PEDIATRIC DYNAMOMETER

NSF Summer Undergraduate Fellowship in Sensor Technologies
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ABSTRACT

Weight-bearing activity has recently been correlated with the growth and development of children's bone density.[1] In order to investigate the relationship, the Children's Hospital of Philadelphia (CHOP) wishes to analyze the kinetic activity of children. Although technology currently exists to perform human kinetic analyses, devices consist of expensive and obtrusive components. An inconspicuous and inexpensive mobile device that can accurately collect and store kinetic activity measurements is needed to advance research in childhood bone development.

Dr. Babette Zemel, CHOP, and Dr. Jay Zemel, ESE, have been developing an in-shoe physical activity dynamometer (Foot-PAD) in order to measure kinetic activities. The device uses piezoelectric polyvinylidene difluoride (PVDF) films as force sensors as the basis to continuously collect information for up to two weeks. Data would be stored and partially processed on board and appropriately accessed for subsequent activity analysis.

Previous projects confirmed that PVDF are appropriate mechanical force sensors and have optimized the circuitry and programming to successfully operate inside a child's shoe. However, the Foot-PAD still needs a PDVF sensor design that provides reproducible and calibrated force information compatible with the in-shoe requirements. After this summer's work, an appropriate device design has been created that collects data with acceptable accuracy while uet meet the requirement for being inconspicuous to the patient.

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1. Introduction

1.1 Background

The effects of exercise on health are a topic of interest for several medical fields. In particular, the Bone Growth and Development research group at The Children's Hospital of Philadelphia (CHOP) is studying the effects of weight-bearing activity on bone density. In order to correlate exercise with bone density, researchers have documented kinetic activities of children. Estimates on the average and peak forces have been made from surveys and questionnaires.[2] However, this method does not provide researchers with the definitive information they need to make accurate conclusions. Inherent sampling and reporting biases create an intolerable amount of error within the data. Bone-health researchers need a new method to collect data.

Current technology already exists for kinetic analyses; however, there is no device that can do this both continuously and inconspicuously. Designs have been created; however, many are either expensive or intrusive. Additionally, designs have been made for specific cases and not general use.[3-5]

CHOP and the ESE Department of University of Pennsylvania have been collaborating to find a solution. Dr. Babette Zemel, CHOP, and Dr. Jay Zemel, ESE, have proposed an in-shoe device to measure physical activity. The device would be able to collect quantitative data researchers need to understand bone density. The device uses piezoelectric polyvinylidene difluoride (PVDF) film sensors to obtain force measurements.

Research has already confirmed the potential for the device; however, no integrated design has been created. Current research has been devoted to the development of such a design. According to an Iowa State University study, there are several things to consider when designing a device to record childhood kinetic activities.[6] The device must be able to record sporadic and intermittent activity while balancing the accuracy/practicality trade-off. Designs may include accurate components; however, they are likely to be expensive or intrusive. A device design must find a middle ground where it can both be reasonably accurate while remaining unobtrusive and inexpensive. The remainder of this paper is devoted to the research into the design of the device.

1.2 Preceding Work

Research on the creation of a pediatric dynamometer started in 2004.[7] The work started by looking at the mechanical properties of the piezoelectric polyvinylidene difluoride sensors (PVDF). The potential for PVDF sensors in a pediatric dynamometer was confirmed. Research continued on the development of circuitry and software of the device. A simple user interface was created along with a programmable circuit. At this point the device was too large, so research was devoted to the electrical circuit design until it was capable of fitting inside a child's shoe. A device was assembled in early 2007, but without a standardized device design. The focus of the current project has been to create a standard design for the device.

1.3 Goals of the Current Project

Recent projects have successfully reduced the size and power usage of the device, but the components have yet to be integrated into an accurate and reproducible foot dynamometer.[8] There are thousands of potential ideas for the design of the device, so the goal of this summer's research was to narrow the possibilities. A successful design for the Foot-PAD must meet the following characteristics:

1. It must be reliable so that it collects measurements with 10% of actual output accuracy
2. It must be comfortable so that the patient is unaware of its presence
3. It must be inexpensive to produce so that it can be widely used by researchers

It is critical that the design meet these standards to be of use to the research needs of the Children's Hospital of Philadelphia. Without accurate force measurements, the data obtained will be meaningless. If the device is uncomfortable, the subject may alter his or her physical activities and if expensive the device would not be widely available for researchers. The goal for the summer's research was to create a design that meets these three standards.

2. Creating a Design for the Pediatric Dynamometer

2.1 Device Overview

The device has three basic components: one 1.125"x 1.406" circuit board, two PVDF sensors, and a combination of design materials including a sole insert. The specifics of the circuitry can be found in previous research.[9] A basic overview of the PVDF sensors can be found in the next section, and the design materials will be discussed Section 2.4. Pictures of each component can be seen below. (The schematic of the circuit can be seen in Appendix A and the design in Appendix B)

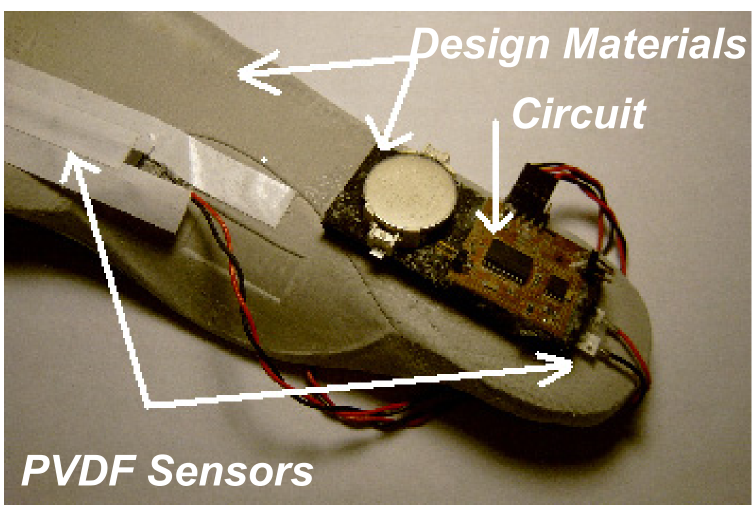
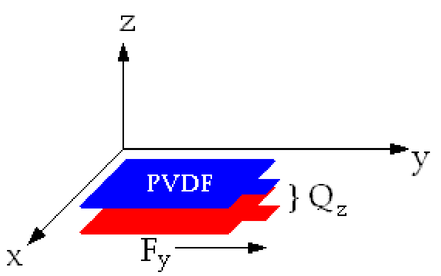


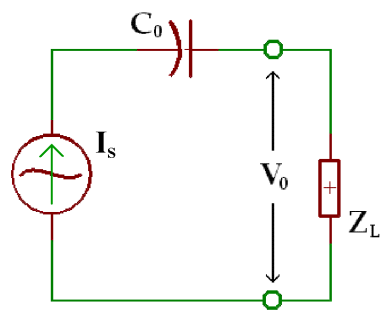
Figure 1.1 Previous Device Design Attempt [10]

2.2 Basics of PVDF sensors

The piezoelectric polyvinylidene difluoride (PVDF) sensor is a crucial part of the pediatric dynamometer. The PVDF is the portion of the Foot-PAD that collects the data used to analyze physical activity (Figure 1.1). A brief summary of the theory of operation of the PVDF sensors, taken from past reports on the pediatric dynamometer, is given below:[11,12]

> The principle behind these sensors is piezoelectricity. PVDF is a piezoelectric thin-film polymer. When the sensor is strained, charges accumulate on the surfaces, inducing current in the external circuit. The figures below show the basic operation of the PVDF sensor in response to a force in the horizontal direction.





Left: PVDF Sensor Force-Charge Relation
Right: PVDF Equivalent Circuit[13]

> The linear relationship governing this charge displacement is: $Q_z = d_{zy}F_y$ where Q_z is the charge displaced across the planar surface, d_{zy} is the longitudinal piezo strain coefficient, and F_y is the force along the y-axis. The equivalent circuit shows a current source I_S in series with the sensor's capacitance C_0. The external circuit is the load, Z_L.
>
> In order to be used with other circuitry, the PVDF is coated with a thin layer of conducting material, typically silver, and is then laminated with a protective plastic coating. A pair of terminals is attached for connection to the external circuit. Charge induced in the external circuit during an instant of time is fundamentally expressed as the definition of current: $dQ/dt = I$. The behavior of the PVDF sensor in a circuit analysis context is as follows: any change in the deflection of the device results in an immediate current flow through the load Z_L. At any period of time when the sensor is stationary the net current through Z_L is zero.

As stated in the description, the piezoelectric effect from the PVDF can be manipulated to measure force. When a mechanical force is placed on a dielectric crystal, a deformation in the lattice occurs. A proportional electric polarization is created from the lattice deformation. The polarization creates an electric field in which a flow of charge known as piezoelectricity occurs. The flow of charge can be observed to find the voltage in the crystal and across the entire film. Therefore, the charge generated in the PVDF is proportional to the force that puts strain on the lattice.
A tensile strain on the PVDF film generates a proportional charge.

$$F_y \propto Q_z$$

The flow of the charge produces a current.

$$I = \frac{dQ_z}{dt} \propto \frac{dF_y}{dt}$$

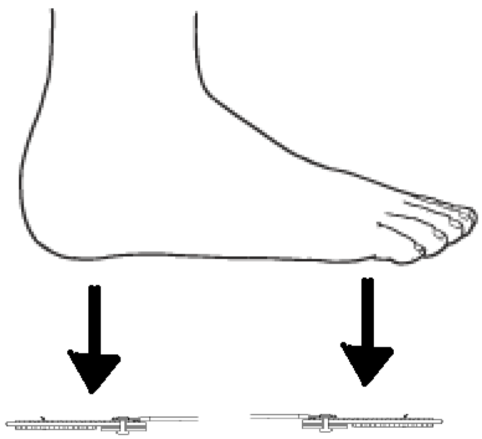
From Ohm's Law, the current can be found with the voltage and resistance.

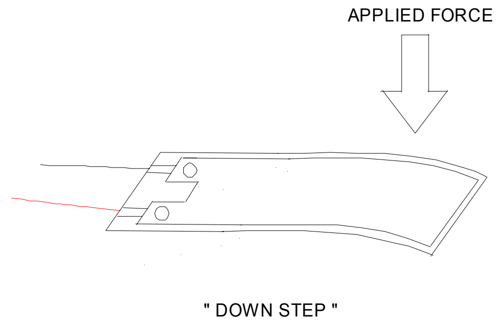
$$F_y \propto \int_{t_{begin}}^{t_{end}} I \cdot dt = \int_{t_{begin}}^{t_{end}} \frac{V}{R} dt$$

With appropriate calibration, the force may be related to the strain on the PVDF and as a result, the force on the foot (examined in the next section).

2.3 Mechanics of the Problem

An understanding of the mechanics of walking and of the device is necessary to understand the problem. When children walk, they exert forces through their feet. The forces are applied to the ground in the vertical direction and create stress on the sole of the shoe. The goal is to find the forces the children exert.





Left: Foot applying a force to a PVDF sensor
Above: PVDF sensor under an applied force, resulting in tensile strain[14]

The applied forces from the child can be found using PVDF sensors and knowing their stress-strain relationship. Since the strain is found from the resistance and voltage of the circuit (see previous section), all that is needed is the stress-strain relationship.

The stress-strain relationship can be determined through a series of tests; however, it is crucial that the relationship be consistent. The reproducibility of the relationship will directly affect the accuracy of the predicted force from the foot. In order to have a consistent relationship, the transduction must be controlled by manipulating the design materials and structures. The design materials and structures will determine the mobility of the PVDF sensors and thus the accuracy of the device.

2.4 Designing a Structure for the Device

The structure of the pediatric dynamometer was the most important part of the research this summer. The research helped to narrow down possibilities for the design of the device. The structure is important because it gives the device its shape and dynamics. The shape of the design will affect the comfort of the device and the dynamics, its accuracy.

Choosing Materials and Design

Materials for potential use in the PD.

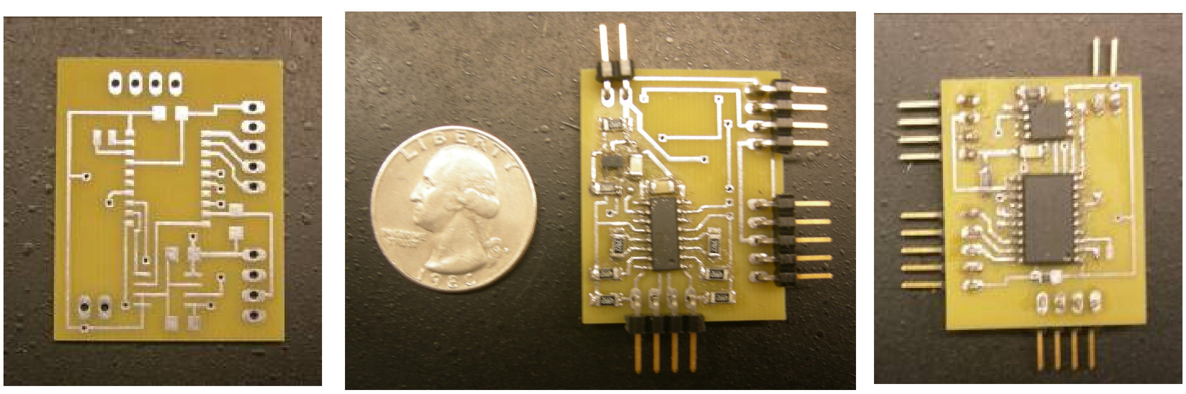
The choice of materials used in the design is important because of its effect on the structure of the device. The structure can take advantage of a material's properties such as a high yield strength, stiffness or flexibility. In the research, the majority of the materials used were elastomers (see picture to the right), spring steel and insert soles. Elastomers are prevalent in shoes because of their linear stress-strain relationship due to compressive forces. Spring steel is also used because of its high yield strength and a small piece is already used in PVDF film. Another material that used was insert soles. The soles can increase comfort and may also be able to conceal the device.

The appropriate piezoelectric polyvinylidene difluoride sensors must also be selected. PVDF sensors come in different shapes and sizes. Depending upon the design, it may be beneficial to change the size or shape of the PVDF.

Many designs were tested during the research leading to those that will be discussed in the results section.

Populating the Electronic Device

The final electronic device was populated with a PIC16F690 microcontroller, a S25FL016A Spansion flash memory, an OPA237N operational amplifier, an INA2126 instrumentation amplifier, 4 JP junctions, 11 resistors and 3 capacitors. Due to the size of the circuit, it was difficult to solder the components without creating a short circuit. However, the soldering was completed and each component was checked to ensure a proper connection was made.



Left: Circuit board of the PD without components (1.125"x 1.406")
Middle: Front of the circuit board with components.
Right: Back of the circuit board with components.

2.5 Testing the Force Sensor Designs

Three different methods of testing were used during this research project. Each of the methods involves simulation techniques. Although no children were ever asked to wear the shoes, simulations of children using the Foot-PAD were done.

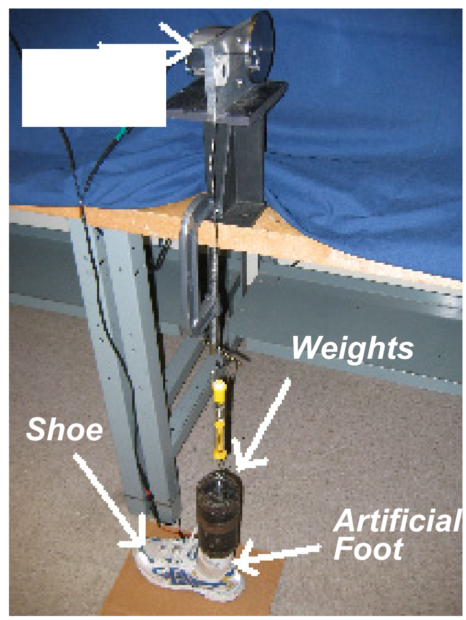
The first and simplest method was a manual application of force. A force was applied to the design by using the heel of the hand. A manual application of force has several advantages. The length and magnitude of force can easily be varied to desired amounts. An intermittent and sporadic force can also be simulated. The magnitude of the force was measured using a digital scale that was placed underneath the design. The biggest disadvantage was the difficulty in creating a force consistent of that to a foot.

The second method was a motor operated force (see picture) that would periodically lift a shoe off the ground. A set of free weights was placed on top on an artificial foot to simulate the force of a child. The periodic motion of the foot simulated the movement of a person walking and the contact with the ground simulated an applied force from the artificial foot.[17]

The final method was the testing using my own shoe. I walked with the device in my shoe to test the accuracy and comfort of a particular design. This was the best way to simulate the actual force of walking and comfort of the design.

Each of these three methods was used to evaluate each design.

Scale used to measure applied force.



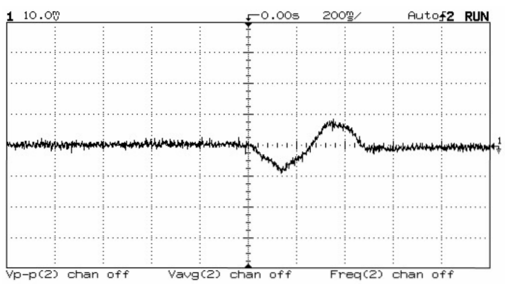
System used to simulate walking.

3. Results

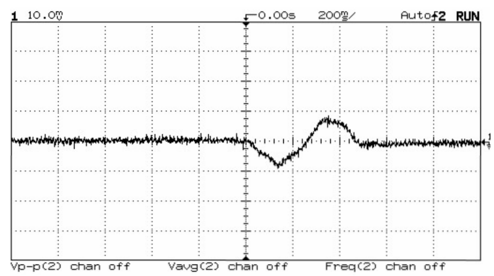
3.1 Materials

The graphs below shows a force applied to an elastomer for a period of five hours. The constant force was applied by the motor operated testing. Over the course of five hours, the signal remains essentially unchanged in shape and magnitude. The only change is that the signal is larger due to a "worn-in" effect. After about two hours, the effect stops. The graphs prove the potential for elastomers to create fairly reliable and reproducible signals even after an extended period of time. However, even small deformations can create problems with the calibration of the device. (See Appendix A for help with analysis)

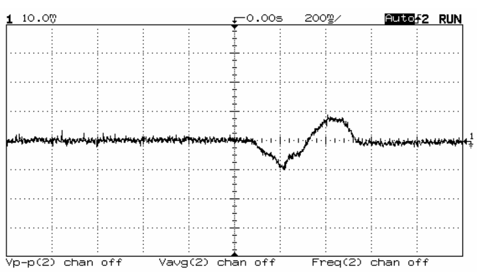
Start



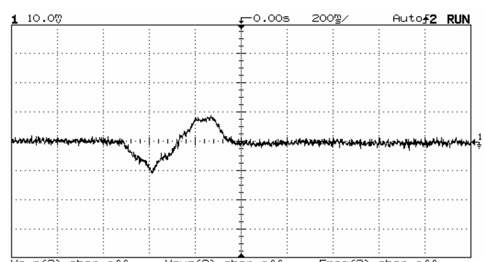
After 1 hour



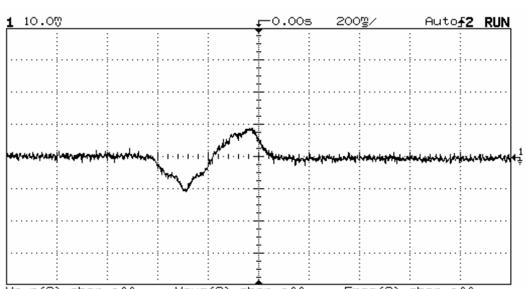
After 2 hours



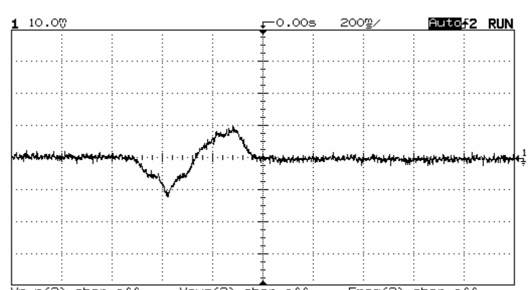
After 3 hours



After 4 hours

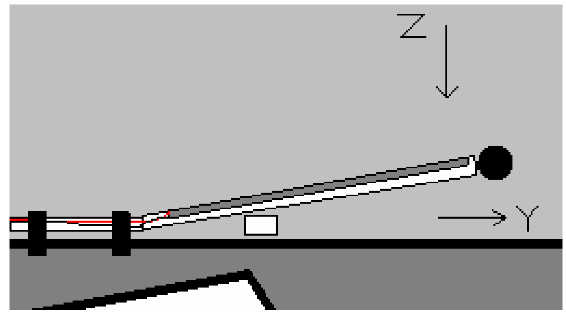


After 5 hours



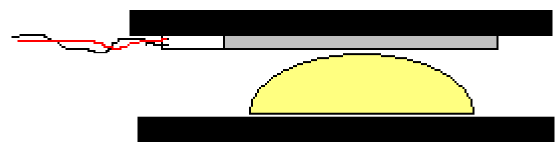
3.2 Designs

Cantilever Beam



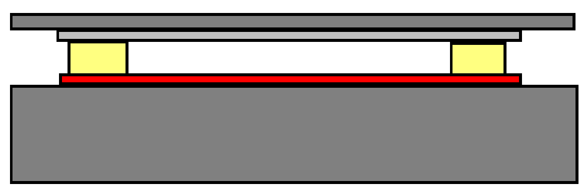
The cantilever beam design was one of the last ideas tested. It is made of thick spring steel, a neoprene pivot and a piezo film on top of the beam. When a vertical force is placed on one end of the beam, the piezo film deforms. The deformation produces force in both the z (compressive) and y (tensile) directions. The spring steel allows the device to deform with a linear stress-strain relationship. The other end of the design is fixed directly to the shoe to act as an anchor. The width of the spring steel and size of the neoprene pivot will determine the stiffness of the design. When tested, this design proved to be accurate, but concerns remain about its comfort in a shoe: the design requires a large amount of steel that may be uncomfortable over time.

Curvature



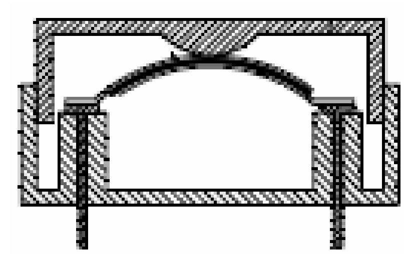
The curvature design is made of two elastomers, and a small, hard and curved material. When a vertical force is applied to the design, the elastomers force the piezoelectric film around the circumference of the curve. The deformation in the piezo film is created by the shape of the curve. Different radii were used during testing to compare accuracy. The design creates a constant deformation with low force; however, after the piezo film completely surrounds the curvature it no longer has a linear stress-strain relationship. Stiff elastomers can be used to increase the yield strength of the design.

Bridge



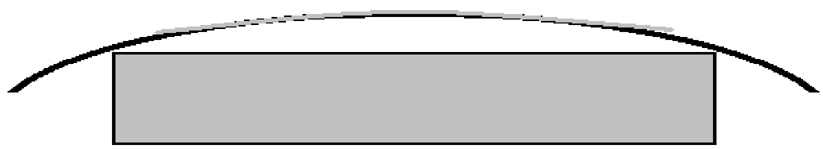
The bridge design uses elastomer foam, steel and two support mechanisms. The elastomer foam is placed on top followed by the steel and then the support mechanisms. The PVDF sensor is placed underneath and rests on top of another elastomer. As a vertical force is applied to the top of the design, the steel bends inward for support and comfort. The force is placed directly on the two supports which in turn place force on either end of the PVDF. The elastomers provide additional stiffness to hold heavier loads.

Bow



The bow design idea came from the MSI Piezo Film Sensors Technical Manual.[15] The basic idea behind the design is that a vertical force will deform the sensor from its initial "bow" shape. The vertical force placed on the apex of the bow is converted into a horizontal force within the piezo film. Spring-like materials are used to increase the stiffness of the design to allow it to work with higher forces. However, the major drawback to this design is its complexity. It uses several spring-like mechanisms when only one is necessary. A simpler design would be better.

Elastomer Support

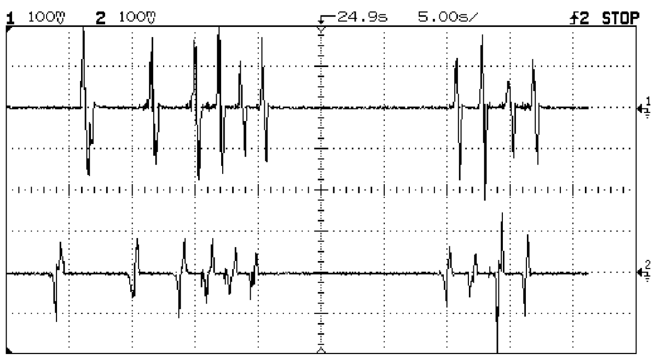


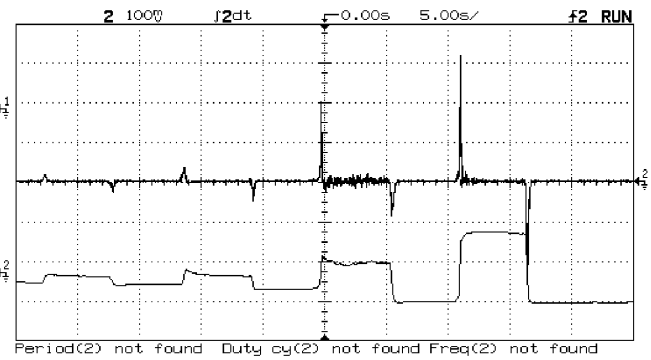
The elastomer support design is made up of a piece of elastomer, a piece of curved steel and the PVDF sensor. The sensor is placed on top of the curved steel and the curved steel is placed on top of the elastomer. When a vertical force is applied to the top of the steel, the steel straightens. The straightening of the steel deforms the sensor proportionally to create a linear relationship. The force put on the steel will also compress the elastomer supporting it. The elastomer support design was a very simple and comfortable design, but did not have the accuracy that was needed. Once the steel completely straightened out, the PVDF would not deform proportional to the vertical force.

4. Conclusion

4.1 Conclusions

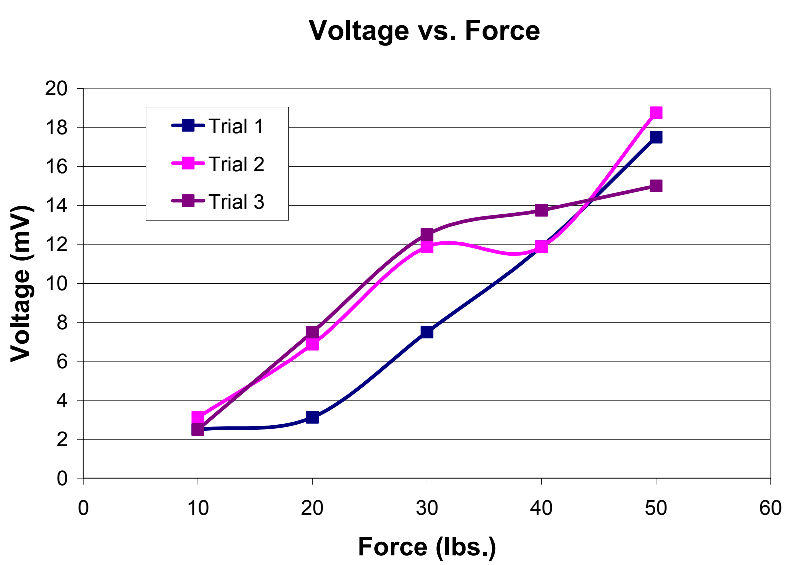
Hundreds of designs were tested throughout the research and a general design was found. The best design according to the three standards ended up to be the “bridge” design. The design was small, fairly accurate and inconspicuous. Although the device design has not met accuracy standards, it is believed to have the most potential.

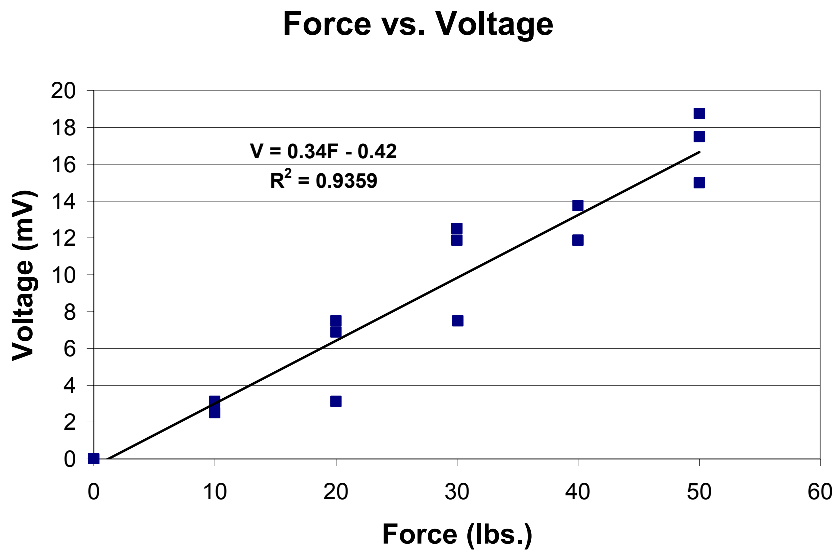




The graph on the left uses the design during a walking exercise. The top function is the sensor at the balls of the feet and the bottom function is the sensor at the heel of the foot. It is clear that the design can obtain measurements during walking.

The graph on the right uses the design for several increasing amounts of force. The top function is the change in the voltage (change in force) of the device and the bottom function is its integral. The bottom function increases with force close to linearly.





The design clearly allows for a linear voltage and force relationship. The problem is that the relationship is not reproducible or accurate enough.

4.2 Future Work

Research has narrowed down the number of potential designs for the device and has confirmed the "bridge" design as having the most potential. Future research should be focused on optimizing the design using modeling techniques. Several parameters that need to tested in order to find the best design. Some of the parameters are listed below:

- Young's Modulus of the spring steel for comfort
- Young's Modulus of the elastomers for accuracy
- Material for two anchors
- Distance between two anchors
- Placement of design in shoe
- Height of two anchors

Once the design is optimized, it should be much more accurate and reproducible. The implementation of the device will be possible soon after.

5. Acknowledgments

First, I would like to thank my advisor Dr. Jay Zemel. Dr. Zemel has been a wonderful person to work with. During the project, he always encouraged and helped me. The thing I appreciate the most was his willingness to put my education before the research. He took time to explain the concepts and significance of the research. He has been a great advisor and has helped prepare me for success in graduate school.

I would like to thank Dr. Van der Spiegel for assembling such a wonderful program. Dr. Van der Spiegel was very supportive and encouraging throughout the summer. I appreciate the effort he put into organizing the great workshops and guest speakers we had during the SUNFEST program.

I would also like to thank David Joffe and Dr. Santiago's lab for being cooperative. I worked with them all summer and they were friendly and welcoming to me. I would like to thank the other SUNFEST and LRSM fellows for making the summer such a wonderful experience. We had a lot of fun over the ten weeks and I will miss the friends that I have made. Finally, I would also like to thank the National Science Foundation for funding this program. I hope they continue to fund programs like this so that future students will have the same opportunity I did.

6. References

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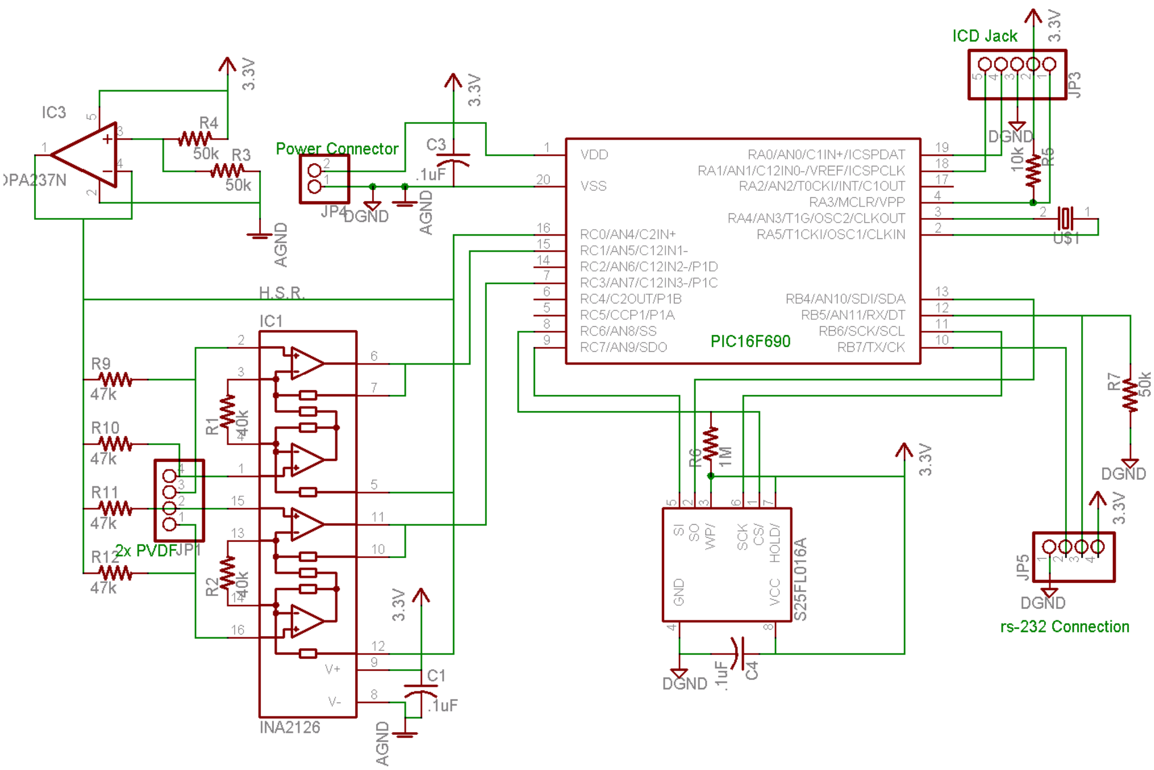
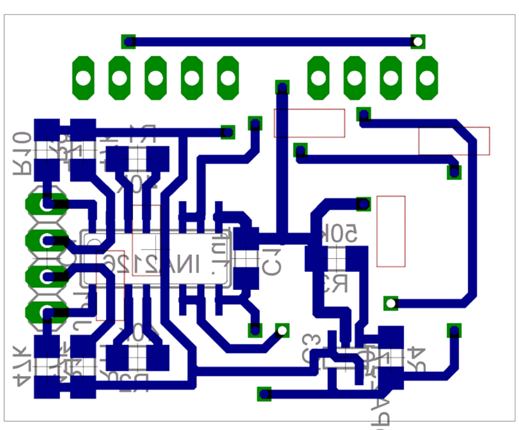
[15] Unpublished Senior Design Report: L. Lamptey, J. Sin, M. Wong; *Pediatric Step Monitor for Bone Health Studies*. Univ. of Pennsylvania, 2005.

[16] Measurement Specialties Inc., Norristown, PA. *Piezo Film Sensors: Technical Manual*. April 1999.

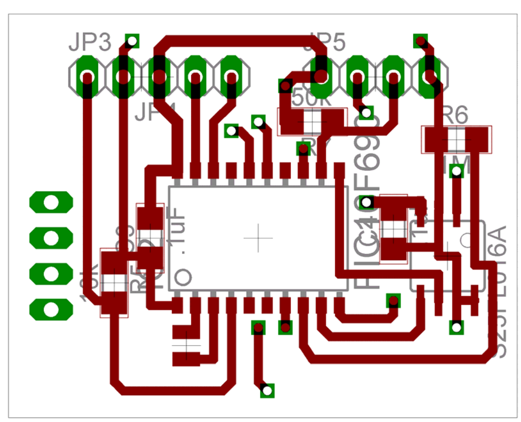
Appendix A. Schematic of the Pediatric Dynamometer Circuit



Appendix B. Design of the Circuit Board



Top of the circuit board



Bottom of the circuit board

Appendix C. Graph Analysis

The graph shown below is a voltage versus time graph of the generated voltage in the piezoelectric film. The function on top is a representation of the change in voltage over time and it is integrated to give the function on the bottom. The basic features of the graph are labeled for an understanding of the results section.