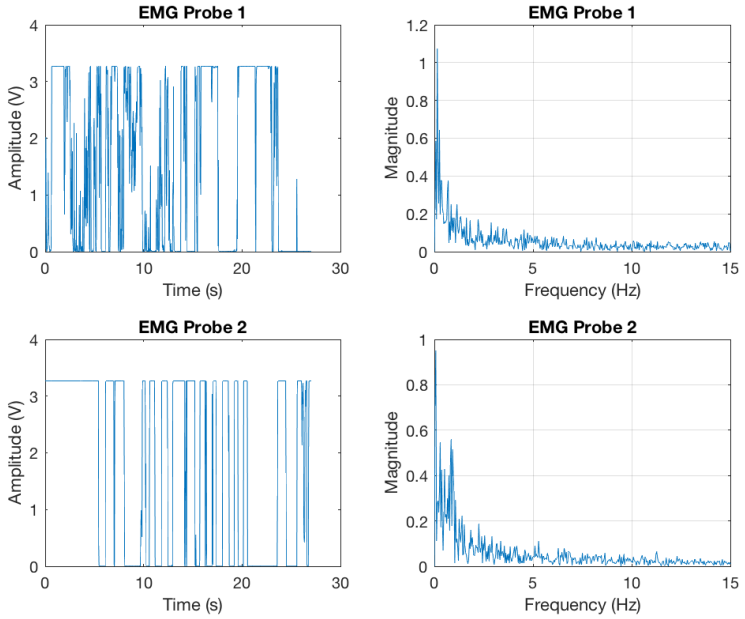


Figure 4.8: EMG sensors data from trial 1

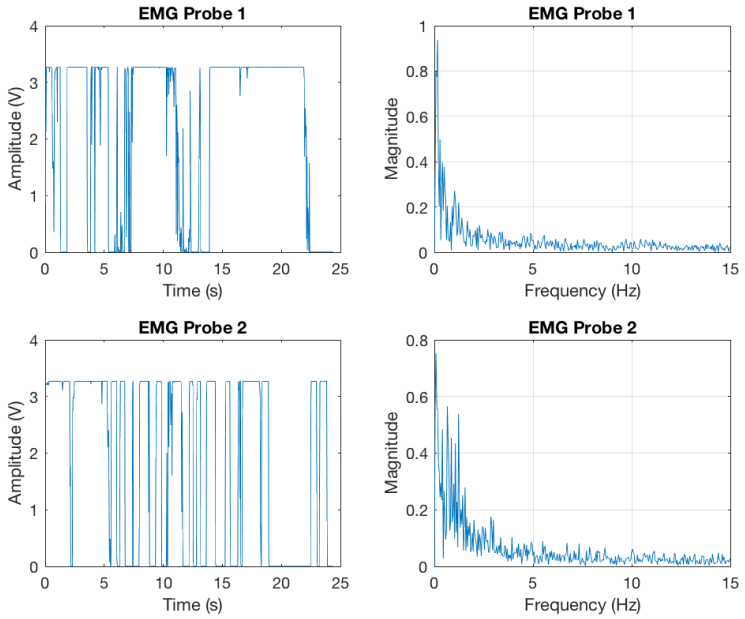


Figure 4.9: EMG sensors data from trial 2

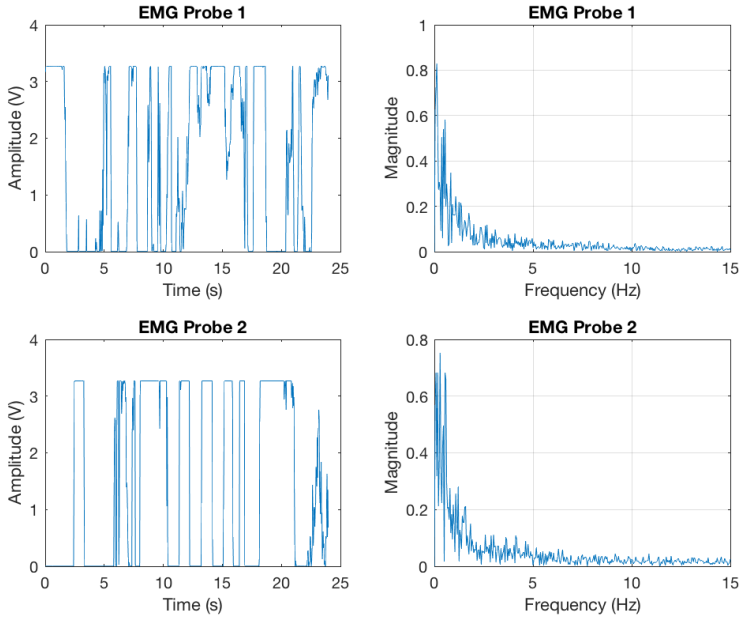


Figure 4.10: EMG sensors data from trial 3

4.3.2 Clipped Sine Wave Analysis

Clipping of the EMG probe signals was done to improve the signal to noise ratio (SNR) which is a common problem with EMG signals because noise is inherent in such a precise and complex system as the human body [7]. It's very likely to pick up signals from other muscles or nerves that aren't desired. Most of the noise can be found in the peaks of the signal which are now a flat line because of the clipping.

The negative effects of clipping a signal are that artifacts may appear when transfered into the frequency domain, displaying frequencies that aren't actually there. This may cause problems in our analysis in the frequency domain. When a pure sine wave is clipped, there will most certainly be extra harmonics introduced. In a dynamic signal such as the EMG probes, it's uncertain how clipping will affect it, but the likelihood of the artifacts canceling each other out is higher than them

being constructive.

Additionally, the total percent of the waveform clipped is probably the most telling of how much harmonics will be introduced. To validate the notion that the clipped EMG signals are still valid in the frequency domain, an analysis of a 1 Hz sine wave was conducted in MATLAB. Figure 4.11 displays the results of this test. The left column shows the 1 Hz sine wave in various levels of clipping and the right column shows the spectral analysis. The top row shows an unclipped sine wave, the middle row shows a sine wave with 9 percent of its max amplitude clipped, and the last row shows the sine wave with 50 percent of its max amplitude clipped. We can see the results of these various levels of clipping on right.

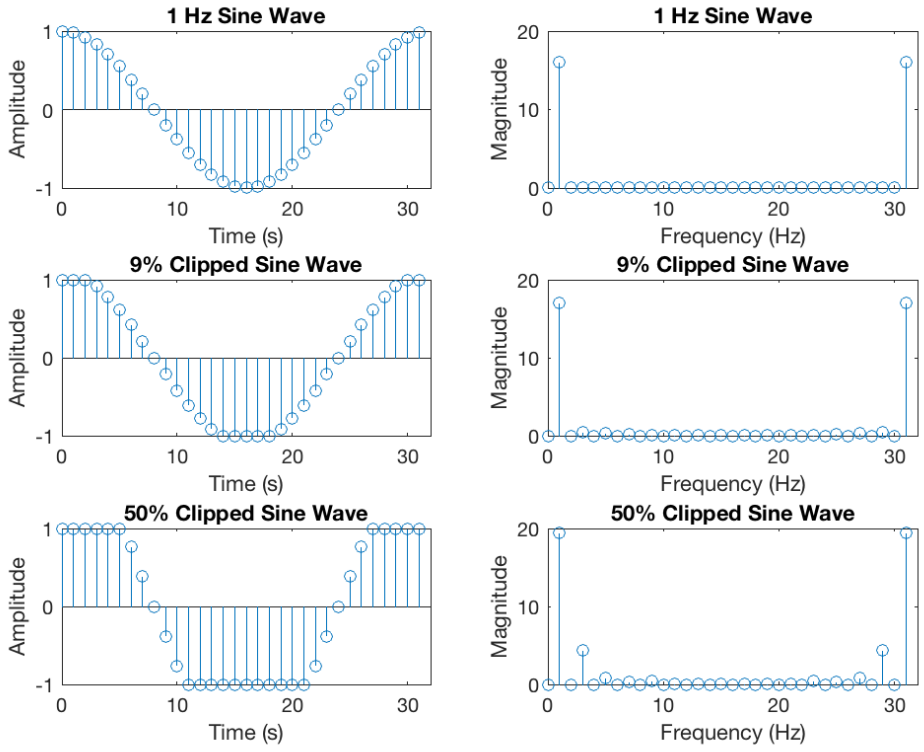


Figure 4.11: 1 Hz sine wave with no clipping, 9 percent of its max amplitude clipped, and 50 percent of its max amplitude clipped

The sine wave that was 50 percent clipped has some noticeable harmonics appearing while the sine wave with only 9 percent clipping has harmonics with very minor amplitudes. The EMG waveforms in this experiment were measured with a multimeter to max out at about 3.5V while the microcontroller clipped these signals to a max value of 3.3V. This leads to only about 6 percent of the EMG waveforms being clipped. The results of the 1 Hz sine wave being clipped by 9 percent validate the notion that these clipped EMG signals will still have valid results in the frequency domain.

4.3.3 Kinematics

Each of the three trials also included kinematics data from the four motion tracking markers attached to the index finger. The markers start with marker 1 being the MCP knuckle, marker 2 is the PIP joint, marker 3 is the DIP joint, and marker 4 being on the tip of the finger. The kinematics results shown in figures 4.12 and 4.13 display the results of one of the three trials and are in the same format as the EMG results. The left side of the figures contain the raw data displaying the distance of the marker from the origin. Each marker has XYZ components to give their position in 3D space as seen on the left column. The right column displays this data in the frequency domain.

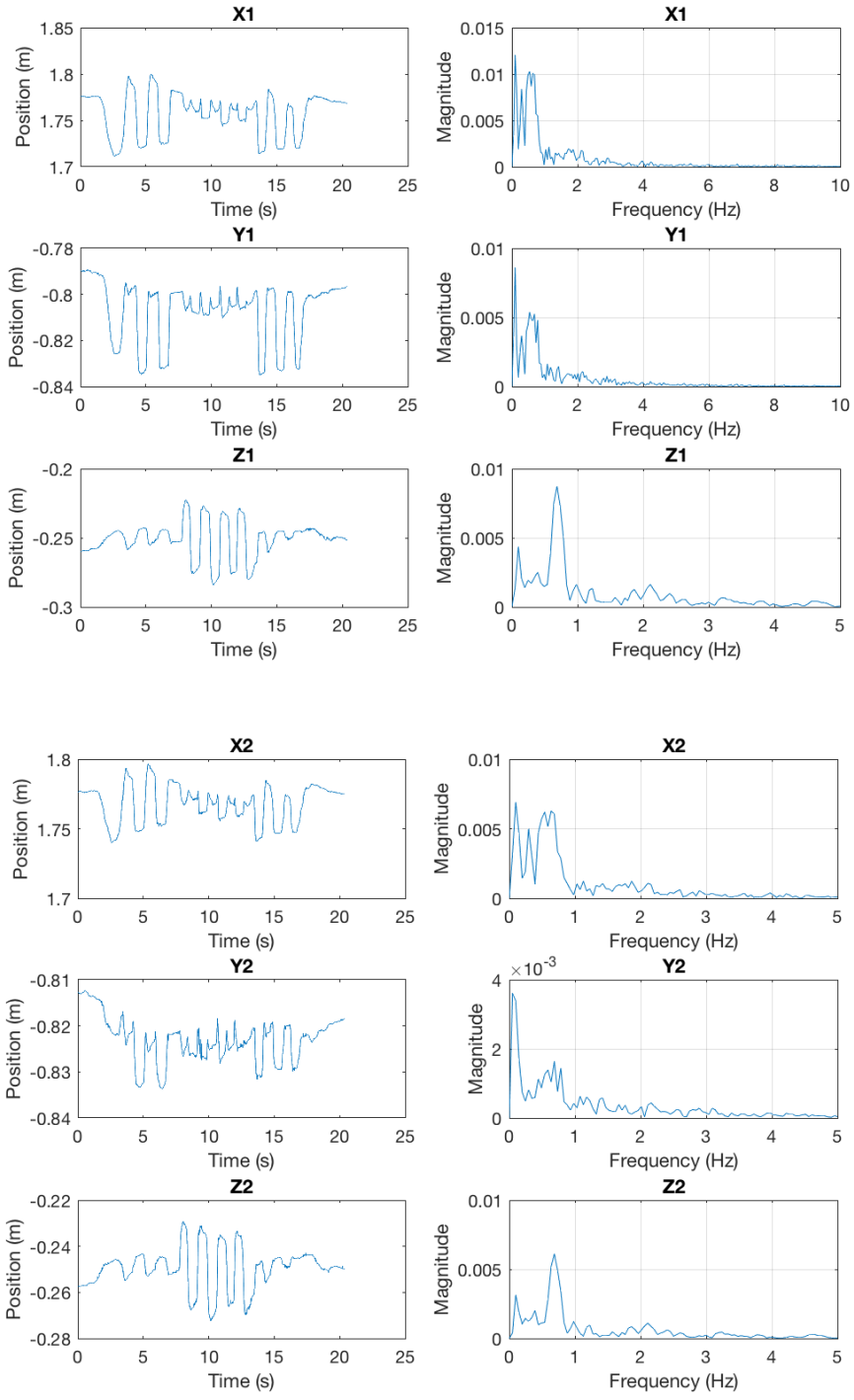


Figure 4.12: Markers 1 and 2 in one of the kinematics trials

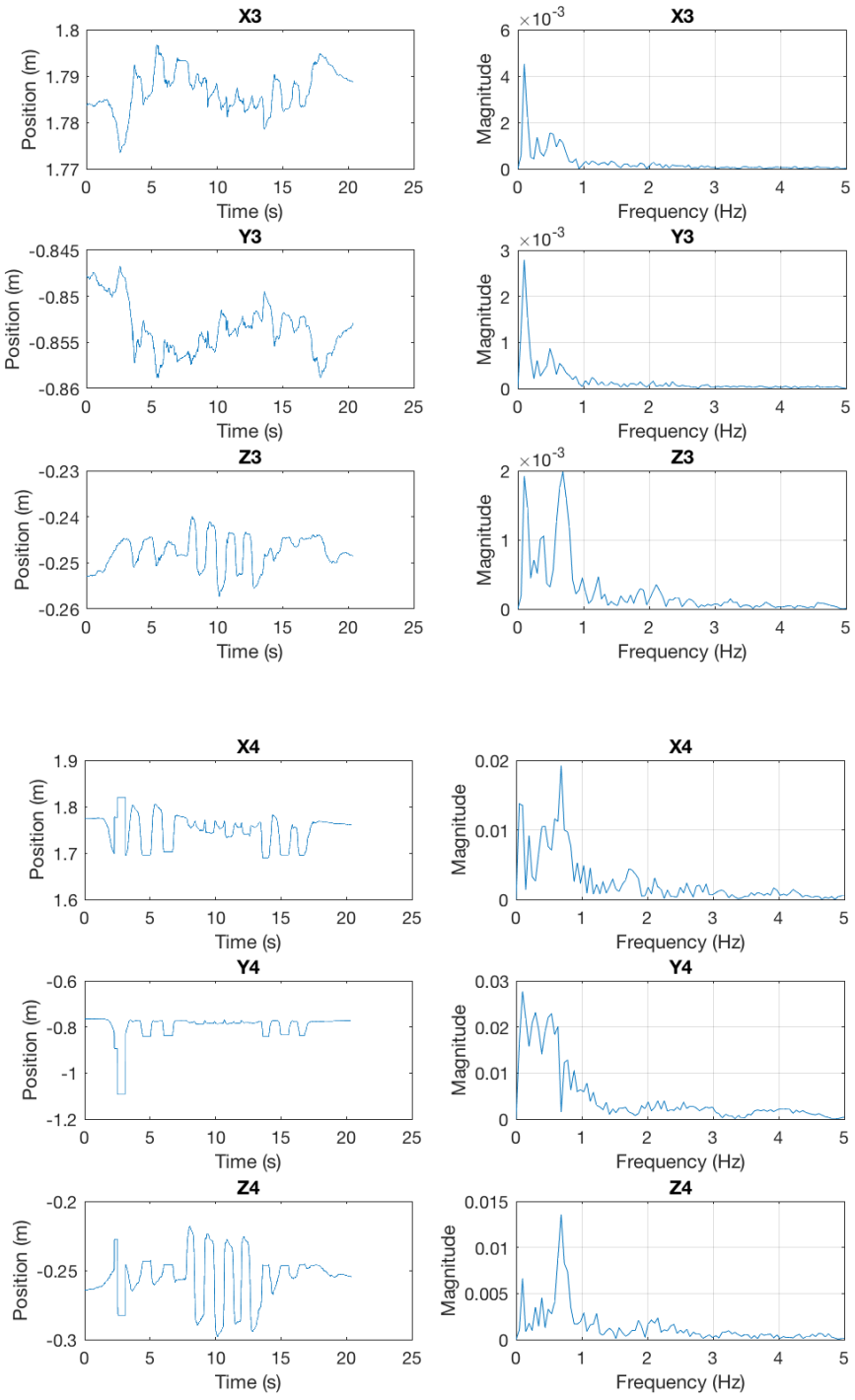


Figure 4.13: Markers 3 and 4 in one of the kinematics trials

4.3.4 Combined Analysis

With the results obtained from importing the EMG and kinematics data into MATLAB, it's now possible to find correlations between the two data sets. Figures 4.14 and 4.15 correspond to trial 1, 4.16 and 4.17 to trial 2, and 4.18 and 4.19 to trial 3. The first figure of each trial shows the top 20 peak frequencies found in the EMG data and below that is the top 20 peak frequencies found in the kinematics data. The second figure of each trial includes this same data but displays the top 10 peak frequencies and finally the top 5 peak frequencies. Comparing the two sets of data in this manner shows that there's indeed a consistent pattern between the two. The relevance of this will be discussed in the conclusion section.

The EMG portion of the figures shows two rows of circles, the blue row corresponding to EMG probe 1 and the orange row corresponding to EMG probe 2. The circles represent a peak frequency that was found in the EMG data. Likewise, the kinematics plot directly below the EMG portion shows similar data. Each row corresponds to one of the four markers used for motion capture. The variety of colors in the kinematics data doesn't represent anything significant, it's simply an automatic gradient that helps distinguish the different circles from each other.

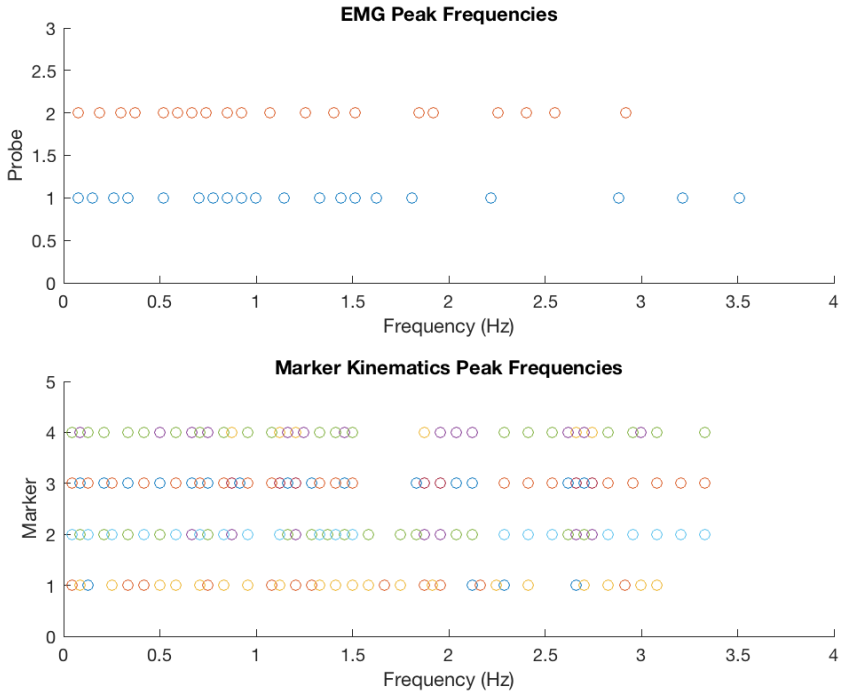


Figure 4.14: Trial 1 comparison of top 20 peak frequencies between EMG and kinematics data

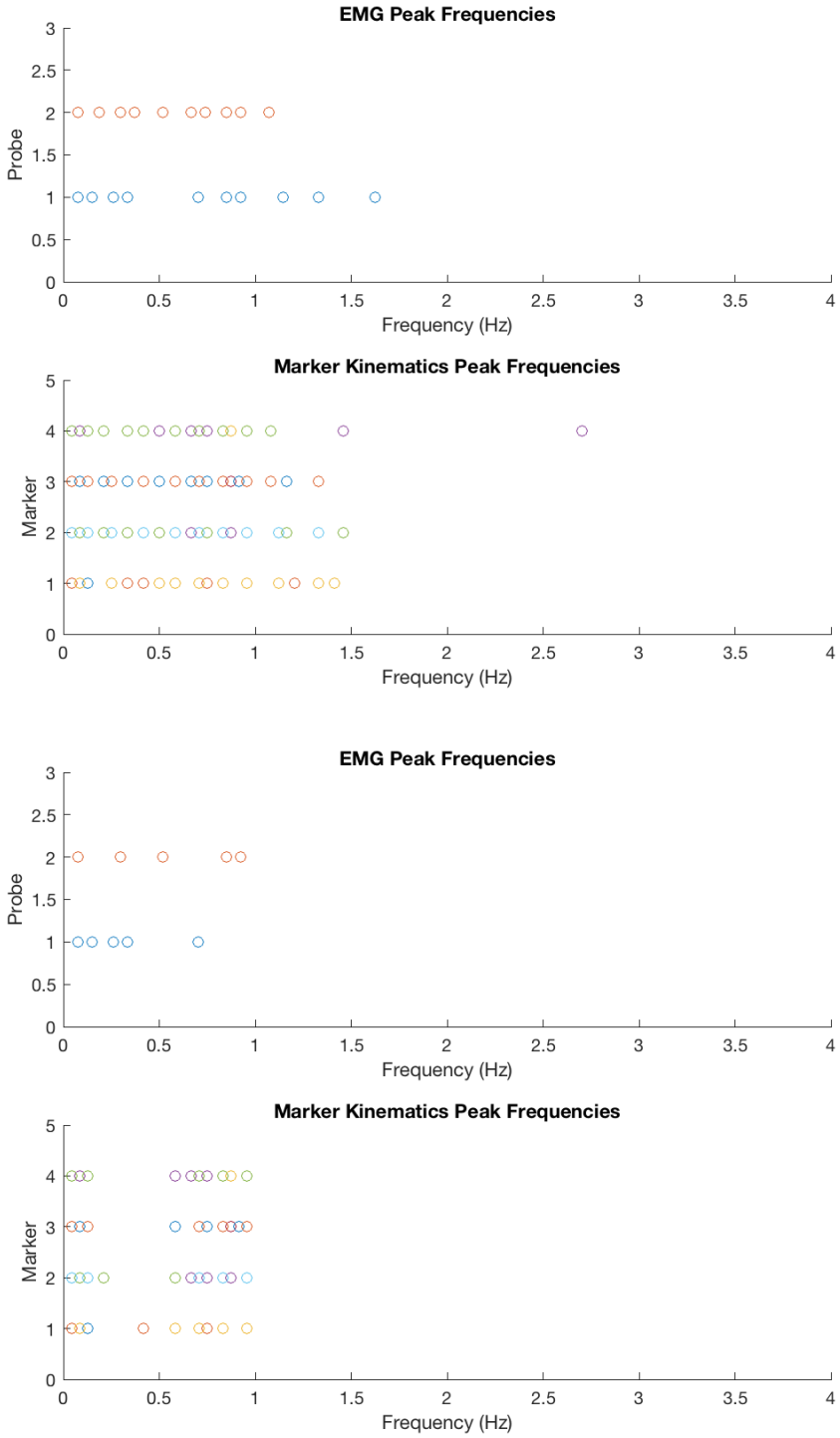


Figure 4.15: Trial 1 comparisons. Top: Top 10 peak frequencies. Bottom: Top 5 peak frequencies.

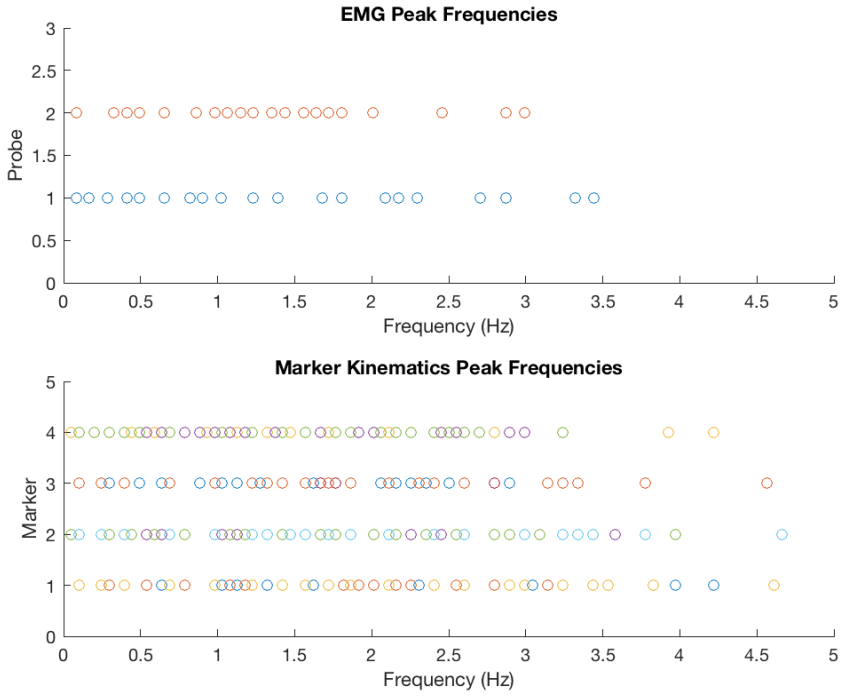


Figure 4.16: Trial 2 comparison of top 20 peak frequencies between EMG and kinematics data

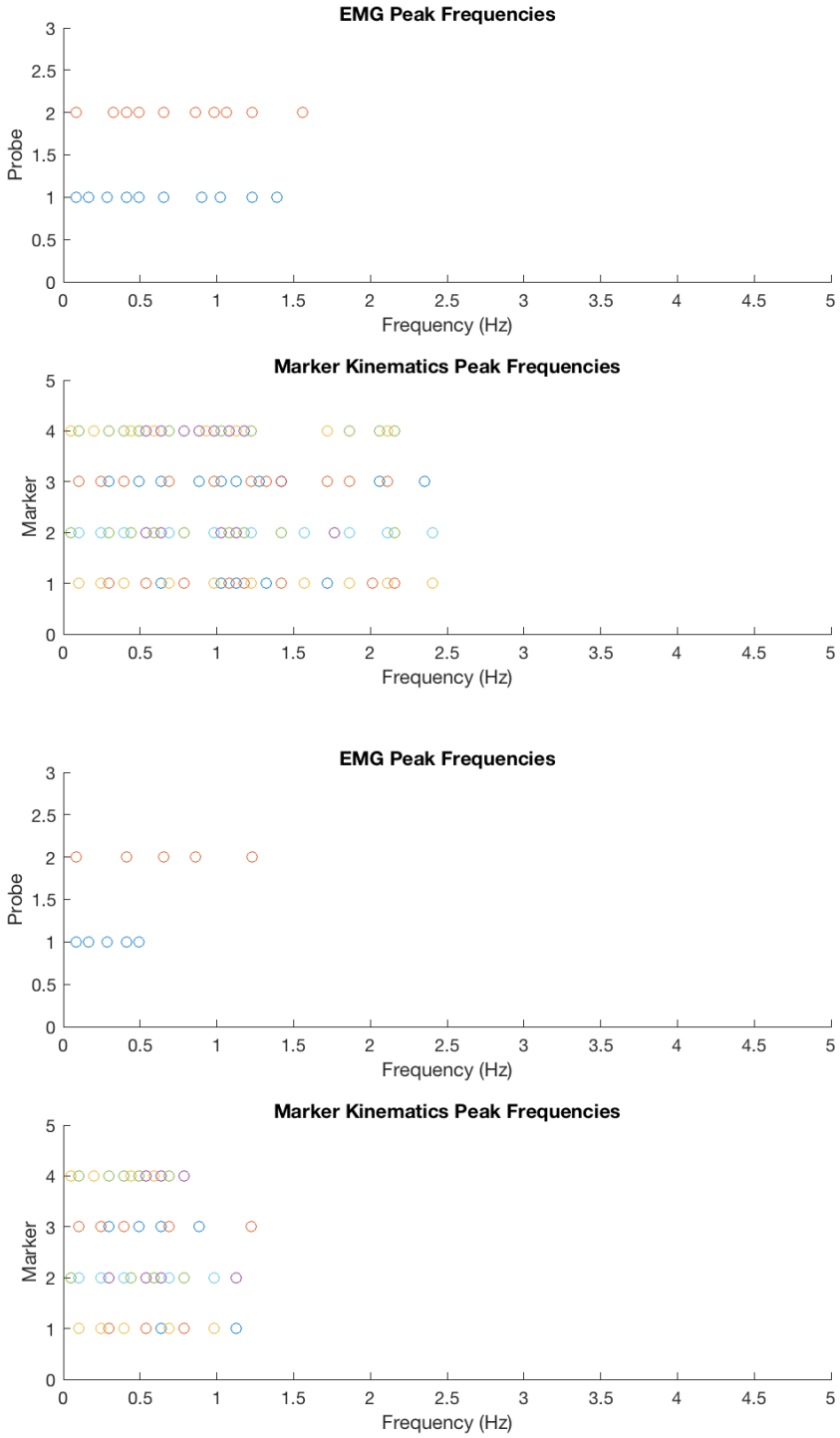


Figure 4.17: Trial 2 comparisons. Top: Top 10 peak frequencies. Bottom: Top 5 peak frequencies.

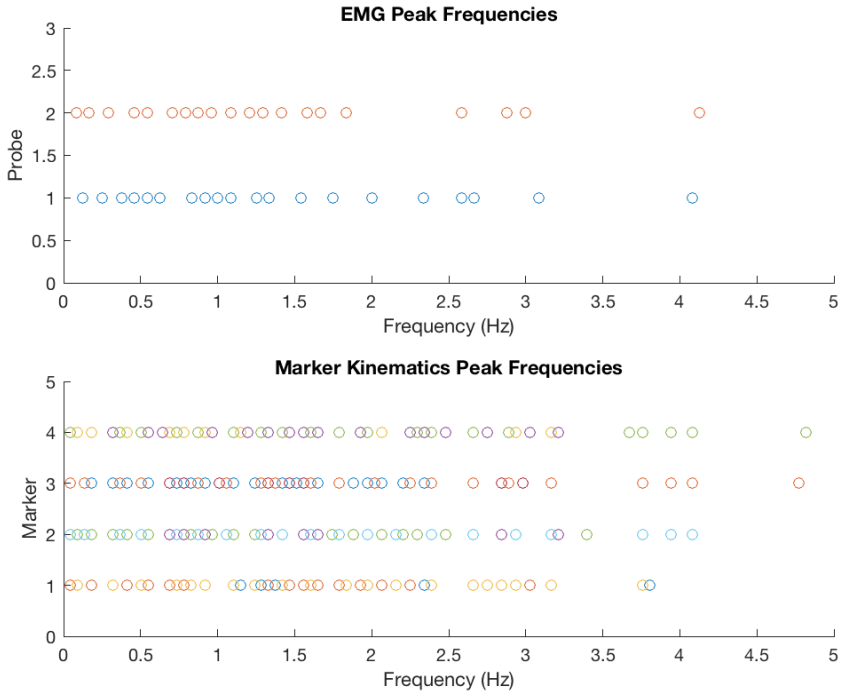


Figure 4.18: Trial 3 comparison of top 20 peak frequencies between EMG and kinematics data

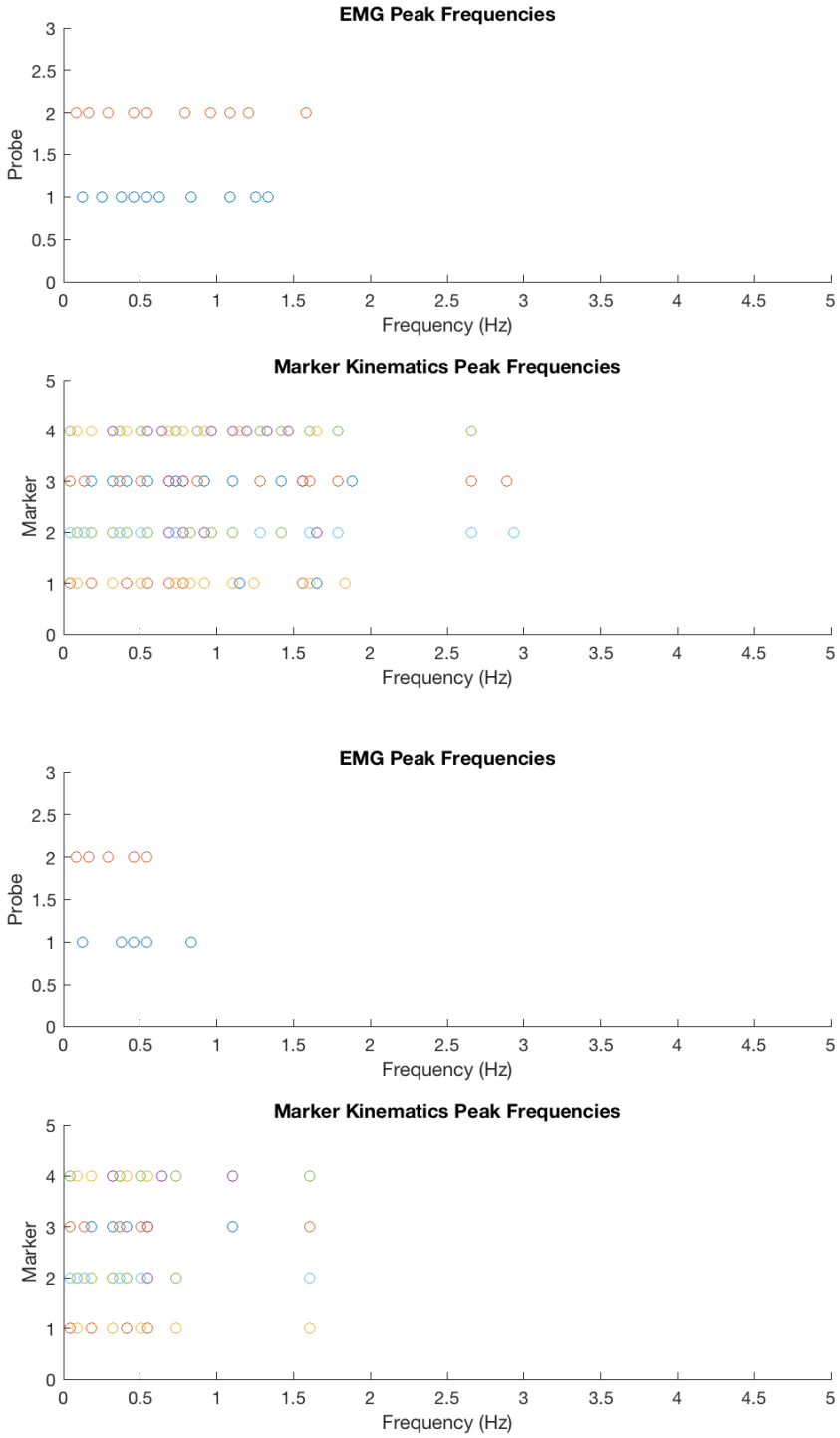


Figure 4.19: Trial 3 comparisons. Top: Top 10 peak frequencies. Bottom: Top 5 peak frequencies.

Chapter 5

Discussion and Future Work

The purpose of this research is to lay down the groundwork of designing an exoglove in a scientific manner. The experiments ran and the data collected may appear very fundamental, but these details are a crucial step in designing any type of successful exoskeleton. Meaningful conclusions may be drawn from the MATLAB simulations and the EMG/kinematics analysis that will be especially useful when going on to more advanced simulations and analysis before development of a physical prototype begins. The conclusions outlined in this section were drawn not only from the extensive literature review undertaken but also from the author's personal experience in building a successful wrist exoskeleton prior to the research conducted in this paper.

5.1 MATLAB

MATLAB is a very powerful tool used by many in industry and academia. With additional toolboxes such as the Robotics Toolkit used in this research, not only can powerful analysis be done but also powerful visualizations. Performing three dimensional visualizations are extremely useful for validation of the results

that were obtained. This ensures the correctness of the data that was recorded in OptiTrack and that it was correctly imported into MATLAB. It also validates the correctness of the mathematics and equations used in the scripts that were written to simulate the specific movements of the index finger.

Graphical visualization is another powerful tool that MATLAB offers. The results produced in MATLAB showing line graphs of the knuckle angles can be used to numerically visualize hand gestures. Seeing these angles being animated with a vertical sweep in conjunction with an animated three dimensional model may give insight when designing a controls system. The line graphs of the knuckle angles may also help finding relationships between them.

Showing this angle data in different respects may also give insight such as figure 4.4 where the top graph shows angles with respect to the parent body and the bottom graph is with respect to the horizontal. An application where this could be useful is controlling an exoglove to pick up a cup off a table. The system would likely need to take into consideration the angle of each knuckle with respect to the parent body for internal calculations. It would also likely need to take into consideration each angle with respect to the horizontal, common to both the system and the cup in this case. Without including both objects inside a single system or having a common reference, it would be extremely difficult to coordinate and interact as intended with such external objects.

The virtual hand that was created in MATLAB could also be expanded to include external objects such as a virtual cup. Running simulations in MATLAB or similar software where the hand can easily be manipulated with mathematical functions can be achieved. This would allow for a better understanding of what to expect in a real system with much less trial and error when testing a physical model.

5.2 OpenSim

Stanford University has developed a very powerful software package called OpenSim that gives unprecedented simulation abilities in biomechanics [19]. MATLAB was a good starting point for this field of research but software such as OpenSim would be the next step if the end goal is to develop a successful exoglove. OpenSim can simulate the biomechanics of any part of the human body, so exoskeleton research of any kind will benefit also.

Work on creating a dynamic model in OpenSim was done but results were never produced. Figure 5.1 shows the dynamic model created of the index finger. It was primarily based on an existing upper extremity model where the finger was extracted. Mass was added to the bone segments which was missing from the upper extremity model that allowed forces to be calculated in the simulated finger. Virtual markers were placed on top of the joints to coincide with the motion tracking markers used in the physical experiments with the hopes of extracting the inverse kinematics from the recorded motion tracking data. Unfortunately there were unresolved issues in the simulation and the movements didn't correspond to the given data. Future work would include debugging this model in order to obtain the dynamics and computed muscle control.

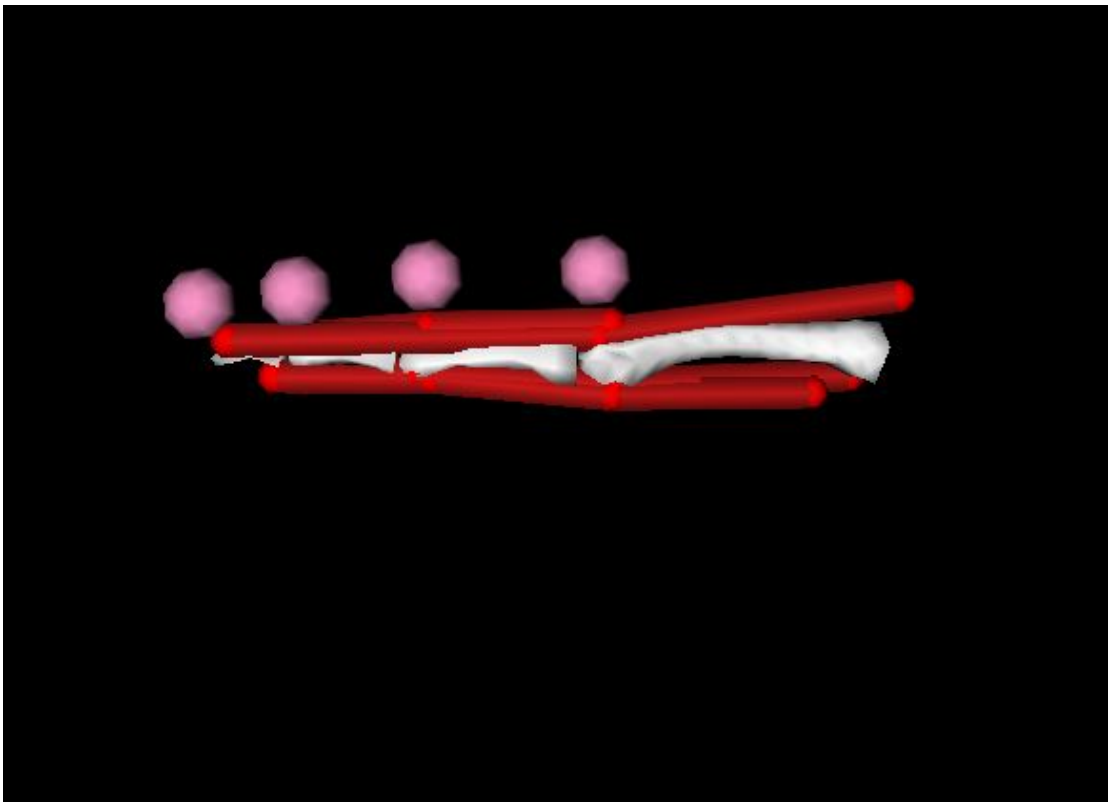


Figure 5.1: Figure of finger model with markers in OpenSim

5.3 EMG and Kinematics

The results comparing the EMG and kinematics in the frequency domain may be the foundation of a controls system for an exoglove in future work. By taking a FFT of the data in MATLAB, we can view the signal's frequency domain and manipulate it for various types of analysis. This is potentially helpful because many of the tasks we do with our fingers involve repetitious movements in a consistent frequency and are therefore fairly linear in nature. Things such as using scissors, typing, and writing are typically done in a consistent fashion or frequency. It's possible that finding similar frequencies between the EMG and kinematics data will allow future research to use EMG sensors and predict certain

motions in the proposed exoglove's fingers in real time.

The two fields of control that might be most useful are stochastic theory and feedback controls theory. Stochastic controls take various inputs and predict the state of the system or which state the system should enter next. These techniques are probabilistic in nature and would allow for the system to predict what motions or gestures to do based on the current and past inputs. Implementing sensors such as IMUs or flex sensors to measure angle, distance, or velocity on the fingers would also allow for feedback controls to be used as well. Combining both fields of controls in the system would be the most robust, but quite a challenge to accomplish. Such a control system would be one of the final building blocks of a complete and successful exoglove.

5.4 ExoGlove Considerations and Final Thoughts

The ultimate goal of this paper is to provide the fundamental steps in building an exoglove. Taken more generally, it can be treated as a basic guide for any type of exoskeleton research. The main techniques emphasized are gathering preliminary data and analysis of these datasets. These are important in any exoskeleton research so that an understanding of the mathematical and scientific principles can be created before development of a physical prototype begins.

There are a few important points that should be expressed after doing an extensive literature review of nearly 60 different exogloves. The first is that many of these papers didn't carry out the fundamental steps that are described in this thesis. The results of most of these prototypes weren't promising. The human hand is an incredibly intricate mechanical system that cannot be easily duplicated. Exoskeletons are unlike prosthetics in that they can't feasibly mimic the details of how the mechanics works in the human hand. Exoskeletons are more constrained

by volume than prosthetics are because most of the internal space is occupied by the user's limb. This means that exoskeletons are simply trying to mimic the overall motions of human limbs, however, this is more of a challenge because they can't duplicate the optimized mechanics of the human body. Novel and clever techniques must be developed.

The extensive literature review showed that there are many attempts in creating novel techniques to accomplish life-like motions. This is evident in the number of different actuation methods used to try to accomplish the same task. Novel techniques especially need to follow similar protocols outlined in this paper because they are experimental in nature, but many of them fail to do so and therefore fail to produce notable results.

The end goal should always be taken into consideration even in the early stages of research and development. Many of the papers display techniques that wouldn't be feasible in a real system where their stated goal is to develop an assistive exoglove. Details such as providing enough DOF to carry out a general task or making sure there's enough torque to lift moderately heavy objects are often overlooked until after the results are produced. This leads to more time being spent to correct these problems or sometimes even going back to square one in design. Time is one finite element of research that can't be manipulated so efficient usage of it is important for success.

Other details such as the weight of the actuators, batteries, and the rest of the system itself are often overlooked. This is problematic because if the goal is to provide extra strength to weakened individuals, then strapping a 15 lb. device on their forearm might do more harm than good. The more successful papers addressed issues like this. One example is a backpack actuation unit to offload the weight from the forearm to the back. These types of problems are slowly

becoming less of an issue as technology in general improves with lighter and more efficient components, but the hard limitations they impose are still there.

Soft robotics has had an increase in research in the exoskeleton field because of its numerous advantages over rigid systems. However, one of the aspects that holds the technology back is the very fact that it's soft and prone to deformation. The basic mechanics of the human body consist of bones as the rigid structure and muscles/tendons to provide force and actuation. Muscles are soft and prone to deformation so a system purely composed of them wouldn't be very useful. This is why a rigid structure like bones are necessary. In a purely soft exoskeleton system, the forces are created by the soft structure to actuate on the rigid structure which is a specific limb of the patient. This leads to all or most of the force being exerted onto the patient rather than a rigid exoskeleton structure. This may be counterproductive if the intended goal is to assist weakened individuals. Depending on the specific medical condition, the patient's joints and limbs may be too sensitive to handle the exerted force from the exoskeleton and could possibly cause injury. A hybrid system that incorporates both rigid and soft structures would be ideal so that the forces are primarily acting on the rigid bodies of the exoskeleton and not the patient.

There are many aspects to consider when attempting such an endeavour as building an exoskeleton. The field is still relatively young when you consider what the common goals are. There are still many fundamental problems to sort out before these technologies become mainstream. Going through the basic motions of data collection and analysis similar to what is outlined in this paper will greatly benefit any type of research involving exoskeletons. The considerations mentioned in this section can all be alleviated or solved by preliminary data collection, analysis, modeling, and simulation.

The result of any engineering project will contain at least some flaws that may or may not be important. What is important is to resolve the flaws that impede the device's intended functionality. Many engineers will think of a solution and implement it only to find out that the new solution has its own flaws. Many of the problems that robotics engineers need to face in exoskeleton design are extremely counterintuitive and therefore very difficult to solve. Instead of iterating prototype after prototype, the most efficient way to solve these fundamental problems is to simulate them. Simulations allow for parameters to easily be modified and many iterations to be performed in a fraction of the time that it takes to build a prototype. Simulations by nature will never be ideal either, but are still an extremely powerful tool to help solve the aforementioned problems.

Engineers should not only appreciate but embrace powerful tools such as simulations to assist them in developing their project. After all, engineers are generally more interested in the high level applications rather than the nitty-gritty details of getting there. This makes simulations even more appealing and sensible to speed up the entire process. Despite this tendency to focus on the end product rather than the details of getting there, engineers are technically considered applied scientists and should embrace science and simulations as an intermediary tool to their final goal.

Chapter 6

Appendix

Table 6.1: Table of Hand/Wrist Exoskeletons

Table 1: Table of Hand/Wrist Exoskeletons

Paper	Wrist	Hand	Soft	Hard	Rotary	Linear	Pneumatic	Passive	Other	Cables	Links	Gears	Direct	EMG	Force	Position	Angle	Other	Rehabilitative	Assistive	VR/Haptic	Dexterous	Rating
[1]		X		X	X					X				X		X			X				2
[2]		X		X			X						X			X	X				X		1
[3]	X			X		X					X			X	X				X	X			2
[4]		X		X	X					X	X			X	X		X		X				2
[5]	X			X	X					X						X			X			X	2
[6]		X		X	X						X				X	X			X				1
[7]		X		X		X					X			X					X				4
[8]		X		X			X				X			X						X			1
[9]		X		X		X				X				X		X			X	X			4
[10]		X		X	X						X			X					X	X			3
[11]		X		X				X			X					X			X				1
[12]		X		X				X					X						X				1
[13]		X		X	X						X				X	X			X		X		2
[14]		X		X	X					X					X	X			X				4
[15]	X	X		X	X						X				X		X		X		X	X	3
[16]		X		X	X					X	X				X		X		X		X	X	4
[17]		X		X	X					X					X	X	X		X		X		1
[18]		X		X	X					X	X	X			X		X		X				3
[19]		X		X			X						X				X		X		X		2
[20]		X		X			X	X			X				X		X		X		X		2
[21]		X		X		X				X	X				X					X			1
[22]		X		X		X				X					X					X			1
[23]	X	X		X	X					X	X							X		X			4
[24]		X		X		X	X		X	X								X	X	X			3
[25]		X		X	X					X	X				X					X			1
[26]		X		X	X						X						X	X		X			1
[27]		X		X	X							X		X						X			1
[28]		X	X				X		X				X		X			X		X			2
[29]		X		X			X		X				X	X				X		X			3
[30]		X		X			X				X				X		X			X			3
[31]		X	X				X		X				X				X			X			2
[32]		X		X			X				X							X		X			2
[33]		X		X					X				X					X		X			1
[34]		X	X		X					X								X		X			4
[35]		X		X	X					X	X	X		X		X	X		X				2
[36]		X		X		X					X					X			X				3
[37]		X		X	X					X	X					X				X			2
[38]																							2
[39]		X		X	X					X	X			X					X	X			3
[40]		X		X	X					X	X					X	X		X		X		2
[41]		X		X	X			X		X	X			X						X		X	3
[42]		X		X	X						X			X			X		X				2
[43]		X		X				X			X				X		X		X				2
[44]		X		X																X			1
[45]		X		X	X					X	X								X				3
[46]		X		X	X						X	X			X	X			X		X		3
[47]		X	X		X					X					X	X					X		3

Table 2: Table of Hand/Wrist Exoskeletons

Paper	Wrist	Hand	Soft	Hard	Rotary	Linear	Pneumatic	Passive	Other	Cables	Links	Gears	Direct	EMG	Force	Position	Angle	Other	Rehabilitative	Assistive	VR/Haptic	Dexterous	Rating
[48]		X		X	X					X	X									X			2
[49]		X		X	X					X	X	X			X		X		X				3
[50]		X		X		X					X					X			X				2
[51]		X		X	X						X	X			X				X				1
[52]		X	X					X	X				X						X		X		2
[53]		X		X	X						X	X							X				2
[54]		X		X	X				X		X				X	X					X		1
[55]		X		X	X					X	X										X	X	4
[56]		X		X	X					X	X								X			X	4
[57]		X	X				X						X				X			X			4
[58]		X		X		X				X					X		X			X			1
[59]																							

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