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Versatile Data Acquisition System for Upper Extremity Force Sensing

A Major Qualifying Project Report submitted to the faculty of
WORCESTER POLYTECHNIC INSTITUTE
in partial fulfillment of the requirements for the degree of Bachelor of Science

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April 28, 2016

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Abstract

Osteoporosis is a bone degenerative disease that affects 53 million Americans that is caused by a decrease in bone density. This decrease in bone density leads to an increased risk of bone fracture. Since bone is able to adapt to its mechanical forces, loads that are delivered to the bone can make it stronger. The purpose of this project was to create a force sensing device that measures the force magnitude and direction on the hands during daily activities. The team created a glove consisting of interchangeable sensors to measure the loads produced on the upper extremities during four different activities. The piezoelectric sensors collected voltage readings through a LabVIEW program. Force values were calculated from the voltage readings using the formulas obtained from the calibration curves. A method was also created to calculate the moment occurring about the wrist.

Acknowledgments

Our group would like to thank our advisor, Professor Karen Troy for all her support and guidance throughout our project. We would also like to thank Lisa Wall, Hristos Giannopoulos, Joshua Johnson, Luke Perrault, and Adriana Hera for all their help over the past year.

Authorship

All team members contributed equally to the research, writing, and editing of this report.

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1 Introduction

The upper extremities, primarily the wrist and hand, are two of the most important parts of the body because they are necessary for many daily activities. Cooking, cleaning, reading, opening doors, brushing teeth, eating, and writing are all examples that require the functionality of the hands and wrists. It is important to understand what types of forces the upper extremities undergo during various daily activities. By looking at the forces that the body experiences can show which activities cause harm leading to degenerative hand diseases as well as those that can be beneficial in preventing these types of diseases.

As age increases, bone begins to deteriorate which has a tremendous impact on daily activities. Some common diseases that affect the function of the hand are osteoarthritis and osteoporosis. In order to determine which activities induce bone growth and which hinder it, technology can be used to study how forces from daily activities affect the bone over time. These results can help individuals who suffer from degenerative hand diseases by showing which types of activities can strengthen the bone and which can lead to further harm. For bone tissue to continually remodel, this tissue must be exposed to different types of loading [1].

Osteoarthritis is a joint degenerative disease that affects around 26.9 million people in the United States. This condition is characterized by cartilage deterioration and inflammation of the joints. [2]-[4]. Osteoarthritis becomes more common as people age and is a painful condition that can inhibit an individual's daily activities [5]. Cartilage is unable to regenerate because it does not receive blood [6]. Since it cannot regenerate, any damage done to the cartilage cannot be reversed, which is why there is no cure for osteoarthritis. Different magnitudes of loading have

various effects on cartilage. When a high impact activity is performed, the cartilage is more vulnerable to wear where as a moderate impact activity is more likely to protect the joint [7]. Another common degenerative disease as people age is osteoporosis, which 53 million Americans experience or are at risk for developing [8]. This occurs when the bones start to weaken, lose their density, and become very brittle [9]. The more brittle bones are, the easier they are to break, therefore, people who have osteoporosis are extremely susceptible to broken bones. Osteoporosis leads to 1.3 million fractures each year [10], [11].

By understanding these diseases and conducting research to see what activities promote healthy bone growth and protect cartilage in the joints, people will be able to learn what exercises they can do to prolong or prevent the onset of diseases like osteoporosis and osteoarthritis. This is especially important because neither of these diseases have any current cures and the treatments available do not reverse any damage. The development of a force sensing device can be used to study the loads on the upper extremities during different activities in order to see the correlation between daily exercises and their effect on bone loading and degenerative diseases.

The purpose of this project is to create a force sensing device for upper extremity activities performed by the hands, wrists, and forearms. The device must measure the magnitude and direction of the force relative to a specific landmark on the wrist while remaining within a required range of accuracies. The force magnitude must be within ± 3 N, the direction within ± 5 degrees, and location within ± 5 mm. The device must also be able to be used with both hands, last up to 5 years, easy to setup and operate, durable in the sense that it will not break if it is dropped or becomes wet, and safe as to not shock or pinch the user. There is a need to develop

a device like this because there are no devices on the market that are able to find the magnitudes and directions of the forces on the hands, wrists, and forearms during everyday activities.

To accomplish the goals described above, the team will use knowledge gathered through technical research to design, build, and test the force sensing device. Research will involve understanding the anatomy and physiology of the hand, wrist, and forearm to establish how the muscles, tendons, and ligaments interact with the bones. The device must also include methods to measure the forces in magnitude and direction acting on the bones. These methods that will be used must help the device meet the objectives; therefore, research will involve looking at many designs within the budget and the set parameters. By combining knowledge of the anatomy and physiology of the hands, wrists, and forearms with that of the different design methods the team will be able to succeed in building a device that can measure the forces on these body parts during the defined upper extremity activities. Once the preliminary device is built, data will be collect by having test subjects perform the four common activities. These activities include: brushing teeth, opening a door with a handle, opening a jar, and typing. In order to determine the validity of the device, a test can be conducted using a predetermined load. For example, a five pound weight can be placed on the device and a reading will be done. The reading should be consistent with the five pound weight, and by knowing the exact load applied, a range of tolerances can be set. Further testing will then be done until the device functions without error.

The next chapter will be an extensive literature review to further understand the background of this project. This will include information on the anatomy of the hand, wrist, and forearm, the

degenerative diseases that occur in the upper extremities, and the types of sensors that could be used to develop the device.

2 Literature Review

2.1 Bone and Cartilage Degenerative Diseases

Bone and cartilage are two of the most important parts of the human body as without them, people would not be able to stand, walk, pick up objects, or even move. Considering how essential all of these tasks are, imagine the difficulty of trying to accomplish everyday activities while having sharp joint pain trying to open a jar or risking a wrist fracture when picking up a heavy box. Since they are an integral part to what makes people able-bodied, bone and cartilage health should be considered especially while aging. In order to maintain healthy bone, one must have a diet consisting of appropriate vitamins and nutrients as well as properly exercising on a regular basis [12].

There has not been a lot of research done to determine what exercises are best to maintain healthy bone and cartilage in the upper extremities. If a device were developed which could measure the magnitude and direction of the forces during daily activities, then the data collected can be compared with research on bone and cartilage degenerative diseases to determine the best exercises to reduce the risk or prolong the onset of these degenerative diseases. The need for a device of this nature stems from the lack of a cure or a treatment that reverses the damage done to bone and cartilage in the upper extremities.

2.1.1 Osteoporosis

One of the most common bone degenerative diseases that affects aging people is osteoporosis. Osteoporosis is a disease where bones become weak, which causes an increased risk of fracturing due to the dramatic decrease in bone density [10]. The decrease in bone density occurs when the osteoblasts and osteoclasts are not functioning together as they should [13] The decrease in bone density develops when new bone cannot grow fast enough to replace

the old bone that is being continually removed; therefore the pore size of the bone increases dramatically, which can be seen in Figure 2.

Approximately 53 million Americans are either diagnosed with or are at risk of developing osteoporosis; and postmenopausal women are the most at risk of developing this disease [14]. Postmenopausal women are more at risk due to a hormonal imbalance of estrogen causing the amount of trabecular bone present in bone to diminish [13]. Bone in the body is composed of 80% cortical bone and 20% trabecular bone. While all bone is subject to fracture, bones that are made up of 50% trabecular bone are more likely to fracture, which is why postmenopausal women have a higher chance of fractures [15]. The likelihood of developing osteoporosis depends upon genetic and environmental factors during childhood and adolescence [16].

However, different types of exercises can reduce the risk of developing bone degenerative diseases. This is because of the loads that are being applied. A study was done to see how different types of exercise loading affect the cross sectional geometry of a tibia. “High-impact, odd-impact and repetitive low-impact exercise loadings were associated with thicker cortex at the distal tibia” [17]. An increase in the thickness of the cortex can significantly increase of bending loads that can be applied to the bone. Figure 1 shows the cross sectional view of the tibia shaft relative to the type of exercise. Doing these types of exercises can make the bones more resilient to bending loads, making them less likely to fracture which can be applied to the bones in the upper extremities [17].

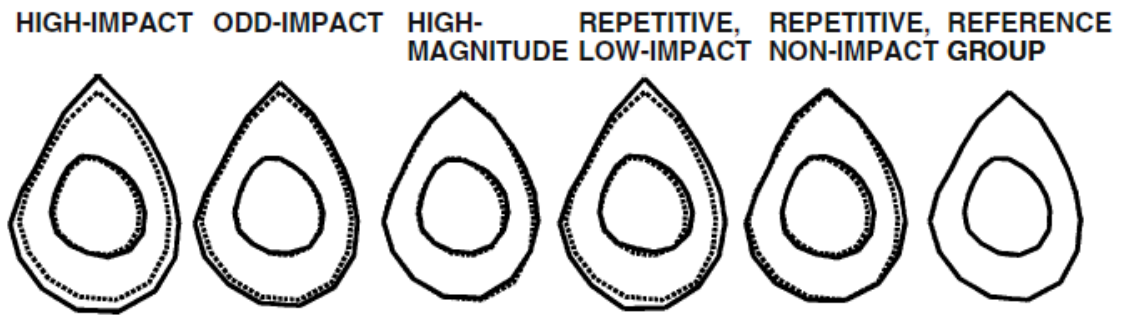


Figure 1: Cross sectional view of tibia during different types of exercise [17].

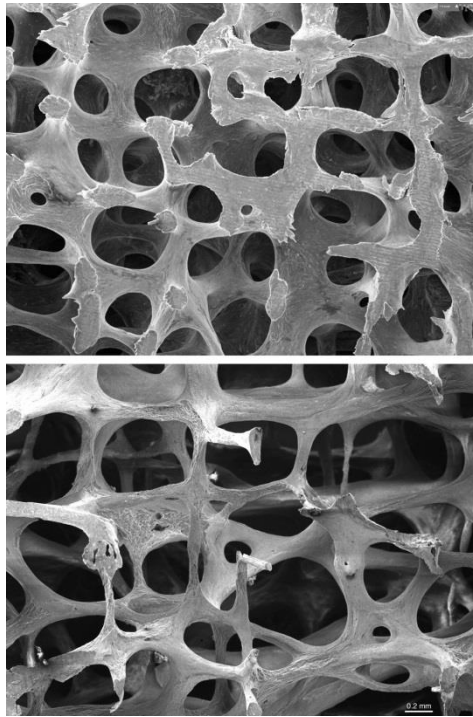


Figure 2: The top image shows a microscopic view of healthy and trabecular bone compared with the lower image which shows trabecular bone with osteoporosis at the same scale [16].

2.1.2 Osteoarthritis

In addition to osteoporosis, another degenerative disease that commonly affects aging people is osteoarthritis. Osteoarthritis is a disease that occurs when the cartilage that protects the ends of bones becomes worn down. The loss of cartilage results in pain, swelling and reduced motion in the afflicted joints [18]. The anatomy of a healthy joint compared to the anatomy of a joint with

osteoarthritis can be seen in Figures 3 and 4. The wearing down of cartilage results in bone rubbing on bone which adds to the debilitating pain for those suffering from osteoarthritis. People who have osteoarthritis in the hands lose a great deal of functionality and ability to perform daily tasks [18]. Activities that apply moderate forces on joints typically protect the cartilage while excessive loading can wear cartilage away [19]. Cartilage does not receive blood from the body, thus is unable to regenerate when damaged. Since it cannot regenerate, it is pertinent that it remains healthy [20]. Approximately 27 million Americans currently suffer from osteoarthritis [21]. Observing the locations and magnitudes of forces acting on the hands can help individuals understand which exercises provide appropriate loading to the cartilage in the hand to prevent deterioration.

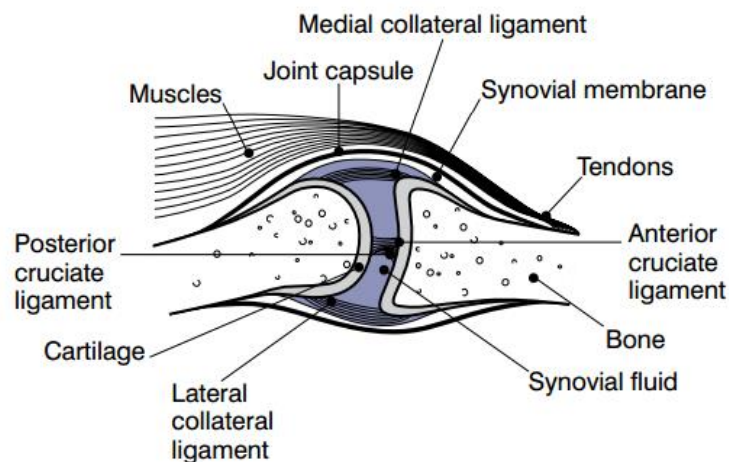


Figure 3: The anatomy of a healthy knee joint [22].

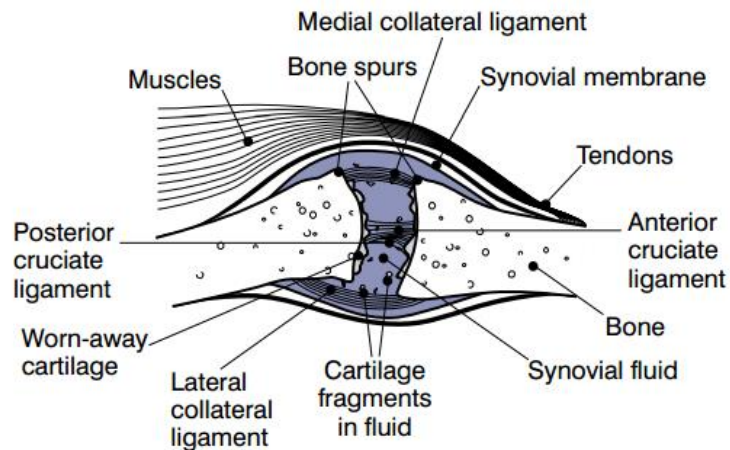


Figure 4: The anatomy of a knee joint with osteoarthritis [22].

2.2 Anatomy and Physiology

The bones, cartilage, muscles, tendons, and ligaments are all affected by the forces applied to the hands, so it is necessary to first know how they interact with each other when forces are applied. Knowledge of the anatomy of the upper extremities will also help with this understanding.

2.2.1 Skeleton of the Hand

It is necessary to understand the basic skeleton of the body part being focused on in order to properly recognize where the forces are being applied. This project will focus on the hands, wrists, and forearms. There are 19 bones in the hand and eight bones in the wrist, as seen in Figure 5 [23]. The bones that make up the hand are the phalanges and the metacarpals, while there are carpal bones in the wrist [23]. The two bones in the forearm, the radius and ulna, can also be seen in Figure 4 [24].



Figure 5: The bones of the hand, wrist, and forearm [25].

There are also several joints that bring all of these bones together and allow for movement at the knuckles and in the fingers. These joints are the metacarpophalangeal joints and the interphalangeal joints, located at the knuckles and on the fingers, respectively [23]. Together, these joints and bones, along with the muscles, tendons, and ligaments, allow the hand and wrist to do a variety of activities.

2.2.2 Bone

The bones in the hand and wrist can be affected easily by the forces applied during basic activities. Bone is a living tissue which acts as the support system of the body. It protects organs and acts as levers for muscles to pull on. It is also the home to bone marrow, which is responsible for producing red and white blood cells [26]. The outer portion of bone is called cortical bone, which is rigid and is arranged into long channels of osteons. Trabecular bone, also known as spongy bone, makes up the interior of the bone, as seen in Figure 6. This is where the

bone marrow and hematopoietic stem cells are located; these cells' primary function is to produce blood.

Both types of bone are comprised of osteoclasts and osteoblasts, which perform two different functions. Osteoblasts develop bone and aid in mineralization, while osteoclasts resorb bone cells [26]. As people age, their bone structure starts to change, including the rate of modeling and remodeling. This causes osteoclasts to remove more minerals, increase the pore size in the bone, and expose the cartilage to more stress [27].

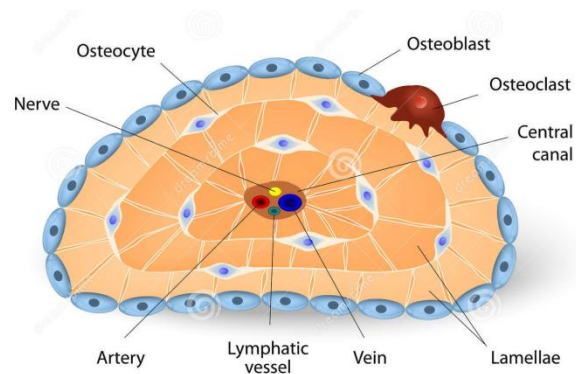


Figure 6: The anatomy of the inside of a bone [28].

Loading of the bones is important and needed for the formation of osteoblasts and osteoclasts. These two types of cells in the bones are responsive to mechanical signals [27]. In order for the osteoblasts to model bone at a reasonable rate which outpaces the osteoclasts removing the bone, sufficient loading forces need to be applied to the bone in the correct direction. Due to the anisotropic nature of bone, the fracture strength is different depending on the direction that the external force is being applied. Based on previous studies which evaluate the fracture strength of bone, cortical bone is found to be more susceptible to fracture when

external forces in the shear direction are applied; by strengthening cortical bone, the risk of fracture decreases [29].

2.2.3 Cartilage

Cartilage is the flexible tissue primarily consisting of chondrocytes that is found between bones in joints [30]. The proteins on surface of cartilage in conjunction with synovial fluid in the joints significantly reduce friction between cartilage and bone in joints to make movement comfortable [31]. The deterioration process of cartilage commonly occurs during aging, where the cartilage is unable to retain as much water as a younger persons can. The reduction in water content means that there is less cushioning provided between the bones in a joint. The loss of water also puts the cartilage at a risk of undergoing more stress, which leads to further breakdown of the cartilage potentially leading to osteoarthritis [32].

2.3 Basic Movements

When developing a device that can measure the forces applied to the hands, wrists, and forearms during a wide array of activities, it is beneficial to narrow down the activities that will be used to validate the function of the device to only a few. Therefore, the motions that will be used with the device must be chosen carefully to ensure that the force measuring device is capable of effectively evaluating a large range of force magnitudes, directions, and locations. The different motions were chosen so that grasping, twisting, pushing, and pulling were each involved in at least one activity. The activities the team chose to study when looking at the forces on the hands, wrist, and forearms are brushing teeth, opening a door with a lever handle, opening a jar, and typing on a keyboard. Activities which are commonly performed are also beneficial as they require no learning curve for the user and are easy to replicate. Choosing the activities that the device will be used for is important as they will affect the requirements and the functionality of the device.

2.3.1 Brushing Teeth

One particularly common activity which requires different movements and forces in the hand is the act of brushing teeth. Assuming the use of a standard manual toothbrush, most dentists recommend using the modified Bass technique for adults to remove the most amount of plaque [33]. The modified Bass technique involves angling the bristles of the toothbrush up toward the gums; and, without moving the bristles, pushing the head of the brush back and forth in short strokes or in small circles. The method calls for slight force to be applied to the teeth; some studies have found that approximately 3N of force applied is sufficient [33]. This method of brushing teeth invokes moving of the hand, wrist, and forearm. Since brushing teeth requires the hands to grasp, push, and pull a toothbrush, it was determined that brushing teeth would be a suitable activity to monitor with the force sensing device. The activity which will be monitored involves grasping a manual toothbrush in the dominant hand and brushing teeth with the modified Bass technique, applying 'gentle pressure' to the teeth. To properly grasp the toothbrush, the small, ring, middle, and index fingers wrap around the handle of the brush and the thumb rests on the handle in the same axis of the handle, an example can be seen in Figures 7 and 8. A firm, but not tight pressure will be applied to the handle, and there will be no bending or twisting of the wrist during this activity.



Figure 7: Side down view of the tooth brush grip



Figure 8: Top down view of the tooth brush grip

2.3.2 Opening a Door Handle

A common activity which involves twisting and pushing or pulling is opening doors with a lever handle. The team decided to use opening a door with a handle as opposed to a knob with both the dominant and non-dominant hand, an image of the door handle which will be used can be seen in Figure 9. The motion which will be monitored involves firmly grasping the handle with the small, ring, middle, and index fingers wrapping around the handle and the thumb resting on the same axis of the handle. The placement of the fingers and the hand can be seen in Figure 9.

The user will rotate the hand about the axis of the wrist. Once the handle has been rotated in a downwards direction of 90 degrees, the user will push or pull the door open with only the hand, wrist, and forearm.



Figure 9: Top down view of door handle grip

2.3.3 Opening a Jar

An activity which requires use of both the dominant and non-dominant hands would be a beneficial task to evaluate the difference in forces in each hand. The simple task of opening a jar employs both hands, one to secure the jar in place, and the other to twist the lid off. The two hands are performing different tasks, and since the device will be ambidextrous, the forces applied to each hand while opening a jar will be observed. To make the motion as normal as possible, the hand typically used to secure the jar will wrap the fingers and palm around the circumference of the jar and place the jar on a flat solid surface, no force should be applied to

hold the jar on the surface. The palm of the other hand will be placed on the top of the lid and the fingers, including the thumb will secure onto the lip of the lid. The placement of the fingers and hands are seen in Figure 10 and 11. The motion will involve keeping the hand which is securing the jar stationary and pushing down and twisting with the opposite hand about the wrist until enough torque is achieved to open the jar. The securing hand is not actively twisting the jar; however, it still experiences forces being applied which are initiated from the other hand attempting to twist the lid off.



Figure 10: Side view of the jar grip



Figure 11: Top down view of the jar grip

2.3.4 Typing

The last activity that the group chose to use to validate the functionality of the force sensing device is typing on a QWERTY keyboard. Although not very common historically, typing is becoming an essential part of working and attending school. The purpose of choosing this motion is a result of the recent increase in people typing frequently on personal laptops and desktops. As computers have become more prominent there is a significant chance that the new repetitive action will change bones and cartilage in the hand after a long period of time. Typing on a keyboard involves pushing down on different keys with the pads of the short, ring, middle, and index fingers. The sides of the thumbs are also used as well as the lower parts of the hand on the desk below. The placement of the hands and wrist can be seen in Figure 12. During the activity, the user will be asked to type a pre-established paragraph while using the force sensing device to monitor the pushing forces while typing.

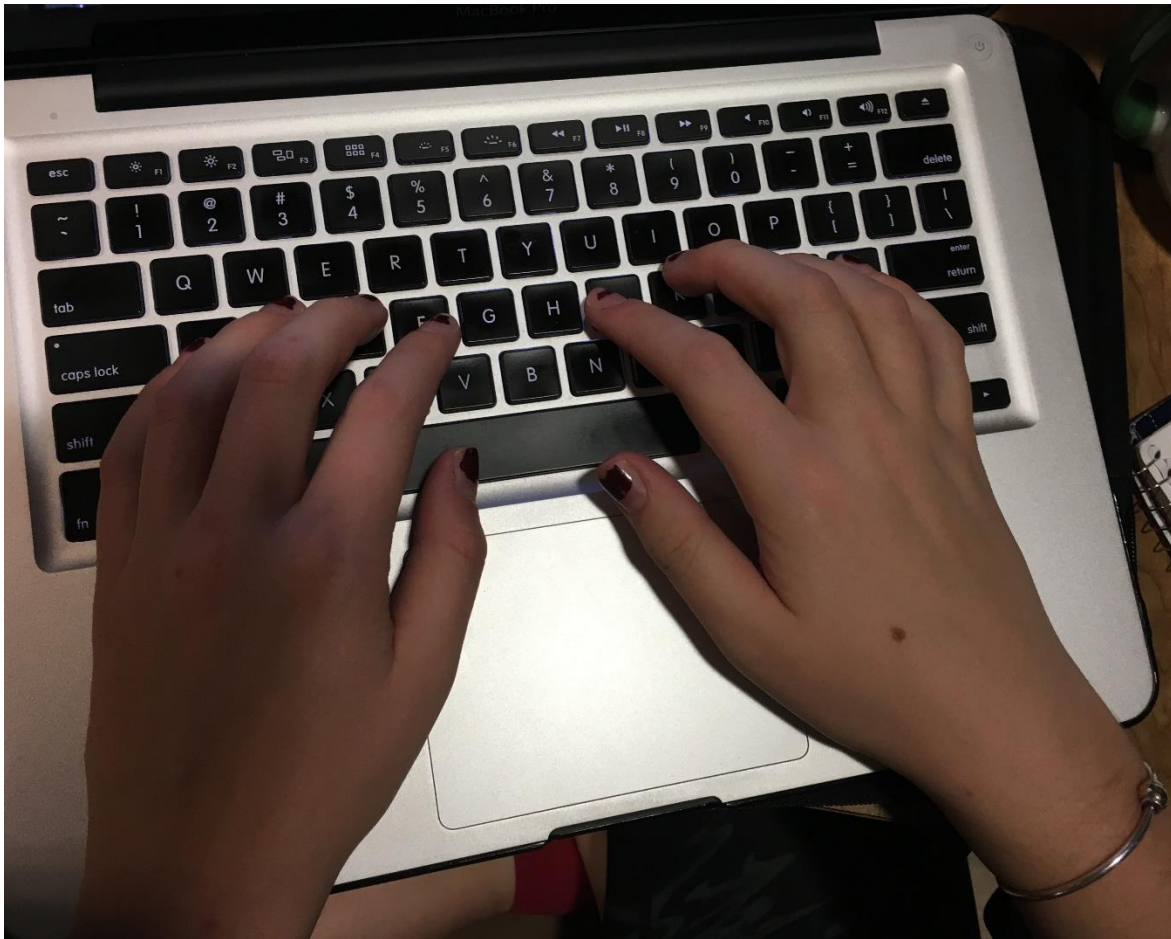


Figure 12: Top down view of the finger and hand placement while typing

2.4 Basics of Sensors

2.4.1 Why Sensors are Important

In order to directly measure the forces that are delivered to the upper extremities, sensors may need to be employed with the device. There are a few different types of sensors that have the capability of measuring the forces as required by this project. In the following sections, basic types of sensors and how they work will be discussed. The sensor or sensors that may be selected for the final design must be able to measure forces and their magnitude for any activities performed by the hand. The basic sensors or even variations on the sensors discussed below may

not be chosen for the final design of the force sensing device but serve as an introduction to potential options.

2.4.2 Strain Gauges

Strain gauges are a common way to measure applied forces. Strain is the change in a material's length and can either be tensile or compressive. Strain gauges work by measuring the amount of change in resistance of a piece of conductive material. The change in resistance is measured across two different points on the piece of conducting material. If there is strain in only one axis of the material, there will be a simultaneous change in the length of the material in other axes according to Poisson's ratio. This principle means that strain will change the length and cross sectional area of the material; and resistance of a material is dependent on the length and cross sectional area. An example of the effect of strain on a conductive material can be seen in Figure 13.

Strain gauge sensors typically consist of conductive wires placed on a carrier, which is the non-conductive, flexible material. The carrier is then placed on or adhered to the location where the forces are being applied. To measure a force being applied using a strain gauge, the change in resistance can be used to calculate the amount of pressure being applied at a location [34].

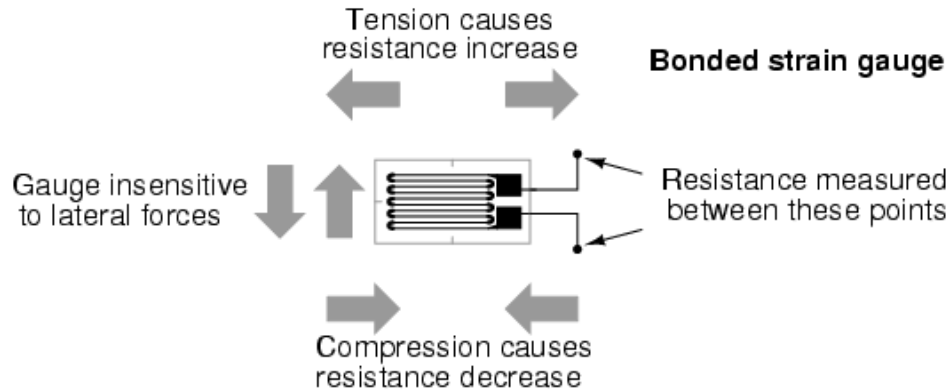


Figure 13: The types of forces that are delivered to a strain gauge [34].

2.4.3 Piezoelectric Strain Gauges

Piezoelectric strain sensors work by converting a mechanical input into an electric output. If a force is applied to a piezoelectric strain sensor, the output of the sensor will be a voltage reading. A greater force that is delivered to the sensor will result in a larger voltage differential [35]. When the force is applied, the length and width of the shape will change, which leads to a change in electrical properties. On the molecular level, when these sensors have strain applied, the result is a buildup of negative or positive charge on the material which can be seen in Figure 14. In the context of a force sensing device for upper extremity activities, piezoelectric sensors would be able to register the force applied during the specified activities and output a proportional voltage differential [35].

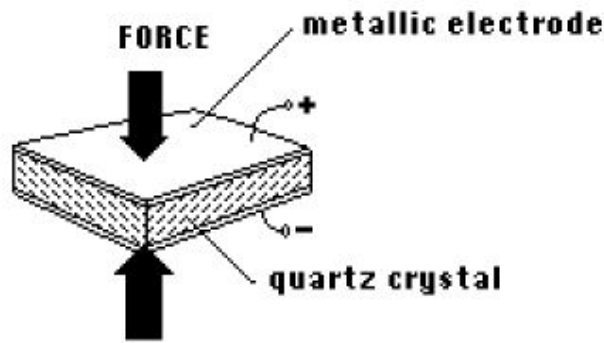


Figure 14: A view of a piezoelectric sensor [36].

2.5 Current Technologies

2.5.1 Tekscan® DX•f Glove

One similar technology to the goal of this project has been created by Tekscan® and it is called a DX•f Glove, which can be seen in Figure 15. This glove is worn to be able to measure the total amount of forces applied on the hands during different daily activities. FlexiForce sensors are used in the glove to measure the forces delivered. FlexiForce is a brand of sensor that is very flexible and has the ability to sense change and rate of change of an applied force. They work by measuring the amount of resistance in the electrical circuit. When a force is applied to a sensor, the resistance decreases and when a force isn't applied, the resistance is at its highest. The data that is collected is translated to deliver the total time and exertion that occurs during the action [37].

Although this device does measure forces, it does not record them in a way that would be useful to this specific project. It measures the total force applied to the hand that the glove is on, while this project requires forces at multiple locations on the hand to be separately recorded at the same time and throughout each activity.



Figure 15: Tekscan DX•f Glove [37]

2.5.2 Tekscan® Grip™ System

The Tekscan® Grip™ System, seen in Figure 16, is used to measure pressures while someone is gripping different types of objects with their hands. It has the ability to measure the pressures in both hands at the same time as well as at multiple locations simultaneously. The grip system records the pressure in enough locations that it can make a pressure diagram of the entire hand. The sensors that are used are very flexible and allow for many different types of movements [38].

Although many of the aspects of this technology coincide with the objectives and goals of this project, it is more complicated than the project requires. The device that will be built by the project team does need to be flexible, measure forces on both hands, and measure forces in multiple locations. However, it does not need to be able to read the forces over the entirety of the hand. The object is also to measure forces and not pressures, therefore the sensors in the Tekscan® Grip™ System are not ideal for this project.



Figure 16: Tekscan® Grip™ System [38]

Neither of these devices are exactly what the team is looking for to satisfy the goals of this project, however their technologies may be useful in the development of the force sensing device. A summary of these current technologies and how they relate to this project can be found below in Table 1. All of the information collected during the literature review will be used to help the design team throughout the engineering design process. The next section of this report will explain the team's design requirements and strategy for the completion of the project.

Table 1: Summary of the current technologies and how they fit/do not fit with the requirements of this project

Current Technology	How it would be helpful	Why it wouldn't work
Tekscan® DX•f Glove	<ul style="list-style-type: none"> • Measures force • Flexiforce sensors 	<ul style="list-style-type: none"> • Only measures total force
Tekscan® Grip™ System	<ul style="list-style-type: none"> • Flexible sensors • Records data from both hands simultaneously • Records data from multiple locations simultaneously 	<ul style="list-style-type: none"> • Measures pressure • Overly complicated

3 Project Strategy

3.1 Initial Client Statement

The team was given an initial client statement from the project advisor Dr. Karen Troy, which is as follows:

“Design and fabricate a force-sensing device for measuring loads produced and acting upon the hands and fingers during various activities. The device must be able to measure force magnitude and direction, relative to an anatomic landmark such as the axis of the forearm and wrist, during activities such as gripping, twisting, pushing, and typing. The device should be capable of measuring the forces on both the dominant and non-dominant hand during a given activity, though not necessarily simultaneously. Force magnitude should be accurate within +/- 3 N, direction should be accurate within +/- 5 degrees, and location should be accurate within +/- 5 mm.”

3.2 Design Requirements (Technical)

3.2.1 Objectives and Secondary Objectives

In order to satisfy the needs of the client, several objectives were first created by the design team to help determine potential designs.

Ambidextrous

As stated in the client statement, the device must work for both hands. It will be designed so that the forces can be read from both the right and left hands during all of the chosen activities. A secondary objective is that the device fits correctly on both hands. If it fits differently on the left and right hands, the device will not give accurate data and skew the results.

Reusable

The design chosen must be reusable based on how expensive the device is to make. It will not be cost effective if it can only be used once or even a couple of times if the device is expensive. If the design chosen is inexpensive, it does not have to be reusable. Our device should last about five years.

Durability

It is important that the device is durable and can withstand normal use. If this were not the case, the device would break too easily and not provide accurate results. The secondary objectives that the device must meet for durability are that the device must withstand being dropped or getting slightly wet.

Safety

Safety is an essential objective, primarily for the user and operator. The secondary objectives that fall under safety are that the device must not have any pinch points and that the device must not put the user at risk of electrical shock.

Portability

The device should be portable as it will be used to test activities which require a full range of motion. It also must be transported easily.

Ease of Use

It is important that the device is also easy to use. The secondary objectives are that it should not be difficult to train someone to use the device or take excessive amounts of time to set up.

Table 2: Pairwise Comparison Chart for Ranking Objectives

Objectives	Ambidextrous	Reusable	Durability	Safety	Portability	Ease of Use	Total
Ambidextrous	X	1	1	1	1	1	5
Reusable	0	X	0.5	1	1	1	3.5
Durability	0	0.5	X	1	1	1	3.5
Safety	0	0	0	X	1	1	2
Portability	0	0	0	0	X	0	0
Ease of Use	0	0	0	0	1	X	1

The pairwise comparison chart, seen in Table 1, shows how the team ranked the objectives. Ambidextrous is the highest ranked objective primarily due to the emphasis placed on the device being capable of collecting data from both hands, as stated in the client statement. It is also pertinent that the device can be used on both hands so that users who are right or left-hand dominant can use the device. Reusability and durability are ranked second, to prioritize that the device is cost and time-effective when it comes to purchasing and how frequently the device can be used.

Although safety falls lower on the list of objectives, it is important to note that based on the nature of this device, there will be very low risk of danger to the user. Ease of use was ranked penultimate because the functionality of the device should be prioritized over how easy it will be to set up and use the device. Portability was ranked last similarly because the functionality and the ease of use of the device would be more beneficial to the client and the user than for the device to be moved around easily.

3.2.2 Constraints

There are also several limitations associated with the project that the design team must keep in mind.

Budget

The budget cap for the project has been set to a value of \$1500. This value was determined after discussion with the client, Dr. Karen Troy. Any expenses, including: prototyping, materials, manufacturing, testing, and any other unforeseen circumstances, must not exceed this \$1500 budget. Although the budget is \$1500, per request of the client, the device will cost much less.

Perform Defined Activities without Issue

The design of the device must not inhibit the performance of any of the chosen activities that are to be studied and tested. If the device were to interfere with the activities, the results would not be accurate and therefore it would not meet the criteria set by the client.

Compatible with Standard Lab Software

To make the device reasonable for use in any lab, all data acquisition that the device completes must be compatible with any standard software. Appropriate software includes but is not limited to: MATLAB, Excel, etc.

3.2.3 Functions

In order to further define this project, it is important to know and decide what the device is supposed to do by defining the functions.

Measure the Forces of the Defined Upper Extremity Activities

From the definition of the project, the device built is supposed to measure the forces that occur during the activities the team has chosen to work with. This is important because the device will be used in future research to determine how the forces that occur during everyday activities affect the bones and cartilage in the hands, wrists, and forearms.

Measure Magnitude and Direction Relative to the Wrist

It is also necessary for the device to be able to measure the magnitude and direction of each of the forces. This knowledge will help to further understand how the biological tissues in the hands are being affected by the forces. The device will also measure this data relative to the wrist because this is the center point of the three body parts (hand, wrist and forearm) the team is looking into. This will allow for calculations regarding forces and moments to be made more easily.

3.2.4 Specifications

Remain within a Required Range of Accuracies

The range of accuracies for the device the team will build includes specifications for the force, direction, and location. The force measurements should be within $\pm 3\text{N}$, the direction should be within ± 5 degrees, and the location should be within ± 5 mm.

3.3 Design Requirements (Standards)

The design team chose to follow IEEE standards and style guidelines for the report format and references. When developing a program for the user in LabVIEW, the design team followed guidelines put forth by National Instruments; and IEEE standards regarding electrical wiring diagrams were also considered. The specific standards that were followed by the design team are more thoroughly described in section 6.3.

3.4 Revised Client Statement

The client statement was revised to include the specific activities the team chose to focus on for the project. The ranges of accuracies were also removed from the client statement because they were specifications. The revised version of the client statement is as follows:

Design and fabricate a force-sensing device for measuring loads produced and acting upon the hands and fingers during various activities. The device must be able to measure force, magnitude, and direction relative to the wrist. The activities that will be measured are opening a door with a handle, opening a jar, brushing teeth, and typing. The device should be capable of measuring the forces on both the dominant and non-dominant hands during each activity, though not necessarily simultaneously.

3.5 Project Approach

In order to help determine how to manage and organize the completion of the project, the team created a Gantt Chart which can be seen in Table 2 and a Work Breakdown Structure which can be seen in Figure 17. The Gantt Chart lays out the timeline for when the team worked on certain parts of the project and when they were completed by. The Work Breakdown Structure separates the larger tasks that needed to be completed into smaller, more manageable components to help verify the success of the project.

Table 3: Gantt Chart

A Term							
Task	1	2	3	4	5	6	7
Research	█	█	█	█	█	█	█
Problem Definition	█						
Conceptual Designs	█	█	█	█	█	█	
Sensor Locations			█	█	█		
Weight Capacity Needed			█	█	█		
Narrow down designs						█	█
Ch 1-3		█	█	█	█	█	█
B Term							
Task	1	2	3	4	5	6	7
Research	█	█	█	█	█	█	█
Prototyping	█	█	█				
Testing Prototypes			█	█	█		
Pros and Cons		█	█	█	█	█	
Choose Final Design					█	█	
Ch 4		█	█	█	█	█	█
Ch 1-3 edits						█	█
C Term							
Task	1	2	3	4	5	6	7
Research	█	█	█	█			
CAD Drawings	█	█	█				
Build Final Design	█	█	█				
Validation Testing			█	█	█	█	
Draft of Final Report		█	█	█	█	█	█
D Term							
Task	1	2	3	4	5	6	7
Final Edits on Final Report	█	█					
Submit Final Report		█	█				
Presentation Preparation	█	█	█	█	█	█	

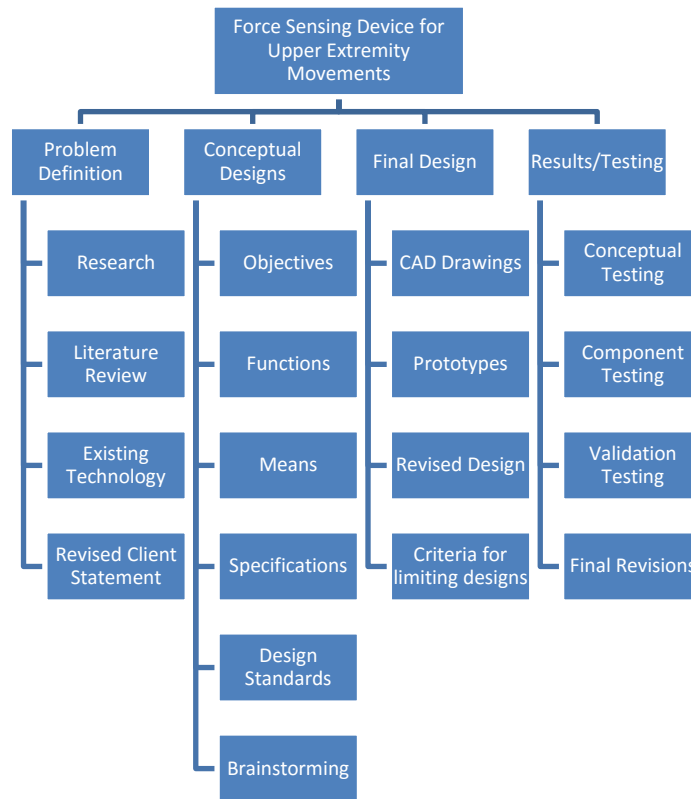


Figure 17: Work Breakdown Structure

3.5.1 A-Term

The timeline of the project that the team created was based by term. To start, the team completed the background research for the literature review and determined a problem definition in order to understand the problem and project fully. This was completed in the beginning of A-Term. Several other items were also completed by the end of A-Term in order to stay on track. Since the device that was built collects force data, the team determined where the forces for each activity are applied on the hand. This was done using paint and paper. By performing the chosen activities with a piece of paper that had wet paint on it, the team was able to determine which parts of the hand use the most force by where the most paint stuck to the hand. The weight capacity of the force measuring method was determined which by doing different tests on a scale and converting pounds to Newton's. The different tests were simply

pushing on the scale with one hand and doing a typing motion. This helped determine what the maximum and minimum forces the device needs to be capable of measuring. By knowing how much force the device needs to collect helped determine what type of design the device should be. Once this was completed, several conceptual designs were made and narrowed down to two or three final designs that were tested during B-Term.

3.5.2 B-Term

During B-term, the conceptual designs that were established previously were partially built and tested for their feasibility; these actions led to the final chosen design being prototyped by the end of B-term. The purpose of testing the different design options was so that the advantages and limitations of each design could be confirmed and from there, a decision was made on the final design of the device. Once the final design was chosen the prototyping phase was able to begin. This involved ordering the parts needed, building parts of the device, and doing preliminary experimentation. The preliminary testing included making sure each part of the device worked properly before the final prototype was completely built, which was done at the end of B-Term. The final verification testing of the device began in C-term.

3.5.3 C-Term

This term consisted primarily of verification testing for the final design as well as finishing a majority of the MQP final report. First, testing was continued on the final design that was chosen during B-Term. The team gathered the results from verification testing to ensure that the design worked correctly, gave the appropriate metrics, as well as remained within the specified tolerances. The team tested the device using a predetermined force to make sure that it delivered values within the specified tolerances. This approach was used to test the validity of the device. Once all of the tests with the different activities were completed and the device was proven to deliver valid results, the team was able to finish up the design. Aside from the design aspect

of this project, the team also be worked on a majority of their MQP final report to have completed chapter five, six, seven and an outline of chapter eight by the end of the term.

3.5.4 D-Term

In D-term, the team revised the final report and completed Chapter 8. The report was then submitted. A two page abstract consisting of a summary of the final report was written and submitted for the Project Presentation Day brochure. The team worked on a final presentation which, after several practice presentations, was presented on MQP Project Presentation Day at Worcester Polytechnic Institute on April 21, 2016.

4 Alternative Designs

4.1 Needs Analysis

A needs analysis helps determine which specifications are necessary or are ‘needed’ for the design and the ‘wants’ are the specifications that the client would like, but are not necessary for the final design to be completed. After a discussion about the device with our client, the team came up with what the specific ‘needs’ and ‘wants’ are. The device needs to be ambidextrous and cannot inhibit motion. It must be simple for the user to calculate results upon collection of data, must be able to measure the forces relative to a location on the wrist as well as measure forces in multiple of pre-selected locations. A ‘want’ is that it is simple for the designers to calculate the measurements as listed above. It is a requirement that the results should be easy to calculate for the client however it is desirable to have the calculations be simple for the designers.

4.2 Functions and Specifications

The design must be ambidextrous so data can be collected from both hands. It must be reusable and durable, such that it will not break too easily or can withstand getting slightly wet. The device must also be safe, such that there are no pinch points and that the device does not put the user at a risk for an electrical shock. The device must also be portable enough to be transported easily to conduct the experiments as well as have a full range of motion for any activity. It must be easy to train the user and should not take excessive amounts of time to set up. The first function the device is that it should measure the forces of the defined upper extremity activities. The next function is that it should measure magnitude and direction relative to a location on the wrist. This location was established by the client.

4.3 Preliminary Designs

At the initial stage of the design process, approximately 10 to 15 design options were brainstormed. Following further research and discussion, the design concepts were narrowed down to four preliminary design options.

For each of the four preliminary designs, the overall concept and a drawing were put together. Then it was discussed in further detail how the design would work and the pros and cons associated with the design were determined. A feasibility study was then conducted in order to decide on a final design to move forward with. This involved first creating a table that included each different design across the top and each of the criteria the design should meet going down the left side. An example of this table can be seen below in Table 4.

Table 4: Chart used to conduct feasibility study

Design Criteria	Putty/Playdough	Sensor Glove	Interchangeable w/load cell	Fujifilm
Doesn't inhibit activities				
Ambidextrous				
Durable				
Reusable				
Burden for user to complete calculations				
Measure forces relative to wrist				
Measure forces in different locations				
Cost effective				
Easy to use				
Total Score:				

Each team member then filled out their own chart in separate areas to avoid any influence from other team members. The design criteria that the team based this study on were as follows. The completed charts can be found in Appendix A.

In order to have the most successful device, the design must not inhibit any of the four activities chosen to work with, it should be able to be used for both the right and left hands, it should be easy to use, and it should be durable, as to not break easily. The design should also be reusable or if made to be for a one time use, cost effective. Other criteria that are necessary for the design to be successful are that the calculations must be easy for the user to do, the forces must be measured relative to the wrist, and the forces must be measured in different locations. Finally, the design should also be cost effective.

4.3.1 Design Alternative 1 - Interchangeable Parts

One preliminary design concept was to use interchangeable parts on a force plate, which can be seen in Figure 18. In this design, a six axes force plate would be retrofitted to have different apparatuses be fixated to, which the activities would be performed on. To obtain the forces that were applied during the activities, the torque around the interchangeable part would be measured. After considering further research, different pros and cons were established for this method as well. Some of the pros of this method involve that it is ambidextrous, any sized hands can use this device, it can be universal for many different parts, and would be reusable. Some cons are that this device is bulky and not portable. Another con is that the attachments have to be made and are specific to one activity at a time.

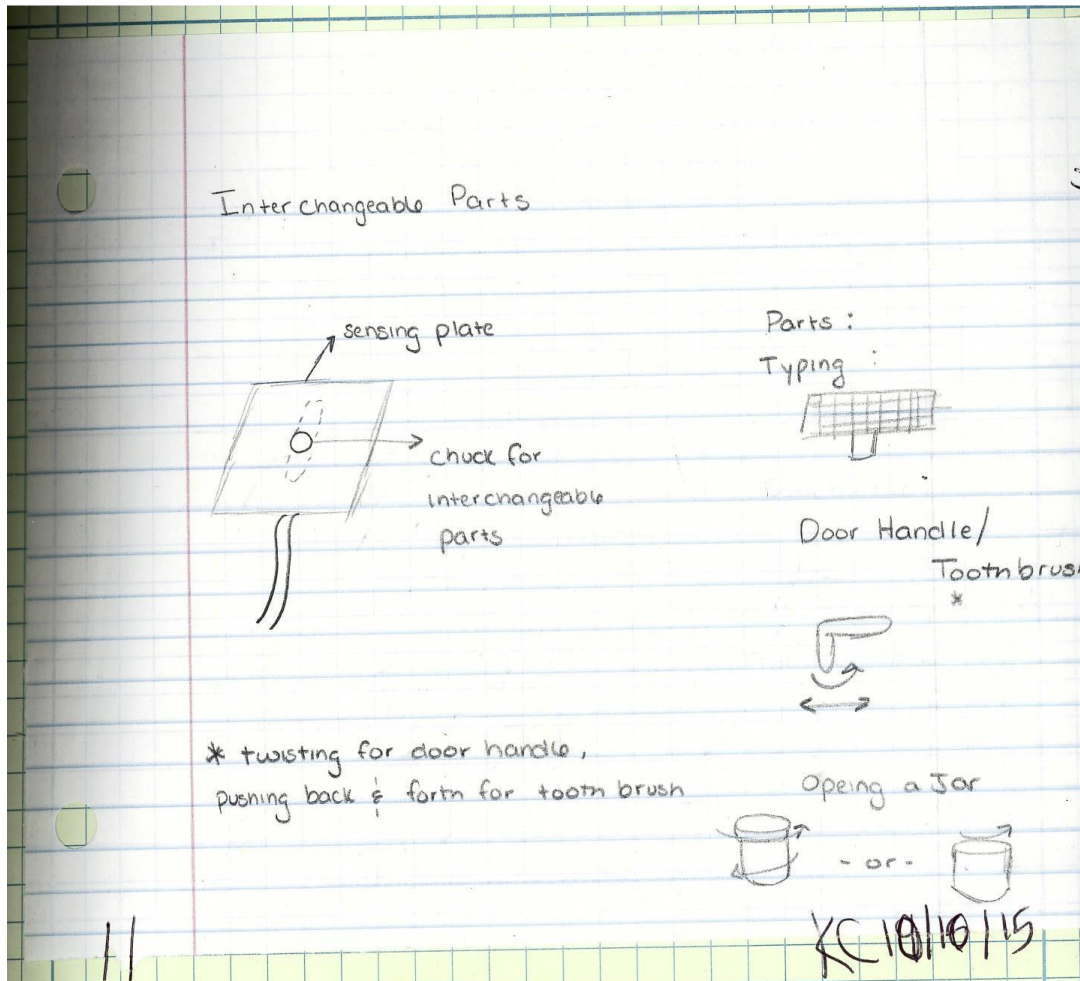


Figure 18: Interchangeable parts design drawing

The interchangeable parts with a load cell design was the third most feasible design. This design was not as ideal as the others because it would be difficult to measure forces in more than one location and it would also be difficult to perform the calculations needed. However, this design would allow use with both the left and right hands, be reusable, durable, and would not inhibit the activities. The team was unable to get available load cells to function properly for this application.

After conducting the feasibility study and experimenting, it was decided that this design would not be the most suitable for this project. While this design would measure the force and torque delivered while doing each activity, it would not deliver the most desirable data. It would be difficult to collect data at different locations using a load cell because it would give the total torque and force for each activity rather than individual ones at specific locations. It would also be difficult to determine the location of the forces because it would not be possible to determine where the exact force was coming from. Because it would be difficult to determine where the individual forces were exactly occurring as well as their location, it was decided that this design would not be the most suitable for this project.

4.3.2 Design Alternative 2 - Playdough/Putty

Another design consideration was to use a playdough or a putty-like material which, when deformed, would maintain the changed shape. This design can be seen in Figure 19. The concept behind this design would be to place the material on the objects being used for the motions (i.e. door handle, keyboard, jar, and toothbrush). Once the user performed the task, and left an imprint in the dough material, the strain would be measured. Using the known Young's Modulus (E), and measuring the applied strain, equation 1 would be used to calculate the stress that occurred during the activity. Once, the stress is known, then equation 2 would be used to calculate the forces that were applied during the activity.

$$E = \frac{\sigma}{\epsilon} \quad (1)$$

$$\sigma = \frac{\text{Force}}{\text{Area}} \quad (2)$$

Following further research and testing, certain pros and cons for the playdough method were established. Some of the pros for the method were that the materials used could be kept

relatively cheap and could be used for many different activities, not just the ones chosen for this project. The cons, however, include the difficulty in measuring the strain applied to the material. Surface metrology methods, including lasers were considered, but the instruments available at Worcester Polytechnic Institute were not suitable for the application. This method would also result in data collected for the entire hand, which leaves a lot of work and difficulty for the user of the device to get the relevant information they actually need. Another disadvantage that was noticed when testing with materials, such as playdough and silly putty, is that they were too elastic; and, that it was difficult to get the material to form to the exact same shape and thickness for each activity without 3-D printing a mold.

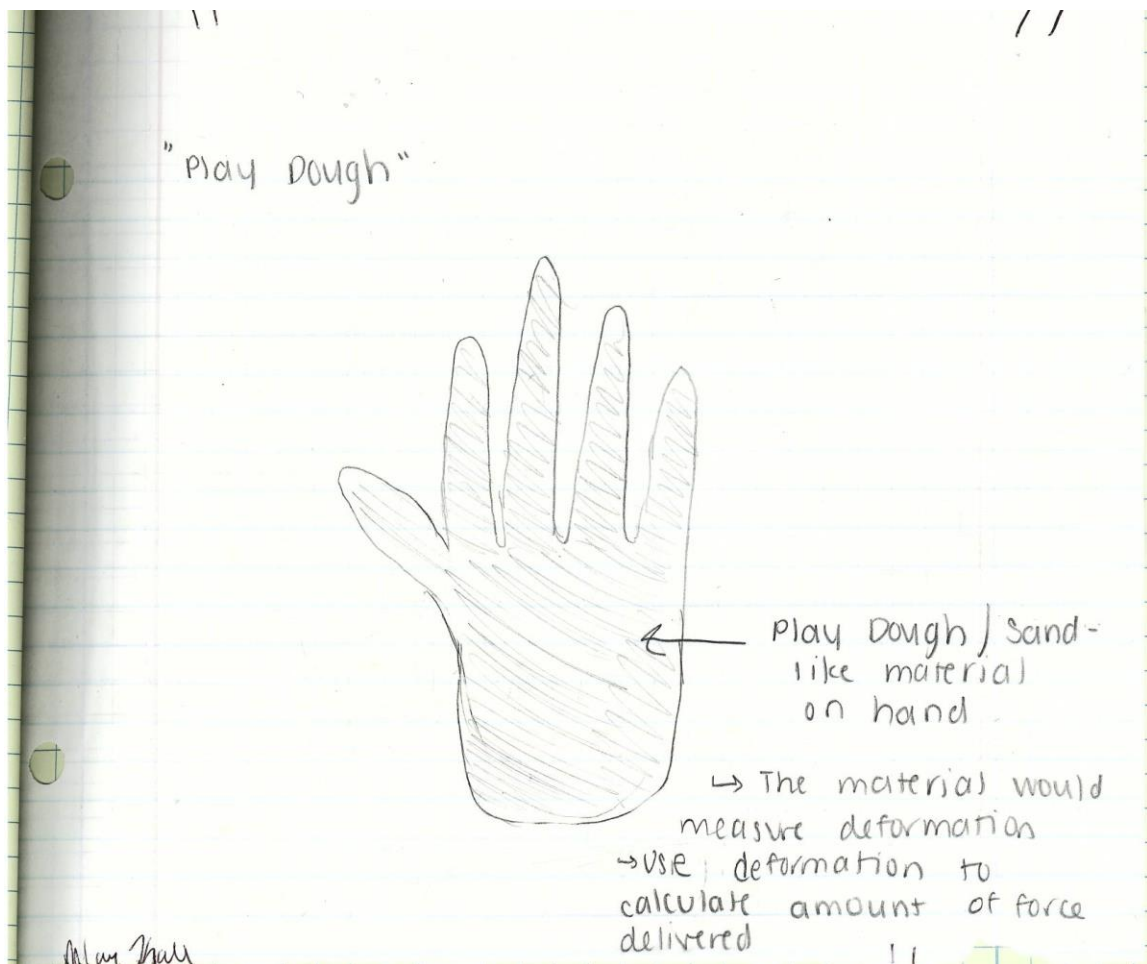


Figure 19: Playdough/putty design drawing

This design would be extremely cost affective, usable for both the left and right hands, would not inhibit activities, and would allow for forces to be measured in multiple locations. However, this design is less feasible because the data collected would not be quantitative, in excess, and the calculations would be difficult to perform. The playdough or putty design was considered to be the least feasible preliminary design.

After experimenting with different types of putty, it was determined that this design would not be suitable for the project. A silly putty substance, made out of Elmer's glue and liquid starch, was created to test this design in addition to purchasing playdough. Both of these substances were tested and proven to be too elastic to work for the design. After the activity was done using each type of substance, the deformation did not remain once the force was removed. Using this design would skew the data and produce inaccurate results because the strain that occurred during each of the action would not be the correct value.

4.3.3 Design Alternative 3 – Fujifilm Pressure Film

A preliminary design the team came up with was using Fujifilm pressure film on a glove. This film is a type of pressure paper that changes colors (to red) when enough pressure is applied. The shade of red becomes darker as more pressure is applied. It comes in several different pressure ratings for different applications; each pressure rating comes with a range of pressures that the paper will change colors for. This allows for small and large pressures to be accounted for [39].

This design would work by placing a layer of Fujifilm pressure film on a glove and then having the person perform the required activities. The pressure film would then show exactly where and how much pressure had been applied based on the shade of the red dye on the film. The

pressures would then be quantified into forces by having the team do a calibration. Different weights would be placed on the film and the corresponding color would represent the force that was applied. This design would be useful because it would be flexible, allowing the user to perform any of the activities with ease. It is also relatively inexpensive. The drawbacks to the Fujifilm pressure paper design would be that the measurements would not be extremely precise and it would not be reusable.

The design team obtained pressure paper that was rated for 2 to 20 psi and performed several activities with the paper. When comparing the marks obtained from the activity, it was difficult to determine if there were large changes between forces applied at different locations on the hand. The Fujifilm design came in second after conducting the feasibility study because it would be able to measure forces at different locations, be usable for both the left and right hands, and be easy to calculate the necessary values with a calibration chart. This design would also be cost effective because although it is not reusable, it is inexpensive making it feasible to be reusable. The Fujifilm design would not inhibit the activities and would be easy to use. The issue the design team saw with this design was that the data would not be within the specifications set forth by the client for accuracy.

After performing the feasibility test and analyzing the pros and cons of the Fujifilm pressure film design in detail, it was decided that it would not work for this project on its own. This design would not work because although it is relatively inexpensive, it is not quite low enough in cost to be used for a non-reusable device. It also would not provide precise enough data as there are pressure ranges for each color, which would be converted into force ranges.

Although this design would not work on its own, it has potential to be used in conjunction with another design to give the design team a better understanding of which parts of the hand apply the most force during each activity.

4.3.4 Design Alternative 4 - Sensor Glove

The last preliminary design concept was to place sensors in a glove to measure the force in predetermined areas of the hand, which can be seen in Figure 20. The sensor glove method would involve securing force sensors on glove in specific locations on the hand based on the activity being performed. The sensors would be secured using hook and loop (Velcro®) in order to allow them to be easily moved to different locations. The forces would be recorded throughout the activities so that the range of forces can be observed throughout. Multiple different force rating sensors would be bought to account for the different forces that occur at different parts of the hand.

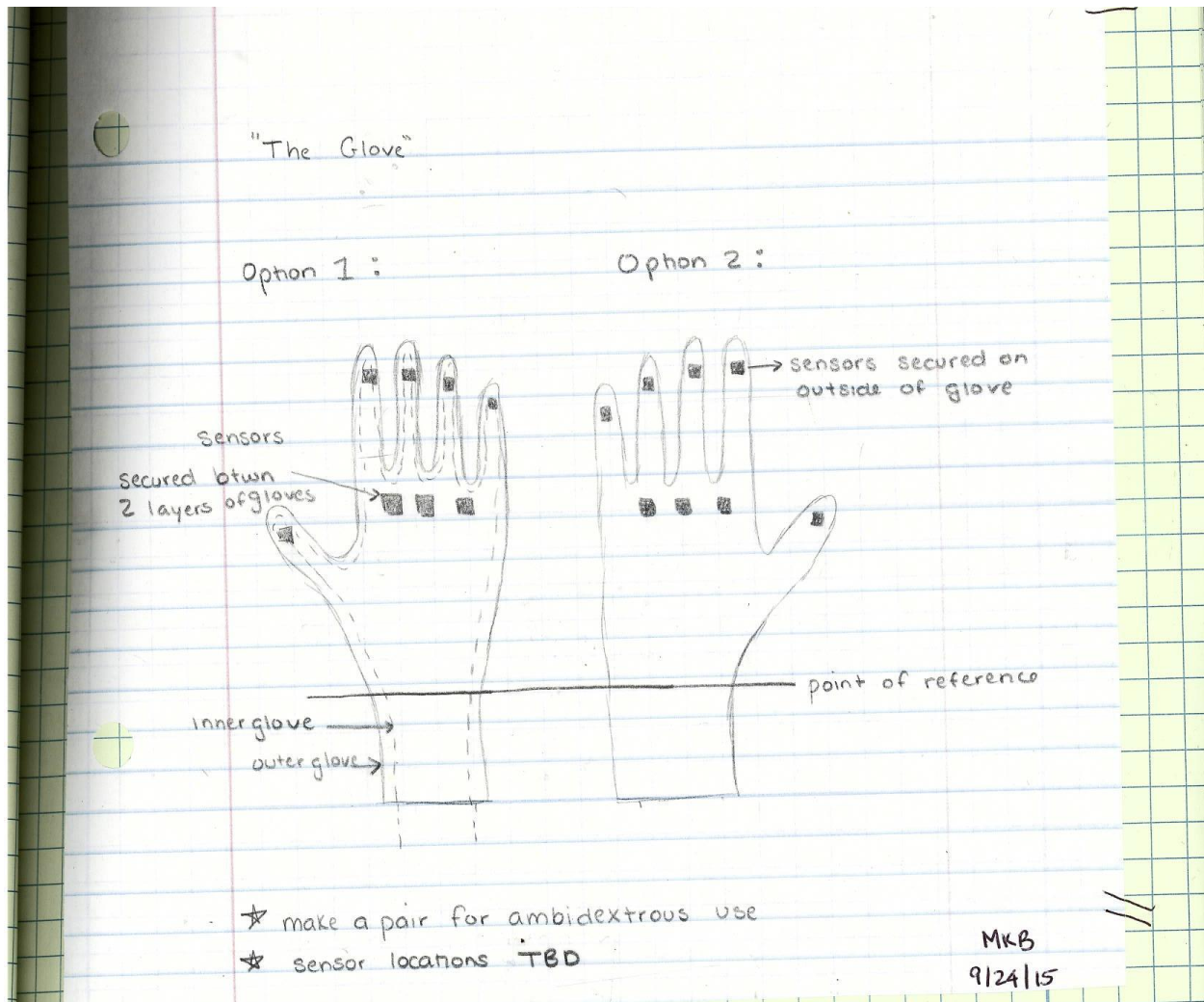


Figure 20: Sensor glove design drawing

The benefits of the sensor glove design are that the data collected would be very precise and relevant, it is compatible with both hands, it is portable, it would not inhibit movement, and it is reusable. The drawback associated with the design is that the data will only be collected from a limited number of locations on the hand.

The sensor glove came out to be the most feasible design. The reasons for this are that it would be reusable, durable, and usable for both hands as two different gloves could be made. The sensor glove would also allow for forces to be measured at multiple locations, be easy for the

user to have the calculations performed once the team creates a code for the specific calculations needed, and would not inhibit the activities. Finally, the sensor glove would be cost effective because the sensors would only have to be bought once due to the gloves being reusable and durable.

To test the feasibility of this method, a Tekscan FlexiForce A201 sensor (rated for 445 N) was obtained. The team found that the size of sensors and the flexibility worked well with the size of the hand and did not inhibit the movements. After this experimentation and a detailed analysis of the pros, cons, and feasibility of the sensor glove design, it was decided that it would be the most suitable option for the final design.

4.4 Decision of Final Design

After conducting research to find different force or pressure sensors, the Tekscan A201 force sensors were chosen based on specifications and qualifications. These thin and flexible piezoelectric force sensors have three force ranges which fall within the specifications required for the activities. The Flexiforce A201 sensors, seen in Figure 21, are available in ranges of 4N, 111N, and 445N. In order to determine the ranges necessary for the different activities being performed, the different activities were done on a simple bathroom scale to get the overall force that would be applied. On the bathroom scale, opening a peanut butter jar and typing on a keyboard were simulated as seen in Figures 22 and 23.



Figure 21: Flexiforce A201 sensors



Figure 22: Tying force testing using bathroom scale.



Figure 23: Jar opening force testing using bathroom scale.

Based on the rough observations obtained, the sensors to be used need to be able to read forces between 15 lbs (66 N) and 43 lbs (191 N) which are obtainable by the Tekscan A201 force sensors.

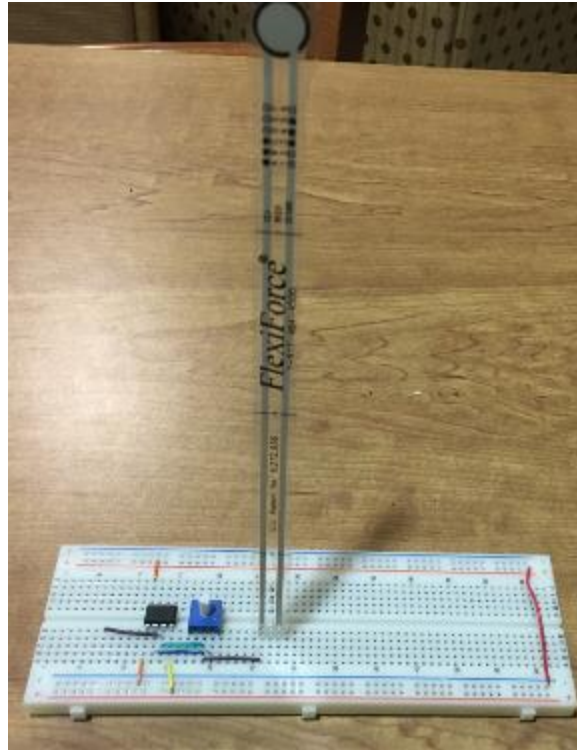


Figure 25: The op-amp circuit set-up with the sensor

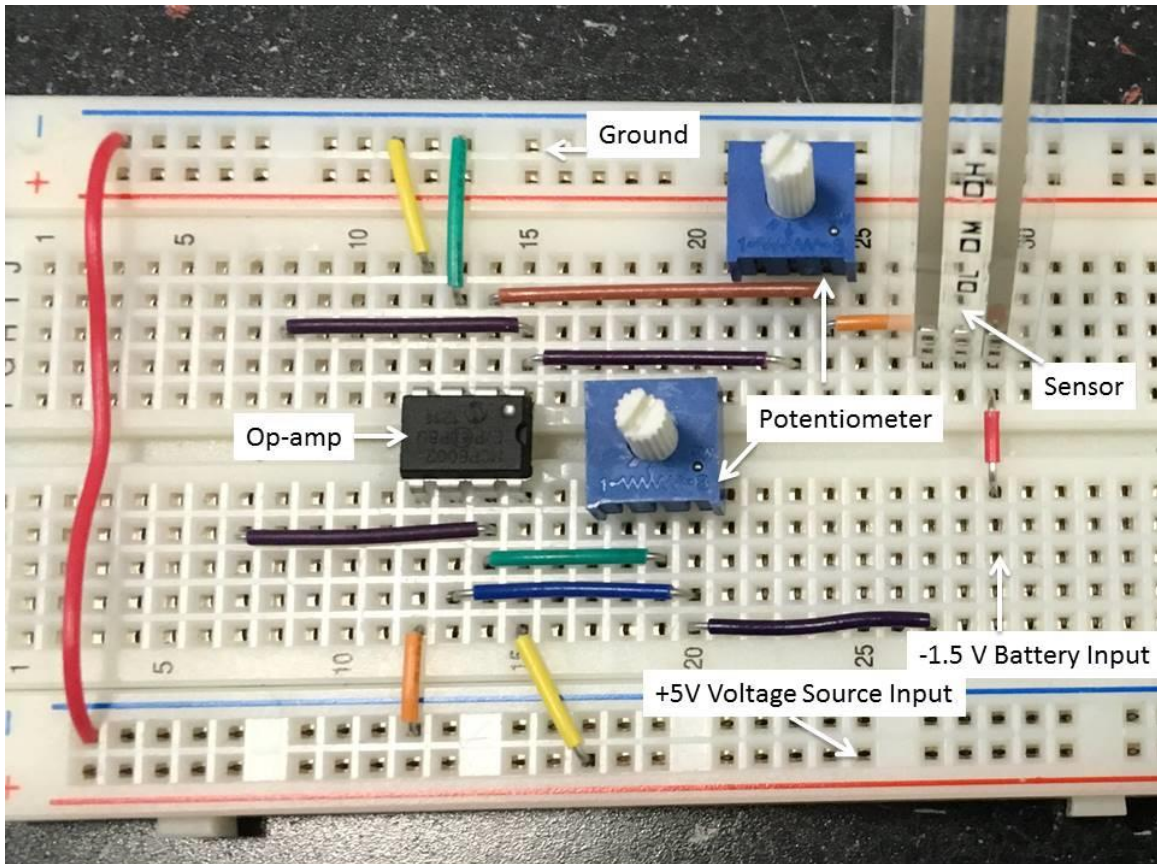


Figure 26: The op-amp circuit set-up with different components labelled. The input locations of the two voltage sources and the grounded column are also indicated.

A power supply with an output of 5V with a current greater than 0 amps, a 1.5 Volt battery and a digital multimeter were connected to the sensor circuit to measure the voltage output from the sensor compared to ground to test the functionality of the circuit. Figures 27 and 28 show the test setup with the voltage output with minimal force applied to the pad of the sensor and then the voltage output with force being applied to the sensor. The sensors rated for 111 N and 445 N were both tested and a large change in voltage was noted when forces were applied. In actuality, the force measuring glove is going to need to measure different forces at different locations on the hand. The circuit will need to be added to in order to accommodate the multiple sensors.

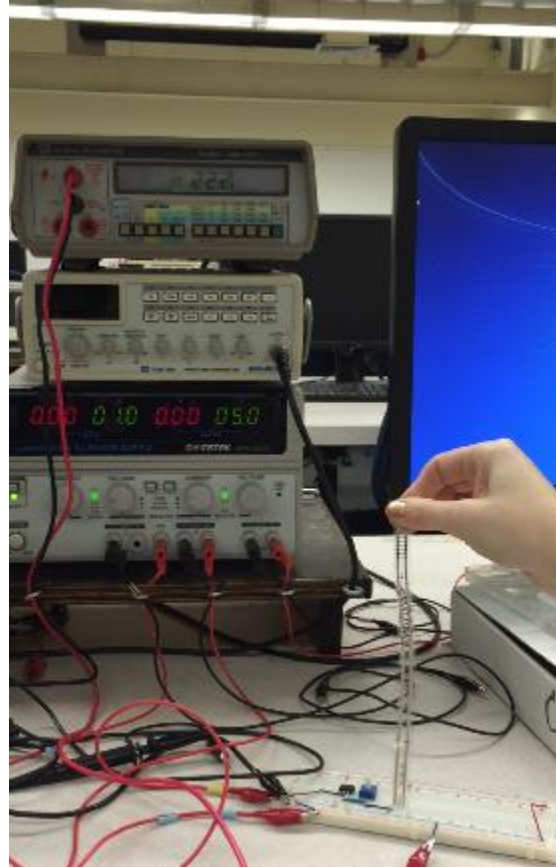


Figure 27: Voltage reading in blue circle while sensor was being pressed upon (22.2mV).

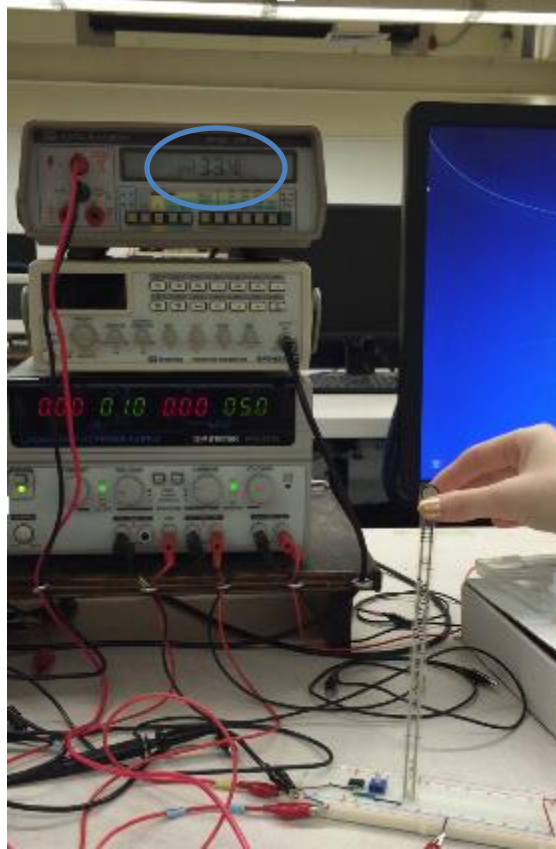


Figure 28: Voltage reading in blue circle before sensor was pressed upon (133.4mV)

As with piezoelectric sensors, the input signal may be a force; but the output is a voltage. A simple calibration curve can be used to convert the voltage output into relevant units of force. By taking known weights, one can calculate the force which the weight applies to a surface it is resting on. If several known forces are applied to the sensors and the corresponding voltage is recorded, then a curve can be plotted so that any voltage that is observed has a corresponding force.

When considering ways to record the data that is being outputted by the sensors, the team decided to use a data acquisition device which meets the requirements of the force sensing device. National Instruments USB-6009 is a data acquisition device (DAQ) which has eight

analog inputs that can be used to record the voltages from up to 8 sensors. The analog inputs provided by the DAQ can be seen in Figure 29. Another benefit of the DAQ is that it also can produce an output of 5V, which is a requirement to power the sensor circuit. Using this one, small device to collect and power the system would eliminate the need for an external power supply and excess bulk. Another benefit of using the DAQ is that the device is compatible with LABVIEW software; which can be easily utilized to provide any necessary calculations and to display and store the data.



Figure 29: National Instruments USB-6009 data acquisition device

To make the force measuring device compatible with a wide range of activities, the force sensors should be adjustable. Different activities have different points of interest for forces on the hands. By enabling the user to adjust the location and the range of the sensor, the device will be versatile which is beneficial to the user. There are several suggestions to modify the glove(s) so that the sensors can be moved as needed; these suggestions include using Velcro® to adhere the sensor to the external portion of the glove and building ‘pockets’ into the glove so that the sensor pad can be secured within the glove itself. The choice of glove type is also important as it should

fit comfortably on the hand; not too loose or too tight for the user. The glove should also have some gripping capabilities to simulate the natural gripping ability of skin on the hands.

One of the design alternatives that was mentioned was to use pressure paper to gauge the pressure being applied to the hand during various activities. While this method was deemed not suitable to accurately measure the forces being applied, it could be of use to help the user decide where the sensors should be placed on the glove. Doing a trial run of the activity while using the pressure paper gives the user a good idea of where the major forces are being applied to the hand during the activity. Using this knowledge, the user can then adjust the location of the sensors as well as the force range of sensor to that part of the glove.

As stated in the client statement, it is also necessary to obtain the location and direction of the forces relative to the wrist. In order to do this the team will use goniometer protractors, which are made specifically for body parts. An example of this type of protractor can be seen below in Figure 30.

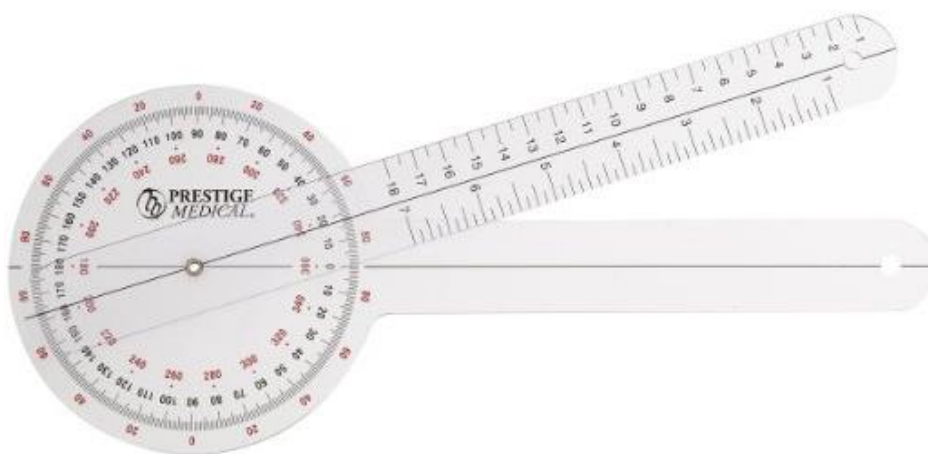


Figure 30: Goniometer [40]

The goniometer will be placed on the wrist and the angle relating to the force will be able to be found. There is also a ruler on the goniometer, so the team will use that to measure how far away from the wrist the force is. Either fiducial markers or other brightly colored markers will be placed at the sensor locations. During the activity, either a video or a series of photographs will be taken, with the goniometer and the sensor markers visible. Using a simple program, like Paint, the located pixels can be used with a scale to determine the distances and directions of each of the sensor markers.

5 Final Design Verification

Prior to collecting data, the team tested the force sensing device in a variety of ways to verify that the different components functioned correctly. The design team was then able to collect data for the four activities that were chosen to work with, including opening a door with a lever handle, brushing teeth, opening a jar, and typing on a computer. In order to collect the data, each of the three team members performed three trials for each of the four activities.

5.1 Verification Tests

Before data could be collected for each of the four activities, the design team had to ensure that each part of the device and data collection method were working properly. To do this, several verification tests were performed.

5.1.1 Sensor Location and Sensor Rating

It is important that the sensors being used are placed in appropriate locations for each activity. If they are not placed correctly, the data will not accurately show the forces that occur across the hand. These sensor locations were also used to determine where the forces are acting when determining the locations of the forces relative to a spot on the wrist. In addition to appropriate sensor locations, the force rating for the sensors at different locations needed to be considered so that appropriate data could be collected.

The first testing method suggested was to use FUJIFilm Pressure paper on the hand during the different activities. This was used to determine the location and the force rating of the sensor in that area. However, while testing, the team found that the carbon paper transferred the ink uniformly across the paper and the shades were indistinguishable. Some of the potential reasons this method did not work properly may be that the paper used was not in the correct pressure range; or that the paper shifted in such a way that the whole sheet underwent pressure. Another test was then developed to determine the proper sensor locations and force ratings.

In order to verify that the sensors were placed in the proper location, the design team performed a test using paint and paper towels. This was a simple, yet effective way to establish where the sensors should go. Initially, a layer of a dark color of paint was placed on a paper towel. The paper towel was then placed on the object required for each activity with the paint making contact on the hand. A member of the design team then performed the activity and immediately took their hand off to reveal where the paint was transferred to. Based on the locations of the paint on the hand, the placement of the sensors for each activity were determined. The results of the paint test and the corresponding sensor placements are seen in Figures 31 – 35. To determine the sensor force rating that is appropriate for the activity; the team simply completed each task with different sensors at the chosen locations and observed graphically whether the forces measured were within the range of the sensor’s capabilities. The results of this testing process can be seen below.

Opening a Jar



Figure 31: This figure shows the paint as a result of opening a jar with the dominant hand on top of the jar lid. Based on the location of the paint on the hand after opening a jar, the sensor locations for the hand were determined as follows: 4 sensors on each of the 4 finger pads, 1 sensor on the side of the thumb pad, and 3 sensors across the palm of the hand. The determined sensor locations can be seen in the yellow indicators on the hand.

Figure 31 illustrates the results of the paint test; and subsequently, the locations of each sensor that will be used on the dominant hand (placed on top of the lid) while opening a jar. The results of the sensor rating test found that the sensors rated for 111 N should be utilized at all eight of the sensor locations.



Figure 32: This figure shows the paint as a result of opening a jar with non-dominant hand holding the side of the jar. Based on the location of the paint on the hand after opening a jar, the sensor locations for the hand were determined as follows: 1 sensor on the pad of the thumb, 1 sensor on the pad of the index finger, 1 sensor on the middle phalanx of the middle finger, 2 sensors on the proximal phalanx of the index and middle fingers, and 3 sensors across the top of the palm. The determined sensor locations can be seen in the yellow indicators on the hand.

Figure 32 illustrates the results of the paint test; and subsequently, the locations of each sensor that will be used on the non-dominant hand (placed on the side) while opening a jar. The results of the sensor rating test found that the sensors rated for 111 N should be utilized at all eight of the sensor locations.

Brushing Teeth



Figure 33: Based on the location of the paint on the hand after brushing teeth with a manual toothbrush, the sensor locations for the hand were determined as follows: 4 sensors on each of the 4 finger pads, 1 sensor on the thumb pad, and 3 sensors below the fingers on the palm of the hand. The determined sensor locations can be seen in the yellow indicators.

Figure 33 illustrates the results of the paint test; and subsequently, the locations of each sensor that will be used on the hand while the user brushes their teeth. The results of the sensor rating test found that the sensors rated for 111 N should be utilized at all eight of the sensor locations.

Typing



Figure 34: Based on the location of the paint on the hand after typing on a keyboard, the sensor locations for the hand were determined as follows: 4 sensors on each of the 4 finger pads, 1 sensor on the side of the thumb pad, 2 sensors at the bottom of the hand, above the wrist, and 1 sensor on the side of the hand below the small finger. The determined sensor locations can be seen in the yellow indicators on the hand.

Figure 34 illustrates the results of the paint test; and subsequently, the locations of each sensor that will be used on the hand while typing on a standard computer keyboard. The results of the sensor rating test found that the sensors rated for 111 N should be utilized at the thumb, two lower palm, and side of the hand locations and the sensors rated for 4 N should be placed on the four fingertips.

Opening a Door



Figure 35: Based on the location of the paint on the hand after typing on a opening a lever door handle, the sensor locations for the hand were determined as follows: 4 sensors on each of the 4 finger pads, 1 sensor on the pad of the thumb pad, and 3 sensors at the top of the hand, below the fingers. The determined sensor locations can be seen in the yellow indicators on the hand.

Figure 35 illustrates the results of the paint test; and subsequently, the locations of each sensor that will be used on the hand while opening a door with a lever handle. The results of the sensor

rating test found that the sensors rated for 111 N should be utilized at all eight of the sensor locations.

It was decided that the sensors need to be in different locations based on the activity that is being performed. Because of this, the gloves will contain Velcro® so the sensors can be put in the necessary spot in order to measure force. The procedure using the paint and paper towels showed where the force was being applied, so based on those results will be where the sensors are placed. The design team is confident in this procedure and the results because the paint showed up in different places for each activity and not just across the whole hand.

5.1.2 Calibration Curves

To verify that the piezoelectric sensors correctly measure the forces applied, the design team developed a calibration curve with a series of different known weights. As the output voltage changes with a dependent on the forces being applied, the design team needed to ensure that the change in forces being applied to the Flexiforce A201 sensors were proportional to the change in the output voltage. Tekscan, the manufacturer of the sensors, recommend utilizing a calibration curve as outlined in the user manual [41].

To determine the calibration curve the team first picked a set of weights to use for each sensor based on the maximum force each sensor can withstand. The weights used for calibrations were in pounds, however the team converted all of the units to Newtons once the calibration points were collected. For the 4N sensors, weights were increased in units of 50 grams, starting with 50 grams and going up to 450 grams. For the 111N sensors the team started with a five pound weight and went up in increments of five pounds until reaching 25 pounds. Finally, for the 445N sensor, the team started with a 10 pound weight and increased the weight in increments of about

10 pounds until 80 pounds was applied. With each sensor, the voltage output for the weight was recorded. Once this was repeated for all of the weights necessary, a calibration curve was generated in Microsoft Excel by plotting the voltage versus the weight. When producing the curve, the weights were converted to Newton's from either pounds or grams in order to keep the units consistent.

The calibration testing resulted in the following curves, seen in Figures 36 – 38.

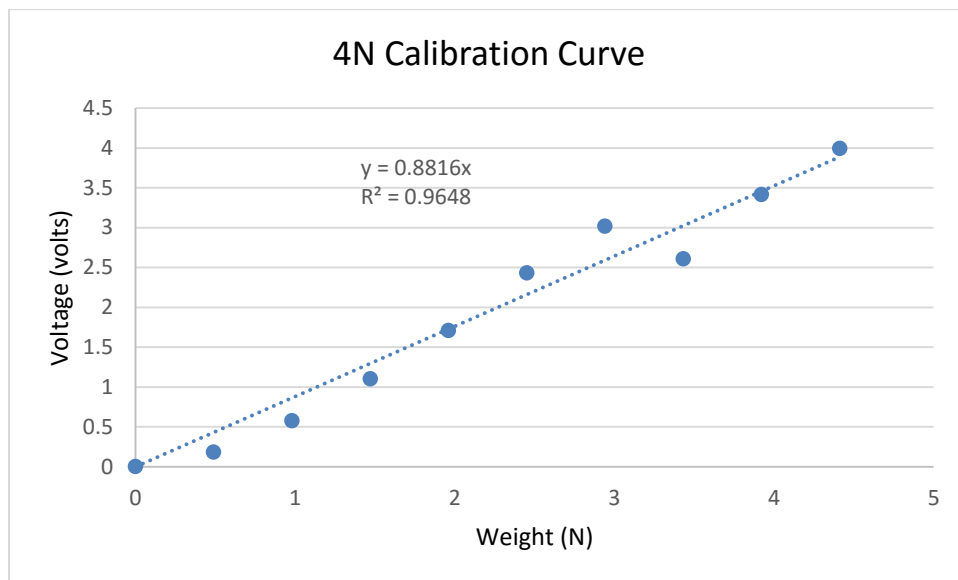


Figure 36: The calibration curve obtained from the 4N sensor is displayed in the solid blue line with the diamond markers representing the data points. The blue dashed line is the line of best fit calculated from the calibration curve. The equation for the line of best fit and the corresponding r-squared value are also displayed on the graph.

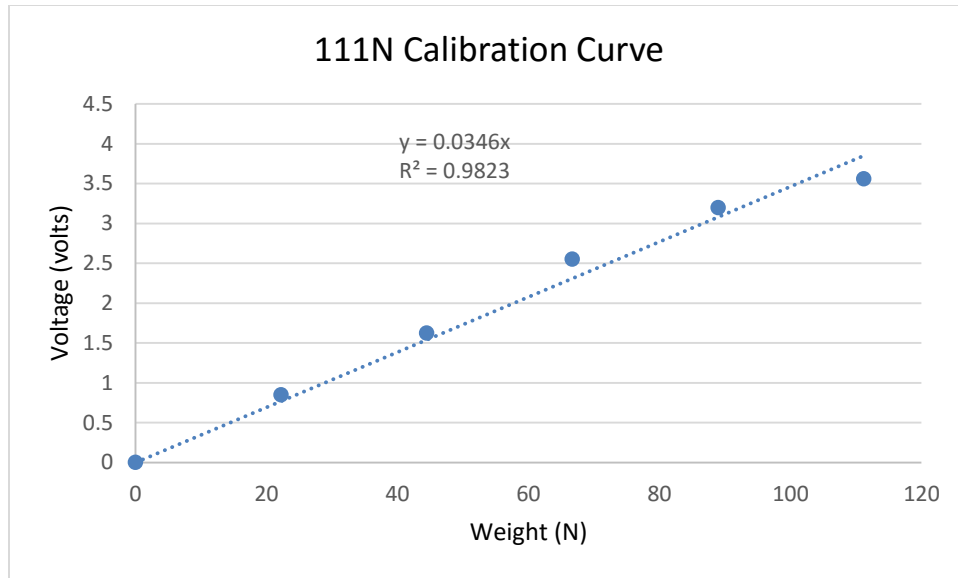


Figure 37: The calibration curve obtained from the 111N sensor is displayed in the solid blue line with the diamond markers representing the data points. The blue dashed line is the line of best fit calculated from the calibration curve. The equation for the line of best fit and the corresponding r-squared value are also displayed on the graph.

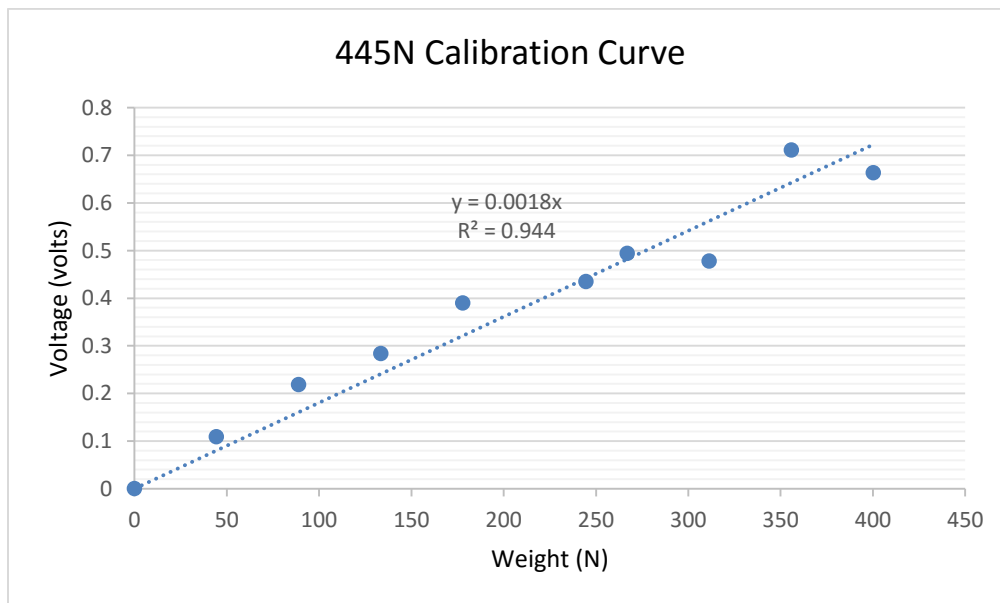


Figure 38: The calibration curve obtained from the 445N sensor is displayed in the solid blue line with the diamond markers representing the data points. The blue dashed line is the line of best fit calculated from the calibration curve. The equation for the line of best fit and the corresponding r-squared value are also displayed on the graph.

When observing the calibration curves of the data, the data appears to not be perfectly linear. However, the r-squared values for the 4 N, 111 N, and 445 N sensors were, respectively, 0.9648, 0.9823, and 0.944. The closer the regression value is to 1, the more similar the data points obtained are to the calculated line of best fit. As the r-squared values are close to 1, the data closely fits the linear regression line; making the calibration curves fairly accurate. In the 445 N sensor calibration curve; there is a noticeable dip in the data when 70 lbs was placed on the sensor pad. The design team believes that there is more variance in the data around this weight as the testing method required many weights to be stacked on top of each other, and to be cautious of safety for the team members and the surrounding equipment, the team had to brace the weights to prevent them from toppling over. Human interference at this point was likely reason for data inconsistencies. However, the team does not anticipate that forces of this magnitude will be experienced by the hand and the device due to the capabilities of the hand.

The calibration curves that were created allowed the team to be able to determine the force output from the voltage that is originally outputted from the DAQ Assistant. Based on the accuracy of the line of best fit line, the team used this equation before data analysis to convert all of the voltages collected into corresponding forces.

5.1.3 LabVIEW Program

The LabVIEW code, seen below in Figures 39 – 41, was developed to monitor and export the data collected by the data acquisition device. A verification test was developed to ensure that this program was functioning properly.

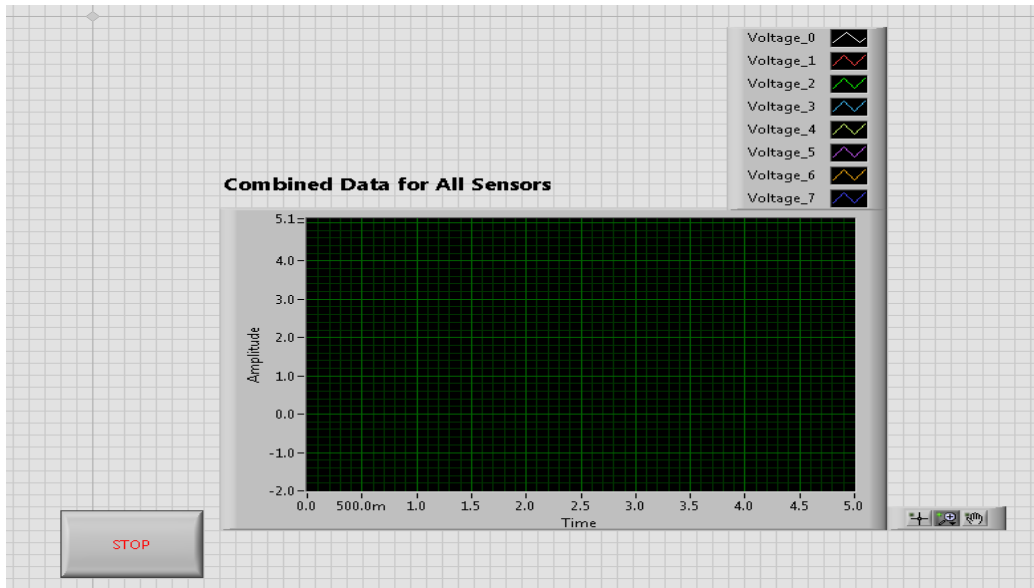


Figure 39: The portion of the front panel of the LabVIEW program with a graph that shows the data from all eight sensors and a button to stop the program when necessary.

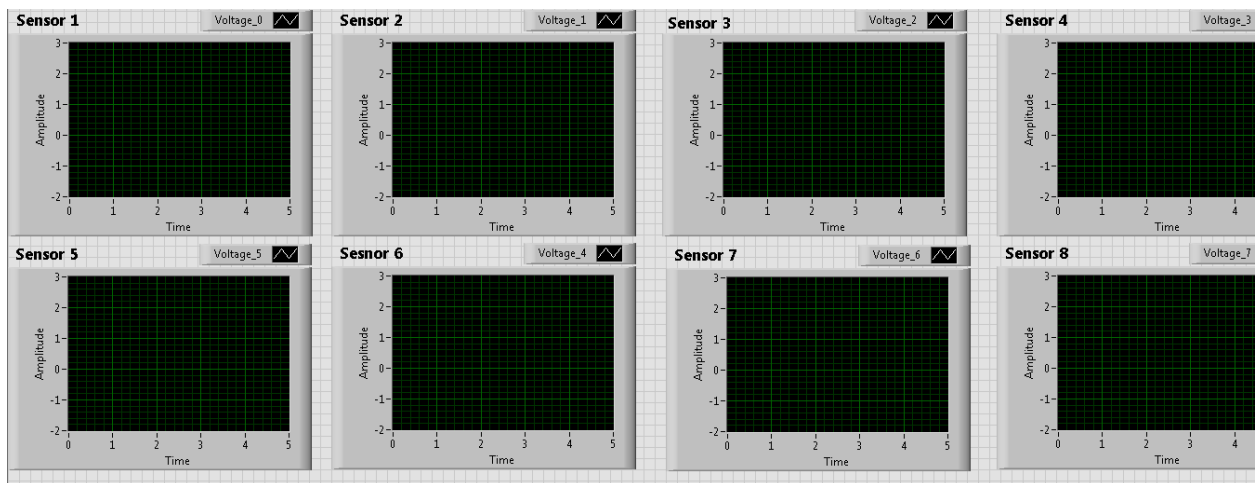


Figure 40: The portion of the front panel of the LabVIEW program with eight separate graphs for each of the eight different sensors.

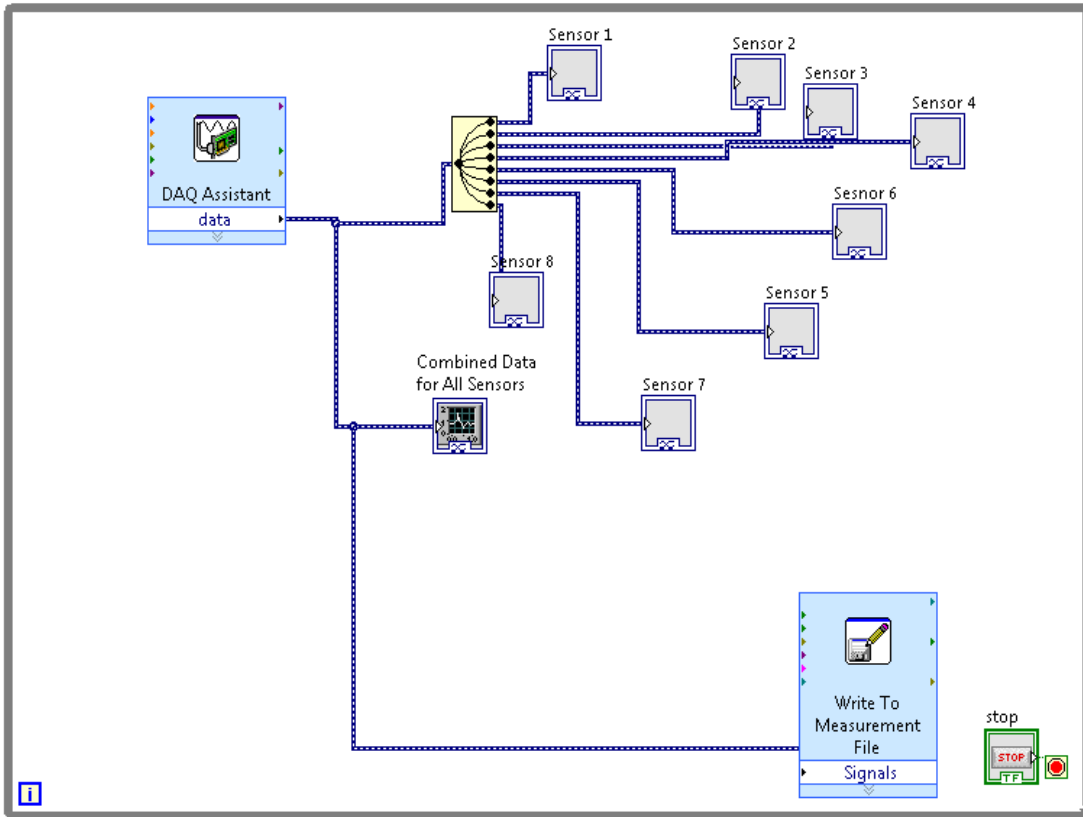


Figure 41: The block diagram of the LabVIEW program.

The LabVIEW program takes output from the sensors and displays it as a voltage. There are eight different graphical indicators on the front panel of the LabVIEW Program, one per each sensor used. There is also one graph that displays all the sensor outputs in one indicator which can be used for comparison. The program also saves the data in a .lvm file that can later be used for further analysis. To verify the that output voltage being represented on the graphs was accurate, the design team used a digital multimeter in conjunction with the graph on the LabVIEW program that displays all the output voltages while using one USB-6009 analog input port per test. The design team applied different weights to the sensors and monitored the output of the multimeter and the graphical results displayed in the LabVIEW program to verify that the voltage values were the same.

While completing this test, the design team also verified that each analog input port on the Data Acquisition Device was displaying in the different output graphs on the LABVIEW Program. Each port was tested individually and the design team noted which output graph the voltage displayed to and verified if the voltage on the individual graphical indicators was the same as the value displayed on the overall graph. The purpose of this test is to make sure that the LABVIEW program was properly displaying each analog input in different graphical indicators. To verify that the data was exporting properly to an output file, the team compared the known output voltages from the multimeter and the LABVIEW graphical results to the data collected in the output file to verify that the correct values were being recorded.

This program accomplished all the tasks it was expected to. It accurately displays all the voltages produced from the sensors. It is able to show the output of each sensor on an individual graph or a graph that shows all the sensors outputs. It also is able to save the data collected to a file so it can be used for any other tests that needs to be done.

5.1.4 Goniometer and Moment Method

The purpose of using the goniometer was to determine the location that the forces are being applied. The goniometer was used to determine the angle and distance between the force point and the predetermined location on the wrist. An example of the set-up can be seen below in Figure 42. After these calculations were made the moment about the wrist was determined using the free body diagram below in Figure 43.

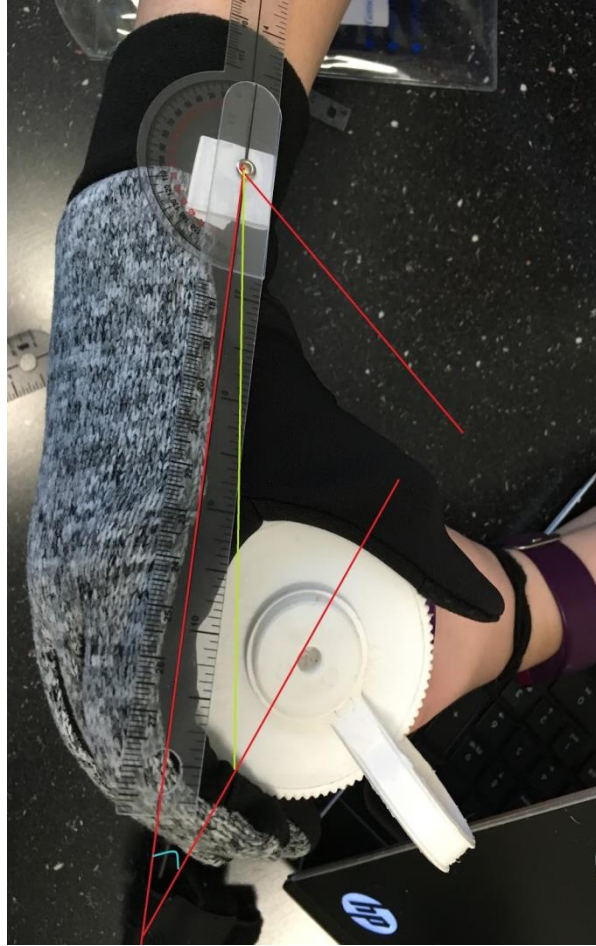


Figure 42: The picture used for the goniometer calculations with lines drawn in to aid in the calculations

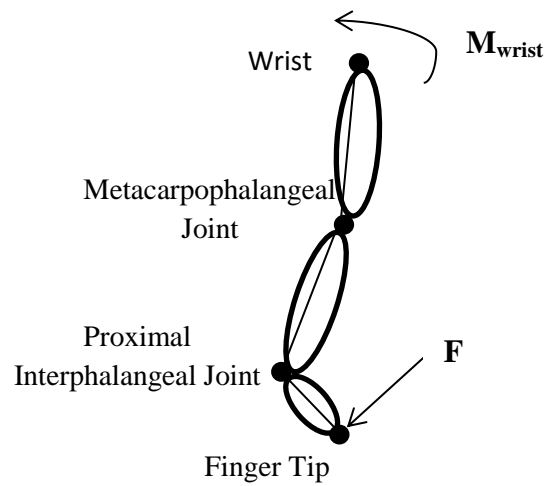


Figure 43: Full free body diagram used to determine the moment about the wrist for the first finger

In order to use the goniometer to find the angle and the distance of the force relative to the wrist, the goniometer was first taped to the wrist prior to the activity being performed. While the activity was performed a picture was taken in which the goniometer and all of the sensors could be seen. This allowed for the proper calculations to be performed.

Once the picture was taken, it was then opened in the program Paint. A line was drawn along the goniometer ruler to extend as far as possible down towards the end of the hand. Another line was then drawn perpendicular to the sensor to intersect the first line. This intersection creates the angle of the force relative to the wrist. These lines can be seen below in Figure 42.

In order to calculate the distance of the force relative to the wrist the pixel location of the wrist was found by using the pixel coordinates provided on Paint. The pixel location along the goniometer was also found. This gave a known distance in millimeters using the ruler on the goniometer. The pixel distance was then calculated using equation 3.

$$distance = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2} \quad (3)$$

This was used along with the known distance in millimeters to make a ratio to convert other pixel distances into millimeters. Next, the pixel location of the force was found and then the pixel distance of the wrist to the force could be calculated using the above formula. Once this distance was determined it was converted to millimeters using the ration mentioned above.

In order to calculate the angle, the pixel location of the intersection where the angle occurs was found. Then the distance from the force to the angle and from the wrist to the angle was

calculated using the distance formula. These numbers could be used in conjunction with the Law of Cosines, equation 4, to calculate the angle of the force relative to the wrist.

$$a^2 = b^2 + c^2 - 2bc(\cos A) \quad (4)$$

The activity performed for the purpose of this verification test was opening a jar. The angle, distance of the force perpendicular to the right index finger relative to the wrist, and moment at the wrist were calculated.

In order to verify that this method worked an example was done using the index finger of top hand while opening a bottle. The pixel locations of the wrist was found to be (1089, 1041) and the location of the 18mm mark on the goniometer was found to be (1021, 1558). Using these locations the distance from the wrist to the 18mm mark was able to be calculated, using equation 5.

$$\text{wrist to 18mm mark distance} = \sqrt{(1089 - 1021)^2 + (1041 - 1558)^2} = \mathbf{521.4528 \text{ pixels}} \quad (5)$$

This distance was used as the reference distance for the other distance calculations because it was known that this distance is 3.5mm. The pixel location of the force was found to be (1061, 3361). This allowed the wrist to force distance to be calculated in pixels and then converted to millimeters using the reference distance as seen in equations 6 and 7. This was one of the parameters that was necessary to calculate per the client's needs.

$$\text{wrist to force distance} = \sqrt{(1089 - 1061)^2 + (1041 - 3361)^2} = \mathbf{2320.169 \text{ pixels}} \quad (6)$$

$$2320.169 \text{ pixels} * \frac{3.5 \text{ mm}}{521.4528 \text{ pixels}} = \mathbf{15.57301 \text{ mm}} \quad (7)$$

The next distance that was necessary to calculate was the force to angle distance. The angle is the one marked in blue in Figure 42 below. To do this the pixel location of the angle was found at (673, 3977). The calculation was then done to find the force to angle distance along with the angle to wrist distance using equations 8 and 10. These distances were then both converted from pixels to millimeters using equations 9 and 11.

$$\text{force to angle distance} = \sqrt{(1061 - 673)^2 + (3361 - 3977)^2} = \mathbf{728.011 \text{ pixels}} \quad (8)$$

$$728.011 \text{ pixels} * \frac{3.5 \text{ mm}}{521.4528 \text{ pixels}} = \mathbf{4.886122 \text{ mm}} \quad (9)$$

$$\text{angle to wrist distance} = \sqrt{(673 - 1089)^2 + (3977 - 1041)^2} = \mathbf{2965.325 \text{ pixels}} \quad (10)$$

$$2965.325 \text{ pixels} * \frac{3.5 \text{ mm}}{521.4528 \text{ pixels}} = \mathbf{19.90331 \text{ mm}} \quad (11)$$

These distances were then used to calculate the angle of the force with reference to the wrist. The Law of Cosines was used to do this calculation, which can be seen below in equations 12 – 15. The wrist to force distance is denoted as the variable a, the angle to wrist distance is denoted as the variable b, and the force to angle distance is denoted as the variable c. This angle was another necessary calculation requested by the client and is the angle of the normal force on the hand relative to an imaginary drawn down the forearm, through the wrist, and to the hand.

$$a^2 = b^2 + c^2 - 2bc(\cos A) \quad (12)$$

$$A = \cos^{-1} \left(\frac{-a^2 + b^2 + c^2}{2bc} \right) \quad (13)$$

$$A = \cos^{-1} \left(\frac{-(15.57301\text{mm})^2 + (19.90331\text{mm})^2 + (4.886422\text{mm})^2}{2 * 19.90331\text{mm} * 4.886422\text{mm}} \right) \quad (14)$$

$$\mathbf{A = 24.14^\circ} \quad (15)$$

The next step was to determine the moment at the wrist. A simplified free body diagram, seen in Figure 43, was made and then the method of segments was used to determine an equation for the moment.

In order to solve any of the equations that were used a reference for the positive x and y directions along with the moment had to be made. This can be seen below in Figure 44. The next step was to break down the diagram into sections, which were defined as Segment 1, Segment 2, and Segment 3, to determine an equation for the moment at the wrist. The first segment that was looked at was from the tip of the finger to the proximal interphalangeal joint. An assumption was made that this portion of the finger was straight. The diagram used for this segment can be seen below in Figure 45 and the equations and calculations can be seen below as well. The angle between the force and the x-axis is denoted as θ . The joint reaction forces in the x and y directions along with the moment at the joint were calculated using equations 16 – 20.

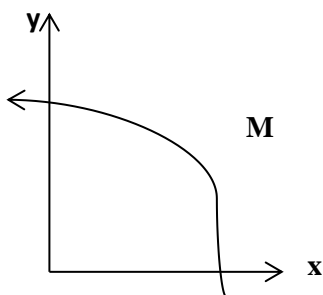


Figure 44: Reference to the positive directions used to solve for the moment

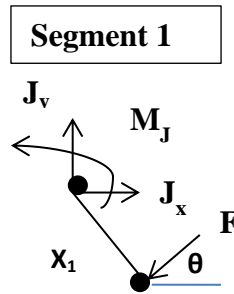


Figure 45: Free body diagram for the distal and middle phalanxes (Segment 1) using the method of segments

$$\Sigma F_x = 0 = J_x - F \cos \theta \quad (16)$$

$$J_x = F \cos \theta \quad (17)$$

$$\Sigma F_y = 0 = J_y - F \sin \theta \quad (18)$$

$$J_y = F \sin \theta \quad (19)$$

$$\Sigma M_J = -FX_1 \quad (20)$$

The next segment that was analyzed was from the proximal interphalangeal joint to the metacarpophalangeal joint. The free body diagram that was used for this segment can be seen below in Figure 46. The angle of the segment to the x-axis is denoted as ϕ . The calculations done can be seen below in equations 21 – 25.

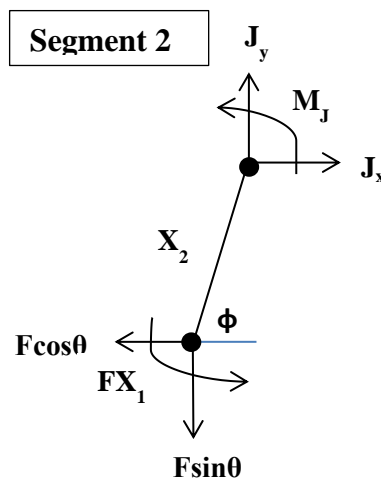


Figure 46: Free body diagram for proximal phalanx (Segment 2) using the method of segments

$$\Sigma F_x = 0 = J_x - F \cos \theta \quad (21)$$

$$J_x = F \cos \theta \quad (22)$$

$$\Sigma F_y = 0 = J_y - F \sin \theta \quad (23)$$

$$J_y = F \sin \theta \quad (24)$$

$$\Sigma M_J = F X_1 - F \cos \theta * X_2 \sin \phi + F \sin \theta * X_2 \cos \phi \quad (25)$$

The final segment used to determine the moment at the wrist was from the metacarpophalangeal joint to the wrist. The free body diagram used for this segment can be seen below in Figure 47.

The angle from the segment to the x-axis is denoted as α . The calculations done can be seen below in equations 26 and 27.

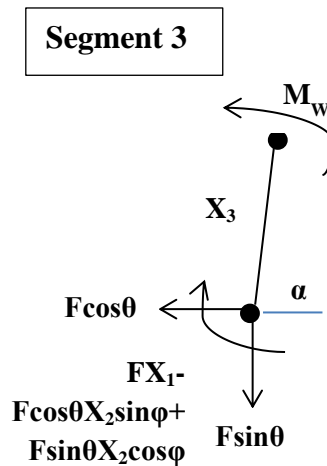


Figure 47: Free body diagram for the segment from the end of the proximal phalanx to the wrist (Segment 3) using the method of segments

$$\Sigma M_W = -F X_1 + F \cos \theta * X_2 \sin \phi - F \sin \theta * X_2 \cos \phi - F \cos \theta * X_3 \sin \alpha + F \sin \theta * X_3 \cos \alpha \quad (26)$$

$$\Sigma M_W = -F X_1 + F \cos \theta (X_2 \sin \phi - X_3 \sin \alpha) - F \sin \theta (X_2 \cos \phi - X_3 \cos \alpha) \quad (27)$$

The outcome of this testing showed that the method used for determining the angle and distance of the force relative to the wrist was successful and can be continued to be used in conjunction with the device. Although this was only done for one sensor in one activity, the same method

can be used to determine the angle, distance, and moment relative to the wrist for other scenarios.

As this project iteration did not have a method for measuring the magnitude of shear forces, the design team made the assumption that the shear forces are equal in magnitude to the normal forces in most cases. However, there are some circumstances that the shear force would be greater than the normal force. When opening and closing a jar, the shear force required at the moment that the lid begins to turn would likely be greater than the normal force as the user needs to overcome the coefficient of static friction between the lid and the jar. Despite the instances where the shear force is greater than the normal force; for the purpose of this project the assumption was made that the magnitudes of the shear and normal forces are the same. A recommendation for future iterations of this project is to further evaluate the different types of forces to provide more information to the user.

5.1.4.1 Example Calculation for the Top Hand while Opening a Bottle

An example of such a calculation can be seen below. An image was taken of the top hand during the opening a bottle activity and used along with the data generated. The image was taken when the index finger was pushing at its hardest while opening the bottle and the highest force for that sensor during that time was determined to be 0.531173 volts. This was then calculated to be 3.451417 pounds which is 15.35267 N. The distance from the wrist to the force was calculated along with the angle of the force to the wrist. Equations 21 – 27 were then used to calculate the moment about the wrists. The calculations can be seen below. The angles θ , ϕ , and α were calculated using the image taken which can be seen below in Figure 48. The angles are denoted as 1, 2, and 3 respectively.

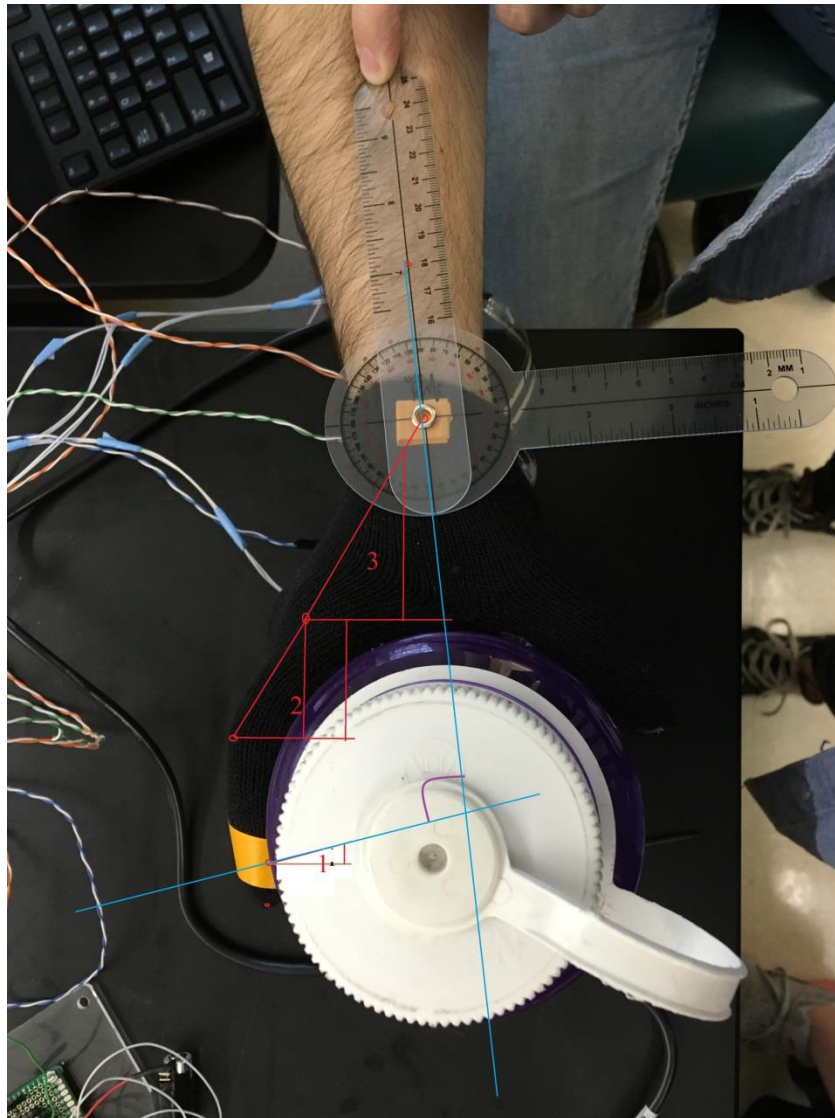


Figure 48: Example image to do the calculations associated with the top hand of opening a bottle.

First the distance from the wrist to the force was calculated using the distance formula as seen below.

$$\text{angle to wrist distance} = \sqrt{(945 - 1497)^2 + (3097 - 1489)^2} = \mathbf{1700.108 \text{ pixels}}$$

$$1700.108 \text{ pixels} * \frac{3.5 \text{ mm}}{554.4439 \text{ pixels}} = \mathbf{10.73216 \text{ mm}}$$

The angle of the force to the wrist was then calculated by finding the distance of the force to the angle and the distance of the angle to the wrist. The Law of Cosines was then used to find the angle as seen below. The angle being calculated can be seen in purple in Figure 48.

$$\text{force to angle distance} = \sqrt{(1653 - 945)^2 + (2917 - 3097)^2} = \mathbf{730.5231 \text{ pixels}}$$

$$730.5231 \text{ pixels} * \frac{3.5 \text{ mm}}{554.4439 \text{ pixels}} = \mathbf{4.611523 \text{ mm}}$$

$$\text{angle to wrist distance} = \sqrt{(1497 - 1489)^2 + (3977 - 2917)^2} = \mathbf{1436.496 \text{ pixels}}$$

$$1436.496 \text{ pixels} * \frac{3.5 \text{ mm}}{554.4439 \text{ pixels}} = \mathbf{9.068069 \text{ mm}}$$

$$a^2 = b^2 + c^2 - 2bc(\cos A)$$

$$A = \cos^{-1} \left(\frac{-a^2 + b^2 + c^2}{2bc} \right)$$

$$A = \cos^{-1} \left(\frac{-(9.068069\text{mm})^2 + (4.611523\text{mm})^2 + (10.73216\text{mm})^2}{2 * 9.068069\text{mm} * 4.611523\text{mm}} \right)$$

$$\mathbf{A = 98.03^\circ}$$

Segment 1

$$\Sigma F_x = 0 = J_x - F \cos \theta$$

$$J_x = 15.35267 \text{ N} * \cos(15.037782)$$

$$\mathbf{J_x = 14.83 \text{ Newton's}}$$

$$\Sigma F_y = 0 = J_y - F \sin \theta$$

$$J_y = 15.35267 \text{ N} * \sin(15.037782)$$

$$\mathbf{J_y = 3.983 \text{ Newton's}}$$

$$\Sigma M_J = -FX_1$$

$$\Sigma M_J = -15.35267 \text{ N} * 2.9725$$

$$\Sigma M_J = -45.64 \text{ N} * \text{mm}$$

Segment 2

$$\Sigma F_x = 0 = J_x - F \cos \theta$$

$$J_x = 15.35267 \text{ N} * \cos(59.11505)$$

$$J_x = 7.881 \text{ Newton's}$$

$$\Sigma F_y = 0 = J_y - F \sin \theta$$

$$J_y = 15.35267 \text{ N} * \sin(59.11505)$$

$$J_y = 13.18 \text{ Newton's}$$

$$\Sigma M_J = F X_1 - F \cos \theta * X_2 \sin \phi + F \sin \theta * X_2 \cos \phi$$

$$\Sigma M_J = 15.35267 \text{ N} * 2.972492 - 15.35267 \text{ N} * \cos(15.03782) * 3.148225 * \sin(59.11505) + 15.35267 \text{ N} * \sin(15.03782) * 15.35267 \text{ N} * \cos(59.11505)$$

$$\Sigma M_J = 36.97 * \text{mm}$$

Segment 3

$$\Sigma M_W = -F X_1 + F \cos \theta (X_2 \sin \phi - X_3 \sin \alpha) - F \sin \theta (X_2 \cos \phi - X_3 \cos \alpha)$$

$$\Sigma M_W = -15.35267 \text{ N} * 2.972492 + 15.35267 \text{ N} * \cos(15.03782) (3.148225 * \sin(59.11505) - 4.572965 * \sin(59.06606)) - 15.35267 \text{ N} * \sin(15.03782) (3.148225 * \cos(59.11505) - 4.572965 * \cos(59.06606))$$

$$\Sigma M_W = -60.81 \text{ N} * \text{mm}$$

In summary, from this example, it was calculated that the distance of the force relative to the wrist is 10.73216 mm, the angle of the force relative to the wrist is 98.03°, and the moment about the wrist is -60.81N*mm.

5.2 Data Collection Results

Once the verification tests were completed and it was proven that the device was functioning properly, the team started to collect data for each of the four activities. Each member of the team

performed each of the four activities three times each. Graphs were created to show how the forces were distributed amongst the eight sensors during each activity and trial. One graph for each activity can be seen below in Figures 49 – 52. The rest of the graphs can be found in Appendix B. Due to technical issues, data was not able to be collected for the opening the door activity. The issue was that the door was too far from the computer, causing wires to be pulled out of the proto board when reaching for the door handle. This made it not possible to record data.

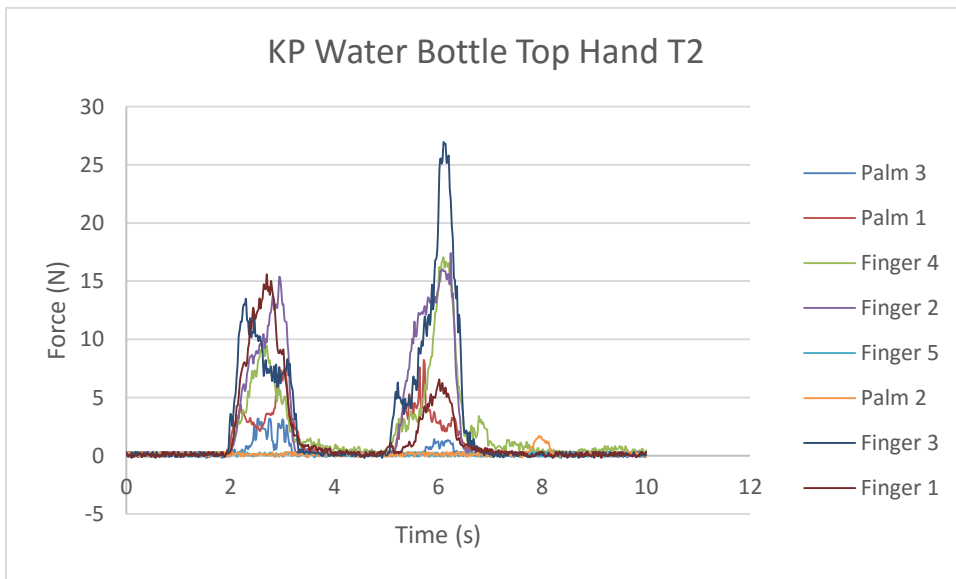


Figure 49: Trial 2 for Person 3 opening a bottle with their top hand.

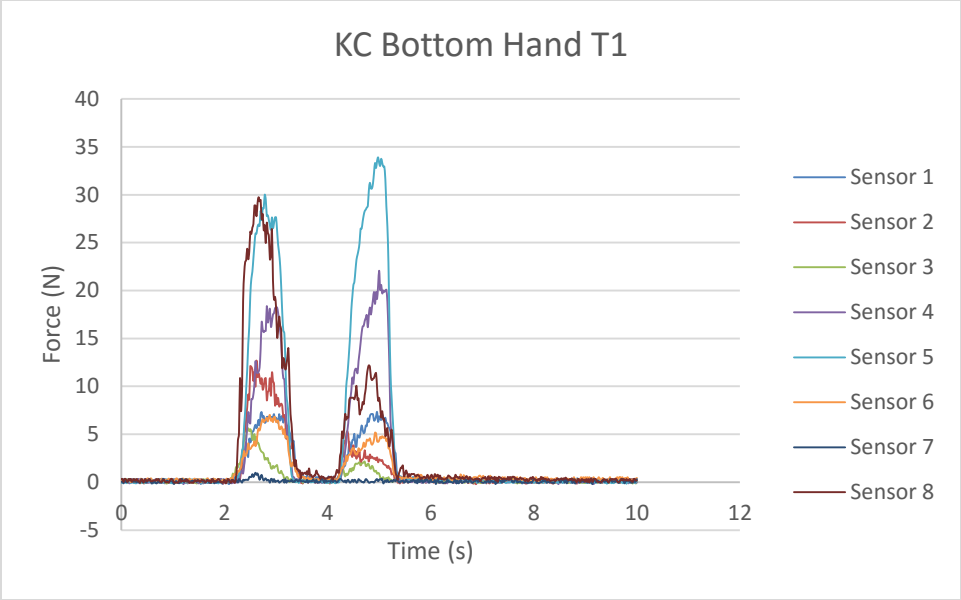


Figure 50: Trial 1 for Person 1 opening a bottle with their bottom hand.

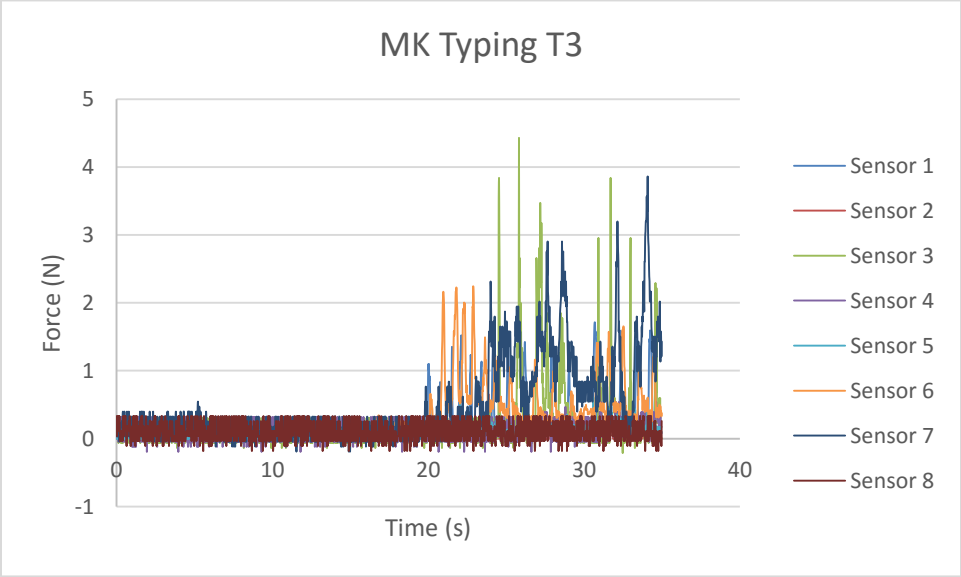


Figure 51: Trial 3 for Person 2 typing on a keyboard.

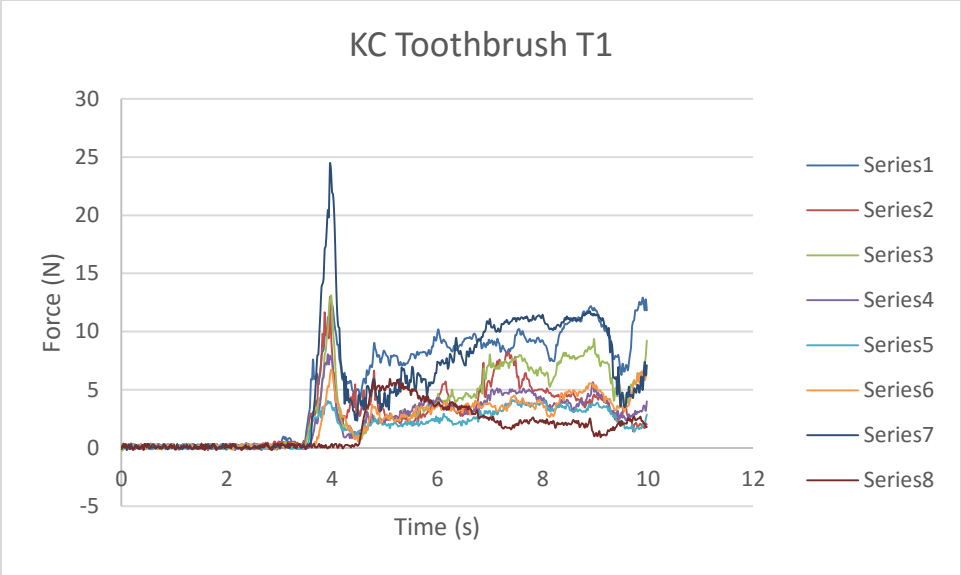


Figure 52: Trial 1 for Person 1 brushing their teeth.

6 Final Design Validation

During the aging process, bone growth diminishes due to the inactivity of osteoblasts. It is important to understand which exercises deliver forces to the bone that can prevent bone degeneration. Significant research has been completed in terms of understanding appropriate exercises for bone in the lower extremities; however there is a lack of knowledge regarding which exercises are beneficial for the hands. Developing a device which can evaluate the magnitude, location, and direction of forces acting on the hand can be used in research to fill this knowledge gap.

Initially, the project team's objectives were that the device must be ambidextrous, reusable, durable, safe, portable, and easy to use. The final design of a glove containing sensors was chosen because it would meet all of these objectives in the best way possible. It is ambidextrous as there are two different gloves, one for each hand, and the sensors are stuck to the glove using Velcro® allowing the sensors to be moved from one glove to the other. It is both reusable and durable because Tekscan® sells sensors that can be used over and over again without breaking. The device is portable as all of the parts are relatively small and do not weigh a lot. Finally, the device is easy to use because the team has created a LabVIEW program and instructions for where all of the sensors should be placed for each activity.

6.1 Creation of the Device

In order to create this device, the team first bought and acquired the necessary supplies. This included a pair of thin and stretchy gloves, Tekscan® FlexiForce A201 sensors, Velcro®, gems for sensor footing, electrical tape, a DAQ assistant, a breadboard, wires, appropriate resistors, and appropriate op-amps. The Velcro® was then placed in the appropriate locations on the glove

as seen below in Figure 53. Elastic loops were then sewn to the glove to hold the sensors in place. They were placed on each finger and several other locations on the palm and heel of the hand. Different Velcro® locations are used for each activity to allow the glove to be versatile and collect data for many different types of activities. Gems were then placed on each of the sensors to be used as footing and electrical tape was placed over the gems to allow for a better grip as seen in Figure 54. This allows the sensor to receive an even force applied to the whole sensor pad, which gives better data collection. The next step in building this device, was putting together the circuit that allows the sensors to collect the data. The circuit amplifies the signal, so that the voltage magnitude increases sufficiently for the DAQ assistant to collect the data. Figure 55 below shows the circuit that Tekscan® suggests to be used. The team then built this circuit on a breadboard and later soldered it onto a proto board to provide more stability and interchangeability for the battery, wires, resistors, and op-amps as seen below in Figures 56 and 57. An electrical schematic drawing and bill of materials for the circuit can be found in Figures 58 and 59. Once the circuit was built, it was then connected to the DAQ assistant. The final device being worn and connected to the DAQ assistant and proto board can be seen below in Figure 60. The next step was to make a LabVIEW program to see the data from all of the sensors used at one time. This program can be seen below in Figures 61 – 63. The program takes the data from the sensors and outputs it to graphs that can be seen in real time as well as an .lvm file that can be analyzed later. The DAQ assistant was then connected to the computer with the sensors connected to the circuit. At this point the team ran the program and successfully received data. Once the design was completed and successfully verified the collection of data was able to begin. A user manual for the device was developed and is referenced in Appendix C.



Figure 53(left): The glove with Velcro® and elastic loops to hold the sensors. To see a bill of materials and instructions on how to make this glove see Appendix D.

Figure 54(right): The gem footing used to provide an equal distribution of the force over the entire sensor area covered in electrical tape for a better gripping.

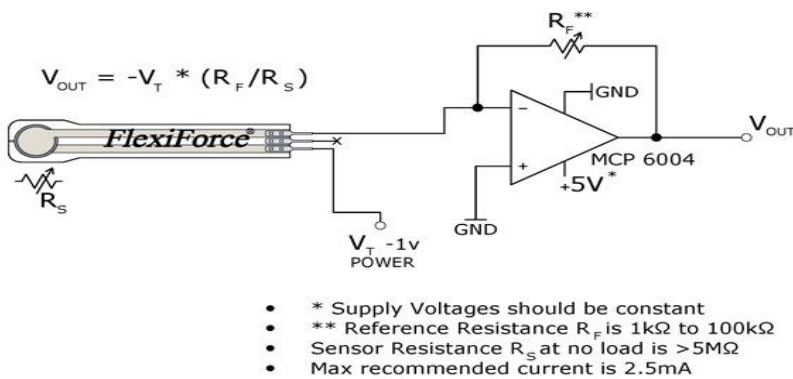


Figure 55: The circuit that Tekscan® suggests to use with their A201 sensors, which were used in the creation of this sensors glove [42].

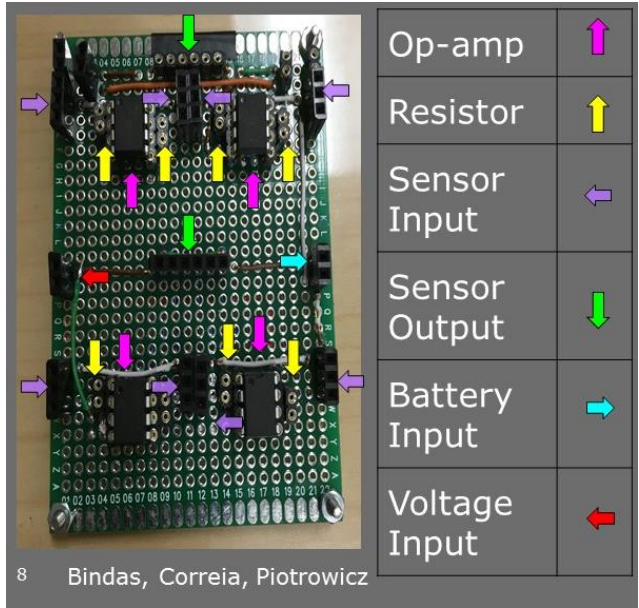


Figure 56: The top of the proto board used with the sensors and DAQ assistant. Wires and op-amps are soldered into place and the resistors are able to stay in permanently. The other black holes are for the sensors and wires that connect to the DAQ.

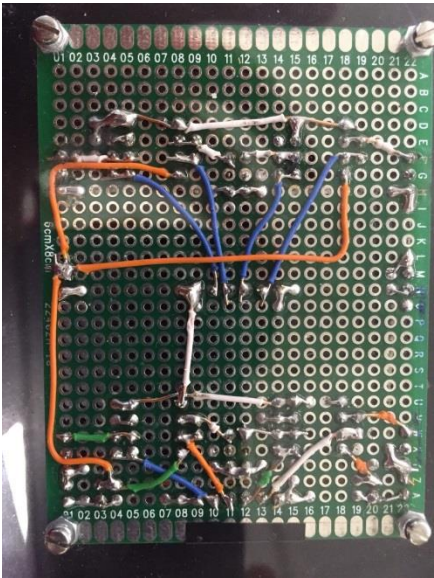


Figure 57: The bottom of the proto board used with the sensors and DAQ assistant. This shows the soldering of the wires underneath the board to create the circuit.

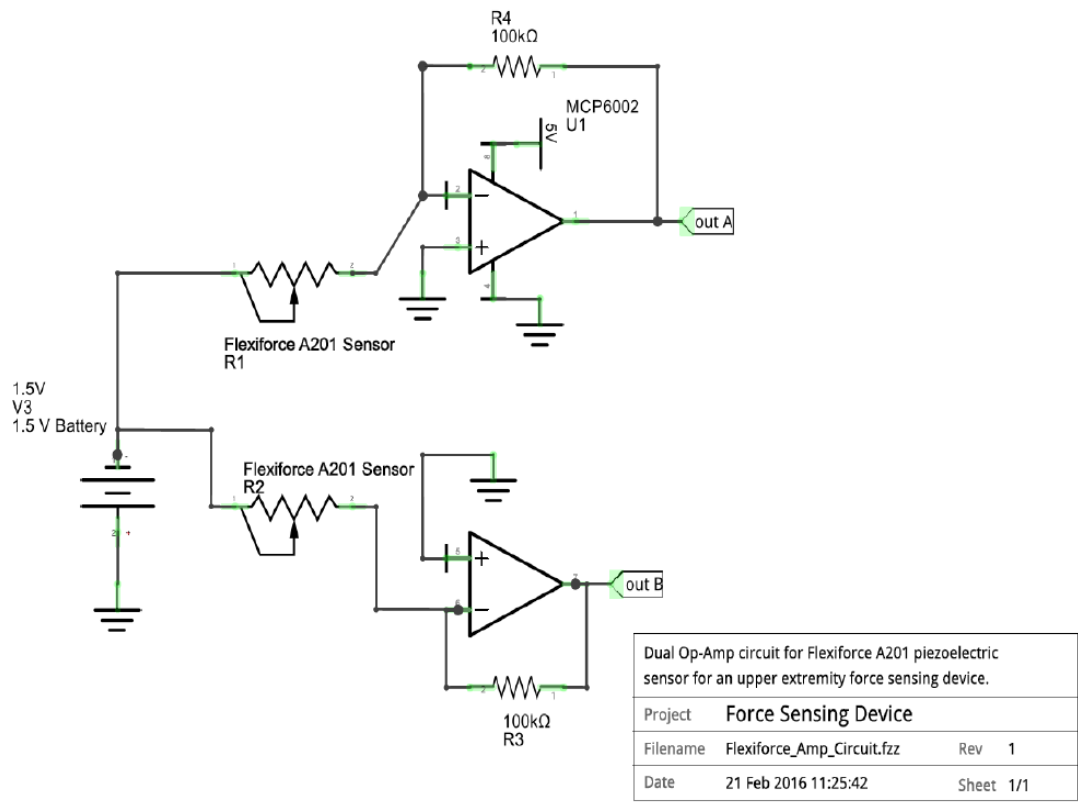


Figure 58: Electrical schematic drawing of the circuit used for this device

Bill of Materials

Part No.	Distributor	Quantity
1.5 V Battery	Duracell	1
MCP 6002 - OP AMP		4
100KOhm Resistor		8
FlexiForce A201 Sensor	Tekscan	8
USB-6009	National Instruments	1

Dual Op-Amp circuit for Flexiforce A201 piezoelectric sensor for an upper extremity force sensing device.		
Project	Force Sensing Device	
Filename	Flexiforce_Amp_Circuit.fzz	Rev 1
Date	21 Feb 2016 11:25:42	Sheet 1/1

Figure 59: Bill of materials for the electrical schematic drawing

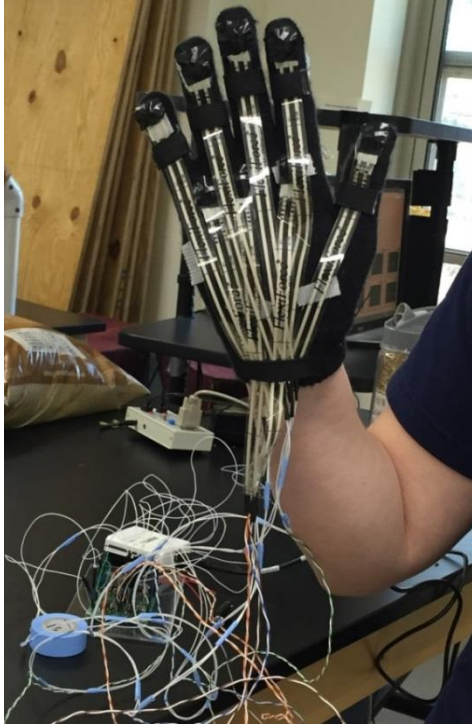


Figure 60: The final device being worn and attached to the DAQ assistant and proto board.

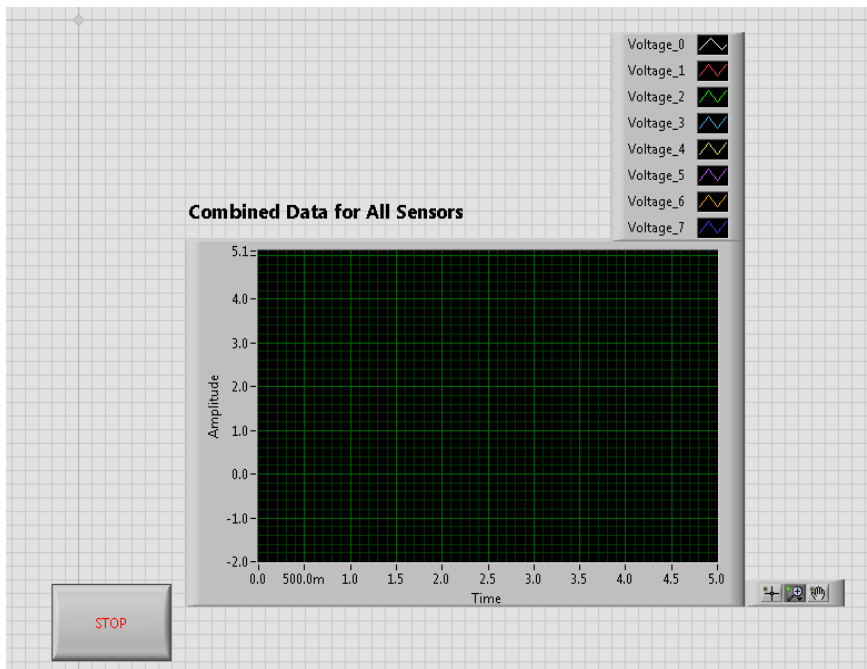


Figure 61: The portion of the LabVIEW program front panel with a graph to show the data from all of the sensors as well as a button to stop the program.

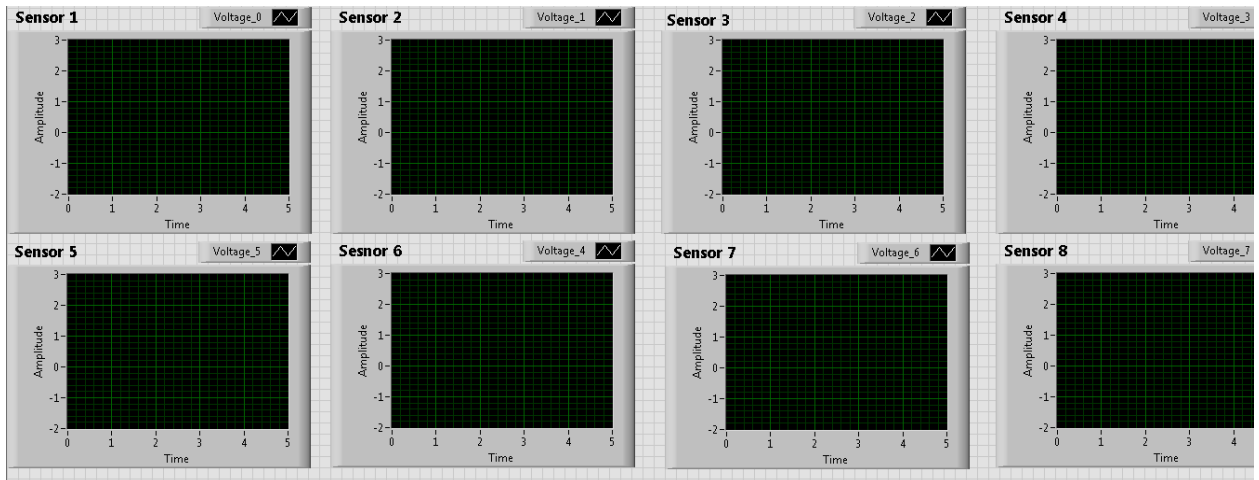


Figure 62: The portion of the LabVIEW program front panel with eight separate graphs for each of the eight sensors.

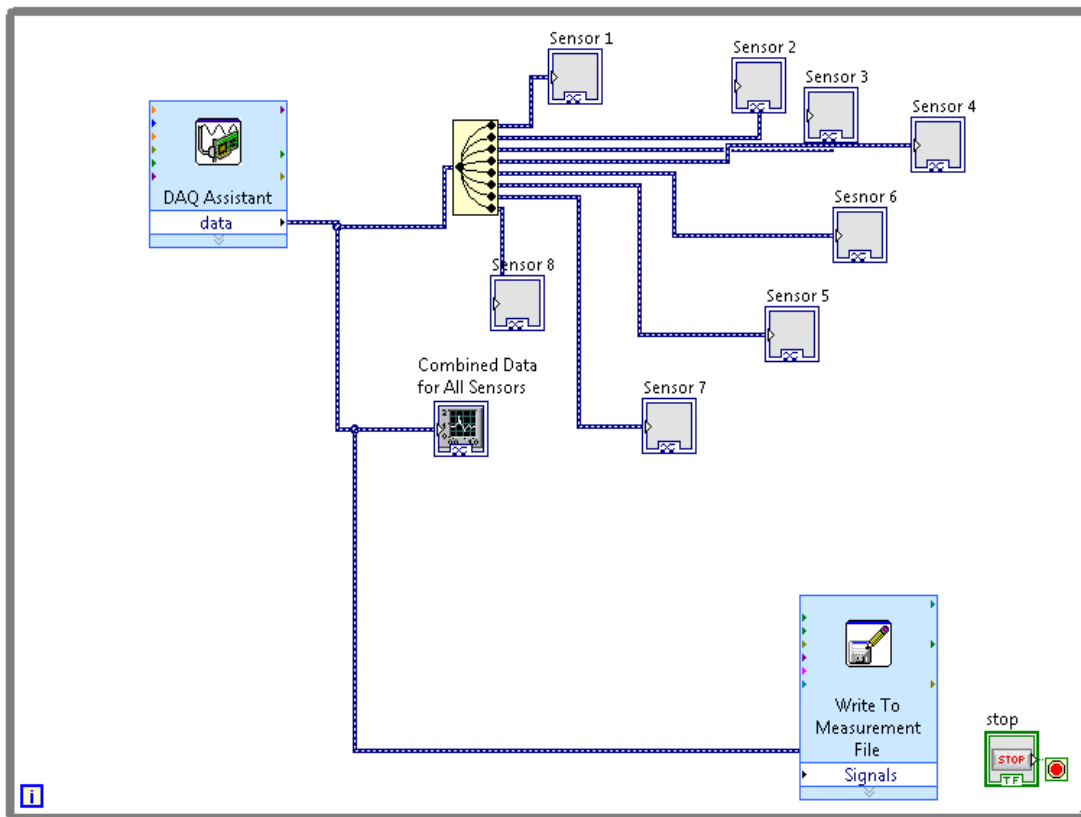


Figure 63: The LabVIEW program block diagram used to collect the data from the sensors.

6.2 Experimental Methods and Data Analysis

The goals of this project were to create a force sensing device that is able to collect data for the different forces that occur on different parts of the hand when performing upper extremity activities. In order to prove that the device works properly, the design team collected data for each of four activities defined earlier in this report. These activities were using a toothbrush, opening a door with a lever handle, opening a bottle, and typing. To collect the data, the team had each of its three members perform each activity three times. This allowed the team to compare the differences amongst the different team members as well as within the three trials for each individual person.

To analyze the data once it was collected, the voltages were converted in forces using the calibration curves. Graphs were then created in Excel. One graph was made for each trial that data was collected for and the data from each of the eight sensors used were put onto one graph. The graphs show the forces experienced by each sensor versus time. Once the graphs were created, the design team was able to compare them. The team looked at the differences between each person performing the activities to see if there was a difference in which parts of the hands used the most force. The differences amongst the three trials that each person completed were also looked at. The team analyzed whether or not a drift started to occur over time as well as if there was a change in which sensors experienced the most force amongst the three trials.

6.3 Standards

There are several standards with which the project must comply. IEEE is the standard at which the team is writing the report at. All citations and report set up must follow the IEEE standards. The general format of the MQP report was developed referencing the IEEE Editorial Style

Manual including table and figure annotations [43]. All references are also completed in accordance with IEEE citation standards [44].

LabVIEW will be used as a computer program to allow the device to run and collect data, the program was written taking into consideration LabVIEW development guidelines established by National Instruments [45]. The electrical schematic that was developed for the amplifier circuit was developed in accordance with the IEEE standard Y32.9-1972 for graphic symbols with electrical wiring diagrams [46]. The device was intended to be built in accordance with ISO standard 17 and its subsequent clauses. This standard outlines the requirements for devices that complete any measurements including on people [47]. Unfortunately the contents of the standards were unavailable to us with the resources provided. Following relevant standards is a necessary component for the force sensing device so that any testing completed with the device can be considered valid and if a market presence was to be considered, following the required standards would help with any approval processes.

6.4 Impacts of the Force Sensing Device

6.4.1 Economics

The first potential impact this project could have is on the economy. Although there are no major impacts that the design team foresees, in the long run it could decrease healthcare costs for individuals. Compared to similar devices on the market, this device would be more affordable. If manufactured on a larger scale, the device would cost about \$290.27 and a budget for this can be seen in Table 5. This price includes the Velcro® and the fabric glue however these items would be able to be used multiple times. The user will also have to purchase a Data Acquisition Device, which cost approximately \$249.00 [48].

6.4.2 Environmental Impact

The only environmental impact associated with this project is battery waste as a battery is used to help power the sensors. In order to address this impact, all batteries used should be properly recycled. Other than this, there is no environmental impact as the product is reusable and there are no hazardous materials being used.

6.4.3 Societal Influence

This device would have an influence on society. It would help those who are suffering from different types of bone degenerative diseases by studying the effect of bone loading during different activities. It would allow researchers to determine which daily activities have a harmful effect on the bones and which can be beneficial. These studies could have a positive effect on society by helping those who are affected by bone degenerative diseases.

6.4.4 Political Ramifications

There are no political ramifications associated with this project.

6.4.5 Ethical Concerns

There are no ethical concerns associated with the design of this force sensing device. However, if studies using this device are able to determine exercises that may prolong the onset of bone degenerative disease, the information gained from the device would result in a higher quality of life and ability to maintain independence for those at risk of these diseases.

6.4.6 Health and Safety Issues

There are several minor health and safety concerns with users utilizing the force sensing device. As the device is going to be placed around the user's hand, there is the concern that the device could pinch or have other minimal abrasions. Another health and safety concern is the use of electrical components with the device which could result in an electrical shock for the user. To address both of these concerns, the design team placed high emphasis on ensuring the

design of final product would not pose a risk to the user. To avoid pinching or abrasions, the design team used soft gloves that prevent the skin from coming into contact with elastics bands or tape. To prevent the risk of electrical shock the maximum voltage used in the device is 5V DC which does not come into contact with the user. The minimal current produced in the current should not cause any harm to the user as well if they were to create a short circuit in the system. Another precaution the design team took was to ensure that all wires had an insulating cover to reduce the risk of creating a short circuit. The long term benefits of using this device to study forces in upper extremities may result in a reduction in those afflicted or severely afflicted with bone degenerative diseases including osteoporosis and osteoarthritis.

6.4.7 Manufacturability

The intended use for the force sensing device is not wide-scale; as its primary use will be limited to use in the laboratory of Dr. Karen Troy at Worcester Polytechnic Institute's Gateway Park. However, if the market for the device exists it would need to be manufactured at a larger scale. If this were the case, the manufacturability as the prototype stands would not be easily manufactured. Some recommendations to produce the device at a larger scale would be to print circuit boards (PCBs) for the electrical components. Software would need to be developed such that it could easily be used by people of varying skill sets.

6.4.8 Sustainability

The device made through this project is sustainable because the materials used are durable and the team anticipates that the device would only have to be rebuilt approximately every five years if it is being regularly used. The sensors used in the device are the Tekscan® Flexiforce A201 sensors which are supposed to last for a million uses with 50 pounds [41]. The wires are the weakest part of the entire device and with proper soldering they should last for about one year. Although the wires may have to be replaced more often, the rest of the device would last for at

least five years, making the whole device only have to be replaced approximately every five years. It also requires little energy to be transported. The device is sustainable because although it uses batteries; the overall power consumption is minimal. The design team also recommends that all users properly recycle batteries.

7 Discussion

After recording the data for each of the four activities using the force sensing device, graphs displaying the data were created. These graphs were analyzed in order to find patterns amongst the forces at different locations on the hand during different activities. The different trials for each person were compared to each other to see if the person performed the activity had similarities. The graphs for each person were also compared to determine evaluate the consistency of the force sensing device.

7.1 Meaning of the Data

7.1.1 Brushing Teeth

The corresponding graphs in Appendix B show the forces that were produced in the hand when each subject brushed their teeth for about 10 seconds. When observing the data that was collected, there are certain patterns that were noted. The forces exerted on the pad of the middle finger consistently had the highest forces applied for all of the test subjects while the sensor located in the middle of the palm experienced the lowest forces among all test subjects. The maximum force experienced by a sensor with any user was 32N; and the range of forces for all users was similar although, the overall pattern of the forces for each user varied. The combined force experienced by all of the sensors at one time varied as the activity was being performed, however the maximum combined force was about 75N.

7.1.2 Opening a Jar – Top Hand

The graphs of the forces for the data collected of the top or dominant hand involved in opening a bottle can be found in Appendix B. From all of the graphs, the team observed that the sensor on the middle finger consistently received the most force along with the index finger. The sensor on the middle of the palm was consistently receiving very low forces. The team also observed that two peaks occurred in the graphs, one when the bottle was being opened and one when it was

being closed. The larger of the peaks occurred when the bottle was being closed on two of the trials. There were similar pattern for all of the users while there were extreme characteristics for two of the users. They all had about the same maximum force, around 27N – 40N. To see if the goniometer and moment methods that were developed are reasonable; an example calculation was completed.

The moment about the wrist that was calculated was -60.81 Nmm, this value was considered reasonable to the team as the direction the wrist rotates while opening a jar is in the negative direction of the free body diagram. The magnitude of the moment also appears to be reasonable because the jar used in the test was required minimal effort to unscrew the lid and the team expects that the magnitude would increase with a jar that is harder to open.

7.1.3 Opening a Jar – Bottom Hand

The forces for the data recorded on the bottom or non-dominant hand involved in opening a bottle can be found in Appendix B. It was observed that the sensor which received the highest force consistently was located on the palm of the hand, closest to the thumb. The sensors on the pad of the index finger and lower portion of the index finger also consistently received high forces. The team observed that the sensors on the middle finger and middle of the palm location received low forces, while the thumb consistently had forces in the middle range. Similar to opening the bottle with the bottom hand, the top hand had two large peaks for all the users and the maximums ranged from 27N – 40N, similar to the top hand. All of the users had high forces on similar sensors.

7.1.4 Typing

The graphs that illustrate the forces that occurred during typing on a keyboard can be found in Appendix B. It was observed that the sensor on the ring finger received the most force overall

along with the middle finger. The sensor on the index finger received forces in the middle range, while the sensors on the palm of the hand received little to no force. The maximum force that was exerted for this activity was in the range of about 4.9N – 8.9N. The sensors that experienced the highest forces were consistent from user to user.

7.2 Overall Observations

One way to evaluate the effectiveness of the force sensing device is to observe if there is repeatability across the data collected for the same activity. Across all of the data, there are not any particularly clear patterns for each of the different activities as each person's results were different. However, each user exhibited similar patterns across different trials of the same activity which suggests that while the three individuals may exert different forces doing the same activity, the force sensing device is able to collect data consistently. It is also important to note that the only way to see an emerging pattern among people completing the same activity is for an experiment to be conducted which collects data from a large sample size of people over many more trials. An experiment of this size is out of the scope for this design project so the team will consider the data collected from members of the team solely at this time.

Another method to observe the effectiveness of the force sensing device is to see if drifting, or a noticeable change in voltage output with a consistent force being applied occurs over time. In order to determine if drifting occurred the team conducted a test where a sensor is pressed upon with the same force for a period of 30 seconds. The data was then analyzed to see if there was a significant change in the force that was read by the sensor over the time period. Since there was not, it was assumed that the device does not cause any drifting.

The design team was able to observe that the device as a whole was able to function properly. It successfully collected results and exported them to a file. The sensors all read data that was appropriate for their rating as well. While some further testing will be conducted to ensure that there is no drifting of the forces being collected; overall, the design team is confident in the effectiveness of the device to collect data regarding the magnitudes of forces in the hands during different activities.

7.3 Limitations of the Data

There are different reasons that may account for any errors in the data collected. First, while there is confidence in the 445 N calibration curve data as the regression value is 0.9432, there are some noticeable errors occurring around the 70 lb to 80 lb area. Collecting the data for the calibration curve required many heavy weights getting stacked upon each other. As it became taller, the weights became unstable, which explains why the data points from 70 lbs - 90 lbs do not exactly follow the linear pattern that can be seen from the lighter weights. However, while data was not able to be collected for weights that high, it will not inhibit the results. None of the activities that will be done for this project involve 445 N sensors. The calibration for the 445 N sensor was to be used for further verification testing of the sensors.

Another potential cause of error in the results was that the gems used to allow the forces to be distributed over the whole sensor, were a little bit too large and hard. This caused them to slide to the side of a finger occasionally and not record the entire force that was being applied. This source of error was helped slightly by adding electrical tape to the top of the gems, giving them a better grip. A recommendation to improve upon this is to use a material that has more friction to prevent the person's hand from slipping when performing the activity.

A limitation of the device, which caused a problem with collecting the data, is that the cord which connects the DAQ assistant to the computer is not long. This makes it difficult to perform the opening the door activity unless a door with a lever handle is located directly by a computer. It could also cause difficulties in recording data for other activities the client may want to perform. This issue could be solved by having the LabVIEW program installed on a laptop, making the device more portable.

8 Conclusion and Recommendations

8.1 Conclusion

The design team was successfully able to complete the goals defined by the client statement for this project. A force sensing device was researched, designed, and built by the team to determine the forces that different parts of the hand experience during different activities. A method was also developed in order to calculate the angle and distance of the force relative to the wrist, along with the moment about the wrist. Throughout this project, the design team was able to design and build the force sensing device while also keeping in mind the objectives, specifications, and constraints that were originally determined. These included that the device had to be ambidextrous, reusable, durable, safe, portable, easy to use, not hinder the activities, and be compatible with standard lab software. All of these requirements were met. The budget of \$1500 was also considered and the final budget can be seen below in Table 5.

Table 5: Final Budget for the Built Device

Item	Quantity	Cost
25 lb sensors	8	\$160
1 lb sensors	4	\$80
DAQ Assistant	1	-----
Gloves	1 pair	\$3.50
Op-Amps	4	\$4
Resistors	8	\$0.80
Wires	-----	\$5
Velcro®	1 pack	\$26.99
Gems	1 pack	\$2.99

Fabric Glue	1 bottle	\$6.99
Total	-----	\$290.27

The completion of this project is an important step in understanding more about how the forces are distributed over the hand in different situations. The device that was built can be used in studies to help learn this and further discover which types of forces can lead to bone degradation. The eventual goal of the development of this device is to determine exercises that will help to prevent or prolong the onset of bone degradative diseases.

8.2 Recommendations for Future Work

Although the design team was successful in meeting the goals defined for this project, improvements can always be made. Some recommendations for future work that the team has are as follows.

8.2.1 Goniometer and Moment Method

This method was developed and equations were developed for one example in one activity. It would be recommended to follow the method and determine the equations for the other sensors in each of the activities. These equations can then be put into a program, such as MATLAB, in order to easily input angles and lengths to calculate the angle and distance of the force relative to the wrist as well.

8.2.2 Testing

In order to get a more accurate representation of if there is repeatability among all of the data more trials need to be done for each activity. This will allow a better comparison and statistical analysis to be done. It would also be recommended that more people take part in these trials. This would allow the user to know if there is repeatability from person to person.

8.2.3 Glove Material

Another recommendation that can be made to further enhance this design is to use different size gloves depending on the user. The glove used in this prototype is extremely stretchy, which is excellent for interchangeability between users. The downfall to this is that it can slide easily, which could potentially lead to skewed results if the user is not careful of the sensors becoming misaligned

8.2.4 Footing Material

The design team recommends changing the material of the sensor footing that allows the force to distribute equally over the sensor pad. The gems being used now are slightly too tall and hard, which makes it difficult to grasp things. A recommended material would be something that is hard, but had a grip to it.

8.2.5 Wires

A beneficial change that can be made to our design that would improve it is changing the wires. The wires used to attach the sensors to the proto board are very thin and did not fit securely into the designated spots so they had to have thicker wires soldered to them at the ends. Also, it would be beneficial for the wires that hook from the DAQ to the proto board to be longer so that the user is not constrained with space and can move the DAQ and proto board around easier. This would make it easier for activities that require more movement or are further away from the computer.

8.2.6 Calibration Techniques

The calibration techniques that we used can always be improved until the regression value is at 1. A better process to obtain the calibration for the higher weight would be useful because those are where the values on the curve started to deviate from the norm. More calibrations done will improve the statistical value and lead to more accurate force data results.

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Appendices

Appendix A: Completed Feasibility Charts

Table 6: Feasibility ranking chart for team member A

Design Criteria	Putty/Playdough	Sensor Glove	Interchangeable w/load cell	Fujifilm
Doesn't inhibit activities	2	4	3	5
Ambidextrous	5	4	3	5
Durable	3	5	5	5
Reusable	5	5	5	1
Burden for user to complete calculations	2	3	4	3
Measure forces relative to wrist	4	3	3	3
Measure forces in different locations	3	5	2	5
Cost effective	1	4	4	4
Easy to use	1	3	4	5
Total Score:	26	36	33	36

Table 7: Feasibility ranking chart for team member B

Design Criteria	Putty/Playdough	Sensor Glove	Interchangeable w/load cell	Fujifilm
Doesn't inhibit activities	4	3	4	3
Ambidextrous	4	5	5	5
Durable	3	4	5	3
Reusable	1	4	4	1
Not a burden for user to complete calculations	1	4	2	3
Measure forces relative to wrist	4	2	1	3
Measure forces in different locations	3	5	2	4
Cost effective	3	4	3	3
Easy to use	4	3	2	4
Total Score	27	34	28	29

Table 8: Feasibility ranking chart for team member C

Design Criteria	Putty/Playdough	Sensor Glove	Interchangeable w/load cell	Fujifilm
Doesn't inhibit activities	4	2	4	4
Ambidextrous	5	1	5	5
Durable	3	4	5	3
Reusable	4	5	5	1
Burden for user to complete calculations	1	5	1	3
Measure forces relative to wrist	2	3	1	3
Measure forces in different locations	4	5	1	3
Cost effective	5	5	3	4
Easy to use	4	5	2	4
Total Score:	32	35	27	30

Appendix B: Graphs of Data for All Activities

Toothbrush Activity

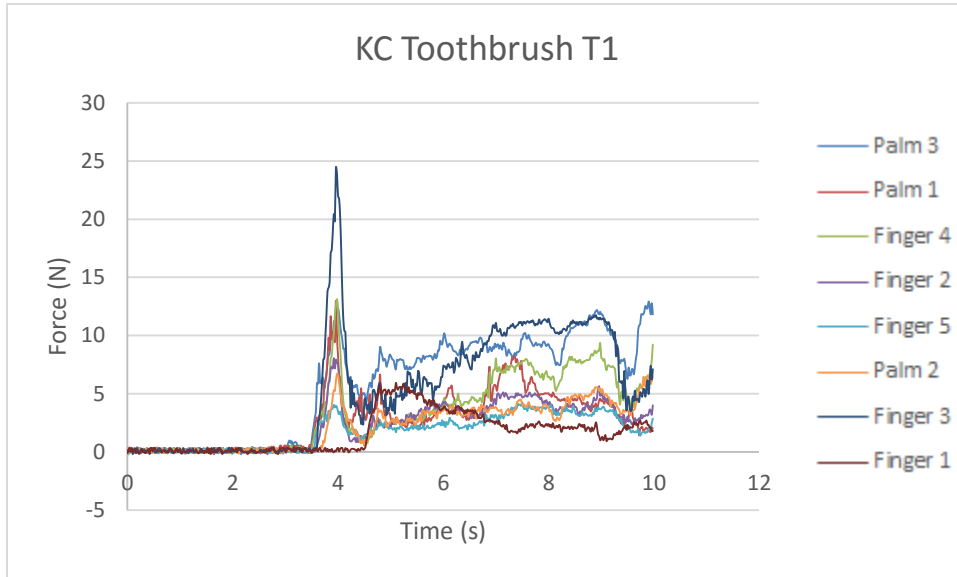


Figure 64: Graph for Trial 1 of Person 1 brushing their teeth

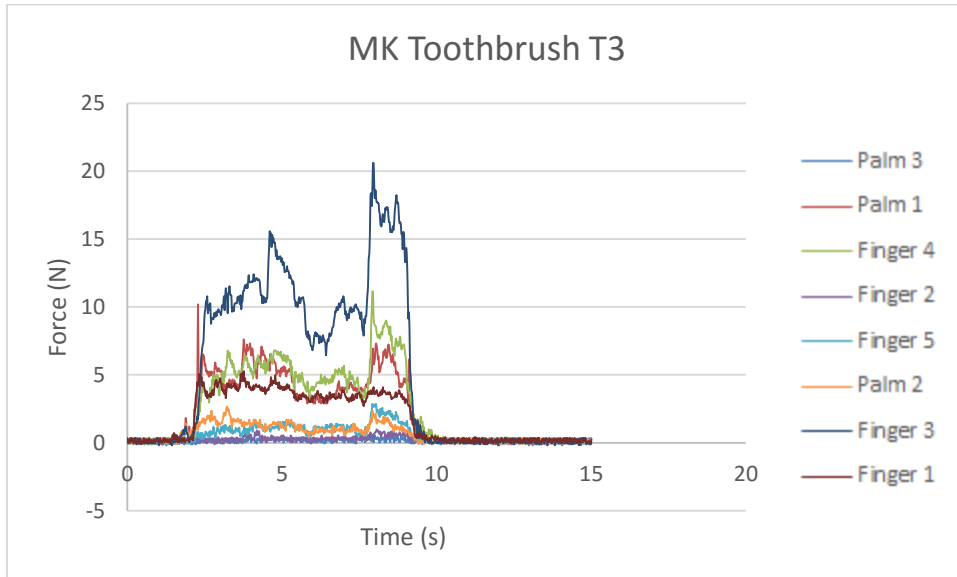


Figure 65: Graph for Trial 3 of Person 2 brushing their teeth

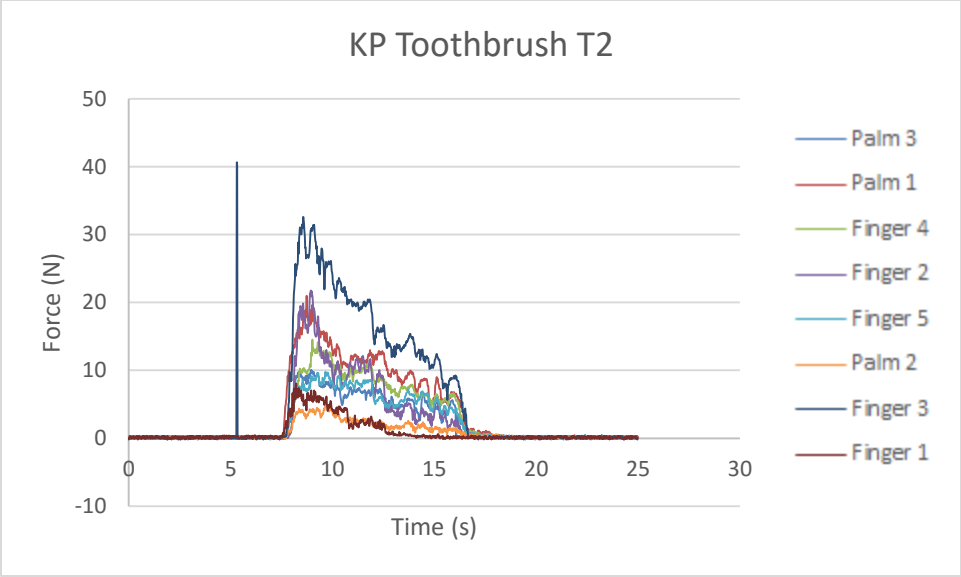


Figure 66: Graph for Trial 2 of Person 3 brushing their teeth

Bottle Opening Activity

Top Hand

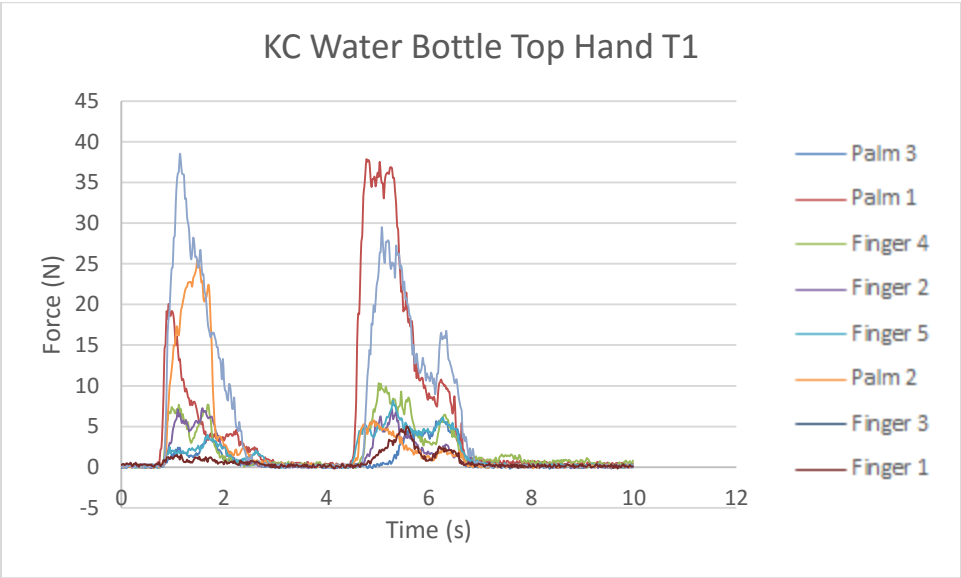


Figure 67: Graph for Trial 1 of Person 1 opening a bottle with their top hand

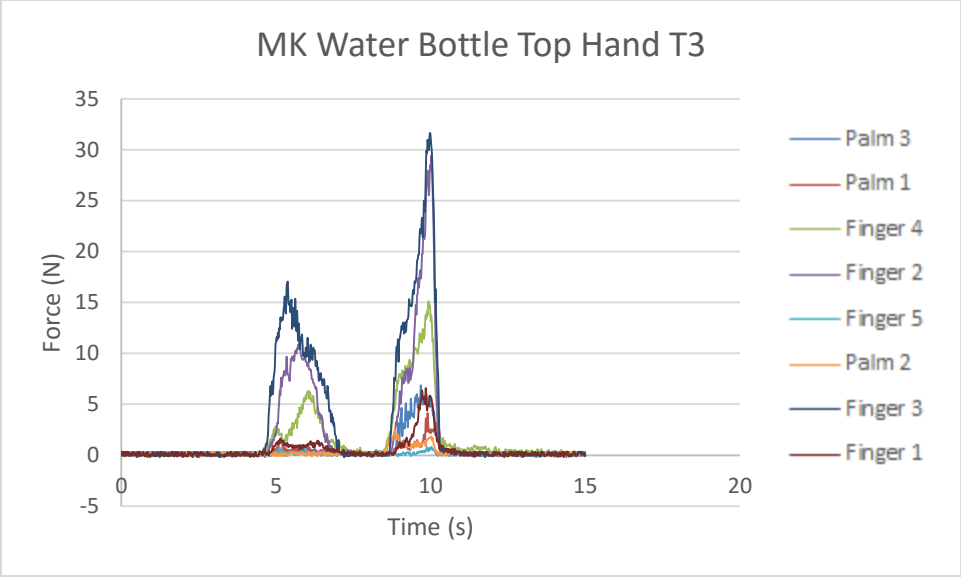


Figure 68: Graph for Trial 3 of Person 2 opening a bottle with their top hand

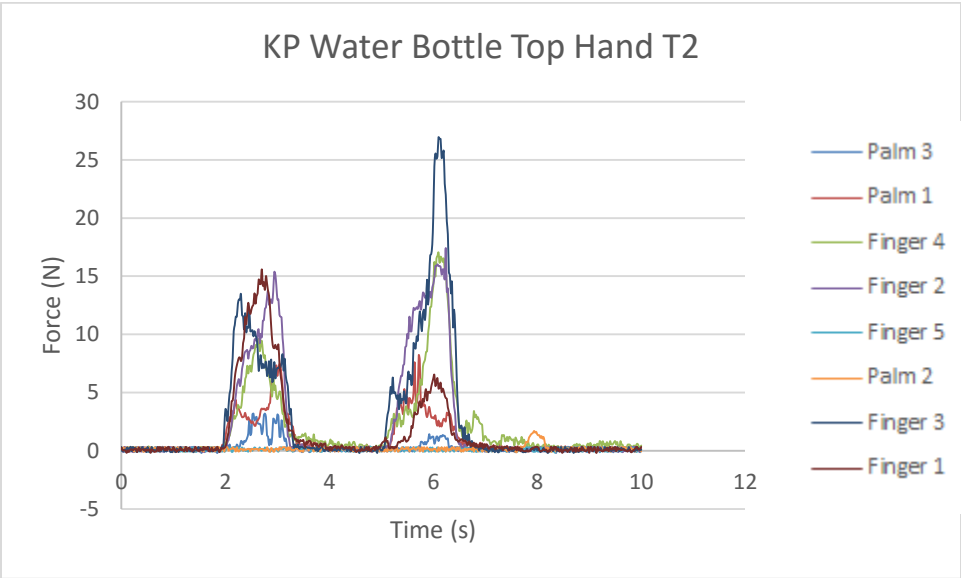


Figure 69: Graph for Trial 2 of Person 3 opening a bottle with their top hand

Bottom Hand

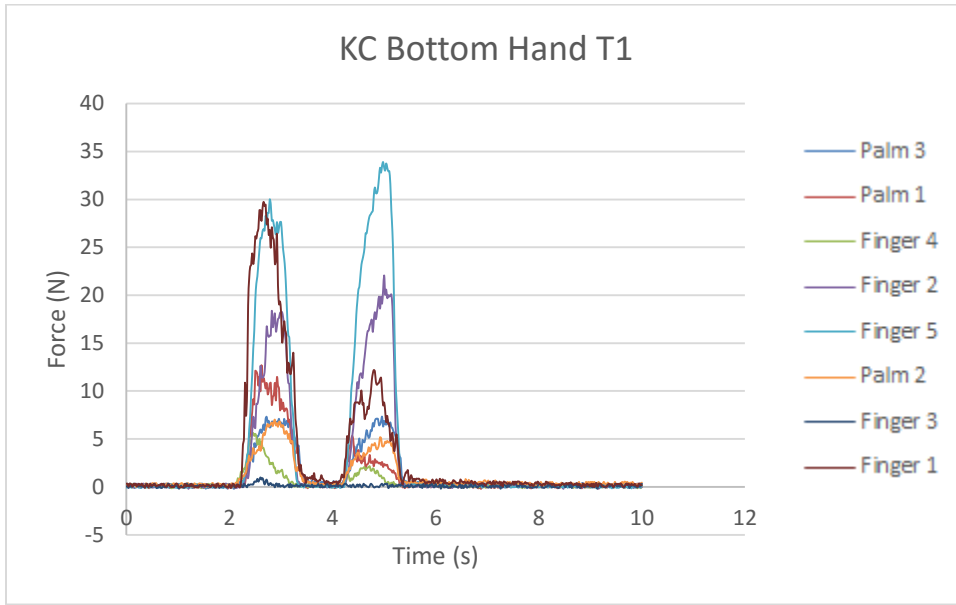


Figure 70: Graph for Trial 1 for Person 1 opening a bottle with their bottom hand

Typing

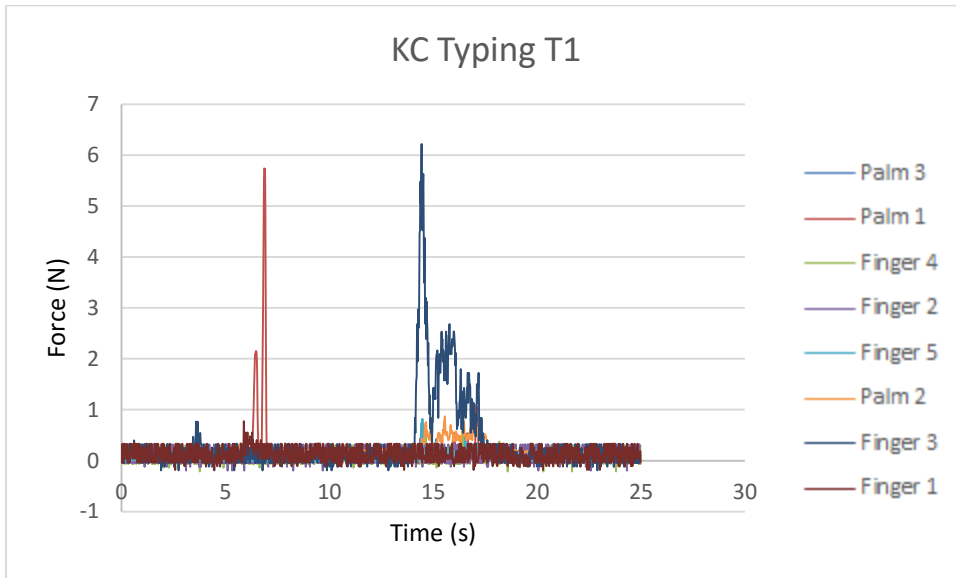


Figure 71: Graph for Trial 1 of Person 1 typing on a keyboard

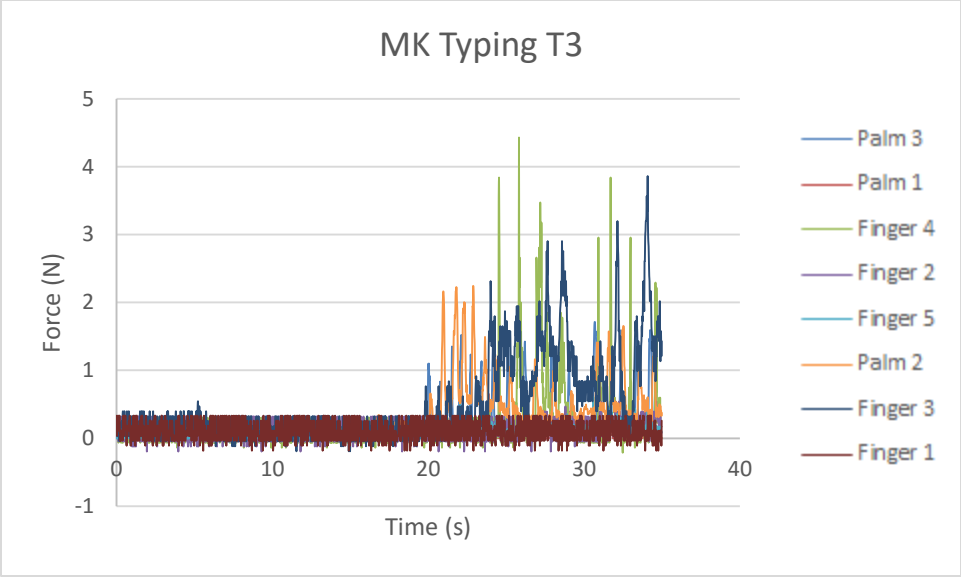


Figure 72: Graph for Trial 3 of Person 2 typing on a keyboard

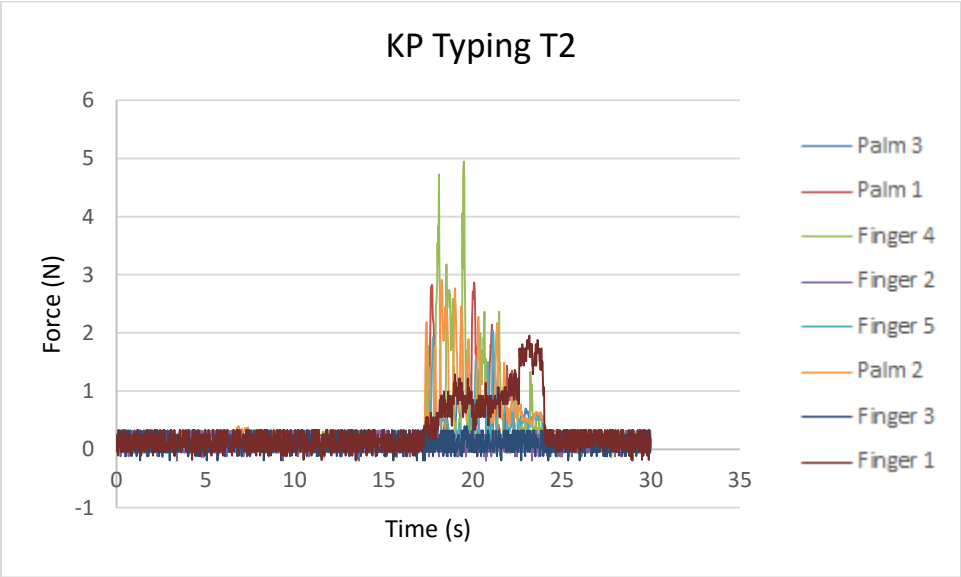


Figure 73: Graph for Trial 2 of Person 3 typing on a keyboard

Appendix C: User Manual for Force Sensing Device

Setup

Materials needed:

- Proto board
- Flexiforce A201 sensors
- National Instruments USB-6009 + USB connector
- 8 100 kOhm resistors
- 2 medium length wires
- 8 long wires
- 1 V battery with connectors

Glove

1.1 Determine the activity to be performed.

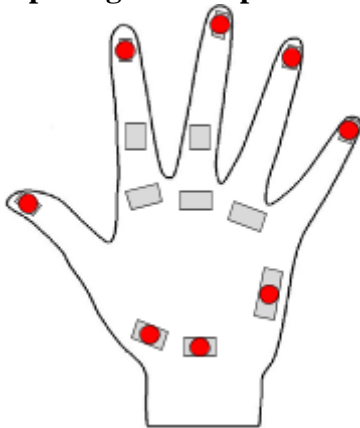
1.2 Orient sensors based on activity chosen using the diagrams below.

1.2.1 The blue tape wrapped around the wires indicate the 25 lb sensors and the black tape wrapped around the wires on the sensors indicate the 1 lb sensors.

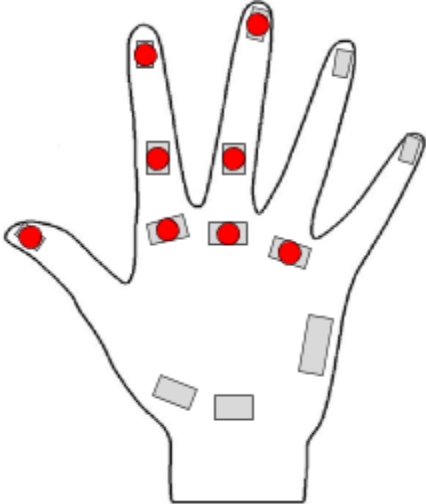
1.2.2 Put the wires and any excess sensor under the elastic bands.

1.2.3. The grey rectangles represent where all of the Velcro patches are located on the glove. The blue dots represent the 1 lb sensors and the red dots represent the 25 lb sensors. All of the diagrams are shown for the palm of the left hand, however they can be mirrored for the palm of the right hand. There is tape on the sensors indicating its force level.

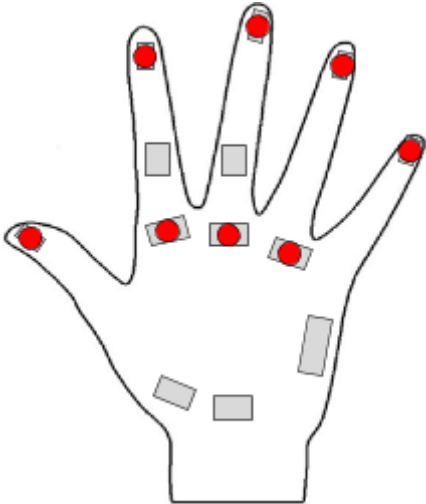
Opening Jar - Top Hand



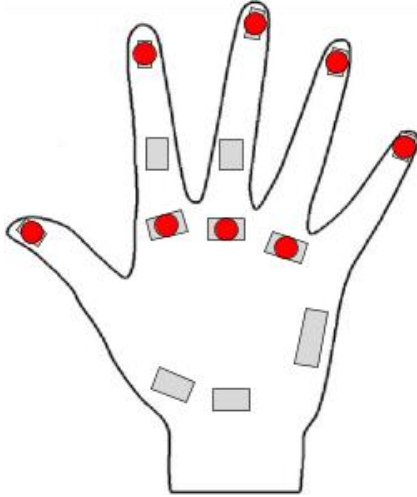
Opening Jar - Bottom Hand



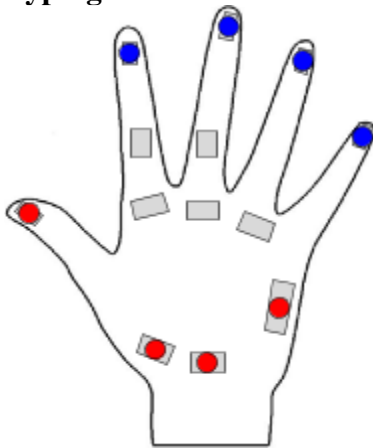
Toothbrushing



Opening a Door



Typing



Proto Board

2.1 Orient the proto board so that the tape on the board is in the 'up' position. There is a piece of black tape adhered to one edge of the protoboard for orienting purposes.

2.2 Battery

2.2.1 Connect the wire attached to the negative terminal of the battery to port B2 on the protoboard as seen below in picture 2.4. The battery terminals are soldered to male connectors for easy insertion to female connectors on the protoboard. Most batteries indicate the positive terminal with a '+' and they are commonly the protruding side of the battery.

2.2.2 Connect the wire attached to the positive terminal of the battery to port B1 on the protoboard as seen in picture 2.4

2.3 Power

2.3.1 When securing the wires for powering the amplifier circuit, ensure that the wires are screwed into the DAQ first, and then plugged into the proto board afterwards.

2.3.2 Using a small flat head screwdriver, secure a medium length wire into the port labelled +5V on the digital side of the DAQ and secure another medium length wire into the port labelled GND on the digital side of the DAQ. Gently pull on each wire to ensure they are properly secured.

2.3.3 Insert the wire attached to the GND port of the DAQ into port P1 on the protoboard as seen in picture 2.4

2.3.4 Insert the wire attached to the +5V port of the DAQ into port P2 on the protoboard as seen in picture 2.4.

2.4 Collect eight 100kohm resistors and insert each end into the ports circled in yellow in picture 2.4 on the protoboard, the direction of the resistors do not matter. Check to make sure that both ends are fully inserted into both ports

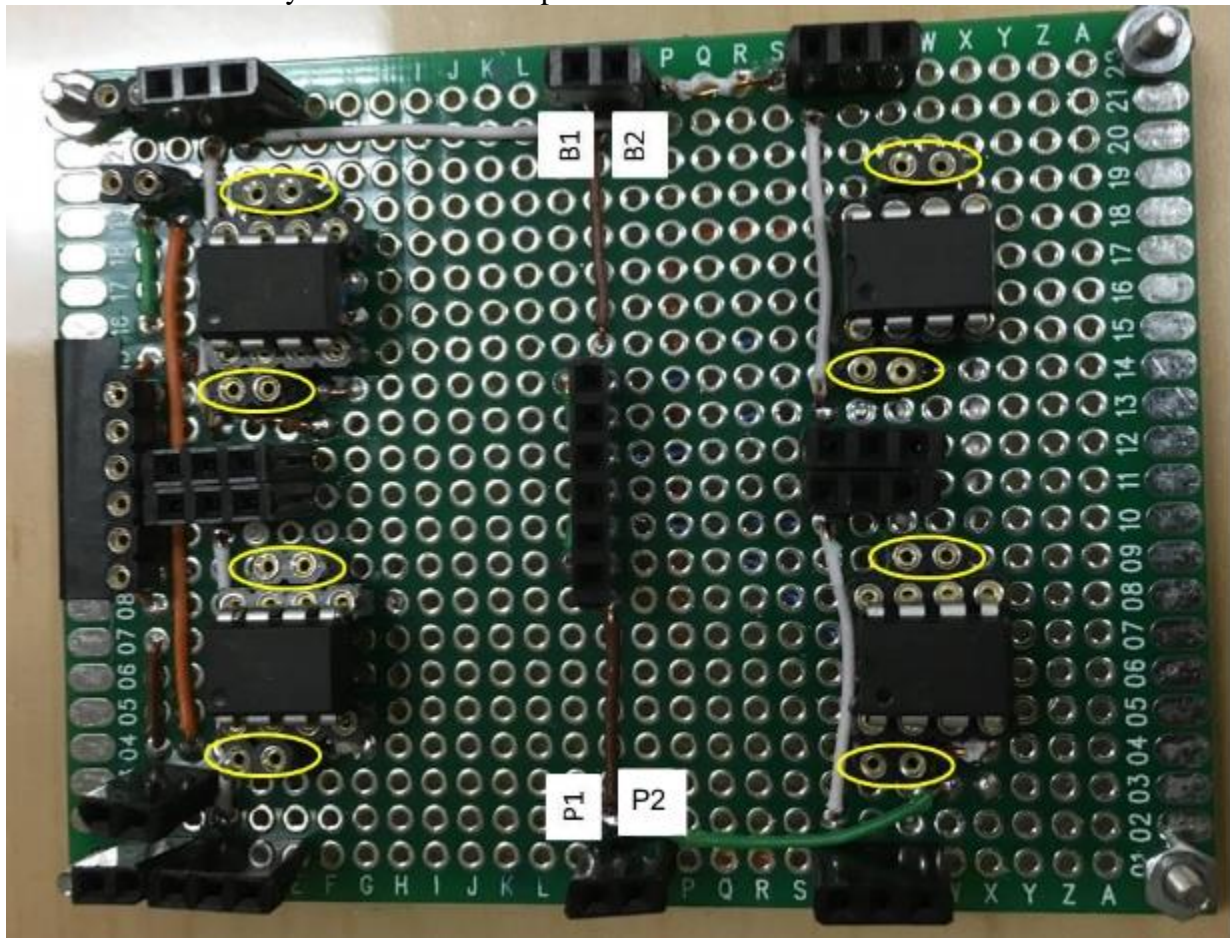


Figure 2.4

2.5 Protoboard and DAQ connection

2.5.1 Collect 8 long wires, and using a small flat head screwdriver, secure one end of each wire into DAQ ports AI0+, AI0-, AI1+, AI1-, AI2+, AI2-, AI3+, AI3- on the analog side of the DAQ.

2.5.2 To connect each port on the DAQ to the protoboard output port, use the rows in the chart below to connect the DAQ Port to the corresponding Output Port on the proto board by inserting the other end of the wire into the female connector. See picture 2.5 for port locations to insert the wires on the proto board.

Table 9: The corresponding Proto board port, DAQ port, and LabVIEW graphical indicator for the system are grouped together in rows. If the proper port on the proto board is connected to the DAQ port indicated in the same row, then the sensor that is connected to that port can be seen in the graphical indicator in the same row.

Sensor Port	Output Port	DAQ Port	Graphical Indicator in LabVIEW
S1	O1	AI0+	1
S2	O2	AI0-	5
S3	O3	AI1+	2
S4	O4	AI1-	6
S5	O5	AI2+	3
S6	O6	AI2-	7
S7	O7	AI3+	4
S8	O8	AI3-	8

2.5.3 When securing the sensors to the protoboard, document the location that the sensors will be placed on the glove as well as the sensor port on the protoboard. Picture 2.5 shows the locations of the sensor ports on the protoboard. Use the rows in Table 9 to identify which graphical indicator each sensor will be represented on the LabVIEW Program.

2.5.4 To insert the sensors into the female connectors, insert them into the two outer ports of the 3 adjacent female connectors that have arrows pointing to them.

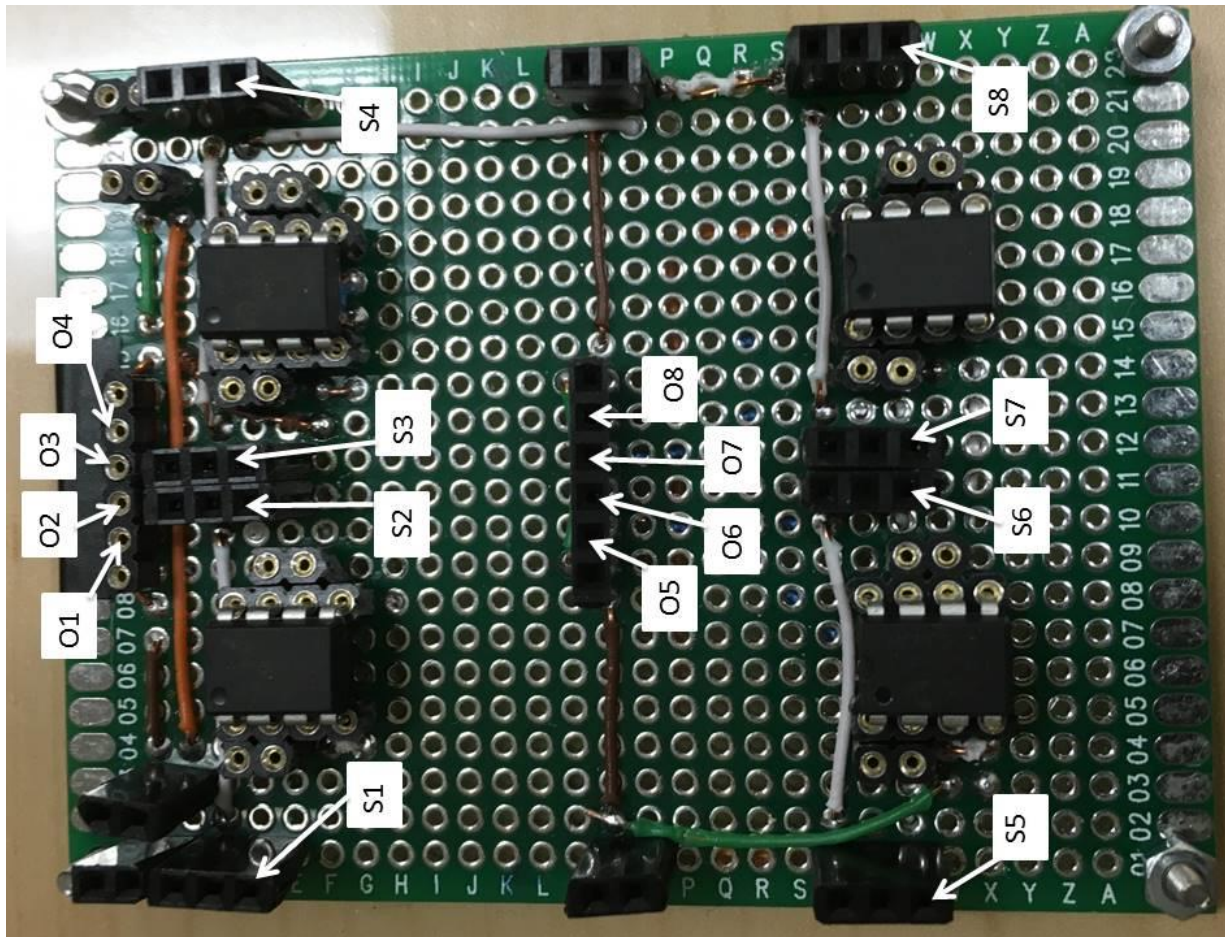


Figure 2.5

LabVIEW

- 3.1 Attach the DAQ to the computer by plugging the USB into the port on the left side of the laptop.
- 3.2 The LabVIEW program must then be opened.
- 3.3 Make sure eight channels are setup as described in the following steps.
 - 3.3.1 The front panel is the panel with all of the graphs and will pop up first when the program is opened
 - 3.3.2 To open the block diagram, which has the program portion, press “ctrl-E”.
 - 3.3.3 In the block diagram, double click on the DAQ assistant.
 - 3.3.4 If there are eight channels, close the DAQ assistant.
 - 3.3.5 If there are not eight channels click “add channel” and add a voltage channel until there are eight of them.
- 3.4 Run the program and collect data
 - 3.4.1 Click the run arrow at the top of the front panel
 - 3.4.2 Save the data in the box that pops up.
 - 3.4.3 Perform the activity.
- 3.5 Stop the program from collecting data by clicking the button that reads “STOP” in the front panel.
- 3.6 Convert the data file to a .xlsx file to open in Excel

Force to Voltage

- 4.1 Open the data file of the chosen activity.
- 4.2 Delete all extraneous information that appears in the excel spreadsheet.
- 4.3 Use the pre-determined information to recall which sensor force each of the sensors used is
- 4.4 If the sensor is 1lb, divide the voltage points by .0086. If the sensor is 25lb, divide the voltage points by .1539. This will give you the force values.
- 4.5 Highlight the time column and all force columns and create a scatter plot in excel.

Appendix D: Glove Instructions

Table 10: Glove Bill of Materials – All materials can be purchased at a craft store.

Material	Quantity
Glove	1 pair
Adhesive Velcro	1 ft
Elastic band ¼” wide	1 ft
Fabric glue	1 bottle

Instructions:

1. Cut 20 strips of Velcro in 1” x ½” long sections
2. Using fabric glue adhere the Velcro to the following locations on both gloves in the pair:
 - a. The top of each finger tips of the gloves, including the thumb. Orient the strips so that the length goes down the length of the finger.
 - b. One strip 3” proximal from the top of the pinky finger. Orient the strip so that the length is parallel to the side of the hand.
 - c. One strip 2” proximal from the top of the index finger. Orient the strip so that the length is along the width of the finger.
 - d. One strip 2” proximal from the top of the ring finger. Orient the strip so that the length is along the width of the finger.
 - e. Two strips 5” from the tip of the index finger and the middle finger. This should align so that the lengths are along the width of the wrist. There should be ¼” of space between the two strips.
3. Cut 10 strips of elastic band 1” in length.
4. Cut 2 strips of elastic band 3” in length
5. On both gloves in the pair sew the widths of bands in the following locations:
 - a. Sew the 1” long strips ¼” proximal to all of the fingers and the thumbs. The lengths of the bands should span the widths of the fingers and should allow an opening directly below each Velcro strip.
 - b. Sew the 3” long strips ¼” from the opening of the gloves at the wrist. The length of the bands should be parallel to the opening of the glove. Sew widths of the bands so that the opening is along the length.
6. A visual guide to the layout of the gloves can be seen in Figure 53.