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Textile-Based Sensor Development for the Continuous Monitoring of Proper Orthopedic Cast Fit

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Textile-Based Sensor Development

For the Continuous Monitoring

Of Proper Orthopedic Cast Fit

A thesis submitted in partial satisfaction

of the requirements for the degree Master of Science

in Electrical Engineering

by

Carson Andrew Umsted

2013

ABSTRACT OF THE THESIS

Textile-Based Sensor Development

For the Continuous Monitoring

Of Proper Orthopedic Cast Fit

by

Carson Andrew Umsted

Master of Science in Electrical Engineering

University of California, Los Angeles, 2013

Professor William J. Kaiser, Chair

The ability to determine the level of support a cast provides to a fractured arm through the course of healing does not currently exist yet is very useful information in being proactive to make adjustments to the fit of the cast. The method to which these measurements can occur is constrained by the physician's constraints which require a

non-invasive, compact solution that can continuously monitor the level of support at a reasonable interval while maintaining a simple and low-cost implementation. These objectives require the use of the latest in textile innovation. The SmartCast system utilizes textile properties to create pressure resistive sensors that can be directly placed between the injured arm and the cast while not impacting patient comfort. The development of this system has allowed the provision of level of support information validated with the initial cast-based tests.

The thesis of Carson Andrew Umsted is approved.

Robert N. Candler

Gregory J. Pottie

William J. Kaiser, Committee Chair

University of California, Los Angeles

2013

I dedicate this thesis to my parents, sister, and grandparents. With their support I was able

to reach the goal of becoming an engineer by completing my academic studies to start

my career and continue life.

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I would like to thank Professor William J. Kaiser, Henrik Borgstrom, Bijan Mapar, and

Mahdi Ashktorab for their advice and guidance during development. I would also like

to acknowledge committee members Professor Robert N. Candler and Professor

Gregory J. Pottie for their advice and approval of this thesis.

Chapter 1: Introduction

The treatment of fractured bones has remained fairly the same over the past several decades. When one has a bone injury, it is necessary to set the bone and wrap up the region with a hard plaster cast. With the advancement of technology, improving the effectiveness of this treatment is possible. Through research of different types of materials and circuitry, a compact, non-invasive monitoring system has been prototyped and ready for initial patient deployment and evaluation.

1.1 Background

When a child fractures his or her arm, it is a very unpleasant experience and places a restrictive cast over the region to provide a rigid support. This is done in steps by first setting the bone in place then wrapping the arm in gauze. Then, another layer is applied prior to the cast material. When applied, the cast wrap is damp and very flexible like normal cloth, allowing the technician to wrap the arm as tightly as is deemed necessary and in the appropriate position. Once dry, the material is very hard, providing support for the injured arm. This allows for the fractured bone to remain in place and heal back together. Normally, after about six weeks, the cast is removed and the child can return to their normal activities [1]. However, there are instances where this case gets prolonged due to improper healing.

In some cases, when the swelling of the arm decreases as the injury heals, the rigid cast doesn't always provide the necessary support to prevent the bones from shifting before the fracture interface has a chance to heal because of the child's active movement [1]. If the bones shift before they have a chance to fuse back together, then cast will have to be removed and the bone re-fractured by a physician. This restarts the healing process, leaving the patient another long recovery.

If the physician had the ability to monitor the support of the cast to the patient's arm, early intervention can be initiated to correct the poor fitting cast and prevent unnecessary pain, discomfort and suffering of the patient. However, there is currently no device on the market that is available to continuously monitor for an ineffective cast. To the best of my knowledge through the research of articles, there has not been an attempt to solve this problem. The risk of having to re-fracture the patients arm later has gone unmitigated.

1.2 Objectives and Contributions

This thesis aims to provide a non-intrusive and low-cost cast support detection system, also known as SmartCast. This system will be capable of providing meaningful measurements for the detection of casts which are not providing the necessary support to keep fractured bones in place. The SmartCast system is designed to periodically monitor the pressure between a cast and injured arm with minimal retraining of technicians,

configuration, or adjustment. The system has two main systems and can be improved upon based upon the results of the initial clinical trials. The work contained within this thesis is comprised of three major contributions as listed below:

1. Design of sensor(s) capable of sensing the range of pressures found in the cast environment
   a. Material research and selection that will meet the criteria
   b. Sensor manufacture design to yield accurate and meaningful data
   c. Simplify and improve design for ease of manufacturability and patient comfort

2. Characterization of the sensor performance as related to actual conditions and edge cased
   a. Experiments based on the length of exposure time of a constant pressure
   b. Experiments of dynamic cases through a long period of time
   c. Experiment for testing contamination mitigation
   d. Full system experiment simulating each possible situation within the cast environment

3. Selection of enclosure for containing the sampling circuitry and power source
   a. Estimation of power requirements for life of trial using estimates of sampling and sleep power values to contribute to making a sampling schedule

b. Finding a safe, but compact power source capable of supplying the necessary power for the trial period

c. Selection of a sealed case for the purpose of containing the selected battery and the sampling PCB

Chapter 2: Sensor Design

Throughout the course of research, there were many designs conceived and tested to achieve the goal of developing a simple cast monitoring system. The initial goal was designed using commercial sensors and integrated into a monitoring circuit. However, the use of these sensors was ruled out because of many contributing factors. The ultimate goal was to have a design that did not interfere with the normal process of casting, but required minimal application to be effective to reduce the need for new procedural training.

2.1 Initial Design

The first attempt was to apply a sensor to the patient after the cast had cured. By learning the critical area of where the fracture occurred, it was conceived to extract a small area out of the cast and insert a sensor which would be fastened to a cast. Since a section of the cast was being removed, it was important to still provide support in that region with the device placed there. One way of achieving this was to use a set of parallel plates with springs applying force downward. With the device secured to the outer region of the cast, the lower plate would provide support as a result of the spring force. Figure 1 shows a CAD model of the initial design before springs were added to the posts.
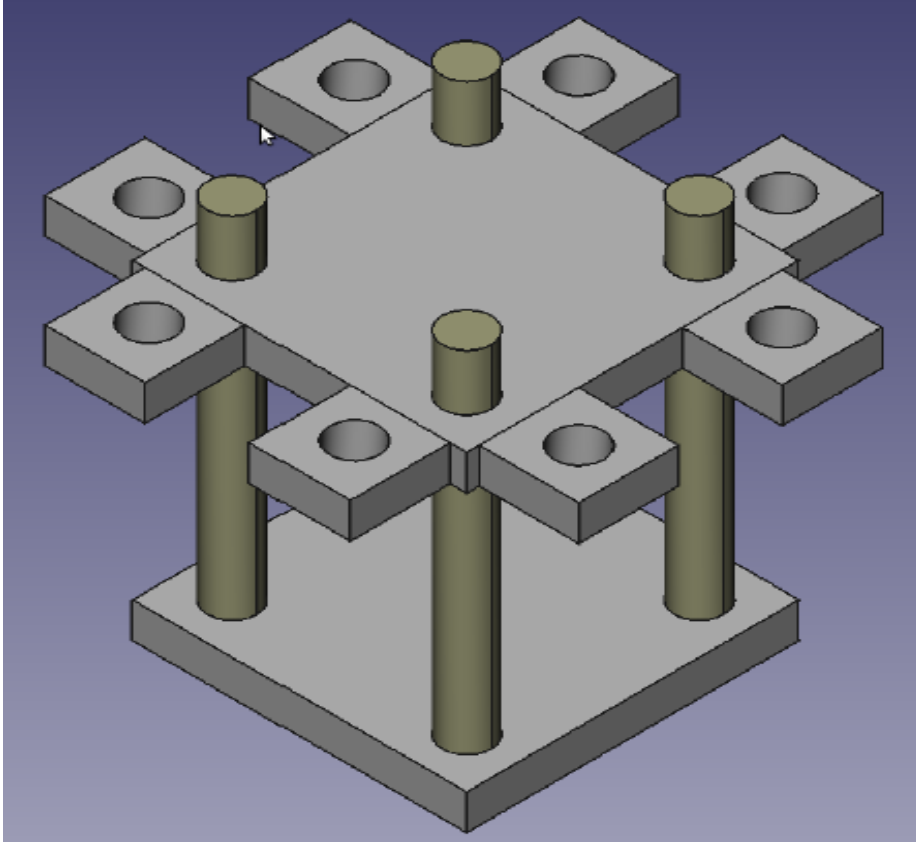
Figure 1: CAD Model of First Prototype

Figure 2 shows the initial prototype of this platform. With springs around each of

the four posts between the parallel plates, the structure will remain in contact with the

patient's arm. Because of this, one can measure the distance between the cast and arm. As

the injury begins to heal and the swelling subsides, the spring loaded platform would

expand to remain in constant contact with the arm. This behavior enables one to fit the

platform with a sensor to detect the change in distance. By knowing the change in

distance, one can estimate the effectiveness of the cast supporting the affected region

through data gathered in patient trials and estimation.

Figure 2: First Prototype for Evaluation

Since the structure only expands linearly and does not move any meaningful

amount laterally, a perfect sensor for this device is a linear potentiometer. The linear

potentiometer acts as any other potentiometer does by have a variable resistance.

However, the resistance is changed by displacing a rod rather than turning a screw or

knob. As the rod is moved the resistance value changes. Measuring the resistance over

time is a key way to gather information about how the arm is healing in regards to the

cast size.

With the potentiometer mounted, the first evaluation of its performance was
carried out. To simulate an arm, an inflated bicycle inner tube was used and a clamp to
apply pressure. Without a cast, this experiment served as a suitable substitute. With the
inner tube inflated initially, the clamp was attached along with the device as shown in
Figure 3. Slowing deflating the inner tube showed that the device indeed expanded and
allowed the observation of changing resistance based on position.
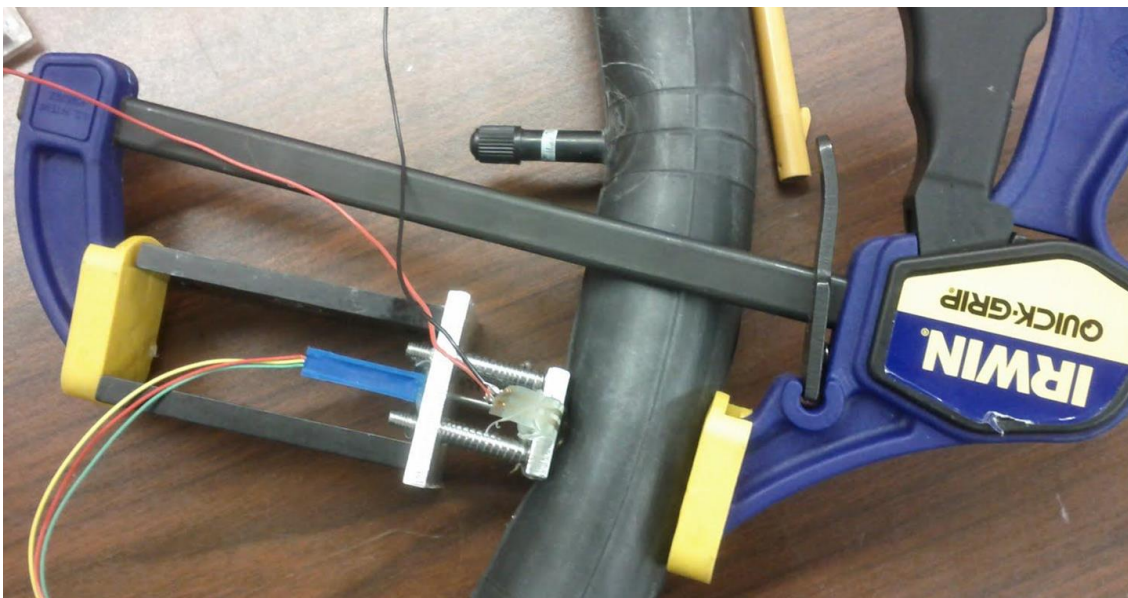
Figure 3: Linear Potentiometer Test

To assist in the characterization of the linear potentiometer based sensor, a force
resistive sensor was placed on the bottom plate between the plate and the bicycle inner
tube. The force sensor came with a datasheet showing its behavior as a result of applied
pressure. Although the absolute pressure value was not needed, the behavior and trend
was in order to deem our potentiometer based device as a viable solution. Data for both
the linear potentiometer sensor and the force resistive sensor are overlaid in Figure 4. As

one can see from the resultant data gathered from this test, the linear potentiometer had a more varied range as compared to the force sensor; however, the trends were the same. A lower pressure corresponds to a lower resistance. With the inner tube at a relatively neutral state, the pump was used to increase the pressure, thus seeing the rise in resistance just before sample 200. Once the tube was fully inflated, air was slowly deflated through the valve stem causing the pressure to decrease. Completely deflated by sample 300, the air pump was used again to inflate it to its peak pressure. There was no obvious sign of degradation of either sensor as they stayed synchronous in their trends.
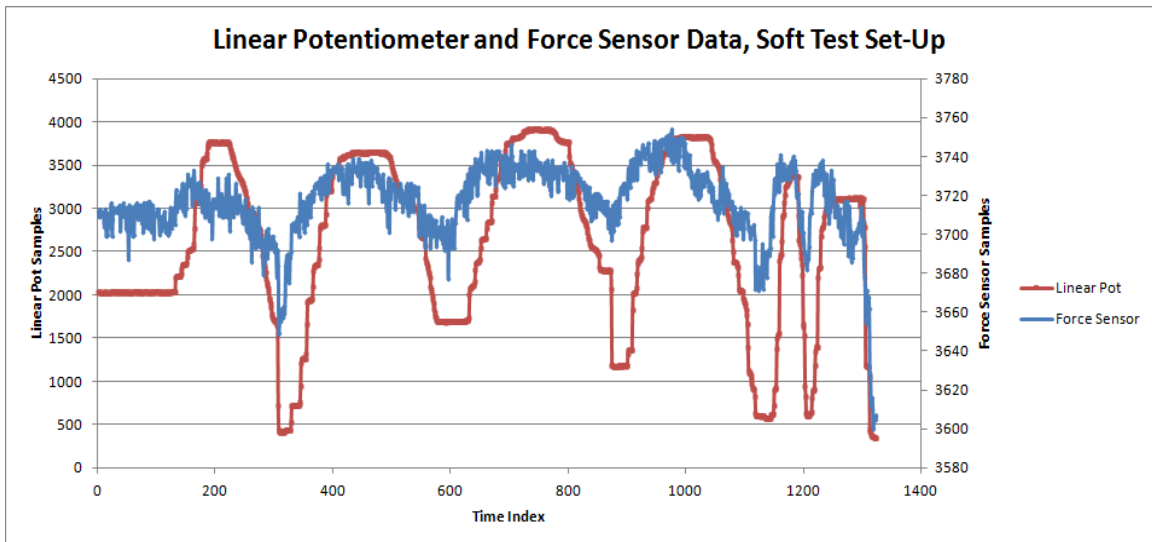

Figure 4: Results of Inner Tube Test

Although this sensor is able to measure pressure indirectly by measuring the distance between the arm and the cast, it has some issues that have been hard to overcome. The most pertinent was reducing the size of the device. As seen in the image of the experimental setup, the potentiometer raises above the surface of the upper plate by

more than a one-half inch. In addition, when first applied, the four posts also rise above.

This poses a safety risk to the children. If the child were to fall down onto the device, it

could potentially cause a laceration. A secondary issue regarding the use of this sensor

design was brought forth later in discussion with physicians. It was noted that in order to

use this device, there would be more training involved with the technicians that would

install the cast. Precise removal of a small section of cast and affixing the sensor to the

surface complicates the process.

2.2 Sensor Array

A drastically different design was needed to meet the needs of the medical

community. A method of monitoring pressure was needed in which the application

required virtually no change in the normal procedure of application. The solution has

been to design a wearable sensor system that would not interfere with installation or the

patient's safety. Because there is a layer or sleeve of gauze under the cast, this gives a

platform that one can mount a sensor to. However, another issue is to have the sensor

flexible enough to not provide wearable discomfort during the six weeks wear period.

The resolution was to use different fabric materials that would have properties which

enable the detection of pressure inside the orthopedic device.

New types of textiles enable the detection of pressure based on their properties.

As mentioned, the goal was to integrate sensing technology without the patient noticing a

difference or discomfort because of it. Fabrics have advanced greatly in the past several years and have enabled the development of the SmartCast prototype. Although these textile materials have been used for similar sensors, there has not been a grid design for this purpose [2, 3, 4, 5]. The commercial force sensor worked very well in the evaluation phase and would work very well between the cast and the arm, with the exception of it being made of a fairly rigid plastic. Also, since the sensors were to be now located between the cast and arm, the opportunity of gathering data from across the entire arm would be useful and potentially more accurate in calculating the cast support on the arm. There are textiles used in electrostatic shielding which have properties of changing conductivity as a result of stretch or pressure [6]. For example, Velostat, manufactured by [7], has a pressure resistive characteristic to it that when force is applied, the resistance across the material decreases, just as the force sensor behaved, and incidentally, how the linear potentiometer's behavior was.

The great challenge of harnessing the behavior of this fabric has been to connect it to a small circuit to measure, monitor, and record the resistance of the sensor. Leveraging methods presented in [8, 9], for connections to be made to each side of the pressure resistive fabric, conductive fabric was applied. This small patch was then stitched to the same type of sleeve material used under the cast. After doing some preliminary tests, it appeared that the performance was very good. Figure 5 below shows the 1/R behavior of the new sensors, some using two layers of pressure resistive material and others using three.
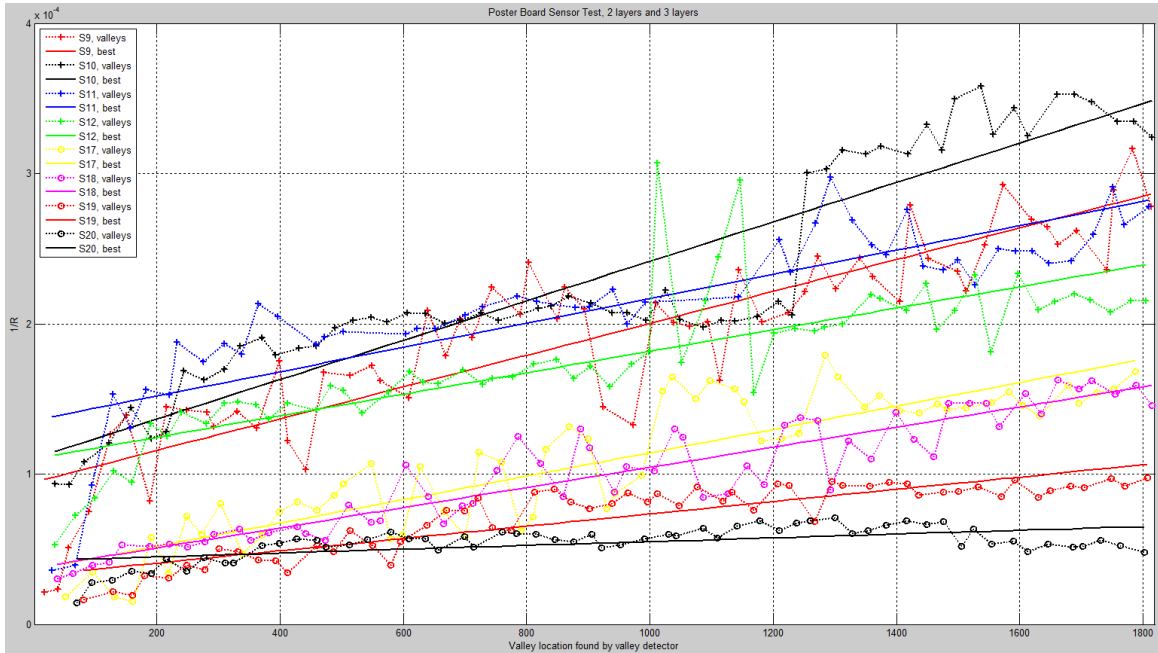
Figure 5: Conductance Plot of 2 and 3 Layer Sensors

After confirming that the behavior between the different number of layers is the same except for a shift in the base resistance, a test with a series of masses was performed with a single layer. Figure 6 shows the results of the test. The test consisted of measuring the sensor value while increasing the mass on it by an increment of five grams at a time. The spikes you see in the graph was where one mass was removed and another added in the case that no more five gram masses were present and a larger base mass was added. These are not anomalies in the readings but rather the actual value read when some mass was briefly removed and another added.

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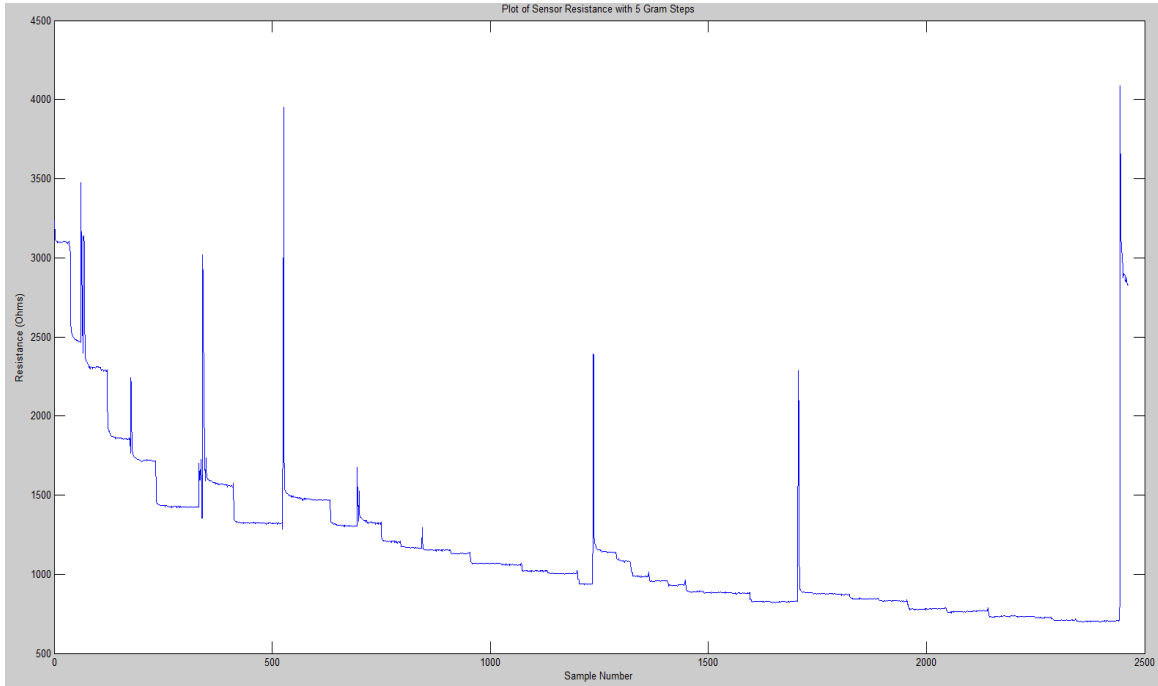
Figure 6: Resistance vs. Mass for Single Layer Sensor

Following the promising results of the test, it was then that a matrix of 16 sensors was stitched on to be both tested, and evaluated for compatibility.

2.3 Conductive Thread Evaluation

To validate the use of conductive thread to stitch together the individual sensors, it was imperative to subject a test sample of it to the extreme conditions that it may see in use. The following describes the experiment taken to test the behavior of the conductive thread in water and to ensure proper current capacity for the end use case. These experiments were conducted in the laboratory under constant environment conditions.

The goal of the first experiment is to characterize the performance of the thread before, during, and after an exposure to water. First, a 10 inch section of the thread was cut from the spool with a pair of scissors and connected to a standard handheld multimeter. With the probes approximately placed 0.25 inches from the end of the thread, the resistance of the thread was measured to be at 6.5 ohms. The conductive thread was then placed under a running water faucet (standard tap water) for 30 seconds to ensure complete submersion and saturation. The resistance was again measured under the same setup and found to be 6.2 ohms.

After allowing the thread dry for 15 minutes, the resistance was again measured and found to be 6.4 ohms. Finally, after the thread was completely dry about two hours later, the resistance was found to be 6.5 ohms as it was prior to the exposure to water. It was also noted that each step of the test showed that there were no noticeable signs of material integrity degradation. The thread maintained the same strength and properties throughout.

Time Index (minutes)	Condition	Measured Resistance (Ohms)
0	Initial	6.4
0.5	Water Saturation	6.2
15.5	Brief dry time	6.4
135.5	Completely dry	6.5

Table 1: Conductive Thread Water Exposure Experimental Data

One final test was to run current through the thread to ensure that it will handle the measurements of the sensors. The current setup runs on the order of microamperes through the circuit. This test ran 107 milliamps at 0.5 volts for 5 minutes. This ensured that the material could handle the current by stress testing at an order of magnitude higher. The thread worked great and handled the current well. There were no signs of heating or physical changes to the test strip.

Looking to find the limit of the material, it was observed that the only time the conductive thread exhibited a failure when stressed to 6 volts and 1.1amps. This is significantly more power than would ever be applied in the system by multiple factors of 10. It is a conclusion that this will be a suitable material to connect SmartCast sensors to the ribbon cable and be used as an interconnect between the sensor nodes.

Chapter 3: Sensor Characterization

Although the sensor performance was good in initial evaluation, to be certain of the performance under both stress stemming from repeated use and also the stability over the period of performance. This was accomplished in a few ways. First, a test devised to test the long term stability under a constant load. This test would help to ensure that the value of the sensor would remain relatively constant over numerous days. The second test carried out was much more complex in the preparation and procedure because it dynamically tested the sensors over a long period of time.

3.1 Longevity

The first major test of the fabric based sensors was to see how they behave to a constant load over several days. This helps to see if there is a degradation or large variance based on subjection to a single mass place on it, mimicking what the sensors will be subjected to in the patient application. Arm swelling does not rapidly subside over a short period of time. Usually this occurs over several days or weeks. As such, it is important to perform a static test of the sensors to demonstrate their reliability and accuracy in use.
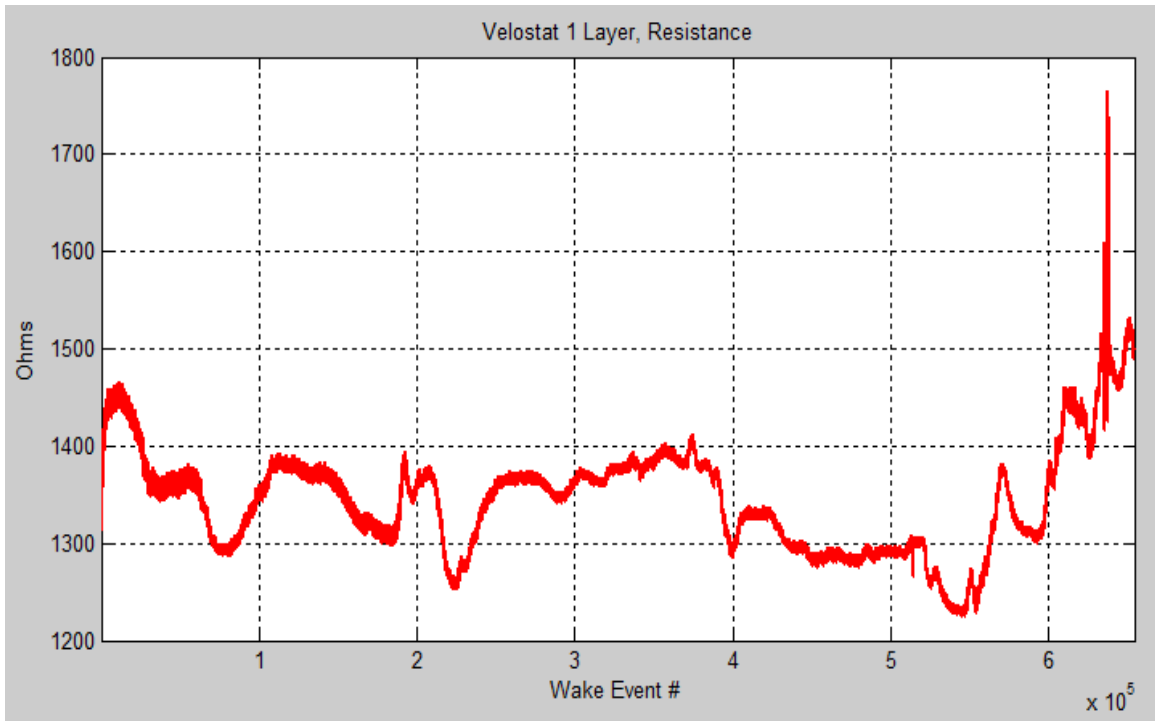
Figure 7: Week-long Static Test

The procedure for testing consisted of taking a single sensor patch and attaching its leads to the test circuit. Then a 200 gram mass was placed upon the patch for a full week of sampling. Figure 7 above shows the results of the test. Looking at the general trend from the test, one can safely assume that the sensor is stable, neglecting small variations on the order of 100 ohms due to the analog sampling nature of the circuit and noise and other environmental interference. A noise factor of this size is acceptable for the use case because for a significant amount of pressure to be removed from the sensor, the resistance would increase by at least two thousand ohms. This is more than a magnitude larger than the noise in the system. The spike seen at the end of the data set

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and subsequent high values is a result of the disassembly of the test apparatus and removal of the mass. The data recording was not paused prior to this being captured.

In the zoomed view of figure 8 we see at the beginning of the test the small amount of setting seen after the mass was first applied. This behavior is not detrimental to the use in the system as the target data is not at the application time but days and weeks later as noted by the swelling issue with the patients. The sudden drop is only seen after a mass is applied and has happened in each bench test performed. With the promising results of this test, the dynamic test would be the final factor before moving on to initial trials.
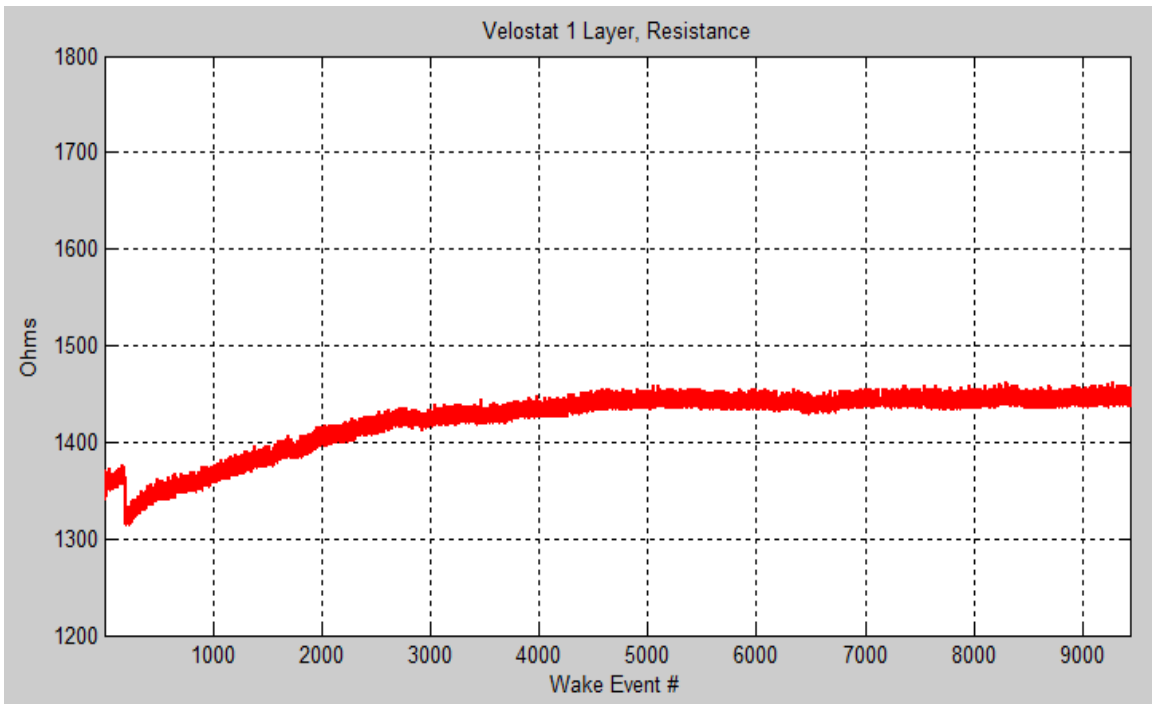

Figure 8: Zoomed View of Start of Static Test

3.2 Test Machine

The dynamic test is much more involved than the static test. The information that was sought from this test is the response of the sensors to repeated actuations over a long duration. Careful planning went into this as the data gleaned from the test will show if the repeated actions of the sensors stay consistent over a long period of time. The usefulness of this knowledge will help to characterize the sensors to know if the readings measured in patient applications are accurate enough to be trusted. If the sensors degrade as a result of use, then they will not be capable of accomplishing the measurement task. Using the array of 16 sensors sewn together, simulating the final array, one can have an idea of the variation between them.

Manually applying a mass to 16 different sensors repeatedly for any length of time is very impractical. The need for a test apparatus which was capable of accomplishing this task arose and thus needed to be designed. I designed and constructed a machine using a variety of aluminum pipe, pulleys, cable, springs, and masses. Constructing a platform out of plywood and two by two inch pieces of lumber, a common plane was made to attach each component of the machine. This ensured a portable setup without the need for realignment and setup.

Once the base was constructed, I soon began work on the mainframe for supporting the pulleys and cable system. The sizing of this was based on the size of the sensor array, measuring roughly ten by ten inches. I sized the frame at twelve by twelve

inches by eighteen inches tall making it out of three quarter inch aluminum pipe and fittings. After the frame was complete, I then drilled and tapped holes at the top in order for the all-thread with pulleys attached. These sections provide an easily adjustable spacing for variations in the patch placement. There are sixteen pulleys to provide the testing of up to a four by four matrix of sensors.

After the main structures were complete, the tedious task of stringing up the springs and masses began. It was not necessary to have them the exact length because of the addition of turnbuckles. Sixteen individual sections of low stretch fishing line was tied to a turnbuckle and laid over a row of pulley, tying the other end to one of four holes on the steel triangular frame. The triangular frame was connected to a single cable running through a pulley and connected to the DC motor shaft adapter.

A DC motor was used to provide the motion of the machine. However, a key challenge was getting an adapter on the shaft that would provide enough swing to fully expand the springs and lift the mass from the sensors. Using the spring constant of the springs and their lengths, it was determined that two inches of motion were needed. To make the adapter, I obtained a three inch diameter piece of aluminum round bar and cut it down to a length of two inches. Using the lathe to smooth the surfaces, I then drilled a section out of the center only slightly larger than shaft to slip over it. Then, measuring one inch from the center on the outer face, I drilled and tapped a hole to bolt on a pulley for the cable attachment as shown in figure 9.
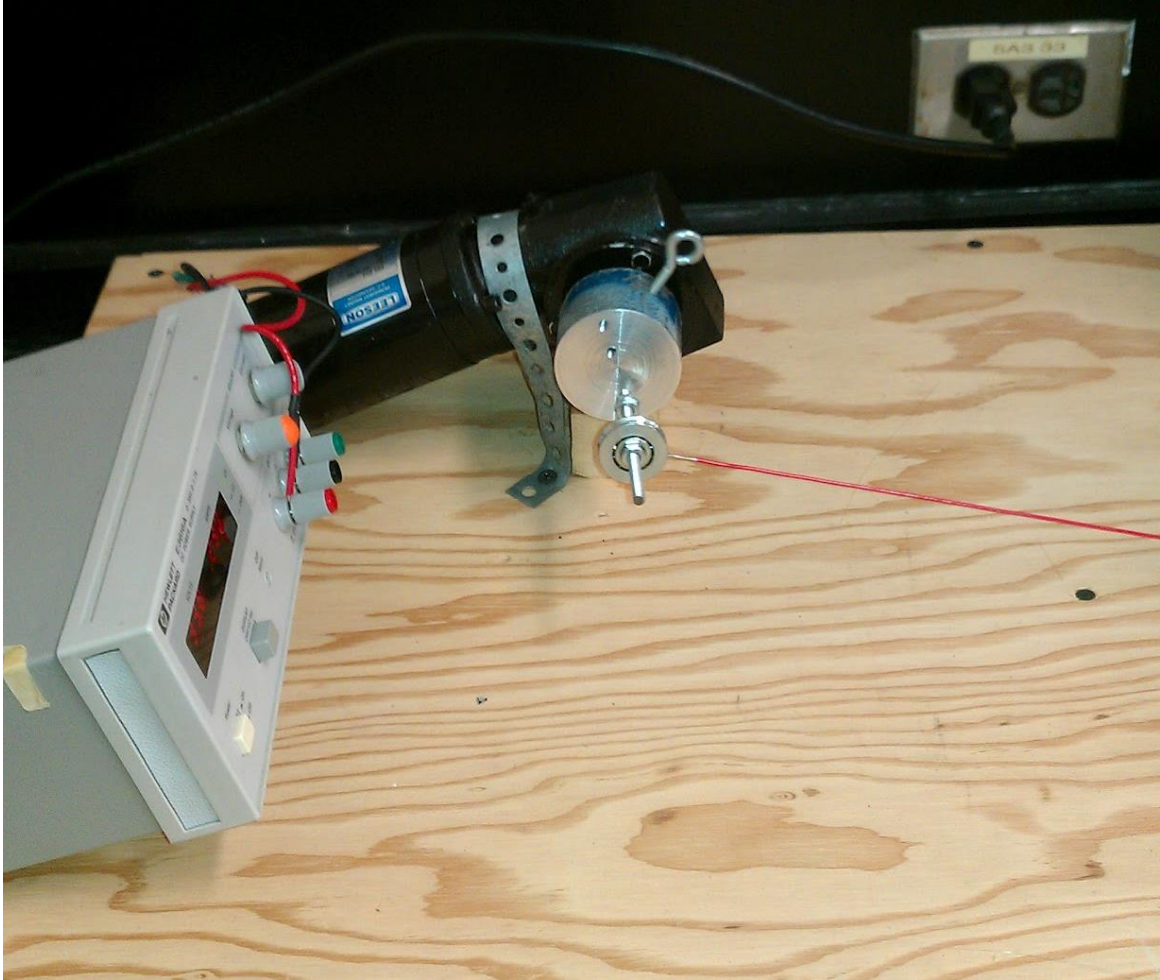
Figure 9: Test Machine Motor with Shaft Adapter

The next step involve attaching the springs and masses to the turnbuckles and then adjusting the lengths. Once the springs and masses were hung on the turnbuckles, the sensor array was placed on the test platform and the motor put in a position at maximum height. Then the turnbuckles were adjusted for length so that the masses were just suspended above the sensors. After a few test cycles, the machine was deemed ready for testing. The completed test apparatus can be seen in figures 9 and 10.
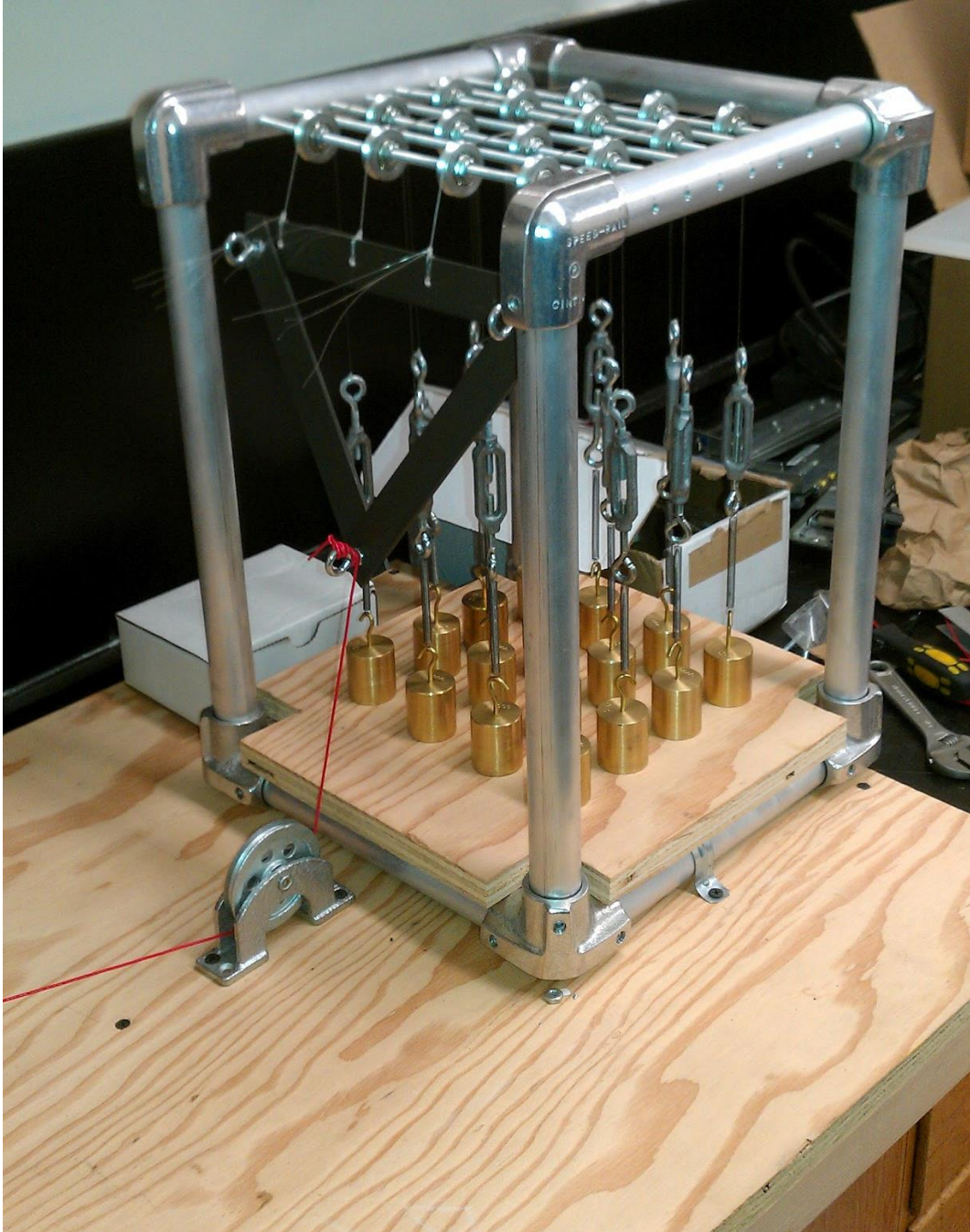
Figure 10: Test Machine Frame with Pulleys, Springs, and Masses

The first test carried out using this apparatus was with 16 sensors without the waterproofing techniques applied. Using a sampling rate of three times the cycle rate of the machine, data was recorded and interpreted as shown in figure 11. The resistance value versus the number of samples allows one to see the reaction of the sensors to the force of the masses as they go through a motion cycle. This test proved that the sensors remained stable in their value based on the force applied by the machine. Although each sensor has its own distinct average value of resistance, this can be calibrated at the initial application to the patient and accounted for in the software.

Figure 11: Test Machine Results of 16 Sensors

3.3 Waterproof Design

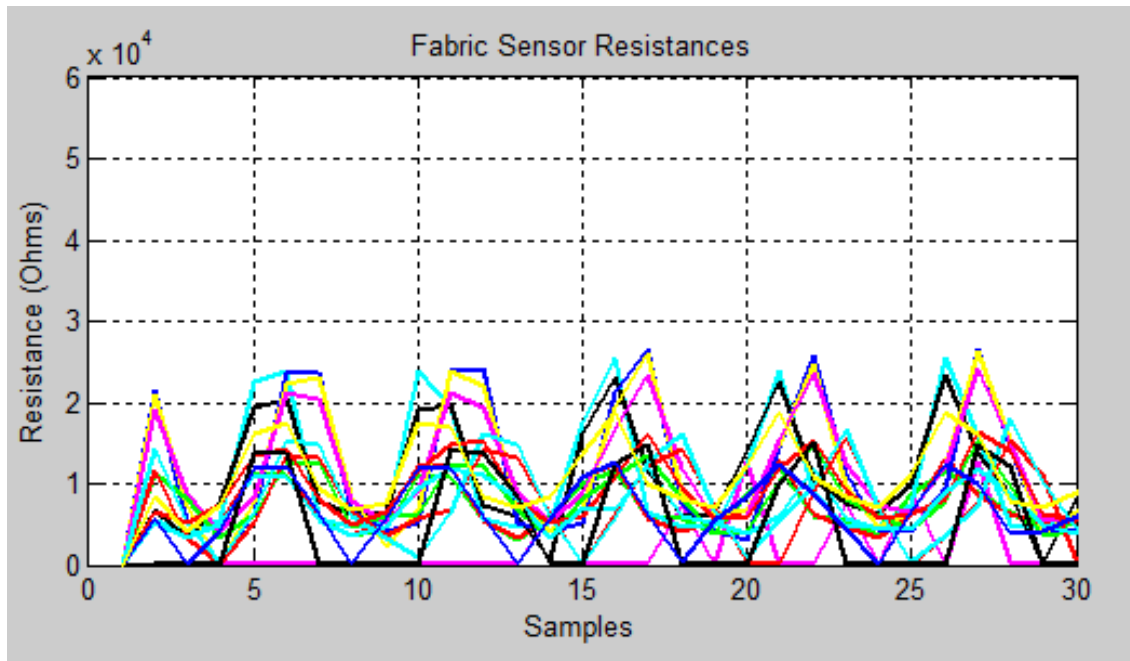These sensors performed great under ideal conditions, however, when in use in the field, there is a chance there are contaminants. Although we know the primary environment is simply skin, gauze, and plaster, however, it is important to not secondary environments as a result of where the patient is or under what conditions they are exposed to. The potential contaminants as a result must be considered in the design.

It is safe to assume that the patient, while wearing the cast, will be in a warm environment. Since the arm is nearly sealed up in a cloth (gauze), the body will see the need to cool it down, thus excreting sweat. Sweat is very conductive as it is composed of water, sodium, potassium, calcium and magnesium [10]. Because the main composition is water, it is easily absorbed into fabric material bringing along the extra minerals for enhanced conductivity. If the patients perspiration is absorbs into the sensors, their readings will be greatly affected. The value of the sensor would read lower than it should as a result of the perspiration contamination. The sensing circuit would read this incorrectly low value and believe that the cast was providing more pressure and support to the patient's arm than was actually present, negating the positive impact of the device.

Another source of contamination which could negatively impact the calibration of the sensors would be normal water contamination. During the treatment phase, patients must still bathe, but carefully avoiding the immersion of the cast. Although instructed by doctors to take proper care to not expose the cast to water, this cannot be guaranteed. As

with the problem of perspiration, the water leaked into the cast can cause the sensors to read a lower than true value.

With the main contributor to possible contamination being water, the sensor design needed to be modified to ensure that exposure to contamination does not affect the reading. A few materials were considered such as iron on vinyl, water repellent spray and self-adhesive nylon. Each was tested individually for its potential use in the final product. Since the contamination of conductive strips and thread has no effect on the sensor, the efforts to waterproof the device were focused to the region directly around the sensor nodes.

The water repellent spray was first tested. It was applied liberally on each side as noted in the application directions. There were some issues with ensuring a uniform application. For example, when applied to the sensor, the drying time was about an hour and the spray was able to run and dry unevenly. Also, the spray made the sensor stiffer than before, making the sensors rigid, an unwanted property considering they need to be flexible with the arm.

The second waterproof solution was the application of the iron on vinyl. At first, this was the method that was thought to be the best solution. However, this was soon found to not be the case. To apply the vinyl to the sensor patch, heat must be applied using something such as a hot soldering iron or heat gun. It was desired to seal the patch inside the and only melt the edge to reduce any impact the material would have on the sensor pliability. The problem with only heating on the edge was that as one heated one

area, the rest became out of shape. Without applying heat evenly across the whole surface, it would not retain the necessary shape that would encapsulate the sensor patch.

The third and only successful waterproof solution found for the SmartCast system was the self-adhesive nylon [11]. The self-adhesive nylon comes in six by eight inch sheets with a peel-off backing which exposes the adhesive. The nylon material is used in tent, umbrella and backpack repair, making sure it is durable and flexible while also holding up to the elements. Two three quarter inch square sections were cut from the sheet. Upon removal of the backing, the two halves were placed around the sensor patches. An initial reading was taking using the lab ohmmeter. Then upon immersion into water, the resistance was again taken, there was no change. Performance remained the same. In addition, the integrity of the nylon was intact and an attempt to peel the material apart was made but no separation occurred.

Since the test of the self-adhesive nylon was promising, the move was made to apply this material to a small matrix of sensors and put them in the test machine. However, instead of subjecting the sensors to plain tap water, it was desired to see the reaction to the other form of contamination, sweat. To mimic perspiration, a solution of water and sodium chloride was made and put into a spray bottle. Throughout the day, the solution would be sprayed onto the sensors that were treated with the chosen waterproofing scheme while the test was ongoing.

The test yielded very good results because over time, there was no change seen in the values measured across the sensors. Also, the values read were unchanged from a dry

untreated patch, showing that the waterproof solution had no negative impact on the data.
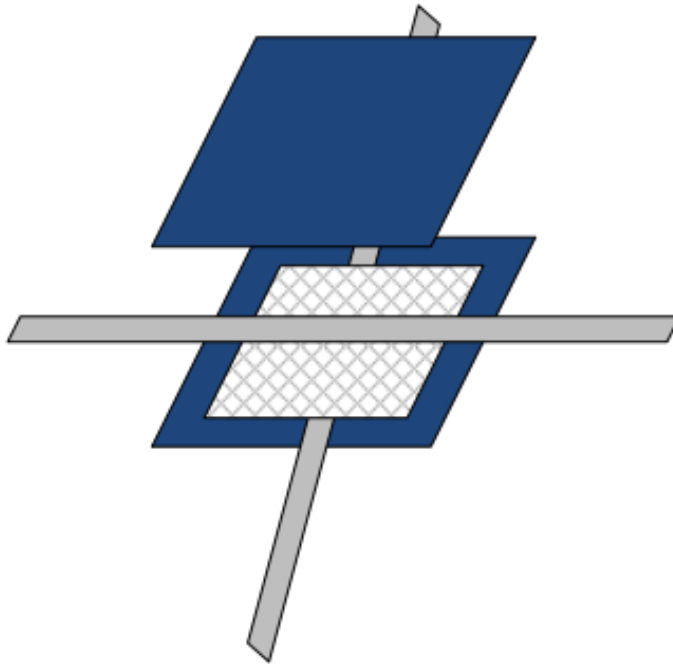

Figure 12: Sensor Patch Exploded View with Nylon

Figure 13 shows a small snippet of the measurement for clarity. As seen in other data taken with multiple sensors, each sensor has its own range. However, that range is detected and for the use of SmartCast, the trend is what is important. One can clearly see that even with the applied sodium chloride solution, the behavior is very clear. Each of the peaks in the data plot represents times when the masses are completely lifted from the material, naturally a short amount of time since the increase mass with the spring is the desired viewpoint. The slope of from the peak to the valley represents this contact. The valleys in the plot are when the mass is fully contacted the surface and the spring tension

is released at its low point. Although the voltage to the motor was held constant

throughout, there was some surprise to see the pattern of narrow followed by wider

valleys. This has been attributed to the gearbox reduction in the motor and that there is a

spot in the rotation where with this motor affected the rotational speed which the torque

applied by the hanging masses are believed to play a role.

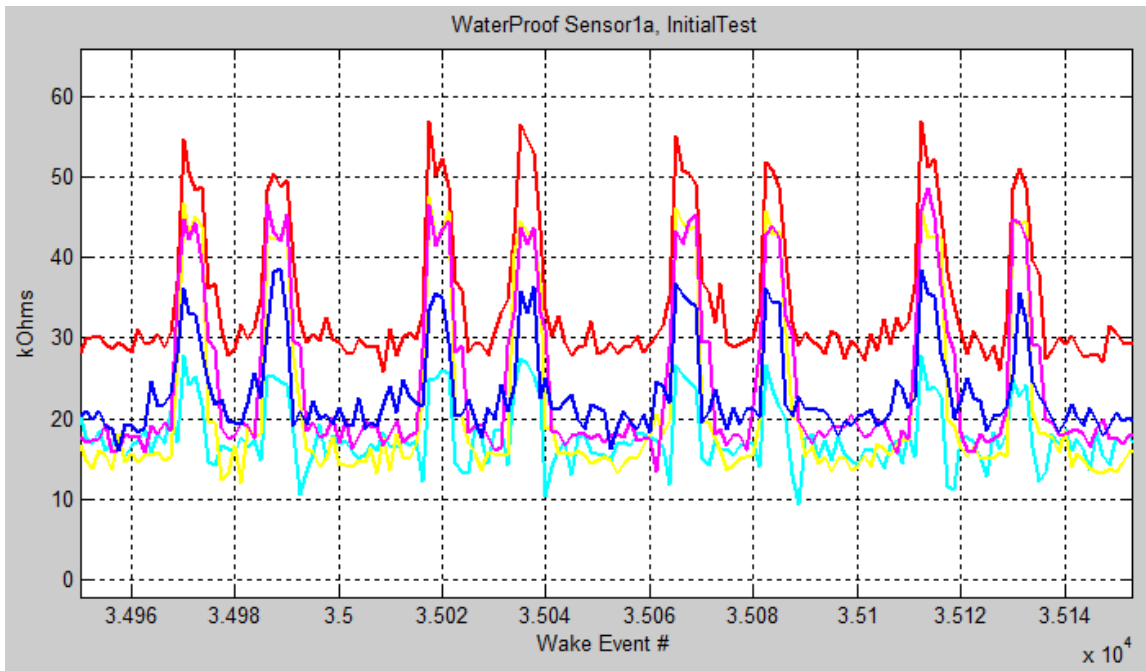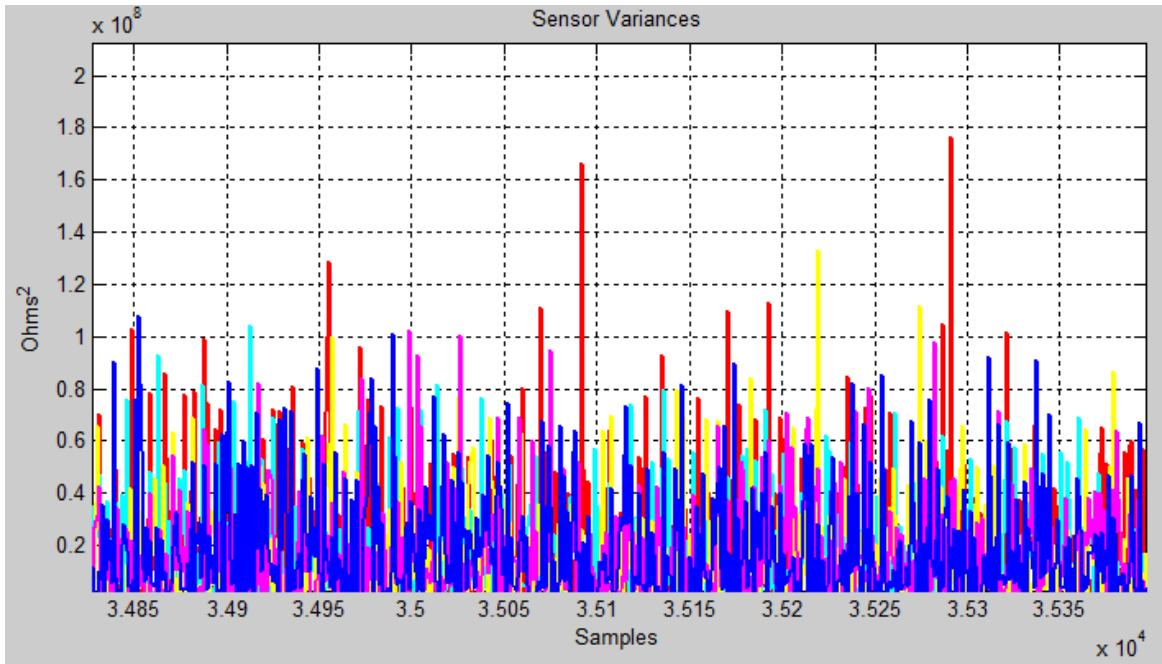Figure 13: Water Exposure Test using Test Machine

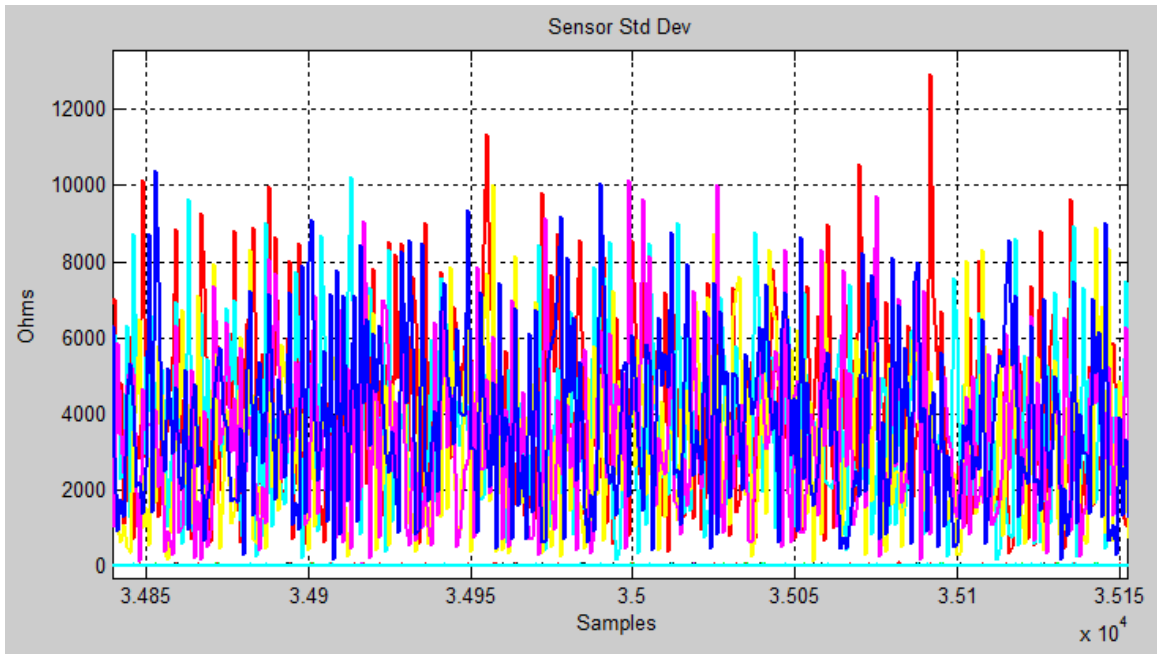Figure 14: Variance Results from Machine Test

Figure 15: Standard Deviation from Machine Test

The information gained from this test shows that the SmartCast system was ready to be fully integrated with the design techniques incorporated. It was time to perform a full system test to see how the efforts worked together to create a functional product.

Chapter 4: System Test

After the sensor material was finalized and tested for waterproofing, the SmartCast system was ready for testing in a simulated use case. By performing this test, one can analyze the results when exposed to the cast environment and the effects on sensor readings. As a result, the design can be modified a final time before moving on to mass production for the initial patient trials.

4.1 Initial Cast Test

The cast test is the final major test for the new type of fabric sensors. Up until now, the test has been with masses and the test platform. However, no test has been carried out in an actual cast environment with the appropriate amount of gauze and padding. It was the intention to determine the minimum, maximum, and nominal pressures seen while in the cast and to ensure that they will be capable of capturing the range of these three conditions. To do this, several different sensors were tested within a cast setup provided by the orthopedic hospital. The cast was cut in half to allow the easy attachment and removal for testing purposes.
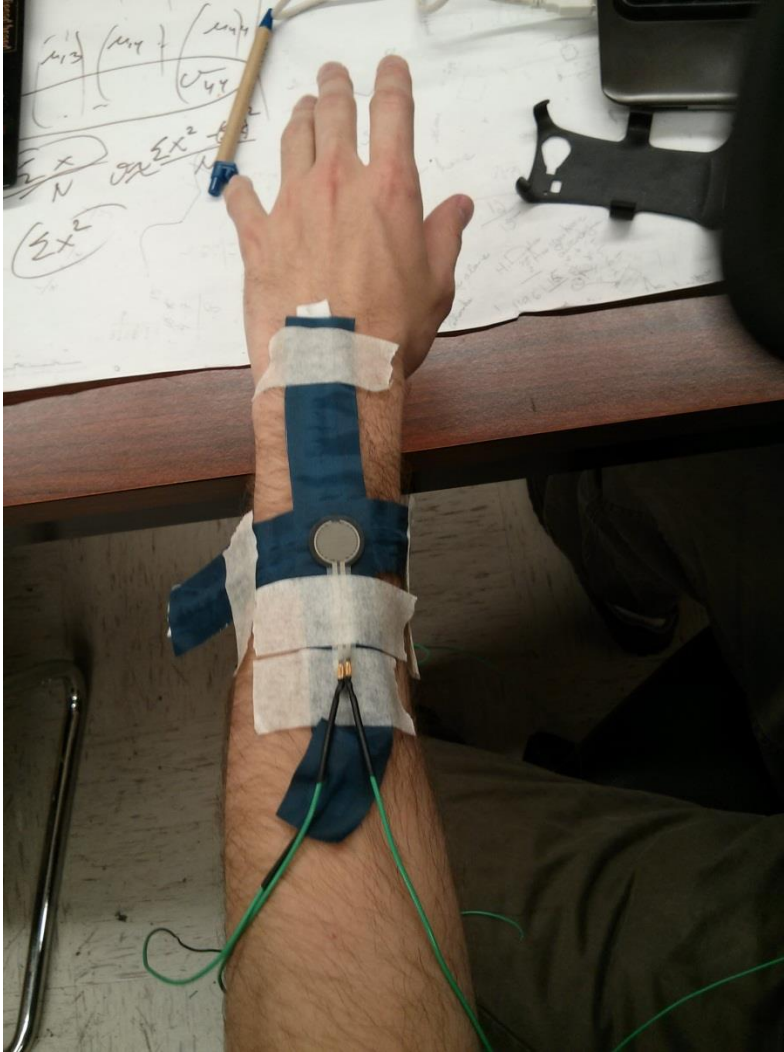
Figure 16: Sensor Placement on Arm for Test

A strict procedure was followed to ensure the same conditions were exhibited on each sensor under test. First, a single point on a test subject's arm was marked so that the sensor would be place in the same location during each test. Then, a sensor was placed in the marked location with the outer part secured using masking tape. Then the cast was

placed around the arm, securing the two halves using masking tape. Once connected to

the sampling circuit, the procedure was followed as outlined in table 2. Upon conclusion

of the procedure, the data was saved and the cast was removed. The sensor under test was

removed and the next sensor placed inside and attached in the same fashion with the next

test commencing.

Figure 17: Cast Closed, Ready for Test

Action	Duration (Samples)
Rest	50
Shake	50
Rest	50
Push	50
Rest	50
Shake	50
Rest	50
Pull	50
Rest	50
Shake	50
Rest	50

Table 2: Test Operation Procedure

The reasoning for the procedure is to help reduce the impact of one event to the other. The data yielded from a shake cycle is not of importance, only which it helps to reset the conditions within the cast. The rest cycles done after a shake cycle are used to see that the sensors are returning to approximately the same value after each cycle is performed. The rest cycle consists of keeping the arm elevated and not touching anything. It is meant as a baseline for the measurements of a properly supported arm inside of a cast. The push cycle consists of placing the cast against a surface and applying force in the direction of the sensor location. This yields the maximum pressure that would be seen in the cast environment. The pull cycle is naturally the opposite of the push cycle

in that force is applied to the opposite side of the location of the sensor. Figure 18 shows

the results of the complete test. The results of this test shows that the measurement range

of the sensors are able to capture each of the extreme cases. The teal colored line does

saturate, however this is the baseline force sensor that has been used in all of the tests

back to the preliminary design using the linear potentiometer. This is not used in the final

sensor system so the data of interest is the other lines which do not saturate. It is with

certainty that the current sensor design will work for the SmartCast sleeve design since

the measurement range can handle the range of pressures that would be seen in the real
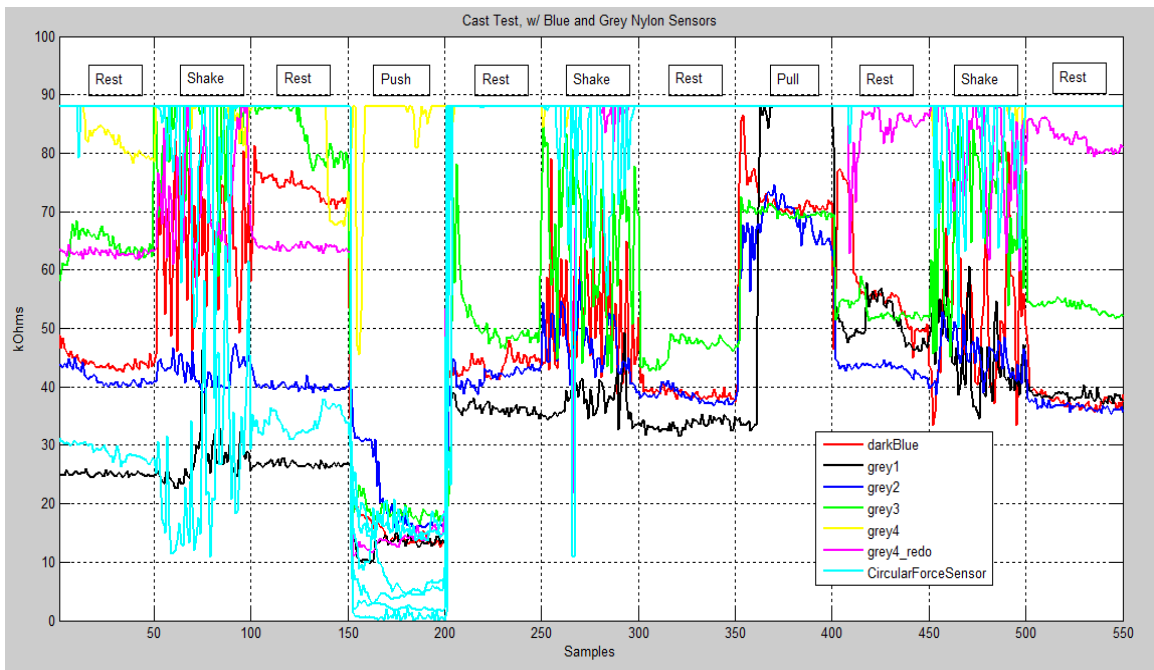
trials.

Figure 18: Cast Mockup Test Results

The differing range of values from the sensors were concerning, but the source of variability has been identified. Although the sensors are of the same material, each have been made by hand. As a result of not using professional, precision machinery to manufacture the sensors, there is variability in the sensors. For example, if the conductive strip is not of the same width across the surface of the pressure resistive material, the basic equation of resistance come explains why different values are being read.

$$R = \frac{\rho \, l}{A}$$

Although the resistivity of the material is unchanged by the assembly, the area in contact across the top and bottom surface of the material is easily a source of error. Although care was taken to maintain the most consistent width, there was some variation as a result of the cutting of the strips. The goal was to have one eighth of an inch wide conductive strip, but later examination showed that some were as much as one quarter of an inch wide in some areas. In addition to this, the length also has some variation because the pressure resistive material also was not cut with great precision. As this dimension is reduced, the length of the resistive body is also reduced. The inverse is also true.

4.2 Final Design for Prototype

Throughout the course of all of the testing, the matrix design of the sensors performed very well. However, the design needed to be refined to improve manufacturability. Previously conductive strips were strung across the entire four by four matrix, but this unnecessarily increases the material cost and impacts the wearability and comfort by the patient. The conductive thread was then put to use since it passed all of the stress tests earlier for the conditions.

One half inch square pieces of pressure resistive material was used with one eighth inch wide conductive strips on each side sandwiched in three quarters of an inch pieces of self-adhesive nylon makes up the final design of the patches themselves. These can be made in mass prior to sleeve assembly. Making the sensor patches in mass separate from the entire sleeve helps to streamline the process. Later stitching them together onto the Lycra sleeve would be much better than the tedious process used in the initial tests, yet provides the same performance in the end. On an unfolded sleeve, the sensors are spaced apart then the conductive thread is used to stitch them down. Then, from the edges, the thread is brought out to a common area where the ribbon cable can be attached and connected to the measurement circuit. Figure 19 shows the layout of the sensors. For a flip through of the assembly process, refer to the appendix.
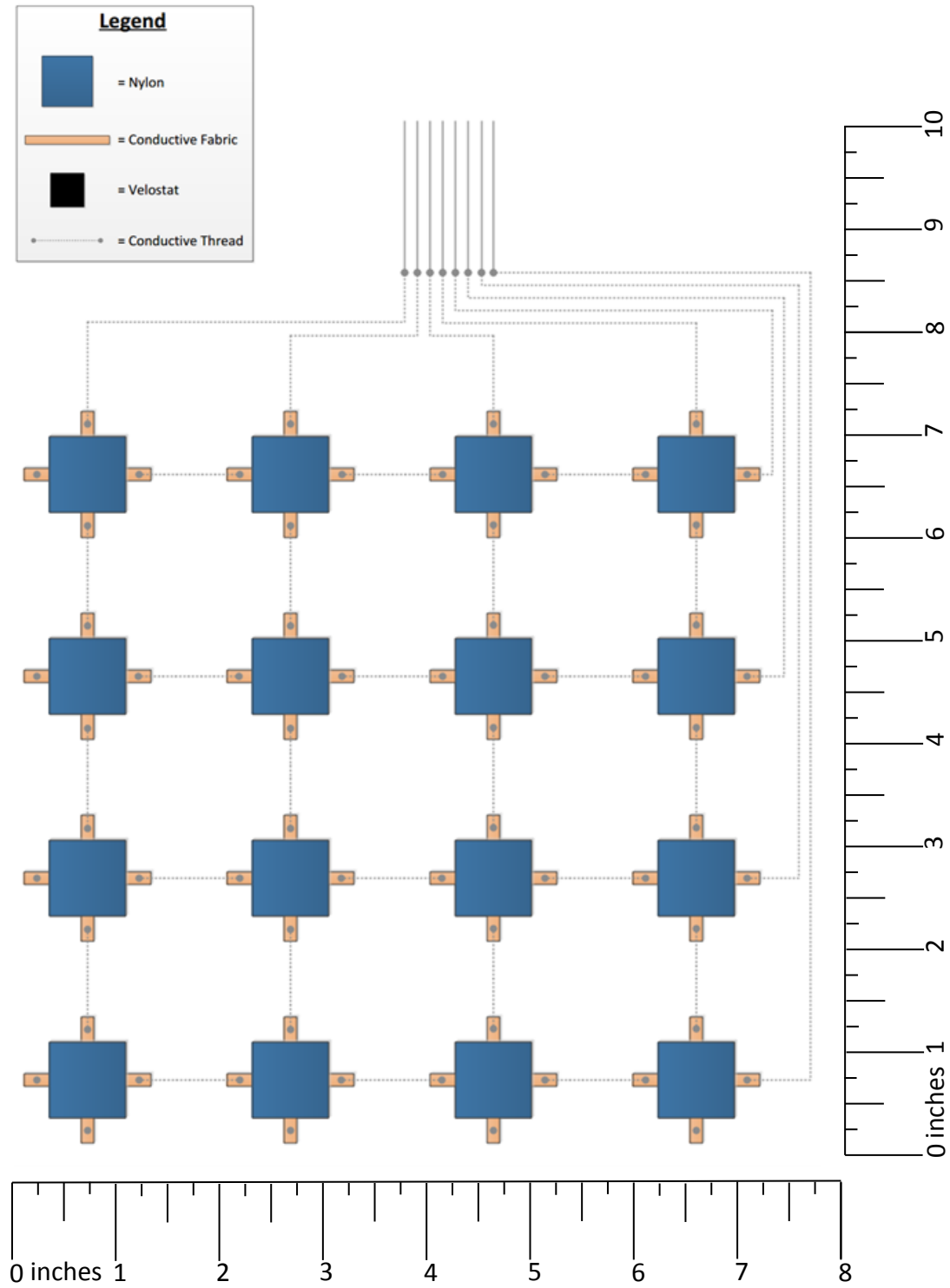
Figure 19: Scaled Diagram of Sensors Stitched to Sleeve

Chapter 5: Enclosure Design

A clean and compact design for a case was needed for containing the measurement circuit and power source. However, the power source can be a large contributor to the size of an enclosure. Through testing and analysis, this was selected and then the volume was added to the PCB size. A final case size was chosen and suitable test cases were vetted.

5.1 Battery Selection

In helping to calculate the sampling schedule for the measurements, the careful selection of a power source was needed. The minimum voltage needed by the circuit is 2.9 volts DC. The first choice based strictly on size and nominal voltage was the coin cell battery CR2032. However, it was soon found that a battery capable of handling a higher discharge current was necessary.

The coin cell battery has a nominal voltage of 3.0 volts which exceeds the minimum voltage requirement. However, the circuit added a micro-SD card slot for simplicity in data retrieval which draws a current of about eighty milliamps. This immediately eliminated the coin cell option once this new storage technology was added to the circuit. The maximum current that a coin cell can adequately provide is fifteen milliamps. Therefore, another battery type had to be chosen.

Based on the battery performance characteristics, the ideal battery type would be lithium ion technology because they have a fairly high energy density and are capable of providing high amount of discharge current. However, since the application of SmartCast will be in the medical field and mounted on the patient, safety concerns come into play. Lithium ion batteries have a history of being unstable at times. A risk to patient safety is never worth taking so the need for a different source was needed.

Alkaline batteries are very common and readily available. In addition, they are capable of supplying the required minimum current to meet the circuit requirements. Each cell is 1.5 volts so two in series would provide 3.0 volts. However, the voltage discharge curve is relatively linear so when a load is applied and energy is consumed, the voltage level will quickly drop dangerously close to the minimum of 2.9 volts. The solution was to use three AAA size alkaline batteries in series to give a voltage for 4.5 volts, using a regulator to step down the voltage. Without having custom batteries designed and manufactured, this was the option which best met our needs.

5.2 Scheduling Scheme for Power Efficiency

There was discussion about different schemes to maximize the power efficiency to increase the lifetime of sampling. The power up sequence for the micro-SD card takes up roughly twenty-five percent of the total sampling time for the period and is at the full eighty milliamps. When integrating that, the energy can add up to be a fair amount of the

battery capacity. A thought was to instead leave the micro-SD card in its idle state so it would immediately be ready for writing. After some analysis, it was found that leaving the storage in idle mode is only beneficial if the sleep time, defined as the time between sampling events, is less than fifty seconds. Since the arm condition does not change often, the sampling was scheduled to occur no quicker than 5 minute intervals. It was decided that the storage should be powered to its off mode when not in use. Figure 20 shows the trade-off plot of the two schemes with the crossover point meeting at fifty seconds. As a note, this only shows the energy consumption for the micro-SD card. The other components of the circuit are drawing additional energy but their values cancel in doing the trade study because they are identical in each case.
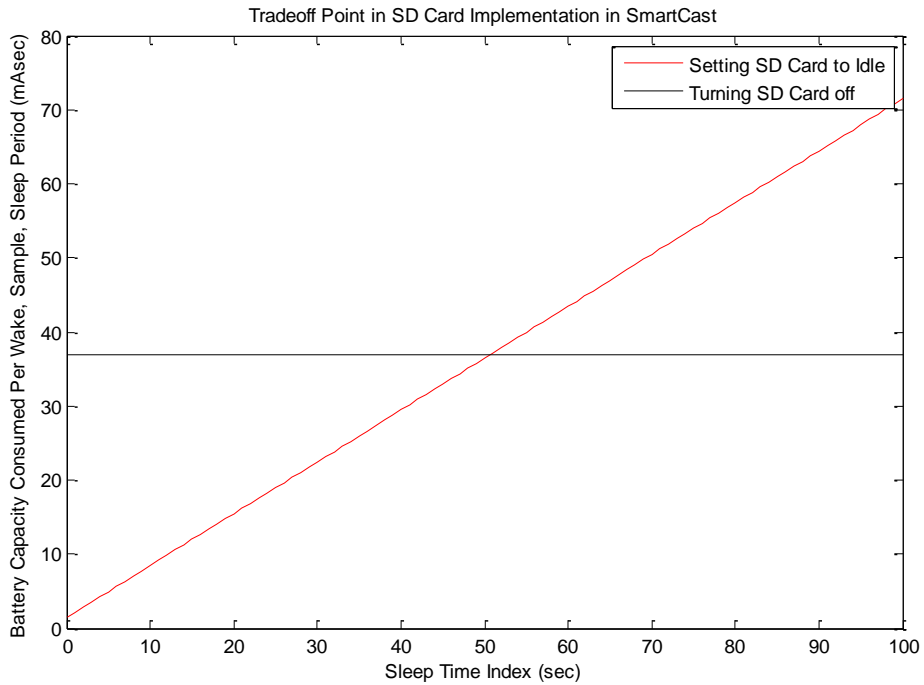

Figure 20: Micro-SD Card Sleep vs. Idle Trade-off

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5.2 Case Sizing and Selection

Since the power source selection was finalized, the necessary information was now known to be able to select an appropriate enclosure for use in the initial clinical trials. Finding the dimensions of the batteries and their holder along with the PCB size, I found a suitable case from Digikey, however it required a slight shape change on the PCB side. Figure 21 shows the case design. The great thing about this is that the board can remain firmly mounted inside without any additional holes being made in the case. Also, the batteries can be mounted with foam tape to keep them secure. Only a small slit needs to be milled to pass the ribbon cable through which can be sealed with silicon epoxy. This small, contained unit works perfect for the initial testing before a more refined, custom enclosure is designed and manufactured.
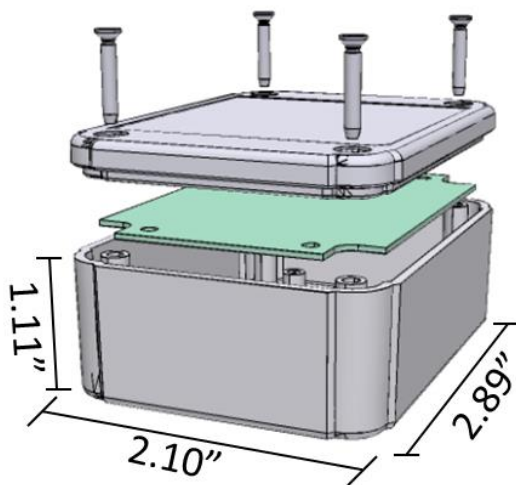

Figure 21: Enclosure Design

Chapter 6: Conclusion

6.1 Conclusion

First described was the design and operation of the SmartCast sensors, specifically in terms of sensor material, construction and assembly, characterization, and testing. The sensor evolution was presented with the design path shown to justify the choices made for the configuration, including the choice of materials. The development made drastic changes in course but the end result was a flexible, non-invasive sensor design.

The procedures and experiments devised for the extensive testing of the sensors were discussed with the results presented with analysis. Also presented were the initial trial evaluations of the SmartCast system using an actual cast mockup showing the sensor response. The experiments showed that the current scheme capable of detecting all conditions of pressure possible inside the environment while remaining resilient to contaminants related to perspiration and water.

Finally, the improvements to the design were outlined for the enhancement of manufacturability. Streamlining the design both improves the appeal of a product and enables a consistent process for production. Other finalization choices were the analysis of the power consumption of the circuit. This permitted a decision to be made on the power source as well as the case design. After evaluating several options for a power

source, the alkaline batteries proved to be the most suitable choice at this stage of product evaluation. The sum of this work will be used to provide valuable data for patient deployment in the future.

6.2 Future Work

This thesis provides a solution for the problem of evaluating the effectiveness of a cast, however, there is potential for future developments and testing. While the current product has performed well in the initial tests, it would be insightful to have the systems professionally manufactured to the current specifications and deployed on several test subjects for clinical trials. Later analyzing the data from these tests will help contribute to any calibration needed before the product goes for the next revision.

In addition, as a result of clinical trials, the data can be used to influence the software algorithm to learn the current condition and on its own identify an ill-supportive cast. Currently the system provides a history and statistics of the measurements which a medical professional can import and analyze. However, a self-analyzing algorithm will greatly enhance the autonomy of the system. This will be accomplished as a result of many trials on both healthy and injured patients of all forms.

Lastly, the next area for future development will be for the design of a custom form-factor battery and case. When all initial clinical trials have concluded and data has been analyzed, any modifications can be made to circuit design and power constraints. At

this point a smaller, more compact enclosure can be customized to minimize the footprint of the sampling component of SmartCast.

Appendices

Appendix A: Power Trade-off MATLAB Code

```matlab
clc; close all; clear all;
%This program finds the tradeoff point for the sd card scheme. We are
%looking for the point where it is better to idle the card, or turn it
off
%completely.


current_off        = 0;   %mA
current_init_off   = 80;  %mA
current_write_off  = 35;  %mA
current_close_off  = 80;  %mA


%
current_idle        = 0.7;  %mA
current_init_idle   = 60;   %mA
current_write_idle  = 40;   %mA
current_close_idle  = 80;   %mA

sample_sleep = 0; %sec
Power_cycle_sd_idle = sample_sleep.*current_idle +
0.010*current_init_idle + 0.0015*current_write_idle +
0.010*current_close_idle %mAsec
Power_cycle_sd_off = sample_sleep.*current_off + 0.440*current_init_off
+ 0.0015*current_write_off + 0.020*current_close_off %mAsec

sample_sleep = 0:1:100;
Power_cycle_sd_idle = sample_sleep.*current_idle +
0.010*current_init_idle + 0.0015*current_write_idle +
0.010*current_close_idle %mAsec
Power_cycle_sd_off = sample_sleep.*current_off + 0.440*current_init_off
+ 0.0015*current_write_off + 0.020*current_close_off %mAsec
sample_sleep_index = 0;

while ((Power_cycle_sd_off(sample_sleep_index+1)) >
(Power_cycle_sd_idle(sample_sleep_index+1))) %while turning the device
completely off is worse than leaving it in idle.
    sample_sleep_index = sample_sleep_index + 1; %sec
end

sample_sleep_index %sec
Power_cycle_sd_idle(sample_sleep_index) %mAsec
```

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```
Power_cycle_sd_off(sample_sleep_index) %mAsec

plot(sample_sleep,Power_cycle_sd_idle,'r')
hold on;
plot(sample_sleep,Power_cycle_sd_off,'k')
ylabel('Battery Capacity Consumed Per Wake, Sample, Sleep Period
(mAsec)')
xlabel('Sleep Time Index (sec)')
title('Tradeoff Point in SD Card Implementation in SmartCast')
legend('Setting SD Card to Idle','Turning SD Card off')
```

Appendix B: Assembly Diagrams of Sensor

Before Assembly

Partially Assembled

Fully Assembled
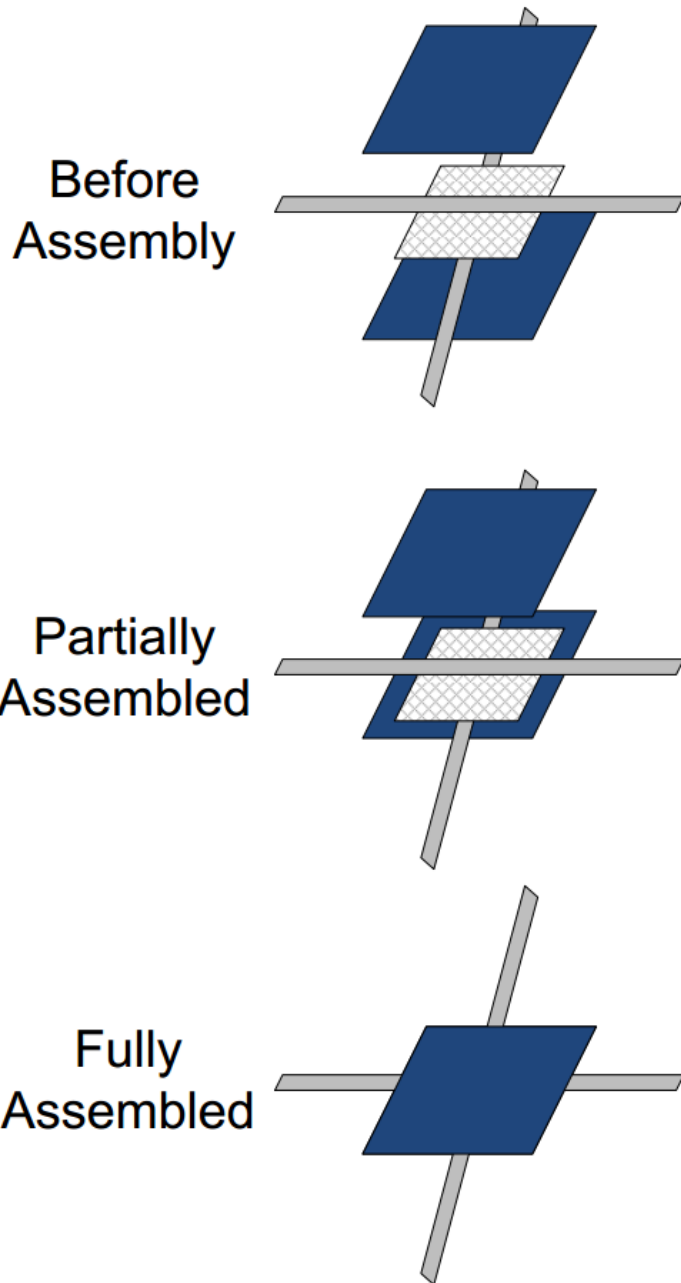
Appendix C: Materials List for Test Machine

Index	Quantity	Part Number	Description
1	20	90034A410	ZincPlated Steel Threaded Rod 1024 Thread, 1' Length
2	1	90480A011	Zinc-Plated Steel Machine Screw Hex Nut 10-24 Thread Size, 3/8" Width, 1/8" Height, packs of 100
3	1	98970A129	Hot Dipped Galvanized Steel Flat Washer USS, 1/4" Screw Size, 47/64" OD, .05"-.08" Thick, packs of 100
4	2	9654K17	Steel Extension Spring 1.50" Length, .188" OD, .015" Wire, packs of 12
5	17	3003T15	Open Aluminum Body Turnbuckle W/Zinc-Plated Eye & Eye Fittings, 3/16"-24 Thread
6	1	9489T47	Light Duty Eyebolt with Nut-Not for Lifting Zinc-Plated, 10-24 Thread, 1" Shank, 7/8" Thread Length, packs of 10
7	8	4698T111	Aluminum Slip-on Rail Fittings 3-Way 90 Degree Elbow, Fits 3/4" Pipe Size
8	2	4698T31	Aluminum Slip-on Rail Fittings 90 Degree Elbow, Fits 3/4" Pipe Size
9	2	4699T228	Aluminum, 3/4" Pipe Size, 8' Length Pipe
10	17	3434T22	Pulley for Wire Rope Zinc-Pltd STL, for 3/32" Rope Dia, 1-1/16" OD, 175#Wll
11	1	9442T1	Clear Nylon Line 0.012" Line Dia, 8 lb Work Load Limit, 990' Length
12	1	4592T29	Architectural Anodized Aluminum (Alloy 6063) U-Channel, 5/8" Base, 7/8" Legs, 1/16" Thick, 6' L
13	17	WHB200	Hooked Masses, brass: 200g

14	1	N/A	3'x4'x0.5" Plywood Sheet
15	1	N/A	2"x2"x8' Pine Lumber

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